COAXIAL-TIP PIEZORESISTIVE CANTILEVER PROBES FOR
HIGH-RESOLUTION SCANNING GATE MICROSCOPY

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Abstract

Scanning probe techniques provide a wealth of information about the nanoscale properties of materials and devices, ranging from topography to surface potential. In scanning gate microscopy (SGM), the current through a sample is recorded as a sharp, conductive tip that modifies the local electrostatic potential is scanned above the surface. SGM has been used to map current flow, carrier density and potential barriers. Existing, unshielded SGM probes have significant stray capacitance, resulting in poor lateral resolution when they are used to image nanostructures. Thus, there is a need for a probe that minimizes stray capacitance to produce highly-localized electric fields. This probe must also self-sense topography for tip-sample alignment, as the conventional laser-based detection methods can disturb photosensitive samples.

In this thesis, we present a new scanning probe that integrates a coaxial tip on a piezoresistive cantilever. The coaxial tip is comprised of a heavily-doped silicon inner conductor and an aluminum outer shield, separated by a silicon dioxide insulator. By shielding the inner conductor up to the tip apex, this tip configuration minimizes stray capacitance to produce narrow electrostatic potential profiles. A piezoresistor is embedded at the root of the cantilever and enables electrical measurement of deflection at the free end.

Scanning gate microscopy is commonly performed at room temperature (room-T) and low temperature (low-T). We discuss the design of piezoresistive cantilevers for atomic force microscopy (AFM) under both temperature regimes. We introduce a numerical optimizer that we used to identify 12 cantilever designs for use at room-T and low-T for hard, semiconductor samples and soft, biological samples. The code
varies piezoresistor and cantilever geometry, operating conditions and fabrication parameters, within supplied constraints, to arrive at a design that optimizes vertical displacement resolution. We show the results of finite-element analysis used to predict the electrostatic potential profiles produced by unshielded and coaxial tips. We investigate how the full-width at half-maximum (FWHM) of the coaxial tip perturbation varies with lift height and tip geometry. We discuss the development of a 7-mask process to fabricate scanning probes with both a coaxial tip and a piezoresistor. We compare two methods to create sub-micron tip apertures with focused ion beam milling, and provide a recipe that can repeatably produce openings with a radius of 30 nm. We describe the characterization of the piezoresistive cantilevers at room-T on a commercial AFM and at low-T on a home-built cryogenic scanning system. Finally, we provide images of the potential profile from the coaxial tip, obtained using a quantum point contact at low-T.

In a measurement bandwidth from 1 Hz–10 kHz, our scanning probes achieve a vertical displacement resolution of 2.8 Å at 293 K and 82 Å at 2 K, where the low temperature performance is limited by amplifier noise. When the coaxial tip is 100 nm above a sample, the FWHM of the electrostatic potential profile it produces at the surface is less than 240 nm, representing a 2.3x improvement in the lateral resolution of SGM over unshielded tips.
Acknowledgement

It has been a long six years, full of ups and downs, successes and frustrations. Frankly, I never thought that I would make it through the Ph.D. I’m not an academic and writing, for me, is a painful and tedious process. And so, it comes as a surprise that I am sitting here now writing the longest document of my life. Certainly, getting to this point would not have been possible without the support of numerous individuals along the way.

First and foremost, I would like to thank my advisor Professor Beth Pruitt for taking a chance on me and in so doing, introducing me to the world of MEMS. Perhaps seeing my anxiousness to get into the fab, she promoted me off the waitlist of ME342 in my first year at Stanford and through her class, I learned the fundamentals of MEMS design, fabrication and characterization. Soon after, she encouraged me to write the exploratory and seed grant proposals that initiated this project. Beth, thank you for your guidance and patience, particularly when progress was slow.

My interest in scanning probes was piqued by the AP275 class. I remember being amazed by images of electron flow in the lecture on scanning gate microscopy given by Professor David Goldhaber-Gordon, who would become my co-advisor and collaborator. David, thank you for being the intellectual anchor of our team and for inspiring me to achieve your level of technical rigor. I apologize for the numerous blank stares over the years.

Professor Roger Howe joined the Electrical Engineering faculty at the same time that I started at Stanford. I hoped then that I would have a chance to interact with one of the “founding fathers” of MEMS. Fortunately, as a member of the Stanford Nanofabrication Facility (SNF) User Advisory Committee, this has been possible.
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Chapter 1

Introduction

This thesis describes the development of a new cantilever probe for scanning gate microscopy. In this chapter, we provide the fundamentals upon which the rest of the thesis is based. We first describe scanning probe microscopy in general and then focus on atomic force microscopy and scanning gate microscopy. We discuss the limitations of existing probes for the latter technique, and motivate the need for a new probe. We introduce the salient features of our scanning probe and finally, provide an overview of the thesis.

1.1 Scanning Probe Microscopy

Scanning probe microscopy (SPM) refers to a family of techniques used to investigate the local (typically micron-scale and smaller) properties of materials and devices. These techniques require a probe, which usually consists of a sharp tip integrated at the free end of a cantilever spring, as shown in Figure 1.1. In most cases, the cantilever is hundreds of microns long, tens of microns wide and several microns thick while the tip apex has a radius of curvature less than 50 nm. Thus, the probe bridges the macroscale (i.e. the system in which it is mounted) and the nanoscale. To perform a measurement, the probe is raster-scanned over the sample of interest while the tip is in contact with or in close proximity to the surface. As the probe is scanned, a specific interaction between the tip and sample is recorded, which provides information about
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Figure 1.1: Basic principle of scanning probe microscopy. A sharp tip integrated at the end of a cantilever spring is raster-scanned while in contact with or in close proximity to the sample surface. While scanning, an interaction between the tip and sample is monitored (e.g. repulsive forces leading to cantilever deflection), which provides information about the sample at the tip location.

The sample at each tip location.

In 1982, Binnig and colleagues demonstrated the first scanning probe technique, scanning tunneling microscopy (STM), a method of imaging the local density of states on a sample surface [1]. In STM, the wavefunction overlap of empty and filled states in the tip and sample, respectively or vice versa, leads to a tunneling current when a voltage is applied between them [2]. This tunneling current decays exponentially with tip-sample separation, and as such, most of the current is carried by the frontmost atom of the tip. Because the probe is effectively a single atom, this technique can achieve atomic resolution with relative ease. STM is typically performed in constant current mode where a feedback loop adjusts the tip height to maintain a current setpoint as the probe is scanned. The STM image is then produced by plotting the tip height in two dimensions.

Despite its tremendous impact on science, STM has a major limitation that results from its dependence on current flow: the tip and sample must be conductive. Furthermore, the surfaces involved in the scanning process must be clean and stable, which typically requires STM to be performed in ultra-high vacuum. Under ambient
conditions, these surfaces are susceptible to adsorption and desorption of particles.

The success of STM led to the development of a vast portfolio of scanning probe techniques to interrogate local properties ranging from magnetization to surface potential. These properties can be accessed by coating the tip with different functional layers and/or by observing different interactions between the probe and the sample while scanning, including changes in cantilever deflection and resonant frequency.

1.2 Atomic Force Microscopy

While developing STM, the researchers observed significant forces acting between the tip and the sample when the two were close enough to elicit a tunneling current. In 1986, Binnig et al. demonstrated atomic force microscopy (AFM), a technique that exploits these forces to map surface topography [3]. Because AFM uses tip-sample forces and not tunneling current, it can be performed under ambient conditions on a wide variety of materials, including insulators. This versatility has made AFM the most commonly-used scanning probe technique today. For an excellent review of advances in AFM, see Ref. [4].

Several types of forces act between the tip and the sample. These forces can be classified by their range, direction and strength. If we approximate the end of the tip and the sample below it as neutral molecules, their interaction can be modeled by the Lennard-Jones potential, seen in Figure 1.2. When the tip approaches a surface, it first experiences a long-range attractive force resulting from van der Waals interactions. On contact, the tip experiences short-range repulsive forces resulting from overlapping electron orbitals and from Coulombic repulsion between positively-charged nuclei. In ambient conditions, a water meniscus often forms between the tip and sample, which leads to strong adhesion forces. More advanced scanning probe techniques such as electrostatic force microscopy and magnetic force microscopy measure other common tip-sample forces, as indicated by their names.

The net force $F$ exerted on the tip causes the cantilever to bend. The displacement at the free end $x$ is given by Hooke’s Law, $F = kx$, where $k$ is the spring constant of the cantilever. In most AFM systems, the cantilever displacement is measured using a
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Figure 1.2: The Lennard-Jones potential $V_{LJ}$, which models energy as a function of inter-particle spacing $r$ between two neutral atoms or molecules. This model approximates the interaction between the tip and sample. At long range, attractive forces due to van der Waals interactions dominate. At short range, repulsive forces due to overlap of electron orbitals and proximity of positively-charged nuclei dominate. The sum of these contributions produces a potential curve with a minimum of $-\varepsilon$ at $r = 2^{1/6} \sigma$. AFM is typically performed in contact, non-contact or tapping mode where contact and non-contact modes utilize the purely repulsive and attractive regimes, respectively, and tapping mode utilizes both regimes.

laser. Commercial AFM systems typically employ the “optical lever” method, where the laser beam is reflected off the back of the cantilever and onto a position-sensitive photodiode (PSPD). More sophisticated AFM systems use optical interferometry. Because they are thin, AFM cantilevers are often coated with a metal film to increase their reflectivity.

Here, we focus on the optical lever method, presented in Figure 1.3, as it is the most common. Prior to scanning, the laser spot is centered on the photodiode by adjusting a mirror in the optical path. As the probe is scanned, changes in cantilever deflection cause the laser spot to move. A difference in the power collected by the
1.2. ATOMIC FORCE MICROSCOPY

Figure 1.3: Schematic of the optical lever method used in most commercial AFM systems to measure cantilever displacement. A laser is reflected off the back of the cantilever and onto a position-sensitive photodiode (PSPD). A mirror in the optical path allows the laser spot to be centered on the PSPD prior to scanning. While scanning, changes in cantilever deflection cause the spot to move. The output of the PSPD goes into a feedback controller that can adjust the height of the probe to maintain a deflection setpoint.

Top and bottom halves of the photodiode indicates cantilever deflection normal to the sample surface while a difference between the left and right halves indicates cantilever torsion. A typical force-distance curve measured by the PSPD as the tip approaches and retracts from the sample is provided in Figure 1.4.

Atomic force microscopy is commonly performed in one of three modes, contact, non-contact or tapping, with each mode operating in a different regime of tip-sample force (see Figure 1.2). Contact mode is the simplest of the three. In this mode, the tip is engaged with the sample surface, where repulsive forces dominate. These forces produce static cantilever deflection, which is measured with the laser. While scanning, either tip height or force is held constant. When height is fixed, the cantilever deflection varies as the probe encounters sample topography. Thus, the image is constructed directly from the output of the photodiode. The main disadvantage of this method is that the probe can be damaged if it collides with surface features. Consequently, contact mode is normally performed with constant force, where a feedback
CHAPTER 1. INTRODUCTION

Figure 1.4: Representative force-distance (F-D) curve measured by the PSPD as the tip approaches and retracts from the sample. On approach, the tip first experiences long-range attractive forces. This force can quickly overcome the restoring force of the cantilever spring, causing the probe to snap into contact with the surface. Approaching further causes the cantilever to deflect in the opposite direction, as the tip now experiences short-range repulsive forces. The location of snap-in and the slope of the F-D curve are functions of the cantilever stiffness. Under ambient conditions, the probe must be retracted further than the point that it snapped in to release it from the surface as it is held by meniscus forces.

loop adjusts the tip height to maintain a user-specified value of cantilever deflection. In this case, a plot of tip height forms the image. Because contact mode requires the tip to be dragged along the sample surface, it can result in significant tip wear and sample damage. To minimize damage, contact mode cantilevers are soft with $k \leq 10 \text{ N/m}$, less than the interatomic spring constants of atoms in a solid [4].

In non-contact mode AFM, the probe tip does not touch the sample surface, minimizing tip and sample degradation. The cantilever is vibrated at a frequency slightly above its fundamental resonant frequency $f_0$. The mechanical oscillation is typically applied using a piezoelectric element built into the probe mount. As the probe approaches the surface, the long-range attractive forces between the tip and sample cause $f_0$ to decrease. This change in resonance in turn causes the oscillation
amplitude to decrease and its phase to shift with respect to the driving signal. While scanning, a feedback loop controls tip height to maintain a setpoint for amplitude, phase or frequency.

The water meniscus that forms under ambient conditions can make it difficult to position the probe close enough to the sample to sense forces without the tip sticking to the surface. Tapping mode AFM was developed to overcome this problem. Like non-contact mode, tapping mode is also dynamic, and the cantilever is vibrated near its resonant frequency. However, the amplitude of oscillation is larger and the probe is positioned closer to the surface, allowing the tip to penetrate the water film. In each cantilever oscillation, the tip touches the surface, sampling both the attractive and repulsive force regimes. As such, this mode is also known as intermittent contact. Example images of surface topography taken with AFM are provided in Figure 1.5.

### 1.3 Scanning Gate Microscopy

In scanning gate microscopy (SGM), the current through a sample is monitored as a conductive probe is scanned above the surface. The bias on the probe modifies
CHAPTER 1. INTRODUCTION

Substrate
Insulator
Sample
Metal Source
$V_s = 0 \text{ V}$
$V_{\text{tip}}$
$V_d > 0 \text{ V}$

$V_{\text{ds}}$

Conductance:

$$G_{\text{ds}} = \frac{I_{\text{ds}}}{V_{\text{ds}}}$$

Figure 1.6: Basic principle of scanning gate microscopy. A voltage $V_{\text{ds}}$ is applied across a sample via metal electrodes, resulting in a current $I_{\text{ds}}$. The conductance of the sample is then $G_{\text{ds}} = I_{\text{ds}}/V_{\text{ds}}$. A conductive probe with voltage $V_{\text{tip}}$ is brought into proximity with the surface and modifies the local electrostatic potential. As the tip is scanned, $G_{\text{ds}}$ is recorded, which can provide local information about current flow, carrier density and potential barriers.

the local electrostatic potential in the sample. SGM has been used to measure and manipulate electron flow and organization, carrier density and potential barriers.

The basic setup for SGM is presented in Figure 1.6. Two ohmic contacts, commonly called the source and the drain, are made to the sample. First, a voltage $V_{\text{ds}}$ is applied across the contacts which results in a current $I_{\text{ds}}$. The conductance through the sample $G_{\text{ds}}$ is then given by $I_{\text{ds}}/V_{\text{ds}}$. Next, a conductive tip is placed in close proximity to the sample surface, but not in contact (typically within 100 nm). The change in electrostatic potential induced by the tip modulates $G_{\text{ds}}$, which is recorded as the tip is scanned. In this way, the tip is analogous to the gate in a metal-oxide-semiconductor field-effect transistor (MOSFET), except that its position is not fixed and its effect is more localized. Unlike most scanning probe techniques including STM and AFM which can only provide information about the sample surface, SGM can investigate buried layers - an advantage that results because the technique relies on capacitive coupling between the tip and the sample.

Scanning gate microscopy was first used to investigate electron flow emanating from a quantum point contact (QPC), as shown in Figure 1.7 [6–9]. This device
Figure 1.7: Procedure for imaging electron flow from a quantum point contact (QPC) with SGM. (a) The sample consists of a two-dimensional electron gas (2DEG) confined in a GaAs/AlGaAs heterostructure. Applying a negative voltage $V_G$ to the surface gates depletes the 2DEG, forming a narrow constriction. Conductance $G_{ds}$ through the QPC is measured by applying an AC excitation $V_{ds}$ across the ohmic contacts and measuring the resulting current with lock-in techniques. A negatively-biased conductive probe is scanned above the surface while $G_{ds}$ is monitored. (b) Top views of the QPC. A change in $G_{ds}$ is observed when the depletion disc created by the tip backscatters electrons. Thus, a spatial map of $\Delta G_{ds}$ reveals electron flow.

consists of a two-dimensional electron gas (2DEG) confined in a GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructure. Two ohmic contacts are made to the 2DEG and two gates are patterned on the sample surface. By applying a negative voltage $V_G$ to the surface gates, the 2DEG below is depleted, leaving a narrow constriction through which electrons can flow from the reservoirs on either side. As before, a voltage $V_{ds}$ is applied across the ohmic contacts and $G_{ds}$ is measured. Next, the conductive tip is introduced. Applying a negative voltage $V_{tip}$ to the tip creates a depletion disc in the 2DEG. Unlike the depletion regions created by the surface gates, the depletion disc created by the tip can be scanned by moving the tip. When the disc is far from electron flow, the change in $G_{ds}$ is small. However, when the disc is placed in a region of high electron flow, they are backscattered by the energy barrier, and $G_{ds}$ is suppressed. Thus, $\Delta G_{ds}$ is proportional to the number of electrons flowing beneath the tip. Plotting $\Delta G_{ds}$ spatially reveals a map of electron flow from the QPC opening as seen in Figure 1.8.
Figure 1.8: SGM image of electron flow emanating from a quantum point contact at 4.2 K, produced by plotting $\Delta G_{ds}$ at each tip location. The flow shows distinct branching and fringing effects. Image courtesy of M.P. Jura.

1.4 Motivation

1.4.1 Pushing SGM into the Nanoscale

Although SGM was first used to study mesoscopic devices, researchers are now attempting to use the technique to investigate a variety of nanostructures of recent scientific interest including carbon nanotubes (CNTs) [10–14], graphene nanoconstrictions [15], quantum dots [16,17] and topological insulators [18]. These nanostructures hold promise as the building blocks of future nanoelectronic devices, including logic and memory elements. As such, it is important to understand how electrons flow through and organize within these nanostructures, a task to which SGM is well suited. However, the limitations of conventional SGM probes have led to several challenges at the nanoscale including insufficient lateral resolution, significant background signal, coupling to surface electrodes and the inability to self-sense topography. In
1.4. MOTIVATION

In this section, we take a closer look at these challenges and motivate the need for a new scanning probe.

### 1.4.2 Lateral Resolution

As discussed earlier, in SGM, a conductive tip is used to locally perturb the electrostatic potential in a sample. The perturbation is introduced strictly via capacitive coupling (i.e. the tip and sample are not in contact). Thus, the lateral resolution of the technique is set by the spatial extent of the electrostatic potential profile produced by the tip. Ideally, the tip produces a delta function perturbation. However, realistically, stray capacitance between the probe and sample broadens the perturbation and degrades lateral resolution.

Stray capacitance can also lead to a significant background signal while imaging. This signal manifests itself as an offset in the DC level of the image. Because this offset is typically not constant over the entire image, nulling it requires non-trivial data processing. Coupling to electrodes on the sample surface can also be problematic if the electrodes are used to set the biasing conditions for the device. For example, in Figure 1.8, the image of electron flow starts \( \sim 200 \text{ nm} \) above the surface gates. If the tip is scanned closer to the gate electrodes, capacitive coupling modulates the effective gate voltage, changing the width of the QPC opening and disturbing the shape of the flow being imaged. To mitigate these effects and maximize lateral resolution, SGM probes must minimize stray capacitance.

### 1.4.3 The Need to Self-Sense Topography

Prior to acquiring an SGM image, the tip must be aligned with the sample. In many scanning systems, particularly those housed in cryostats, there is no access for an optical microscope. Moreover, nanostructures are too small to be resolved optically. As such, tip-sample registration is accomplished through scans of topography. As discussed in Section 1.2, most AFM systems use a laser to measure cantilever deflection. This method is not compatible with SGM when measurements are performed at low temperature. SGM samples are usually photosensitive. While imaging topography,
stray photons from the laser can excite carriers in the sample, which disturbs the subsequent SGM image. At low temperature, excited carriers can take hours or days to relax. Thus, probes designed for SGM should be “self-sensing”, with a built-in sensor that enables electrical measurement of cantilever deflection.

1.4.4 Conventional SGM Probes and Limitations

Researchers currently use two types of probes for SGM, sharpened PtIr wires and metal-coated AFM probes. Although they have been used for basic SGM, both have significant limitations.

The PtIr probes are fabricated by electrochemically etching PtIr wire to produce a sharp tip and then gluing the wire onto a quartz tuning fork [19]. While scanning the tip over the sample, topographic information can be obtained by monitoring the change in resonant frequency of the tuning fork. Thus, these probes are self-sensing. However, they have several drawbacks. First, the fabrication process is serial, producing one probe at a time, and highly manual, requiring the tedious step of mounting the sharpened wire on the tuning fork. Second, the shape of the tip apex is inconsistent between probes and has a relatively large radius of curvature of $\sim 100$ nm, compared with $\sim 10$ nm of commercial AFM probes. Moreover, despite being made from PtIr, a wear-resistant metal alloy, the tip shape changes significantly as the probe is scanned (compare Figure 1.9(h) and (i)). Because the tip shape determines the electrostatic potential profile, it is important for it to be stable and well-known to collect precise data. In Figure 1.9(a)-(g), Gildemeister et al. used a quantum dot (QD) to measure the electrostatic potential profile from a PtIr tip after various in situ cleaning methods, revealing large variations and evidence of multiple effective tips. Third, the tip and wire are unshielded, resulting in significant stray capacitance. When the probe is biased, it produces a broad electric field, which degrades lateral resolution. The long-range effect from the tip is evident in Figure 1.9(d) and (g), where the tip, when placed at the edge of the image, still affects transport through the QD at the center, separated by $>1 \mu m$.

Scanning gate microscopy is most commonly performed with metal-coated AFM.
1.4. **MOTIVATION**

Figure 1.9: (a)-(g) SGM measurements of the current through a 2DEG quantum dot as a function of tip position, used to visualize the electrostatic potential profile induced by the tip. Lines of high current are equipotential lines. (a) Tip potential resulting from initial tip shape. (b)-(g) Tip potential after various *in situ* cleaning procedures. Images show large variation in tip potential and evidence of multiple effective tips and broad electric fields. Also provided are scanning electron microscope images of the tip (h) before and (i) after the measurements, showing a change in tip shape. Reprinted with permission from Ref. [19]. ©2007, American Institute of Physics.

probes as they offer a number of advantages over the PtIr wires. These probes consist of a single crystal silicon cantilever and tip which have been blanket-coated in metal. Typical metal film stacks include Cr/Au, Ti/Au and Ti/Pt. The probes are batch fabricated using standard semiconductor fabrication techniques, allowing hundreds of devices to be manufactured in parallel at a wafer scale. As such, metal-coated AFM probes are available commercially and are frequently used for other scanning probe techniques including conductive AFM, electrostatic force microscopy and scanning capacitance microscopy. The tips are produced using an anisotropic wet etch process, controlled by the crystal planes in silicon, which results in highly-uniform tip shapes. However, these probes usually do not incorporate a sensor to measure cantilever deflection, instead relying on the optical lever method for AFM. Like the PtIr wires, these probes are also unshielded, allowing electric field lines from the entire tip cone...
and cantilever to reach the sample. When researchers attempted to use metal-coated AFM probes to investigate the local gate sensitivity of carbon nanotubes, it resulted in SGM features that were an order of magnitude larger than the diameter of the CNT (Figure 1.10) and a large background signal (Figure 1.11).

In order to maximize the utility of SGM when applied to nanostuctures, we need a new probe that addresses the limitations of the existing designs. The increase in resolution afforded by the new probe will provide more detailed information about previously-studied samples, but will also open the door to new samples and experiments that otherwise would not be possible. This goal is the main motivation behind this work.
1.5 A New Scanning Probe

We have developed a new scanning probe that integrates a coaxial tip on a piezoresistive cantilever [21] as seen in Figure 1.12. In this design, the inner conductor, used to modify the local electrostatic potential in the sample, is completely shielded up to the tip apex. This configuration minimizes stray capacitance, resulting in narrower electrostatic potential profiles than existing probes and improved lateral resolution. The piezoresistor, located at the root of the cantilever, provides self-sensing capability. Its nominal resistance is modulated by strain in the cantilever. As such, cantilever deflection can be measured electrically, without the traditional optical lever setup. Like commercial AFM probes, these probes are batch fabricated using standard semiconductor manufacturing methods. In addition, the tip cone is made from heavily-doped silicon, which can be etched with high repeatability and is wear resistant. In this thesis, we describe the design, fabrication and characterization of this new probe.

1.6 Thesis Overview

The chapters contained in this thesis are organized as follows:
CHAPTER 1. INTRODUCTION

• Chapter 1 Introduction. Fundamentals of scanning probe microscopy with a specific focus on atomic force microscopy and scanning gate microscopy. Motivation of this work through discussion of conventional SGM probes and their limitations. Highlights of our new probe design.

• Chapter 2 Background. Review of the existing technologies and methods upon which this work builds including self-sensing probes, custom tips for electrical SPM and advanced SGM techniques.

• Chapter 3 Design. Description of the constraints placed on the new probe. Selection and justification of the probe materials. Detailed discussion of the piezoresistive cantilever optimization and the finite-element analysis of the coaxial tip.

• Chapter 4 Fabrication. Step-by-step procedure to manufacture the probes along with in-process images. Discussion of problems encountered and improvements for future fabrication runs.

• Chapter 5 Characterization. Testing results including the vertical displacement resolution of the piezoresistive cantilevers at room and low temperature
1.6. THESIS OVERVIEW

and the full-width at half-maximum of the electrostatic potential profile produced by the coaxial tips.

- **Chapter 6 Conclusion and Future Work.** Summary of results and contributions. Suggested next steps both for application of the probes and for subsequent probe designs.

A summary of the symbols commonly used in this thesis, along with their definitions and units, is provided in Table 1.1.

Table 1.1: Alphabetical listing of symbols used in this thesis along with their units and definitions. Greek letters are listed first, followed by Latin letters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Hooge parameter</td>
<td>-</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>Sensitivity efficiency factor</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Resistance efficiency factor</td>
<td>-</td>
</tr>
<tr>
<td>$\theta_{\text{tip}}$</td>
<td>Tip opening half angle</td>
<td>°</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Majority carrier mobility</td>
<td>cm$^2$/V·s</td>
</tr>
<tr>
<td>$\pi$</td>
<td>Piezoresistive coefficient</td>
<td>Pa$^{-1}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Resistivity</td>
<td>Ω·cm</td>
</tr>
<tr>
<td>$\rho_c$</td>
<td>Cantilever density</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>Sheet resistance</td>
<td>Ω/□</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stress</td>
<td>Pa</td>
</tr>
<tr>
<td>$\phi_{\text{tip}}$</td>
<td>Tip electrostatic potential profile</td>
<td>V</td>
</tr>
<tr>
<td>$B$</td>
<td>Measurement bandwidth</td>
<td>Hz</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s modulus</td>
<td>Pa</td>
</tr>
<tr>
<td>$f_0$</td>
<td>Resonant frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_{\text{max}}$</td>
<td>Maximum measurement frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_{\text{min}}$</td>
<td>Minimum measurement frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$F$</td>
<td>Vertical force at tip</td>
<td>N</td>
</tr>
<tr>
<td>$G_{\text{ds}}$</td>
<td>Drain-source conductance</td>
<td>S</td>
</tr>
<tr>
<td>$h_{\text{lift}}$</td>
<td>Lift height (tip-sample distance)</td>
<td>m</td>
</tr>
</tbody>
</table>

continued on next page . . .
Table 1.1: Symbols used in this thesis (continued).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{\text{tip}}$</td>
<td>Tip height</td>
<td>m</td>
</tr>
<tr>
<td>$k$</td>
<td>Spring constant</td>
<td>N/m</td>
</tr>
<tr>
<td>$k_B$</td>
<td>Boltzmann constant</td>
<td>J/K</td>
</tr>
<tr>
<td>$l_c$</td>
<td>Cantilever length</td>
<td>m</td>
</tr>
<tr>
<td>$l_p$</td>
<td>Piezoresistor length</td>
<td>m</td>
</tr>
<tr>
<td>$l_{\text{offset}}$</td>
<td>Tip offset from end of cantilever</td>
<td>m</td>
</tr>
<tr>
<td>$m_{\text{eff}}$</td>
<td>Effective cantilever mass</td>
<td>kg</td>
</tr>
<tr>
<td>$n$</td>
<td>Majority carrier concentration</td>
<td>cm$^{-3}$</td>
</tr>
<tr>
<td>$N$</td>
<td>Total carriers</td>
<td>-</td>
</tr>
<tr>
<td>$P$</td>
<td>Piezoresistance factor</td>
<td>-</td>
</tr>
<tr>
<td>$P_p$</td>
<td>Piezoresistor power dissipation</td>
<td>W</td>
</tr>
<tr>
<td>$q$</td>
<td>Elementary charge</td>
<td>C</td>
</tr>
<tr>
<td>$r_c$</td>
<td>Tip radius of curvature</td>
<td>m</td>
</tr>
<tr>
<td>$r_o$</td>
<td>Shield opening radius</td>
<td>m</td>
</tr>
<tr>
<td>$R$</td>
<td>Piezoresistor resistance</td>
<td>Ω</td>
</tr>
<tr>
<td>$S_{\text{FV}}$</td>
<td>Force sensitivity</td>
<td>V/N</td>
</tr>
<tr>
<td>$S_H$</td>
<td>Hooge noise power density</td>
<td>V$^2$/Hz</td>
</tr>
<tr>
<td>$S_J$</td>
<td>Johnson noise power density</td>
<td>V$^2$/Hz</td>
</tr>
<tr>
<td>$S_{\text{xV}}$</td>
<td>Displacement sensitivity</td>
<td>V/m</td>
</tr>
<tr>
<td>$t_c$</td>
<td>Cantilever thickness</td>
<td>m</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>$V_{\text{bias}}$</td>
<td>Piezoresistor voltage</td>
<td>V</td>
</tr>
<tr>
<td>$V_{\text{bridge}}$</td>
<td>Wheatstone bridge input voltage</td>
<td>V</td>
</tr>
<tr>
<td>$V_{\text{lc}}$</td>
<td>Voltage on tip inner conductor</td>
<td>V</td>
</tr>
<tr>
<td>$\sqrt{V_{\text{noise}}^2}$</td>
<td>Total noise power</td>
<td>V$^2$</td>
</tr>
<tr>
<td>$V_{\text{out}}$</td>
<td>Wheatstone bridge output voltage</td>
<td>V</td>
</tr>
<tr>
<td>$V_{\text{ox}}$</td>
<td>Voltage across tip insulator</td>
<td>V</td>
</tr>
</tbody>
</table>

continued on next page...
1.6. THESIS OVERVIEW

Table 1.1: Symbols used in this thesis (continued).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{sh}$</td>
<td>Voltage on tip outer shield</td>
<td>V</td>
</tr>
<tr>
<td>$V_A^2$</td>
<td>Amplifier noise power</td>
<td>V$^2$</td>
</tr>
<tr>
<td>$V_H^2$</td>
<td>Hooge noise power</td>
<td>V$^2$</td>
</tr>
<tr>
<td>$V_J^2$</td>
<td>Johnson noise power</td>
<td>V$^2$</td>
</tr>
<tr>
<td>$w_c$</td>
<td>Cantilever width</td>
<td>m</td>
</tr>
<tr>
<td>$w_p$</td>
<td>Piezoresistor width</td>
<td>m</td>
</tr>
<tr>
<td>$x_{\text{min}}$</td>
<td>Vertical displacement resolution</td>
<td>m</td>
</tr>
<tr>
<td>$x_{tm}^2$</td>
<td>Thermomechanical noise</td>
<td>m$^2$</td>
</tr>
</tbody>
</table>
Chapter 2

Background

Having motivated the development of a new probe for scanning gate microscopy, we now review the literature on self-sensing probes, custom tips for electrical SPM and enhancements to the basic SGM technique. The review highlights the tradeoffs between competing technologies that we considered in the high-level probe design and summarizes the existing work on which our contributions are based.

