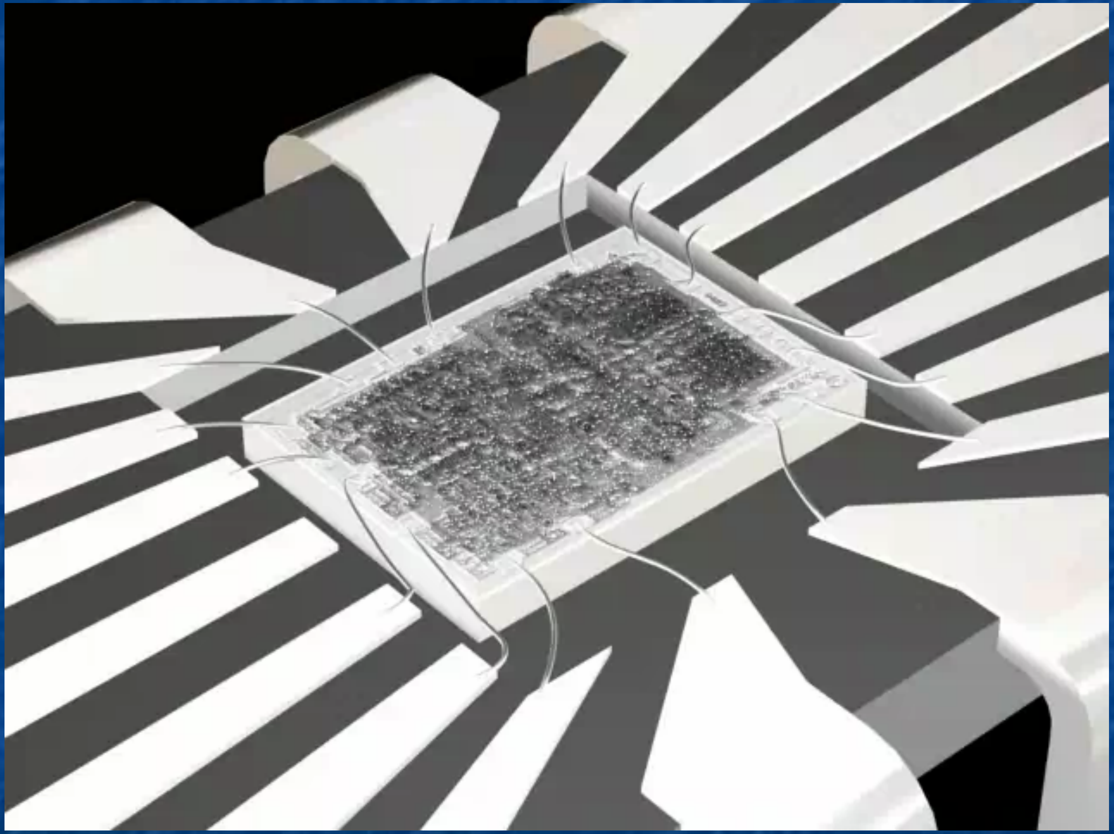
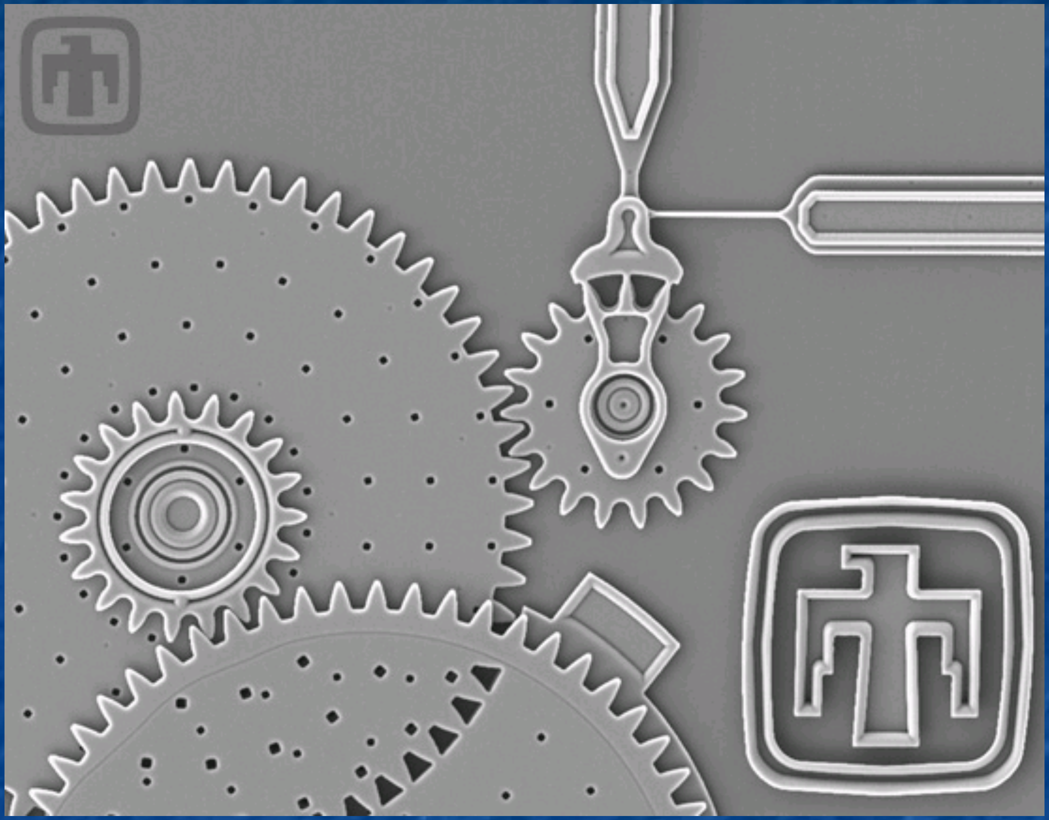
MEMs and Microfabrication

Microfabrication . . . that's how you make integrated circuits, right?

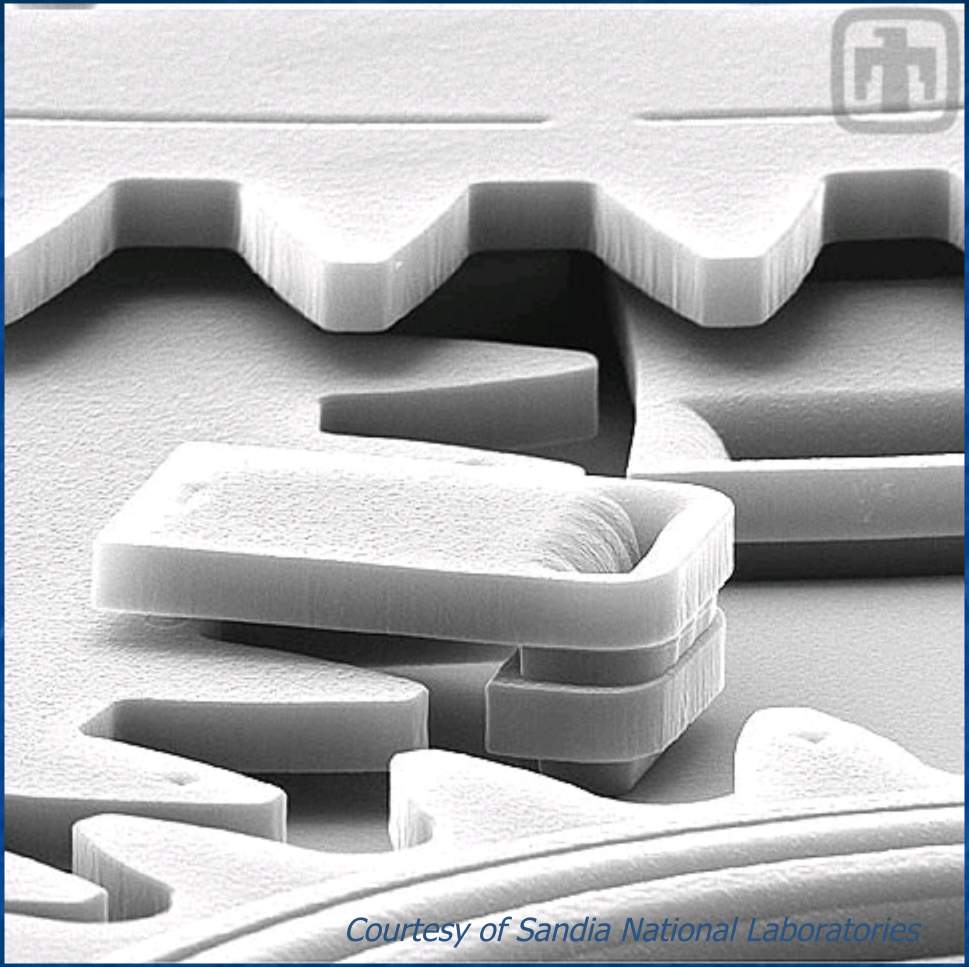


It's now about a lot more, including "Micro-electro-mechanical Systems (MEMS)



Multiple Gear Speed Reduction Unit

This and images to follow are "Courtesy of Sandia National Laboratories, SUMMiTTM Technologies, www.mems.sandia.gov"
Images were found at http://mems.sandia.gov/scripts/images.asp



Alignment Clip

Used in conjunction with a transmission to maintain the alignment of the two layers of gears

This complex device is entirely batch-fabricated, with no assembly required

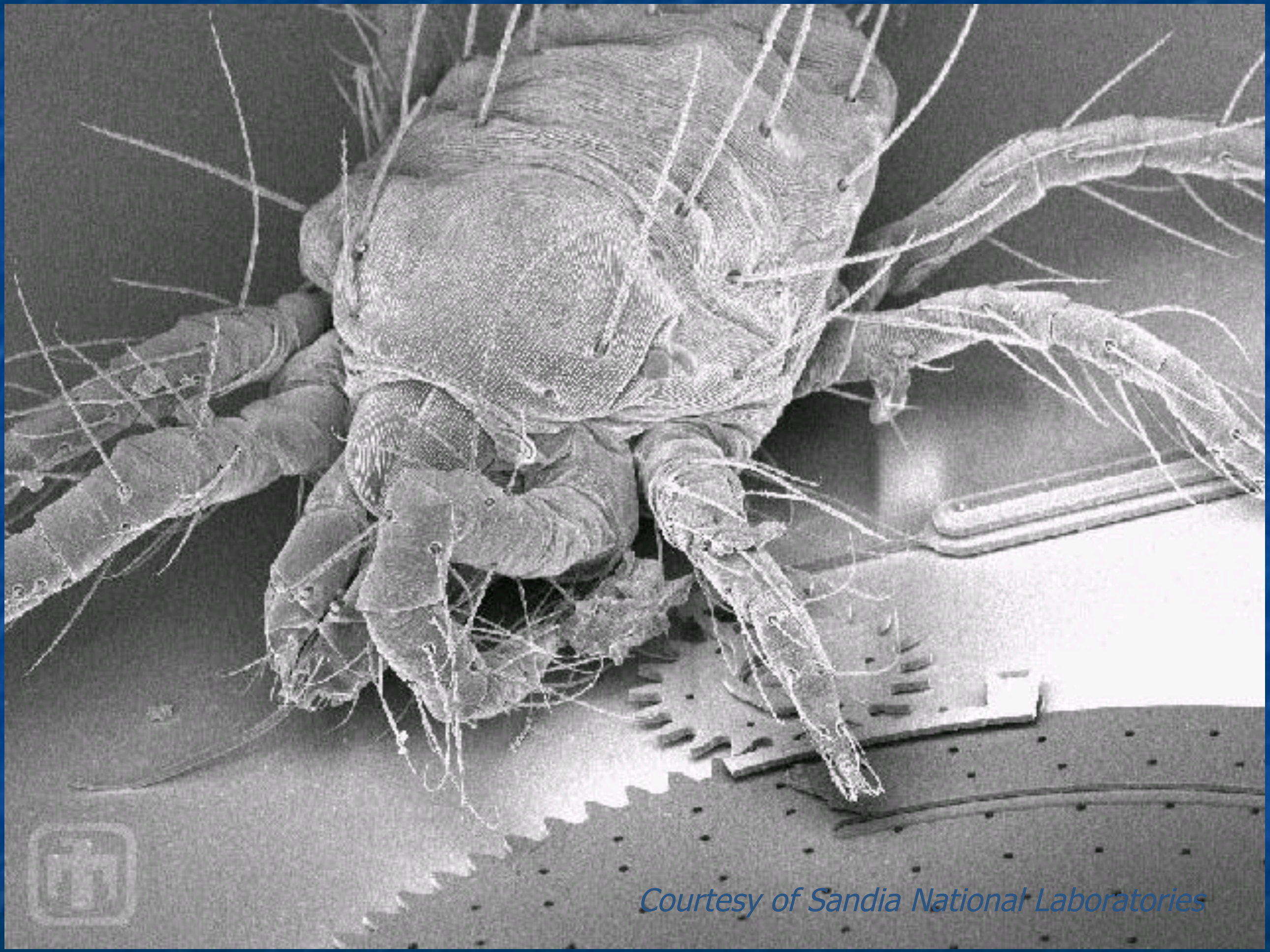
But How Big is This?

