Optical Detection for Micromechanical Cantilever Arrays

Ph.D. Oral Defense

Scott Manalis

May 6, 1998

Quate Group, Ginzton Laboratory, Stanford University
Semiconductor Imaging

Integrated Circuit

vertical scale: 4 µm

Epitaxial Silicon

vertical scale: 10 angstroms

Digital Instruments, Santa Barbara CA

Quate Group, Stanford University
Biological Imaging

Human Chromosomes

vertical scale: 200 nm

DNA

vertical scale: 5 nm

Digital Instruments, Santa Barbara CA

Bustamante Group, University of Oregon

Quate Group, Stanford University
Array of Fifty Cantilevers Spanning 1 cm

S.C. Minne, Stanford University

Quate Group, Stanford University
Outline

I. High Speed Imaging
II. The Interdigital Cantilever
III. Thermal Detection

Quate Group, Stanford University
Zinc Oxide Cantilever

- Metal
- Zinc Oxide
- Bridge
- Heavily Doped Silicon (not piezoresistive)
- Piezoelectric ZnO Actuator
- Piezoresistive Deflection Sensor
- Silicon Cantilever

Quate Group, Stanford University
ZnO-Induced Movement

Schematic View

- Equilibrium position
- Electric field expands ZnO
- New equilibrium results in bending
Final Device

ZnO Actuator

Silicon Piezoresistor

100Å Silicon Tip

S.C. Minne, Stanford University

Quate Group, Stanford University
High Speed Atomic Force Microscopy

Drive Frequency (kHz)

Amplitude (arb)

piezo tube

ZnO
Imaging at a Tip Velocity of 3 mm/s

- Synchronous detection of piezoresistor eliminates electrical coupling from actuator and allows high speed imaging.

- Acquire 512 x 512 Pixel Image in ~10 seconds
Imaging with Constant Force using an Optical Lever Sensor and ZnO Actuator

1) Initial position - tip/sample force is near zero.

2) Cantilever is scanned over a topographical step and the thinner portion is strained.

3) A voltage is applied to the ZnO to relieve the strain and the tip/sample force is restored to zero.

Angle of reflection in (1) and (3) are not equal.
Constant Force with the Optical Lever using a Linear Correction Circuit

- Linear correction circuit eliminates the ZnO-induced deflection.

- Servo loop detects only the strain-induced deflection.
Closed Loop Frequency Response using Optical Lever Sensor with ZnO Actuator

- Imaging bandwidth ~ 33 kHz
- 77 kHz mechanical resonance of cantilever limits bandwidth
Optical Diffraction from a One Dimensional Grating

(REFLECTED MODES)

- 0th Order Mode (specular)
- -1st Order Mode
- +1st Order Mode

Alternating fingers displaced by 1/4 of illumination wavelength

Illumination at \( \lambda \)
Diffracted Modes:

-1
0
+1

Interdigital Cantilever (longitudinal)
Diffracted Modes:

-1
0
+1

cantilever
substrate

Interdigital Cantilever (transverse)

reference portion
moving portion
Simulated Diffraction Pattern from the Interdigital Cantilever

- $z = 0$
- $z = 0.1 \text{ mm}$
- $z = 1 \text{ mm}$
- $z = 2 \text{ mm}$
- $z = 10 \text{ mm}$

150 µm
Simulated Optical Response

Illuminate with Cylindrical Laser

Optical Pattern at z = 3 cm

Detector Output vs Cantilever Deflection

Quate Group, Stanford University
Interdigitated Finger Design

order: -1 0 +1

\[ \frac{\lambda h}{d} \]

\[ \sin \theta = \frac{\lambda}{d} \]

order spacing > order width

\[ \frac{\lambda h}{d} > \frac{\lambda h}{N d} \]

\[ N > 1 \]

number of illuminated finger pairs

Quate Group, Stanford University
Fabrication Process

1. 10 µm silicon
   - substrate silicon

2. 

3. 

4. 

5. 

6. 