2.1 Self-Sensing Probes

As discussed in Section 1.4.3, probes used for cryogenic SGM must be self-sensing as the optical lever method can disturb photosensitive samples. Self-sensing probes confer several additional advantages. Integration of the sensing element on the probe eliminates the need for the external laser and photodiode. With less hardware, the overall apparatus is smaller and less expensive, making it well-suited to portable systems and harsh or space-constrained environments. The tedious process of aligning the laser spot on the cantilever and on the detector is also no longer necessary. Because optical measurement relies on light reflected off of the cantilever, it places a lower limit on cantilever size. Laser spots on commercial AFM systems are typically tens of microns in diameter. Cantilevers much narrower than the laser spot do not reflect enough light onto the detector. The same problem arises when the cantilevers are too thin (as determined by the absorption coefficient of the cantilever material at...
2.1. SELF-SENSING PROBES

the laser wavelength) or are fabricated from an optically-transparent material such as silicon nitride. The dimensions of self-sensing probes can be smaller, allowing for higher force sensitivity and increased bandwidth. Furthermore, if an array of cantilevers is desired for high-throughput imaging, optical measurement requires a laser and detector pair for each cantilever or a sophisticated multiplexing scheme to allow one pair to interrogate several cantilevers \[22\]. Arrays of self-sensing cantilevers are more practical, as each cantilever has its own built-in sensor \[23\]. The challenge for these arrays is routing the data lines off chip.

Self-sensing probes have been demonstrated with capacitors \[24\], piezoelectrics \[25\], quartz tuning forks \[26\] and piezoresistors \[27\]. Here, we focus on the latter two as they are most often used for cryogenic SGM.

2.1.1 Quartz Tuning Forks

We briefly alluded to the use of quartz tuning forks for self-sensing probes when discussing PtIr tips. Here, we describe their operation in greater detail.

Quartz tuning forks are produced in large quantities for use as frequency references in wrist watches and electronic devices. When the base of the fork is fixed and the fundamental resonance is excited, the prongs oscillate in opposite directions. As such, the forces exerted by the prongs are cancelled in the base. Because the fork is crystalline, the internal losses are also small. This combination of geometric and material properties results in large quality factors \( Q \), exceeding 10,000 in air, while silicon cantilevers have \( Q \) values of several hundred under the same conditions \[28\]. Furthermore, the temperature coefficient of the resonant frequency can be made negligible by cutting the quartz along specific crystal orientations. High \( Q \) values and temperature stability are favorable properties for frequency references.

To use a quartz tuning fork as a self-sensing probe, a sharp tip is attached to one of the prongs. Because quartz is piezoelectric, the tuning fork can be made to oscillate by applying a voltage at its resonant frequency. The oscillations are monitored by measuring the displacement current through the fork. This current is converted into a voltage using a current preamplifier. When the tip is brought in close proximity to
a sample surface, tip-sample forces cause a shift in the resonant frequency, resulting in a phase shift between the driving voltage and the oscillation signal. The phase shift is measured with a lock-in amplifier and is used to modulate the driving frequency to match the new resonant frequency. A feedback loop adjusts the tip height to maintain a set frequency shift. Figure 2.1 shows the readout circuit for a tuning fork probe.

Guethner et al. were the first to demonstrate quartz tuning forks as self-sensing probes [26]. They attached the sharp tip to one prong and allowed the other prong to oscillate freely. However, the added mass of the tip and the forces experienced by the tip while scanning introduced an asymmetry in the tuning fork, causing $Q$ to decrease. The damping placed a limit on scan rates and made it difficult to interpret the imaging signal. Giessibl demonstrated that the decrease in $Q$ could be mitigated by fixing one prong and allowing only the prong with the tip to oscillate [28]. A review of advancements in tuning fork probes is included in Ref. [4].

The main advantage of quartz tuning forks as self-sensing probes is low power
dissipation, in the order of nW. In comparison, piezoresistive cantilevers typically dissipate mW. They can be operated with just pW, but because the displacement sensitivity of piezoresistive cantilevers is proportional to the square root of the power they dissipate (see (3.12) and (3.22)), measuring cantilever deflection at lower power levels usually requires lock-in techniques. Quartz tuning forks also have disadvantages. First, the process of mounting tips on tuning forks is not only tedious, but limits the types of tips that can be used and results in performance variation between probes. Second, the readout circuit for tuning forks is more complex than that of piezoresistive cantilevers, and requires more expensive components (e.g. a lock-in amplifier or phase-locked loop).

Recently, a new type of tuning fork probe has been developed that consists of a silicon cantilever bridging the free ends of the prongs \[31\]. In this configuration, the in-plane motion of the prongs is converted to out-of-plane motion of the cantilever. The cantilever integrates a sharp tip and determines the overall stiffness of the probe. In principle, the cantilevers can be attached to the tuning forks in a batch process, a major advantage over previous tuning fork probes.

### 2.1.2 Piezoresistive Cantilevers

Piezoresistance is the change in resistivity of a material resulting from an applied stress. Cookson coined the term piezoresistance \[32\], but the earliest work on change in resistance with elongation was reported by William Thomson (Lord Kelvin) \[33\].

The resistance $R$ of a homogeneous material with resistivity $\rho$, length $l$ and cross-sectional area $A$ is given by

$$R = \rho \frac{l}{A} \quad (2.1)$$

When a stress $\sigma$ is applied to this resistor, the change in its resistance is given by

$$\frac{\Delta R}{R} = (1 + 2\nu)\epsilon + \frac{\Delta \rho}{\rho} \quad (2.2)$$

where $\nu$ is the Poisson’s ratio of the material and $\epsilon$ is the strain induced by $\sigma$. The first and second terms on the right hand side of this expression result from the change
in resistor geometry and the piezoresistive effect, respectively. The stress and strain are related by the Young’s modulus of the material, $E = \sigma/\epsilon$.

In general, resistivity is a function of temperature as well as stress. Thus,

$$\frac{\Delta \rho}{\rho} = \pi \sigma + \alpha_T \Delta T$$  \hspace{1cm} (2.3)

where $\pi$ is the piezoresistive coefficient, $\alpha_T$ is the temperature coefficient of resistivity (TCR) and $T$ is temperature. Substituting (2.3) into (2.2), we have an expression for change in resistance with stress and temperature,

$$\frac{\Delta R}{R} = (1 + 2\nu)\epsilon + \pi \sigma + \alpha_T \Delta T.$$  \hspace{1cm} (2.4)

In the absence of a temperature change, (2.3) simplifies to the constitutive relationship for piezoresistance in a homogenous material,

$$\frac{\Delta \rho}{\rho} = \pi \sigma.$$  \hspace{1cm} (2.5)

For an anisotropic material, (2.5) takes a more complicated form

$$\frac{\Delta \rho_i}{\rho} = \sum_{j=1}^{6} \pi_{ij} \sigma_j$$  \hspace{1cm} (2.6)

where $\Delta \rho/\rho$ and $\sigma$ are six-component tensors and $\pi$ is the second-order tensor of coefficients that relates them \cite{34}. The silicon crystal lattice has cubic symmetry. As such, its piezoresistance tensor is populated with just three coefficients, $\pi_{11}$, $\pi_{12}$ and $\pi_{44}$. These coefficients depend on temperature, doping type and doping concentration \cite{34}.

The gauge factor (GF) of a strain gauge is defined as $(\Delta R/R)/\epsilon$. Metal strain gauges have GFs of 1.4 to 2.0, primarily resulting from the geometric term in (2.2). Bardeen and Shockley predicted that crystalline semiconductors should exhibit large
2.1. SELF-SENSING PROBES

Changes in mobility, and thus resistivity, in response to mechanical deformation potentials \[35\]. This prediction was validated by Smith, who performed the first measurements of the piezoresistive coefficients in silicon and germanium \[36\]. Because of their significant piezoresistivity, silicon and germanium strain gauges have GFs that are 50 to 100 times larger than those of metal strain gauges. In semiconductor strain gauges, the geometric contribution to GF is negligible.

Doped silicon piezoresistors are commonly used in microelectromechanical systems (MEMS) to transduce mechanical signals into the electrical domain. The first silicon strain gauges were reported by Mason and Thurston \[37\]. Shortly after, Pfann and Thurston proposed the integration of a piezoresistor with a force collecting element \[38\] which Tufte et al. realized in the form of a pressure-sensing diaphragm \[39\]. Subsequently, piezoresistors have been demonstrated in accelerometers \[40\], gyroscopes \[41\], and shear stress sensors \[42\]. For a comprehensive review of piezoresistance and its application to microsystems, see Ref. \[43\].

Piezoresistors are attractive as MEMS sensors because they can be readily fabricated using CMOS-compatible processes including ion implantation, diffusion and \textit{in situ} doping during epitaxial growth. Changes in resistance can be detected with a simple circuit consisting of a Wheatstone bridge, differential amplifier and low pass filter (see Figure 2.2). Other benefits of piezoresistive transduction include linear response to stress and large dynamic range (>140 dB \[44\]).

Despite their ease of fabrication and readout, doped-silicon piezoresistors have several disadvantages as strain sensors. First, the resistance of these devices is not only modulated by applied stress, but is also a function of ambient temperature and incident light (through thermal and photo generation of carriers, and the temperature dependence of mobility). For ease of contact placement, piezoresistors are often patterned into loops, which makes them more susceptible to external electromagnetic fields. Both of these effects can be compensated, but require a second unstrained piezoresistor in close proximity to the active one. When both resistors are placed in the same branch of the Wheatstone bridge, any common-mode signals are cancelled. Second, the piezoresistive coefficients themselves depend on temperature, resulting in a non-negligible temperature coefficient of sensitivity. Compensation of this effect
Figure 2.2: Readout circuit for a piezoresistive cantilever. The piezoresistor is placed into a Wheatstone bridge configuration with three matched resistors. A compensation resistor, placed in close proximity to the piezoresistor and made of the same material, can be placed in the same branch as the piezoresistor such that any common-mode signals are cancelled. The outputs of the bridge are connected to a differential amplifier with voltage gain $G$. The amplifier output is filtered and forwarded to the AFM system which adjusts tip height to maintain a deflection setpoint.

requires temperature calibration. Third, in most cases, piezoresistive transduction cannot achieve the displacement/force resolution of optical detection methods. Last, because they exhibit relatively large $1/f$ noise, piezoresistors suffer from long-term drift.

Piezoresistive cantilevers for AFM were first demonstrated by Tortonese [27]. Since then, researchers have continued to improve piezoresistive cantilevers for AFM by integrating actuators [45], enabling measurement of lateral forces [46], integrating on-chip signal conditioning [47], and optimizing force resolution [48,49]. Piezoresistive cantilevers have also been used for various other applications including biological and chemical sensing [50,51], characterization of electrical contacts [52], data storage [53], and the study of mechanotransduction in biological samples [54,56]. Here, we optimize the displacement resolution of piezoresistive cantilevers for high-bandwidth AFM at room and cryogenic temperatures.
2.2 Custom Tips for Electrical SPM

While the majority of electrical SPM techniques are performed with heavily-doped or metal-coated silicon AFM probes, there have been efforts to replace these basic tips with more sophisticated ones to improve lateral resolution and robustness. Here, we briefly review carbon nanotube tips and coaxial tips.

2.2.1 Carbon Nanotube Tips

Owing to their high aspect ratio, mechanical strength and wear resistance, carbon nanotubes are well suited as scanning probe tips. Single-walled carbon nanotubes have diameters of 1-2 nm, yielding exquisite lateral resolution for AFM. The small radius of curvature at the end of the nanotube results in tight electric field confinement when the nanotube is biased, which is beneficial for electrical SPM modes. For example, CNT tips have been used to write domains of a few nanometers in diameter in a ferroelectric thin film, giving storage densities in excess of 1 Tbit/in$^2$ [57].

Although it is likely that CNT tips can be used for high-resolution SGM, these specialized tips have several associated challenges. First, CNTs are susceptible to buckling, which can introduce imaging artifacts. This problem can be mitigated by shortening the CNTs (typically to 100 nm in length) [58] or coating them in a rigid material such as SiO$_2$ [57], both of which add processing complexity. Second, and more importantly, mass production of CNT tips is non-trivial. To obtain CNT tips, researchers commonly attach CNTs to the sides of the pyramidal tips of commercial AFM probes with the use of optical or electron microscopes. Alternatively, a probe can be scanned repeatedly over a sample of vertically-aligned CNTs in order to pick one up. Both methods are tedious and produce one CNT tip at a time. Yenilmez et al. had success growing CNTs at the ends of probes at the wafer scale [58]. However, after the nanotubes were grown, they needed to be shortened, which was accomplished by the serial process of oxygen discharge.
2.2.2 Coaxial Tips

Scanning near-field optical microscopy (SNOM) is a technique that enables sub-wavelength optical imaging [59]. The first tips for this technique consisted of a sharpened dielectric waveguide coated in metal with a narrow aperture at the apex. A major limitation of these tips is the transmission loss through the aperture – the transmitted flux drops off with the sixth power of the opening radius [60]. Researchers realized that this limitation could be overcome with coaxial tips consisting of an inner conductor, insulator and outer shield. Thus, this tip configuration was first used for SNOM in the microwave [60], infrared [61] and visible [62] regimes. However, the tips were rudimentary in construction, made from open-ended transmission line [60], pulling of glass fibers with metal cores [62] and manual assembly of electrochemically sharpened wire in machined metal cones [61].

More recently, several microfabricated coaxial tips have been reported [63–69]. While these tips demonstrate significant advancements in miniaturization and ease-of-fabrication over the earlier designs, they still have limitations. First, in one case, the tips were fabricated at the wafer scale, but not integrated on cantilevers and thus, not suitable for use in an AFM setup [63]. Second, some of the tips were produced by modification of individual, commercially-available AFM probes, a fabrication process that is not easily scaled [64, 69]. Third, on many of the tips, the diameter of the aperture is ≥0.5 µm, limiting lateral resolution [63, 64, 66, 68]. Last, and most importantly, none of the coaxial tips have been integrated on a self-sensing cantilever.

2.3 Enhanced SGM Techniques

Instead of redesigning the probes used for SGM, some researchers have modified the technique itself to improve lateral resolution. We briefly discuss these enhancements here as it can be argued that they are simpler alternatives to custom probe development. However, they cannot be applied in all situations. Furthermore, because our probe is compatible with these enhancements, they are not mutually exclusive. It may be possible to use both for even greater performance.
2.3. ENHANCED SGM TECHNIQUES

2.3.1 Contact SGM

Scanning gate microscopy is usually performed with the tip in proximity with, but not contacting, the sample surface. The tip-sample distance is known as the lift height. The electric field produced by the tip diverges over this distance. Thus, the lateral resolution degrades with increasing lift height. One simple enhancement to SGM is to operate in contact with the surface to minimize the divergence of electric field \[70\].

In order to perform SGM in contact, the sample surface must be insulating to prevent current flow between it and the tip. Thus, this enhancement is not applicable to all samples, in particular those with surface electrodes. Furthermore, continuous contact between the tip and sample can result in sample damage and increased tip wear.

2.3.2 Tip-Modulation SGM

Standard SGM is limited by the slow decay of capacitance with distance, which results in poor lateral resolution and a large background signal. Thus, a scanning measurement based on a quantity that decays at a faster rate than capacitance should provide superior results. This is the principle behind tip-modulation scanning gate microscopy (tmSGM), first demonstrated by Wilson and Cobden \[20\]. As in standard SGM, a DC voltage is applied to the tip. However, in tmSGM, the tip is oscillated at its resonant frequency. The induced conductance oscillations in the sample are measured using a lock-in amplifier. This signal is proportional to the derivative of capacitance with respect to tip height, which is a more local quantity than the capacitance. Whereas capacitance is proportional to the inverse of distance, the derivative of capacitance is proportional to the inverse square of distance.

Tip-modulation SGM requires an actuator, typically a small piezoelectric element, on the probe mount to excite the cantilever at its resonant frequency. While this is standard equipment on commercial AFM systems (for non-contact and tapping modes), it is not always available on cryogenic or home-built systems. Careful consideration is needed when selecting the probe for tmSGM. Its resonant frequency cannot exceed the bandwidth of the lock-in amplifier or the bandwidth set by the
$RC$ delay of the circuit, where $R$ is resistance of the sample and $C$ is the parasitic capacitance. These limits on resonant frequency may increase scan times when the same probe is used for AFM.
Chapter 3

Design

This chapter covers the design of the coaxial-tip piezoresistive scanning probes. We start with the design constraints for SGM probes and then describe the process of converting these constraints into device geometries, fabrication process parameters and operating conditions. The design of the piezoresistive cantilevers is handled first, followed by the design of the coaxial tips.

3.1 Constraints for SGM Probes

Scanning gate microscopy can be performed at cryogenic or room temperatures. Although we are primarily interested in studying semiconductor samples, we would also like to apply SGM to biological samples. Thus, in this section, we consider the design constraints for three use-cases of SGM probes: low temperature (low-T) and room temperature (room-T) measurements of semiconductor samples and room-T measurements of biological samples.

We typically perform AFM in contact mode. As such, the cantilever spring constant $k$ must be tuned to the sample hardness. For semiconductor samples, a $k$ value of 1-10 N/m is desirable. Cantilevers with spring constants below 1 N/m are susceptible to external vibrations and to jump-to-contact during SGM measurements, where the tip is lifted above the surface. On the contrary, the large contact force exerted by cantilevers with spring constants above 10 N/m increases tip wear and can cause
sample damage. For biological samples which tend to be soft, cantilevers with spring constants below 0.1 N/m are common. For room-T measurements on semiconductor samples, we would like the ability to perform AFM in non-contact mode. In this case, we need stiffer cantilevers, with \( k \) greater than 10 N/m, to limit thermomechanical noise (see Section 3.3.7), and further reduce the probability of jump-to-contact.

The resonant frequency of the cantilever \( f_0 \) places a maximum limit on the measurement bandwidth \( B \) and thus determines the total acquisition time for an image. Other factors that limit \( B \) include amplifier bandwidth and RC delay in the readout circuit. Currently, the largest measurement bandwidth we use is 512 Hz, corresponding to a scan rate of 1 second per line with 512 sample points per line. Under these conditions, it takes \( \sim 8.5 \) min to collect an image. To allow for faster scans and higher pixel densities, we designed for \( B = 10 \) kHz. To ensure a flat frequency response of the cantilever in this bandwidth, we set \( f_0 \geq 2B \). Because the cantilevers for biological samples are softer, achieving high resonant frequencies can be challenging. For these cantilevers, we set \( B = 1 \) kHz.

For low-T measurements, the maximum power dissipation in the piezoresistor \( P_{p,\text{max}} \) is limited by the cooling power of the cryostat. Our \(^3\text{He} \) cryostat (HelioxTL, Oxford Instruments, Concord, MA) has a cooling power of \( \sim 25 \) µW at 0.3 K. This power budget is shared with the 3 other resistors in the Wheatstone bridge, which are also at low-T. Thus, we limited \( P_{p,\text{max}} \) for low-T probes to 6 µW. For room-T probes, we specified \( P_{p,\text{max}} \) of 2 mW to limit self-heating, which has been shown to increase low-frequency noise [56].

AFM is used to align the tip and the sample. In SGM, we measure the conductance through the sample while scanning. This means that there are usually patterned electrodes on the sample surface that can be used as landmarks for the alignment process. Registration marks or grids can also be defined for this purpose. In either case, the step heights of these features are tens of nanometers. Therefore, the displacement resolution needed for alignment is \( \sim 10 \) nm, even if the structure through which current is flowing has sub-nanometer topography. For biological samples, the requirement on displacement resolution is even less stringent. Nonetheless, for maximum versatility, we designed our scanning probes for high-resolution AFM, specifying minimum step
3.2. PROBE MATERIALS

Table 3.1: Design constraints for three use-cases of SGM probes: low-T and room-T measurements of semiconductors (semicon.) and room-T measurements of biological samples (bio.)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature</td>
<td>0.3</td>
<td>293</td>
<td>293</td>
</tr>
<tr>
<td>Spring constant</td>
<td>1-10</td>
<td>&gt;1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>&gt;20</td>
<td>&gt;20</td>
<td>&gt;2</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>6</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>Displacement resolution</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

heights of 0.5 nm for semiconductor samples (e.g. a single monolayer of graphene) and 1 nm for biological samples. Note that in the case of low-T measurements, the tip and sample are coarsely aligned at room-T prior to cooling down. Thus, probes designed for low-T operation must also be capable of AFM at room-T. The design constraints for SGM probes are summarized in Table 3.1.

3.2 Probe Materials

We chose single-crystal silicon (c-Si) as the structural material for the scanning probes to allow fabrication of high sensitivity, low noise piezoresistors as demonstrated in Refs. [44, 55, 56]. The mechanical properties of c-Si are well known and it can be micromachined with standard techniques [71]. We attempted to minimize the number of thin films deposited on the cantilever in the process of fabricating the inner conductor, insulator and outer shield of the coaxial tip. With each additional film, the radius of curvature of the tip apex increases, reducing the lateral resolution of AFM. In addition, it becomes more challenging to model the cantilever mechanical properties and to control intrinsic stresses that cause undesired cantilever bending.

In SGM, a potential perturbation in the sample is produced by capacitive coupling to the conductive tip. No current flows between the tip and the sample, and as such, the resistances of the inner conductor and outer shield are not critical. However, a
displacement current flows in the inner conductor when either the tip-sample capacitance or voltage is time varying (i.e. an AC voltage is applied to the inner conductor or the cantilever is vibrated at its resonant frequency). With no strict requirement for low resistance, we selected doped silicon for the inner conductor. Using this material simplifies fabrication as it eliminates the need for multiple metal films on the cantilever and vias to connect them. Instead, the inner conductor can be defined at the same time as the piezoresistor. Silicon is also more mechanically robust than most metals, making it a good material for the inner conductor which is brought into contact with the sample when the probe is used for AFM. The inner conductor and piezoresistor must be degenerately doped to prevent freeze out at low-T [72].

We chose silicon dioxide for the electrical insulator between the inner conductor and the outer shield. We determined empirically that conformal, pin-hole free films of this material can be deposited at 400°C. At this temperature, dopant diffusion is negligible, so the piezoresistor dopant profile, an important determinant of vertical displacement resolution, is unaffected. Silicon dioxide also has a high dielectric strength (5-10×10^6 V/cm for thermal oxide [73]). Thus, only a thin film is needed to sustain a large voltage difference between the inner conductor and outer shield.

The material for the outer shield should be chemically inert. In particular, it should not readily oxidize. In addition, because SGM measurements can be performed in an external magnetic field, the outer shield should not become superconductive at cryogenic temperatures. If it did, in the transition to the superconductive state, the magnetic field would be expelled from the shield. This process, known as the Meissner effect [74], could produce a net force on the cantilever. Candidate materials for the outer shield include noble metals such as gold and platinum. However, for contamination reasons, the only metals allowed in the deep reactive ion etcher at the Stanford Nanofabrication Facility (SNF) are aluminum, titanium and tungsten. This tool is used to release the scanning probes at the end of the process. Of these metals, only Al and Ti can be sputtered at SNF without exposing the wafers to gold contamination. Both of these metals become superconductive at cryogenic temperatures (Al at 1.16 K and Ti at 0.39 K [75]). We selected Al for the outer shield.
3.3 Piezoresistive Cantilevers

To design scanning probes that meet the constraints outlined above, we need to be able to predict their mechanical and electrical properties. In this section, we cover the governing equations for these properties and discuss the numerical optimization process we used to arrive at the final piezoresistive cantilever designs. Here, we expand on work presented in [54–56].

3.3.1 Cantilever Geometry

Our scanning probes are based on two types of cantilevers, one with a monolithic construction and one with four “legs” at the fixed end. In the latter geometry, the silicon between electrical traces is removed to reduce current leakage paths. The cantilevers have length \( l_c \), width \( w_c \) and thickness \( t_c \). The length and width of the legs, denoted \( l_p \) and \( w_p \), are equal to those of the piezoresistor. Although the in-plane dimensions of the cantilevers are defined lithographically, \( t_c \) is set by the wafer device layer thickness. We chose a thickness of 3 \( \mu \)m so the cantilever lengths were reasonable for the desired spring constants. Cantilevers thicker than 1 \( \mu \)m are also less susceptible to breakage during fabrication.

We included two variations of the outer shield, “partial” and “full”. The partial shield covers all of the cantilever, except for the region occupied by the piezoresistor. The full shield covers the entire cantilever. The full shield protects the sample from electric field lines emanating from the piezoresistor. However, because the shield overlaps the piezoresistor in this design, capacitive cross-talk between these conductors is increased. Thus, the partial shield design is better suited to measurements in which cross-talk is likely to be problematic (e.g. when an AC bias is applied to the outer shield). The four combinations of cantilever type and shield length are presented in Figure 3.1 (a)-(d).

We selected a nominal tip height \( h_{tip} \) of 3 \( \mu \)m. The tips are etched early in the fabrication process and their height sets the minimum thickness of photoresist required for uniform spin coatings. In turn, the photoresist thickness places a minimum limit on the feature sizes that can be resolved. Our most aggressive probe designs have
critical dimensions of 2 µm, so we restricted $h_{\text{tip}}$ to 3 µm. This tip height also matches
that of the Veeco Piezolevers (Veeco, Santa Barbara, CA) previously used for SGM in
the Goldhaber-Gordon lab \[9\]. Each tip is offset from the free end of the cantilever by
a distance $l_{\text{offset}}$, typically 5 µm, to ensure that it is not damaged when the cantilever
is defined. Scanning probes are usually mounted at angle with respect to the sample
plane to ensure that on approach, the tip engages the surface before the die or the
wire bonds do. It is important that $l_{\text{offset}}$ is not too large, or even at small angles,
the free end of the cantilever will touch the surface before the tip does. With $h_{\text{tip}}$ of
3 µm and $l_{\text{offset}}$ of 5 µm, the probe can be tilted 31° before this condition is satisfied.
A side view of the cantilever geometry is shown in Figure 3.1(e).

3.3.2 Spring Constant

The spring constant at the free end of a monolithic cantilever with a rectangular
cross-section is given by \[76\]

$$k_{\text{mono}} = \frac{Ew_cl_c^3}{4l_c^3} \quad (3.1)$$

where $E$ is the Young’s modulus of the cantilever material. The spring constant at
the free end of a cantilever with four legs is more complex,

$$k_{\text{4legs}} = \frac{Ew_cl_c^3}{4\left(\frac{l_c^3}{w_c} + l_p \left(\frac{1}{w_p} - \frac{4}{w_c}\right)(l_p^2 - 3l_cl_p + 3l_p^2)\right)} \quad (3.2)$$

The derivation of (3.2) is provided in Appendix A. Silicon is anisotropic which means
that the value of $E$ to use in these expressions depends on the orientation and geometry
of the cantilever.

Our cantilevers are subjected to small deflections (<10% of $l_c$). As seen later in the
discussion, they are aligned to the [100] direction and have $l_c \gg t_c$ and $l_c > 5w_{\text{eff}}$ where
$w_{\text{eff}}$ is the effective width at the root of the cantilever. For a monolithic cantilever,
$w_{\text{eff}} = w_c$ and for a cantilever with four legs, $w_{\text{eff}} = 4w_p$. Thus, the cantilevers are
governed by axial stress and we use $E_{[100]} = 130$ GPa \[77\].
3.3. PIEZORESISTIVE CANTILEVERS

Figure 3.1: Schematics of the scanning probe geometries from (a)-(d) the top and (e) the side. Silicon between electrical traces is intact in (a) and (c) while in (b) and (d) it is removed to minimize current leakage paths. The partial shield in (a) and (b) reduces capacitive cross-talk with the piezoresistor, but the full shield in (c) and (d) blocks the electric field it produces. In all designs, the inner conductor runs under the outer shield to the tip.

3.3.3 Resonant Frequency

The resonant frequency of a generalized mass-spring system is given by

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}}. \]  

(3.3)

For a monolithic cantilever, this becomes

\[ f_{0,\text{mono}} = \frac{1}{2\pi} \sqrt{\frac{k_{\text{mono}}}{m_{\text{eff}}}}. \]  

(3.4)
Because the mass of cantilever is distributed along its length, and not concentrated at the free end, we must use a corrected mass $m_{\text{eff}}$. For a cantilever with a rectangular cross-section, $m_{\text{eff}} = 0.243m$. Substituting $m_{\text{eff}}$ and (3.1) into (3.4), we have

$$f_{0,\text{mono}} = \frac{t_c}{4\pi l_c^2} \sqrt{\frac{E}{0.243\rho_c}}. \tag{3.5}$$

Here, we have also used $m = \rho_c l_c w_c t_c$ where $\rho_c$ is the density of the cantilever material. The resonant frequency of a cantilever with four legs can be estimated using the Rayleigh-Ritz method \[78\] which gives

$$f_{0,\text{4legs}} = \frac{1}{2\pi} \left[ \frac{k_{\text{4legs}} x^2(l_c)}{\rho_c t_c \left( \int_0^{l_p} 4w_p x^2(y) \, dy + \int_{l_p}^{l_c} w_c x^2(y) \, dy \right) \right]^{1/2}. \tag{3.6}$$

where $x(y)$ is the vertical displacement of the cantilever in response to an arbitrary force $F$ at a position $y$ along its length. The derivation of (3.6) and an expression for $x(y)$ are provided in Appendix A. We calculate $f_{0,\text{4legs}}$ by numerical integration.

### 3.3.4 Resistance

The total nominal resistance $R$ of the piezoresistor can be separated into active resistance $R_{\text{active}}$ that contributes to displacement sensing and inactive resistance $R_{\text{inactive}}$ that degrades sensitivity,

$$R = R_{\text{active}} + R_{\text{inactive}}. \tag{3.7}$$

The resistance of the two longitudinal legs of the piezoresistor is active. The inactive resistance includes contact resistance $R_c$, resistance of doped traces to the piezoresistor $R_{\text{trace}}$ and resistance of the transverse portion of the piezoresistor loop $R_{\text{trans}}$. We assume that the resistance of the metal traces and wire bonds is negligible. In general, the carrier concentration $n$ in the piezoresistor varies with depth. It is possible to obtain uniform profiles by in situ doping during epitaxial growth. However, diffusion and ion implantation both produce non-uniform profiles. Thus, to determine $R$, we
3.3. PIEZORESISTIVE CANTILEVERS

must first calculate sheet resistance

\[ \rho_s = \frac{1}{\int_{t_c/2-t_p}^{t_c/2} q\mu(n) n(z) \, dz} \]  

(3.8)

where \( z = t_c/2 \) is the top surface of the cantilever, \( t_p \) is the junction depth, \( q \) is the elementary charge on an electron and \( \mu \) is the carrier mobility. Note that \( \mu \) is also a function of \( n \), as described in [79]. Then,

\[ R_{\text{active}} = 2\rho_s \frac{l_p}{w_p} \]  

(3.9)

and

\[ R_{\text{inactive}} = 2(R_c + R_{\text{trace}}) + R_{\text{trans}}. \]  

(3.10)

We define a resistance efficiency factor which is used in Section 3.3.6

\[ \gamma = \frac{R_{\text{active}}}{R} \]  

(3.11)

3.3.5 Power Dissipation

The power dissipated in a piezoresistor is

\[ P_p = \frac{V_{\text{bias}}^2}{R} = \frac{V_{\text{bridge}}^2}{4R} \]  

(3.12)

where \( V_{\text{bias}} \) is the voltage across the piezoresistor which equals \( V_{\text{bridge}}/2 \) in a balanced Wheatstone bridge.

3.3.6 Displacement Sensitivity

Consider a piezoresistor located at the top surface of a cantilever with a rectangular cross-section as shown in Figure 3.2(a). At the free end of the cantilever, we apply a force \( F \). In general, the piezoresistive coefficient and the resulting stress are not constant throughout the volume of the piezoresistor. Thus, we define the local change
in resistivity,
\[
\frac{\Delta \rho(y,z)}{\rho(y,z)} = \pi_1(z)\sigma_1(y,z). \tag{3.13}
\]
where the subscript on \(\pi\) and \(\sigma\) indicates the longitudinal direction. In order to find the overall change in resistance, we then average (3.13) over the piezoresistor volume.

According to Euler-Bernoulli beam theory \cite{76}, \(F\) induces a stress
\[
\sigma_1(y,z) = \frac{12F(l_c - y)z}{w_{\text{eff}} t_c^3}. \tag{3.14}
\]
The variation of \(\sigma_1\) in the \(y\) and \(z\) axes is shown in Figure \text{3.2}(b) and (c).

The carrier concentration in the piezoresistor can also vary with depth as seen in Figure \text{3.2}(d). The piezoresistive coefficient is a function of \(n\), decreasing at high.
3.3. PIEZORESISTIVE CANTILEVERS

Table 3.2: Values of $\pi_{l,\text{max}}$, $a$ and $b$ for p- and n-type piezoresistors.

