Applications of MEMS Actuators in Optical and Ultrasound Imaging

Jason M. Zara
ECE Department
Biomedical Engineering Professor
MEMS Devices Developed at Sandia National Laboratories

Silicon Gear and Chain – Chain Links 50 µm Apart

Spider Mite Crawling on Micro-Mirror Device
Polyimide MEMS Devices for Medical Imaging

• Our research group has been working for years on applications of polyimide based MEMS devices in medical imaging probes
• This work has been done in ultrasound and optical imaging applications
• The primary application of these probes is endoscopic and catheter based imaging
Advantages of MEMS Scanners

- The probe we are developing uses a MEMS actuator to mechanically steer a mirror for scanning.
- MEMS devices are fabricated using photolithography so they can be made to be inexpensive and disposable for endoscopic and catheter applications.
- Very small devices with low power consumption are possible for catheter applications.
- Entire scanning mechanism can be contained in tip of probe to avoid complications with catheter bending.
MEMS Ultrasound Scanning Devices
Modeling and Design of IC Fabricated Devices

• Hand-built devices were time consuming to build and inconsistent
• Devices needed to be developed that could be fabricated on silicon wafers
• Modeling was done with one-dimensional beam models and ANSYS finite element analysis
• Devices were then fabricated and tested
• New fabrication methods allow for design of a side looking scanner
Schematics of Designed Devices

Forward Viewing Probe

1 mm and 2 mm probes

3 µm Thick Hinges

- PZT
- Polyimide
- Air Gap
- Contact Vias
- Electrical Connections

Side Viewing Probe

1 mm and 2 mm probes

IFA Attachment Flap

3 µm Thick Torsion Hinges

Linear Actuator (IFA) Attached to Table to Sector Ultrasound Beam
Forward Viewing Devices After Liftoff

- Devices fabricated with 3-layer process using photolithography
- 3 µm metallized polyimide layer for electrical connection
- 30 µm polyimide layer for table and rigid supports
- Vias connect top level to electrical traces
- Liftoff done with HF to remove sacrificial oxide layer
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MEMS Device Used to Steer Beams: The Integrated Force Array (IFA)

- Microelectromechanical System (MEMS)
- Hundreds of thousands of deformable capacitors
- 2-mask process of patterned polyimide and angled metallization
- 1 cm long, 2.2 µm thick and 1 mm or 3 mm wide
• Applied voltages create electrostatic forces which contract cells in a linear fashion
• 20% strains and 13 dyne forces at 130 Volts
• Scaling down devices produces equivalent forces

\[
\text{Force} = \frac{\varepsilon AV^2}{2L^2}
\]
Assembled Forward Viewing Devices

• 20 MHz piston on 2 mm by 2.25 mm table
• 3 mm wide IFA attached to side of table
• Hinges 1.8 mm long and .75 mm wide

• 30 MHz piston on 1 mm by 1.125 mm table
• 3 mm wide IFA attached to side of table
• Hinges 1.8 mm long and .375 mm wide
Assembled Side Viewing Devices

- 20 MHz piston on 2 mm by 2.25 mm table
- 3 mm wide IFA attached to side of table
- Hinges 180 µm wide and 250 µm long

- 30 MHz piston on 1 mm by 1.125 mm table
- 1 mm wide IFA attached to side of table
- Hinges 90 µm wide and 250 µm long
30 MHz Forward Viewing Probe and 1 mm Wide IFA

- 4 visible wires
- Estimated scan angle 7.6 degrees
Ultrasound Device Summary

- Devices were modeled using FEM and fabricated on silicon wafers
- Device scan angles below desired 60° sector angles
- Hinge curling, nonlinear stiffening, and fluid damping are major factors in performance shortfalls
- Displacements in air were very large, up to 60°, but images were not as successful
- The development of new actuators is underway to increase force – thicker IFAs – may be able to overcome fluid problems
MEMS Optical Scanning Devices
Optical Beam Scanner

• In order to take advantage of the large displacements in air, devices similar to the ultrasound devices were developed as optical scanners
• A gold coated silicon mirror replaces the PZT on the table
• Devices have deflected laser beams up to 118° at frequencies of 120 Hz
• Could be used to sector laser beams in optical coherence tomography (OCT) scanners
Small Optical Scanner

1 mm square mirrors, 1.125 mm wide tables, 1mm wide IFAs
Large Scanning Devices

Gold/Silicon Mirror
3 µm Thick Torsion Hinges
IFA Actuator
30 µm Thick Support Structure

1.5 mm square mirrors, 2.25 mm wide tables, 3 mm wide IFAs
Scanner Displacements

Calibrated Target Fixed 1.2 cm from Scanner

Small

Scanner at Rest

Quasi-Static

Near 2\textsuperscript{nd} Resonance

Large
Optical Displacement vs. Frequency

64° displ. at 31.2 Hz,
89° displ. at 62 Hz

77° displ. at 20.6 Hz,
142° displ. at 41.2 Hz
Scanner is relatively linear at frequencies less than 8 Hz.