- silicon
- oxide
- nitride
- polyimide

Quate Group, Stanford University
Atomic Force Microscope

Interdigital Detection

- Laser
- (A - B)
- Feedback Control
- Actuator Driver
- Display

Sample

X Y Z Actuator

Quate Group, Stanford University
Force Curve from the Interdigital Cantilever

Optical Response (µW)

Piezo Tube Position (µm)
Atomic Images of Graphite

10 Å

2.5 Å
Constant Force Imaging with the Interdigital Cantilever

topography (piezo tube position)

350 nm

error signal (diffracted mode intensity)

Quate Group, Stanford University
Constant Force Imaging with the Interdigital Cantilever

3 µm vertical scale

*in collaboration with Dennis Adderton at Digital Instruments*
RMS noise in a 10 Hz to 1 kHz bandwidth is ~ 0.02 Å

Interdigital cantilever is 10x more sensitive than the optical lever detector.
Parallel Operation with Interdigital Cantilevers

Cylindrically Focused Laser Beam

-1 0 +1 Diffracted Orders

Interdigital Cantilevers

Photodiode Detectors
Microscope Schematic for Cantilever Array Detection

- Laser Diode
- Collimating Lens
- Cylindrical Lens
- Slit
- Imaging Lens
- Photodetector
- Slit
- Interdigital Cantilever Array

Quate Group, Stanford University
Parallel Imaging with Interdigital Canitlevers

200 µm
Parallel Images using Interdigital Cantilevers
Temperature Sensitive Cantilever Bimorphs

Applications:
- monitor heat evolution of chemical reactions
- microcalorimetry
- photothermal spectroscopy
- IR detection
Thermal Sensing with the Interdigital Cantilever

Temperature resolution $\sim 5 \, \mu K/\sqrt{\text{Hz}}$

*in collaboration with IBM, Zurich
Fresnel Zone Plate

TOP VIEW

CROSS-SECTION

glass

metal

incident plane wave
The Spiral Bimorph

TOP VIEW

CROSS-SECTION

Source/Detector

Visible Light

IR Radiation
Simulated Diffraction above a Spiral

(REFLECTED LIGHT)
Thermal Mechanical Simulations with ANSYS

*simulations by G. Yaralioglu and A. Atalar, Bilkent University, Turkey
Simulated Optical Response

Temperature Difference: 0 5 K 10 K

*Simulations by G. Yaralioglu and A. Atalar, Bilkent University, Turkey

Quate Group, Stanford University
SEM of Spiral Bimorph Array
Measured Optical Response

Absorbed Power:
- 0 µW
- 100 µW
- 200 µW

Intensity vs. Position

Quate Group, Stanford University
Simulated Optical Response

Temperature Difference: 0 5 K 10 K

*simulations by G. Yaralioglu and A. Atalar, Bilkent University, Turkey

Quate Group, Stanford University
Direct IR to VISIBLE Conversion

IR Heating OFF

IR Heating ON
Conclusion

Scan speed of AFM increases from 100 µm/s to 1 mm/s by using a microfabricated actuator. 30 Å sensitivity
  - synchronous detection of piezoresistor eliminates electrical coupling from actuator

Optical lever detection increases scan speed to 1 cm/s with Angstrom sensitivity.
  - real-time correction scheme subtracts actuator induced bending

Interdigital detection reduces optical alignment requirements and achieves 0.02 Å sensitivity.

Two-dimensional bimorphs can be used as thermal sensors to detect infrared radiation.
  - demonstrated direct conversion of spatial variations of temperature to spatial variations of visible light.
  - power resolution of 20 nW/Hz with a 270 µs thermal response time
Conclusion

**High Speed Imaging**: scan speed increased nearly 100x
- 0.01 cm/s with bulk piezoelectric tube
- 0.1 cm/s with integrated actuator + piezoresistive sensor
- 1 cm/s with integrated actuator + optical lever sensor

**Interdigital Cantilevers**: optical detector for arrays
- 0.02 Å vertical resolution
- Two cantilever image with split-photodiode detector
- Future work: custom photodiode arrays integrated actuators

**Spiral Bimorphs**: direct conversion of IR to visible
- 2D array of micromechanical bimorphs with 100 µm pitch
- Remote detection of mechanical bending eliminates need to integrate electronics with sensor