Sandia did not include scale markers

I'd guess layers are ~ 0.1 um thick

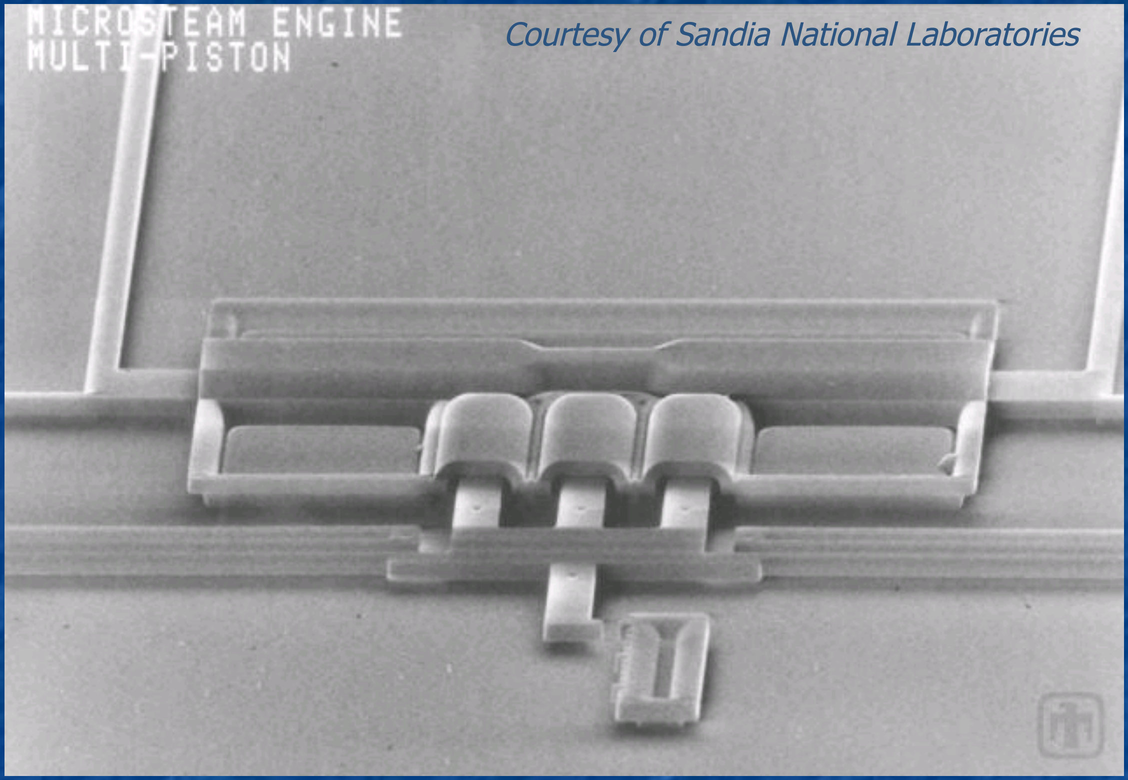
For scale they did include this:

A spider mite:



What else can you make?

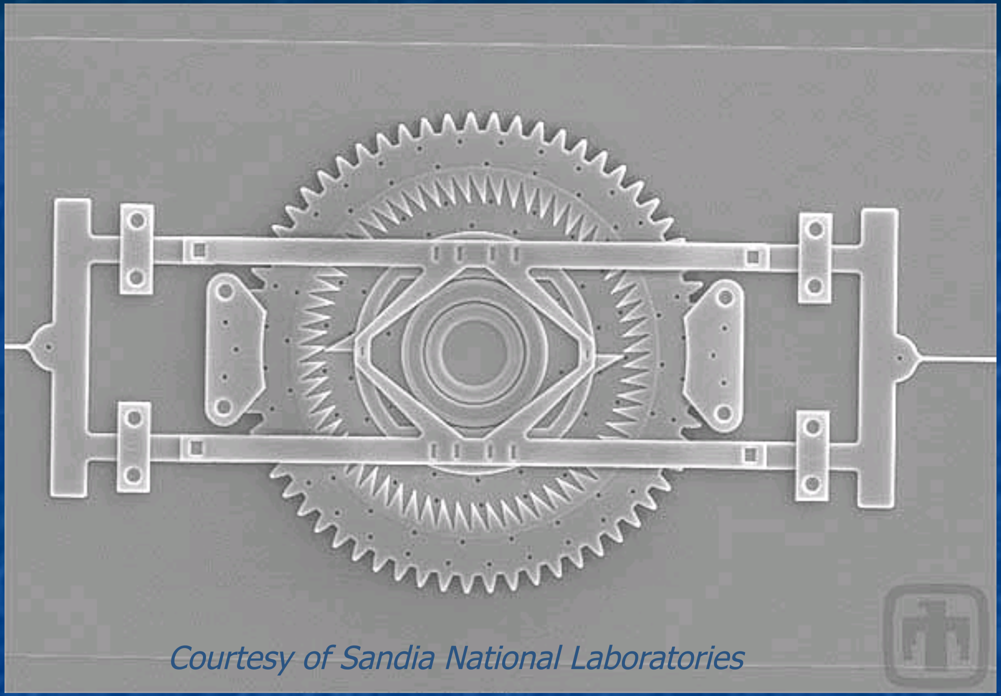
How about a steam engine?

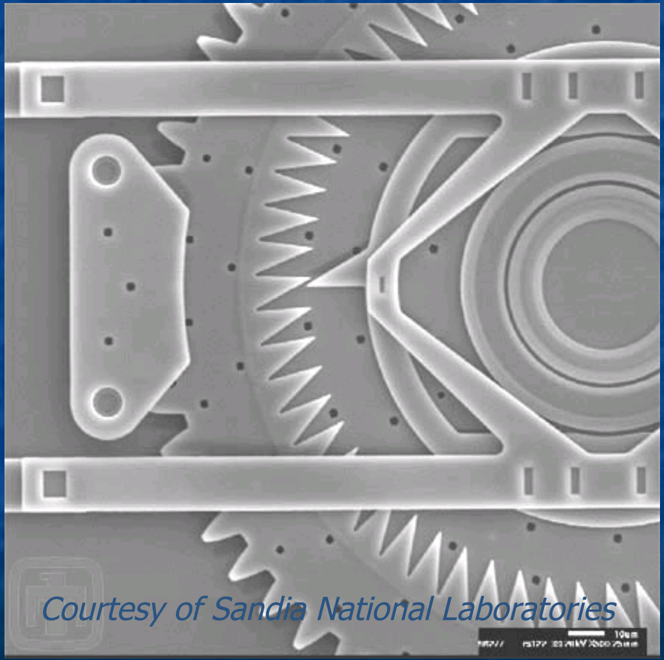


Triple-Piston Microsteam Engine

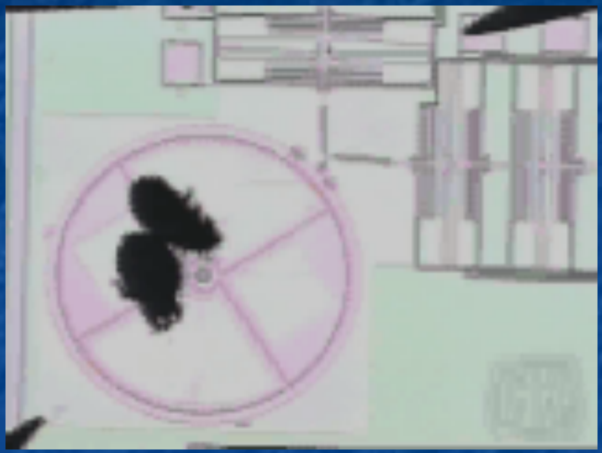
Water inside of three compression cylinders is heated by electric current and vaporizes, pushing the piston out. Capillary forces then retracts the piston once current is removed.

Or a ratchet indexing motor:





Which can be used for . . . revenge!



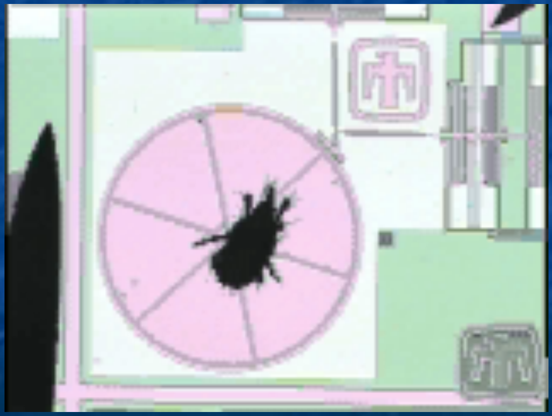
Spider mites helping to demonstrate motor:

Actuator (probably electrostatic) at top

Driving ratchet and pawl on gear

Yielding a "mite go round"

Tne spider mite really giving motor a work out:



Supporting webpage with embedded animations:
[Lecture 4 - Supporting Materials - Animations_1_2]

Courtesy of Sandia National Laboratories

But how is all of this done?

For very good reasons, it is sometimes called "micro-machining"

Classic Machining: 1) Start with big block of metal

2) "Machine" away parts you don't want

Use variety of lathe bits, mills and drills

But all are basically scraping & gouging away material

Micro-machining: 1) Start with Silicon wafer (~ 1/4 mm thick, up to 300 mm diameter)

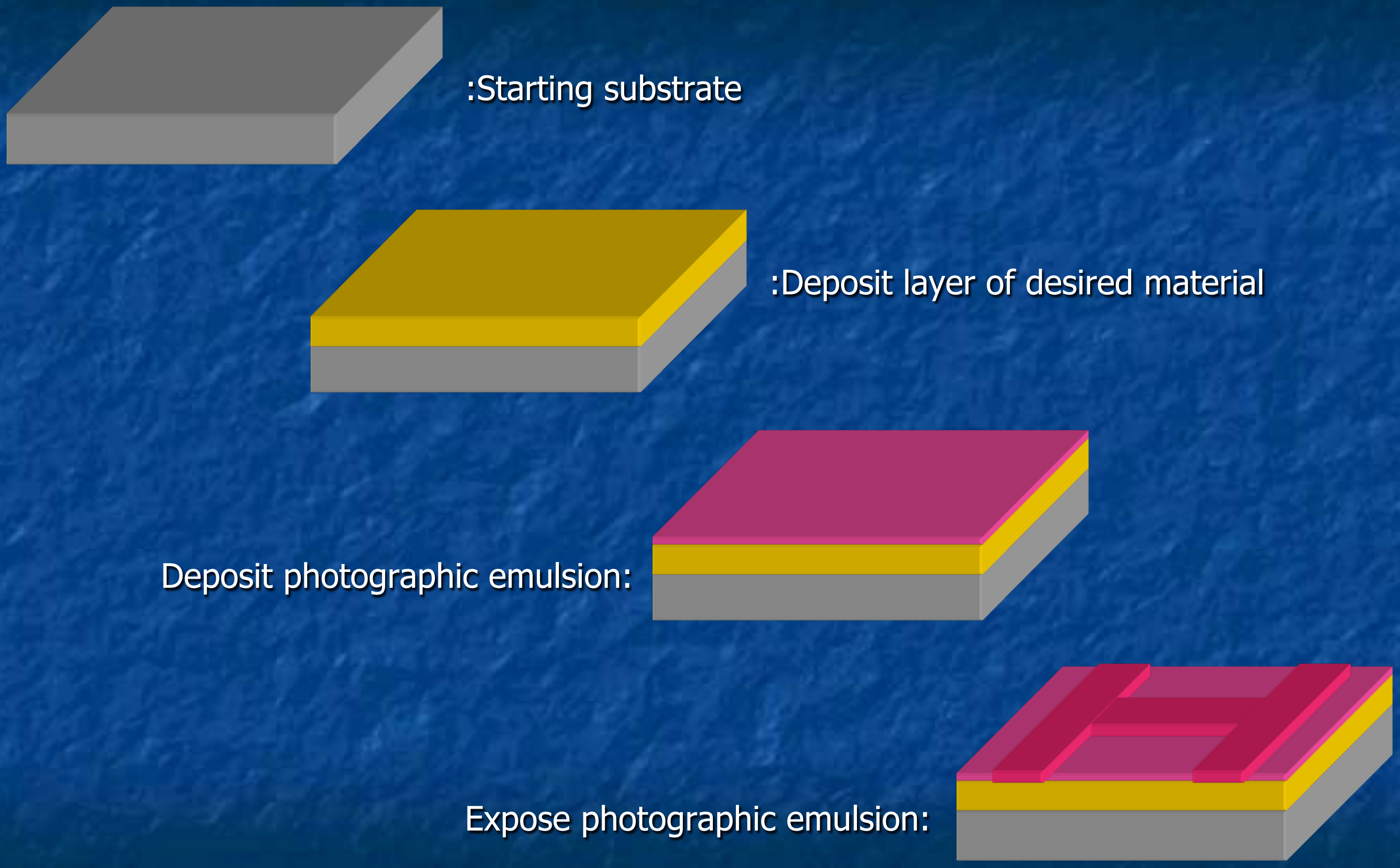
2) Spray on or grow on additional layer

3) Apply, expose, develop pattern in photographic emulsion

4) Etch or blast away material not protected by emulsion

5) Strip off emulsion → Cycle back to step 2

Schematically:



Schematically (cont'd):

:Develop photographic emulsion

Etch desired materal:

Remove photographic emulsion:

After SEVEN steps, finally get desired 3D shape of new material!

