IEEE SF Bay Area MEMS & Sensors

http://sites.ieee.org/scv-mems/

October 22, 2014

Meeting Sponsor

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Thanks to Dr. Jim Knutti, President / CEO

Upcoming Meetings

- **Nov. 19th, 2014 (Wednesday) 7:45 PM to 8:45 PM.**
  Title: Innovative Pressure Sensing Solutions.
  Speaker: Mr. Holger Doering, Chief Operating Officer, Silicon Microstructures, Inc.
  Location: Qualcomm, Building B, Room 132, 3165 Kifer Road, Santa Clara, CA.
  Food: Pizza and beverages will be available starting at 7:15 pm for a **$5 donation** at the door.

- **Feb. 25th, 2015 (Wednesday) 7:45 PM to 8:45 PM.**
  Title: Building Successful MEMS Company: From Start to IPO
  Speaker: Mr. Steve Nasiri, Nasiri Ventures.
  Location: TBD

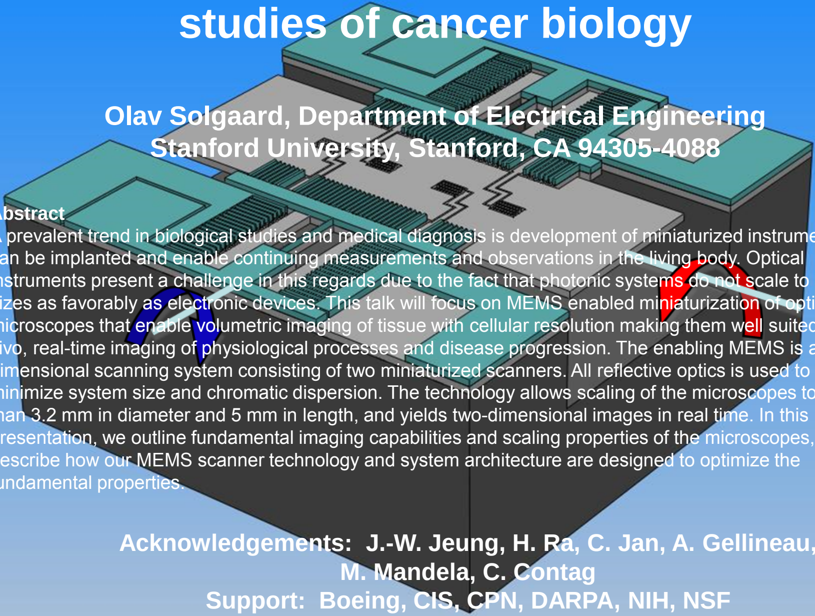
- **Mar. 25th, 2015 (Wednesday) 5:30 PM to 7:30 PM.**
  IEEE MEMS and Sensors Happy Hour
  Location: TBD

Invited talk by Prof. Olav Solgaard

Oct. 22nd, 2014 (Wednesday) 7:45 PM to 8:45 PM.
Title**:** MEMS enabled microscopes for *in-vivo* studies of cancer biology.
Speaker**:** Prof. Olav Solgaard, Electrical Engineering, Stanford University.

Olav Solgaard earned his Ph.D. degree from Stanford University in 1992. His doctoral dissertation: “Integrated Semiconductor Light Modulators for Fiber-optic and Display Applications” was the basis for the establishment of a Silicon Valley firm Silicon Light Machines (SLM), co-founded by Dr. Solgaard in 1994. From 1992 to 1995 he carried out research on optical MEMS as a Postdoctoral Fellow at the University of California, Berkeley, and in 1995, he joined the Electrical Engineering faculty of the University of California, Davis. His work at UC Davis led to the invention of the multi-wavelength, fiber-optical switch, which has been developed into commercial products by several companies. In 1999 he joined Stanford University where he is now a Professor of Electrical Engineering and the Director of the Edward L. Ginzton Laboratory. Professor Solgaard’s research interests include optical MEMS, Photonic Crystals, optical sensors, microendoscopy, atomic force microscopy, and solar energy conversion. He has authored more than 350 technical publications and holds 60 patents. Professor Solgaard came to Stanford with the support of a Royal Norwegian Council for Scientific and Industrial Research Fellowship in 1986 and was named a Terman Fellow at Stanford for the period 1999-2002. He is a Fellow of the Optical Society of America, the Royal Norwegian Society of Sciences and Letters, and the Norwegian Academy of Technological Sciences.

MEMS enabled microscopes for in-vivo studies of cancer biology



Olav Solgaard, Department of Electrical Engineering
Stanford University, Stanford, CA 94305-4088

Abstract

A prevalent trend in biological studies and medical diagnosis is development of miniaturized instruments that can be implanted and enable continuing measurements and observations in the living body. Optical instruments present a challenge in this regards due to the fact that photonic systems do not scale to small sizes as favorably as electronic devices. This talk will focus on MEMS enabled miniaturization of optical microscopes that enable volumetric imaging of tissue with cellular resolution making them well suited for in-vivo, real-time imaging of physiological processes and disease progression. The enabling MEMS is a three-dimensional scanning system consisting of two miniaturized scanners. All reflective optics is used to minimize system size and chromatic dispersion. The technology allows scaling of the microscopes to less than 3.2 mm in diameter and 5 mm in length, and yields two-dimensional images in real time. In this presentation, we outline fundamental imaging capabilities and scaling properties of the microscopes, and describe how our MEMS scanner technology and system architecture are designed to optimize the fundamental properties.

