Plasma Etching for Optical MEMS: *Scanning Micromirrors Based on Self-Aligned Vertical Combdrive Actuators*

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PLASMA ETCH USERS GROUP MEETING
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National Semiconductor Auditorium, Santa Clara, CA

Abstract

There is great demand for high-speed, high-resolution micromirrors in a variety of optical applications including optical scanning, optical switching and spectroscopy. For many of these applications, electrostatic combdrives are the preferred actuation mechanism, because combdrives provide high speed and relatively high force, and they can be made using standard materials. We present design, fabrication and characterization of micromirrors that are driven by self-aligned, vertical combdrives based on Deep Reactive Ion Etching (DRIE) of Silicon-On-Insulator (SOI) wafers.

Combdrives produce large deflections at relatively low voltages with continuous stable control over the full range of motion. In vertical combdrives the two sets of comb teeth of a conventional comb drive are staggered in the vertical direction. A voltage applied between the movable top comb array and the static bottom comb array produces a vertical electrostatic force that can be applied to create torsional or piston-like motion of micromirrors.

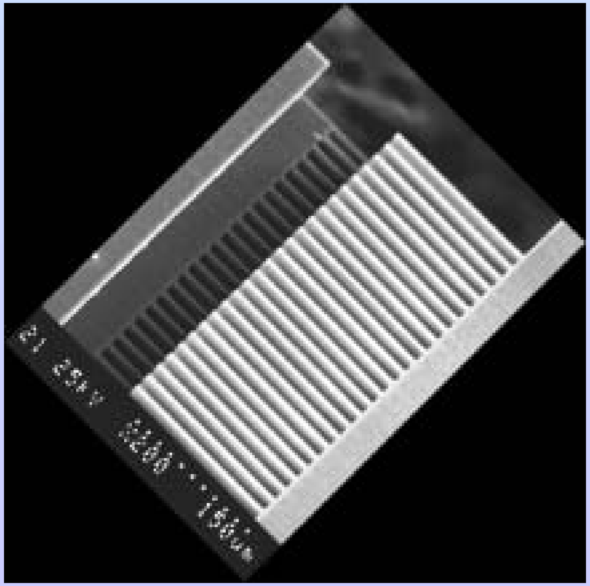
A critical aspect of combdrive design is the spacing between adjacent comb teeth, because the generated force is inversely proportional to this gap size. Combdrives with small gaps are, however, more susceptible to misalignment between the top and bottom comb arrays. For the actuator to be operational, the misalignment tolerance level between the top and bottom teeth should be an order of magnitude smaller than the gap width.

We have developed a simple fabrication process based on plasma etching that produces self-aligned vertical combdrives. Self-alignment makes it possible to fabricate reliable narrow-gap, high-force actuators with excellent yield. A resonance frequency for 300 mm x 100 mm mirrors around 5.5 kHz has been achieved.

After a first part covering the above described specific application of plasma etching, the needs concerning plasma etching for optical MEMS components will be discussed in a broader context.

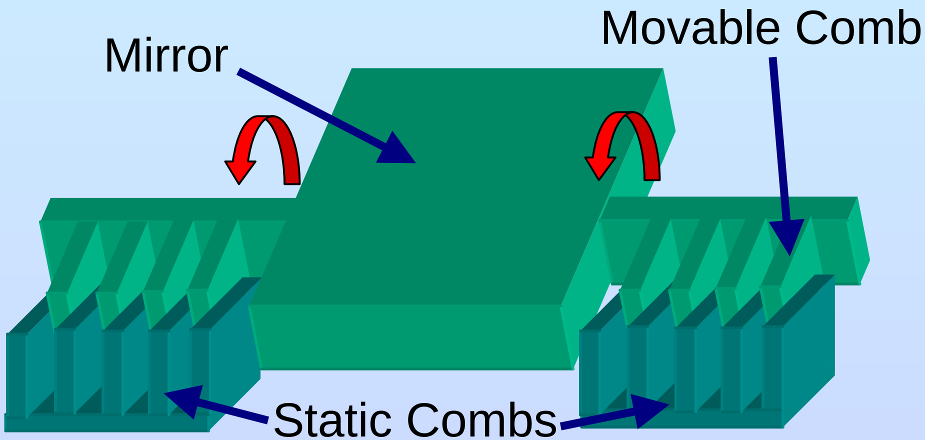
Outline

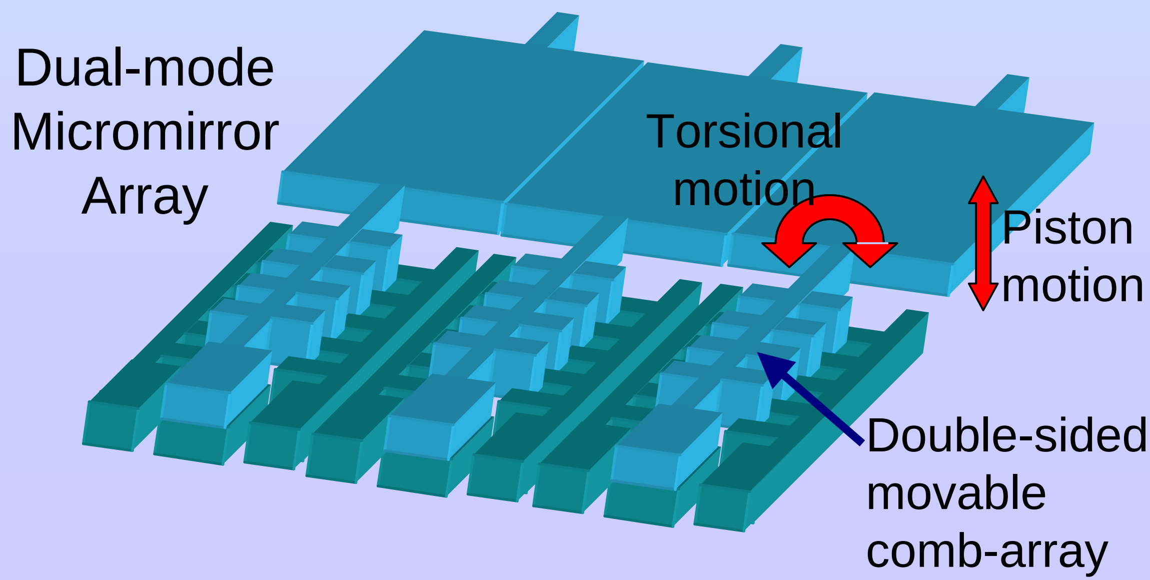
- Objective
  - Vertical combdrives for large force
  - Dual-mode Mirrors and Phased Arrays
- Fabrication
  - STEC process
  - Self-aligned process
- Characterization
- General Plasma Etching Needs for Optical MEMS
- Conclusions