BUT CAN DO THIS SIMULTANEOUSLY AT A BILLION DIFFERENT POINTS!!

Or going over that a little more slowly:

Step 1) Start with Silicon wafer

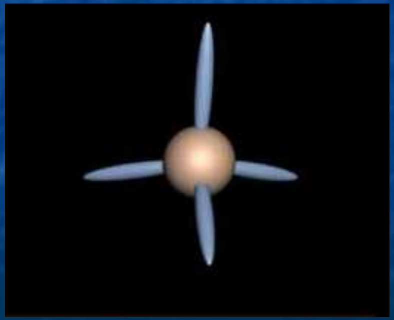
Silicon, element 14 in the periodic table, is known as a semiconductor:

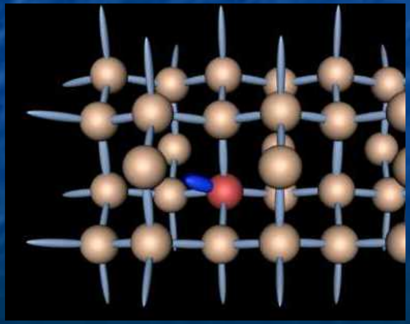
- Insulators: Electrons held so strongly in bonds they can't move around

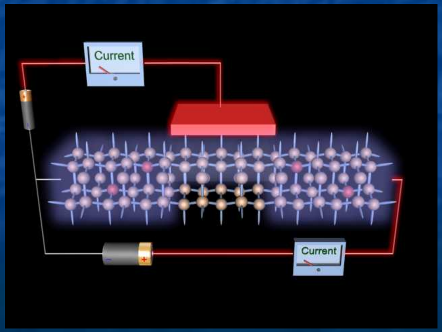
- Conductors (metals): Electron bonds so weak, electrons wander everywhere

- Semiconductor: Electrons can escape bonds (w/ heat)
  or
  Extra non-bonding electrons can be added via impurity atoms

For details see "UVA Virtual Lab" webpage on [How Semiconductors and Transistors Work]







It really isn't electronic properties that make silicon so special:

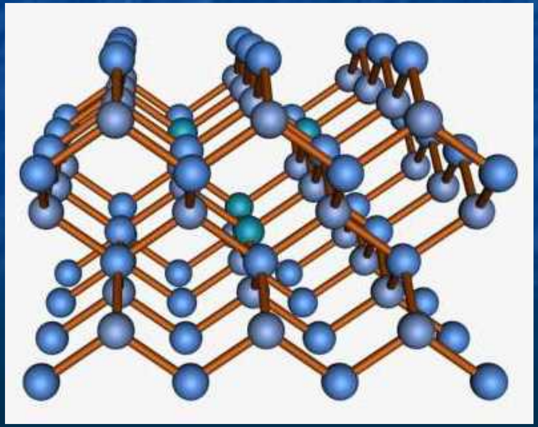
It is incredibly hard and strong!

	Knoop Hardness Index (kg/mm2)
Diamond	7000
Silicon Carbide	2480
Silicon	1150
Stainless Steel	600
Tungsten	485

So, large but thin wafers will not break with handling!

Strong bonds also → High thermal conductivity (carries away dissipated power)

And provides for almost flawless crystals (more about this later):



Step 2) Spray on or grow on additional layer

Alternative i) Spray via evaporation:

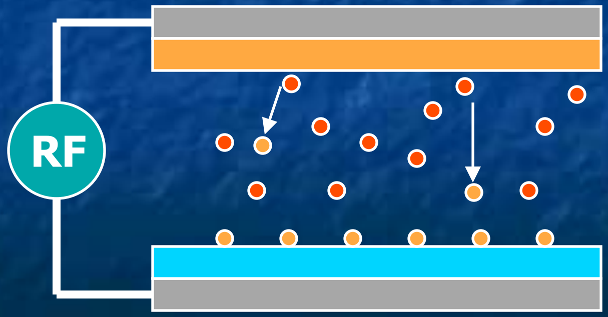
Heat up the material you want to deposit until it starts to fall apart

Do this in a vacuum so that what comes off goes in straight line and doesn't react with anything in-flight

However doesn't work for many materials that don't come apart as compounds

Example SiO_2 (solid) → SiO (vapor) + 1/2 O_2

Alternative ii) Spray via blasting (or "sputtering") - This DOES work with compounds!



Gas is excited, ionized and energized by RF field

It blasts desired material off one plate

To condense on other plate (covered with wafer)

Alternative iii) "Grow" a layer of what you want

Sort of like rusting iron: $2\ Fe + 3/2\ O_2 \rightarrow Fe_2O_3$

Except that where iron oxide is a crumbly porous mess,

Silicon oxide is . . . glass! $Si\ (solid) + 1/2\ O_2\ (gas) \rightarrow SiO_2$

Chemically, glass in incredibly tough

In what do chemists use to store almost ALL of their chemicals?

(Can almost count exceptions on one hand: HF, KOH . . .)

Although brittle, it is mechanically strong: *"fiber-glass" reinforced . . ."*

Can also "Grow" via gas phase chemical reactions:

$SiH_4 + O_2 \rightarrow SiO_2\ (solid) + 2\ H_2$ (Disclaimer: Goes "boom" if don't carefully dilute!!)

And works for other related insulators

$3\ SiH_4 + 4\ NH_4 \rightarrow Si_3N_4\ (solid) + 14\ H_2$

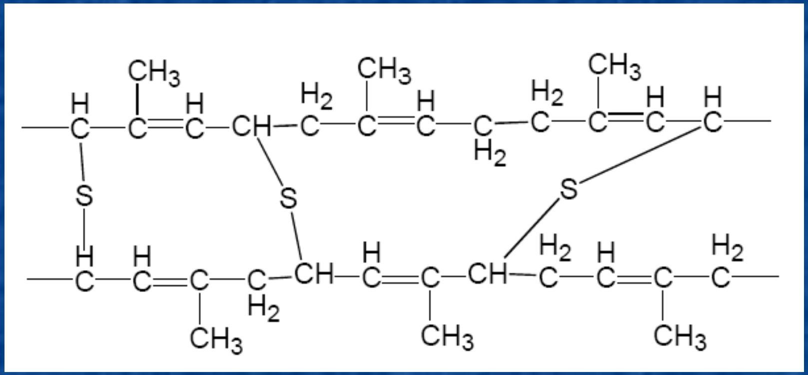
Step 3) Apply, expose, develop pattern in photographic emulsion

Emulsion is also called "resist" because we want it to resist chemical etching

OK, after glass, what is chemist's second choice for chemical container?

(HINT: Advice given to Dustin Hoffman's character in movie The Graduate -1967)

A "cross-linked" polymer (here "vulcanized" rubber)



This and figures to follow are from Professor R. Bruce Darling's superb notes for EE-527 - Microfabrication, at the University of Washington

A link to his class website and cached copies of his class lecture note can be found at:

Lecture 4 - Supporting Materials - Darling

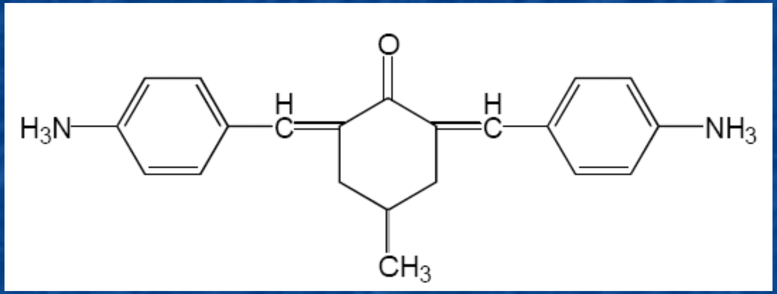
Hydrocarbon monomers (lone carbon-based chains) can be very chemically resistant

Are here held together by the sulfur atoms - But sulfur linking is induced by heat not light!!

So you need different LIGHT stimulated way of linking/unlinking monomers

One way (used in Kodak's KTFR, workhorse of the early integrated circuits):

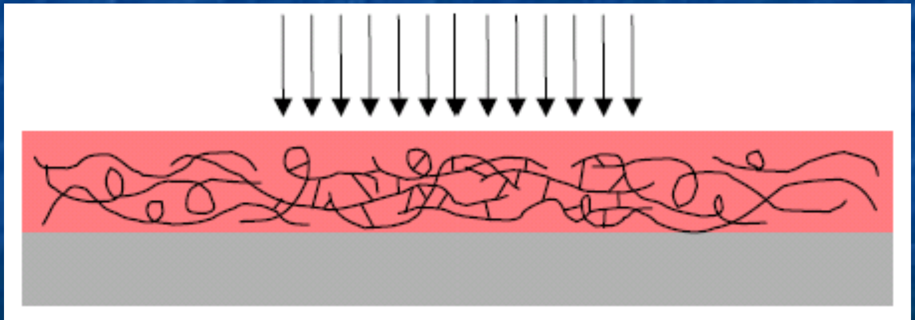
2,6-bis(4-azidobenzal)-4-methylcyclohexanone or just "ABC" (I didn't make this up!)



Source: R. Bruce Darling
University of Washington

Light reacts with "azide" NH_3 end units, converting them to reactive radicals

So that they then bind themselves to the monomers ("cross-linking" them):

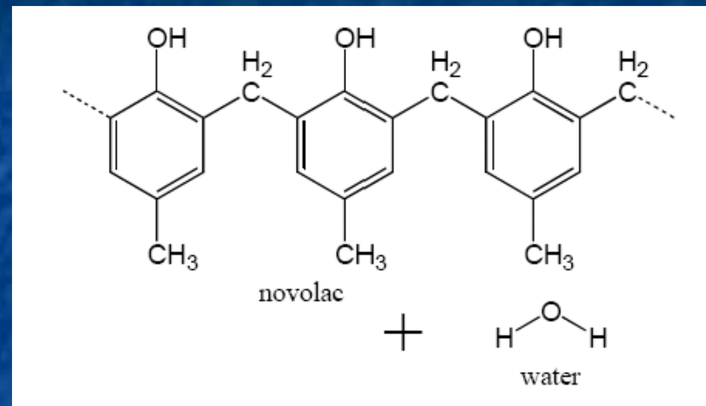


Unlinked | Linked | Unlinked

Source: R. Bruce Darling
University of Washington

Modern "photoresists" use different chemical mixtures and different tricks:

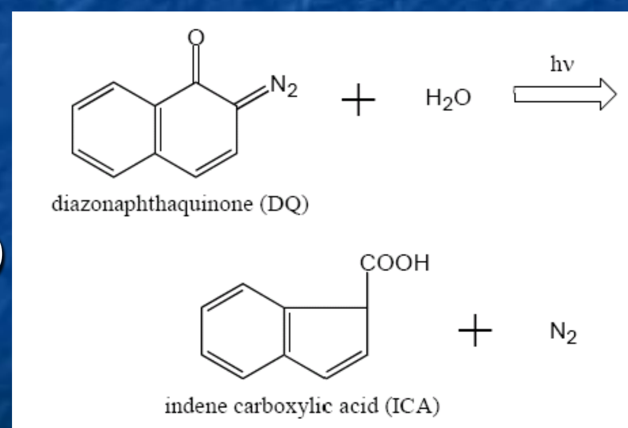
Phenolic "resin" (monomer):



Source: R. Bruce Darling
University of Washington

PLUS photoactive compound (PAC) that light switches from hydrophobic to philic

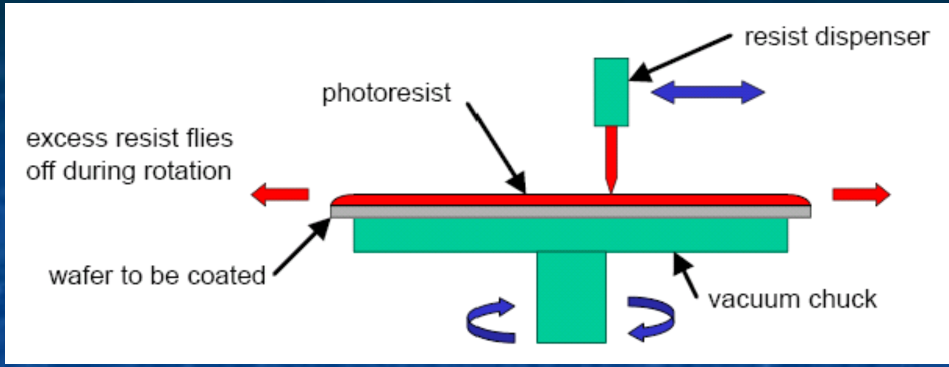
Where not struck by light →
Sheds water-based remover
(and thus everything stays put)



Where hit by light, sucks in
water-based remover
(which removes all)

