Low-impedance shielded tip piezoresistive probe enables portable microwave impedance microscopy

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New scanning probes suitable for microwave impedance microscopy (MIM) measurements on any scanning platform using a piezoactuator are presented. The authors microfabricated piezoresistive cantilevers integrated with low-impedance, electrically shielded transmission lines to enable simultaneous topographical and electrical scanning probe microscopy. The probes provide topography feedback with nanometre vertical resolution for samples or setups where laser detection is not feasible or desirable. MIM is a scanning probe technique that uses the interaction of a gigahertz electrical signal with a sample, and yields a conductivity map of the sample at the nanoscale. The proposed design exhibits vertical displacement resolution of 3.5 nm in a measurement bandwidth from 1 to 10 kHz. The capacitance between shield and inner conductors measured with an impedance analyser is 9.5 pF and the trace resistance is 32 Ω. Sample location and topographic scanning capabilities using the self-sensing piezoresistor are demonstrated.

1. Introduction: Since the development of atomic force microscopy (AFM) by Binnig and Quate in 1986 [1], scanning probe microscopy has been gaining increasing interest in various fields, such as electronics [2], material science [3] and biology [4]. In particular, applications using microwave signals have emerged to study local electronic properties of materials. Microwave impedance microscopy (MIM) has demonstrated great promise for mapping local electronic properties [5, 6]. MIM enables the study of local complex dielectric constants in novel electronic materials. MIM uses radio frequency (RF) signals (~1 GHz) to measure the local tip–sample impedance. The RF signal is guided to the tip and is reflected at the tip–sample interface. The near-field interaction at the tip-sample interface yields information about the complex dielectric constants of the sample. As the tip scans across the sample, the reflected signal changes, providing a map of electrical properties. As the dimension of the tip–sample interaction is much smaller than the wavelength at 1 GHz, the spatial resolution is determined by the size of the tip apex. Although recent probes have capacitance and resistance as low as 1 pF and 5 Ω, respectively [7], they rely on optical beam bounce for topography feedback. This technique is effective at room temperature, but when photosensitive materials are studied at cryogenic temperature, stray photons from the laser can produce excitations in the sample that decay over long time scales. This creates a challenge for aligning the tip and the sample.

Piezoresistivity is the change in resistivity in a material in response to a mechanical stress. This effect is widely used as a transduction mechanism in microelectromechanical system/nanoelectromechanical system (MEMS/NEMS) devices, such as pressure sensors [8], force sensors [9] and accelerometers [10]. Although laser detection for AFM still gives the best resolution, the latest research in single crystal silicon piezoresistive cantilevers has demonstrated sub-nanometre resolution at room temperature [11].

In this Letter, we present the design and fabrication of a low-impedance shielded tip piezoresistive probe. The self-sensing cantilever allows topography feedback where the laser beam bounce technique is not available or hard to implement. Furthermore, the low parasitic impedance of the tip enables MIM measurements.

2. Design: To leverage the repeatable mechanical properties of single crystal silicon [12], we used it as the main material for our cantilever and tip. Single crystal silicon also exhibits significant piezoresistivity [13], which we used to develop a self-sensing probe.

As heavily doped silicon has a higher parasitic capacitance and resistance compared with metal conductors such as aluminium or gold, we used a 0.5 μm-thick aluminium layer as the inner conductor to the tip. To further reduce the parasitic impedance, we separated the tip and the main cantilever structure with a strip of silicon nitride to electrically isolate both parts. The nitride strip is also used to support the metal lines connected to the tip (Fig. 1) and isolate them from the background silicon. We designed probes with three different lengths, corresponding to three different stiffnesses to accommodate for contact and tapping mode as well as soft samples. The targeted spring constants of the cantilevers were 1, 10 and 15 N/m.

The piezoresistor geometry and doping profile were designed using previously reported Matlab optimisation code [14]. Indeed, the minimum detectable force $F_{\text{min}}$ was optimised according to the design bounds such as stiffness, bandwidth and power density. The authors microfabricated piezoresistive cantilevers integrated with low-impedance, electrically shielded transmission lines to enable simultaneous topographical and electrical scanning probe microscopy. The probes provide topography feedback with nanometre vertical resolution for samples or setups where laser detection is not feasible or desirable. MIM is a scanning probe technique that uses the interaction of a gigahertz electrical signal with a sample, and yields a conductivity map of the sample at the nanoscale. The proposed design exhibits vertical displacement resolution of 3.5 nm in a measurement bandwidth from 1 to 10 kHz. The capacitance between shield and inner conductors measured with an impedance analyser is 9.5 pF and the trace resistance is 32 Ω. Sample location and topographic scanning capabilities using the self-sensing piezoresistor are demonstrated.

Figure 1 Sketch of the probe designed with all the features and materials. Background silicon between the piezoresistor legs is etched to minimise leakage current. The inner conductor and outer shield are both made with aluminium and are deposited on the nitride before connecting the tip.