Research support: NSF, DARPA, BSAC

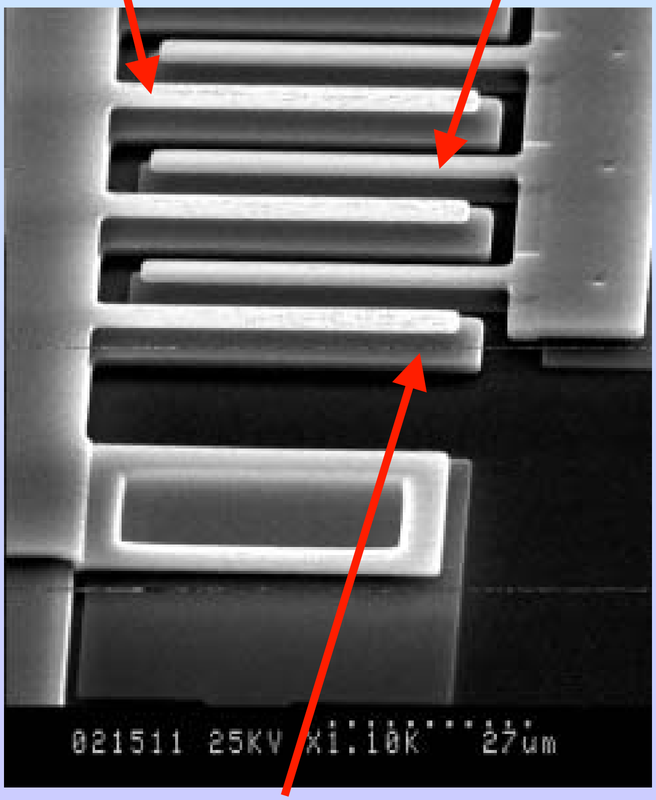
Scanners and Phased Arrays

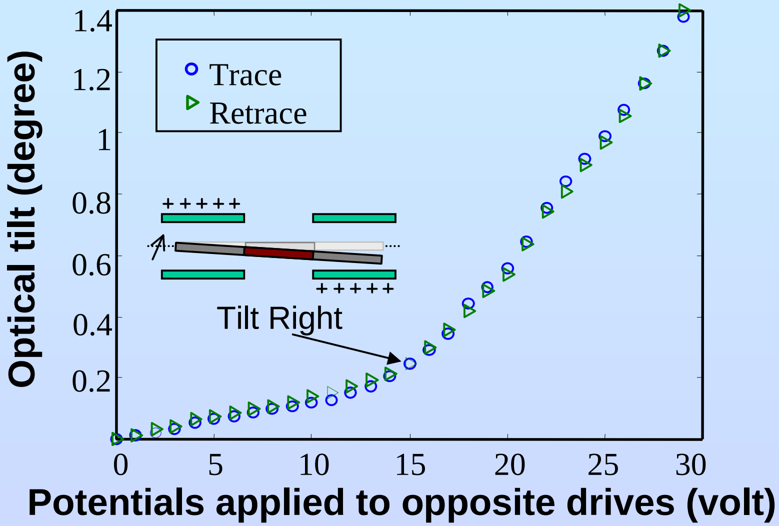


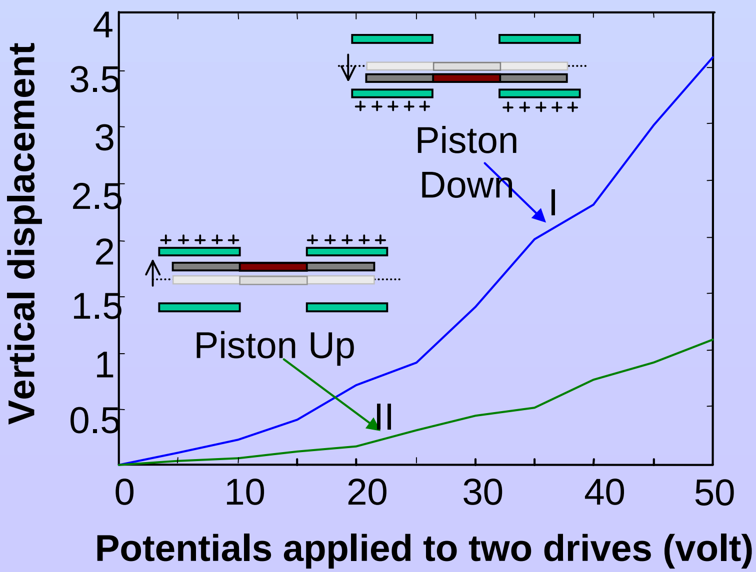


- **Electrostatic Actuators**
  - **Material Compatibility**
- **No sliding surfaces**
  - **Repeatability, stability**
- **Vertical combdrives**
  - **Large Force**
  - **Controllable range of motion**
- **Suitable for dual-mode operation and phased-arrays**