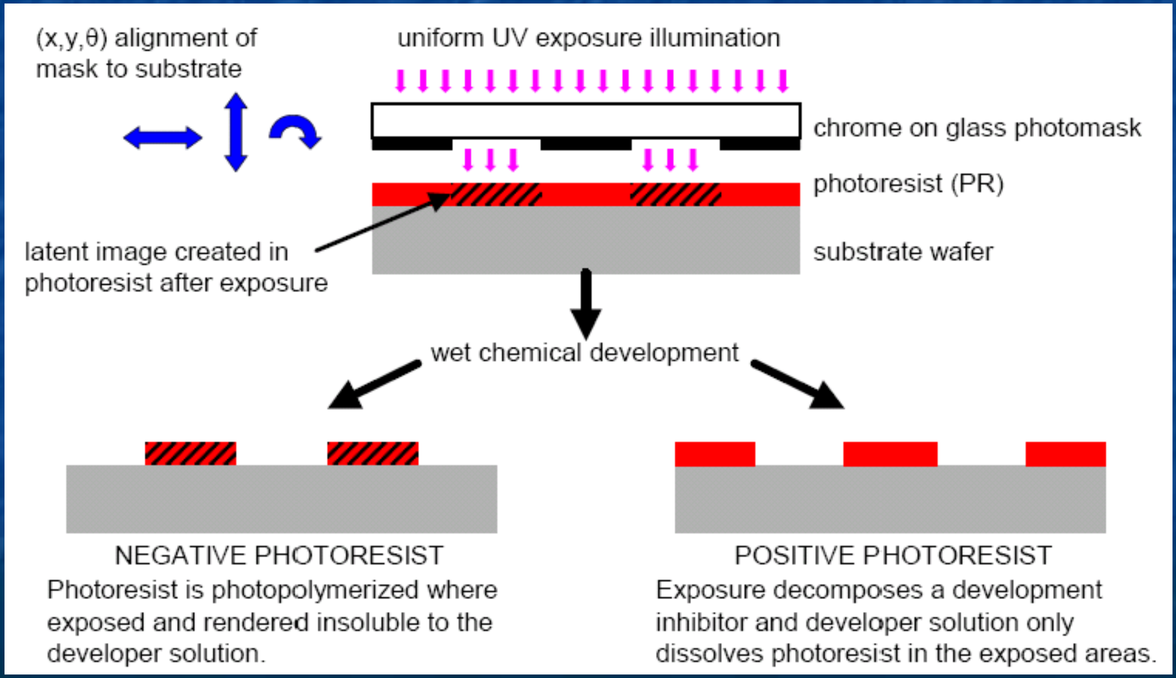
Source: R. Bruce Darling
University of Washington

Apply this "resist" to the wafer by spinning it on:



Source: R. Bruce Darling
University of Washington

Then expose pattern through photographic shadow "mask:"



Source: R. Bruce Darling
University of Washington

Actually done in a tool called a "mask aligner" which (in older non-automated versions):

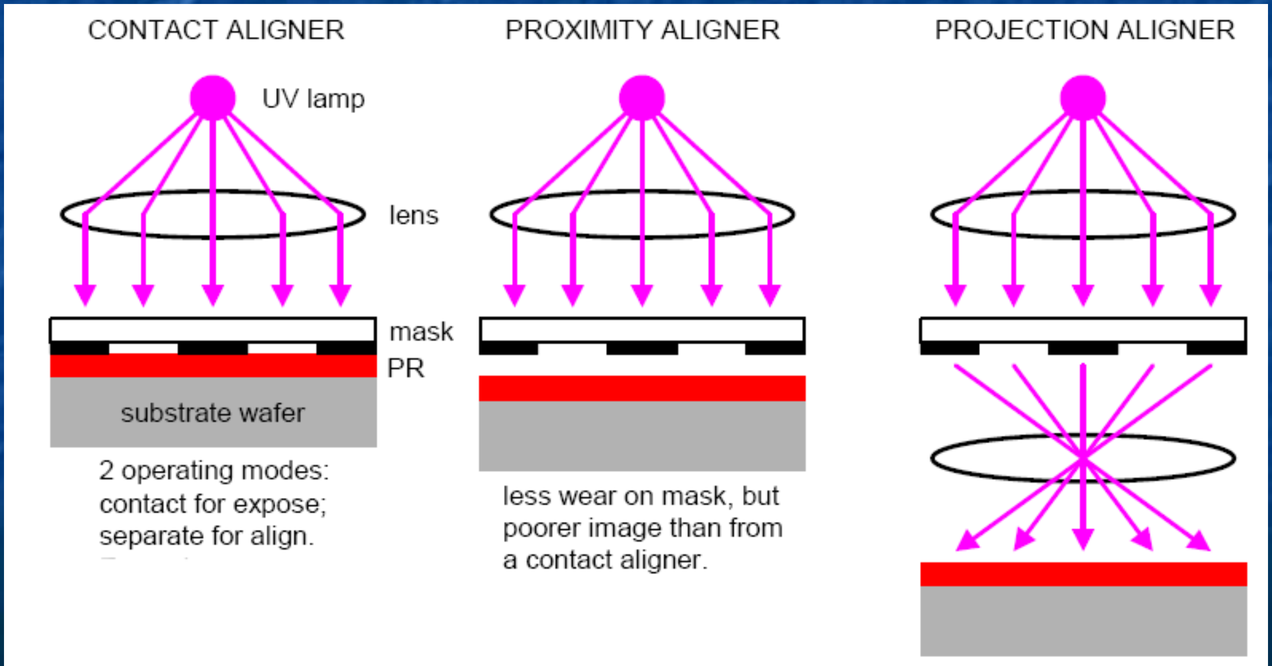
- Uses microscope allowing you to first position the resist covered wafer below the mask

- In "contact" machine, it then clamps resist/wafer tightly against mask

- UV light is then projected down through transparent regions of mask onto resist/wafer

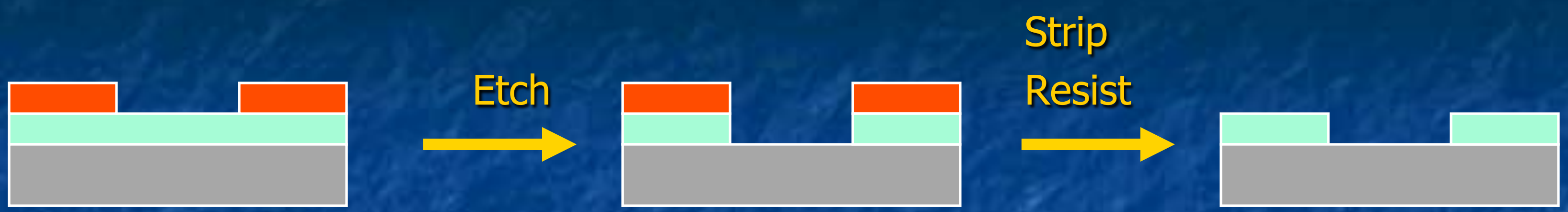
In "projection" machine, shadow image of mask is de-magnified and projected onto resist/wafer at perhaps 1/5 original mask size.

- Wafer is then released, "stepped" to new position, and a new area exposed

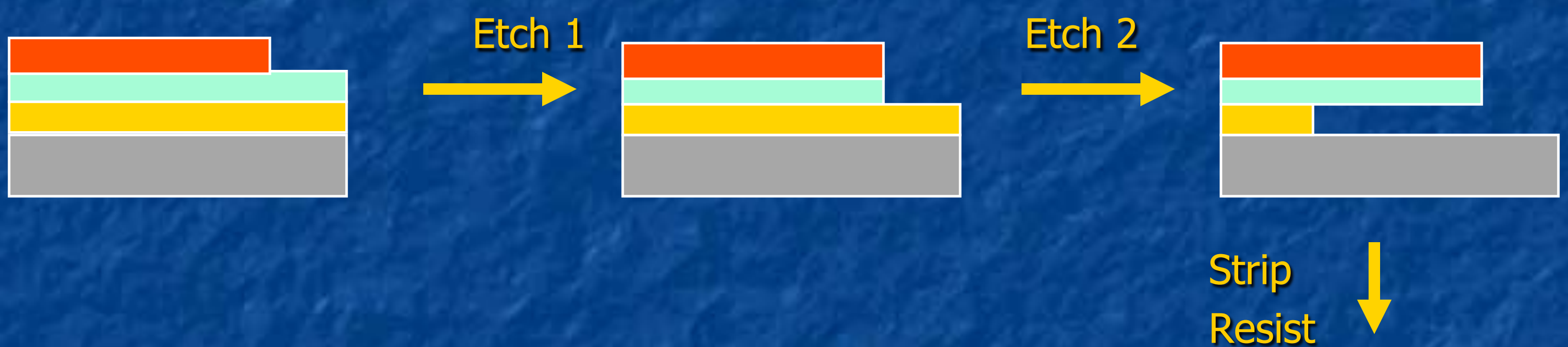


Source: R. Bruce Darling
University of Washington

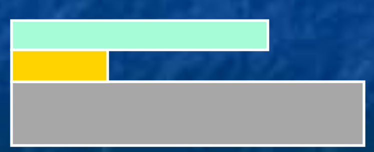
Step 4) Etch or blast away material not protected by emulsion



But can also get fancy and use multiple layers and multiple etches:

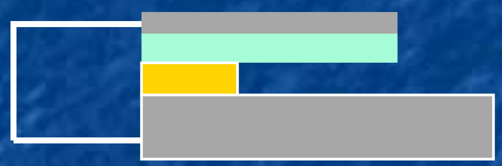


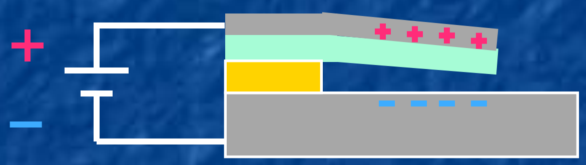
End up with a sort of diving board like structure:



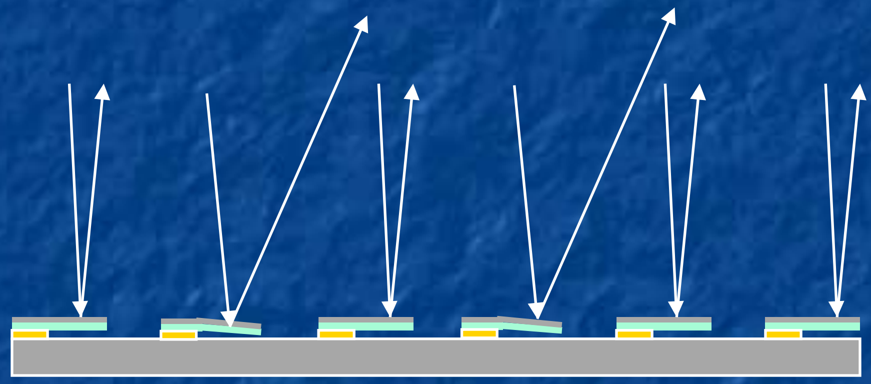
What if "diving board" were metallic (or covered by metal)?

And you then applied suitable voltages:





And tried bouncing a laser off a whole bunch of these:



Remember: all "diving boards" made SIMULTANEOUSLY

What would you get?

Hints: *1) I talked about this technology in lecture 1*

2) We MAY be using it at this very moment

It's the Heart of a "DLP" Projection TV

From the DLP.com / Texas Instruments Website:

Voltage applied at front

Voltage applied at rear:

Supporting webpage with embedded animations:

Lecture 4 - Supporting Materials - Animation 3

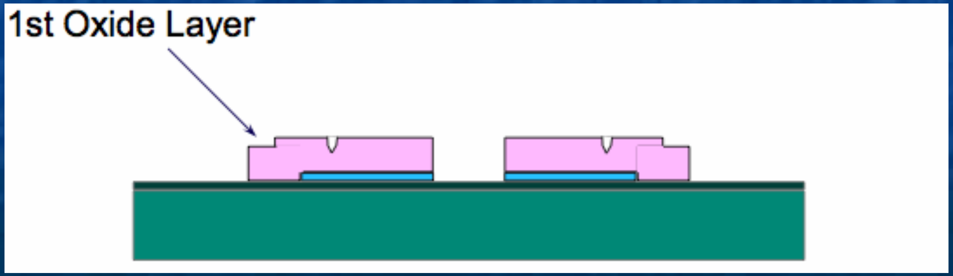
But how did they make those bound yet free-to-rotate gears?