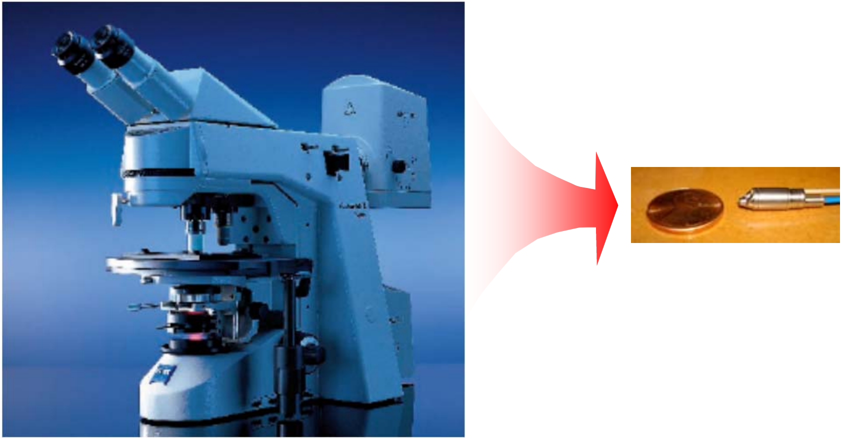
Acknowledgements: J.-W. Jeung, H. Ra, C. Jan, A. Gellineau, M. Mandela, C. Contag
Support: Boeing, CIS, CPN, DARPA, NIH, NSF

Outline

- Why miniaturized microscopes?
  - Science
  - Translation to the clinic
- Applications
  - Endoscopy, Brain imaging, Continuous intravital microscopy, cancer diagnostics, stem cell therapy
- Dual Axis Confocal Microscope
  - MEMS Design and operation
  - Fabrication and Packaging
- Single cell stethoscope
- Fiber Atomic Force Microscope
- Conclusions and Prospects

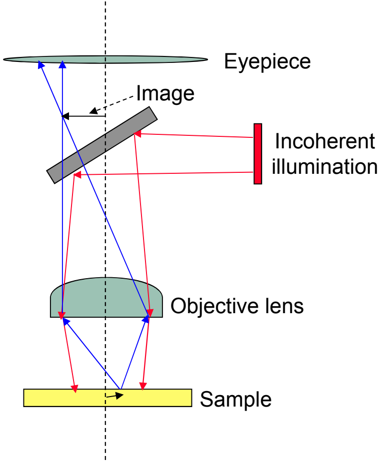
Miniaturization

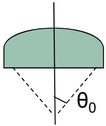
Fix it even though it is not broken (only inefficient, bulky, and impractical)



Standard Optical Microscope

- Principle of Operation

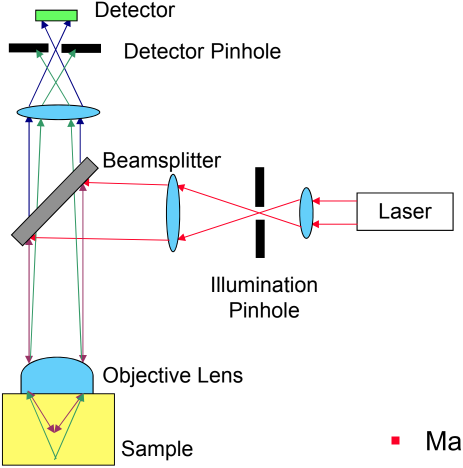




Numerical Aperture (NA) $= n \sin \theta_0$

Confocal Microscopy

- Basic Principle



- Point Illumination
- Point Detection
- Scanned Image

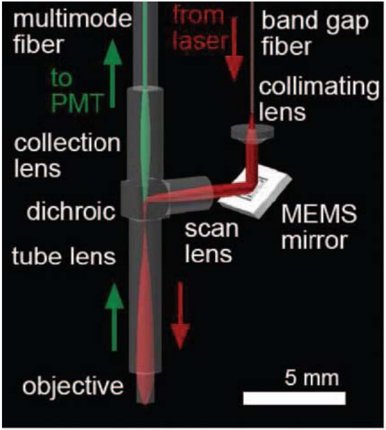
↓

3D imaging

- Marvin Minsky- First scanning confocal microscope (1955)

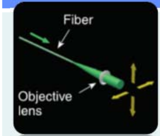
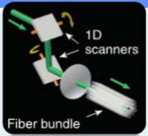
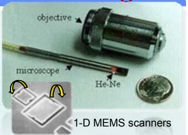
Confocal imaging modalities

- Reflection
- Fluorescence
- Two-photon Fluorescence
  - Laser illumination (red arrows) and fluorescence collection (green arrows) pathways
- Second harmonic generation



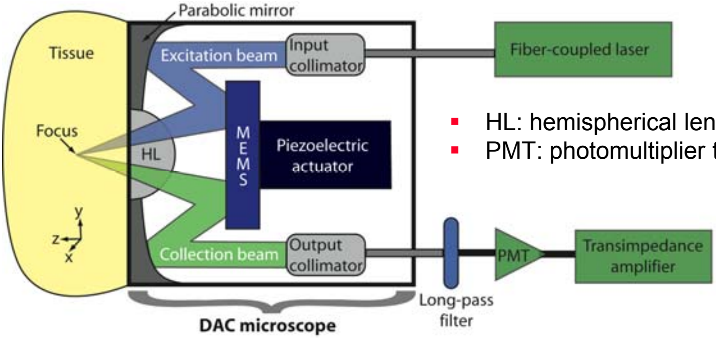
Piyawattanametha et al, August 1, 09, Vol. 34, No. 15, OPTICS LETTERS

Miniaturized Confocal Microscopes

Lens Scanning[1]	Fiber Scanning[2]	Fiber Bundle[3]	MEMS Scanning
			
Giniunas, et al., Electron. Lett, 1991 *Dikensheets, et al., SPIE 1994*	*Harris, US patent # 5,120,953, 1992* *Dabbs, et al., Applied Optics, 1992*	*Sung, et al., Optics Express, 2003* *Thiberville, et al., PATS, 2009*	*Dikensheets and Kino, Optics Letters, 1996*
(+) Relatively simple optics	(+) Miniaturized system	(+) Simple design at distal end	(+) Fast scanning (+) High range of motion (+) Compact size
(-) Limited angular scanning range	(-) Off-axis aberration (-) Slow scan speed	(-) Resolution limited due to pixelation (-) No imaging depth variation	