<table>
<thead>
<tr>
<th>Doping type</th>
<th>Longitudinal direction</th>
<th>$\pi_{l,\text{max}}$ (Pa$^{-1}$)</th>
<th>$a$</th>
<th>$b$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>[110]</td>
<td>$72 \times 10^{-11}$</td>
<td>34</td>
<td>$0.2014$</td>
</tr>
<tr>
<td>n</td>
<td>[100]</td>
<td>$103 \times 10^{-11}$</td>
<td>34</td>
<td>$0.2330$</td>
</tr>
</tbody>
</table>

carrier concentrations [34]. As such, $\pi_1$ varies in the $z$ axis,

$$\pi_1(z) = P(n(z))\pi_{l,\text{max}}.$$  \hfill(3.15)

Here, $\pi_{l,\text{max}}$ is the maximum achievable piezoresistive coefficient, dependent on crystal orientation, and $P$ is the piezoresistance factor [49]

$$P(n) = \log \left( \frac{b}{n} \right)^a.$$  \hfill(3.16)

Table 3.2 summarizes the values of $\pi_{l,\text{max}}$, $a$ and $b$ that we used.

In the hypothetical case of an infinitesimally thin piezoresistor with uniform doping and $\pi_1(z) = \pi_{l,\text{max}}$ (i.e. low carrier concentration), the overall change in resistance is maximized. From (3.13), (3.14) and (3.15), it is

$$\left( \frac{\Delta R}{R} \right)_{\text{max}} = \frac{1}{l_p} \int_0^{l_p} \frac{\Delta \rho(y)}{\rho(y)} \, dy$$

$$= \frac{1}{l_p} \int_0^{l_p} \frac{6F(l_c - y)\pi_{l,\text{max}}}{w_{\text{eff}}t_c^2} \, dy$$

$$= \frac{6F(l_c - l_p/2)\pi_{l,\text{max}}}{w_{\text{eff}}t_c^2}$$  \hfill(3.17)

where we have used $z = t_c/2$. For all other cases, we scale (3.17) by the sensitivity efficiency factor $\beta^*$ as defined in [55],

$$\beta^* = \frac{2}{t_c} \frac{\int_{-t_c/2}^{t_c/2} q \mu(n)n(z)P(n)z \, dz}{\int_{-t_c/2}^{t_c/2} q \mu(n)n(z) \, dz}. \hfill(3.18)$$
This efficiency factor is the ratio of $\Delta R/R$ for a finite-thickness piezoresistor (calculated using a conductivity-weighted average of $\pi_l \sigma_l$ over the thickness) to $(\Delta R/R)_{\text{max}}$. Thus, in general, the change in resistance is given by

$$\frac{\Delta R}{R} = \beta^* \left( \frac{\Delta R}{R} \right)_{\text{max}}.$$  

(3.19)

The output voltage of a quarter-active Wheatstone bridge is

$$V_{\text{out}} = \frac{1}{4} \left( \frac{\Delta R}{R} \right) V_{\text{bridge}}.$$  

(3.20)

Combining (3.17), (3.19) and (3.20), we arrive at an expression for the force sensitivity,

$$S_{FV} = \frac{V_{\text{out}}}{F} = \frac{3(l_c - l_p/2)\pi_{l_{\text{max}}}^2}{2w_{\text{eff}}t_c^2} V_{\text{bridge}} \gamma \beta^*$$

(3.21)

where we have introduced $\gamma$ to account for sensitivity losses due to inactive resistance. Finally, the displacement sensitivity is given by

$$S_{xV} = \frac{V_{\text{out}}}{x} = k \cdot S_{FV} = \frac{3k(l_c - l_p/2)\pi_{l_{\text{max}}}^2}{2w_{\text{eff}}t_c^2} V_{\text{bridge}} \gamma \beta^*$$

(3.22)

where the appropriate $k$ is given in Section 3.3.2.

3.3.7 Noise

The displacement resolution of the piezoresistive cantilever is limited by the overall system noise which is comprised of Johnson and 1/$f$ noise from the piezoresistor, thermomechanical noise from the cantilever and amplifier noise from the readout circuit [43,49,54].

Johnson Noise

Johnson noise is a property of all resistors and results from the thermal motion of carriers [81,82]. It is independent of frequency, and thus referred to as “white” noise.
The power spectral density of Johnson noise (units of \( V^2/Hz \)) is given by

\[
S_J = 4k_BTR
\]

(3.23)

where \( k_B \) is the Boltzmann constant. Integrating (3.23) over the measurement bandwidth from \( f_{\text{min}} \) to \( f_{\text{max}} \), the Johnson noise power (units of \( V^2 \)) is

\[
V_J^2 = 4k_BTR(f_{\text{max}} - f_{\text{min}}).
\]

(3.24)

Equation (3.24) is also the total Johnson noise power of a balanced Wheatstone bridge, which is equal to that of a single resistor in the bridge. Figure 3.3 shows the calculated noise characteristics of a piezoresistor. As seen in this plot, Johnson noise dominates at high frequencies. Because the power dissipated in the piezoresistor is small, Joule heating has a negligible effect on Johnson noise.

1/f Noise

1/f noise is caused by conductivity fluctuations. The source of these fluctuations is still debated, with both mobility noise and variations in the number of free carriers cited in the literature \[83\,85\]. According to Hooge \[85\], the power spectral density of 1/f noise in a piezoresistor (units of \( V^2/Hz \)) can be modeled as

\[
S_H = \frac{\alpha V_{\text{bias}}^2}{Nf}
\]

(3.25)

where \( N \) is the total number of carriers in the piezoresistor and \( f \) is frequency. The dimensionless parameter \( \alpha \) is empirically determined and related to crystal lattice quality. In our design, we use \( \alpha = 3 \times 10^{-5} \), which we extracted from the noise spectra of fabricated test structures. The noise power (units of \( V^2 \)) after integrating (3.25) over the measurement bandwidth is

\[
V_H^2 = \frac{\alpha V_{\text{bias}}^2}{N} \ln \left( \frac{f_{\text{max}}}{f_{\text{min}}} \right).
\]

(3.26)
Figure 3.3: Noise characteristics of a piezoresistor calculated with parameters given at the top right of the plot. $1/f$ noise is caused by conductivity fluctuations and dominates at low frequencies. Johnson noise is caused by the thermal motion of carriers and dominates at high frequencies. At the corner frequency $f_c$, $1/f$ and Johnson noise voltage densities are equal.

As seen in Figure 3.3, $1/f$ noise dominates at low frequencies. When the Wheatstone bridge contains a second piezoresistor for temperature compensation (see Section 3.3.10), the total $1/f$ noise power is increased by 2x as the noise sources are uncorrelated. Thus, the $1/f$ noise power of the Wheatstone bridge is

$$\frac{V^2_{\text{H,bridge}}}{2N} = \frac{\alpha V^2_{\text{bridge}}}{2N} \ln \left( \frac{f_{\text{max}}}{f_{\text{min}}} \right).$$

(3.27)

**Thermomechanical Noise**

Thermomechanical noise is the mechanical analog of Johnson noise [86]. It manifests itself as physical oscillations of the cantilever beam. According to the equipartition
3.3. PIEZORESISTIVE CANTILEVERS

Theorem, if a system is in thermal equilibrium, every independent quadratic term in its total energy has a mean value equal to \(1/2k_B T\) \(^{87}\). The potential energy stored in a cantilever with tip displacement \(x\) is given by \(1/2kx^2\). Thus, the equipartition theorem demands

\[
\frac{1}{2} k \overline{x_{tm}^2} = \frac{1}{2} k_B T
\]

\[
\overline{x_{tm}^2} = \frac{k_B T}{k}
\]

(3.28)

where \(\overline{x_{tm}^2}\) is the mean squared tip displacement caused by thermal vibrations. As an example, consider a cantilever with \(k = 1\) N/m. From (3.28), its root mean squared tip displacement (over all frequencies) at 293 K is 0.64 Å. We neglected thermomechanical noise in our analysis for two reasons. First, it is typically an order of magnitude smaller than the equivalent displacement noise resulting from electrical sources (see Section 3.3.9). Second, it is greatest at the cantilever resonant frequency \(^{49}\), which we set to be outside of our measurement bandwidth.

Amplifier Noise

The readout circuit also adds to the overall system noise. With careful selection of the circuit components, the additional noise is dominated by the first-stage amplifier. For room-T measurements, we use the INA103 low noise instrumentation amplifier (Texas Instruments, Dallas, TX) with a gain \(G\) of 1000x. The noise characteristics of this amplifier are provided in Figure 3.4. The amplifier noise power (units of \(V^2\)) can be modeled as

\[
\overline{V_A^2} = C_H^2 \ln \left( \frac{f_{\text{max}}}{f_{\text{min}}} \right) + C_J^2 (f_{\text{max}} - f_{\text{min}})
\]

(3.29)

where \(C_H = 5.5\) nV and \(C_J = 1.0\) nV/\(\sqrt{\text{Hz}}\) for \(G = 1000\) \(^{54}\).
Figure 3.4: Voltage noise characteristics of the INA103 instrumentation amplifier, referred to input (RTI) [88]. For room-T measurements, we use a gain $G$ of 1000x.

**Total Noise**

Each of the noise sources discussed above is uncorrelated. Therefore, to find the total system noise power, we add the noise power of each source,

$$ V_{\text{noise}}^2 = V_J^2 + V_{\text{bridge}}^2 + V_A^2. \quad (3.30) $$

### 3.3.8 Displacement Resolution

The displacement resolution of a piezoresistive cantilever is given by

$$ x_{\text{min}} = \frac{V_{\text{noise}}}{S_{xV}} \quad (3.31) $$
Having determined the displacement sensitivity in (3.22) and the total noise in (3.30), we can now expand this expression,

\[
x_{\text{min}} = \frac{2w_{\text{eff}}l_c^2}{3k(l_c - l_p/2)\pi_{1,\text{max}}V_{\text{bridge}}\gamma\beta^*} \left[ (4k_BT R + C_j^2)(f_{\text{max}} - f_{\text{min}}) + \left( \frac{aV_{\text{bridge}}^2}{2N} + C_H^2 \right) \ln \left( \frac{f_{\text{max}}}{f_{\text{min}}} \right) \right]^{1/2}.
\]

The displacement resolution is a complicated function of piezoresistor geometry \((R, l_p)\), cantilever geometry \((w_{\text{eff}}, t_c, k, l_c)\), fabrication process parameters \((R, \alpha, N, \pi_{1,\text{max}}, \gamma, \beta^*)\) and operating conditions \((C_J, C_H, V_{\text{bridge}}, T, f_{\text{min}}, f_{\text{max}})\). We used a numerical optimizer to minimize this function while satisfying the design constraints.

### 3.3.9 Numerical Optimization

The numerical optimizer runs in Matlab and uses the theory developed in the previous sections. It can calculate the properties of a user-specified design or, given an optimization goal and constraints, can vary the parameters of an initial design to arrive at a more optimized one. Details on the design and operation of the optimizer can be found in [54]. All cantilever mechanical properties predicted by the optimizer, including spring constant and resonant frequency, were verified using COMSOL.

We made several modifications to the code to support our application requirements. The code was originally written to optimize piezoresistive cantilevers for force-sensing applications. Thus, the optimization goal was set to minimize the resolvable force at the free-end of the cantilever. In AFM, we sense cantilever displacements, so we added the ability to minimize \(x_{\text{min}}\). As SGM can be performed at cryogenic temperatures, we also permit a user-specified ambient temperature instead of fixing it at 300 K. Currently, changing the temperature only affects the calculation of Johnson noise. However, it is possible to add the temperature dependence of mobility [89], piezoresistive coefficients [34,80] and dopant activation.

Code modifications were also necessary to support our cantilever designs. The code was written to optimize monolithic cantilevers. We added the relevant equations for cantilevers with four legs. In addition, the code previously assumed loading at the free end of the cantilever. However, in the case of a scanning probe, the sharp tip
interacts with the sample. This tip is offset from the free end by \( l_{\text{offset}} \). To calculate the cantilever properties at the tip location, we replaced occurrences of \( l_c \) with \( l_{\text{eff}} \) where \( l_{\text{eff}} = l_c - l_{\text{offset}} \). Finally, the original version of the code used a fixed value for the resistance efficiency factor \( \gamma \). We now calculate \( \gamma \) for each design using (3.11). The version of the source code we used is provided in Appendix B.

Prior to starting the optimization process, we needed to choose the doping type and method for our piezoresistive cantilevers. We selected n-type phosphorus diffusion for several reasons. First, this process allows us to easily fabricate doping profiles with high surface concentrations and shallow junction depths. The surface concentration is limited by the solid solubility of phosphorus in silicon at the diffusion temperature. As such, we can achieve degenerate doping, necessary to prevent freeze-out at cryogenic temperatures. For a given piezoresistor geometry, heavier doping also results in lower resistance and larger number of carriers, which reduce Johnson and \( 1/f \) noise, respectively. Because longitudinal stress varies linearly through the thickness of the cantilever, a shallow junction depth maximizes the average stress that the piezoresistor experiences. Second, we were concerned that ion implantation would damage the sharp tips, which are exposed during the doping process to form the inner conductors. Last, phosphorus diffusions can be performed in-house at SNF.

As seen earlier, predicting cantilever performance requires accurate modeling of the carrier concentration profile in the piezoresistor. The optimization code uses the model developed by Tsai \[90\] to predict the phosphorus concentration profile for a given diffusion time and temperature. We convert the dopant concentration profile into a carrier concentration profile using activation data from Fair and Tsai \[91\]. We validated the model by performing several test diffusions and extracting their carrier concentration profiles with spreading resistance analysis (Solecon, Reno, NV). Figure 3.5 shows the predicted and measured profiles for a 15 min phosphorous diffusion performed at 850°C. The profiles agree well to a depth of \( \sim 0.26 \) \( \mu \text{m} \), which accounts for 99.9% of the total carriers.

In addition to the design constraints described in Section 3.1, we placed several fabrication-related constraints on the optimizer. We specified a minimum diffusion time \( t_{\text{diff}} \) of 15 min to control process variation among lots. We restricted the diffusion
3.3. PIEZORESISTIVE CANTILEVERS

Figure 3.5: Predicted and measured carrier concentration profiles for a 15 min phosphorus diffusion performed at 850°C. The measured profile was obtained by spreading resistance analysis. The profiles show good agreement in the region near the surface that accounts for 99.9% of the total carriers.

In total, we used the optimizer to design 24 piezoresistive cantilever variations corresponding to 3 SGM use-cases, 2 cantilever types, 2 minimum line widths and 2 shield variations. These designs are presented in Tables 3.3 and 3.4. Because the shield length does not significantly impact cantilever performance, these variations are not listed.

In Table 3.3 we see that the cantilever geometry is the same for the room and low temperature scanning probes. However, the optimizer converged on longer piezoresistors for the low-T probes. These piezoresistors have larger $R$ which increases Johnson noise but also have larger $N$ which reduces $1/f$ noise. Because $\overline{V_f^2} \propto T$, the effect of
$R$ on Johnson noise is counter-balanced, and overall system noise is reduced.

3.3.10 Other Considerations

Temperature Compensation

As seen in Equation (2.4), the resistance of a piezoresistor is modulated by temperature as well as applied stress. Resistivity is inversely proportional to carrier mobility and concentration. Temperature affects both of these properties through phonon and impurity scattering and thermal generation. In doped silicon, the temperature coefficient of resistance (TCR) can be large enough that the contribution to $\Delta R/R$ from temperature fluctuations overwhelms that from applied stress. Therefore, if we wish to measure stress resulting from cantilever deflection, we must compensate for changes in temperature. Compensation is particularly important for room-T measurements, in which the ambient temperature is not tightly controlled.

We included a compensation cantilever on each die with a piezoresistor matched to that of the active cantilever. Because of their proximity and identical geometry, the piezoresistors respond equally to changes in temperature. When scanning, we employ a differential readout scheme, such that the common temperature signal is cancelled. This method also helps to reject other common mode signals including ambient light (which affects resistivity through photogeneration) and vibrations, when both cantilevers are free standing.

The TCR of silicon depends on carrier concentration, decreasing monotonically from $1 \times 10^{14}$ to $1 \times 10^{19}$ cm$^{-3}$ and increasing only slightly beyond $1 \times 10^{19}$ cm$^{-3}$ [92,93]. Thus, with heavily-doped piezoresistors, we not only reduce Johnson and $1/f$ noise, but also reduce sensitivity to temperature fluctuations.

Frontside Clamp

The cantilever length is defined lithographically on the front side of the wafer and typically has tight tolerances (<1%). However, the clamp condition at the fixed end is set by the position of the sidewall of the backside release etch. For several reasons, the sidewall often does not align exactly with the root of the cantilever, increasing
### Table 3.3: Design parameters and predicted AFM performance of scanning probes for room-T (R) and low-T (L) measurements of semiconductor samples.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
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<td>M</td>
<td>FL</td>
<td>M</td>
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### Table 3.4: Design parameters and predicted AFM performance of scanning probes for room-T measurements of biological samples.

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*Table 3.4: Design parameters and predicted AFM performance of scanning probes for room-T measurements of biological samples.*
the effective cantilever length. First, the lithographic overlay error in front-to-back alignment tends to be larger than in front-to-front alignment. Second, because the handle layer is 300-500 µm thick, a small deviation in the sidewall profile from the vertical can lead to tens of microns of misalignment. Third, footing can cause an increase in lateral etching near the end of the release [94]. Footing occurs when a reactive ion etch terminates on an insulator, as is the case when devices are released from a silicon-on-insulator (SOI) wafer. When the buried oxide (BOX) is exposed at the end of the etch, it accumulates charge. Incoming ions are deflected laterally due to Coulomb repulsion, causing the sidewall to be attacked. For a review of DRIE and parameters controlling sidewall profile and footing, see Ref. [95].

As seen in Equations (3.1) and (3.2), the spring constant of a cantilever has an inverse cubic dependence on its length, meaning that even small variations in length cause large variations in mechanical properties. According to (3.22), decreasing the spring constant degrades displacement sensitivity. To mitigate the effects of the uncertainty in the sidewall position, we designed a method to set the clamp condition on the front side of the wafer. During the tip etch, we protect the silicon on the die, which produces a step at the root of the cantilever. The 2x increase in thickness here results in an 8x increase in stiffness, providing a reasonable anchor even if unsupported by the handle wafer below. A similar method was demonstrated by Chui et al. [96], but it requires thickening the base of the cantilever with selective epitaxial growth, a complex and expensive process. As discussed later, our method requires an etch chemistry that produces sloped sidewalls to facilitate step coverage of electrical traces from the die to the cantilever. Figure 3.6 compares scanning probes with and without the frontside clamp.

**Substrate Contact**

In addition to the contacts to the n-type diffusions of the piezoresistor and inner conductor, we included a contact to the p-type substrate. This contact serves several purposes. First, it allows us to reduce leakage current by adjusting the energy barrier height between neighboring n-type diffusions. This ability is particularly beneficial for the monolithic cantilever design which does not have electrically-isolating air gaps.
between the n-type diffusions. Second, it allows us to place a known voltage on the substrate, instead of letting it float. Third, it gives us control of the depletion width at the p-n junction. Each of these factors can impact electrical noise. Leakage current can have its own noise, uncorrelated to that of the piezoresistor. If the substrate is floating, it is more susceptible to electromagnetic interference from the environment. Carrier generation and recombination in the depletion region cause fluctuations in the number of free carriers, which are manifested as a conductivity noise [97].

3.4 Coaxial Tips

We used COMSOL to compare the electrostatic potential profiles from an unshielded tip and a coaxial tip and to investigate how these profiles change with tip geometry. To minimize computation complexity, we chose a two-dimensional axially-symmetric coordinate system, which is compatible with our conical tips. In the model, the tip is placed a height \( h_{\text{lift}} \) above the surface of a GaAs/Al\(_{0.3}\)Ga\(_{0.7}\)As heterostructure containing a buried 2DEG, a sample that has been extensively investigated with SGM. The 2DEG is treated as a metallic sheet. The distance between the sample surface and the 2DEG is 57 nm as in Sample A of [9]. The unshielded tip consists of a silicon cone with an opening half angle of \( \theta_{\text{tip}} \) and a radius of curvature \( r_c \) at the apex.
The coaxial tip is coated with 400 Å of SiO₂ and 400 Å of Al. A circular opening with radius \( r_o \) is defined in these layers at the apex. The ambient surrounding the tip is vacuum. We use dielectric constants of 11.7 for Si, 4.2 for SiO₂ and 12.24 for Al₀.₇Ga₀.₃As [70].

Dirichlet boundary conditions consisting of fixed potentials \( V_{ic} \) and \( V_{sh} \) are applied to the Si inner conductor and the Al shield, respectively. The 2DEG is grounded. Neumann boundary conditions, which force the gradient of potential to zero, are enforced at the external boundaries of the model. These conditions allow the finite-element problem to be solved, but cause deviations from the true infinite problem at the external boundaries. In order to minimize calculation errors, we made the overall geometry large, such that the external boundaries were far from the area of interest.

We considered tips produced by dry, isotropic etching in SF₆ plasma and wet, anisotropic etching in KOH solution. Early process characterization revealed that our dry-etched tips are conical with \( \theta_{tip} \) of 33°. Our wet-etched tips are bound by eight (338) planes and have \( \theta_{tip} \) of 19.3° [98]. The finite-element model for a coaxial tip and relevant simulation parameters are presented in Figure 3.7.

Figure 3.8 shows the electrostatic potential profile from an unshielded tip, a coaxial tip with \( V_{ic} = V_{sh} \) and a coaxial tip with a grounded shield. In all cases, \( h_{lift} = 100 \text{ nm} \), \( \theta_{tip} = 33^\circ \), \( r_c = 10 \text{ nm} \) and \( V_{ic} = -1 \text{ V} \). The coaxial tips have \( r_o = 100 \text{ nm} \). Qualitatively, we can see the benefit of a coaxial tip. The potential decays slowly with distance from the tip when it is unshielded. For a coaxial tip with a grounded shield, the potential drop is localized near the tip apex. It is important to note that, because it is effectively blunter, the coaxial tip with \( V_{ic} = V_{sh} \) produces a broader potential profile than the unshielded tip. Experimentally, when evaluating the lateral resolution enhancement achievable with a coaxial tip, it may be convenient to use the coaxial tip with \( V_{ic} = V_{sh} \) as a proxy for an unshielded tip. This avoids having to exchange tips which may introduce other variables, particularly if the experiment is performed at cryogenic temperatures and would require a thermal cycle. However, the simulations demonstrate that using the coaxial tip with \( V_{ic} = V_{sh} \) as a basis for comparison overestimates the enhancement in lateral resolution.

When SGM is used to image ballistic transport of electrons through a QPC, the
Figure 3.7: Two-dimensional, axially-symmetric finite-element model of a coaxial tip above a 2DEG in a GaAs/Al\textsubscript{0.3}Ga\textsubscript{0.7}As heterostructure. The 2DEG is treated as a metallic sheet 57 nm below the sample surface. Dirichlet boundary conditions are applied to the inner conductor (red), outer shield (blue) and 2DEG (green). Neumann boundary conditions are applied to the top and right outer edges of the geometry (black). All other boundaries (orange) are unconstrained. Inset is a magnified view of the tip-sample geometry, showing the tip radius of curvature $r_c$, shield opening radius $r_o$ and lift height $h_{lift}$. For analyses of unshielded tips, the insulator and shield layers are not present. The tip opening half angle $\theta_{tip}$ is 33° for dry-etched tips and 19.3° for wet-etched tips.

Lateral resolution is determined by the full-width at half-maximum (FWHM) of the induced charge density profile $\Delta n$ in the 2DEG [70]. Thus, we used this metric to quantify our comparison of unshielded and coaxial tips. We also investigated how the FWHM changes as we vary parameters in the model geometry. Figure 3.9 shows $\Delta n$ for the three conditions investigated in Figure 3.8. In this case, we see that the coaxial tip with a grounded shield produces a 2.3x narrower perturbation than an unshielded tip (FWHM of 241 nm versus 562 nm). The perturbation from the unshielded tip also suffers from a “long tail” that produces a background signal in SGM images. When the sample is a QPC, this long tail also limits how close we can scan to the point contact gates. If the tip is too close, it modulates the channel width, which
Figure 3.8: Electrostatic potential profiles from (a) an unshielded tip, (b) a coaxial tip with $V_{ic} = V_{sh}$ and (c) a coaxial tip with a grounded shield. In all cases, $h_{lift} = 100$ nm, $\theta_{tip} = 33^\circ$, $r_c = 10$ nm and $V_{ic} = -1$ V. The coaxial tips have $r_o = 100$ nm. To create the plots, the simulation data was mirrored about the axis of symmetry ($r = 0$ nm). In (a), the potential decays slowly with distance from the tip while in (c), the potential drop is localized near the tip apex. If $V_{ic}$ and $V_{sh}$ are not tuned, the coaxial tip can produce a broader profile than an unshielded tip as seen in (b).
Figure 3.9: Induced charge density profile $\Delta n$ in the 2DEG for the conditions in Figure 3.8. The perturbation produced by the coaxial tip with a grounded shield is 2.3x narrower and has a maximum 1.8x smaller than that of the unshielded tip. The coaxial tip with $V_{ic} = V_{sh}$ has a broader profile than the unshielded tip.

Figure 3.9 demonstrates that to obtain the same maximum $\Delta n$, the voltage on the inner conductor of the coaxial tip with a grounded shield must be 1.8x larger than the voltage on the unshielded tip. This has implications on the thickness of the insulator between the inner conductor and outer shield, which must sustain $|V_{ox}| = |V_{ic} - V_{sh}|$ without electrical breakdown. When scanning with an unshielded tip, the voltage applied between the tip and sample is typically 2-3 V [99]. We designed for $|V_{ox}| = 10$ V to provide additional safety margin.

In Figure 3.10, we plot the effect of lift height on the FWHM of $\Delta n$ for unshielded and coaxial configurations of dry- and wet-etched tips with $r_c = 10$ nm. For the coaxial tips, we only consider the case where the shield is grounded, as we have
shown that when $V_{ic} = V_{sh}$, the lateral resolution is poorer than that of an unshielded tip. The coaxial tips have $r_o = 100$ nm. In contact ($h_{lift} = 0$ nm), we assume the zero tip-sample force so there is no elastic deformation. For all tips, the FWHM increases with $h_{lift}$ as there is a larger distance between the tip and the 2DEG over which the electric field broadens. The effect is more pronounced for the unshielded tips because the electric field emanates from the entire cone. Over the entire studied range of $h_{lift}$, the FWHM of the dry-etched unshielded tip is larger than the wet-etched unshielded tip because it has a larger opening half angle.

The FWHM of the wet-etched coaxial tip is larger than that of the dry-etch coaxial tip when the tip is far from the sample. However, the opposite is observed when the tips are $<10$ nm from the surface. To understand this phenomenon, we must first consider the portion of the tip cone that extends beyond the outer shield, which we refer to as the protrusion. The surface area of the protrusion is given by

$$A = \frac{\pi r_o^2}{\sin \theta_{tip}}. \quad (3.33)$$

The height of the protrusion is given by

$$h_{pro} = \frac{r_o}{\tan \theta_{tip}}. \quad (3.34)$$

Thus, for a given $r_o$, both $A$ and $h_{pro}$ for the wet-etched tip are larger than they are for the dry-etched tip. If we replace the protrusion by a metal plate with the same effective capacitance to the 2DEG, this capacitance has the relationship

$$C_{eff} \propto \frac{A}{h_{lift} + c h_{pro}} \quad (3.35)$$

where $c$ is a constant and $0 \leq c \leq 1$ indicating that the plate should be located along the height of the protrusion. When $h_{lift}$ is large, $C_{eff}$ depends primarily on $A$. Thus, the effective capacitance for the wet-etched tip $C_{eff,wet}$ is larger than the effective capacitance for a dry-etched tip $C_{eff,dry}$, which results in a larger FWHM. As the tip approaches the surface, $h_{pro}$ becomes more important. Eventually, despite having a larger $A$, $C_{eff,wet}$ becomes smaller than $C_{eff,dry}$, resulting in a smaller FWHM.
Figure 3.10 indicates that for high lateral resolution, we should scan as close to the sample surface as possible and that at small lift heights, a coaxial tip provides less benefit. However, in practice, SGM is rarely performed in contact because it results in high tip wear and can cause shorts when there are conductors on the surface. Thus, \( h_{\text{lift}} \) is determined by sample topography. Lift heights between 10 and 50 nm are typical \([9, 11, 12, 20]\). Furthermore, although the FWHM of an unshielded tip approaches that of a coaxial tip at small lift heights, the long tail in \( \Delta n \) is still problematic.

The electric field from the tip diverges not only in the ambient between the tip and the surface, but in the sample as well, between the surface and the buried 2DEG. The rate of this broadening is different in the two media due to the sharp discontinuity in dielectric constant. The result is that the values of FWHM presented here are larger than they would be if the system of interest were located at the surface. Thus, if the depth of the system can be specified (e.g. via the sample growth conditions), we have another means of improving lateral resolution.

In Figure 3.11, the FWHM of \( \Delta n \) is plotted against opening radius of the coaxial tips at \( h_{\text{lift}} \) of 10 nm and 100 nm. At either lift height, the FWHM increases with \( r_o \), as more of the tip protrudes beyond the shield. At \( h_{\text{lift}} = 100 \) nm, \( A \) dominates \( C_{\text{eff}} \) causing the wet-etched tip to produce a larger FWHM than the dry-etched tip, irrespective of \( r_o \). However, at \( h_{\text{lift}} = 10 \) nm, the type of tip that produces a smaller FWHM depends on \( r_o \). When \( r_o \) is large, both tips have large \( A \), and \( h_{\text{pro}} \) is more important. Thus, the wet-etched tip produces a smaller FWHM. As \( r_o \) decreases, \( A \) gets smaller, and controls \( C_{\text{eff}} \). In this regime, the dry-etched tip produces a smaller FWHM. The plots show that for maximum lateral resolution, we should minimize \( r_o \).

Figure 3.12 presents the FWHM of \( \Delta n \) as a function of \( r_c \) at \( h_{\text{lift}} \) of 10 nm and 100 nm. In these simulations, the tip is lowered as it is rounded in order to maintain \( h_{\text{lift}} \). The plots demonstrate that \( r_c \) has a smaller effect on the FWHM than \( h_{\text{lift}} \) or \( r_o \). At \( h_{\text{lift}} = 100 \) nm, where \( A \) dominates \( C_{\text{eff}} \), increasing \( r_c \) reduces the FWHM because \( A \) gets smaller. As \( r_c \to \infty \), the inner conductor approaches a circular plate with \( A = \pi r_o^2 \). At \( h_{\text{lift}} = 10 \) nm, there is an initial decrease in FWHM as \( r_c \) goes from 10 nm to 25 nm, because \( A \) shrinks rapidly. However, when \( r_c \) exceeds ~25 nm, the
3.4. COAXIAL TIPS

Figure 3.10: FWHM of $\Delta n$ versus lift height for dry-etched unshielded (●), wet-etched unshielded (▼), dry-etched coaxial (■) and wet-etched coaxial (▲) tips. For the coaxial tips, $r_o = 100$ nm and for all tips, $r_c = 10$ nm. FWHM increases with $h_{\text{lift}}$ as there is a larger distance between the tip and sample over which the electric field can diverge.

FWHM begins to increase. Here, the reduction in $h_{\text{pro}}$ with $r_c$ has a larger impact than the reduction in $A$.

When SGM is performed in contact, the tip and sample surface deform elastically. If the end of the tip is approximated as a sphere and the sample surface as a plane, the circular contact area between the two is described by Hertzian mechanics. For a set applied force, the radius of the contact area $r_{\text{con}}$ increases with radius of curvature of the tip. When $r_{\text{con}}$ approaches the depth of the 2DEG, further increases in contact area cause the FWHM to increase [70]. Thus, for maximum lateral resolution in this mode, we should minimize $r_c$.