Couldn’t get an answer from Sandia, but did find this in another prof’s lecture notes:

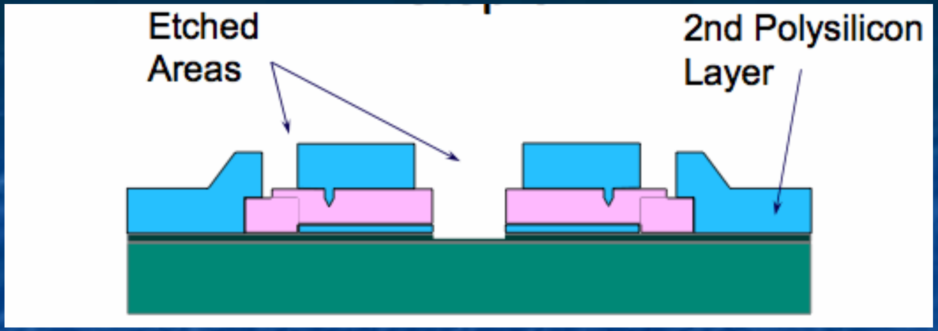
Source: Prof. LaVern Starman, Wright State University
http://www.cs.wright.edu/people/faculty/kxue/mems/MEMS_3FabricationM06.pdf

On a substrate (likely a Si wafer with capping layers) deposit layer of polycrystalline Si (baby blue).
Then deposit and pattern a photoresist layer (red):

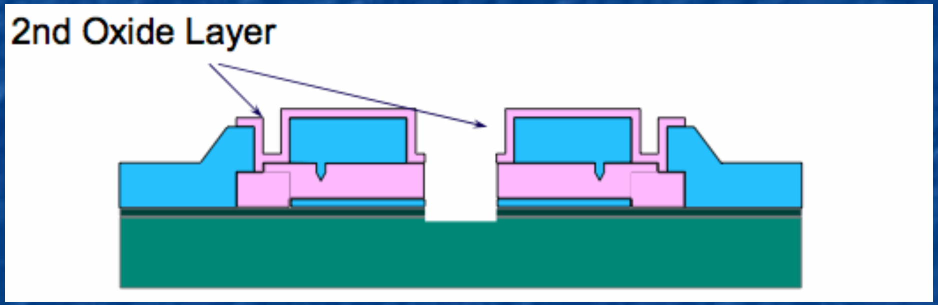
Deposit and pattern a thick oxide layer (pale purple):



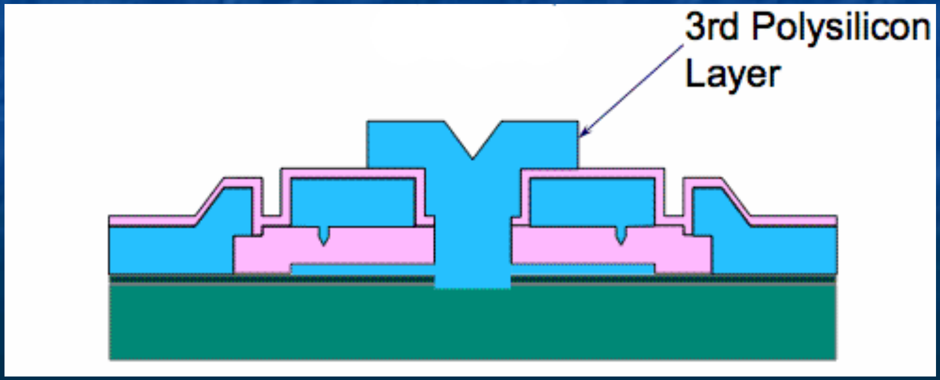
Deposit and pattern a second polysilicon layer (pale blue):



Deposit and pattern a thin oxide layer (pale purple):

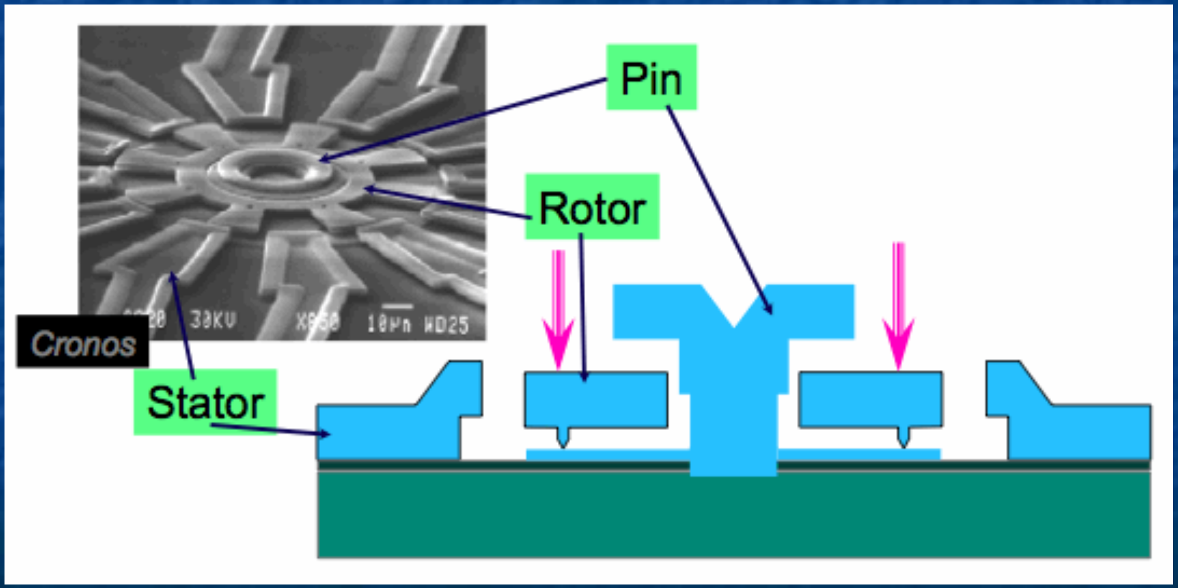


Deposit and pattern a third polysilicon layer (pale blue):

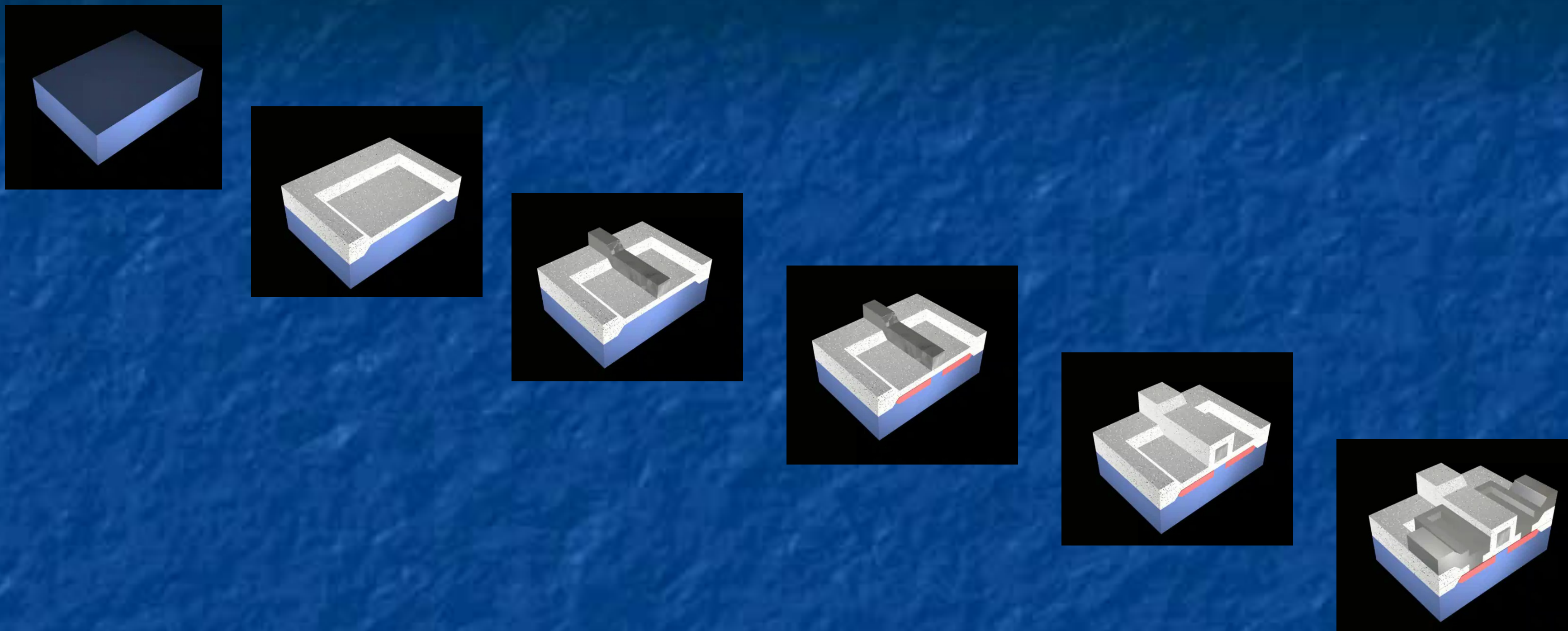


Etch away “sacrificial” oxide layers using hydrofluoric (HF) acid:

Rotating ring then settles onto base yielding final structure of MEMS electric motor:



Or can use to make the transistors of an integrated circuit:



The complete depiction (fourteen 3D animated scenes!) including deposition of all layers, patterning via four photo-masking steps, and etching can be viewed at the “UVA Virtual Lab” webpage on “How Integrated Circuits are Made:”

www.virlab.virginia.edu/VL/IC_process.htm

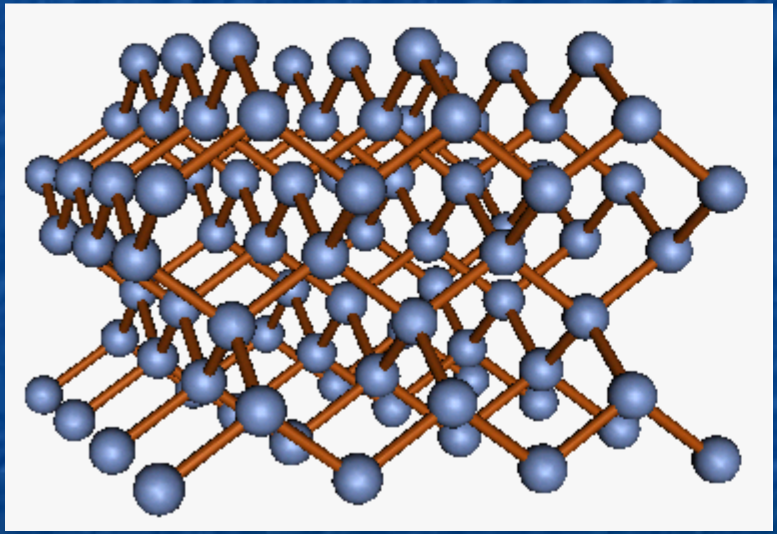
To complete Microfabrication's bag of tricks, need one more thing:

"Anisotropic Etching"

By default, etches (liquid or gas) tend to etch at ~ same rate in any direction

But, Crystals + Very Special Etches → Direction dependent (anisotropic) etching

Depends on exact form of atoms at crystal's (e.g. silicon) surface:



Look closely at the top surface of this Si crystal

EVERY atom on this top plane has TWO bonds to TWO atoms in plane below

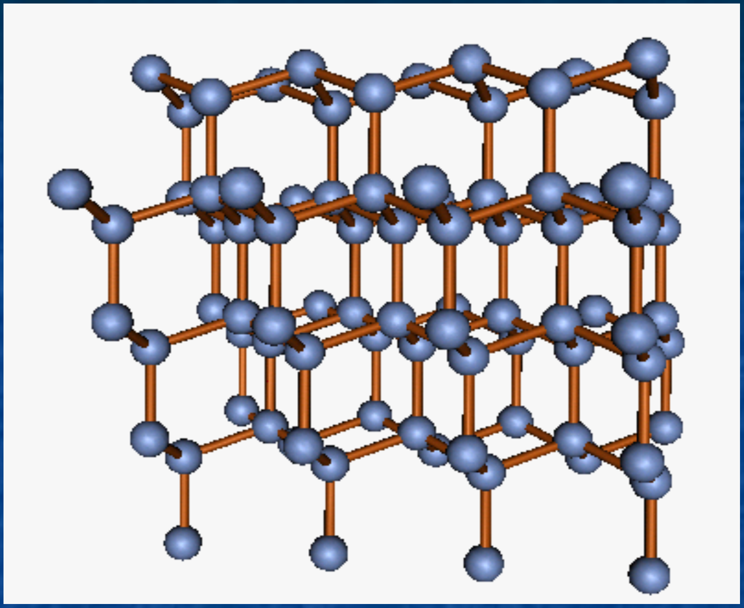
As EVERY atom in second plane is also bonded with two bonds to two atoms below it

This surface is called a (100) crystal surface

From "UVA Virtual Lab" webpage on "Semiconductor Crystals:

www.virlab.virginia.edu/VL/Semiconductor_crystals.htm

Compare to different face of SAME (Si) crystal:



EVERY atom in topmost plane has THREE bonds to THREE atoms in plane below

EVERY atom in next plane has ONE bond to ONE atom in plane below it

This surface is called a "(111)" crystal surface

To remove atom from surface of PREVIOUS crystal, must always break 2 bonds

To remove atom from surface of THIS crystal, alternate breaking 3 bonds then 1

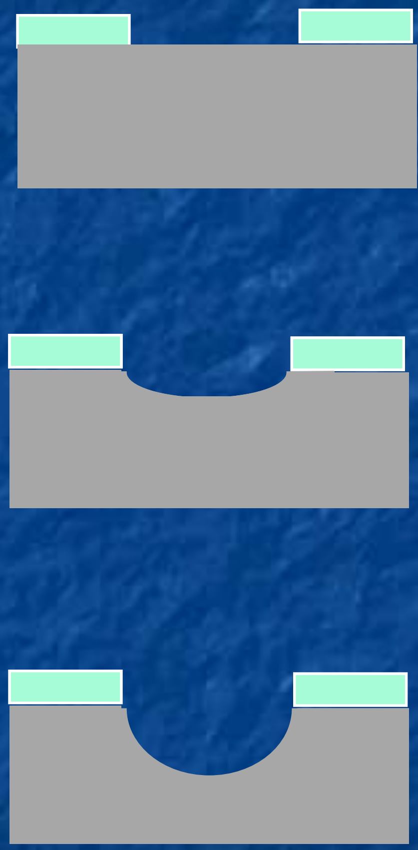
1 bond = easy to break

2 bonds = harder to break

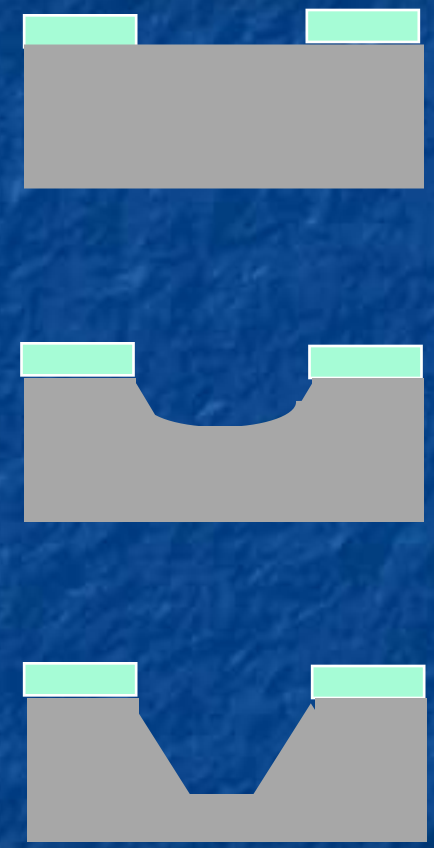
3 bond = very hard to break *Etch can come to a complete stop on "(111)" !!!*