1 – 3. Images from B.A. Flusberg, et al, Nature Methods, Vol. 2, No. 12, 2005

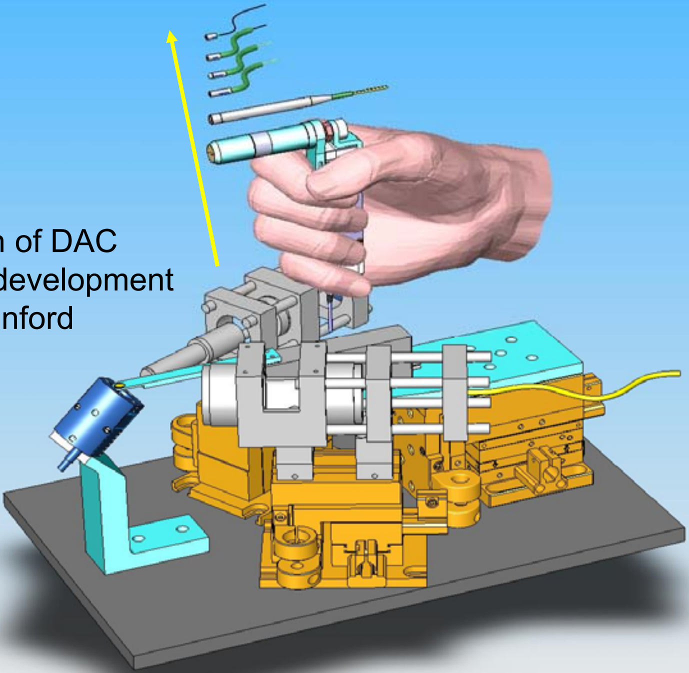
Dual Axis Confocal (DAC) Microscope



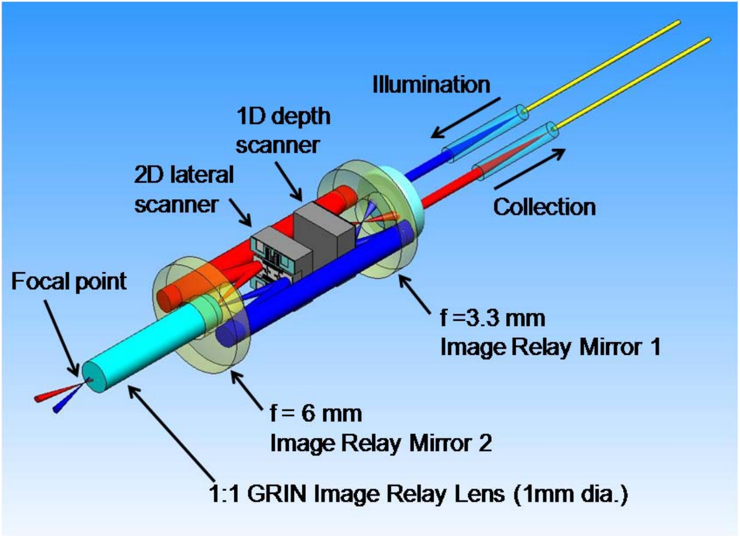
- HL: hemispherical lens
- PMT: photomultiplier tube

- Advantages of the DAC:
  - Larger dynamic range – deeper imaging
  - Low NA objective lens – miniaturization
  - Longer working distance – post-objective scanning
  - Cellular resolution in both transverse and axial dimensions

Evolution of DAC microscope development at Stanford

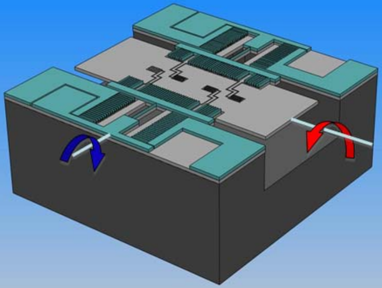


3-D MEMS Scanning System

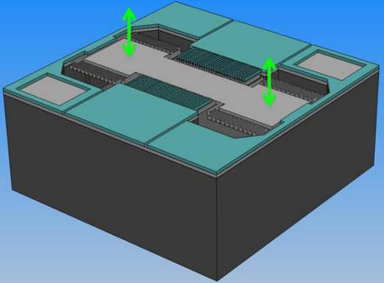


MEMS Scanners

2-D Lateral Scanner



1-D Vertical Scanner

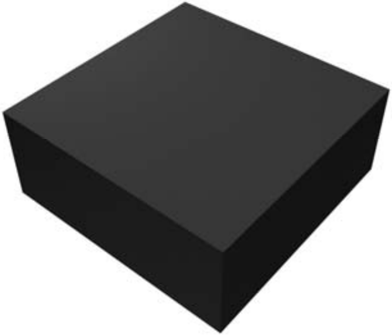


- Electrostatic actuation by self-aligned vertical combdrives
- Serpentine springs to minimize the required space
- Double SOI structure
  - Electrical Isolation
  - Precise thickness control
- Solid substrate integrity for robust chip design

J.-W. Jeong, et al, JMEMS, Dec. 2011

Frontside Processing

Silicon Wafer



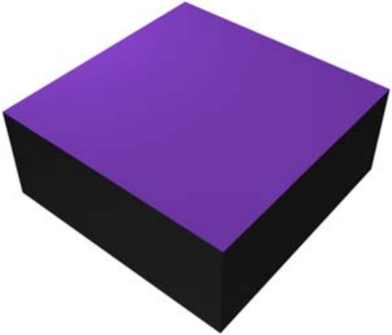
⬛ Substrate

🟪 Low Temperature Oxide (LTO)

J.-W. Jeong, et al, JMEMS, Dec. 2011

Frontside Processing

Deposit LTO (Low Temperature Oxide)

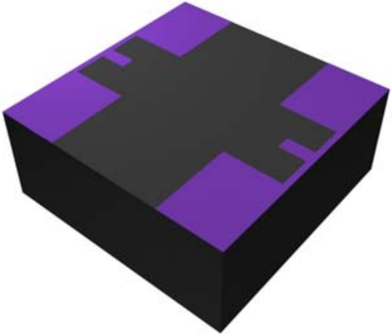


⬛ Substrate

🟪 Low Temperature Oxide (LTO)