According to the simulations, when the tip is lifted above the surface, the minimum FWHM is not achieved with the smallest $r_c$. However, in order to achieve the highest
Figure 3.11: FWHM of $\Delta n$ versus shield opening radius for dry-etched (■) and wet-etched (▲) coaxial tips at $h_{\text{lift}}$ of (a) 10 nm and (b) 100 nm. Tips have $r_c = 10$ nm. FWHM increases with $r_o$ as more of the tip protrudes beyond the shield.
3.4. COAXIAL TIPS

lateral resolution for AFM, we must minimize $r_c$, introducing a trade-off. Because it is difficult to fabricate tips with a precisely specified $r_c$, we explored the extremes of this trade-off by fabricating tips where we minimized $r_c$ and tips where we truncated the apices, effectively setting $r_c = \infty$.

Neither of the tip styles we simulated produced smaller FWHM values in all situations. As a result, we fabricated two versions of each piezoresistive cantilever design, with each version having either a dry- or wet-etched tip.
Figure 3.12: FWHM of $\Delta n$ versus radius of curvature for dry-etched (■) and wet-etched (▲) coaxial tips at $h_{\text{lift}}$ of (a) 10 nm and (b) 100 nm. Tips have $r_o = 100$ nm. In (a), the competing effect of $r_c$ on $A$ and $h_{\text{pro}}$ results in non-monotonic relationship of FWHM with $r_c$. In (b), the effect of $A$ dominates, and FWHM decreases with increasing $r_c$. 
Chapter 4

Fabrication

In this chapter, we discuss the fabrication of the coaxial-tip piezoresistive scanning probes. We describe the starting material, reticle design, wafer layout, and process flow. All processing was performed in the Stanford Nanofabrication Facility (SNF) and the Stanford Nanocharacterization Laboratory (SNL).

4.1 Starting Material

The scanning probes were fabricated from 4-inch (100) double-side polished p-type silicon-on-insulator (SOI) wafers with device, buried oxide (BOX) and handle layer thicknesses of 6.5 µm, 0.5 µm and 400 µm. The wafers were purchased from MEMS Engineering & Material, Inc. (Sunnyvale, CA). As seen in Equations (3.1) and (3.2), cantilever spring constant has a cubic dependance on thickness. Thus, in order to minimize variation in the cantilever mechanical properties, it is important to have tight control over thickness. We elected to use SOI wafers instead of bulk silicon wafers as the BOX provides an effective stopping layer for the etches that define the cantilevers. To use bulk silicon wafers, which are an order of magnitude less expensive than SOI wafers, the etches must be precisely timed and highly uniform. These wafers must still be double-side polished to allow backside deep reactive ion etching (DRIE).

The boron doping of the device layer doping has the opposite polarity of the phosphorus doping of the piezoresistors and inner conductors, forming back-to-back...
p-n junctions for electrical isolation. A nominal resistivity of 1-5 Ω·cm, corresponding to a doping concentration of $\sim 1 \times 10^{16}$ cm$^{-3}$, was selected to minimize reverse leakage current in the junctions while providing a reasonable breakdown voltage of $\sim 50$ V \cite{100}. The actual resistivity, measured using the Prometrix four-point probe (average of 4 points on an 80 mm diameter circle and 1 center point), was $\sim 31$ Ω·cm. Nonetheless, we proceeded with these wafers knowing that for half of the designs, the silicon between electrical traces would be etched to produce insulating air gaps (see Section \ref{sec:3.3.1}).

Our process includes two thermal oxidations with target thicknesses of 0.5 µm and 0.1 µm. Because of the 2.2x volumetric expansion when Si is oxidized into SiO$_2$ \cite{73}, these steps consume 0.27 µm of Si. The desired tip height and cantilever thickness were 3 µm each. Thus, a total device layer thickness of 6.27 µm was required. The vendor tolerance on thickness was ±0.5 µm, so we specified 6.5 µm. The BOX and handle layers should be as thin as possible to minimize etch time during release of the cantilevers. However, the BOX must be thick enough such that it is not completely removed while overetching to clear the handle layer. Furthermore, it must withstand a differential pressure of $\sim 10$ Torr from the helium backside cooling during this step. The handle layer provides the wafer with mechanical rigidity, which puts a limit on how thin it can be. We specified 0.5 µm for the BOX and 400 µm for the handle, but these were conservative values and could safely be reduced to 0.3 µm and 300 µm, respectively. Below a handle layer thickness of 300 µm, the wafers become susceptible to breakage during processing. For the procedure we followed to evaluate starting material, see Appendix \ref{sec: Appendix C}.

We included several test grade (100) single-side polished bulk silicon wafers in the fabrication run which were used to characterize tools and recipes prior to committing the SOI wafers. These wafers were p-type (boron) with a resistivity of 1-10 Ω·cm and were purchased from the SNF stockroom.
4.2 ASML Stepper

All exposures were performed on the ASML PAS 5500/60 5:1 reduction stepper. This tool has a number of practical advantages over the contact aligners in the SNF (e.g. the Karl Suss MA-6). First, because the ASML uses projection lithography, the reticle is never brought into contact with the wafer, and is less susceptible to contamination and damage. Second, because of the 5:1 reduction optics, features on the reticle are 5x larger than they appear on the wafer, making them easier to print. This is particularly important for producing high-fidelity circles, used in this process as masks for the tip etch. In our earlier fabrication runs that relied on contact lithography, these circles were printed as ellipses, resulting in tips that terminated in knife edges instead of sharp points. Third, because the wafer handling and alignment is automated, exposures are much faster than they are on a manual contact aligner. Fourth, the ASML is capable of resolving features with a critical dimension of \( \sim 0.4 \mu m \), while the Karl Suss is limited to \( \sim 1 \mu m \). This is a significant advantage for projects pushing the limits of optical lithography (e.g. photonic crystals), in this process, though, the smallest feature is 2 \( \mu m \).

We also exploited several advanced features of the ASML including focus offset, reticle blading, multiple exposures and 3DAlign. Contact lithography works best when exposing features on the wafer surface because diffraction of light from openings in the mask occurs only over the thickness of the resist. Challenges arise when attempting to expose features at a different plane than the wafer surface (e.g. in a deep trench) because the focal plane is fixed by the contact between the reticle and wafer. On the ASML, the exposure chuck is capable of moving not only in the x-y plane, parallel to the reticle, but also in the z-direction. When aligning the wafer, the tool sets the z height to maximize signal from the alignment marks, thereby finding the top surface of the wafer. However, for each image exposed, it is possible to specify a focus offset from this plane. We etch tips early in the process, producing \( \sim 3 \mu m \) topography on the wafer. Moreover, we need to expose 2 \( \mu m \) features at the bottom of this topography, which is the cantilever surface. By specifying a +3.0 \( \mu m \) focus offset, the wafer is moved closer to the reticle for these exposures, and broadening
due to diffraction is minimized.

In the light path of the ASML are moveable opaque blades which can be used to select a region of the reticle to expose and mask the rest. The ability to “blade off” sections of the reticle is extremely powerful as it allows images for different lithography steps to be combined on one reticle. In addition to blading, the ASML allows multiple images to be exposed in each cell on the wafer. In this case, the final pattern after developing the photoresist is the result of stitching together several images on the reticle. There are two important benefits of image stitching. First, in a process that has many device variations, common features can be placed into one image that is reused and only the features that differ are then placed in separate images. This partitioning technique can dramatically reduce the reticle area required to accommodate all variations, as the common features are often large and do not need to be repeated. For example, in this process, most of the variation between devices occurs on the cantilever (geometry, length of shielding, presence of legs) while the die, which is consumes most of the area, remains constant (see Figure 4.1). Second, if several generic features are included on the reticle, such as circles and squares of varying dimensions, it is possible to create an arbitrary pattern in the resist by stitching tens or hundreds of them together. This capability can be used to explore “on-the-fly” designs not originally included on the reticle or to fix errors in existing images. Interestingly, as the size of the feature being repeated is decreased, this stitching process begins to look like e-beam lithography, where individual pixels are exposed to produce the final image. Through the combination of blading and stitching, all the images for this process fit on 1 reticle, whereas contact lithography would have required 7.

Releasing the scanning probes requires lithography on the backside of the wafer using alignment marks on the frontside. We accomplished this front-to-back alignment using the 3DAlign option of the ASML. Unlike the Karl Suss MA-6, which has special objectives to find the alignment marks when the wafer is frontside down, the ASML relies on a system of mirrors below the exposure chuck and 4 windows in the chuck itself as illustrated in Figure 4.2.

All of the process information needed to run the ASML stepper is contained in a job file. This includes the locations and names of images on the reticle, the locations
Figure 4.1: Reticle images to pattern bond pads and outer shield for two scanning probe designs (a) without and (b) with image stitching. In (a), two 3.58 mm x 2.50 mm images are required even though most of the features are identical. In (b), the common die features are grouped into one 3.58 mm x 2.50 mm image and the differences on the cantilever are separated into two 0.70 mm x 0.10 mm images, saving reticle area. To produce the final resist pattern, we expose the die image and one cantilever image successively. Note that a chrome box is required in the location of the second exposure (arrow) to prevent double-exposure of the resist. Images are drawn digitized data clear and dimensions are at wafer scale (1x).

and types of alignment marks on the wafer, the cell layout on the wafer and the names of the layers in the process and the images to be exposed in each. This information is discussed in the following sections.

4.3 Reticle Design

The reticle for this process is a standard 5-inch chrome-coated quartz plate with an image field of approximately 90 mm x 113 mm at reticle level (5x). We fit 69 images
Figure 4.2: For backside lithography, the wafer is placed frontside down on the exposure chuck. A system of mirrors below the chuck and 4 windows in the chuck guide laser light to the marks on the frontside of the wafer for alignment. In this way, the same top-side optics can be used for frontside and backside alignment. Alignment marks for backside lithography must be patterned at four specific locations on the wafer, corresponding to the locations of the windows.

in the available area including the images for all of the design variations and electrical test structures (see Figure 4.3). We also included images of exposure grids, digits 0 to 9 for die numbering, Karl Suss alignment marks to allow contact lithography if necessary and squares ranging from 2 µm x 2 µm to 25 µm x 25 µm for general use. The images are separated by 7 mm of chrome (at 5x) as required to accommodate reticle blading. The reticle was designed in L-edit (Tanner Research, Monrovia, CA) and printed by Compugraphics (Los Gatos, CA). All patterns were drawn digitized data clear to facilitate the printing process. Frame data that surrounds the image field, including a unique bar code and reticle alignment marks, were provided by the vendor. For more information on the reticle images, see Appendix D.

4.4 Wafer Layout

Two types of alignment marks can be used with the ASML: XPA and PM. The XPA marks are larger and more robust than the PM marks. However, at the time we wrote
Figure 4.3: Image field of the ASML reticle containing 69 images. The colors represent different layers (lithography steps) in the process. Prior to printing, the images were flattened onto a single layer and the outlines used for spacing were deleted. All images are drawn digitized data clear.
the job file, XPA marks were not qualified for backside alignment. Thus, we used 8 alignment marks, 4 XPA marks for frontside alignment and 4 PM marks for backside alignment. Prior to placing a wafer on the exposure chuck, the stepper attempts coarse alignment on a prealign chuck to correct gross misalignments that would otherwise cause the wafer to be rejected. By default, it uses the same alignment marks that it uses on the exposure chuck, provided they are in special prealign windows. We placed the XPA marks in the prealign windows and the PM marks at the preset the locations for 3D Align as shown in Figure 4.4(a).

The quantity of devices and their locations are defined by dividing the wafer into a two-dimensional array of cells and then specifying the images to be exposed in each cell. Each scanning probe occupies 3.58 mm x 2.50 mm of wafer area. We set the cell size to be 5.58 mm x 4.50 mm, creating a 1 mm border around each probe. We also populated the cells in a checkerboard fashion, skipping every other one. Combined with an edge exclusion of 3 mm, this yielded 122 probes per wafer. There are two reasons we carefully limited the number of probes. First, the DRIE process to release the probes is sensitive to silicon loading. We have observed that uniformity and etch rate decline as the percent of wafer area exposed to the plasma exceeds 10%. With 122 probes, only 4.4% of the wafer is exposed during the release. Second, with a large number of probes, the wafer becomes fragile after release and is easily broken by handling, particularly when singulating devices.

Section 3.3.9 summarizes the design variations we fabricated. We placed 12 variations on each wafer. As many processes have center-to-edge non-uniformity, we arranged the probes of each variation radially (see Figure 4.4(b)) to prevent marginality in a process from impacting all of them. Note that we can easily change the quantity and types of devices on new wafers as these parameters are specified in the job file and not fixed on the reticle. As such, we initially fabricated many design variations for testing but future fab runs will focus on those with the highest yield and performance. For complete wafer layouts, see Appendix E.

For tracking purposes, it is common to apply a unique label to each die. Patterning these labels with contact lithography is straightforward as they can all be placed on the reticle. With a stepper, which is designed to expose the same images in each cell,
4.5. PROCESS SPLITS

Table 4.1: Assignments of the 6 starting SOI wafers to the 3 fabrication process splits.

<table>
<thead>
<tr>
<th>Wafer</th>
<th>Tip Etch</th>
<th>Diffusion Temperature</th>
<th>Frontside Clamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>Wet (KOH)</td>
<td>850°C</td>
<td>No</td>
</tr>
<tr>
<td>S1</td>
<td>Wet (KOH)</td>
<td>850°C</td>
<td>Yes</td>
</tr>
<tr>
<td>S2</td>
<td>Wet (KOH)</td>
<td>900°C</td>
<td>No</td>
</tr>
<tr>
<td>S3</td>
<td>Wet (KOH)</td>
<td>900°C</td>
<td>Yes</td>
</tr>
<tr>
<td>S4</td>
<td>Dry (SF&lt;sub&gt;6&lt;/sub&gt;)</td>
<td>850°C</td>
<td>No</td>
</tr>
<tr>
<td>S5</td>
<td>Dry (SF&lt;sub&gt;6&lt;/sub&gt;)</td>
<td>900°C</td>
<td>No</td>
</tr>
</tbody>
</table>

Applying unique die labels requires additional effort when writing the job file and a larger number of exposures per wafer. Consequently, many ASML customers print a contact reticle specifically for labels. The disadvantage of this strategy is that by committing to a wafer layout, they forfeit the ability to change it in the job file. We included images of the digits 0 to 9 on our reticle and enough area on each probe die to accommodate 3 digits. In our job file, we placed a unique three-digit number on each die. While this approach was tedious, it maintains our ability to modify the wafer layout in the job file alone.

As shown in Section 3.3.6, the longitudinal axes of the n-type piezoresistors should be aligned with the [100] direction to maximize \( \pi_1 \). To accomplish this, we specified a wafer rotation of 45° in the job file, effectively rotating the scanning probes with respect to the primary flat, while being transparent to the reticle design and wafer layout. A corresponding wafer rotation of -45° was required for backside lithography.

4.5 Process Splits

To fabricate the remaining design variations, we divided the 6 starting SOI wafers into 3 process splits related to the tip etch, diffusion temperature and frontside clamp condition. These splits are discussed further in the following sections, but are summarized for convenience in Table 4.1.
Figure 4.4: Wafer layout: (a) The wafer is divided into a 2D array of cells. We use 4 XPA marks in the prealign windows for frontside alignment and 4 PM marks at the 3DAAlign locations for backside alignment. Cells overlapping the 3 mm edge exclusion are not populated. (b) We placed 12 design variations on each wafer, represented by colors, arranging probes of each variation radially. Each die is assigned a unique number. Also shown are locations of test structures (T), exposure grids (E), alignment marks (M) and overlay crosses (A). Not drawn to scale.
4.6 Process Flow

The fabrication process consists of 7 photolithography mask steps and ~90 total steps. A cartoon of the process is presented in Figure 4.5. For a detailed runsheet (including tool names, recipes and parameters) and information on the pre-mixed wet etchants and resist strippers used in the process, see Appendices F and G.

4.6.1 Alignment Marks

To begin the process, we labeled the wafers with a diamond scribe and cleaned them in Piranha solution (9 H₂SO₄:1 H₂O₂) at 120°C. Next, we singed the wafers at 150°C and primed them with hexamethyldisilazane (HMDS). We always performed this step prior to spinning resist, but for brevity, mention it once here. We patterned the alignment marks in 1 µm of Shipley 3612 resist, as shown in Figure 4.6. The images for the XPA and PM marks are located on the COMBI reticle provided by the SNF. The marks were etched 1200 Å into the device layer with CHF₃/O₂ plasma and the resist was stripped with a combination of O₂ ashing and Piranha (Figure 4.5(a)). The selected etch depth maximizes the signal amplitude of the interferometric measurement used by ASML for alignment.

4.6.2 Sharp Tips

We oxidized the wafers at 1100°C for 39 min in a wet ambient to grow a 5000 Å hard mask for the subsequent tip etch. At this point, the wafers were split into two lots, denoted W and D, for wet and dry etched tips. Lot W was further split into two lots, W1 and W2, corresponding to wafers with the frontside clamp condition described in Section 3.3.10 and those without. We spun 1.6 µm of Shipley 3612 resist, patterned it according to the lot type, etched the oxide in CHF₃/O₂ plasma and stripped the resist (Figure 4.5(b)).

On the wafers in lot W, the oxide was patterned into squares with 7.5 µm sides at the tip locations. On the wafers in lot W2, the oxide everywhere else was cleared.
Figure 4.5: Fabrication process: (a) The wafer is cleaned and alignment marks are etched. (b) Oxide is grown and patterned into a square or circle at the tip location. (c) The mask is undercut by wet KOH or dry SF₆ plasma etching to form a silicon tip. (d) The mask is stripped and another oxide layer is grown to sharpen the tip. This layer is patterned and masks a phosphorus diffusion that dopes the piezoresistor and the tip. (e) The mask is removed and LTO is deposited to form the insulator in the coaxial tip. Contact windows are opened to the diffusions. (f) Aluminum is sputtered and patterned into the outer shield and bond pads. (g) The cantilever is defined by dry etching through the device layer and (h) released by DRIE through the handle layer and dry etch of the BOX. Not drawn to scale.
4.6. PROCESS FLOW

while on those in lot W1, it was left intact over the die. Tip precursors were produced by anisotropically undercutting the square masks in 45% KOH solution at 60°C [98, 101–103]. The etch rate of (100) silicon in KOH solution depends on the KOH concentration and the temperature [104]. At high concentrations, the etch rate decreases because the availability of water, needed for the etch reaction, is limited. We used the stock concentration of KOH solution at SNF and moderate heating to achieve a slow, controlled etch rate of $\sim 0.23 \, \mu m/min$. Because even thin oxides are an effective mask for KOH, we performed a 50:1 HF dip immediately before the etch to remove the native oxide. On the wafers in lot D, the oxide was patterned into circles with 4 $\mu m$ diameters and undercut isotropically in SF$_6$ plasma [105, 106].

We chose the oxide mask dimensions to yield tip heights of $\sim 3 \, \mu m$. We stopped the etches when the tops of the silicon precursors beneath the transparent masks could no longer be resolved with an optical microscope (Figure 4.5(c)). The dry etched precursors were conical while the wet etched ones were pyramidal and bound by eight symmetric crystal planes [98] as seen in Figure 4.7. It is important that the oxide masks are completely symmetric to yield tips with a single point. In our first fab runs, the precursors took the shape of knife blades because the masks were slightly elliptical instead of perfect circles (resulting from an error during photomask printing). While etching, if the oxide masks begin to fall off the precursors, the etch must be stopped. Although further wet etching will not blunt the tip, it will cause a

Figure 4.6: Optical microscope images of (a) PM and (b) XPA alignment marks patterned in 1 $\mu m$ of Shipley 3612 resist.
CHAPTER 4. FABRICATION

Figure 4.7: Scanning electron microscope (SEM) images of silicon tips etched with (a) SF$_6$ plasma and (b) KOH solution. The dry, isotropic etch produces conical tips while the wet, anisotropic etch produces pyramidal tips, bound by eight symmetric crystal planes. Tips have been sharpened by oxidation. Images were taken with the substrate tilted 41° from the horizontal (indicated simply as 41° tilt in subsequent figures).

The rapid reduction in tip height as the (100) plane at the apex is exposed to the solution. Further dry etching can result in blunt tips or anomalous tip shapes.

Wafers that were etched in KOH were decontaminated in 5 H$_2$O:1 HCl:1 H$_2$O$_2$ at 70°C to remove K$^+$ ions, which are well-known CMOS contaminants. We stripped the oxide masks in 6:1 buffered oxide etch (BOE) and oxidized the wafers at 900°C for 43 min in a wet ambient. At temperatures below 950°C, oxidation is inhibited at regions of high stress, which sharpens the tip precursors [107].

4.6.3 Piezoresistors and Inner Conductor

The 1000 Å oxide layer grown for tip sharpening was also used as a hard mask for the phosphorus diffusion. On each probe, the trace to the tip and the active and compensation piezoresistor loops were opened in 3 µm of SPR220-3 resist. The oxide was etched in 6:1 BOE and the resist was stripped, as seen in Figure 4.8. Prior to the wet etch, the wafers were exposed to O$_2$ plasma for 30 seconds to make the resist surface more hydrophilic, allowing the aqueous solution to enter small openings. We used thick resist for this lithography step and all following to achieve planar, uniform spin coatings over the tip topography. For all etches and resist strips in which the
4.6. PROCESS FLOW

![SEM images (at 41° tilt) of the oxide mask for the phosphorus diffusion to create the piezoresistors and inner conductor. (a) View of the entire die, including compensation piezoresistor (arrow). (b) Magnified view of the diffusions on the cantilever.](image)

piezoresistors or tips were exposed, we avoided dry etches as plasma-induced damage has been shown to increase $1/f$ noise in piezoresistors \[108\] and could also blunt the tips.

The numerical optimizer calculated diffusion time and temperature combinations for each design variation. For ease of fabrication, we chose two diffusion conditions, 850°C for 15 min and 900°C for 15 min, which reasonably satisfied all of the calculated combinations. We split the wafers into the two lots according to the design variations on each. Both diffusions were performed in a POCl$_3$ furnace (Figure 4.5(d)). The phosphosilicate glass (PSG) deposited during the diffusion and the oxide mask were then stripped in 6:1 BOE.

4.6.4 Insulator

To passivate the piezoresistors and build the insulator for the coaxial tip, we deposited 400 Å of oxide by low pressure chemical vapor deposition at 400°C. Selecting the thickness of this film required a tradeoff between the electrical quality of the insulator and rounding of the tip (see Figure 4.9) which degrades lateral resolution. We determined empirically that 400 Å is the minimum thickness that can sustain 10 V between the inner conductor and outer shield without electrical breakdown. We chose low temperature oxide (LTO) instead of thermal oxide to minimize dopant diffusion,
which would have resulted in a broader profile than predicted by the numerical optimizer. Furthermore, thermal oxidation causes a pile-up of phosphorus at the silicon surface due to dopant segregation, which can enhance formation of P complexes and SiP precipitates and reduce the electrical activity of the dopants [109]. Contacts to the n-type silicon were opened by etching the LTO in 20:1 BOE with a patterned mask of 4 µm of SPR220-3 resist (Figure 4.5(e)).

4.6.5 Bond Pads and Outer Shield

Once the contacts were opened, we stripped the resist and sputtered 400 Å of aluminum. Care was taken to deposit the metal immediately after the LTO etch to minimize native oxide growth. The metal was patterned into the outer shield of the coaxial tip and the bond pads for the piezoresistors and the inner conductor using AL-11 wet etchant at 40°C with 4 µm of SPR220-3 resist as the mask (Figures 4.5(f) and 4.10). All remaining resist strips were performed in PRX-127 solution, which is designed to remove organics without corroding aluminum.

We selected the aluminum film thickness as a compromise between tip rounding and the following three factors. First, in order to maximize $\gamma$ and displacement sensitivity, the bond pads must not contribute significantly to the inactive resistance.
4.6. PROCESS FLOW

Figure 4.10: SEM images (at 41° tilt) of patterned aluminum forming the outer shield of the coaxial tip and the bond pads. (a) View of entire die, including metal patch for die label (arrow). (b) Magnified view of electrodes to the cantilever: I. inner conductor, II. and III. active piezoresistor loop, and IV. outer shield.

Second, they must be thick enough that wire bonding is possible without punching through to the substrate below. Third, at high current densities, aluminum is susceptible to electromigration, which causes void formation and failure.

4.6.6 Cantilevers and Release

The cantilevers and die outlines were defined by DRIE or HBr/Cl₂ plasma through the device layer silicon, stopping on the BOX (Figure 4.5(g)). We tried the latter plasma chemistry to avoid the scalloped sidewalls of DRIE, but encountered difficulties as discussed in Section 4.7.1. The etch was again masked by 4 µm of SPR220-3 resist.

When processing the backside of a wafer, it is desirable to protect features on the frontside from contact with chucks, wafer handling arms, etc. Typically, a thick layer of photoresist (>7 µm) is used for this purpose. However, placing photoresist in contact with the exposure chuck on the ASML is prohibited as it may flake off, resulting in particle contamination. Because we were particularly concerned about damage to the sharp tips, we investigated several alternatives to photoresist including polyimide, LTO and dicing tape.

Like photoresist, polyimide can be applied by spin coating. We considered PI-2611 (HD MicroSystems, Cupertino, CA) which is formulated for films 3-9 µm thick, and has a coefficient of thermal expansion that is matched to silicon. It requires
VM-651 adhesion promoter (HD MicroSystems, Cupertino, CA) and must be cured at 350°C in an N₂ ambient. Polyimide is not attacked by standard resist strippers or solvents, so removing a thick layer requires many hours of O₂ plasma. For this reason, it was unsuitable for our process, as we wanted to minimize the plasma exposure of the tips and piezoresistors.

Low temperature oxide is another possibility as a protection layer, as several microns can be deposited conformally even on wafers that already have metallization. However, in our process, because the LTO would be deposited on oxide and aluminum already on the frontside of the wafers, removing it without damaging these layers would have been challenging.

We collaborated with Lintec of America (Phoenix, AZ) and the ASML process staff to evaluate Adwill D-210 dicing tape as a protection layer. This tape is comprised of 100 μm of PET as the base material and 25 μm of acrylic as the adhesive. To release the tape after use, it must be exposed to 160 mJ/cm² of UV radiation at ~365 nm, which degrades the adhesive. Two problems arose with this tape that prevented us from using it. First, although the tape is designed to release cleanly, we observed some residues either from the adhesive or the detaping process at Lintec. Second, despite the tape being transparent at 632.8 nm, the wavelength of the laser used by the stepper for alignment, wafers with the tape could not be aligned. We hypothesize that the addition of the tape thickness to the 3DAlign optical path (see Figure 4.2) moved the alignment marks out of the focal plane. A thinner tape such as Adwill D-203 (50 μm base material) may have overcome this problem, but we did not investigate further.

Without a satisfactory protection method, we developed a process for backside lithography that minimizes contact between the frontsides of the wafers and the equipment. First, we spun 7 μm of SPR 220-7 resist on the backsides of the wafers. We moved the wafers between stations on the coater track manually, to avoid contact with the transfer belts. Before placing each wafer onto the spinner chuck, we cleaned it thoroughly with a clean wipe soaked in acetone. Instead of pre-baking the resist on the track hotplate, we used an oven at 90°C. Next, we exposed the resist with the ASML stepper, verifying that the vacuum systems on the robot arm and exposure
chuck were not affected by the topography on the frontside. Prior to developing the resist, we coated the wafer frontsides with 7 µm of SPR 220-7 resist, using the afore-mentioned track protocol. In this case, the oven step served as a pre-bake for the frontside resist and a post-exposure bake for the backside resist. Finally, the backside resist was developed.

To release the cantilevers, we etched through the handle layer with DRIE, again stopping on the BOX, then cleared the BOX in CHF$_3$/O$_2$ plasma (Figure 4.5(h)). The resist was stripped and the wafers were given a final clean in PRS-1000. The scanning probes remain held in the wafer by two tabs of the handle silicon which are broken as needed. Images of a released device are provided in Figure 4.11.
4.6.7 Opening the Outer Shield

The coaxial tip structure was completed by milling an opening in the outer shield at the tip apex with a focused ion beam (FIB). We used an FEI Strata 235DB dual-beam FIB/SEM (FEI, Hillsboro, OR) with a Ga\(^+\) ion beam. In this tool, the electron beam (E-beam) and ion beam (I-beam) are coincident on the sample and separated by an angle of 52°. Sample mounts and Electrodag 502 conductive adhesive were purchased from Ted Pella (Redding, CA). We used two methods to open the shield metal, “annulus” and “cleaning cross-section”, named after the milling pattern used in each. These methods are presented in Figure 4.12. We used the lowest possible ion beam current of 1 pA to achieve a slow, controlled etch rate and to limit damage to the tip while imaging with the I-beam. With both methods, our goal was to produce an opening with the smallest possible diameter, as this dimension largely controls the FWHM of the electric field from the inner conductor.

In the annulus method, the scanning probe was attached to a flat mount and the stage was tilted 52° such that the I-beam was perpendicular to the cantilever. We drew an annulus milling pattern concentric with the apex of the tip and etched the pattern with short I-beam pulses (\(\sim 4\) sec) until clear contrast was observed between the exposed inner conductor and outer shield in both the I-beam and E-beam images. There are two main challenges with this method. First, it can be difficult to obtain sufficient contrast in the I-beam image to clearly identify the apex. Because we are looking down on the tip, the contrast due to topography is small. In addition, the tip is initially coated in aluminum, so there is no material contrast. Misalignment between the center of the annulus and the tip apex often results in blunted tips. Second, it was difficult to produce openings smaller than \(\sim 300\) nm in diameter. We had the greatest success with an annulus having an inner radius \(r_i\) of 50 nm and an outer radius \(r_o\) of 150 nm. We attempted annulus patterns with smaller dimensions, but these would often result in blunted tips as well.

A cleaning cross-section (CCS) is a rectangular milling pattern that is scanned line-by-line from one side to the opposite side (instead of repeatedly scanning the entire pattern for the duration of the etch, as is done with a normal box pattern). CCS patterns are frequently used to prepare samples for transmission electron microscopy.
because they produce high-quality surfaces. In our second method, we attached the scanning probe to a 45° mount and tilted the stage 7° to align the I-beam parallel to the cantilever. Next, we drew and etched a CCS pattern with the minimum resolvable overlap with the tip apex. We repeated the process, redrawing the CCS pattern with larger overlap each time, until an opening in the shield was visible in the E-beam image. The dimensions of the pattern are somewhat arbitrary, as long as the overlapping portion of the tip is fully enclosed. We typically drew a rectangle having a width $w_e$ of 300 nm and a height $h_e$ of 100 nm. The CCS method yields high contrast because when observed from the side, the tip is surrounded by vacuum. In addition, if the $w_e$ is much larger than the width of the overlapping portion of the tip, misalignment in the axis parallel to the width is not an issue. As such, using this method, we could repeatably produce openings $\sim 60$ nm in diameter. The disadvantage of this method is that it increases the radius of curvature at the apex, which can degrade lateral resolution when the probe is used for AFM. Images of tips opened with both methods are shown in Figure 4.13. For more information on the FIB recipes we used, see Appendix H.

4.7 Lessons Learned and Improvements

In this section, we discuss the major challenges we encountered during the fabrication process and suggest possible solutions for future fabrication runs.

4.7.1 Plasma Etching with HBr/Cl$_2$

Initially, we etched the device layer silicon to define the cantilevers and die outlines using HBr/Cl$_2$ plasma. This etch chemistry yields straight sidewalls, unlike the switched SF$_6$/C$_4$F$_8$ plasma of the Bosch process (DRIE), which produces scalloped sidewalls. The scallops were of particular concern for scanning probes with 2 µm wide legs, where narrowing would cause a significant change in mechanical properties from predicted values. Furthermore, by consuming silicon from the n-type diffusions and creating sidewall surfaces with a high defect density, the scallops would result
in noisier piezoresistors with a higher than expected nominal resistance. Trenches etched with HBr/Cl\textsubscript{2} plasma are limited to $\sim$10 $\mu$m in depth. In our case, the device layer had already been thinned by 3.5 $\mu$m during the tip etch and thermal oxidations, leaving only 3 $\mu$m to the BOX.