Normal vs. Anisotropic Etch:

Normal (isotropic):



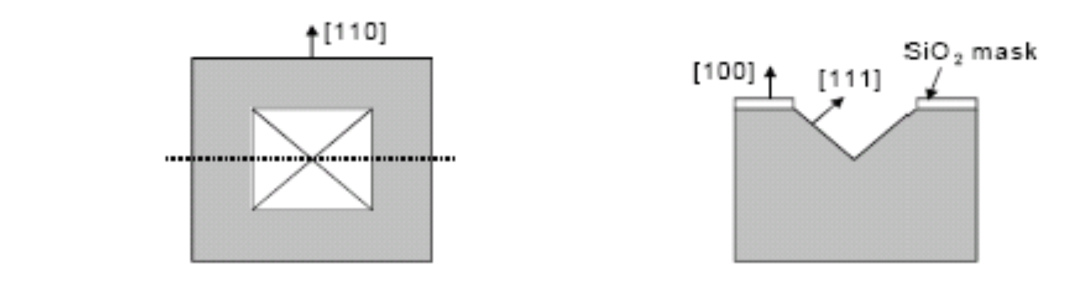
Anisotropic:



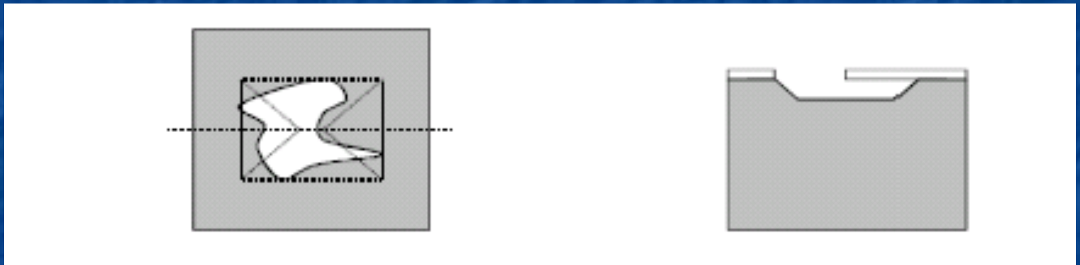
Anisotropic etched surface develops (111) facets !!!

And this opens a very wide door:

Start with square hole in masking layer → Pyramidal pit in silicon



But start with irregularly mask hole and STILL etch silicon toward pyramidal pit



Chews up random surfaces quickly, then collides with (111) surface planes!

Figures again from Professor R. Bruce Darling's Microfabrication Notes - University of Washington http://www.ee.washington.edu/research/microtech/cam/PROCESSES/NEWtutorial.html

Or to make (nearly) free-standing structures:

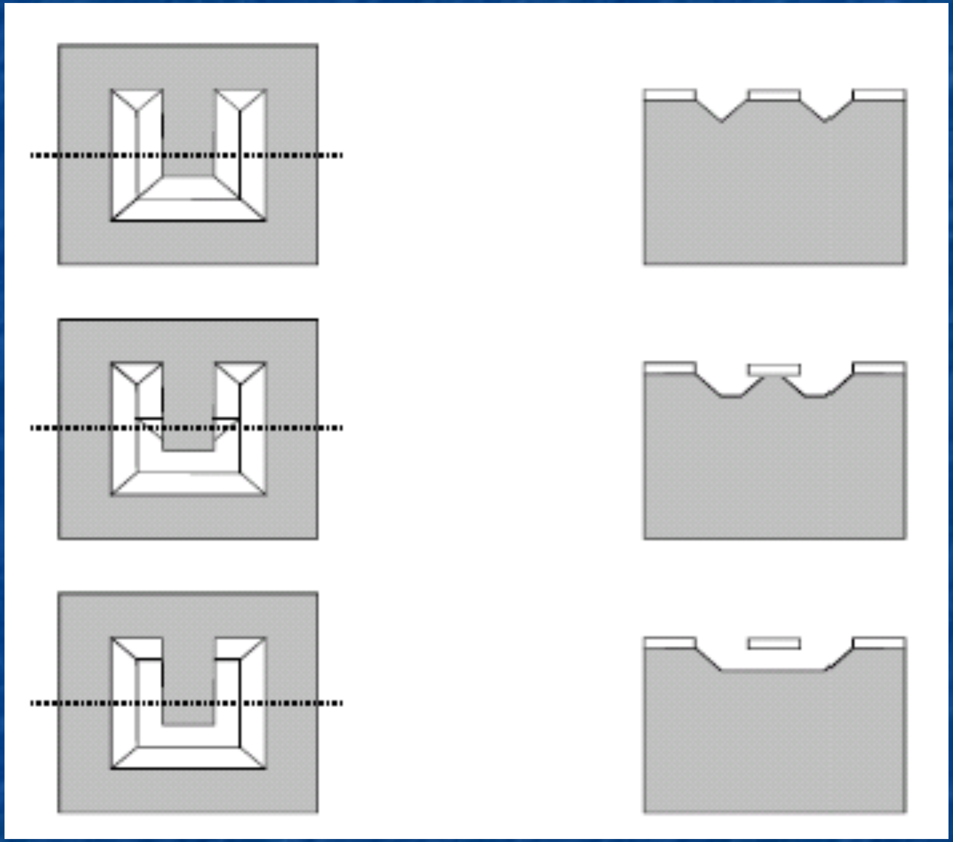
Start with "U" shaped hole in masking layer:

First - Faceted trench in Si

Trenches begin to undercut mask

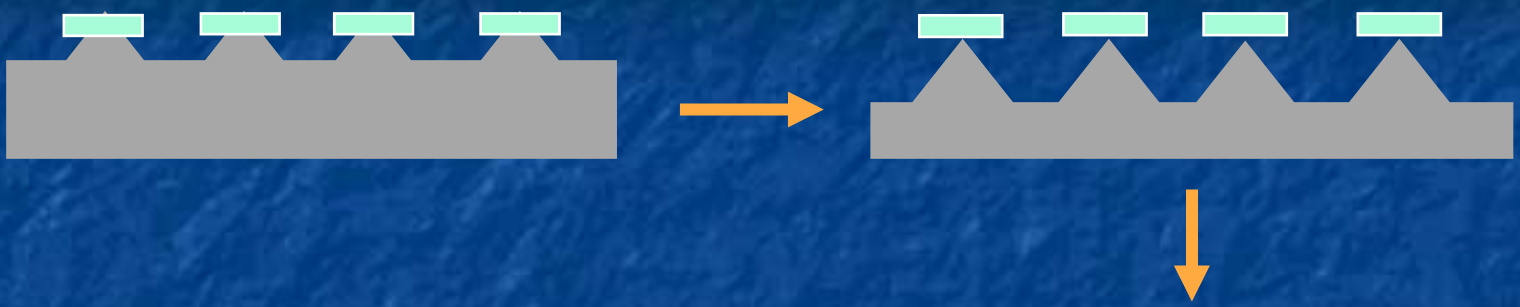
Finally part of mask left free-standing

Diving board over swimming pool!



Source: R. Bruce Darling
University of Washington

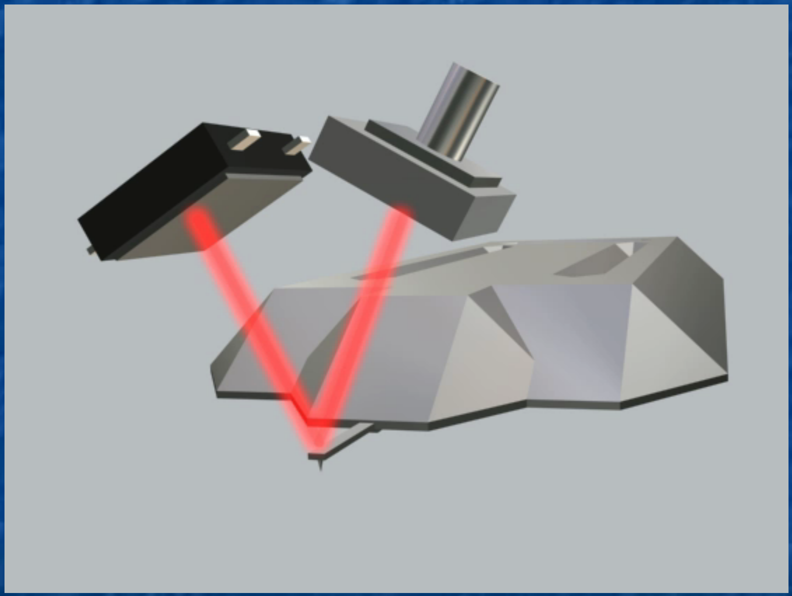
Or if leave islands of masking layer on top of the silicon:



Yielding almost atomically sharp Si cantilever assemblies YOU will use with this class's Atomic Force Microscopes !!

Entire object at bottom is "micro-machined" from single piece of silicon

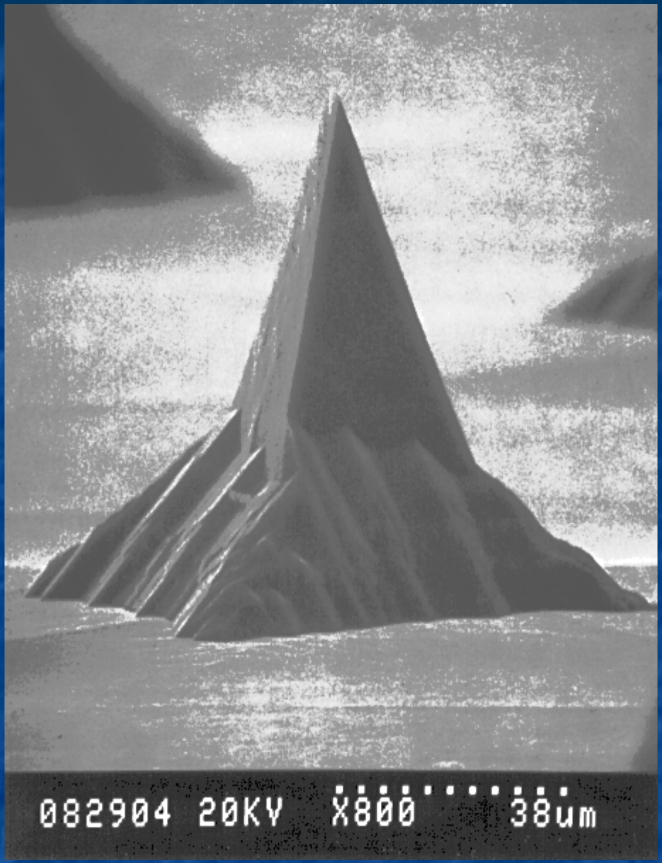
Its' hugely exaggerated in size, largest dimension actually ~ 3mm



From UVA "Virtual Lab" webpage on "Atomic Force Microscope"

www.virlab.virginia.edu/VL/easyScan_AFM.htm

Or similar techniques used by Prof. Michael Reed here at UVA to make:



He sticks these things inside people!

(to repair arteries, stitch tissue together . . .)

All of these tricks and capabilities make Microfabrication:

An incredibly powerful precursor to nanotechnology

Cheap fast way of *simultaneously* making BILLIONS of micro things

Not something that will be easily surpassed!!