Frontside Processing

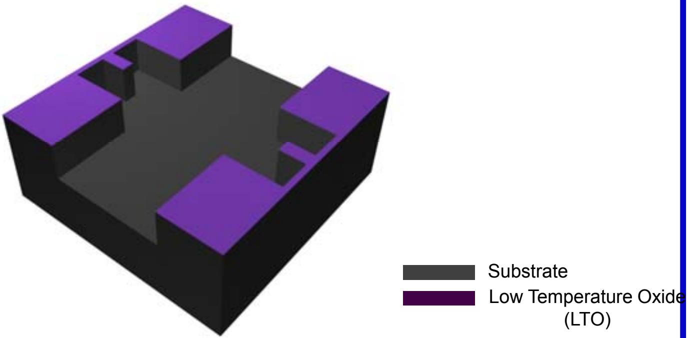
Pattern LTO to define a large cavity (Mask 1)



▬	Substrate
▬	Low Temperature Oxide (LTO)

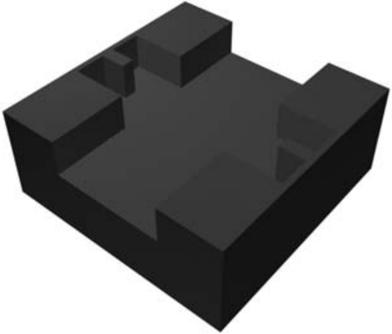
Frontside Processing

DRIE (Deep Reactive Ion Etching) to make a cavity



Frontside Processing

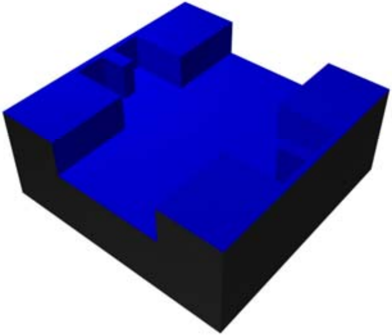
Remove LTO by buffered oxide etching



⬛ Substrate

Frontside Processing

Thermal oxidation

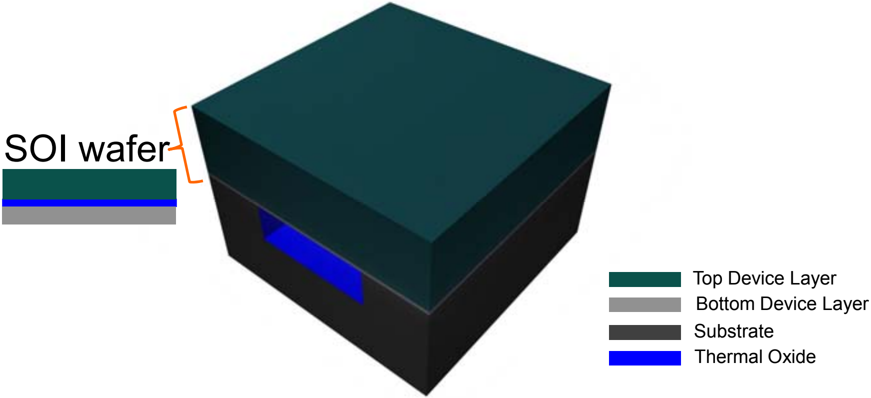


⬛ Substrate

🟦 Thermal Oxide

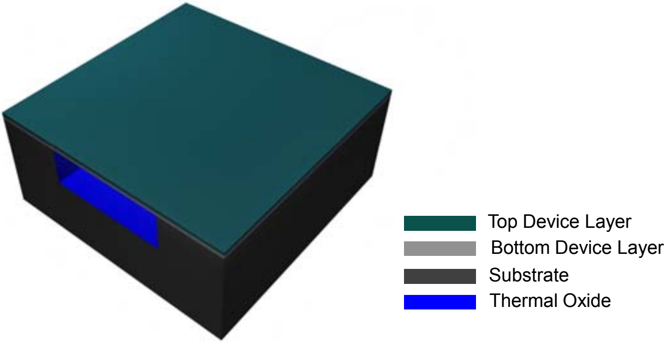
Frontside Processing

Fusion-bond a SOI (Silicon-On-Insulator) wafer on top



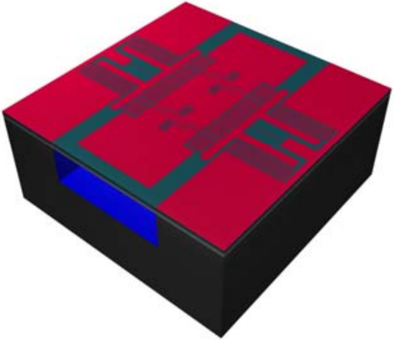
Frontside Processing

Grind and polish the substrate of the SOI wafer



Frontside Processing

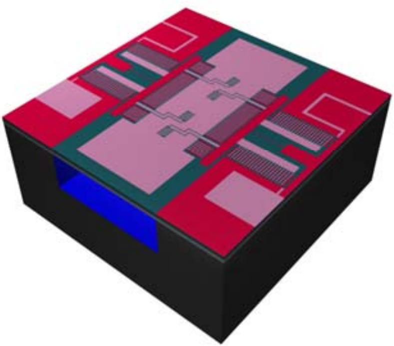
Self-alignment mask patterning of LTO (Mask 2)



- 🟩 Top Device Layer
- ◼ Bottom Device Layer
- ⬛ Substrate
- 🟦 Thermal Oxide
- 🟥 Low Temperature Oxide (LTO)

Frontside Processing

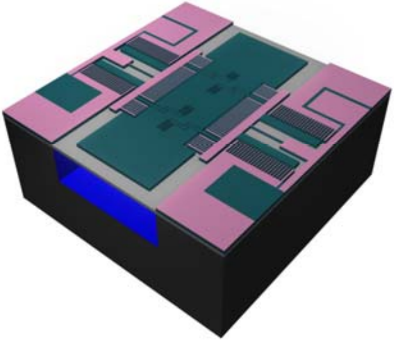
Partial etching of LTO hard mask (Mask 3)