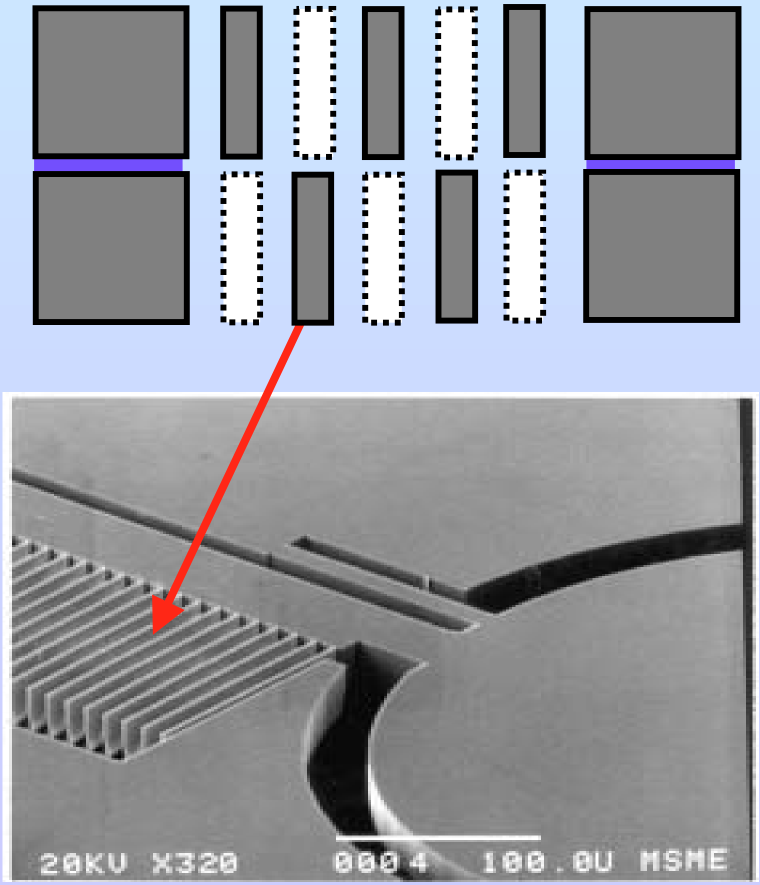
Surface Micromachined Dual-mode Mirrors







MEMS Mirrors in SOI

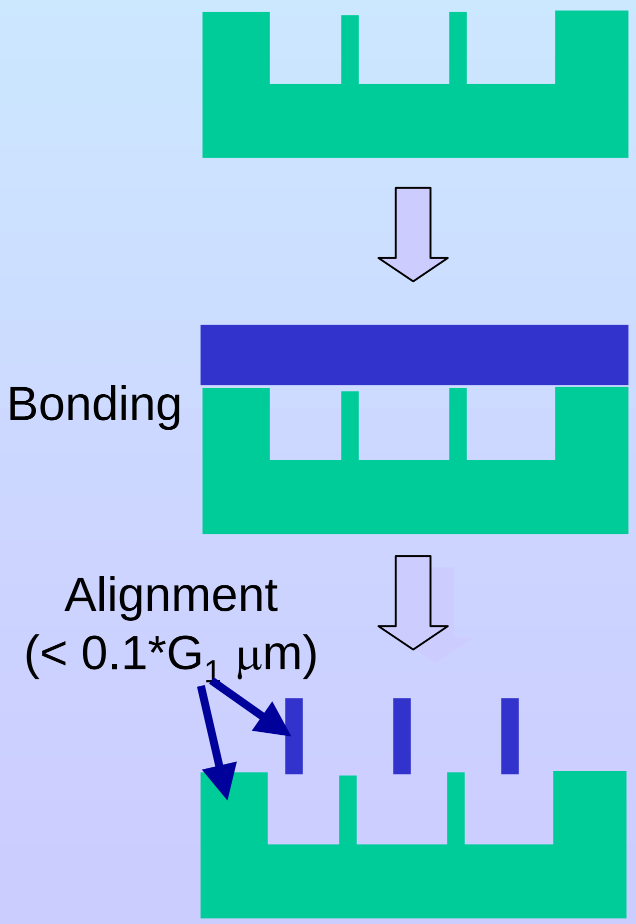


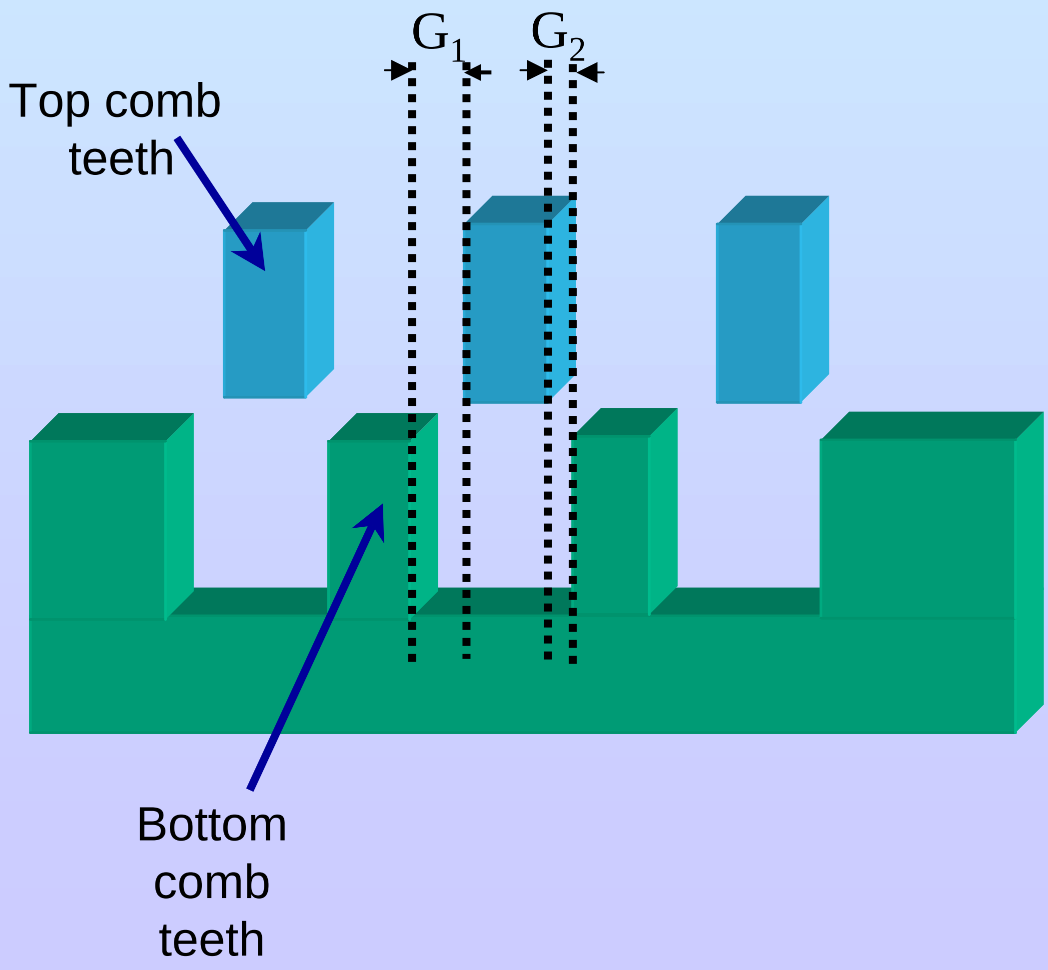
Courtesy Robert A. Conant, BSAC

- DRIE etching of SOI materials
- High quality, flat, and stiff mirrors
- Beam quality!
- High-speed
  - High force => high speed
  - Dual-mode actuators
  - Phased arrays
- Combs are lithographically aligned
  - Reliability
  - Yield

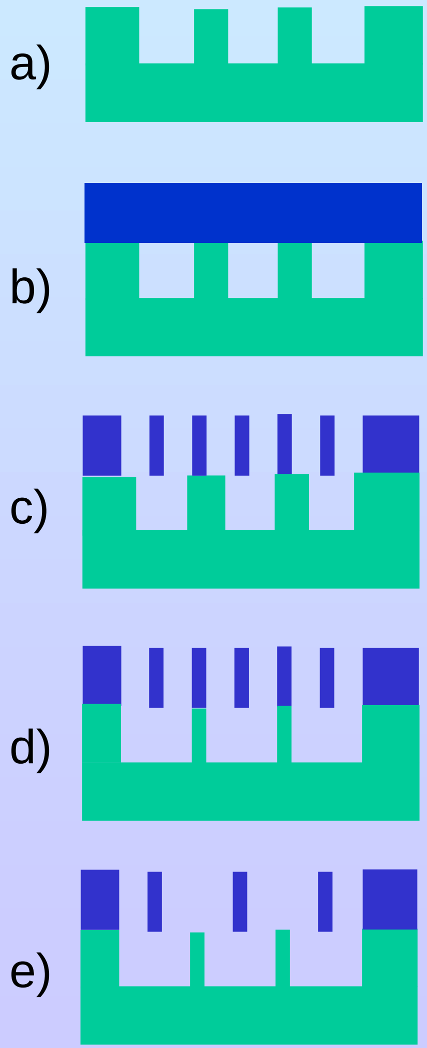
STEC Fabrication

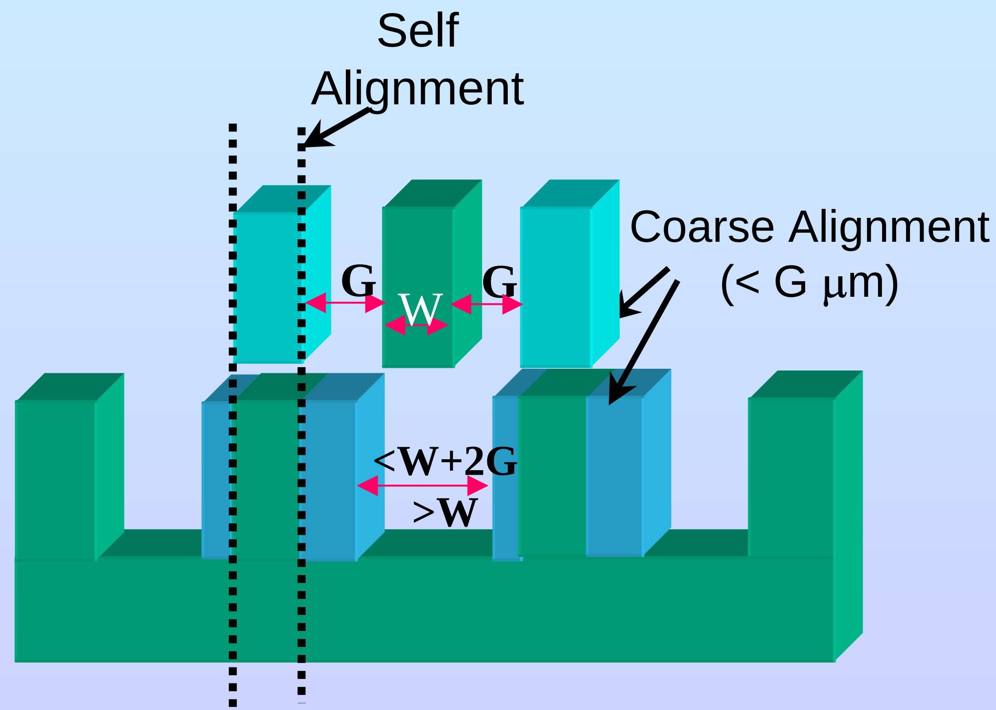
STEC (Staggered Torsional Electrostatic Combdrive)