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dissipation. We calculated $F_{\text{min}}$ by dividing the total integrated voltage noise $V_{\text{noise}}$ by the force sensitivity $S_{FV}$ (1). The two dominant noise sources considered were Johnson and Hooge noise [15]:

$$F_{\text{min}} = \frac{V_{\text{noise}}}{S_{FV}}$$  

(1)

The force sensitivity is defined by geometrical parameters and process parameters:

$$S_{FV} = \frac{3(l_c - 0.5l_p)\sigma_{\text{max}}}{8w_p l_c^2} \gamma V_{\text{bridge}} \beta^2$$  

(2)

where $l_c$ is the cantilever length, $l_p$ is the piezoresistor length, $t_c$ is the cantilever thickness, $\sigma_{\text{max}}$ is the longitudinal piezoresistive coefficient, $\gamma$ is the contact resistance ratio $V_{\text{bridge}}$ is the Wheatstone bridge bias voltage and $\beta^2$ is the doping correction factor [14]. Although we need to optimise the minimum detectable displacement $d_{\text{min}}$ for an AFM probe design, we can easily reformalise this using Hooke’s law (3) as previously reported [15]:

$$F_{\text{min}} = k \cdot d_{\text{min}}$$  

(3)

where $k$ is the cantilever stiffness. Therefore the displacement sensitivity $S_{dV}$ and $d_{\text{min}}$ can be experimentally measured using (4) and (5):

$$S_{dV} = \frac{D}{d}$$  

(4)

$$d_{\text{min}} = \frac{V_{\text{noise}}}{S_{dV}}$$  

(5)

3. Fabrication process: We started with (100) single-crystal silicon on insulator wafers with an 8.5 μm-thick device layer, a 0.5 μm buried silicon oxide (BOX) and a 400 μm handle layer. The device layer and handle wafer were p-type silicon with a resistivity of 1 – 5 and 0.05 – 0.1 Ω cm, respectively. Throughout the process, the wafers were singed and primed at 150 °C in hexamethyldisilazane before spinning resist. The photoresist was exposed using an ASML PAS5000/60 5:1 reducing stepper. In addition, because we designed the piezoresistor with n-type doping, the wafers were rotated 45° to maximise the piezoresitive coefficient [13].

As illustrated in Fig. 2, the fabrication process consisted of eight photolithography steps. After cleaning the wafer in piranha (20 min in 9:1 H$_2$SO$_4$:H$_2$O$_2$ at 120°C), we patterned alignment marks in 1-μm SPR 3612 photoresist, etched them 1200 Å deep with a CHF$_3$/O$_2$ plasma and stripped the resist in piranha. Next, we RCA cleaned (10 min 4:1 H$_2$SO$_4$;H$_2$O$_2$ at 90°C, 10 min in 5:1:1 H$_2$O:HCl:H$_2$O$_2$ at 70°C and 30 s in 50:1 HF) then oxidised the wafer for 39 min at 1000 °C in a wet atmosphere to grow a 5000 Å-thick oxide mask. We spin coated 1.6 μm-thick SPR 3612 photoresist film and patterned circles with 4.5 μm radius. We etched the oxide mask in a CHF$_3$/O$_2$ plasma and removed the resist in piranha.

We created the 6 μm-tall tips by undercutting the oxide mask in 45% KOH at 70 °C for 22 min. Then we cleared the oxide in 6:1 BOE (H$_2$O$_2$:NH$_4$F/HF).
Then, the cantilever structure was defined in 7 μm-thick SPR 220–7 photoresist and etched in a HBr/Cl\textsubscript{2}/O\textsubscript{2} plasma. We stripped the resist in piranha and sharpened the tips by growing a 200 nm-thick oxide at 900°C in a wet atmosphere. We then deposited a 2 μm-thick silicon-rich LPCVD silicon nitride film at 600°C, followed by a 200 nm-thick low-temperature oxide (LTO) film at 400°C. We defined the nitride isolation structure into 7 μm-thick photoresist, etched the LTO mask in 6:1 BOE and cleaned the resist in piranha. We finally etched the silicon nitride for 15 h in 85% H\textsubscript{3}PO\textsubscript{4} at 155°C.

Next, we patterned 7 μm of resist and etched the remaining oxide from the tip sharpening step in 6:1 BOE to define the piezoresistor and inner conductor to the tip. We stripped the resist in piranha and doped the wafer by phosphorus diffusion with POCL\textsubscript{3} for 15 min at 900°C. We cleared the oxide in 6:1 BOE. To create the tip inner conductor and piezoresistor’s contacts, we sputtered 0.5 μm of aluminum and wet etched in AL-11 aluminum etchant (25:8:1:1 H\textsubscript{3}PO\textsubscript{4}:H\textsubscript{2}O\textsubscript{2}:CH\textsubscript{3}COOH:HNO\textsubscript{3}) at 4°C with a 7 μm resist mask. We cleaned the photoresist in PRX-127.

To measure the probe displacement sensitivity, we mounted a probe on a Witec a300 AFM system. Next, we engaged the tip with a glass slide and used the amplified piezoresistor’s output as the feedback signal. We then performed a force displacement curve and recorded the piezoelectric stage position and piezoresistor output to obtain the sensitivity of the device. The resolution was calculated as the integrated noise spectrum in a given bandwidth divided by the sensitivity (Fig. 4). The resolution in a bandwidth from 1 Hz to 10 kHz was found to be 3.5 nm.

We performed contact mode AFM scans on 300 nm-thick patterned aluminum electrodes deposited on silicon dioxide (Fig. 5). Our probe clearly resolved the electrode and thus was capable of locating the sample of interest for further MIM studies.

5. Conclusions: We report the design and fabrication of a piezoresistive cantilever with a low-impedance conduction line to our...
electrically shielded tip. Although with reduced resolution, the measured impedance suggests that MIM measurement can be obtained. Indeed probes with lower tip impedance have been reported before, but do not provide self-sensing. Nevertheless, lower MIM resolution can be achieved with lower tip impedance. To achieve lower impedance thicker metal conductors and thicker insulator should be used, however, thicker layers would change the cantilever mechanics and may decrease the piezoresistor sensitivity. Gold as a conductor layer can also be used instead of aluminium, but because of the high diffusivity of gold, it cannot be used in a CMOS compatible processes, and thus the fabrication and facilities will have to be revisited.

We also demonstrate topography scans using piezoresistive read-out with 3.5 displacement resolution. We therefore present a unique cantilever design that provide piezoresistive feedback and low tip impedance that enable coupled topography scans and MIM images.

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7 References