- 🟩 Top Device Layer
- ⬜ Bottom Device Layer
- ⬛ Substrate
- 🟦 Thermal Oxide
- 🟥 LTO
- 🟪 Partially-etched LTO

Frontside Processing

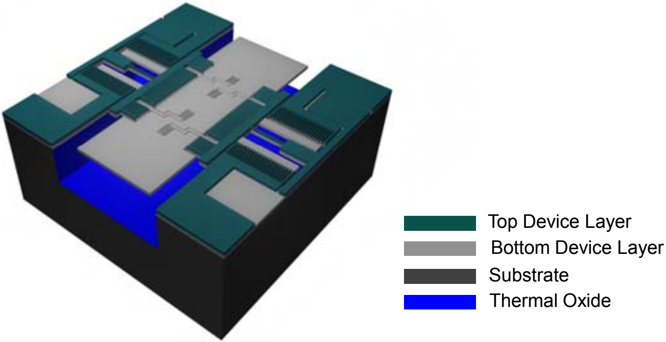
DRIE of the top device layer and plasma oxide etching



- 🟩 Top Device Layer
- ⬜ Bottom Device Layer
- ⬛ Substrate
- 🟦 Thermal Oxide
- 🟪 Partially-etched LTO

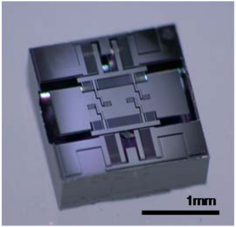
Frontside Processing

DRIE of the bottom device layer defined by Mask 2, followed by plasma oxide etching

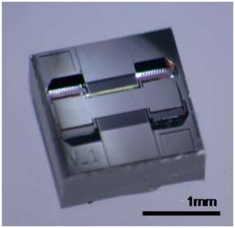


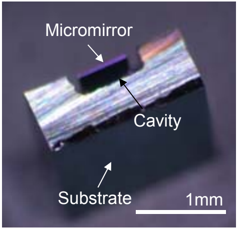
Fabricated MEMS Scanners

2-D Lateral Scanner



1-D Depth Scanner



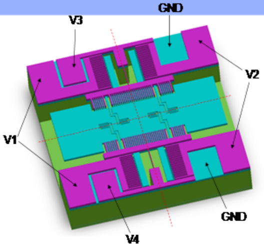


Frontside Processing → Fabrication yield ~90%

Chip size: 1.8 x 1.8mm^2

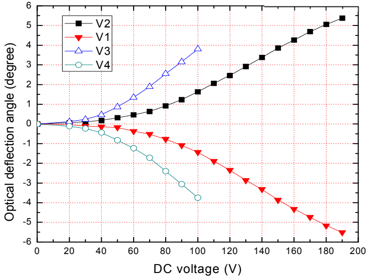
J.-W. Jeong, et al, JMEMS, Dec. 2011

2-D Scanner Characterization



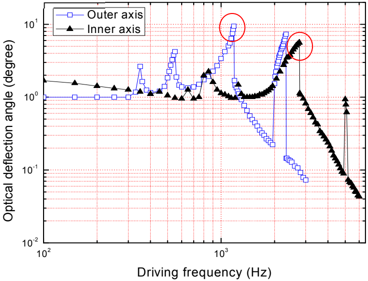
V1 and V2 = Outer-axis rotation
V3 and V4 = Inner-axis rotation

Static mode



- Outer axis: ±5.5°
- Inner axis: ±3.8°

Dynamic mode



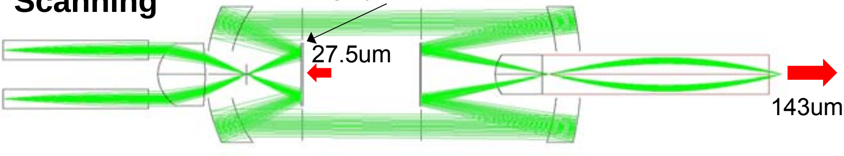
- Outer axis: ±11.8°@1.18kHz
- Inner axis: ±8.8°@2.76kHz

All MEMS-based 3-D Scanning
(Scanning volume = 340um × 236um × 286um)

Vertical Scanning

FOV$_z$ (Δz axis=+/-27.5um) = 286um

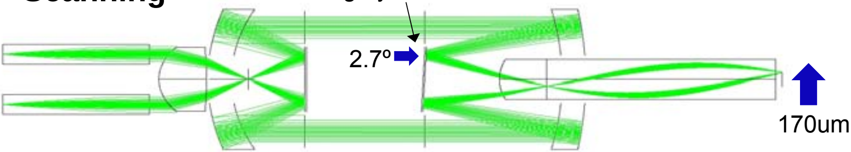
Z-scanning by 1-D depth scanner



Lateral Scanning

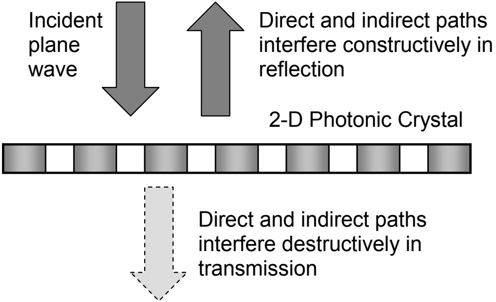
FOV$_x$($\Delta\theta$=+/- 2.7deg) = 340um / FOV$_y$ (Dq=+/- 1.9deg) = 236um