Self-aligned vertical-comb actuator

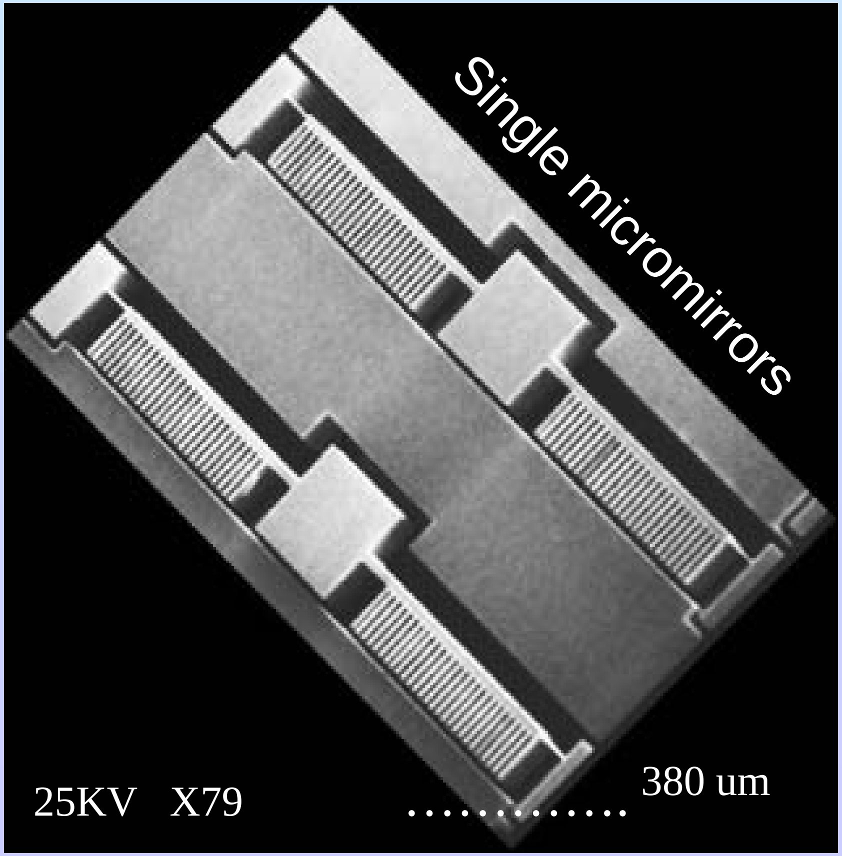


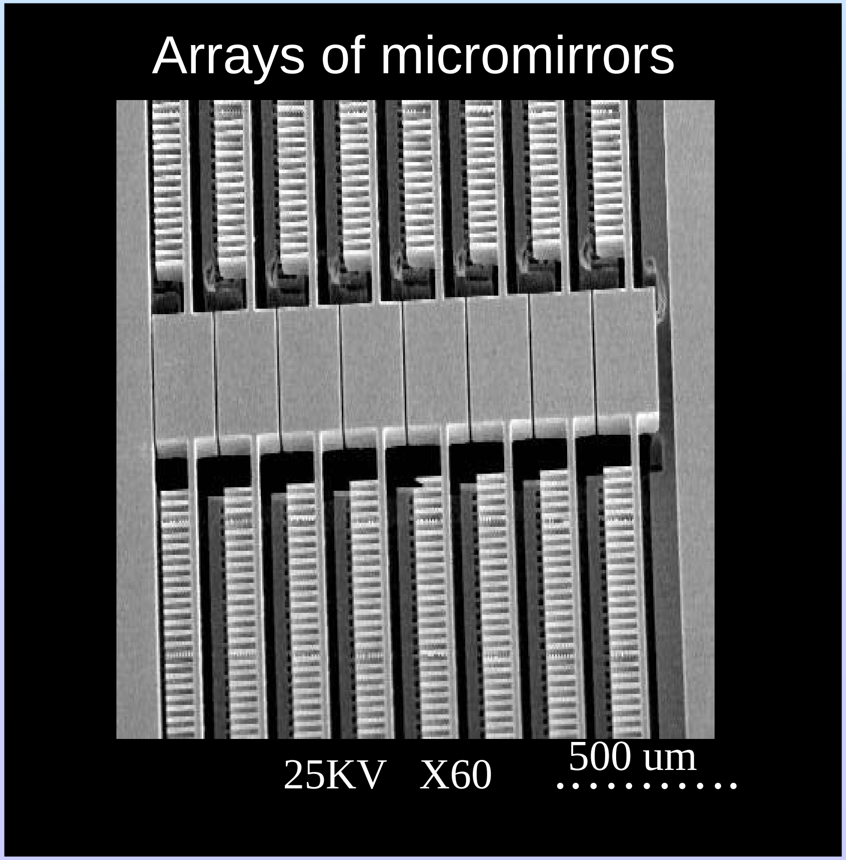


Single mask self-alignment step

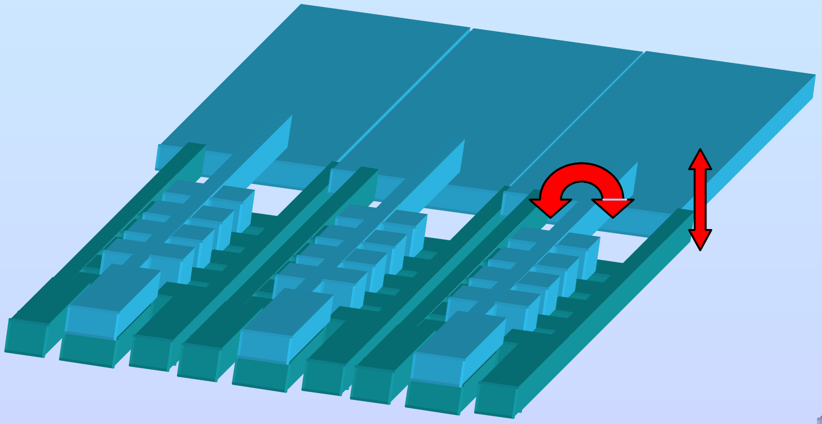
More complex fabrication process
is required for dual-mode mirrors

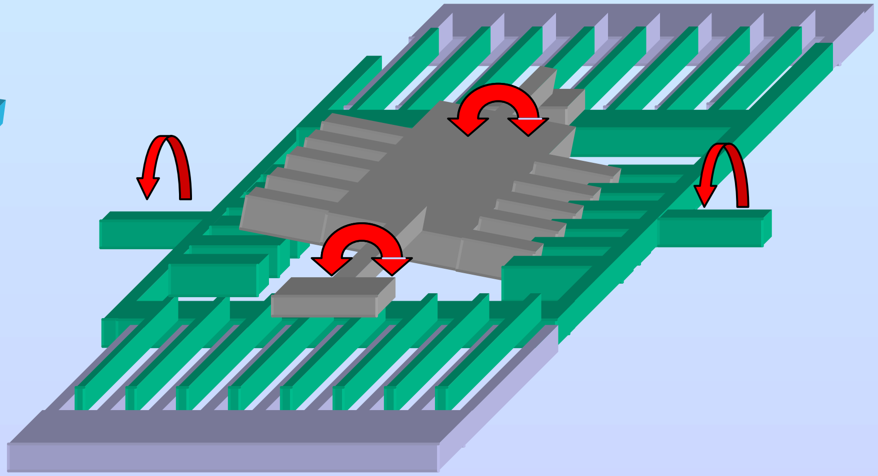
Fabricated Micromirrors





Current work





- Double sided comb actuators
- Torsional and piston style motion
- Isolated electrodes on SOI wafer
- Array operation
- Gimbals

Conclusions (1st Part)

- Vertical comb drives are the preferred actuators for high-speed, high-resolution MEMS scanners
- Fabricated and characterized *self-aligned*, vertical, comb-driven single-crystal micromirrors using DRIE and wafer bonding
  - High force and large deflection
  - Increased stability and yield
- Applications
  - Optical scanners, Fiber switches, Spectroscopy, Microscopy, Optical coherence tomography, External cavity lasers, Barcode readers, Adaptive optics, Printers, Optical vector scanners, Surveillance, Optical interconnects, Mask-less lithography.....