77° displ. at 20.6 Hz,
142° displ. at 41.2 Hz
Optical Coherence Tomography (OCT)

- Analogous to ultrasound or radar, but measures reflected infrared light
- As small as 4 µm resolution, but only 2-3 mm of penetration in tissue
- Has cell level resolution, could be used as an ‘Optical Biopsy’ technique
- Applications include eye, skin, intravascular imaging
- Most current probes are circular side-scanning, a forward looking probe would have certain advantages – can look ahead of probe and also guide interventional procedures
OCT in Bladder Cancer

• We are currently working with Dr. Michael Manyak of the GWUMC Urology Department in a clinical trial to investigate the use of OCT in bladder cancer.

• For probes to be most useful for this application the scan ranges need to be wide and the devices need to be robust and predictable.

• For this reason we have begun to investigate a new way to scan optical beam for endoscopic OCT that will be more robust.
OCT Detection of Bladder Cancer

Normal Bladder Tissue

Invasive Tumor

No Defined Tissue Layers

1.5 mm

LP
SM
MS

U

1.8 mm

1.8 mm

1.5 mm
Lateral Scanners in OCT

• Lateral scanner is used to move the OCT beam across the target to generate 2-D image

• This scanner must be compact for endoscopic and catheter based applications

• Clinical endoscopic OCT scanners use spinning wires or push-pull devices

• There are certain advantages to a probe that scans in a sector to the front or side of the probe rather than a circular scanning geometry
Many groups have investigated spinning probes
Tearney et.al. *Science* 1997
Rollins et.al. *Optics Letters* 1999

Other groups have also investigated sector scanning probes
Boppart et.al. *Optics Letters* 1997
Bouma et.al. *Optics Letters* 1999
Pan et.al. *Optics Letters* 2001
MEMS scanner integrated into scanning arm of OCT scanners, system is different for galvanometer based scanner
Integration Into Slow OCT System

• The MEMS based scanners were initially integrated into the scanning arm of a galvanometer based OCT system and used to make *in vivo* images of human fingers at imaging rates of less than 1 Hz

**System Specifications**

• Light source
  – Super luminescent diode (SLD)
    • FWHM bandwidth - 28.1 nm
    • Center frequency - 1288.8 nm
    • Coherence length - 20.2 µm
    • 3 mWatts power delivered to target

• Galvanometer based system
  – Reference arm displaced by mirror mounted on galvanometer
    - images obtained at a rate of 2-3 seconds per image
    –104 dB dynamic range
In vivo Images Made With Galvanometer Based System

- Cuticle
- Fingernail
- Stratum Corneum
- Stratum Spinosum
- Stratum Gemanitivum
- Sweat Gland
High Speed RSOD System

• After some success at lower scan rates, the scanners were then inserted into a high-speed RSOD OCT system and images of human fingers and excised porcine tissue were made at image rates from 4-8 Hz

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• RSOD High speed system
  – Reference arm is an oscillating diffraction grating
    – 4 kHz Scan rate
    – images from 4-8 Hz
Images were obtained of (a) ruler (b) in vitro porcine colon (c) in vitro porcine eye (d) in vivo human finger tip
Piezoelectric MEMS Optical Scanning Devices
Piezoelectric Scanning Mirror Motion

Silicon Mirror

3 \mu m Torsion Hinges

PZT Bimorph

Image Scale 1 mm

Constant Optical Axis

Image Scale 1 mm
Measurements were taken using a calibrated target. A 4mW He-Ne laser (633nm) was used to produce the beam and a digital video camera captured the images.
OCT Images Made With Piezo Scanner

(a) 5 mm

Finger
Cuticle
Nail Bed

(b) 5 mm

Stratum Corneum
Dermis
Research Directions

• Eventual development of a catheter scanner incorporating high frequency ultrasound with an OCT Scanner - incorporating the two complementary modalities and increase the information received

• Investigation of new fabrication techniques for incorporating photolithography with medical imaging

• Two-dimensional beam scanning

• IC chip cooling with MEMS

• Electronic nose enhancement

• Other medical applications of MEMS devices (microfluidics, etc.)