X-Y scanning by 2-D lateral scanner



J.-W. Jeong, et al, Optical MEMS and Nanophotonics, 2011

High-reflectivity 2-D PC



Incident plane wave

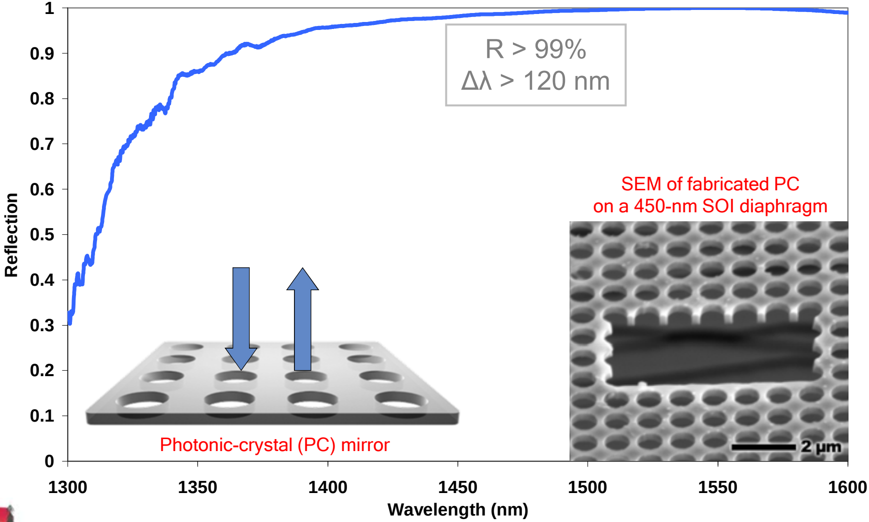
Direct and indirect paths interfere constructively in reflection

2-D Photonic Crystal

Direct and indirect paths interfere destructively in transmission

- The incident optical plane wave excites two different types of modes in the crystal; plane waves and guided resonances
- These modes set up two (or more) pathways through the plate
- In a crystal that is designed for high reflectivity, these two pathways interfere destructively in transmission over the wavelength band of interest
- The modes then interfere constructively in reflection and establish high reflection from the single-layer crystal.

High-reflectivity Polarization-independent mirror

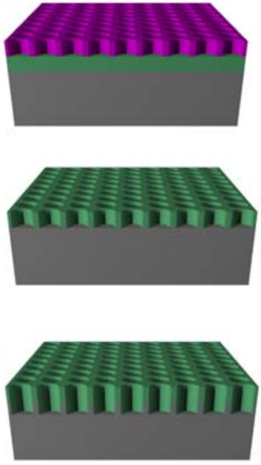


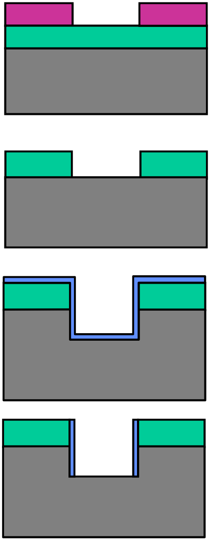
R > 99%
Δλ > 120 nm

SEM of fabricated PC
on a 450-nm SOI diaphragm

Photonic-crystal (PC) mirror

GOPHER (Generation Of PHotonic Elements by RIE)





1) Lithography

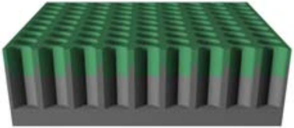
2) Etch oxide mask

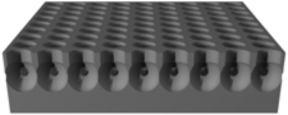
3) Etch Si and deposit oxide

4) Directional oxide etch (remove oxide on horizontal surfaces)

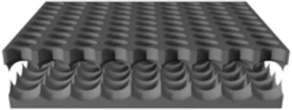
🟪 PMMA
🟩 Oxide
◼ Silicon

The GOPHER-process

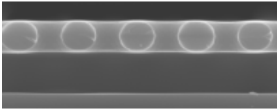


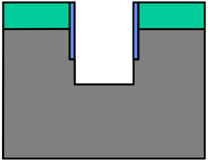


Isotropic plasma etch (short)

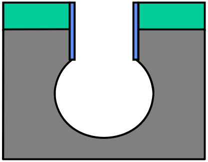


Isotropic plasma etch (long)

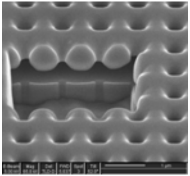




4) Directional Etch to create undercut

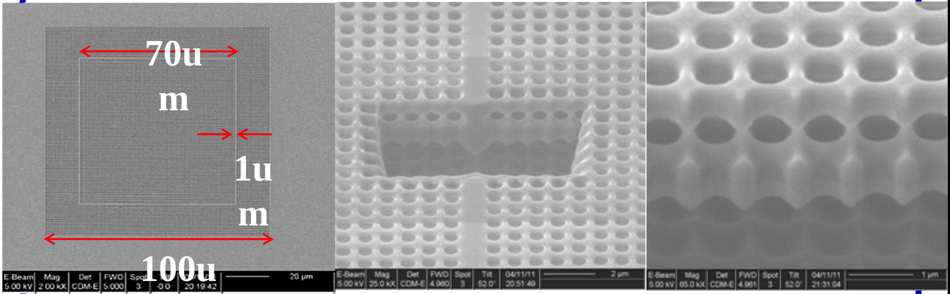


5) Isotropic plasma etch. A short etch creates a well-connected PC. A long etch creates a free-standing PC.



6) Hydrogen anneal to remove rough edges and improve optical quality.