Plasma Etching for MOEMS: Current Needs and Challenges

	Electrostatic Combdrives	Micromirrors	Refractive Devices	Diffractive Devices	Waveguides	LEDs & VCSELs	Photonic Crystals	Organic Devices (OLEDs)	System Integration
Vertical Sidewalls	X	X	X	X	X	X	X	X	X
High Aspect Ratio	X	X	X	X	X	X	X	X	X
Low Surface Roughness	X	X	X	X	X	X	X	X	X
Small Feature Size	X	X	X	X	X	X	X	X	X
High Etch Rate Uniformity	X	X	X	X	X	X	X	X	X
Selectivity	X	X	X	X	X	X	X	X	X
New Materials	X	X	X	X	X	X	X	X	X
Control of Sidewall Angle	X	X	X	X	X	X	X	X	X
Critical Wafer Handling	X	X	X	X	X	X	X	X	X

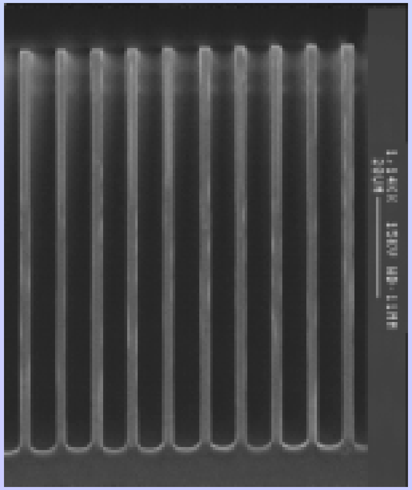
Smooth Vertical Surfaces for Optical Switches

- **Verticality**
- **Narrow linewidth (high force)**
- **Smooth vertical surfaces (λ/10 - λ/50)**

Silicon trenches, 80µm deep

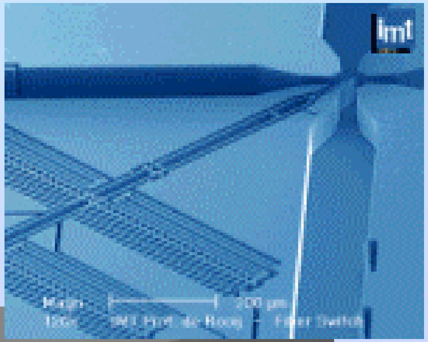
4.5µm space / 2µm line width

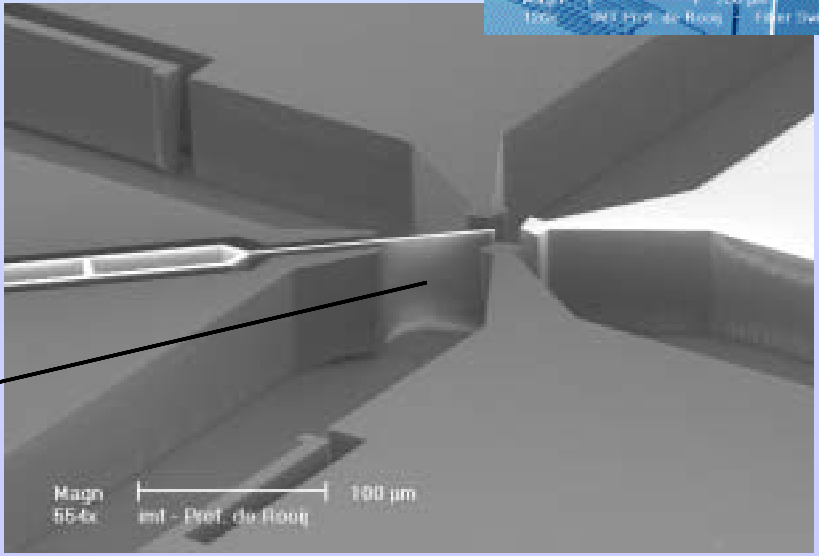
Etch rate ≈ 2.2µm/min



Surface Technology Systems
http://www.stsystems.com/

2x2 Optical Switch



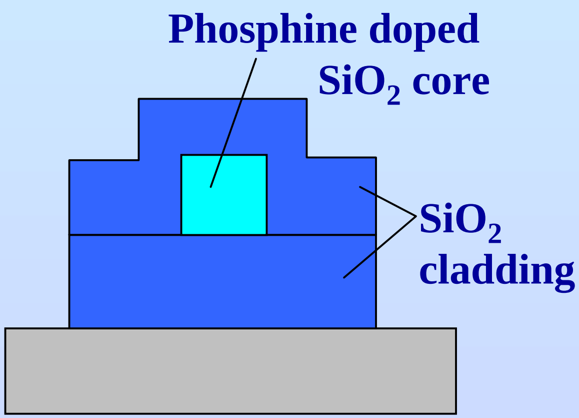


Vertical Mirror

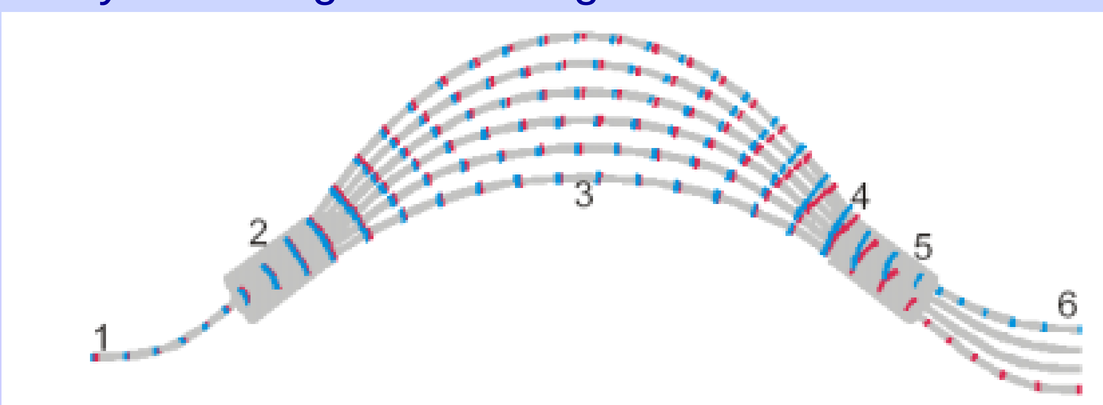
University of Neuchatel, Switzerland
http://www-samlab.unine.ch/Activities/Activity.htm

Waveguides

- Etching of up to 30 μm thick (SiO_2) Films
- Smooth surfaces (reduction of losses – 0.01dB/cm)
- Vertical and smooth edges (coupling losses)
- Functionality sensitive towards geometry changes
- New materials (polymers, GaN …)

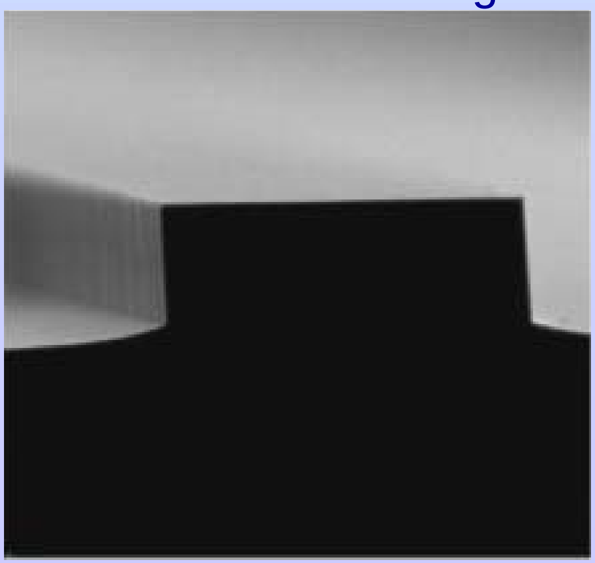


Arrayed Waveguide Grating



www.lightwavemicro.com/PDFs/
Lamwhitepaper.pdf

AlGaAs Waveguide



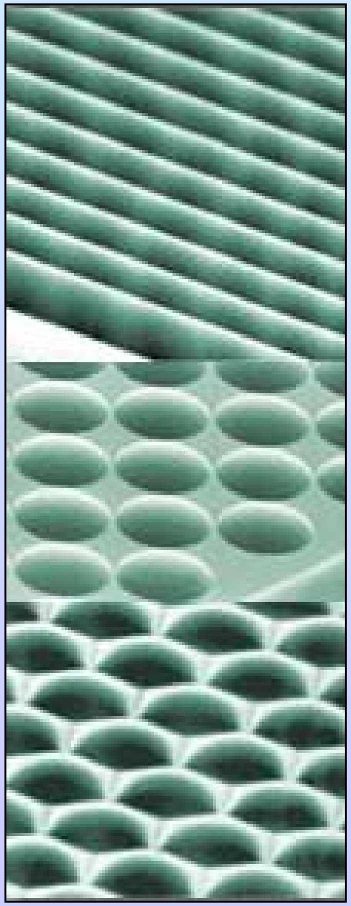
Stanford University, Prof. Harris, Prof. Feyer