As discussed above, we deposited and patterned aluminum into the bond pads and outer shields prior to the frontside silicon etch. We encountered two complications with HBr/Cl\textsubscript{2} etching, both related to the aluminum on the wafers. First, the aluminum near the etched sidewalls was corroded by the chlorine. During the etch, chlorine is incorporated in the passivation that builds on and protects the sidewalls. When the wafer is removed from the process chamber and exposed to air, this chlorine reacts with water vapor to form local pockets of concentrated HCl. This acid quickly

Figure 4.12: (a) Annulus and (b) cleaning cross-section methods of opening the outer shield at the tip apex with the FIB. Grey, black and red shading represents the tip cone, tip apex and milling pattern, respectively. Annulus is defined by inner radius ($r_1$) and outer radius ($r_o$). CCS is defined by width ($w_e$) and height ($w_e$). Red arrow indicates direction of line scans in CCS pattern. Not to scale.
Figure 4.13: E-beam images of tips before and after opening the outer shield with (a,b) annulus and (c) CCS methods. Tips (a) and (c) were originally dry etched and tip (b) was wet etched. In (a,b), the n-type silicon inner conductor protrudes above the opening while in (c), it is flush. The inner conductor and shield are separated by 400 Å of low temperature oxide. A smaller opening radius $r_o$ is possible with the CCS method, at the cost of tip sharpness.
undercuts the photoresist and attacks the aluminum. The standard practice to prevent this corrosion is to ash the photoresist and sidewall passivation immediately after the etch, without breaking vacuum. However, the SNF currently does not have a tool with this capability (chamber D of the Applied Materials P5000 etcher is intended for this purpose). Alternatively, but less effectively, after venting, the wafer can be placed in DI water to dilute the HCl that has formed and to dissolve remnant chlorine. The latter process helped to minimize corrosion, but because the outer shield traces are only 2 or 5 \( \mu \text{m} \) wide (and 400 Å thick), many were electrically opened even before the wafers could be unloaded from the etcher load-lock (Figure 4.14(a)).

Second, we had difficulty stripping the sidewall passivation after the etch. The passivation that forms in HBr/Cl\(_2\) plasma typically contains C, O, Br, Cl and in our case, possibly some Al. Consequently, it behaves more like an oxide than the Teflon-like polymer deposited in the Bosch process. To remove the passivation (and resist), it is common to use 50:1 HF, followed by O\(_2\) plasma and Piranha. With aluminum on the wafers, each of these processes was undesirable. The 50:1 HF could undercut the resist and attack the Al, the O\(_2\) plasma could oxidize the Al (and blunt the tips by physical sputtering), and it is well known that Piranha corrodes Al. Thus, we tried PRX-127 and PRS-1000 organic strippers, which are designed to remove resist and organometallic passivations. After little success, we tried low-power, short O\(_2\) and CF\(_4\)/O\(_2\) plasma etches which removed more of the passivation but still not all of it. The passivation is insulating, and therefore benign if it remains on the sidewalls. However, it would often detach in wet processing and wrap around the cantilever or cover the tip (Figure 4.14(b)), rendering the scanning probe unusable.

Because of the challenges with HBr/Cl\(_2\) plasma, we switched to DRIE to etch the device layer silicon. In future fabrication runs, we would consider depositing a thicker film of aluminum that is less susceptible to corrosion, offsetting the edge of the metal from the edge of the silicon etch to reduce access of chlorine to the aluminum, and using a metal that is not corroded by HCl. Further investigation is required to develop a passivation removal process that is safe for aluminum. Alternatively, the process flow could be re-designed with the frontside etch before aluminum deposition to avoid these problems entirely.
4.7. LESSONS LEARNED AND IMPROVEMENTS

Figure 4.14: SEM images (at 41° tilt) of the challenges encountered with the HBr/Cl₂ plasma etch. (a) An aluminum trace on a probe leg corroded by HCl which formed from chlorine in the sidewall passivation and water vapor in the air. The contrast of the metal on either side of the corrosion front is unequal, indicating that the trace is no longer electrically continuous. (b) Passivation which could not be removed in PRX-127 or O₂ plasma detached from the sidewall. The resulting “ribbon” appears to be taller than the tip, in which case, it would touch the sample first when the scanning probe is used for AFM.

4.7.2 Metal Coverage of Wet-Etched Tips

We sputter deposited 400 Å of aluminum for the outer shield of the coaxial tip. We chose sputtering as this technique produces more conformal films than evaporation. Although the metal completely covered the dry-etched tips, coverage on many of the wet-etched tips, which have a higher aspect ratio, was poor (see Figure 4.15(a)). It is unknown whether the deposition itself failed to cover the tips or if the metal was damaged in subsequent processing (e.g. poor resist coverage of the wet-etched tips during the metal patterning).

One way to improve metal coverage of the tips may be to deposit a thicker film of aluminum. This will increase tip rounding, which is why we initially chose a thin film, but it is likely that a more optimal thickness that balances coverage and sharpness can be found. Furthermore, tip rounding can be mitigated by milling excess shield metal with the FIB to expose the sharp inner conductor.

We used the FIB to deposit ~10 nm of platinum on tips with poor aluminum
Figure 4.15: SEM images (at 52° tilt) of a wet-etched tip on a released scanning probe. In (a), the sputtered aluminum does not appear to conformally coat the tip. Discontinuities in the film are evident at the base of the tip (arrow). In (b), the tip has been coated in \(\sim 10\) nm of Pt deposited with the FIB.

We drew a circle with a radius of 2 \(\mu\)m, centered on the tip apex, as the deposition pattern and set the I-beam current to 1 pA. We chose this combination of pattern geometry and beam current for a slow deposition rate (\(\sim 2.5\) nm/min) as faster rates led to severe roughening of the tip sidewalls. A gas injection system (GIS) needle is inserted into the FIB chamber to provide the organometallic precursor gas. Once the tip was coated in Pt, we proceeded with one of the previously described opening methods.

### 4.7.3 Frontside Clamp and Wafer Rotation

For scanning probes with the frontside clamp, the die was protected by a rectangular oxide mask during the KOH etch of the tips. Thus, only the device layer silicon that eventually formed the cantilever was thinned by 3 \(\mu\)m (the tip height). With thicker
silicon on the die than the cantilever, the clamp condition is set on the frontside of the wafer and not with the release etch, which has poorer alignment tolerance (see Section 3.3.10 for details). Because KOH is an anisotropic etchant, we expected the height difference between the die and the cantilever would be bridged by the slow-etching (111) plane, with the well-known 54.74° angle from the horizontal. This sloped sidewall would facilitate step coverage of the electrical traces, in particular, the thin aluminum shield. However, we neglected to consider the 45° wafer rotation necessary to align the longitudinal axes of the n-type piezoresistors in the [100] direction. With the rotation, the edges of the oxide mask were parallel to the [100] direction, and instead of exposing the (111) plane, the KOH etch exposed the (100) plane perpendicular to the (100) wafer surface, as seen in Figure 4.16. Although the n-type diffusions for the inner conductor and piezoresistor were continuous over the resulting 3 µm vertical step, the shield was not. The fast etching of (100) in KOH also caused the step to move in toward the die such that it was no longer coincident with the root of the cantilever.

There are two possibilities to correct the slope between the die and cantilever on devices with the frontside clamp. First, the reticle image used to pattern the oxide mask for the KOH etch can be modified to align the edges of the die protection with the [110] direction. Second, p-type doping can be used for the inner conductor and piezoresistor. In this case, no wafer rotation is required because πl is maximized when the longitudinal axis of the piezoresistor is parallel to [110]. Note that switching doping type has further implications on the process, including the method of introducing the dopant atoms into the wafer and the initial doping of the substrate.

4.7.4 Image Stitching Seams

As discussed in Section 4.2 with image stitching we were able to fabricate all of our design variations with a single reticle. Because most of the differences between designs are on the cantilevers, we placed the main seam between images at the root of the cantilever. We drew the images defining the die and those defining the cantilever such that they abut with no overlap, for two reasons. First, we were concerned that
the critical dimensions at the root (2 or 5 \( \mu m \)) would be enlarged in cases where overlap resulted in double-exposure of the resist. Second, we expected misalignment between these images to be negligible, as the 6\( \sigma \) overlay specification of the ASML stepper is 60 nm [110]. In general, this stitching strategy worked well. However, we observed cases where misalignment resulted in a <100 nm line of resist at the stitching seam, which acted as an effective mask for the subsequent etch as exemplified by Figure [4.17(a)].

Although the defect produced by the thin line of resist is mainly cosmetic, it is best if it does not occur at the root of the cantilever, which is a critical region in determining the mechanical properties and displacement sensitivity of the scanning probe. As such, we propose moving the stitching seam onto the die in future designs, where defects are better tolerated. Furthermore, because features are larger on the die, a 0.25 \( \mu m \) overlap of neighboring images here can be used to eliminate the possibility of a stitching defect without concern about enlargement from double-exposure.
4.7. LESSONS LEARNED AND IMPROVEMENTS

Figure 4.17: (a) SEM image (at 41° tilt) of a line defect at the image stitching seam (arrow) after the frontside silicon etch. (b) Comparison of the current and proposed seam locations. Features on the die are larger and less affected by defects.

4.7.5 Other Improvements

Additional improvements to the process that we noted are listed below.

1. Expand wafer exclusion zone to 5 mm. The exclusion zone is the region inset from the edge of the wafer in which no devices are placed. We selected a zone width of 3 mm to account for tweezer handling and 2 mm edge bead removal after spinning photoresist. However, several of the dry etchers have clamp fingers that extend beyond 3 mm. These fingers landed on devices, masking the etch or causing physical damage.

2. Include etch windows for in-process monitoring. Dielectric film thicknesses are typically measured with an interferometer or an ellipsometer. Monitoring etch progress through a dielectric film to determine when it has been cleared is facilitated with windows at least 2 mm x 2 mm which are large enough to accommodate the light beam width of these tools.

3. Release the electrical test structures along with the scanning probes. We originally planned to cleave the test structures out of the wafer, but avoiding neighboring scanning probes made this process infeasible. Thus, it is advisable to use DRIE to release the test structures as is done with the probes.
Chapter 5

Characterization

We characterized the performance of our scanning probes to determine their limits, validate our modeling and investigate the outcomes of our design decisions. In particular, we measured the vertical displacement resolution of the piezoresistive cantilevers and the electrostatic potential profiles produced by the coaxial tips. In this chapter, we discuss our testing procedures, present the measurement results and compare them to the predicted values. We again separate the discussion of piezoresistive cantilevers and coaxial tips.

5.1 Piezoresistive Cantilevers

We characterized vertical displacement resolution at room- and low-T for the corresponding piezoresistive cantilever designs. In both cases, we recorded the voltage noise spectrum in the measurement bandwidth and the displacement sensitivity. Then, according to (3.31), we divided the integrated noise by the sensitivity to arrive at the displacement resolution.
5.1. PIEZORESISTIVE CANTILEVERS

5.1.1 Room Temperature

At room-T, we mounted each scanning probe on a custom printed circuit board (PCB), shown in Figure 5.1, with 5-minute epoxy (Devcon, Danvers, MA). We wire-bonded the probes with aluminum wire. We measured nominal resistance with a digital multimeter. On selected devices, we captured a current-voltage (I-V) curve trace for the piezoresistor with a Hewlett Packard HP4145B parameter analyzer to verify linearity. A representative I-V curve from a scanning probe with design R2* is provided in Figure 5.2. The asterisk indicates that this probe has a frontside clamp. All representative plots in this section are taken from the same device. Next, we connected the probes to a readout circuit, shown in Figure 5.3(a), placing the active and compensation piezoresistors in a Wheatstone bridge configuration with two matched metal-film resistors. On the readout circuit PCB, the output of the bridge is connected to a Texas Instruments INA103 amplifier with 1000x gain, followed by an Analog Devices AD8221 amplifier with selectable gains of 1x, 2x and 5x. For all of the results below, the AD8221 was set to 1x. Finally, we loaded the probes into a Witec Alpha300 AFM (Ulm, Germany) by attaching the probe PCB to the magnetic probe hand, as seen in Figure 5.3(b). We secured the readout circuit to the AFM and added strain relief to the connecting cable to minimize torques while scanning (Figure 5.3(c)).

Noise

We first measured the noise floor of the INA103 by shorting the differential inputs of the amplifier and measuring the output voltage spectrum from 1 Hz to 10 kHz with an HP3562A signal analyzer. Then, with the bridge connected to the amplifier, $V_{\text{bridge}}$ set to 2 V and the cantilever free standing in air, we repeated the experiment to measure the total noise spectrum. In Figure 5.4(a), we show representative results from the R2* probe. The noise data has been referred to the input (RTI) of the amplifier (i.e. the 1000x gain has been divided out). We see that at frequencies above $\sim 10$ Hz, the amplifier noise floor is 1 nV/$\sqrt{\text{Hz}}$, agreeing with the device specification. For the entire spectrum, the amplifier noise is below the total noise, indicating that
Figure 5.1: Printed circuit board used to mount a scanning probe for room-T measurements, seen from (a) top and (b) bottom. A probe is glued to the bottom side with epoxy and wirebonded to the gold-coated pads with aluminum wire. A washer is glued to the top side which mates with the magnetic probe hand of the Witec Alpha300 AFM.

Figure 5.2: I-V curve for a scanning probe with design R2*. The piezoresistor is linear with a nominal resistance of 1590 Ω.
Figure 5.3: (a) Readout printed circuit board (PCB) consisting of a Wheatstone bridge, amplifiers and optional low-pass filter. The potentiometers are used to balance the bridge. The metal enclosure (shown with lid off) shields external electric fields. (b) A magnet in the probe hand mates with the washer on the probe PCB. (c) Complete setup for room-T measurements.
the displacement resolution is limited by the piezoresistor noise. The piezoresistor exhibits $1/f$ and Johnson noise, with a corner frequency of $\sim 300$ Hz. For this probe, there is excellent agreement between the predicted and measured total noise.

**Displacement Sensitivity**

To measure displacement sensitivity, we connected the readout circuit to an auxiliary input on the AFM and brought the probe tip in close proximity to a glass slide. With $V_{\text{bridge}}$ again set to 2 V, we recorded the circuit output while extending and retracting the piezoelectric stage, producing a voltage-displacement curve. We observed a full cycle of tip contact, cantilever deflection, cantilever relaxation and tip release. The stage height was measured independently with a built-in capacitive sensor. We assumed that the deformation of the glass slide was negligible. In Figure 5.4(b), we show representative results from the R2* probe. Again, the data has been referred to the input of the amplifier. We see that the piezoresistor response is linear and exhibits no hysteresis. The measured sensitivity is within 12% of the predicted value (discussed below).

**Displacement Resolution**

We calculated the displacement resolution in a measurement bandwidth $B$ starting at $f_{\text{min}} = 1$ Hz by integrating the total noise in $B$ and dividing by the displacement sensitivity. A plot of displacement resolution versus bandwidth for the R2* device is presented in Figure 5.4(c). In a 1 Hz–10 kHz bandwidth, the probe can resolve $2.30 \, \text{Å}$ displacements.

**Resonant Frequency**

We measured resonant frequency by vibrating probes with the piezoelectric element embedded in the probe hand. In this case, we left the tip out of contact. We swept the frequency of vibration and recorded the output of the readout circuit. The resonant frequency was identified by a sharp peak in the circuit output, corresponding to maximum cantilever oscillation.
5.1. PIEZORESISTIVE CANTILEVERS

Figure 5.4: Predicted and measured (a) noise spectra, (b) displacement sensitivity and (c) displacement resolution for a scanning probe with design R2*. Predicted and measured values agree within 15%. The high-frequency roll-off in amplifier noise is caused by a low-pass filter with $f_{-3dB} = 8$ kHz. The measured resolution in the 1 Hz–10 kHz bandwidth is 2.30 Å.
Deviations in Cantilever Geometry

We adjusted our predictions of cantilever performance from Table 3.3 because of two deviations from the designed geometry introduced in the fabrication process (see Figure 5.5). First, the clamped ends of the cantilevers are undercut as a result of poor sidewall angle control (see Section 3.3.10). In the most severe case, wafer S4, the undercut measures 29 µm or 27% of the length of the shortest cantilever. Second, the cantilever thickness is 2.5 µm instead of 3 µm. This thickness is set by the etch that defines the tip. This etch is timed and thus has poorer control than an etch that terminates on a stopping layer. The resulting increase in effective length and decrease in thickness reduce the cantilever spring constant and displacement sensitivity.

Analysis and Comparison of Designs

Table 5.1 summarizes our room-T measurements for device types R1, R2 and R2*, where we have updated the predicted values as discussed above.

We see that the scanning probe with design R1 has lower performance than predicted, with 24% smaller displacement sensitivity and 2.5x larger total noise. We believe that the degradation in sensitivity is a result of leakage current between the piezoresistor legs. This design has a monolithic cantilever, where the heavily-doped n-type legs are separated by the lightly-doped p-type background silicon, forming two back-to-back diodes. When a voltage is applied to the piezoresistor, the leakage
5.1. PIEZORESISTIVE CANTILEVERS

Table 5.1: AFM performance of fabricated scanning probes at room temperature. Boldface values are measured, others are predicted (updated for fabricated geometry). If listed, n is the number of devices measured, otherwise n = 1. For n > 1, values are given as average ± standard deviation. Measurements taken at $T = \sim 293$ K with $V_{bridge} = 2$ V and $B = 1$ Hz–10 kHz. Asterisk indicates the presence of a frontside clamp.

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R2*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic (M) or Four Legs (FL)</td>
<td>M</td>
<td>FL</td>
<td>FL</td>
</tr>
<tr>
<td>Spring constant (N/m)</td>
<td>4.78</td>
<td>2.96</td>
<td>4.46</td>
</tr>
<tr>
<td>Resonant frequency (kHz)</td>
<td>140</td>
<td>105</td>
<td>129</td>
</tr>
<tr>
<td></td>
<td>131</td>
<td>100</td>
<td>123</td>
</tr>
<tr>
<td>Resistance (kΩ)</td>
<td>$1.24 \pm 0.0804$</td>
<td>$1.59 \pm 0.0274$</td>
<td>$1.59$</td>
</tr>
<tr>
<td></td>
<td>(n = 4)</td>
<td>(n = 4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.57</td>
<td>1.57</td>
<td>1.57</td>
</tr>
<tr>
<td>Displacement sensitivity (kV/m)</td>
<td>$1.43 \pm 0.0115$</td>
<td>$2.06 \pm 0.0520$</td>
<td>$2.36$</td>
</tr>
<tr>
<td></td>
<td>(n = 3)</td>
<td>(n = 3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.88</td>
<td>2.03</td>
<td>2.68</td>
</tr>
<tr>
<td>Total noise (nV)</td>
<td>$1440 \pm 347$</td>
<td>$571 \pm 30.7$</td>
<td>$542$</td>
</tr>
<tr>
<td></td>
<td>(n = 4)</td>
<td>(n = 3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>581</td>
<td>581</td>
<td>581</td>
</tr>
<tr>
<td>Displacement resolution (Å)</td>
<td>$10.1$</td>
<td>$2.77$</td>
<td>$2.30$</td>
</tr>
<tr>
<td></td>
<td>3.10</td>
<td>2.86</td>
<td>2.17</td>
</tr>
</tbody>
</table>

Current between the legs is determined by the saturation current of the diode that is reverse biased. For a p-n junction where the doping concentration is much greater on one side than the other, the saturation current is inversely proportional to the doping concentration on the lightly-doped side. In this case, the saturation current depends on the p-type background which has a doping concentration of only $\sim 5 \times 10^{14}$ cm$^{-3}$ (31 Ω·cm). Thus, the leakage current is large. Note that if the wafers had met the resistivity specification (1-5 Ω·cm), the doping concentration would have been $\sim 1 \times 10^{16}$ cm$^{-3}$, reducing leakage current by more than an order of magnitude. The presence of a leakage path diverts current from the active resistance, which reduces displacement sensitivity. Our hypothesis is further supported by the fact that the measured nominal resistance is lower than the predicted value.

Two factors could cause the measured noise of design R1 to exceed the predicted
value. First, the leakage current that degrades sensitivity also has noise associated with it. In particular, it has been shown that the reverse saturation current in a p-n junction exhibits $1/f$ noise \[111\]. Second, a large depletion region exists in the lightly-doped region of the monolithic cantilever. Carrier generation and recombination in this region leads to a fluctuation in the number of free carriers, which causes conductivity noise. If these processes are assisted by traps (i.e. Shockley-Reed-Hall generation and recombination), the frequency spectrum of this noise depends on the distribution of relaxation times associated with the traps \[97\]. Both noise sources are uncorrelated with the noise of the piezoresistor, and thus add to the total noise power of the system. As seen in Figure \[5.6\], the total noise measured for R1 is predominantly $1/f$. The reduced sensitivity and increased noise that we measured result in a displacement resolution of 10.1 Å, larger than our design goal of 5 Å.

When we remove the p-type silicon between the n-type traces to create a cantilever with four legs, as in design R2, we reduce the leakage current and the volume of the depletion region. In this case, we see excellent agreement between the measured and predicted performance and the scanning probe is able to resolve 2.77 Å displacements. Figure \[5.6\] shows the reduction in noise when the piezoresistor legs are separated by electrically-isolating air gaps.

Table \[5.1\] also highlights the benefit of the frontside clamp. Despite challenges fabricating the clamp (see Section \[4.7.3\]), it still mitigates the softening of the cantilever caused by the undercut, and boosts displacement sensitivity. We suspect that non-idealities associated with the piezoresistor traversing the vertical clamp step prevent this device from reaching its full predicted sensitivity. Regardless, this scanning probe design yields the best displacement resolution of 2.30 Å.

**Process Variation**

The standard deviation values presented in Table \[5.1\] provide a means of evaluating the repeatability and uniformity of the fabrication process. We first consider variation within a wafer. For design R1, we see that the standard deviations (SD) of resistance and displacement sensitivity are within 6% of their nominal values which is reasonable given that the probes were fabricated in an academic lab where, unlike an industrial
5.1. PIEZORESISTIVE CANTILEVERS

Figure 5.6: Comparison of the measured voltage noise spectra from scanning probe designs R1 and R2 which have monolithic and four-legged cantilevers, respectively. Removing the silicon between the piezoresistor legs reduces leakage current and the volume of the depletion region, both sources of noise. Integrated noise from 1 Hz to 10 kHz shown in parentheses.

In our process, wafer-to-wafer variation is more difficult to evaluate because no two wafers have the same set of designs. Nevertheless, the predicted values of resistance and total noise for designs R2 and R2* (from wafers S4 and S1, respectively) are
identical. We see that the measured values agree within 5%, providing further support of the robustness of the process.

**Atomic Force Microscopy**

To demonstrate topographic imaging, we used the output of the readout circuit as the control signal for the z-axis feedback loop of the Alpha300 and scanned a probe with design R2 over a test sample. The resulting image is shown in Figure 5.7 where the ∼10 nm step heights are clearly resolved.

**5.1.2 Low Temperature**

For low-T measurements, we used a home-built scanning system in a top-loading $^3$He HelioxTL refrigerator (Oxford Instruments, Concord, MA). The scanning system consists of a piezoelectric scan tube (Staveley Sensors, East Hartford, CT) mounted
at the end of slip-stick nanopositioners (Attocube Systems, Munich, Germany). The nanopositioners and scan tube are responsible for coarse and fine positioning of the tip, respectively. We attached the scanning probes to a custom tip mount and placed them at the end of the scan tube. More details on the low-T apparatus can be found in Ref. [99].

The low-T readout circuit for tip displacement consists of a Wheatstone bridge followed by two Stanford Research Systems SR560 amplifiers in series. The amplifiers have gains of 100x and 500x, yielding a total gain of 50,000x. The on-die compensation piezoresistor is not used because the temperature in the cryostat is well controlled. The three matching resistors in the bridge are located close to the scanning probe. Thus, when the system is cold, they are at approximately the same temperature as the active piezoresistor. The amplifiers are at room-T.

As in the room-T characterization, we first measured the total noise with the tip out of contact and then deflected the cantilever with a hard sample while recording the readout circuit output. We did not have an additional sensor to measure the extension of the piezoelectric scan tube. Therefore, before calculating displacement sensitivity, we calibrated the scan tube using a sample with known step heights.

Analysis and Comparison of Designs

Table 5.2 summarizes our low-T measurements. The predicted values have been updated to account for the fabricated geometry and for the noise performance of the SR560 amplifiers (the original design assumed an INA103 as the first-stage amplifier).

We see that for both probes L1 and L2, the measured displacement sensitivity is \(\sim 20\%\) lower than predicted. The predictions were calculated using room-T values for the piezoresistive coefficient \(\pi_l\) as we did not have data for n-type diffusions at 2 K. Thus, the discrepancy between measured and predicted values may be explained by the variation of \(\pi_l\) with temperature. In Figure 5.8, we plot \(\pi_l\) for n-type diffusions with different surface concentrations \(n_s\) down to 77 K, taken from Tufte and Stelzer [80]. Because the carrier concentration varies with depth in the diffusions, the measured \(\pi_l\) is a conductivity-weighted average of the piezoresistive coefficient through the thickness. We see that below \(\sim 100\) K, \(\pi_l\) decreases with temperature.
Table 5.2: AFM performance of fabricated scanning probes at low temperature. Boldface values are measured, others are predicted (updated for fabricated geometry and low-T amplifier). If listed, \(n\) is the number of devices measured, otherwise \(n = 1\). For \(n > 1\), values are given as average \(\pm\) standard deviation. Measurements taken at \(T = \sim 2\) K with \(V_{\text{bridge}} = 0.2\) V and \(B = 1\) Hz–10 kHz.

<table>
<thead>
<tr>
<th></th>
<th>L1</th>
<th>L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic (M) or Four Legs (FL)</td>
<td>M</td>
<td>FL</td>
</tr>
<tr>
<td>Spring constant (N/m)</td>
<td>4.78</td>
<td>2.67</td>
</tr>
<tr>
<td>Resonant frequency (kHz)</td>
<td>131</td>
<td>103</td>
</tr>
<tr>
<td>Displacement sensitivity (kV/m)</td>
<td>(0.150)</td>
<td>(0.140 \pm 0.00640) (n = 4)</td>
</tr>
<tr>
<td></td>
<td>0.181</td>
<td>0.178</td>
</tr>
<tr>
<td>Total noise (nV)</td>
<td>1150</td>
<td>1150</td>
</tr>
<tr>
<td></td>
<td>422</td>
<td>422</td>
</tr>
<tr>
<td>Displacement resolution (Å)</td>
<td>76.7</td>
<td>82.1</td>
</tr>
<tr>
<td></td>
<td>23.3</td>
<td>23.7</td>
</tr>
</tbody>
</table>

The values of \(\pi_l\) extracted from our piezoresistors, with \(n_s = 1.3 \times 10^{20}\) cm\(^{-3}\) as verified by spreading resistance measurements, show good agreement with the existing data and can be used for future designs intended for operation below 77 K.

At room-T, the monolithic cantilever R1 showed lower sensitivity than the four-legged cantilever R2 due to leakage current between the piezoresistor legs. This current is proportional to the minority carrier concentration in the p-type substrate, given by \(n_i^2/N_A\) where \(n_i\) and \(N_A\) are the intrinsic carrier and the acceptor doping concentrations. But, \(n_i \propto T^{3/2} \exp(-E_g/2k_B T)\), so the leakage current at low-T is negligible and we see that L1 and L2 have similar performance. Thus, it is less critical for probes designed strictly for low-T operation to have electrical isolation between the piezoresistor legs.

The total measured noise at low-T is 2.7x larger than predicted, which significantly degrades displacement resolution. In Figure 5.9, we show predicted and measured noise spectra. Two important features can be seen in this plot. First, the total system noise is equal to the noise from the amplifier by itself, with its inputs grounded. Under low-T operating conditions, the piezoresistor noise is below the noise floor of
the amplifier because $V_j^2 \propto T$ and $V_H^2 \propto V_{bridge}^2$. Consequently, the displacement resolution is limited only by the amplifier noise. Second, there are significant peaks at the 60 Hz harmonics, likely coupling in from the scanning system, which cause the amplifier noise to exceed the predicted noise obtained from the data sheet. To improve resolution, the SR560 (4 nV/$\sqrt{\text{Hz}}$ at 1 kHz) should be replaced with a quieter amplifier and the noise peaks should be addressed. With the INA103 used for room-T measurements (1 nV/$\sqrt{\text{Hz}}$ at 1 kHz) and no noise peaks, L1 and L2 should be able to resolve displacements of 7.0 Å and 7.5 Å, respectively.
Figure 5.9: Noise spectra taken at low-T. The SR560 spectrum was taken with the amplifier inputs grounded. Total system noise was measured with an L2 probe in the Wheatstone bridge. The SR560 and total noise spectra are equal, indicating that the piezoresistor noise is below the amplifier noise floor. Both measured spectra show significant peaks at the 60 Hz harmonics, likely coupling in from the scanning system.

5.2 Coaxial Tips

We measured the electrostatic potential profile produced by our coaxial tips using a quantum point contact. However, instead of imaging the electron flow through the QPC as described earlier, we used the QPC as a local potential sensor. At low-T, we first obtained a plot of conductance $G_{ds}$ through the QPC versus voltage $V_G$ on the split gates. To measure $G_{ds}$, we applied a small AC voltage (~4 µV) across the ohmic contacts and recorded the resulting current using a DL 1211 current preamplifier and an EG&G 124A lock-in amplifier. Dividing the measured current by the applied voltage gives us $G_{ds}$. Then, we selected $V_G$ such that the QPC was between pinch-off and the first conductance plateau. In this region, $dG_{ds}/dV_G$ is approximately linear. When the tip is placed in proximity to the QPC, it acts as a third gate and
5.2. COAXIAL TIPS

Table 5.3: Properties of the QPC devices used to map tip potential (from [99]).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($10^{11}$ cm$^{-2}$)</td>
<td>4.3</td>
</tr>
<tr>
<td>Mobility ($10^6$ cm$^2$/Vs)</td>
<td>0.14</td>
</tr>
<tr>
<td>Mean free path ($\mu$m)</td>
<td>1.5</td>
</tr>
<tr>
<td>Distance from surface to 2DEG (nm)</td>
<td>57</td>
</tr>
<tr>
<td>Distance from donors to 2DEG (nm)</td>
<td>22</td>
</tr>
<tr>
<td>Width of split gate opening (nm)</td>
<td>300</td>
</tr>
<tr>
<td>Thickness of metal gates (nm)</td>
<td>30</td>
</tr>
</tbody>
</table>

The potential from the tip modulates the channel conductance. Thus, by recording $G_{ds}$ as the tip is scanned over the QPC, a spatial map of the tip potential can be obtained. The properties of the QPC devices we used for tip characterization are given in Table 5.3 measured at 4.2 K.

5.2.1 Annulus-Opened Tip

In Figure 5.10 we present 2D maps of $G_{ds}$ acquired with a dry-etched tip opened with the annulus method. The maps are 8 $\mu$m x 8 $\mu$m. The tip has a shield opening radius $r_o$ of 155 nm and was scanned at a height $h_{lift}$ of 100 nm above the semiconductor surface. We set $V_G$ at $-1.35$ V, yielding $G_{ds}$ of $1.02 \ e^2/h$. We varied the inner conductor voltage $V_{ic}$ and the outer shield voltage $V_{sh}$ from $-2$ V to $2$ V in steps of $2$ V to produce a 3x3 grid of maps. The color bar is chosen such that white represents the nominal $G_{ds}$ while red and blue represent suppression and enhancement of conductance respectively.

The maps show that we can independently address the inner conductor and the shield and that both are capable of gating the QPC. Qualitatively, we see that by tuning $V_{sh}$, we can narrow the perturbation created by the inner conductor and eliminate the slow decay in potential that is characteristic of an unshielded tip. Consider the bottom row of images where $V_{ic} = -2$ V. When $V_{sh} = -2$ V, $G_{ds}$ is suppressed in the entire scan window. Even when the tip is several microns from the QPC, the long range fields from the inner conductor and shield result in a negative $\Delta G_{ds}$. 
Figure 5.10: (a) SEM image of tip and shield opening at 0° tilt. (b) Topography of the split gates that define the QPC. (c) QPC conductance as a function of split gate voltage, showing the operating setpoint. (d) 2D maps of $G_{ds}$ collected as the tip is scanned above the QPC with $h_{	ext{lift}} = 100$ nm. The dotted outlines indicate the position of the split gates.
When $V_{sh} = 0$ V, the region of strong suppression from the inner conductor is reduced. Furthermore, with this biasing, when the tip is not directly above the QPC, $G_{ds}$ returns to its nominal value (except at the top and right edges, discussed below). Finally, when $V_{sh} = +2$ V, the perturbation produced by the inner conductor is even narrower. However, the potential on the shield now enhances $G_{ds}$ which, for actual SGM scans, may be undesirable. For additional clarity, Figure 5.11 provides linecuts of $G_{ds}$ perpendicular to the QPC gates for the maps where $V_{ic} = -2$ V.