Double-layer Si PC

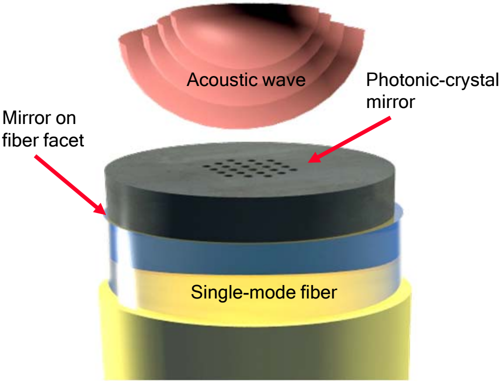


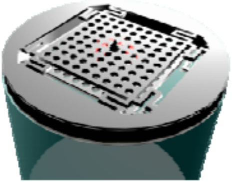
- 1st PC layer: p=820nm, d=515nm, t=500nm
- 2nd PC layer: p=820nm, d=430nm, t=400nm
- gap between the layers < 750nm

* p=periodicity, d = hole diameter, t = slab thickness

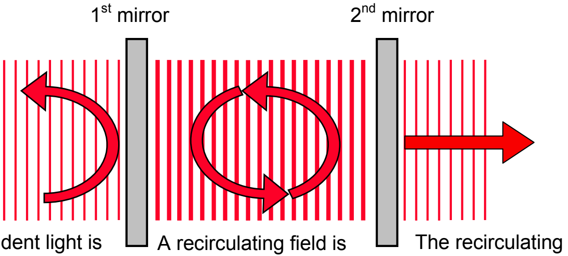
Fabry-Perots with PC mirrors

PC mirrors
High reflectivity in IR (99.5% reflectivity)
Thermally robust
High power handling
Flexible polarization
Single dielectric layer
MEMS compatible, flexible post processing
Complex phase response
Small angular range
Limited wavelength range





Fabry-Perot Resonator



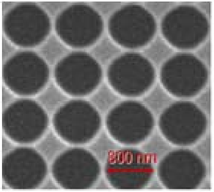
The incident light is partly reflected and partly transmitted

A recirculating field is built up inside the F-P

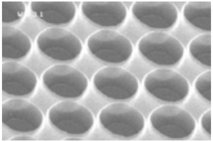
The recirculating field creates an output field

- Principle of Operation:
  - The incident light is partially transmitted through the first mirror
  - Light is reflected between the two mirrors to build up a recirculating field
  - On resonance: Integer number of wavelengths between the mirrors
  - => the recirculating field builds up => the reflection goes to zero
- The reflection measures the distance between the mirrors
- A measurand that changes mirror distance can be measured

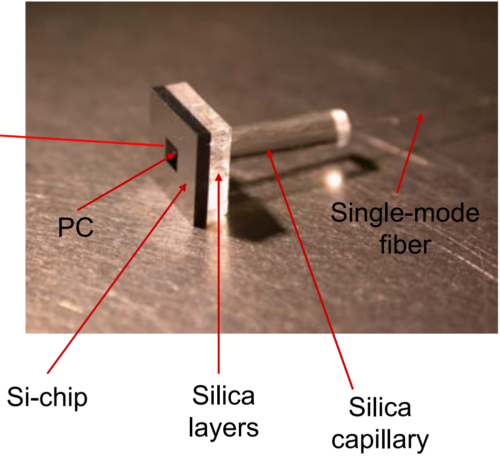
Packaged acoustic fiber sensor



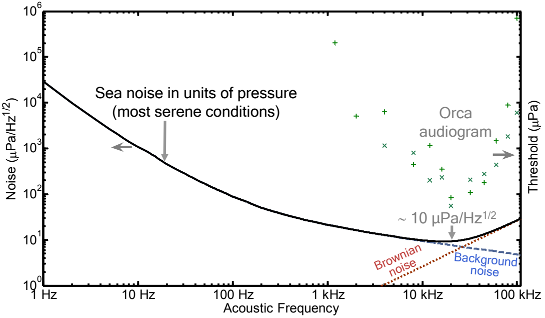
Top view

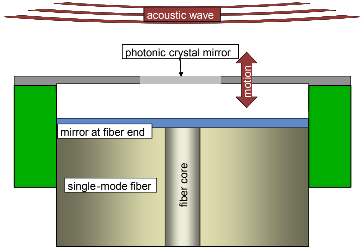


Angled view



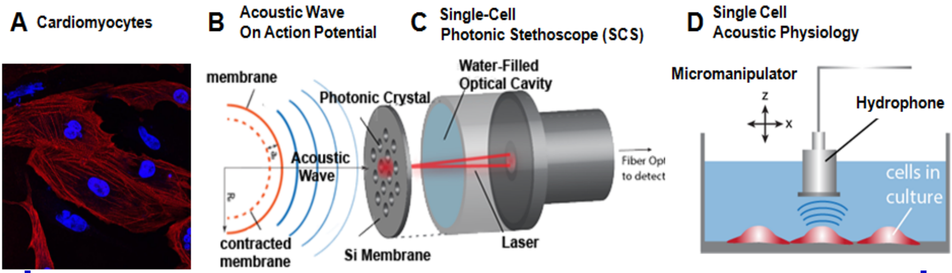
PC Microphone/Hydrophone





- A compact, fiber-based hydrophone / microphone, with no electrical parts
  - Based on a low-order, high-finesse fiber Fabry-Perot with a deflectable high-reflectivity photonic-crystal mirror
  - A high sensitivity (**<10^{-4} Å** displacement detection) with a very high dynamic range (**~160 dB measured, 200 dB calculated**)
- Measured **~10 μPa/Hz$^{1/2}$** in air and **~11 μPa/Hz$^{1/2}$** in water at high acoustic frequencies (**>30 kHz**)

Single-cell photonic stethoscope



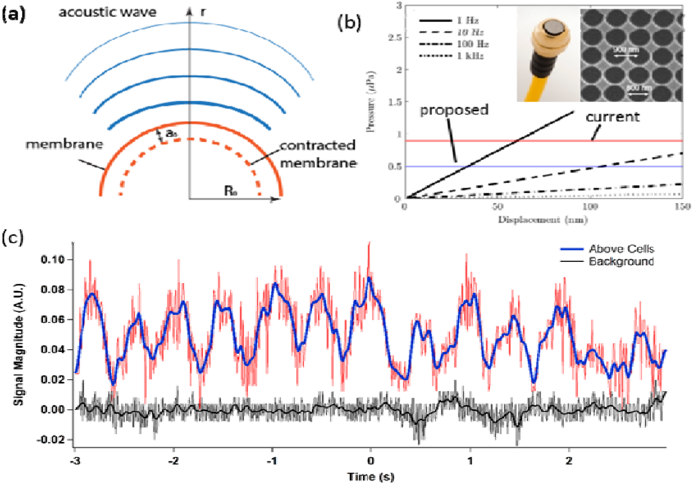
a) Cardiomyocytes perform like an underwater speaker; each action potential causes a rapid constriction and release producing a pressure wave in the surrounding liquid

b) Acoustic pressure waves propagate outwards from the cell

c) The signal is detected by a cell stethoscope

d) The cell stethoscope is precisely positioned to record the acoustics of live cardiomyocytes in culture