Probably an essential tool in inducing nanoscale self-assembly (later classes)

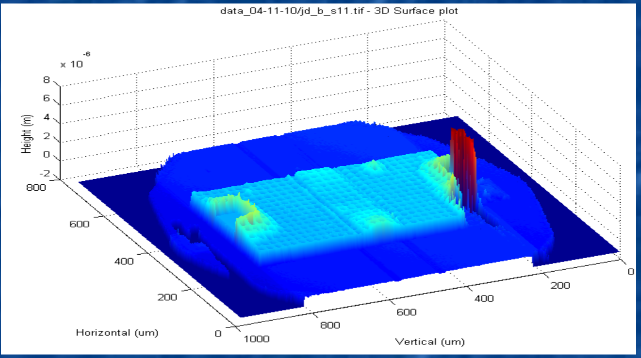
Likely an ultimate partner *with* nanotechnology

as future devices combine both technologies, one atop another,

exploiting what each does best

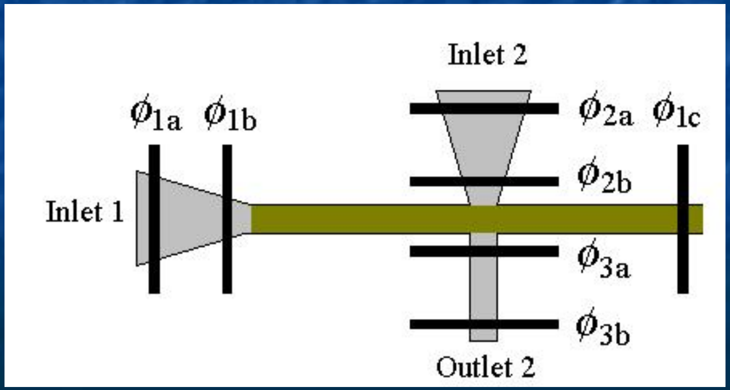
Carleton Micro-Systems Technology Research

RF MEMS

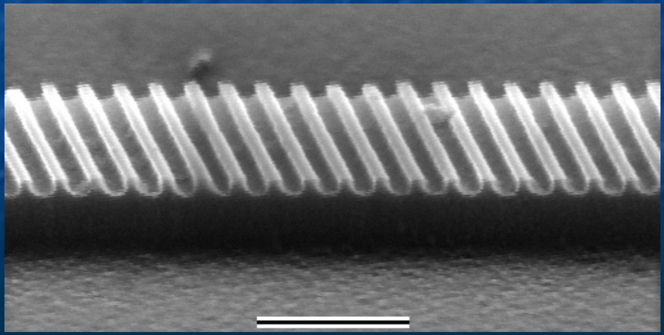


Sensors

Microfluidics

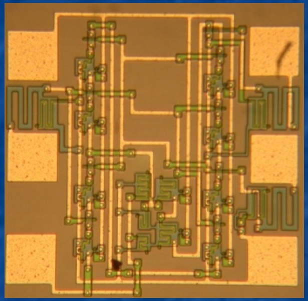


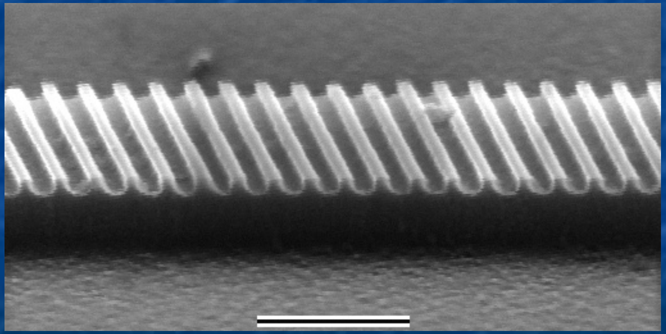
Photonics

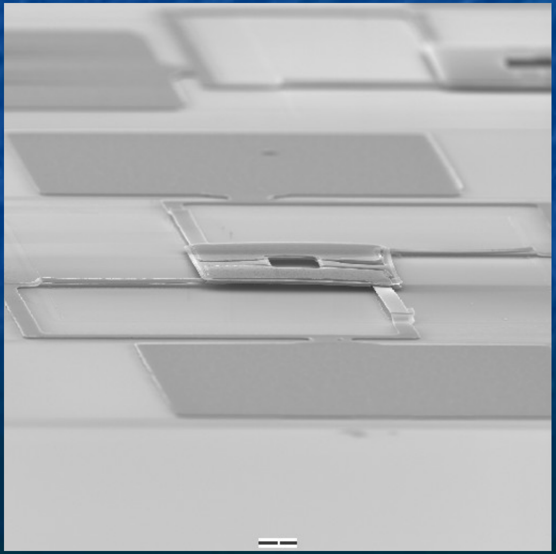


Carleton
Fabrication Infrastructure

- Complete facility for fabrication of silicon devices and small prototype IC’s.
- Emphasis on CMOS, but open for other uses including MEMS and photonics.
- E-beam direct write capability tested to 0.1μm.
- ECR gate etching with cryogenic substrate cooling.
- RTCVD of SiGe alloy.

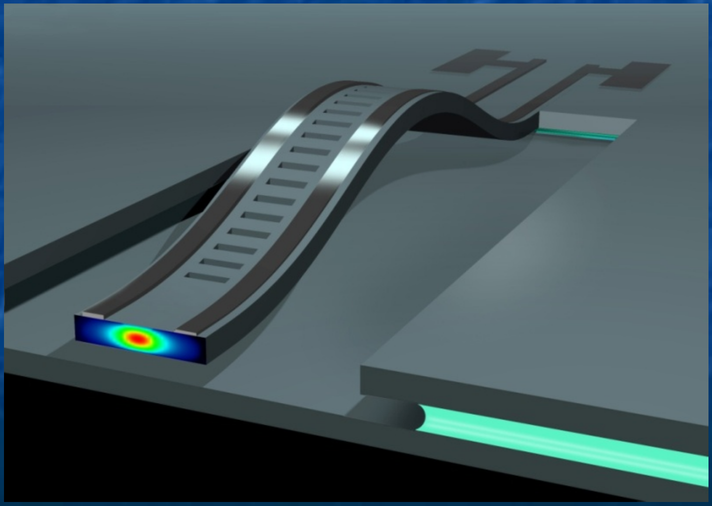


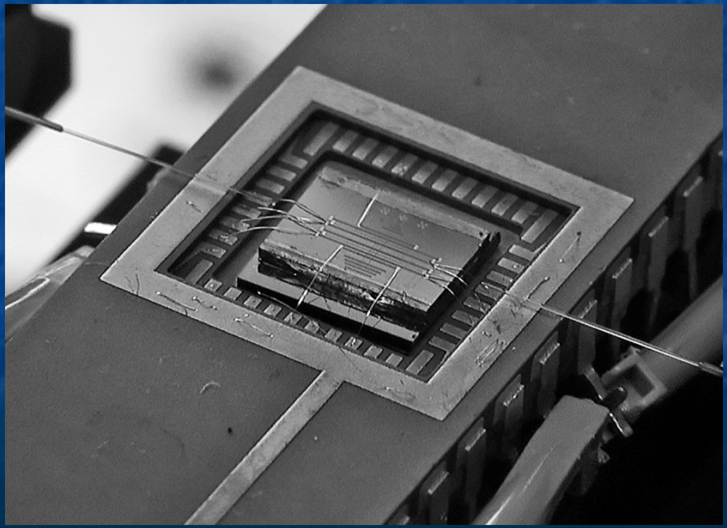




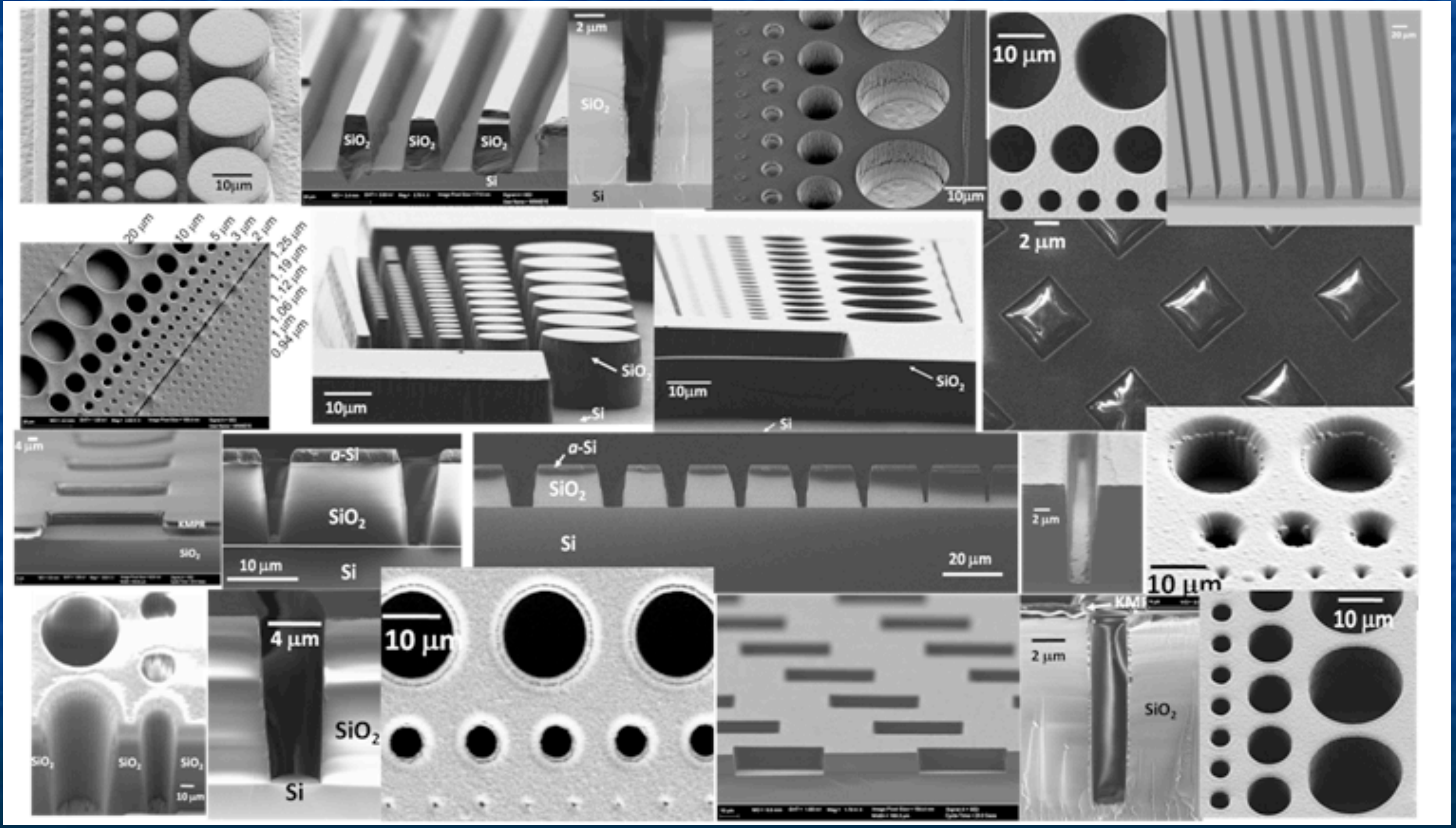
Photonics

- SOI rib waveguide suspended Bragg grating filter tuned by thermal actuation through the buckling transition.