http://snf.stanford.edu/About/Research/2001/Yu.pdf

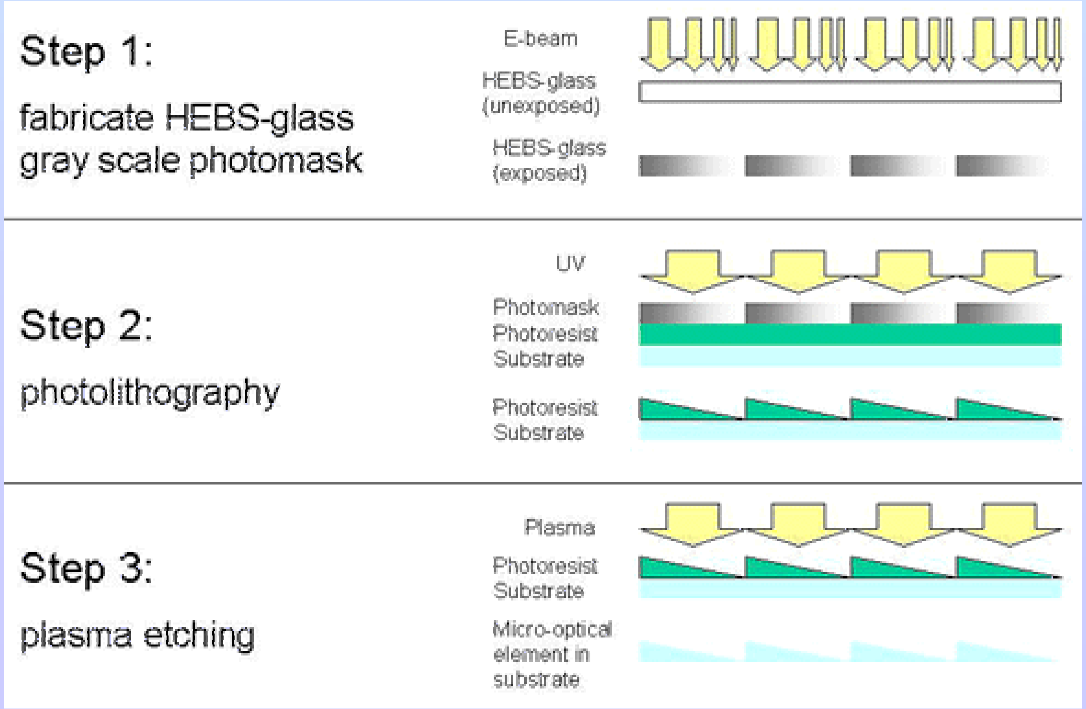
Refractive and Diffractive Devices

- Pattern transfer from photoresist to substrate (e.g. glass)
- Smooth surfaces
- Control of etch depth
- Uniformity across wafer
- Gray Scale Lithography (500 levels, 100 nm resolution)
- Tuning of etch rate ratios

Microlenses



MEMS Optical Inc.
http://www.memsoptical.com/prodserv/products/microlensar.htm



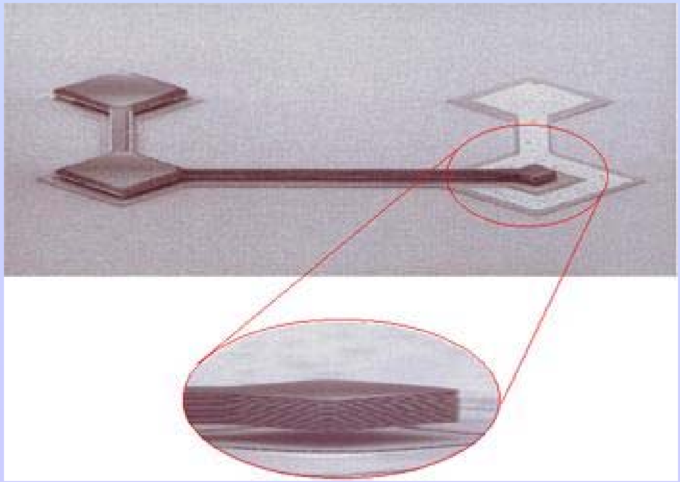
Canyon Materials Inc., http://www.canyonmaterials.com/

Active Optical Devices

- **VCSEL: Etch stop at defined depth (uniformity)**
- **Smooth vertical surface (edge emitting laser diode)**
- **New materials (organic LEDs)**

Kodak, OLED Display
http://www.kodak.com/US/en/corp/display/index.jhtml

Tunable VCSEL (InAlGaAs)
Cantilever with Top-Mirror, ca. 4 um thick



Bandwidth9
http://www.bandwidth9.com/content-template.cfm?display=products&sub=products

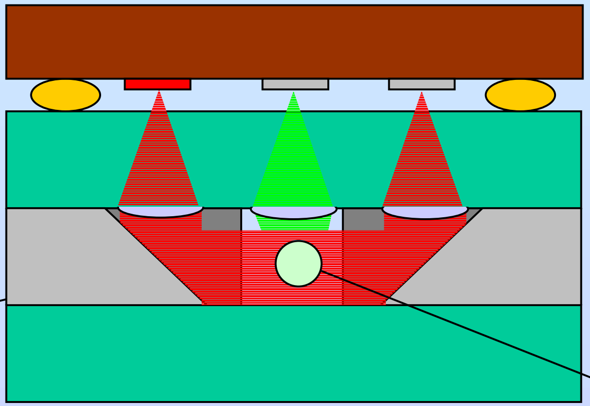
AlGaAs LED
Mask: Gold, Etch Rate: 1.54 um/min.
Etch Depth: 60 um

SAMCO Inc.
http://www.samcointl.com/apps/Optoelectronics.html

Sidewall Angle Control
Facilitates System Integration

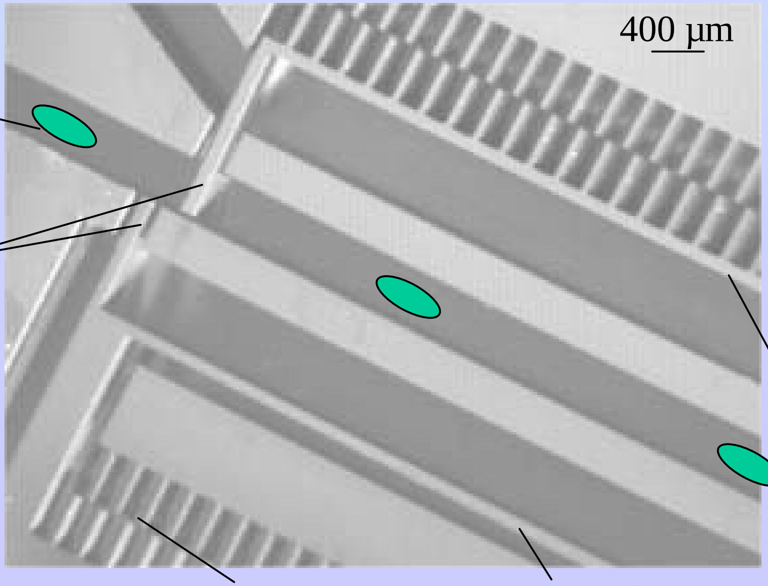
- **Mirror surface at 45 ° facilitates integration**
- **Here: Integration of fluidics and optics for fluorescence detection in embryos**
- **Gray Scale Lithography ?**

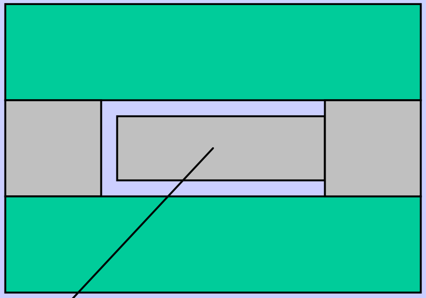
Optical Chip with LED/VCSEL and Photodetector