Measurements



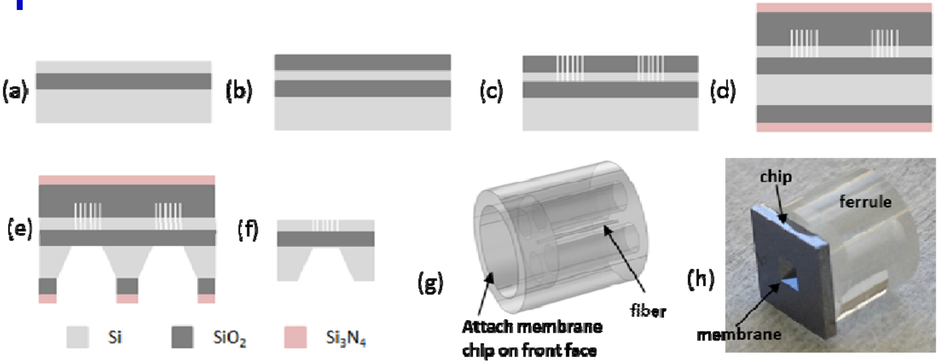
a) Model of a pressure wave from a cylindrical or spherical cell

b) Calculated cardiomyocyte acoustic pressure amplitude

c) Pressure vs time from a hydrophone suspended above a beating culture of cardiomyocyte cells

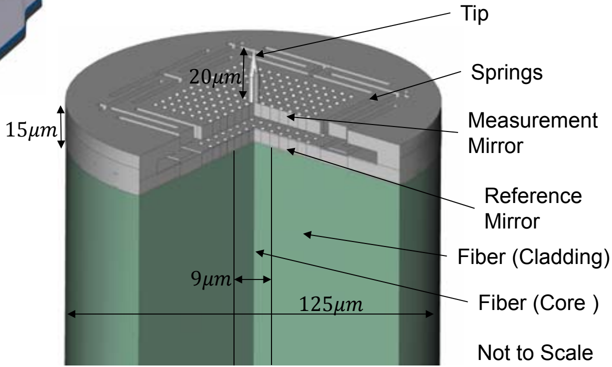
  - Each pressure pulse corresponds with a beat, and has both positive and negative components

Cell Stethoscope fabrication



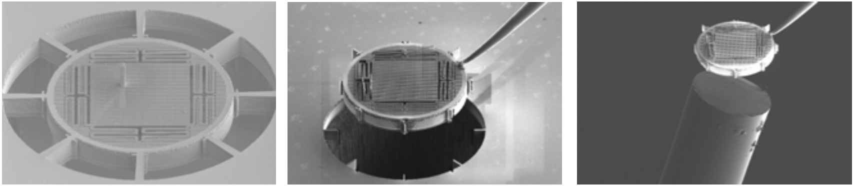
IN-VIVO ATOMIC FORCE MICROSCOPY

Bruker Dimension Icon Atomic Force Microscope

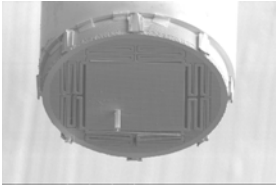


Not to Scale

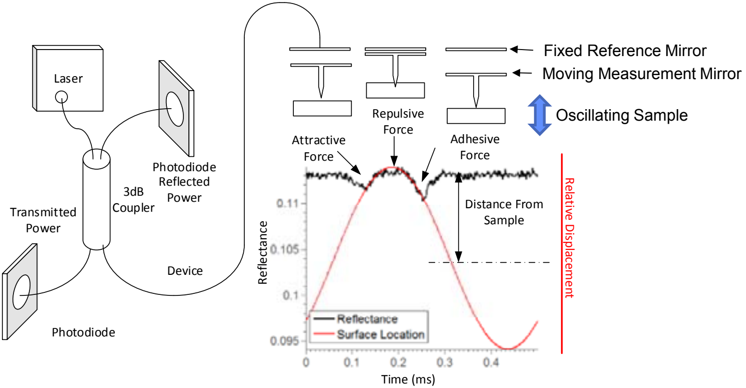
Fabrication



- AFM fabricated on SOI wafers
- The AFM is lifted off the wafer and placed on the facet of a single mode fiber
- The AFM tip is FIBed onto the sensor either at the wafer level or after fiber mounting



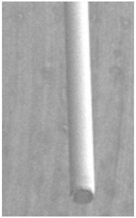
Measurement Setup



BENEFITS OF FIBER AFM

Optical
Lever
(~cm)

Optical Lever	Optical Fiber
Good Force Sensitivity	Very High ForceSensitivity
Free Space Coupled	Fixed Alignment
High Measurement Noise (4 Large Photodiodes)	Low Noise (2 Small Coupled Diodes)
Aqueous operation is difficult	Designed for aqueous operation
Challenging miniaturization	Integrated directly on optical fiber



Optical
Fiber
(125um
Dia)

- Goal: In-vivo measurements

Conclusions

- Optical Microsystems provide an ideal window to observe fundamental biological processes
  - Non-invasive, good spatial resolution
  - Confocal microscopy gives *in-vivo* view of cell structure (reflection) and molecular function (fluorescence)
- MEMS scanners + DAC architecture => Miniaturized confocal microscope
- Front-side processing:
  - Cost-effective and simple process, Compact and robust design, Easy handling and packaging
- Applications of *In-vivo* microscopy
  - Early-stage cancer detection, gene expression, disease progression, stems differentiation and growth
- Continuous intravital optical microscopy will lead to new understanding of fundamental biological processes