Two surprising features are apparent in the maps. First, when both $V_{ic}$ and $V_{sh}$ are set at 0 V, we intuitively expect to see no change in the QPC conductance. However, centered above the QPC, we see a region of strong suppression. In a previous study in which a QPC was used as a displacement sensor [112], a change in $G_{ds}$ was also observed in response to a grounded cantilever. The authors believed that the
modulation of conductance was a result of trapped charge or differences in surface potential. In our case, we believe that the former explanation is correct. Figure 5.12 provides linecuts of $G_{ds}$ where $V_{sh}$ is held at 0 V while $V_{ic}$ is swept from $-2$ V to $+2$ V and vice versa. The linecuts exhibit two distinct dips in $G_{ds}$, marked by arrows. These dips cannot be eliminated by increasing either $V_{sh}$ or $V_{ic}$, which would be the case if they were caused by surface potential differences. Furthermore, the dips are separated by $\sim500$ nm, which roughly corresponds to the diameter of the shield opening (310 nm), given that the tip is 100 nm from the sample surface. Thus, we suspect that the dips are caused by trapped charges in the oxide separating the inner conductor and shield. These charges were likely introduced during the annulus opening process, in which a high-energy beam of Ga$^+$ ions was directed at the tip apex from above (see Figure 4.12). After etching through the shield metal, the underlying oxide was exposed to the beam, which may have resulted in implantation of ions or broken Si-O bonds, both of which can produce fixed charges.

Second, we observe unexpected contrast at the top and right edges of the images. When the tip is scanned in these regions, the body of the cantilever is not directly above the QPC. As such, the QPC is affected more by the inner conductor exposed on the sides of the cantilever than the Al shield on the top surface. When $V_{ic}$ and
$V_{sh}$ have opposite polarity, the effect is particularly clear in the conductance maps. When these probes are used for SGM imaging, the electric field from the sides of the cantilever may introduce long-range effects if the device being studied extends beyond the cantilever and is sensitive to gating at numerous locations (e.g. a mm-long carbon nanotube with several defects). To address this issue in future probe designs, the inner conductor can be inset from the edges of the cantilever. It may also be possible to shield all of the cantilever surfaces by depositing the metal with atomic layer deposition or another highly-conformal process.

The presence of trapped charge in the oxide makes it difficult to assess the FWHM of the electrostatic potential profile produced by the coaxial tip. With the inner conductor and shield grounded, the charge alone forces the QPC near pinch off. Applying a small negative $V_{ic}$ completely pinches off the channel. At this point, the QPC response is saturated, and the peak in $|\Delta G_{ds}|$ needed to calculate FWHM cannot be measured. Thus, we consider instead the case of positive voltage on the inner conductor. We assume that the total response of the QPC is a linear superposition of its responses to the inner conductor, shield and trapped charge. This allows us to subtract the linecut for $(V_{ic}, V_{sh}) = (0 \text{ V}, 0 \text{ V})$ from the linecut for $(V_{ic}, V_{sh}) = (+2 \text{ V}, 0 \text{ V})$ to remove the contribution of the trapped charge. The FWHM of the resultant curve is 442 nm. This value is larger than the FWHM of 305 nm predicted in Section 3.4 for a dry-etched tip with $r_o = 150 \text{ nm}$. There are several explanations for the discrepancy between the predicted and measured FWHM values. First, in our modeling, we only considered capacitive coupling between the coaxial tip and the buried 2DEG. However, the tip also interacts with the surface gates, which are larger than the QPC channel. This interaction may increase the apparent width of the tip perturbation. Second, the QPC channel itself does not sample the electrostatic potential at a single point in space. It responds to the potential in a nearby volume, which can be represented by a point spread function (PSF). The PSF sets the spatial resolution of QPC when it is used as a sensor. The measured curves of $G_{ds}$ are convolutions of the tip potential profile with this PSF and thus, are broader than the actual tip potential profile. Last, the tip we measured had $r_o = 155 \text{ nm}$ while the simulated tip had $r_o = 150 \text{ nm}$.
5.2.2 CCS-Opened Tip

We also characterized the electrostatic potential profile from a dry-etched tip opened with the cleaning cross-section (CCS) method. The tip had an opening radius of $\sim 30$ nm, 5x smaller than that of the tip opened with the annulus method. As before, we scanned the tip at $h_{\text{lift}} = 100$ nm. A different QPC device was used for this investigation. We set $V_G = -0.730$ V, corresponding to a linear region between the first and second conductance plateaus. This gate voltage yielded a nominal $G_{ds} = 2.56 \frac{e^2}{h}$. Figure 5.13 presents 2D maps of $G_{ds}$ for the tip opened by the CCS method.

We again see that by tuning $V_{sh}$, we can narrow the tip perturbation and eliminate the long tail in its decay. However, there are two important differences compared to Figure 5.10. First, when the inner conductor and shield are grounded, we see a smaller region of conductance suppression centered on the QPC, surrounded by a halo of enhancement. A linecut through this pattern is provided in Figure 5.14. The lack of the suppression dips seen in Figure 5.12 supports our hypothesis that these dips are caused by trapped charge in the oxide. When tips are opened with the CCS method, the Ga\textsuperscript{+} ion beam is directed perpendicular to the apex (see Figure 4.12). Thus, any material that is damaged by ion bombardment is subsequently removed. The remaining surface is smooth and “clean” of ions. For this reason, the CCS technique is also used to prepare thin samples for transmission electron microscopy.

Without trapped charges dominating the effect of the tip, the halo of the enhancement is revealed. This halo is caused by the work function difference between the Al shield and the GaAs/AlGaAs heterostructure. Unlike the suppression dips, the halo can be eliminated by applying a voltage to the shield that nulls the work function difference. As seen in Figure 5.14, this “minimum invasive voltage” is $-0.6$ V. This voltage results in a flat $G_{ds}$ response when the tip is not directly above the QPC. The same voltage was also reported to null the work function difference between the Al island of a single-electron transistor scanning electrometer and an GaAs/AlGaAs heterostructure [113]. Figure 5.14 also tells us that the difference in work function between the n-type Si inner conductor and the QPC has the opposite polarity of that between the Al shield and the QPC. In general, for SGM imaging with the coaxial tip, $V_{sh}$ should be tuned to the minimum invasive voltage such that the perturbation
Figure 5.13: (a) SEM image of tip and shield opening at 52° tilt. (b) Topography of the split gates that define the QPC. (c) 2D maps of $G_{ds}$ collected as the tip is scanned above the QPC with $h_{lift} = 100$ nm. The dotted outlines indicate the position of the split gates.
Figure 5.14: Linecuts of $G_{ds}$ along the dashed line in Figure 5.13 for $V_{ic} = 0$ V and various $V_{sh}$. When $V_{sh} = -0.6$ V, the enhancement peaks (arrows) caused by the work function difference between the Al shield and GaAs/AlGaAs heterostructure are eliminated.

created in the sample is strictly from the inner conductor. Although $-0.6$ V is least invasive to the 2DEG, we see that this voltage suppresses $G_{ds}$ when the tip is above the QPC because of capacitive coupling between the shield and the surface gates. Thus, the presence of surface gates makes it difficult to find a single shield voltage that is non-perturbing to the entire sample.

The second difference we see is that the electrostatic potential profile from the tip appears elliptical instead of circular, with the long axis of the ellipse perpendicular to the split gates. As stated earlier, the 2D maps of $G_{ds}$ represent convolutions of the tip potential profile with the PSF of the QPC. The shape of the resulting convolution is controlled by the broader of these two inputs. From our modeling of the coaxial tip in Section 3.4, we expect that the FWHM of the potential profile produced by the CCS-opened tip is below the spatial resolution of the QPC. Thus, when the QPC is
used to measure this profile, the map of $G_{ds}$ instead takes the shape of the QPC PSF. We believe the PSF of the QPC is elongated in the axis perpendicular to the split gates because the gates screen the tip potential. Thus, when the tip is scanned along the gates, its effect decays more rapidly than when it is scanned along the QPC channel. In addition, the flow of electrons through the QPC is collimated [6,9], with the maximum flow occurring through the center of the channel. The flow decreases at larger angles from the straight-line trajectory. Because fewer electrons are backscattered at large angles, the tip has a smaller effect in these locations.

In order to visualize the effect of the QPC PSF on the measurement of tip potential profiles, we performed 2D spatial convolutions in Matlab. We approximated the potential profiles of the annulus- and CCS-opened tips as circles with diameters of 400 nm and 140 nm, respectively. We modeled the PSF as an ellipse with a long axis of 450 nm and short axis of 300 nm (equal to the opening in the surface gates). The results of the convolutions are presented in Figure 5.15. For the annulus-opened tip, the convolution is broader than the potential profile, but still a reasonable representation of its shape. For the CCS-opened tip, the convolution is elliptical.

To calculate the FWHM of the convolution, which gives an upper bound on the FWHM of the tip potential profile, we considered maps of $G_{ds}$ with $V_{sh} = -0.6$ V. We subtracted the map with $V_{ic} = 0$ V from the map with $V_{ic} = -2$ V to eliminate the effect of capacitive coupling between the shield and the surface gates and measured the FWHM of the result. Because the convolution is elliptical, we measured the FWHM in the x and y axes, yielding 350 nm and 240 nm respectively. Even as upper bounds, these values demonstrate that the potential profile from the CCS-opened tip is narrower than that of the annulus-opened tip. Note also that the FWHM in the y-axis roughly corresponds to the 300 nm wide opening in the split gates defined by e-beam lithography.

In Figure 3.10, we showed that the FWHM of the perturbation induced by a dry-etched unshielded tip at $h_{lift} = 100$ nm is 560 nm. Here, we showed that the FWHM of the potential profile produced by a dry-etched CCS-opened coaxial tip at the same lift height is $\leq 240$ nm. Thus, under these conditions, our coaxial tips achieve $\geq 2.3x$ improvement in the lateral resolution of SGM.
Figure 5.15: Results of 2D spatial convolutions performed in Matlab between estimates of the tip potential profiles and the QPC point spread function (PSF). We model the PSF as an ellipse, with the long axis perpendicular to the split gates (dotted lines), due to shielding by the gates and to the collimated nature of electron flow through the QPC. (a) The potential profile of the annulus-opened tip is similar in size to the PSF. The resulting convolution is broader than the profile, but a reasonable representation of its shape. (b) The potential profile of a CCS-opened tip is smaller than the PSF. The resulting convolution takes the elliptical shape of the PSF. Measurements of the FWHM of the convolutions (i.e. the maps of $G_{ds}$) are upper bounds for the corresponding measurements on the tip potential profile.
Chapter 6

Conclusion and Future Work

In this chapter, I briefly summarize the work in this thesis and enumerate my contributions. I also provide future directions both for applications of the coaxial-tip probes and for improved designs of the probes themselves.

6.1 Summary

In scanning gate microscopy, the current through a sample is measured as a conductive tip that modifies the local electrostatic potential is scanned above the surface. SGM enables measurement and manipulation of local current flow, carrier density and potential barriers. Conventional SGM probes have significant stray capacitance, resulting in poor lateral resolution when they are used to investigate nanostructures.

We have demonstrated a new scanning probe that integrates a coaxial tip on a piezoresistive cantilever. By shielding the inner conductor up to the tip apex, the coaxial tip minimizes stray capacitance and produces tightly-confined potential profiles. The piezoresistor provides self-sensing capability, allowing cantilever deflection to be measured electrically, without the traditional optical lever setup that can disturb photosensitive samples.

We designed the piezoresistive cantilevers with the aid of a numerical optimizer that we adapted for AFM at room and low temperature. The code varies the piezoresistor and cantilever geometry, operating conditions and diffusion parameters, within
the supplied constraints, to arrive at a design that optimizes vertical displacement resolution. We included two cantilever variations, one with a uniform, monolithic geometry and the other with four legs, where the electrical traces are isolated by air gaps. We used finite element analysis to compare the electrostatic potential profiles from unshielded and coaxial tips and to investigate the effects of tip geometry on the lateral resolution of SGM. We established that a coaxial tip produces a narrower profile than an unshielded tip. In addition, we showed that lift height and shield opening radius have the largest effect on profile width, and should be minimized for optimal lateral resolution.

We developed a 7-mask process to fabricate scanning probes with both a piezoresistor and a coaxial tip. We started with silicon-on-insulator wafers and then etched alignment marks, etched sharp tips, doped the tips and created the piezoresistors with a phosphorus diffusion, deposited a low-temperature oxide as an insulator, opened contacts, deposited and patterned aluminum into electrodes and the outer shield, and finally, defined and released the cantilevers with deep reactive ion etching. We developed two focused ion beam milling methods, annulus and cleaning cross-section, to open the shield metal at the tip apex. The smallest apertures we produced were \( \sim 30 \) nm in radius using the CCS method.

We characterized the AFM performance of the probes by measuring the total system noise with the tip out of contact and then recording the readout circuit output while deflecting the cantilever with a hard sample to calculate displacement sensitivity. The four-legged probes can self-sense tip displacements of 2.8 Å at 293 K and 82 Å at 2 K in a 1 Hz–10 kHz bandwidth, where the low-T performance is limited by amplifier noise. At room-T, we showed that the electrical isolation of the four legs minimizes leakage current and improves vertical displacement resolution. At low-T, leakage current is negligible, and the isolation is less critical. Finally, we imaged the potential profiles produced by the coaxial tips using a quantum point contact. We demonstrated that the annulus method creates trapped charge in the insulator of the coaxial tip, but the CCS method does not. At a lift height of 100 nm, the CCS-opened coaxial tips produce profiles that are \( \geq 2.3x \) narrower than those of unshielded tips.
6.2 Future Work

Future work on this project can be divided into new applications of the coaxial-tip probe and improvements to the probe design. We discuss each of these possibilities in the sections below.

6.2.1 Applications

Imaging Carbon Nanotube Field Effect Transistors

From Section 5.2, we see that there are two main challenges associated with using a QPC to map the electrostatic potential profile from a coaxial tip. First, the Au split gates and GaAs/AlGaAs heterostructure have different work functions. Thus, there is no single shield voltage that minimizes the tip perturbation over the entire sample. Second, the spatial resolution of the QPC is \( \sim 300 \) nm. When the FWHM of the tip potential profile is below this limit, the resulting conductance maps reflect the point spread function of the QPC. To overcome these challenges, we need a sensor that approaches a spatial delta function in at least one dimension. In addition, the metal electrodes that contact the sensor should be far from the scanning area. With the correct geometry, carbon nanotube field effect transistors can satisfy both of these constraints. Scanning these devices will provide a more accurate estimate of the FWHM of the tip potential profile.

Mapping Electrons in Quantum Dots

A promising application of our coaxial-tip probes is mapping electron probability density functions (PDFs) in quantum dots (QDs). One method of forming a QD is to confine a pool of electrons in a 2DEG by depleting the surrounding region using surface electrodes, as seen in the inset of Figure 6.1(a). Varying the gate voltage \( V_g \) shifts the ladder of quantized states in the QD with respect to the Fermi levels of the source and drain electrodes. If we measure conductance through the QD as a function of \( V_g \), we observe a series of sharp peaks characteristic of the Coulomb blockade effect. A representative plot is shown in Figure 6.1(a). Each peak corresponds to an energy
When a tip is placed in proximity to the QD, the tip potential shifts the conductance peaks. According to first-order perturbation theory, the shift in gate voltage of the $i$th peak is given by

$$\Delta V_{g,i} \propto \int \Psi_i^*(r) \phi_{\text{tip}}(r) \Psi_i(r) \, dr$$  \hspace{1cm} (6.1)$$

where $\Psi_i(r)$ is the electron wavefunction of the $i$th eigenstate and $\phi_{\text{tip}}(r)$ is the tip potential. Thus, if we measure $\Delta V_{g,i}$ and $\phi_{\text{tip}}(r)$ is well known, we can deconvolve (6.1) to solve for $|\Psi_i(r)|^2$. In practice, this problem is intractable. However, if the tip potential profile is highly-localized, we can approximate it as a delta function,

$$\phi_{\text{tip}}(r) = \delta(r - r_0)$$  \hspace{1cm} (6.2)$$

where $r_0$ is the tip location. Then (6.1) becomes

$$\Delta V_{g,i} \propto \int \Psi_i^*(r) \delta(r - r_0) \Psi_i(r) \, dr$$

$$\propto |\Psi_i(r_0)|^2.$$  \hspace{1cm} (6.3)$$

Now, the shift in the $i$th conductance peak is proportional to the PDF of the $i$th eigenstate, evaluated at the tip location. By plotting $\Delta V_{g,i}$ as the tip is scanned above the QD, we can produce a spatial map of the $|\Psi_i(r)|^2$. This concept is presented graphically in Figure 6.1(b).

The key to the success of this procedure is the ability to make the approximation in (6.2). With a conventional SGM probe, the tip potential profile is too broad and (6.2) does not apply. A coaxial tip, on the contrary, may provide a sufficient sharp perturbation.
Figure 6.1: (a) Sharp peaks in conductance through a quantum dot versus gate voltage, characteristic of the Coulomb blockade effect. Inset: topographic image of surface electrodes arranged to create a QD. (b) Scanning technique to image electron organization in the QD. When the tip potential is a delta function, the shift in gate voltage of a conductance peak is proportional to the PDF of the corresponding eigenstate evaluated at the tip position. Thus, plotting $\Delta V_{g,t}$ as the tip is scanned reveals a map of $|\Psi_i(r)|^2$. Images courtesy of M.A. Topinka.

### 6.2.2 Probe Design

**Summary of Previously-Discussed Enhancements**

We have already discussed several specific enhancements to the probe design in Sections 4.7 and 5.2. We summarize them here for convenience:

- Increase the aluminum thickness from 400 Å to improve corrosion resistance and tip coverage. The resulting increase in tip rounding can be addressed in the opening process.
- Inset the inner conductor from the edge of the cantilever such that it is better shielded by the aluminum layer.
- Modify the reticle or eliminate wafer rotation (requires p-type piezoresistors) such that the frontside clamp is a slope and not a step.
- Move the image stitching seams from the root of the cantilever to a less critical
location on the die.

- Expand the wafer exclusion zone to 5 mm.
- Include 2 mm x 2 mm windows for in-process etch monitoring.
- Release the electrical test structures along with the scanning probes.

**Alternative Metals for the Outer Shield**

As stated earlier, gold is the ideal metal for the outer shield as it is chemically inert and does not become superconductive at cryogenic temperatures. However, in order to comply with the contamination policies of the SNF, we opted to use aluminum. This decision should be revisited in future probe designs.

Using gold for the outer shield requires several modifications to the fabrication process. By itself, gold adheres poorly to silicon dioxide. Thus, a thin layer of titanium or chromium should be deposited first as a wetting layer. Optionally, a layer of platinum can be deposited next to act as a diffusion barrier between the wetting layer and the gold layer, preventing the formation of resistive and unstable inter-metallic alloys [114]. If Pt is included, the metal stack must be patterned with lift-off, which requires the polarity of the Metal images on the reticle to be inverted. If not, Ti, Cr and Au can all be patterned with standard wet etchants and no change is needed to the reticle.

To minimize the fabrication steps that must be performed outside SNF once the wafers are gold-contaminated, the device layer silicon should be patterned prior to metal deposition (i.e. swap steps (f) and (g) in Figure 4.5). Then, the final DRIE to release the scanning probes can be performed at an external vendor or other academic lab with less-stringent contamination policies (for example, the UC Santa Barbara Nanofabrication Facility or the University of Michigan Lurie Nanofabrication Facility). Etching the device layer silicon earlier in the process also makes the cantilever sidewalls accessible for metal deposition to improve shielding. For good sidewall coverage, the deposition process should be highly-conformal. Sputtering may be sufficient. Atomic layer deposition (ALD) is a more promising option, but in this case, an ALD recipe must exist for the desired metal (e.g. Pt) [115,116].
6.2. FUTURE WORK

Batch Opening of Coaxial Tips

Using a focused ion beam to open the shield metal at the tip apex of each probe is a low-throughput, costly and error-prone process. Thus, it is highly desirable to find a process that can open all of the tips on a wafer in parallel. Here, we describe several promising batch opening techniques we would like to investigate which build on the work in [63,66–68].

The first technique requires the smallest perturbation to the existing process. Currently, after depositing aluminum, we spin and pattern 4 $\mu$m of SPR220-3 resist. The resist is thick enough to fully cover the 3 $\mu$m tall tips. At this point, we could introduce an O$_2$ plasma etch step to slowly thin the resist above the tips, eventually exposing just the apices. Tight process control, involving precise timing and continual observation under optical microscope and SEM, would be necessary to stop the etch exactly when the apices are exposed as overetching would result in large apertures. As before, the wafers would then be placed in AL-11 etchant to define the bond pads. This step would also open the shield at the apices, which is now accessible to the etchant. Two significant challenges exist with this technique. First, there is no clear endpoint for the O$_2$ plasma etch. It is unlikely that the protrusion of the apices above the resist can be resolved under the optical microscope. Under SEM, the resist will accumulate negative charge, making observation of small features difficult. Furthermore, optical endpoint detection cannot be used to terminate the etch as aluminum will already be exposed to the plasma at the start of the etch. Thus, the change in the plasma emission spectrum when the apices are exposed will be negligible. Second, this process requires excellent tip height uniformity across the wafer. Irregular tip heights will result in some apices being exposed before others and ultimately, a large variation in opening diameters.

A modification of the above technique may allow for optical endpoint detection. Here, an additional resist spin step is added after the bond pads are patterned. This resist would be used strictly for tip opening, and not patterned by optical lithography. As such, it would fully protect the wafer at the beginning of the O$_2$ plasma etch. No aluminum would be exposed to the plasma until the apices were cleared of resist. Thus, it may be possible to detect the resulting change in the plasma emission
CHAPTER 6. CONCLUSION AND FUTURE WORK

spectrum and terminate the etch.

Another technique that may be more tolerant of tip height variation involves spray coating a conformal layer of resist over the tips and then reflowing the resist at elevated temperature to expose the apices. The SNF recently acquired a spray coater from EV Group (Tempe, AZ). To obtain a conformal layer, a “dry” resist mixture is needed. This mixture contains a large weight fraction of high vapor pressure solvent (e.g. MEK) such that after dispensing, the droplets dry on contact with the wafer surface and do not flow. The Accumist nozzle is designed for conformal coatings. It has a low dispense rate and 10° dispense solid angle. After coating, the wafer can be heated to 90-110°C to allow controlled reflow of the resist. Surface tension should cause the resist to recede from the apices.

A final alternative is to spray coat successive thin layers of resist to produce a final layer that protects the majority of the tip cone, leaving only the apex exposed. In this case, the Vortex planarizing nozzle (high dispense rate, 45° solid angle) and a “wetter” resist composition containing more low vapor pressure solvent should be used such that surface tension and gravity are the controlling forces in the film morphology. This will cause resist that initially deposits on the apex to flow toward the base of the cone.

A Universal Probe for Electrical Microscopy

Having demonstrated a coaxial-tip piezoresistive cantilever probe for scanning gate microscopy, a reasonable extension is the development of a probe that brings the advantages of self-sensing and improved lateral resolution to all electrical scanning probe techniques including scanning microwave microscopy (SMM), scanning Kelvin probe microscopy (SKPM), electrostatic force microscopy (EFM) and scanning capacitance microscopy (SCM). However, some of these techniques, SMM in particular, place stricter requirements on the probe than SGM.

In SMM, the probe is used to transmit a microwave signal to the sample and to collect the reflected signal. Small changes in the amplitude and phase of the reflected signal provide information about the local electrodynamic properties of the sample [117]. For maximum sensitivity and lateral resolution, the parasitic resistance
and capacitance of the conductor to the tip must be minimized. Ideally, the resistance should not exceed 3 Ω and the capacitance to ground should not exceed 5 pF. Our coaxial-tip probe design does not meet these requirements because the inner conductor is doped silicon, and the insulator between the inner conductor and outer shield is only 400 Å thick.

In order to produce a universal probe, our probe must be modified such that the inner conductor is a thick metal and the insulator is a thick low-k dielectric. Furthermore, the cantilever substrate should be an insulator such as silicon nitride instead of lightly-doped silicon to minimize microwave losses. Although these modifications seem trivial, they introduce a number of design challenges. First, if the cantilever is comprised of several thick films of different materials, it is susceptible to bending as a result of intrinsic stresses in the films. Even if it does not bend immediately after release, the difference in coefficients of thermal expansion may result in bending with change in temperature. Second, the thick films can cause rounding of the sharp tip, which degrades lateral resolution when the probe is used for AFM. Third, if the cantilever is not single-crystal silicon, it is difficult to integrate a piezoresistor. While it is possible to build a piezoresistor in a layer of poly-crystalline silicon deposited on the insulating cantilever, these piezoresistors tend to be noisier and less sensitive [118]. Solutions to these problems, including tapered film thickness (thick on the die, thin on the cantilever) and hybrid cantilevers (silicon nitride near the tip, silicon near the root), are worth investigating – a successful design will further advance the state-of-the-art in electrical scanning probes. For details on the initial steps that we have taken in this direction, see Appendix I.
Appendix A

Mechanical Properties of a Cantilever with Four Legs

Figure A.1: Coordinate system used to derive the mechanical properties of a cantilever with four legs. The blue line represents the neutral axis of the cantilever. The total length of the cantilever is $l_c$ and the length of the legs is $l_p$. A force $F$ is applied at the free end.

A.1 Spring Constant

Consider a force $F$ applied to the free end of a cantilever with four legs (Figure A.1). From Hooke’s law, the displacement $x$ of the free end is related to $F$ by

$$F = k_{\text{legs}} x \quad (A.1)$$
A.1. SPRING CONSTANT

where \( k_{\text{4legs}} \) is the spring constant. In order to determine \( k_{\text{4legs}} \), we must solve for \( x \). The curvature of a beam under small displacements is given by

\[
EI \frac{d^2 x}{dy^2} = M(y)
\]

\[
EI \frac{d^2 x}{dy^2} = F(l_c - y)
\]

(A.2)

where \( M(y) \) is the bending moment at the cross-section at location \( y \), \( E \) and \( l_c \) are the Young’s modulus and length of the beam, and \( I \) is its moment of inertia with respect to the neutral axis. The cantilever has four legs in the region \( 0 \leq y \leq l_p \) and becomes monolithic in the region \( l_p < y \leq l_c \). Therefore, \( I \) is a piecewise function,

\[
I = \begin{cases} 
\frac{w_p t_c^3}{3} & y \leq l_p \\
\frac{w_c t_c^3}{12} & y > l_p 
\end{cases}
\]

(A.3)

where \( w_c \) and \( t_c \) are the width and thickness of the cantilever and \( w_p \) is the width of each leg. Integrating (A.2) and substituting (A.3), we have

\[
\frac{dx}{dy} = \begin{cases} 
\frac{3F}{E w_p t_c^3} \left( l_c y - \frac{1}{2} y^2 \right) + c_1 & y \leq l_p \\
\frac{12F}{E w_c t_c^3} \left( l_c y - \frac{1}{2} y^2 \right) + c_2 & y \geq l_p 
\end{cases}
\]

(A.4)

where \( c_1 \) and \( c_2 \) are unknown constants. To solve for \( c_1 \), we apply the boundary condition at \( y = 0 \), where the cantilever has no linear or angular degrees of freedom

\[
\left. \frac{\partial x}{\partial y} \right|_{y=0} = 0
\]

\[
\frac{3F}{E w_p t_c^3}(0) + c_1 = 0
\]

\[
\therefore c_1 = 0.
\]

(A.5)
To solve for $c_2$, we first substitute (A.5) into (A.4) and then apply a continuity condition at $y = l_p$,

$$
\left. \frac{dx}{dy} \right|_{y=l_p^+} = \left. \frac{dx}{dy} \right|_{y=l_p^-} = \frac{3F}{Ew_p t_c^3} \left( l_c l_p - \frac{1}{2} l_p^2 \right) = \frac{12F}{Ew_c t_c^3} \left( l_c l_p - \frac{1}{2} l_p^2 \right) + c_2
$$

$$
\therefore c_2 = \frac{3F}{E t_c^3} \left( l_c l_p - \frac{1}{2} l_p^2 \right) \left( \frac{1}{w_p} - \frac{4}{w_c} \right). \quad (A.6)
$$

Integrating (A.4), we have

$$
x(y) = \begin{cases} 
\frac{3F}{Ew_p t_c^3} \left( \frac{1}{2} l_c y^2 - \frac{1}{6} y^3 \right) + c_3 & y \leq l_p \\
\frac{12F}{Ew_c t_c^3} \left( \frac{1}{2} l_c y^2 - \frac{1}{6} y^3 \right) + c_2 y + c_4 & y \geq l_p 
\end{cases} \quad (A.7)
$$

where $c_3$ and $c_4$ are unknown constants. To solve for $c_3$, we again employ the boundary condition at $y = 0$,

$$
x(0) = 0
$$

$$
\frac{3F}{Ew_p t_c^3} (0) + c_3 = 0
$$

$$
\therefore c_3 = 0. \quad (A.8)
$$

Substituting (A.8) into (A.7) and applying continuity at $y = l_p$, we have

$$
x(l_p^-) = x(l_p^+)
$$

$$
\frac{3F}{Ew_p t_c^3} \left( \frac{1}{2} l_c l_p^2 - \frac{1}{6} l_p^3 \right) = \frac{12F}{Ew_c t_c^3} \left( \frac{1}{2} l_c l_p^2 - \frac{1}{6} l_p^3 \right) + c_2 l_p + c_4
$$

$$
\therefore c_4 = \frac{3F}{E t_c^3} \left( \frac{1}{3} l_p^3 - \frac{1}{2} l_c l_p^2 \right) \left( \frac{1}{w_p} - \frac{4}{w_c} \right). \quad (A.9)
$$
A.2. RESONANT FREQUENCY

Now, we substitute (A.6) and (A.9) into (A.7) and evaluate at $y = l_c$,

$$x(l_c) = \frac{12F}{Ew_c l_c^3} \left( \frac{1}{2} l_c^3 - \frac{1}{6} l_c^2 \right) + \frac{3F}{Ew_c l_c^3} \left( l_c l_p - \frac{1}{2} l_p^2 \right) \left( \frac{1}{w_p} - \frac{4}{w_c} \right) l_c$$

\[ + \frac{3F}{Ew_c l_c^3} \left( \frac{1}{3} l_p^3 - \frac{1}{2} l_c l_p^2 \right) \left( \frac{1}{w_p} - \frac{4}{w_c} \right) \]

\[ = \frac{4Fl_c^3}{Ew_c l_c^3} + \frac{3F}{Ew_c l_c^3} \left( \frac{1}{w_p} - \frac{4}{w_c} \right) \left( \frac{1}{3} l_p^3 - \frac{1}{2} l_c l_p^2 - \frac{1}{2} l_c l_p^2 + \frac{1}{2} l_c l_p^2 \right) \]

\[ = \frac{F}{Ew_c l_c^3} \left[ 4l_c^3 + \left( \frac{1}{w_p} - \frac{4}{w_c} \right) \left( l_p^3 - 3l_c l_p^2 + 3l_c^2 l_p \right) \right]. \tag{A.10} \]

Finally, we substitute (A.10) into (A.1) and rearrange to give

$$k_{4\text{legs}} = \frac{Et_c^3}{4 \frac{l_c^3}{w_c} + l_p \left( \frac{1}{w_p} - \frac{4}{w_c} \right) \left( l_p^3 - 3l_c l_p^2 + 3l_c^2 l_p \right)}. \tag{A.11}$$

Note that if $l_p = 0$, $k_{4\text{legs}}$ reduces to $k_{\text{mono}}$ as expected.