Fluidic Chip with Integrated Lenses and Mirror Surfaces

Fluidic System for automated Fruit Fly Embryo Handling





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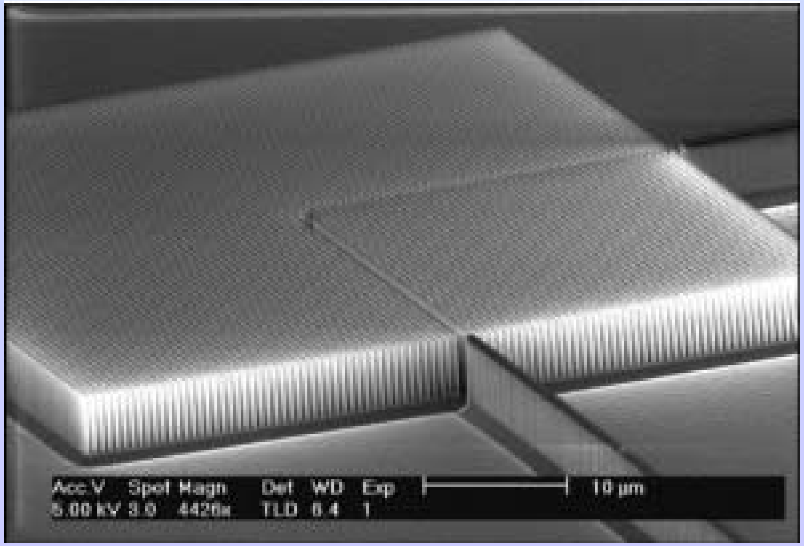
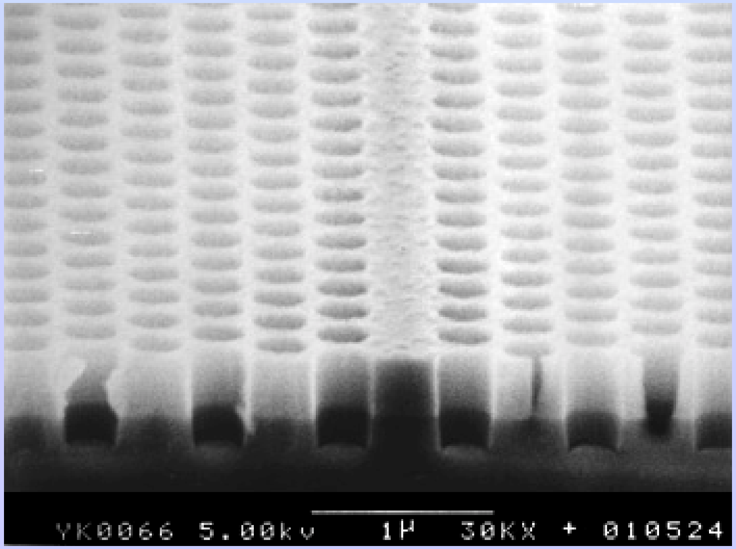
http://www.stanford.edu/group/SML/

Plasma Etching of Small Features For Photonic Crystals

- Photonic Crystals require sub-wavelength feature size
- Tight fabrication tolerances
- Vertical, smooth sidewalls
- No notching at interfaces (good etch rate uniformity)



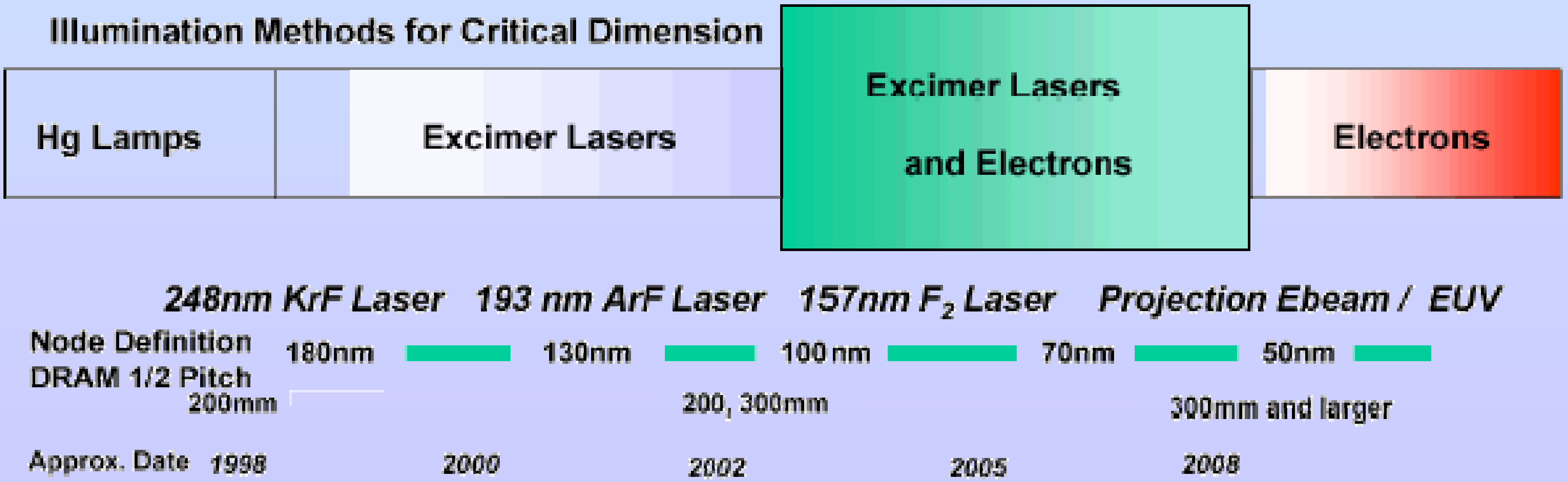
www.mrs.org/publications/bulletin
'MATERIALS SCIENCE ASPECTS OF PHOTONIC CRYSTALS'



SAMCO Inc.
http://www.samcointl.com/apps/PC_SOI.html

New Illumination Methods for Smaller Feature Sizes

- SCALPEL® – E-Beam Projection Lithography
- EUV (Extreme Ultra Violet) Lithography



http://www.bell-labs.com/project/SCALPEL/
-> Dec. 1999 White Paper

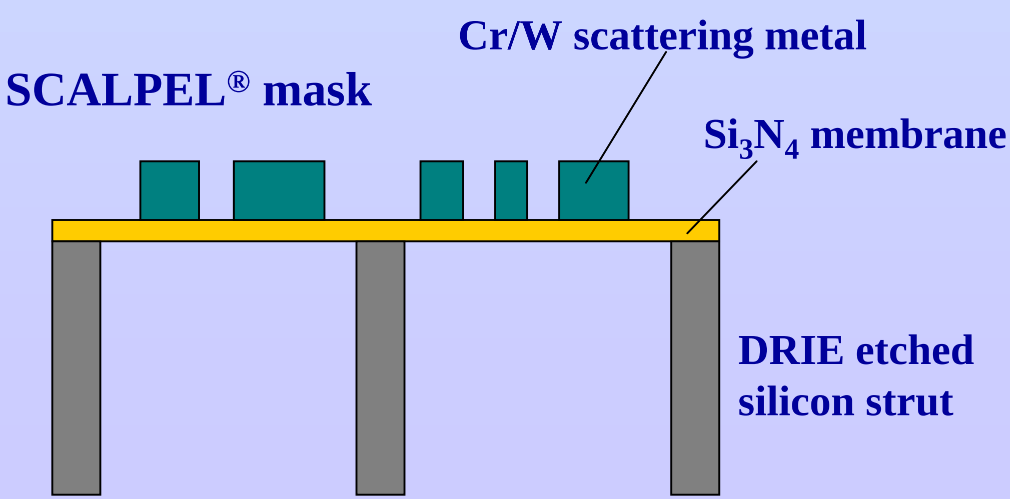
SCALPEL® Technology for E-Beam Lithography

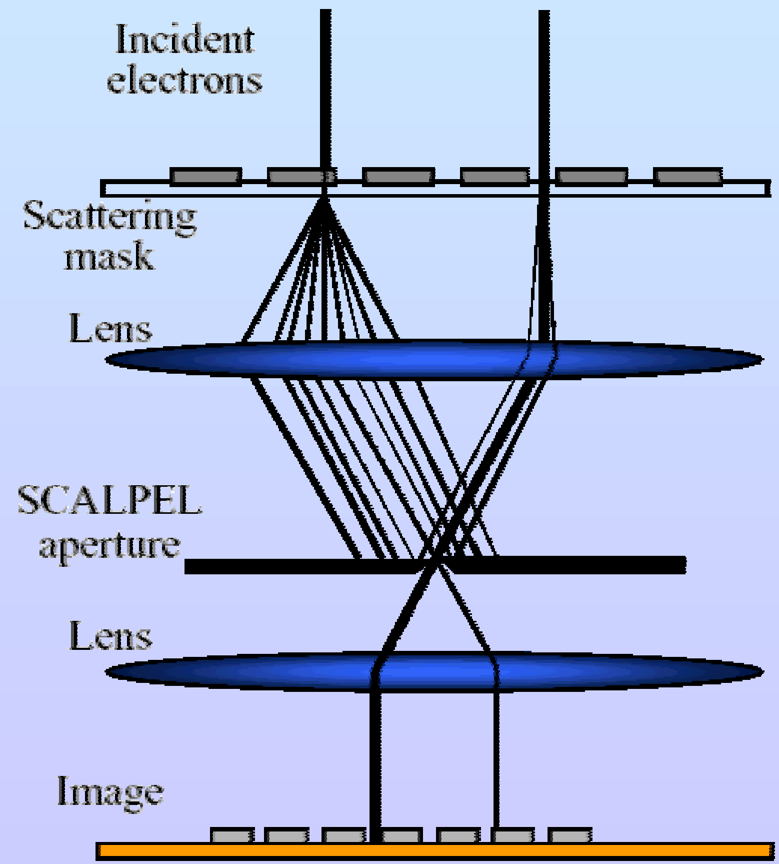
SCALPEL®

Scattering with Angular Limitation

Projection Electron Beam Lithography

- SCALPEL combines high resolution e-beam lithography with high throughput of a projection system
- Achievable IC feature size of 50 nm

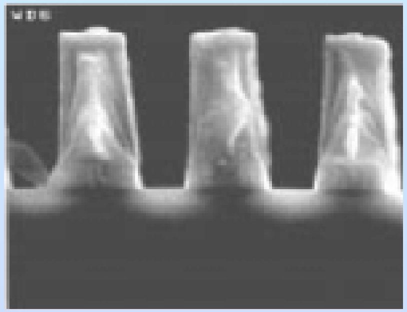




http://www.bell-labs.com/project/SCALPEL/
-> Dec. 1999 White Paper

SCALPEL® Technology for E-Beam Lithography

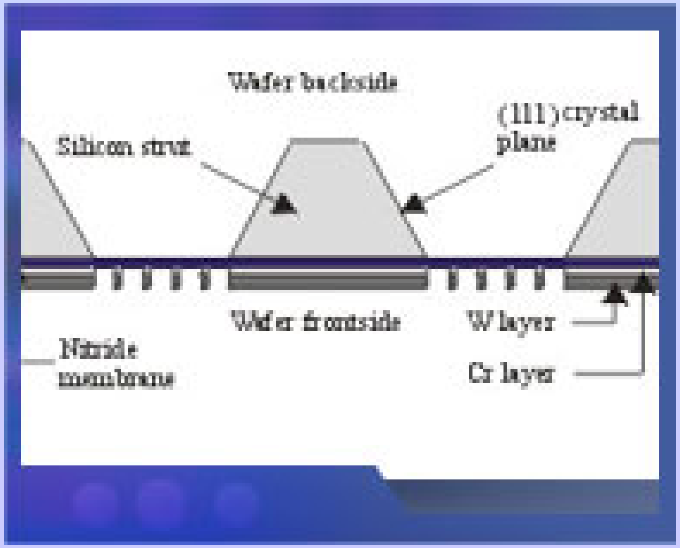
250 nm Al1%Si lines



Trikon Technologies
http://www.trikon.com

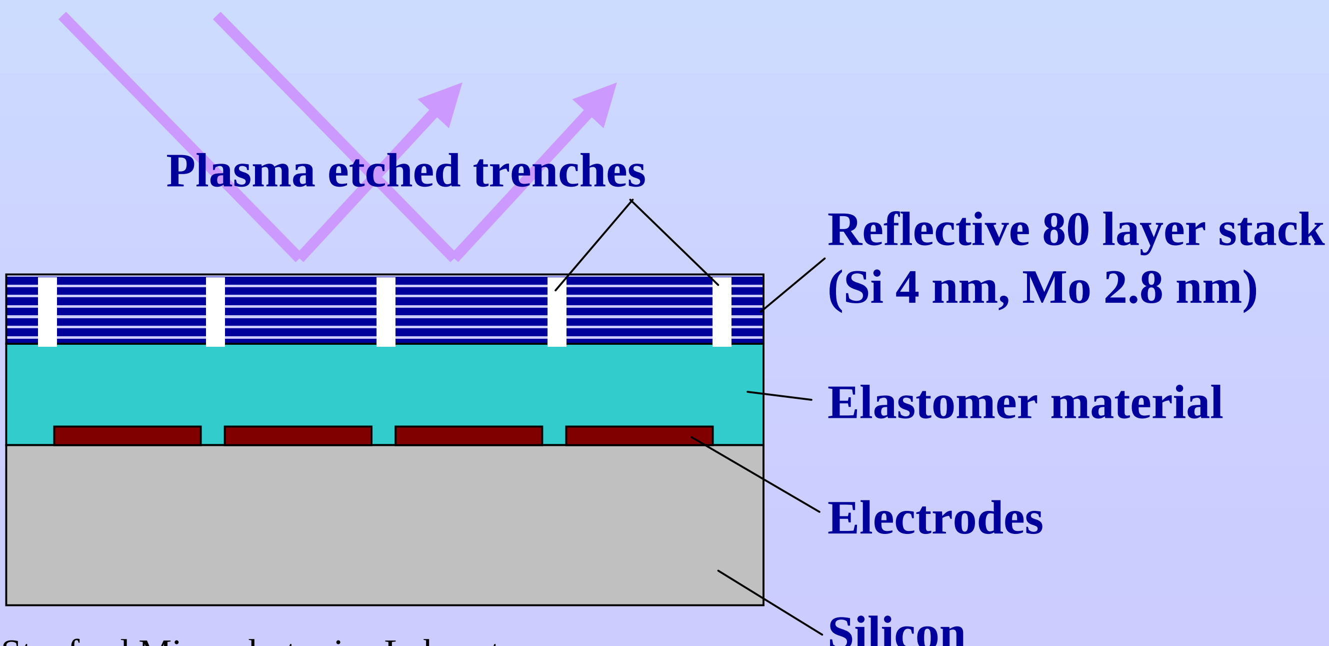
- Etching of Si-struts (load effect compensation)
- Etching of scattering metal (< 200 nm)
- Handling of wafer with 100 nm thin Si_3N_4 membrane

Surface Technology Systems
http://www.stsystems.com/latest_news/high_rate.html



Spatial Light Modulators for EUV Lithography

- Light source at 13 nm wavelength (Extrem Ultra Violet)
- Reflective mask necessary
- Micromirror array for maskless lithography
- Pattern on wafer formed by interference
- Plasma etched trenches to avoid cross-talk



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http://www.stanford.edu/group/SML/

25 nm Oxide etch, AR 30:1

Trikon Technologies
http://www.trikon.com

Conclusions

- Electrostatic combdrives suitable for actuation in MOEMS
- Self-aligned etching process

  $\Rightarrow$ narrow gaps, higher forces, higher reliability

- Vertical sidewalls
- Higher aspect ratio
- Controllable sidewall angle
- Smooth lateral and vertical surfaces
- Uniformity of etch rate / load effect
- Etching of small features
- Etching processes for new (organic) materials
- Handling of wafer with fragile structures