A.2. Resonant Frequency

To calculate the resonant frequency of the cantilever $f_{0,4\text{legs}}$, we use the Rayleigh-Ritz method \[78\], which equates potential energy $W_p$ stored under maximum deflection with kinetic energy $W_k$ at zero deflection under the assumption of no dampening. Thus,

$$W_p = W_k$$

\[ \frac{1}{2} k_{4\text{legs}} |x(l_c)|^2 = \frac{1}{2} m |v|^2 \tag{A.12} \]

where $m$ and $v$ are the mass and velocity of the beam. We model the cantilever as a simple harmonic oscillator. Therefore, the time response of its displacement is

$$x(y, t) = x(y) e^{i\omega_0 t} \tag{A.13}$$
APPENDIX A. PROPERTIES OF A CANTILEVER WITH FOUR LEGS

where $\omega_0$ is the resonant frequency in radians/s. Then, the velocity is

$$v = \frac{\partial x(y, t)}{\partial t} = i\omega_0 x(y) e^{i\omega_0 t}. \quad (A.14)$$

We see that $m$ and $v$ are distributed along the length of the beam. Thus, we substitute (A.14) into (A.12) and integrate the right hand side of the equation from $y = 0$ to $y = l_c$,

$$k_{4\text{legs}} x^2(l_c) = \omega_0^2 \rho_c t_c \left[ \int_{0}^{l_p} 4w_p x^2(y) \, dy + \int_{l_p}^{l_c} w_c x^2(y) \, dy \right] \quad (A.15)$$

where $\rho_c$ is the density of the cantilever. Rearranging (A.15), we have

$$f_{0, 4\text{legs}} = \frac{1}{2\pi} \left[ \frac{k_{4\text{legs}} x^2(l_c)}{\rho_c t_c \left( \int_{0}^{l_p} 4w_p x^2(y) \, dy + \int_{l_p}^{l_c} w_c x^2(y) \, dy \right)} \right]^{1/2} \quad (A.16)$$

This equation can be solved analytically using (A.7), but doing so is tedious. Instead, we use numerical integration. The derivations above are adapted from Arlett [119].
Appendix B

Matlab Code

The code below is adapted from Doll et al. [54].

B.1 cantilever.m

classdef cantilever
    properties
        l % Cantilever length (m)
        w % Cantilever width (m)
        t % Cantilever thickness (m)
        w_pr_ratio % PR width ratio
        l_pr_ratio % PR length ratio
        tip_offset % Offset from free end to center of tip (m)
        legs % Presence of legs (0 or 1)
        rho_cantilever = 2330; % Cantilever density (kg/m^3)
        doping_type = 'boron';
        v_bridge % Bridge voltage (V)
        alpha = 3e-5; % Hooge noise parameter
        freq_min
        freq_max
        T % Operating temp (K)
\[ k_b = 1.38 \times 10^{-23}; \] Boltzmann (J/K)  
\[ k_b eV = 8.617343 \times 10^{-5}; \] Boltzmann (eV/K)  
\[ q = 1.60218 \times 10^{-19}; \] E l e c t r o n i c charge (C)  

```
opt_type % Optimize 'force' or 'disp' resolution
```  

methods (Abstract)  
```
doping_profile(self)
optimization_scaling(self)
cantilever_from_state(self, x0)
initial_conditions_random(self)
current_state(self)
optimization_bounds(self, constraints)
```  

end  

methods  
```
% Constructor
function self = cantilever(freq_min, freq_max, l, w, t, l_pr_ratio, ...
    w_pr_ratio, tip_offset, v_bridge, doping_type, T, opt_type, legs)
    
    self.l = l;
    self.w = w;
    self.t = t;

    self.w_pr_ratio = w_pr_ratio;
    self.l_pr_ratio = l_pr_ratio;

    self.tip_offset = tip_offset;
    self.legs = legs;

    self.v_bridge = v_bridge;

    self.freq_min = freq_min;
    self.freq_max = freq_max;

    self.doping_type = doping_type;
    self.T = T;

    self.opt_type = opt_type;
```  

end  

% Calculate the actual dimensions  
```
function l_pr = l_pr(self)
    l_pr = self.l * self.l_pr_ratio;
```  

end
function w_pr = w_pr(self)
    w_pr = self.w * self.w_pr_ratio;
end

% = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =
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function print_performance(self)
    fprintf(‘Cantilever l/w/t (um): %f %f %f
’, self.l*1e6, self.w*1e6, self.t*1e6)
    fprintf(‘PR l/w (um): %f %f
’, self.l_pr() * 1e6, self.w_pr() * 1e6)
    fprintf(‘Legs: %g \n’, self.legs)
    fprintf(‘Tip offset (um): %f \n’, self.tip_offset * 1e6)
    fprintf(‘\n’)
    fprintf(‘Wheatstone bridge voltage (V): %f \n’, self.v_bridge)
    fprintf(‘Resistance (Ohm): %g \n’, self.resistance())
    fprintf(‘Power dissipation (nW): %g \n’, self.power_dissipation() * 1e3)
    fprintf(‘\n’)
    fprintf(‘Force resolution (N): %g \n’, self.force_resolution())
    fprintf(‘Force sensitivity (V/N) %g \n’, self.force_sensitivity())
    fprintf(‘Displacement resolution (m): %g \n’, self.displacement_resolution())
    fprintf(‘Displacement sensitivity (V/m) %g \n’, self.displacement_sensitivity())
    fprintf(‘Beta %g \n’, self.beta())
    fprintf(‘Gamma %g \n’, self.gamma())
    fprintf(‘\n’)
    fprintf(‘Integrated noise (V): %g \n’, self.integrated_noise())
    fprintf(‘Integrated Johnson noise (V): %g \n’, self.integrated_johnson_noise())
    fprintf(‘Integrated 1/f noise (V): %g \n’, self.integrated_hooge_noise())
    fprintf(‘Knee frequency (Hz): %g \n’, self.knee_frequency())
    fprintf(‘Johnson/Hooge: %g \n’, self.integrated_johnson_noise() / self.integrated_hooge_noise())
    fprintf(‘\n’)
    fprintf(‘Sheet resistance (ohm/sq): %g \n’, self.sheet_resistance())
    fprintf(‘\n’)
    [x, doping] = self.doping_profile();
    Nz = trapz(x, doping*1e6);
    fprintf(‘Nz (atoms/mˆ2): %g \n’, Nz)
    fprintf(‘Number of carriers: %g \n’, self.number_of_carriers())
    fprintf(‘\n’)
    fprintf(‘Stiffness (N/m): %g \n’, self.stiffness(0))
    fprintf(‘Vacuum freq (Hz): %f \n’, self.omega_vacuum_hz())
fprintf(' Freq range (Hz): %f to %f \n', self.freq_min, self.freq_max)
fprintf('\n')
end

function print_performance_for_excel(self)
    variables_to_print = [self.l*1e6, self.w*1e6, self.t*1e6, ...
                        self.l_pr()*1e6, self.l_pr_ratio, self.w_pr()*1e6, self.w_pr_ratio, ...
                        self.v_bridge, self.resistance(), self.power_dissipation()*1e3, ...
                        self.force_resolution(), self.force_sensitivity(), ...
                        self.displacement_resolution(), self.displacement_sensitivity(), ...
                        self.beta(), ...
                        self.integrated_noise(), self.integrated_johnson_noise(), ...
                        self.integrated_hooge_noise(), self.knee_frequency(), ...
                        self.sheet_resistance(), self.number_of_carriers(), ...
                        self.stiffness(0), self.omega_vacuum_hz(), ...
                        self.freq_min, self.freq_max];

    for print_index = 1:length(variables_to_print)
        fprintf(' %g \t', variables_to_print(print_index));
    end
end

% =========== Calculate resistance ==========
% Total resistance (including parasitics)
% Units: ohms
function resistance = resistance(self)
    longitudinal_squares = self.resistor_length()/self.w_pr();
    resistance = longitudinal_squares * self.sheet_resistance() + self.inactive_resistance();
end

% Parasitic resistance
% Units: ohms
function inactive_resistance = inactive_resistance(self)
    contact_resistance = 120;
    transverse_squares = 2; % transverse portion of loop
    trace_squares = 3.3; % leading up to loop
    doped_resistance = (transverse_squares + trace_squares) * self.sheet_resistance();
    inactive_resistance = 2*contact_resistance + doped_resistance;
end

% PR length, used for resistance and number of carriers
% Units: m

function resistor_length = resistor_length(self)
    resistor_length = 2*self.l.pr(); % PR has 2 legs
end

% Sheet resistance
% Depends upon abstract method self.doping_profile()
% Units: ohms/sq
function Rs = sheet_resistance(self)
    [x, doping] = self.doping_profile(); % x -> m, doping -> cm^-3
    conductivity = self.conductivity(doping); % 1/ohm-cm
    Rs = 1/trapz(x*1e2, conductivity); % integrate, convert x to cm
end

% Conductivity from doping
% Units: 1/ohm-cm
function sigma = conductivity(self, dopant_concentration)
    mu = self.mobility(dopant_concentration); % cm^2/V-sec
    sigma = mu.*self.q.*dopant_concentration; % C/V-sec-cm
end

% Mobility from doping
% Data from Masetti, Serveri and Solmi
% Units: cm^2/V-sec
function mobility = mobility(self, dopant_concentration)
    n = dopant_concentration;
    p = dopant_concentration;
    switch self.doping_type
    case 'arsenic'
        mu_0 = 52.2;
        mu_max = 1417;
        mu_1 = 43.4;
        C_r = 9.96e16;
        C_s = 3.43e20;
        alpha = 0.680;
        beta = 2.0;
        mobility = mu_0 + (mu_max - mu_0)./(1 + (n./C_r).^alpha) - mu_1 ./(1 + (C_s./n).^beta);
    case 'phosphorus'
        mu_0 = 68.5;
        mu_max = 1414;
        mu_1 = 56.1;
        C_r = 9.2e16;
        C_s = 3.41e20;
        alpha = 0.711;
    end
beta = 1.98;

mobility = mu_0 + (mu_max - mu_0)./(1 + (n./C_r).^alpha) - mu_1./((C_s/n).^beta);

case 'boron'
    mu_0 = 44.9;
    mu_max = 470.5;
    mu_1 = 29.0;
    C_r = 2.23e17;
    C_s = 6.1e20;
    alpha = 0.719;
    beta = 2.00;
    p_c = 9.23e16;
    mobility = mu_0.*exp(-p_c./n) + mu_max./(1 + (p./C_r).^alpha) - mu_1.((C_s/p).^beta);
end
end

% = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =
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% = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =
% The number of current carriers in the piezoresistor
% Calculated by integrating the number of carriers to the junction
% depth and multiplying by the in–plane dimensions of the piezoresistor
% Units: none

function number_of_carriers = number_of_carriers(self)
    [x, doping] = self.doping_profile(); % Units: x -> m, doping -> N/cm^-3
    Nz = trapz(x, doping*1e6); % doping: N/cm^-3 -> N/m^-3
    number_of_carriers = Nz*self.resistor_length()*self.w_pr();
end

% 1/f noise density for entire Wheatstone bridge
% Assume two piezoresistors with 1/f noise and two resistors w/o 1/f noise
% Units: V

function hooge_noise_density = hooge_noise_density(self)
    hooge_noise_density = sqrt(2)*sqrt(self.alpha*(self.v_bridge/2)^2/self.number_of_carriers());
end

% 1/f noise density in BW for the entire Wheatstone bridge
% Units: V

function integrated_hooge_noise = integrated_hooge_noise(self)
    integrated_hooge_noise = self.hooge_noise_density() * sqrt(log(self.freq_max / self.freq_min));
end
% Johnson noise density for the entire Wheatstone bridge
% Assume four matched resistors each equal to R
% Units: V/Hz^{0.5}
function johnson_noise_density = johnson_noise_density(self)
    johnson_noise_density = sqrt(4 * self.k_b * self.T * self.resistance());
end

% Johnson noise in BW for the entire Wheatstone bridge
% Units: V
function integrated_johnson_noise = integrated_johnson_noise(self)
    integrated_johnson_noise = self.johnson_noise_density() * sqrt(self.freq_max - self.freq_min);
end

% Assume INA103 at 1000x gain
% 1/f noise density for amplifier
% Units: V
function amp_hooge_noise_density = amp_hooge_noise_density(self)
    amp_hooge_noise_density = 5.5e-9;
end
function integrated_amp_hooge_noise = integrated_amp_hooge_noise(self)
    integrated_amp_hooge_noise = self.amp_hooge_noise_density() * sqrt(log(self.freq_max / self.freq_min));
end

% Johnson noise density for amplifier
% Units: V/Hz^{0.5}
function amp_johnson_noise_density = amp_johnson_noise_density(self)
    amp_johnson_noise_density = 1e-9;
end
function integrated_amp_johnson_noise = integrated_amp_johnson_noise(self)
    integrated_amp_johnson_noise = self.amp_johnson_noise_density() * sqrt(self.freq_max - self.freq_min);
end

% Calculate the knee frequency, 1/f = Johnson
% Units: Hz
function knee_frequency = knee_frequency(self)
    knee_frequency = self.alpha * self.v_bridge^2/(2 * self.number_of_carriers() * self.johnson_noise_density)^2;
end

% Total noise in BW (sum of squares)
% Units: V
function integrated_noise = integrated_noise(self)
integrated_noise = sqrt(self.integrated_johnson_noise()^2 + ...
    self.integrated_hooge_noise()^2 + ...
    self.integrated_amp_hooge_noise()^2 + ...
    self.integrated_amp_johnson_noise()^2);

% Noise in V/Hz^0.5 at a given frequency
function voltage_noise = voltage_noise(self, frequency)
    hooge_noise = self.hooge_noise_density() ./ sqrt(frequency); % V/rtHz
    amp_hooge_noise = self.amp_hooge_noise_density() ./ sqrt(frequency); % V/rtHz
    johnson_noise = self.johnson_noise_density(); % V/rtHz
    amp_johnson_noise = self.amp_johnson_noise_density(); % V/rtHz
    voltage_noise = sqrt(hooge_noise.^2 + johnson_noise.^2 + amp_hooge_noise.
        ^2 + amp_johnson_noise.^2);
end

function plot_noise_spectrum(self)
    frequency = logspace(log10(self.freq_min), log10(self.freq_max), 1e4);
    noise = self.voltage_noise(frequency);
    loglog(frequency, noise);
end

% =========== Calculate sensitivity =====
% ===========

% Piezoresistive factor
% Following Harley's calculation
% Units: none
function piezoresistance_factor = piezoresistance_factor(self, dopant_concentration)
    switch self.doping_type
        case 'boron'
            % Harley's fit for p-type
            b = 1.53e22;
            a = 0.2014;
        case 'phosphorus'
            % Tufte and Stelzer's fit for n-type
            b = 5.62e21;
            a = 0.2330;
        end
    piezoresistance_factor = log10((b./dopant_concentration).^a);
    piezoresistance_factor(find(piezoresistance_factor > 1)) = 1;
end

% Max PR coefficient from Kanda
% Units: Pa⁻¹

function max_factor = max_piezo resistance_factor(self)
    switch self.doping_type
        case 'boron'
            max_factor = 72e−11; % [110]
        case 'phosphorus'
            max_factor = 103e−11; % [100]
        case 'arsenic'
            max_factor = 103e−11; % [100]
    end
end

% Reduction in sensitivity for arbitrarily shaped profile (after Park)
% Units: None
function beta = beta(self)
    [x, doping_concentration] = self.doping_profile();
    % x is supposed to vary from t/2 to -t/2
    x = (self.t/2 - x)*1e2; % x: m -> cm

    mu = self.mobility(doping_concentration); % cm²/V-s
    P = self.piezo resistance_factor(doping_concentration);

    numerator = trapz(x, self.q.*mu.*doping_concentration.*P.*x);
    denominator = trapz(x, self.q.*mu.*doping_concentration);
    beta = 2*numerator/(self.t*1e2*denominator); % t: m -> cm
end

% Reduction in sensitivity from inactive resistance
function gamma = gamma(self)
    gamma = (self.resistance() - self.inactive_resistance())/self.resistance();
end

% Units: V/N
function force_sensitivity = force_sensitivity(self)
    if self.legs == 1
        force_sensitivity = 3*(self.l - self.tip_offset - self.l_pr/2)*self
        .max_piezo resistance_factor()/(8*self.w_pr*self.t*2)*self.beta()
        *(self.gamma)*self.v_bridge;
    else
        force_sensitivity = 3*(self.l - self.tip_offset - self.l_pr/2)*self
        .max_piezo resistance_factor()/(2*self.w*self.t*2)*self.beta()
        *(self.gamma)*self.v_bridge;
    end
end
APPENDIX B. MATLAB CODE

% Units: V/m
function displacement_sensitivity = displacement_sensitivity(self)
    % Use stiffness at sharp tip
    displacement_sensitivity = self.force_sensitivity() * self.stiffness(0);
end

% _______________________________________________________________________
% == Calculate power dissipation ==
% _______________________________________________________________________

% Power dissipation in PR
% Units: W
function power_dissipation = power_dissipation (self)
    power_dissipation = (self.v_bridge/2)^2 / self.resistance();
end

% _______________________________________________________________________
% == Calculate resolution ==
% _______________________________________________________________________

% Units: N
function force_resolution = force_resolution(self)
    force_resolution = self.integrated_noise() / self.force_sensitivity();
end

% Units: m
function displacement_resolution = displacement_resolution(self)
    displacement_resolution = self.force_resolution() / self.stiffness(0);
end

% _______________________________________________________________________
% == Beam mechanics ==
% _______________________________________________________________________

% Look-up elastic modulus based upon dopant type
% Assuming we orient PR for max sensitivity
% Units: Pa^{-1}
function elastic_modulus = modulus(self)
    switch self.doping_type
        case 'boron'
            elastic_modulus = 169e9; % [110]
        case 'phosphorus'
            elastic_modulus = 130e9; % [100]
        case 'arsenic'
            elastic_modulus = 130e9; % [100]
    end
end
% Bending stiffness of the cantilever to a point load
% Units: N/m

function stiffness = stiffness(self, at_end)
    % We normally want stiffness at sharp tip, except when calculating f_0
    if at_end == 1
        offset = 0;
    else
        offset = self.tip_offset;
    end
    if self.legs == 1
    else
        stiffness = self.modulus() * self.w * self.t^3 / (4*(self.l - offset)^3);
    end
end

% Resonant frequency for undamped vibration
% Based on Rayleigh–Ritz
% Units: rad/sec

function omega_vacuum = omega_vacuum(self)
    n = 1000;
    k = self.stiffness(1);
    if self.legs == 1
        l_p = self.l_pr();
        w_p = self.w_pr();
        y1 = linspace(0, l_p, n);
        y2 = linspace(l_p, self.l - self.w/2, n);
        y3 = linspace(self.l - self.w/2, self.l, n);
        c_2 = (self.l*l_p - 1/2*l_p^2) * (1/w_p - 4/self.w);
        c_4 = (1/3*l_p^3 - 1/2*self.l*l_p^2) * (1/w_p - 4/self.w);
        x1 = (1/w_p) * (1/2*self.l * y1.^2 - 1/6*y1.^3);
        int1 = trapz(y1, x1.^2);
        x2 = (4*1/self.w) * (1/2*self.l*y2.^2 - 1/6*y2.^3) + c_2*y2 + c_4;
        int2 = trapz(y2, x2.^2);
        x3 = (4*1/self.w) * (1/2*self.l*y3.^2 - 1/6*y3.^3) + c_2*y3 + c_4;
        int3 = trapz(y3, x3.^2);
omega_vacuum = \sqrt{\left( k \times x^2(n) \right)^2 / \left( \text{self.rho.cantilever*self.t*(4*w_p*int1 + self.w*int2 + (self.w/2)*int3)} \right)};  

else  
  y1 = linspace(0, self.l - self.w/2, n);  
  y2 = linspace(self.l - self.w/2, self.l, n);  
  x1 = (4/self.w) * (1/2*self.l*y1.^2 - 1/6*y1.^3);  
  int1 = trapz(y1, x1.^2);  
  x2 = (4/self.w) * (1/2*self.l*y2.^2 - 1/6*y2.^3);  
  int2 = trapz(y2, x2.^2);  
  omega_vacuum = \sqrt{\left( k \times x^2(n) \right)^2 / \left( \text{self.rho.cantilever*self.t*(self.w*int1 + (self.w/2)*int2)} \right)};  
end  
end  

% Resonant frequency for undamped vibration  
% Units: Hz  
function omega_vacuum_hz = omega_vacuum_hz(self)  
  omega_vacuum_hz = self.omega_vacuum() / (2*pi);  
end  

% = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =  
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% Calculate force/displacement resolution (goal) from state variable vector  
function resolution = optimize_resolution(self, x0)  
  c_new = self.cantilever_from_state(x0);  
  switch self.opt_type  
    case 'disp'  
      resolution = c_new.displacement_resolution()*1e12;  
    case 'force'  
      resolution = c_new.force_resolution()*1e12;  
  end  
end  

% Nonlinear optimization constraints  
% All constraint components (e.g. C(1)) must be negative  
function [C, Ceq] = optimization_constraints(self, x0, omega_min_hz, max_power)  
  c_new = self.cantilever_from_state(x0);  
  C(1) = omega_min_hz - c_new.omega_vacuum_hz();  
  C(2) = c_new.power_dissipation() - max_power;  
  C(3) = -c_new.force_resolution();  
end
% Optional constraints
C(4) = c_new.stiffness(0) - 10; % k

% Optional equality constraints
Ceq = [];
Ceq(1) = c_new.t - 3e-6; % thickness
Ceq(2) = c_new.diffusion_time - 1098;
Ceq(3) = c_new.diffusion_temp - 1173;
end

% This cantilever problem isn’t guaranteed to converge, and in
% practice it fails to converge about 1% of the time for random
% initial conditions. For this reason, it is best to start from a
% random initial seed and perform the optimization and checking to
% make sure that it converges repeatedly.
function optimized_cantilever = optimize_performance(self, ...
    max_power, omega_min_hz, constraints)

    n = 3; % the number of trials
    percent_match = 0.01;
    randomize_starting_conditions = 1;

    for ii = 1:n
        c{ii} = self.optimize_performance_once(max_power, omega_min_hz, ...
            constraints, randomize_starting_conditions);
        resolution(ii) = c{ii}.resolution();
    end

    best_index = find(resolution == min(resolution));
    optimized_cantilever = c{best_index};

    min_resolution = min(resolution);
    max_resolution = max(resolution);

    if (1 - min_resolution/max_resolution) > percent_match
        fprintf(['Optimization did not converge at least once. Values = ' ...
            num2str(resolution) '\n'])
    end
    fprintf(['Optimization converged. Values = ' num2str(resolution) '\n'])
end

% Optimize, but don’t randomize starting point
function optimized_cantilever = optimize_performance_from_current(sself, ...
    max_power, omega_min_hz, constraints)
    randomize_starting_conditions = 0;
APPENDIX B. MATLAB CODE

```matlab
optimized_cantilever = self.optimize_performance_once(max_power,
    omega_min_hz, ...,
    constraints, randomize_starting_conditions);
end

function optimized_cantilever = optimize_performance_once(self, ...)
    max_power, omega_min_hz, constraints, random_flag)

    scaling = self.optimization_scaling();
    problem.objective = @self.optimize_resolution;

    % If random_flag = 1, start from random conditions. Otherwise
    % start from the current cantilever state vector
    if random_flag == 1
        problem.x0 = scaling.*self.initial_conditions_random(constraints);
    else
        problem.x0 = scaling.*self.current_state();
    end

    [lb ub] = self.optimization_bounds(constraints);
    problem.lb = scaling.*lb;
    problem.ub = scaling.*ub;

    problem.options.TolFun = 1e-12;
    problem.options.TolCon = 1e-12;
    problem.options.TolX = 1e-12;

    problem.options.MaxFunEvals = 5000;
    problem.options.MaxIter = 1000;
    problem.options.Display = 'iter';

    problem.options.Algorithm = 'Interior-point';
    problem.solver = 'fmincon';

    problem.nonlcon = @(x) self.optimization_constraints(x, omega_min_hz,
                          max_power);

    x = fmincon(problem);
    optimized_cantilever = self.cantilever_from_state(x);
end
end
```

B.2 cantilever_diffusion.m

```matlab
classdef cantilever_diffusion < cantilever
```
B.2. CANTILEVER_DIFFUSION.M

properties
    diffusion_time
    diffusion_temp
end

methods

function self = cantilever_diffusion(freq_min, freq_max, l, w, t, ...
    l_pr_ratio, w_pr_ratio, tip_offset, v_bridge, doping_type, ...
    T, opt_type, legs, diffusion_time, diffusion_temp)

    % Call superclass constructor
    self = self@cantilever(freq_min, freq_max, l, w, t, l_pr_ratio, ...
        w_pr_ratio, tip_offset, v_bridge, doping_type, T, opt_type, legs);

    self.diffusion_time = diffusion_time;
    self.diffusion_temp = diffusion_temp;
end

function print_performance(self)
    print_performance@cantilever(self);
    fprintf('Diffusion time (min), temp (C): %f %f
', self.diffusion_time /60, self.diffusion_temp-273);
    fprintf('Junction depth (nm): %f', self.junction_depth()*1e9);
    fprintf('
')
end

function print_performance_for_excel(self)
    fprintf('%s \t', self.doping_type);
    variables_to_print = [self.stiffness(), ...
        self.l*1e6, self.w*1e6, self.t*1e6, ...
        self.l_pr_ratio, self.w_pr_ratio, ...
        self.diffusion_time, self.diffusion_temp, ...
        self.v_bridge, self.freq_min, self.freq_max, ...
        self.force_resolution(), self.displacement_resolution(), ...
        self.omega_vacuum_hz(), self.force_sensitivity(), ...
        self.beta(), self.junction_depth()*1e9, ...
        self.resistance(), self.power_dissipation()*1e3, ...
        self.integrated_noise(), self.integrated_johnson_noise(), ...
        self.integrated_hooge_noise(), self.knee_frequency()];

    for print_index = 1:length(variables_to_print)
        fprintf('%g \t', variables_to_print(print_index));
    end
    fprintf('
');
end

% = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =
% Calculate the carrier concentration profile resulting from diffusion

function [x, doping] = doping_profile(self)
    N_background = 1e15;  % N/cm^3
    N_surface = 1e20;  % N/cm^3
    n_points = 1000;  % points in the profile

    switch self.doping_type
        case 'arsenic'
            D_0 = 9.17;  % cm^2/sec
            E_a = 3.99;  % eV

            % Simple diffusion model
            D = D_0*exp(-E_a/(self.k_b_eV*self.diffusion_temp));
            diffusion_length = sqrt(D*self.diffusion_time)*1e-2;  % cm \rightarrow m
            junction_depth = 2*diffusion_length*erfcinv(N_background/N_surface);
            x = linspace(0, junction_depth, n_points);
            doping = N_surface*erfc(x/(2*diffusion_length));
        case 'boron'
            D_0 = 1.0;
            E_a = 3.5;

            % Simple diffusion model
            D = D_0*exp(-E_a/(self.k_b_eV*self.diffusion_temp));
            diffusion_length = sqrt(D*self.diffusion_time)*1e-2;  % cm \rightarrow m
            junction_depth = 2*diffusion_length*erfcinv(N_background/N_surface);
            x = linspace(0, junction_depth, n_points);
            doping = N_surface*erfc(x/(2*diffusion_length));
        case 'phosphorus'
            k_b_eV = 8.617343e-5;
            x = linspace(0, self.t*1e2, n_points);  % m \rightarrow cm
            T = self.diffusion_temp;
            t = self.diffusion_time;
            t = t + 1*60;  % tylan recipes have 1 min of overhead

            % Tsai's model for phosphorus diffusion which accounts for the kink
            doping = N_surface*erfc(x/(2*diffusion_length));
        case 'phosphorus'
            k_b_eV = 8.617343e-5;
            x = linspace(0, self.t*1e2, n_points);  % m \rightarrow cm
            T = self.diffusion_temp;
            t = self.diffusion_time;
            t = t + 1*60;  % tylan recipes have 1 min of overhead

            % Dopant activation from Solmi and Nobili
B.2. CANTILEVER_DIFFUSION.M

\[ \text{surface\_concentration\_active} = 1.3 \times 10^{22} \exp\left( -0.37 / (k_b eV^*T) \right) \]
\[ \text{surface\_concentration\_total} = 2.5 \times 10^{23} \exp\left( -0.62 / (k_b eV^*T) \right) \]
\[ Cs = \text{surface\_concentration\_total} \]

\% Parameters for fit to Solecon data (15 min @ 850C)
\[ \alpha = 0.1769 \exp\left( -1.6954 / (k_b eV^*T) \right) \]
\[ Da = 220.0905 \exp\left( -3.7805 / (k_b eV^*T) \right) \]
\[ Db = 2.4489 \exp\left( -1.9307 / (k_b eV^*T) \right) \times 10^{-5} \]
\[ Cb = 2.6367 \exp\left( -0.9032 / (k_b eV^*T) \right) \times 10^{23} \]
\[ x_0 = \alpha t \]
\[ \kappa = Cb/Cs \]

\[ F_1 = \text{erfc}\left( \frac{x + \alpha t}{2 \sqrt{Da t}} \right) + \text{erfc}\left( \frac{x - 3 \alpha t}{2 \sqrt{Da t}} \right) \]
\[ F_2 = \text{erfc}\left( \frac{x + \alpha t}{2 \sqrt{Db t}} \right) + \text{erfc}\left( \frac{x - 3 \alpha t}{2 \sqrt{Db t}} \right) \]

\[ \text{Ca} = \left( 1 - \kappa \right) / 2 \times C_s \exp\left( -\alpha / (2 Da) \times (x - \alpha t) \right) \times F_1 \]
\[ \text{Cb} = \kappa / 2 \times C_s \exp\left( -\alpha / (2 Db) \times (x - \alpha t) \right) \times F_2 \]

\[ C = \text{Ca} + \text{Cb} \]
\[ C(\text{find}(x <= x_0)) = C_s \]
\[ C(\text{find}(C > \text{surface\_concentration\_active})) = \text{surface\_concentration\_active} \]
\[ C(\text{find}(C < 7.5 e14)) = 7.5 e14 \]
\[ \text{doping} = C \]
\[ x = x \times 1 e - 2; \% cm \rightarrow m \]

\end

\% Used by optimization to bring all state variables to O(1)
\function scaling = optimization\_scaling(self)
\hspace{1cm} l\_scale = 1 e 6;
\hspace{1cm} w\_scale = 1 e 6;
\hspace{1cm} t\_scale = 1 e 9;
\hspace{1cm} l\_pr\_ratio\_scale = 1;
APPENDIX B. MATLAB CODE

v_bridge_scale = 1;
diffusion_time_scale = 1e-3;
diffusion_temp_scale = 1e-3;

scaling = [l_scale ... w_scale ...
t_scale ...
l_pr_ratio_scale ...
v_bridge_scale ...
   diffusion_time_scale ...
   diffusion_temp_scale ];
end

% Unpack state variables and create new cantilever

function new_cantilever = cantilever_from_state(self, x0)
    scaling = self.optimization_scaling();
    x0 = x0 ./ scaling;
    l = x0(1);
    w = x0(2);
    t = x0(3);
    l_pr_ratio = x0(4);
    v_bridge = x0(5);
    diffusion_time = x0(6);
    diffusion_temp = x0(7);
    new_cantilever = cantilever_diffusion(self.freq_min, self.freq_max, ... 
                                      l, w, t, l_pr_ratio, self.w_pr_ratio, self.tip_offset, v_bridge, self .doping_type, ... 
                                      self.T, self.opt_type, self.legs, diffusion_time, diffusion_temp);
end

% Return state vector for the current state

function x = current_state(self)
    x(1) = self.l;
    x(2) = self.w;
    x(3) = self.t;
    x(4) = self.l_pr_ratio;
    x(5) = self.v_bridge;
    x(6) = self.diffusion_time;
    x(7) = self.diffusion_temp;
end

% Set the minimum and maximum bounds for the cantilever state
% variables. Bounds are written in terms of the initialization
% variables. Secondary constraints (e.g. power dissipation,
% piezoresistor thickness rather than ratio, resonant frequency)
% are applied in optimization_constraints()

function [lb ub] = optimization_bounds(self, constraints)

min_l = 1e-6;
max_l = 10e-3;

min_w = 2e-6;
max_w = 10e-3;

min_t = 1e-6;
max_t = 10e-3;

min_lpratio = 0.01;
max_lpratio = 1;

min_vbridge = 0.05;
max_vbridge = 5;

min_diffusion_time = 15*60; % min for furnace repeatability
max_diffusion_time = 60*60; % max for practicality

% T range where we have good modeling of dopant profiles
min_diffusion_temp = 273+850;
max_diffusion_temp = 273+900;

% Override the default values if any were provided
% constraints is a set of key value pairs, e.g.
% constraints = {{'min_l', 'max_v_bridge'}, {5e-6, 10}}
if ~isempty(constraints)
    keys = constraints{1};
    values = constraints{2};
    for ii = 1:length(keys)
        eval([keys{ii} ' = ' num2str(values{ii})]);
    end
end

lb = [min_l, min_w, min_t, min_lpratio, min_vbridge, ...
     min_diffusion_time, min_diffusion_temp];
ub = [max_l, max_w, max_t, max_lpratio, max_vbridge, ...
     max_diffusion_time, max_diffusion_temp];
end

function x0 = initial_conditions_random(self, constraints)
[lb, ub] = self.optimization_bounds(constraints);
APPENDIX B. MATLAB CODE

% Random generation bounds. We use the conditions from
% optimization bounds so that we don't randomly generate
% something outside of the allowable bounds.
l_min = lb(1);
l_max = ub(1);
w_min = lb(2);
w_max = ub(2);
t_min = lb(3);
t_max = ub(3);
l_pr_ratio_min = lb(4);
l_pr_ratio_max = ub(4);
v_bridge_min = lb(5);
v_bridge_max = ub(5);
diffusion_time_min = lb(6);
diffusion_time_max = ub(6);
diffusion_temp_min = lb(7);
diffusion_temp_max = ub(7);

% Generate the values
l = l_min + rand*(l_max - l_min);
w = w_min + rand*(w_max - w_min);
t = t_min + rand*(t_max - t_min);
l_pr_ratio = l_pr_ratio_min + rand*(l_pr_ratio_max - l_pr_ratio_min);
v_bridge = v_bridge_min + rand*(v_bridge_max - v_bridge_min);
diffusion_time = diffusion_time_min + rand*(diffusion_time_max - diffusion_time_min);
diffusion_temp = diffusion_temp_min + rand*(diffusion_temp_max - diffusion_temp_min);
x0 = [l, w, t, l_pr_ratio, v_bridge, diffusion_time, diffusion_temp];

end

B.3 sample_code.m

T = 293;
B.3. SAMPLE_CODE.M

```matlab
2 opt_type = 'disp';
3 tip_offset = 5e-6;
4 legs = 1;
5
6 % Constraints
7 freq_min = 1;
8 freq_max = 10e3;
9 omega_min_hz = 2*freq_max;
10 max_power = 2e-3;
11
12 % Bounds
13 constraints = {{'min_l','min_w'}, {100e-6,35e-6}};
14
15 % Initial values
16 l = 200e-6;
17 w = 35e-6;
18 t = 3e-6;
19 wprm_ratio = 1/7;
20 lprm_ratio = 0.5;
21 v_bridge = 2;
22 doping_type = 'phosphorus';
23 concentration_initial = 1e18;
24 diffusion_time = 20*60;
25 diffusion_temp = 800 + 273;
26
27 % Initial cantilever
28 c_diffusion = cantilever_diffusion(freq_min, freq_max, l, w, t, ...
29     lprm_ratio, wprm_ratio, tip_offset, v_bridge, doping_type, T, opt_type, ...
30     legs, diffusion_time, diffusion_temp);
31 c_diffusion.print_performance();
32
33 % Optimized cantilever
34 c_diffusion = c_diffusion.optimize_performance_from_current(max_power, omega_min_hz, ...
35     constraints);
36 c_diffusion.print_performance();
```
Appendix C

Quality Control of Starting Material

Our early fabrication runs were unsuccessful because the starting wafers we received did not match their specification. In particular, we ordered n-type SOI wafers such that we could create p-type piezoresistors by ion implantation of boron. The devices that resulted from these runs all exhibited piezoresistors with a nominal resistance of $\sim 400 \, \Omega$ when the theoretically predicted value was $\sim 2 \, k\Omega$. While debugging, we discovered that although the device layer was indeed n-type near the surface, it transitioned to p-type $2 \, \mu m$ above the buried oxide. Boron that we implanted merged with this p-type layer after drive-in and activation, causing the shorts. Other researchers have recently verified this observation [120]. Having invested significant resources to understand a problem ultimately caused by the vendor, we adopted the controls below to validate all starting material.

C.1 Doping Type and Resistivity

Prior to accepting a wafer lot from a new vendor, we submitted a wafer piece (typically from a wafer that broke during fabrication) for spreading resistance analysis (Solecon, Reno, NV). This technique yields a depth profile of doping type and resistivity. The resistivity values are converted to majority carrier concentration using mobility values
C.1. DOPING TYPE AND RESISTIVITY

Figure C.1: Carrier concentration profile of a virgin SOI wafer obtained by spreading resistance analysis. The device layer is specified as n-type, but the profile reveals an anomalous p-type region that begins 2 μm above the buried oxide.

from Thurber and coworkers [121, 122]. As an example, the carrier concentration profile of a wafer from the lot that caused shorts is provided in Figure C.1. Because spreading resistance analysis (SRA) is not limited to a measurement on the surface of the wafer, it is able to identify non-uniform doping and buried junctions. However, SRA is a destructive technique and is costly and time-consuming.

After validating the first lot from a new vendor with SRA, we randomly selected wafers from subsequent lots and measured their sheet resistance $\rho_s$ with the Prometrix four-point probe. We typically selected 5 measurement sites: 4 on an 80 mm diameter circle and 1 in the center of the wafer. If the layer thickness $t_d$ is well-known, the resistivity can be calculated from $\rho = \rho_s t_d$ and compared against the specification.

When measuring the device layer resistivity, $t_d$ should be verified independently
(see Section C.2). Note that the calculated resistivity is an average over \( t_d \). Thus, the four-point probe is incapable of revealing non-uniform doping. Furthermore, it is necessary to know \( a \text{ priori} \) if there is a buried junction. In this case, the four-point probe will only sample the surface layer and \( t_d \) is the junction depth.

One additional drawback of the four-point probe technique is that it cannot distinguish between p- and n-type doping. A “quick-and-dirty” method for this purpose is a hot probe. Here, the two leads of a standard voltmeter are placed on the sample and the positive lead is heated with a soldering iron. The increase in thermal energy causes majority carriers to drift away from the hot probe. If the material is n-type, electrons flow away from the positive lead, leaving behind positive ionized donors. As a result, the voltmeter shows a positive voltage. By the same reasoning, the voltmeter shows a negative voltage for p-type material.

C.2 Layer Thicknesses

We also confirmed the thicknesses of the SOI wafers and the layers that comprise them. These values were used to determine etch times throughout the process. The thickness of the device layer also controls the spring constants of the cantilevers and is needed in the calculation of resistivity.

The total wafer thickness was measured with a Mitutoyo digital micrometer. The device layer thickness was determined by measuring the silicon step height in the edge exclusion region using the P2 profilometer. A more accurate alternative is to use the Woollam ellipsometer which can measure the thicknesses of the device and buried oxide layers simultaneously. The handle layer thickness can then be calculated by subtracting these values from the total wafer thickness.
Appendix D

Reticle Images
Figure D.1: Reticle images, after stitching, for a representative scanning probe featuring a 35 µm wide x 145 µm long cantilever, a wet-etched tip, a partial shield, and four "legs". Each figure column contains full images (left) and magnified views of the probe (right). Digitized data is clear.
Figure D.2: Auxiliary reticle images used for process characterization. Electrical test structures include: (1) one and (5) ten square traces to measure contact resistance and diffusion sheet resistance, MOS capacitors with (2) n-type diffused and (3) p-type background silicon, and (4) a ten square “dog bone” geometry to measure metal sheet resistance. Structure (5) also allows a four-point probe measurement. Digitized data is clear.
Appendix E

Wafer Layouts
Figure E.1: Wafer layouts by diffusion temperature: (a) 850°C and (b) 900°C. There are 12 design types per layout, represented by colors (see legend at right). The suffix on each type indicates a partial (P) or full (F) shield. The cell numbers correspond to die labels. Also shown are the locations of alignment marks (M), exposure grids (E), test structures (T), and overlay crosses (A). The rightmost column provides a breakdown of the numbers of probes and additional structures. See Table 4.1 for wafer splits.
Appendix F

Fabrication Process Run Sheet
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Parameters</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measure sheet resistance</td>
<td>5 point 80 mm diameter (Prometrix 5), Probe head C</td>
<td>prometrix</td>
</tr>
<tr>
<td>2</td>
<td>Measure thickness</td>
<td></td>
<td>mitutoyo</td>
</tr>
<tr>
<td>3</td>
<td>Label</td>
<td>Only scribe frontside</td>
<td>diamond scribe</td>
</tr>
<tr>
<td>4</td>
<td>Clean</td>
<td>20 min in 9 H₂SO₄:1 H₂O₂ at 120°C</td>
<td>wbnnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, spin rinse dry (SRD)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Adhesion promoter</td>
<td>HMDS</td>
<td>yes oven</td>
</tr>
<tr>
<td>6</td>
<td>Spin resist</td>
<td>1 µm SPR3612 w/o VP 2 mm EBR</td>
<td>svgcoat1/2</td>
</tr>
<tr>
<td>7</td>
<td>Expose: ALIGN</td>
<td>Energy: 60 mJ/cm², Focus offset: 0 µm</td>
<td>asml</td>
</tr>
<tr>
<td>8</td>
<td>Develop</td>
<td>60 s bake at 110°C, develop, 60 s bake at 110°C</td>
<td>svgdev1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Programs 9/1, 3/1</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Si etch</td>
<td>5:13 min Program 4</td>
<td>amtfetcher</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target: 1200 Å</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 min seasoning prior to etch</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Strip resist</td>
<td>Program 013</td>
<td>gasonics</td>
</tr>
<tr>
<td>11</td>
<td>Measure etch depth</td>
<td></td>
<td>zygo</td>
</tr>
<tr>
<td>12</td>
<td>Clean</td>
<td>20 min in 9 H₂SO₄:1 H₂O₂ at 120°C</td>
<td>wbnnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Prediff clean</td>
<td>10 min in 4 H₂SO₄:1 H₂O₂ at 90°C</td>
<td>wbdiff</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 min in 5 H₂O:1 HCl:1 H₂O₂ at 70°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>continued on next page . . .</td>
<td></td>
</tr>
<tr>
<td>Step</td>
<td>Description</td>
<td>Parameters</td>
<td>Tool</td>
</tr>
<tr>
<td>------</td>
<td>------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>6</td>
<td>cycles dump rinse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>30 s in 50:1 HF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>cycles dump rinse, SRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Complete &lt;1 hr before next step</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Oxidation</td>
<td>39 min WET1100</td>
<td>tylan1/2</td>
</tr>
<tr>
<td>15</td>
<td>Measure oxide</td>
<td>Oxide on silicon</td>
<td>nanospec</td>
</tr>
<tr>
<td>16</td>
<td>Adhesion promoter</td>
<td>HMDS</td>
<td>yes oven</td>
</tr>
<tr>
<td>17</td>
<td>Spin resist</td>
<td>1.6 µm SPR3612 w/o VP 2 mm EBR</td>
<td>svgcoat1/2</td>
</tr>
<tr>
<td>18</td>
<td>Expose: TIP</td>
<td>Energy: 65 mJ/cm², Focus offset: 0 µm</td>
<td>asml</td>
</tr>
<tr>
<td>19</td>
<td>Develop</td>
<td>120 s bake at 110°C, develop, 120 s bake at 110°C</td>
<td>svgdev1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Programs 9/2, 4/2</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Oxide etch</td>
<td>17 min Program 3</td>
<td>amtetcher</td>
</tr>
<tr>
<td>21</td>
<td>Measure oxide</td>
<td>Thin oxide on silicon</td>
<td>nanospec</td>
</tr>
<tr>
<td>22</td>
<td>Strip resist</td>
<td>Program 013</td>
<td>gasonics</td>
</tr>
<tr>
<td>23</td>
<td>Clean</td>
<td>20 min in 9 H₂SO₄:1 H₂O₂ at 120°C</td>
<td>wbnnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>HF dip</td>
<td>180 s in 50:1 HF</td>
<td>wbnnonmetal</td>
</tr>
</tbody>
</table>

continued on next page
Table F.1: Fabrication process run sheet (continued).

<table>
<thead>
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<th>Step</th>
<th>Description</th>
<th>Parameters</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet-etched Tips</td>
<td>Si etch</td>
<td>~13 min in 45% KOH at 60°C</td>
<td>wbgenerall</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>Etch for 13 min to start, then increment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rinse thoroughly after each etch</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hotplate setting: Black line on dial</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heating time: ~1:15 hr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inspect tips</td>
<td></td>
<td>sem4160</td>
</tr>
<tr>
<td></td>
<td>Decontaminate</td>
<td>20 min in fresh 5 H$_2$O:1 HCl:1 H$_2$O$_2$ at 70°C</td>
<td>wbsilicide</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD at wbnitride</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cassette and handle only:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 min in fresh 5 H$_2$O:1 HCl:1 H$_2$O$_2$ at 70°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD at wbnitride</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 rinses of hotpot with DI water</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clean</td>
<td>20 min in 9 H$_2$SO$_4$:1 H$_2$O$_2$ at 120°C</td>
<td>wbnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>or</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry-etched Tips</td>
<td>Si etch</td>
<td>66 s Program 80</td>
<td>lampoly</td>
</tr>
<tr>
<td>25</td>
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</tr>
</tbody>
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Table F.1: Fabrication process run sheet (continued).

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<th>Step</th>
<th>Description</th>
<th>Parameters</th>
<th>Tool</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Run 5 dummy wafers first</td>
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<td>sem4160</td>
</tr>
<tr>
<td>26</td>
<td>Oxide etch</td>
<td>5:30 min in 6:1 BOE</td>
<td>wbnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target: 5000 Å</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Measure etch depth</td>
<td></td>
<td>zygo</td>
</tr>
<tr>
<td>28</td>
<td>Prediff clean</td>
<td>10 min in 4 H₂SO₄:1 H₂O₂ at 90°C</td>
<td>wbdiff</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 min in 5 H₂O:1 HCl:1 H₂O₂ at 70°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 s in 50:1 HF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Oxidation</td>
<td>43 min WET900</td>
<td>tylan1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target: 1000 Å</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total time: 2:03 hr</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Measure oxide</td>
<td>Oxide on silicon</td>
<td>nanospec</td>
</tr>
<tr>
<td>31</td>
<td>Adhesion promoter</td>
<td>HMDS</td>
<td>yes oven</td>
</tr>
<tr>
<td>32</td>
<td>Spin resist</td>
<td>3 µm SPR220-3 w/o VP 2 mm EBR</td>
<td>svgcoat2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wait 1 hr after spin</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Expose: DIFFUSION</td>
<td>Energy: 95 mJ/cm², Focus offset: 3 µm (adjust for etch depth)</td>
<td>asml</td>
</tr>
<tr>
<td></td>
<td></td>
<td>continued on next page ...</td>
<td></td>
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Table F.1: Fabrication process run sheet (continued).

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Parameters</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>Develop</td>
<td>90 s bake at 110°C, develop</td>
<td>svgdev1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Programs 9/3, 7/9</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>O$_2$ plasma</td>
<td>30 s Program 1 (150 mT)</td>
<td>drytek2</td>
</tr>
<tr>
<td>36</td>
<td>Oxide etch</td>
<td>90 s in 6:1 BOE</td>
<td>wbnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target: 1000 Å</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Strip resist</td>
<td>20 min in 9 H$_2$SO$_4$·1 H$_2$O$_2$ at 120°C</td>
<td>wbnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>Inspect tips</td>
<td></td>
<td>sem4160</td>
</tr>
<tr>
<td>39</td>
<td>Prediff clean</td>
<td>10 min in 4 H$_2$SO$_4$·1 H$_2$O$_2$ at 90°C</td>
<td>wbdiff</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 min in 5 H$_2$O·1 HCl·1 H$_2$O$_2$ at 70°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 s in 50:1 HF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Diffusion</td>
<td>15 min POCL850 or POCL900</td>
<td>tylan6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total time: 92 min</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Measure oxide</td>
<td>Oxide on silicon</td>
<td>nanospec</td>
</tr>
<tr>
<td>42</td>
<td>Oxide etch</td>
<td>130 s in 6:1 BOE</td>
<td>wbnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
</tbody>
</table>

continued on next page ...
Table F.1: Fabrication process run sheet (continued).

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Parameters</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>Measure sheet resistance</td>
<td>5 point 80 mm diameter (Prometrix 5), Probe head C</td>
<td>prometrix</td>
</tr>
<tr>
<td>44</td>
<td>Prediff clean</td>
<td>10 min in 4 H₂SO₄:1 H₂O₂ at 90°C</td>
<td>wbdiff</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 min in 5 H₂O:1 HCl:1 H₂O₂ at 70°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 s in 50:1 HF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>LTO deposition</td>
<td>2:46 min LTO400PC</td>
<td>tylanbpsg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target: 400 Å</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total time: 73 min</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>Measure oxide</td>
<td>Oxide on silicon</td>
<td>nanospec</td>
</tr>
<tr>
<td>47</td>
<td>Adhesion promoter</td>
<td>HMDS</td>
<td>yes oven</td>
</tr>
<tr>
<td>48</td>
<td>Spin resist</td>
<td>4 μm SPR220-3 w/o VP 2 mm EBR</td>
<td>svgcoat2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wait 1 hr after spin</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>Expose: CONTACT</td>
<td>Energy: 150 mJ/cm², Focus offset: 3 μm</td>
<td>asml</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wait 35 min after expose</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Develop</td>
<td>90 s bake at 110°C, develop</td>
<td>svgdev1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Programs 9/3, 7/9</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>Oxide etch</td>
<td>90 s in 20:1 BOE</td>
<td>wbnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
</tbody>
</table>

continued on next page . . .
Table F.1: Fabrication process run sheet (continued).

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Parameters</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target: 400 Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>Strip resist</td>
<td>20 min in 9 H$_2$SO$_4$:1 H$_2$O$_2$ at 120°C</td>
<td>wbnonmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>Prediff clean</td>
<td>10 min in 4 H$_2$SO$_4$:1 H$_2$O$_2$ at 90°C</td>
<td>wbdiff</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 min in 5 H$_2$O:1 HCl:1 H$_2$O$_2$ at 70°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 s in 50:1 HF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles dump rinse, SRD</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>Metallization</td>
<td>Lock program: Heat only</td>
<td>gryphon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process program: 90 s, 2.5 kW, 12 RPM</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target: 400 A of Al</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>Adhesion promoter</td>
<td>HMDS</td>
<td>yes oven</td>
</tr>
<tr>
<td>56</td>
<td>Spin resist</td>
<td>4 μm SPR220-3 w/o VP 2 mm EBR</td>
<td>svgcoat2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wait 1 hr after spin</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>Expose: METAL</td>
<td>Energy: 115 mJ/cm$^2$, Focus offset: 3 μm</td>
<td>asml</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wait 35 min after expose</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>Develop</td>
<td>90 s bake at 110°C, develop</td>
<td>svgdev1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Programs 9/3, 7/9</td>
<td></td>
</tr>
<tr>
<td>59</td>
<td>Metal etch</td>
<td>H$_2$O dip</td>
<td>wbmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

continued on next page . . .
Table F.1: Fabrication process run sheet (continued).

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Parameters</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 s</td>
<td>in AL-11 at 40°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>cycles dump rinse, SRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Strip resist</td>
<td>20 min in PRX-127 at 40°C</td>
<td>wbmetal</td>
</tr>
<tr>
<td>6</td>
<td>cycles dump rinse, SRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>Adhesion promoter</td>
<td>HMDS</td>
<td>yes oven</td>
</tr>
<tr>
<td>62</td>
<td>Spin resist</td>
<td>4 µm SPR220-3 w/o VP 2 mm EBR</td>
<td>svgcoat2</td>
</tr>
<tr>
<td></td>
<td>Wait 1 hr after spin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>Expose: FRONTSIDE</td>
<td>Energy: 150 mJ/cm^2, Focus offset: 3 µm</td>
<td>asml</td>
</tr>
<tr>
<td></td>
<td>Wait 35 min after expose</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>Develop</td>
<td>90 s bake at 110°C, develop</td>
<td>svgdev1/2</td>
</tr>
<tr>
<td></td>
<td>Programs 9/3, 7/9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>Metal etch</td>
<td>H_2O dip</td>
<td>wbmetal</td>
</tr>
<tr>
<td></td>
<td>10 s in AL-11 at 40°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cycles dump rinse, SRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>66</td>
<td>Oxide etch</td>
<td>1.5 min Program 3</td>
<td>amtetcher</td>
</tr>
<tr>
<td></td>
<td>Target: 400 Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>67</td>
<td>Si etch</td>
<td>2:30 min SMOOSHAL</td>
<td>stsetch</td>
</tr>
<tr>
<td>68</td>
<td>Strip resist</td>
<td>20 min in PRX-127 at 40°C</td>
<td>wbmetal</td>
</tr>
<tr>
<td></td>
<td>cycles dump rinse, SRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>69</td>
<td>Adhesion promoter</td>
<td>HMDS</td>
<td>yes oven</td>
</tr>
<tr>
<td></td>
<td>yes oven</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

continued on next page . . .
Table F.1: Fabrication process run sheet (continued).

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Parameters</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>Spin resist (backside)</td>
<td>7 µm SPR220-7 w/o VP 2 mm EBR</td>
<td>svgcoat1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wait &gt;2 hr after spin</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>Expose: BACKSIDE</td>
<td>Energy: 350 mJ/cm², Focus offset: 0 µm</td>
<td>asml</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wait 35 min after expose</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>Spin resist (frontside)</td>
<td>7 µm SPR220-7 w/o VP no bake</td>
<td>svgcoat1</td>
</tr>
<tr>
<td>73</td>
<td>Bake</td>
<td>30 min at 90°C</td>
<td>litho oven</td>
</tr>
<tr>
<td>74</td>
<td>Develop</td>
<td>Program 6/9</td>
<td>svgdev1/2</td>
</tr>
<tr>
<td>75</td>
<td>Si etch</td>
<td>~180 min DEEP to BOX</td>
<td>stsetch</td>
</tr>
<tr>
<td>76</td>
<td>O₂ plasma</td>
<td>1 min Program 1 (500 mT)</td>
<td>drytek2</td>
</tr>
<tr>
<td>77</td>
<td>Oxide etch</td>
<td>17 min Program 3</td>
<td>amtetcher</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target: 5000 Å</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Attach to handle wafer with kapton tape</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pause every 5 min to cool</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>O₂ plasma</td>
<td>5 min Program 1 (500 mT)</td>
<td>drytek2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Remove handle wafer after etch</td>
<td></td>
</tr>
<tr>
<td>79</td>
<td>Strip resist</td>
<td>20 min in PRX-127 at 40°C</td>
<td>wbmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 cycles manual rinse, air dry</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Clean</td>
<td>10 min in PRS-1000 at 40°C</td>
<td>wbmetal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 x (6 cycles manual rinse, air dry)</td>
<td></td>
</tr>
</tbody>
</table>
Appendix G

Wet Etchants and Resist Strippers

Table G.1: Pre-mixed wet etchants used in the fabrication process.

<table>
<thead>
<tr>
<th>Etchant</th>
<th>Supplier</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>50:1 HF</td>
<td>J.T. Baker (Phillipsburg, NJ)</td>
<td>1% HF 99% H₂O</td>
</tr>
<tr>
<td>20:1 BOE</td>
<td>J.T. Baker (Phillipsburg, NJ)</td>
<td>38% NH₄F 2.5% HF 60% H₂O</td>
</tr>
<tr>
<td>6:1 BOE</td>
<td>J.T. Baker (Phillipsburg, NJ)</td>
<td>34% NH₄F 7% HF 59% H₂O</td>
</tr>
<tr>
<td>AL-11</td>
<td>Cyantek Corp. (Fremont, CA)</td>
<td>72% H₃PO₄ 3% CH₃COOH 3% HNO₃ 22% H₂O</td>
</tr>
</tbody>
</table>
Table G.2: Pre-mixed resist strippers used in the fabrication process.

<table>
<thead>
<tr>
<th>Resist Stripper</th>
<th>Supplier</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRX-127</td>
<td>Rohm and Haas (Marlborough, MA)</td>
<td>&lt;30% $\text{CH}_3(\text{OC}_3\text{H}_6)_2\text{OH}$&lt;br&gt;75% $(\text{CH}_3)_2\text{SO}$&lt;br&gt;&lt;4% $\text{C}<em>4\text{H}</em>{13}\text{NO} \cdot 5 \text{H}_2\text{O}$</td>
</tr>
<tr>
<td>PRS-1000</td>
<td>J.T. Baker (Phillipsburg, NJ)</td>
<td>10-20% $\text{C}<em>6\text{H}</em>{14}\text{O}_3$&lt;br&gt;25-45% $\text{C}_4\text{H}_8\text{O}_2\text{S}$&lt;br&gt;35-55% $\text{C}_5\text{H}_9\text{NO}$&lt;br&gt;1-10% $\text{C}<em>8\text{H}</em>{18}\text{O}_5$</td>
</tr>
</tbody>
</table>
Appendix H

Focused Ion Beam Recipes

Table H.1: Focused ion beam recipes for the annulus and cleaning cross-section (CCS) methods of opening the outer shield and for platinum (Pt) deposition on tips with poor metal coverage. In all cases, we used an ion beam current of 1 pA for well-controlled milling or deposition. We used search mode (SRH) for magnifications up to 35 kX and ultra-high resolution mode (UHR) above that. For Pt deposition, a gas injection system (GIS) needle was inserted into the chamber to introduce the organometallic precursor gas. The typical number of pulses is provided for each recipe. The endpoint condition for milling was observed contrast between the exposed inner conductor and outer shield and for deposition was initiation of roughening on the tip sidewalls.

<table>
<thead>
<tr>
<th>Sample mount</th>
<th>Annulus</th>
<th>CCS</th>
<th>Pt deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage tilt</td>
<td>52°</td>
<td>7°</td>
<td>52°</td>
</tr>
<tr>
<td>Ion beam current</td>
<td>1 pA</td>
<td>1 pA</td>
<td>1 pA</td>
</tr>
<tr>
<td>Working magnification</td>
<td>100 kX (UHR)</td>
<td>100 kX (UHR)</td>
<td>35 kX (SRH)</td>
</tr>
<tr>
<td>Material file</td>
<td>si.mtr</td>
<td>si.mtr</td>
<td>pt_high.mtr</td>
</tr>
<tr>
<td>GIS needles</td>
<td>none</td>
<td>none</td>
<td>Pt</td>
</tr>
<tr>
<td>Pattern</td>
<td>annulus</td>
<td>CCS</td>
<td>circle</td>
</tr>
<tr>
<td>r_i = 0.05 µm</td>
<td>w_e = 0.3 µm</td>
<td>r_o = 2 µm</td>
<td></td>
</tr>
<tr>
<td>r_o = 0.15 µm</td>
<td>h_e = 0.1 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location (with respect to tip apex)</td>
<td>centered</td>
<td>overlapped</td>
<td>centered</td>
</tr>
<tr>
<td>Depth</td>
<td>0.01 µm</td>
<td>0.1 µm</td>
<td>0.01 µm</td>
</tr>
<tr>
<td>Number of pulses</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

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Appendix I

Toward a Universal Probe for Electrical Microscopy

Keji Lai and Worasom Kundhikanjana of the Z. X. Shen lab led an effort to develop a new probe for scanning microwave microscopy (SMM) in collaboration with AppNano (Santa Clara, CA). This company has a production process that enables fabrication of silicon nitride cantilevers with integrated heavily-doped silicon tips. This probe design provides an excellent platform on which to build an SMM probe as it combines an insulating cantilever, with low loss in the microwave regime, and a robust, conductive tip. We collaborated on the project to review the probe design and fabrication process and to provide expertise with finite-element analysis of the cantilever. Here, we document the salient features and limitations of the probe, the steps that were taken to address the challenges discussed in Section 6.2.2 and the common process failure modes. The intent of this overview is to provide a starting point for any new process to fabricate a universal probe.

In Figure I.1, we provide a schematic of the probe which highlights several features useful for SMM and electrical microscopy in general. First, the tip has a coaxial structure, where the inner conductor is heavily-doped silicon, the insulator is silicon dioxide and the outer shield is gold. This coaxial tip is similar to the one integrated on the probes presented in this thesis. However, a major difference is that the electrical trace along the cantilever is aluminum instead of doped silicon. As such, the probe
APPENDIX I. TOWARD A UNIVERSAL PROBE

Figure I.1: SMM probe fabricated by AppNano, featuring a coaxial tip integrated on an insulating cantilever. Tapered film thicknesses minimize parasitics resistance and capacitance on die while limiting cantilever bending. The probe does not integrate a silicon piezoresistor. Fabrication yield was poor, resulting from unreliable contact between the aluminum trace on the cantilever and the heavily-doped silicon tip.

benefits from a robust tip with low parasitic resistance. In addition, because the outer shield is gold, it is chemically inert and does not become superconductive at cryogenic temperatures. Second, on the die, there is a 4 \( \mu m \) thick layer of SiO\(_2\) below the nitride, which reduces the parasitic capacitance between the inner conductor and handle wafer. Third, the design uses tapered film thicknesses. On the die, the inner conductor and insulator are 2 \( \mu m \) thick, while on the cantilever they are 100 nm thick. This method helps to minimize parasitic resistance and capacitance, while limiting tip rounding and cantilever bending (due to film stresses or thermal bimorph effects).

The probe also has two limitations. First, because there is no silicon present at the root of the cantilever, the probe lacks a piezoresistor. In order to provide rudimentary self-sensing capability, we incorporated a metal strain gauge in the outer shield layer, but as stated earlier, the gauge factors of metal strain gauges are 50-100x smaller than those of semiconductor strain gauges. Second, the outer shield at the tip apex must be opened with focused ion beam milling.

One of the main concerns with the multilayer design was the susceptibility to bending. To investigate this possibility, Lai and Kundhikanjana built a finite-element model of the cantilever in COMSOL. To accurately predict the mechanical properties of the cantilever, the model required values for the intrinsic stress of the films in the stack. Thus, we had AppNano deposit a known thickness of each film they planned to
Table I.1: Intrinsic stress in AppNano thin films calculated from wafer curvature measurements.

<table>
<thead>
<tr>
<th>Film</th>
<th>Thickness (nm)</th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>50</td>
<td>22.2</td>
</tr>
<tr>
<td>Au</td>
<td>500</td>
<td>28.1</td>
</tr>
<tr>
<td>PtIr</td>
<td>20</td>
<td>194</td>
</tr>
<tr>
<td>Si$_x$N$_y$</td>
<td>1000</td>
<td>14.8</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>200</td>
<td>−369</td>
</tr>
</tbody>
</table>

use in the process on 2 bulk silicon test wafers. Prior to deposition, we measured the thickness and curvature of the wafers using a drop gauge and the Flexus 2320 Stress Gauge in the SNF. The latter tool determines curvature using a laser that is scanned across the wafer surface. After deposition, we again measured wafer curvature. The in-plane stress in the film was then calculated using Stoney’s equation,

$$\frac{1}{R_f} - \frac{1}{R_i} = \frac{6(1 - \nu)\sigma h}{Et^2}$$ (I.1)

where $R_i$ and $R_f$ are the initial and final radii of curvature, $\nu$, $E$ and $t$ are the Poisson’s ratio, Young’s modulus and thickness of the substrate and $\sigma$ and $h$ are the stress and thickness of the film. Table[I.1 summarizes our results. After adding the stress values to the model, it predicted negligible cantilever bending, which was verified on the completed devices.

Two common failure modes were observed during fabrication that resulted in poor yield. First, on many devices, the aluminum trace along the cantilever failed to make contact with the silicon tip. The process of integrating the silicon tip with the nitride cantilever results in a vertical step at the joint between the two materials. Because the aluminum on the cantilever was only 100 nm thick, it was not able to bridge this step. Second, several tips were severely damaged during processing making them unusable for scanning. We suspect that this damage occurred because the tips were inadequately protected while patterning one of the layers on the cantilever. The tips are formed early in the process, making it difficult to keep them pristine through the many steps that follow.
Bibliography