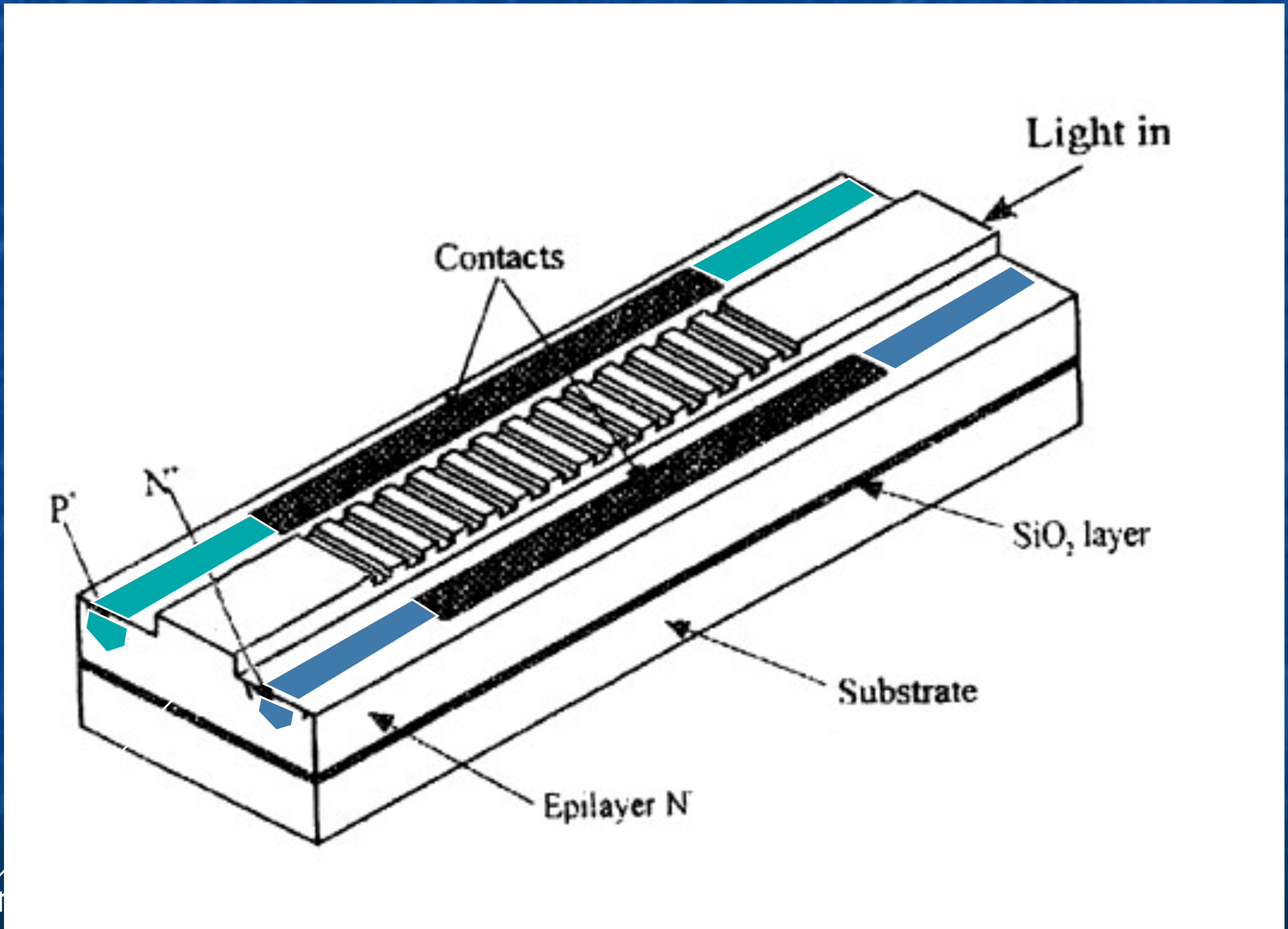




Photonics (light) and Nano – Prof. Winnie Yee



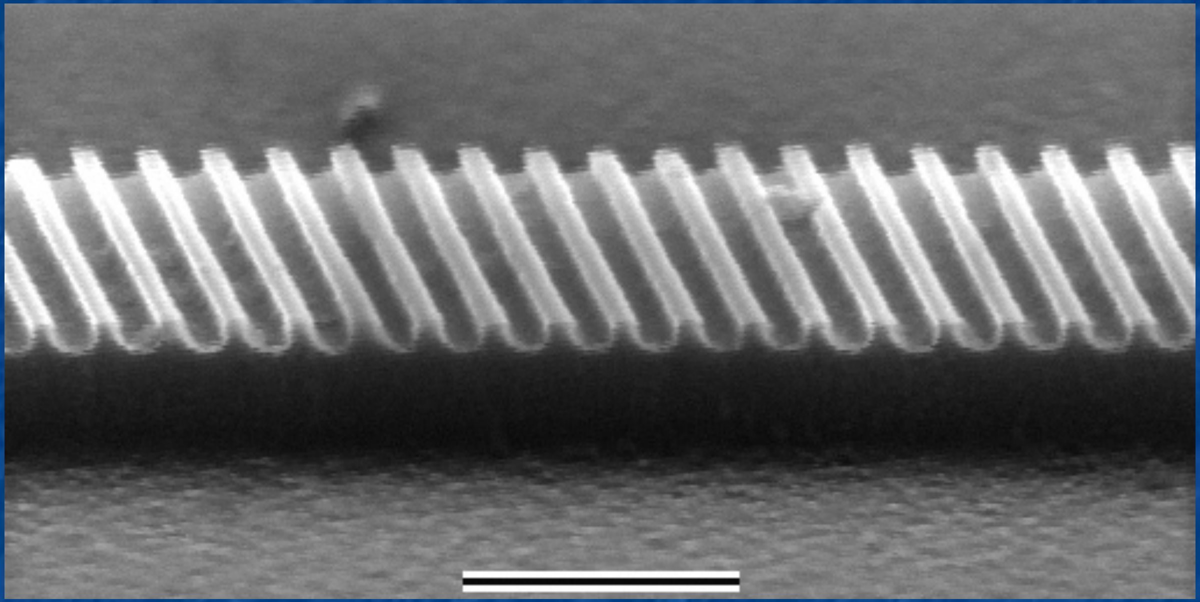
Bragg Filter



intr

A. Cutolo, M. Iodice, A. Irace, P. Spirito, L. Zeni (1997)

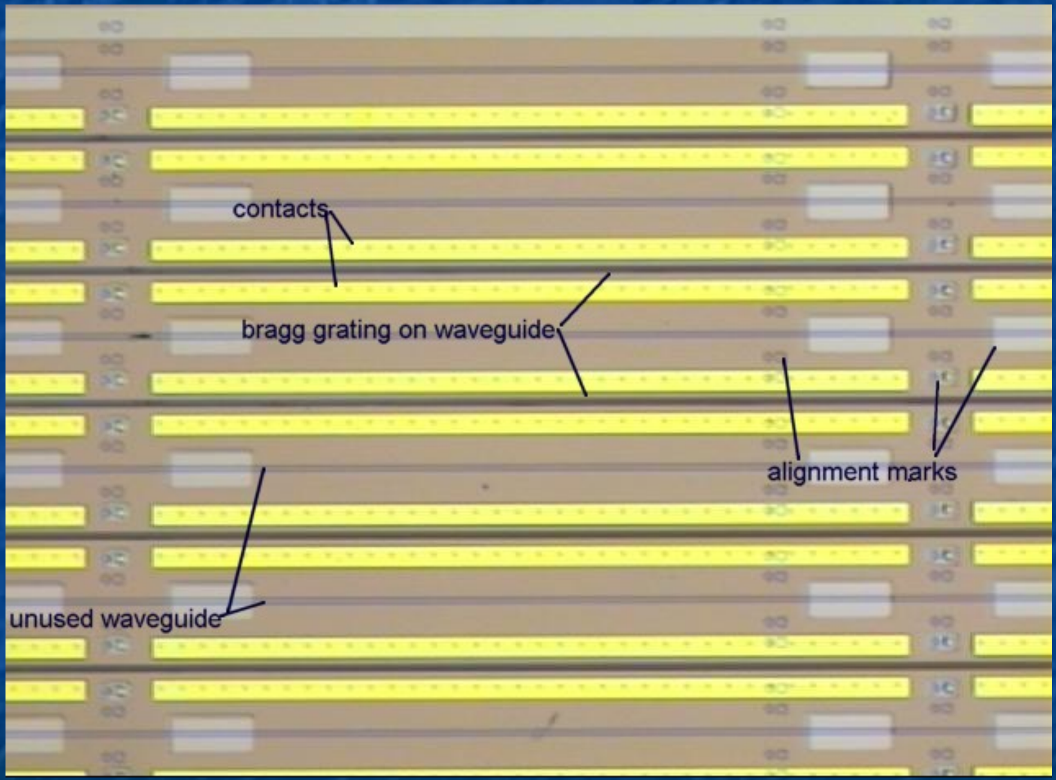
Bragg Filter: Grating



1 um

Final grating before the diode fabrication

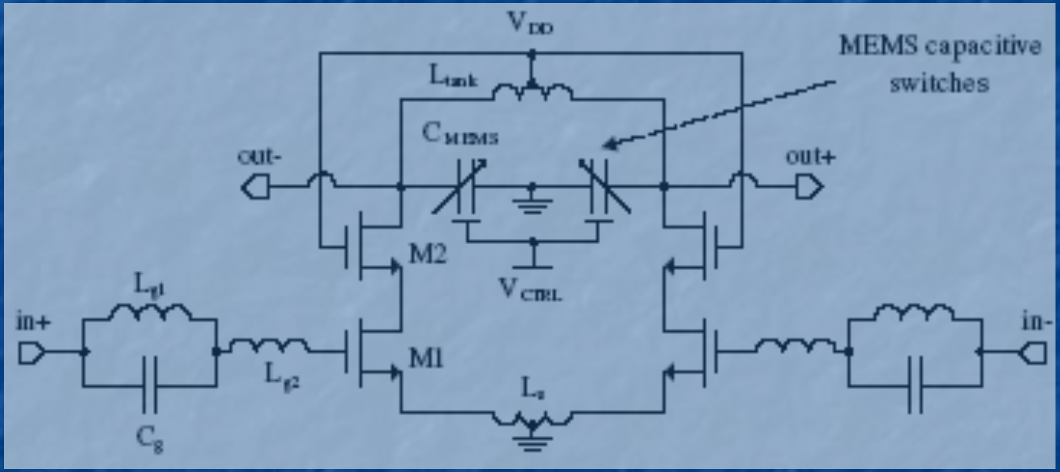
Bragg Filter: Wafer

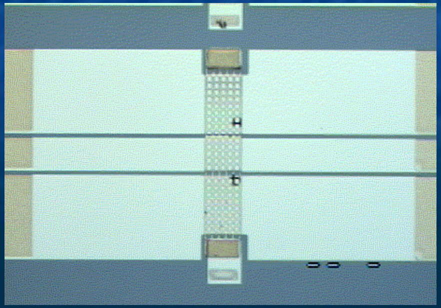


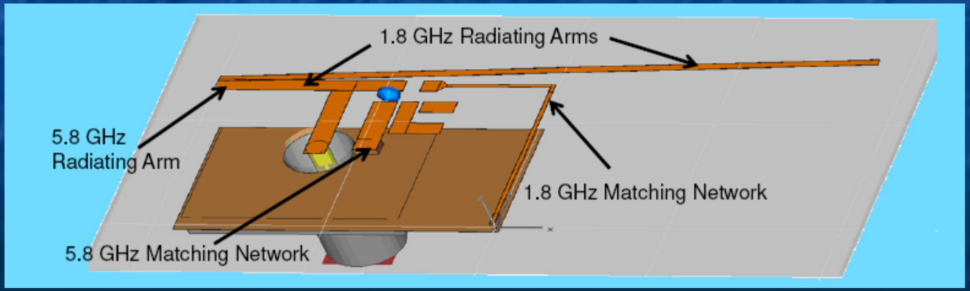
Top view of wafer before metallization

RF MEMS

- Capacitive switch technology (CPW)

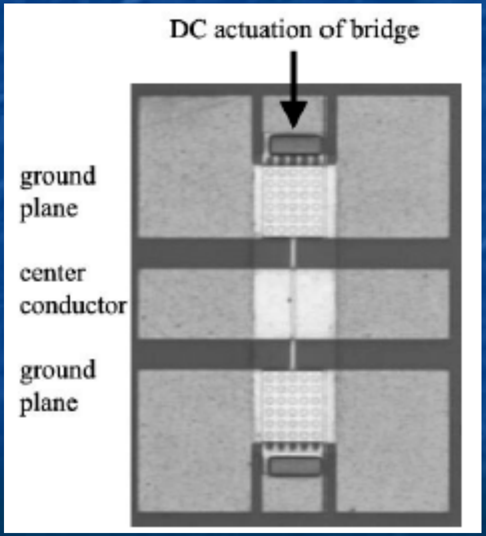






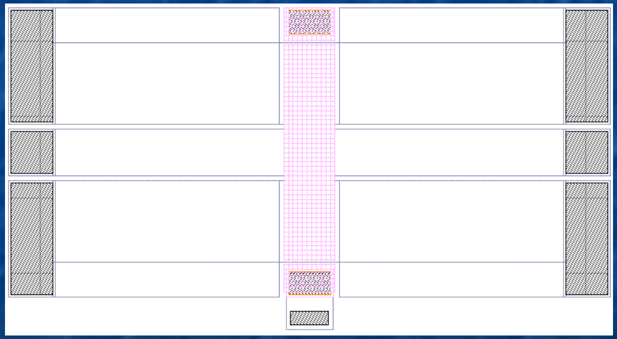
Carleton RF MEMS – Prof. Niall Tait

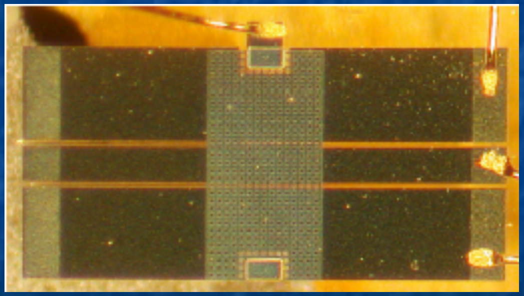
- Carleton brings together experts in thin film materials, custom MEMS fabrication, RF circuit design, and microwave design.
- MEMS switches can operate from DC to >100 GHz, and enable circuit research in a variety of applications.
- RF(CMOS) circuit design
  - RF MEMS switch (J. Danson, Prof. C. Plett)
    - band switching low noise amplifier
    - tunable match power amplifier
  - Thin film bulk acoustic resonator
    - RF filter
- Microwave circuit design
  - MEMS microwave switch
    (J. Rose, M. Mariani, Prof. L. Roy)
    - Tunable coplanar waveguide filter



MEMS Switch
Design for an LNA

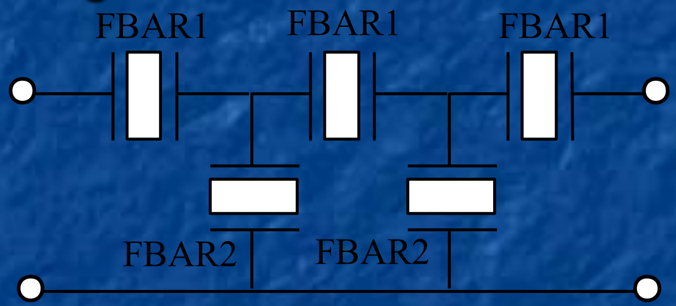
- Preliminary Design
  - Required size of 90 fF and 1.7 pF
  - Started with base mask and Si_3N_4 (ε_r=7.5)
  - scaled design by 3x to get required size

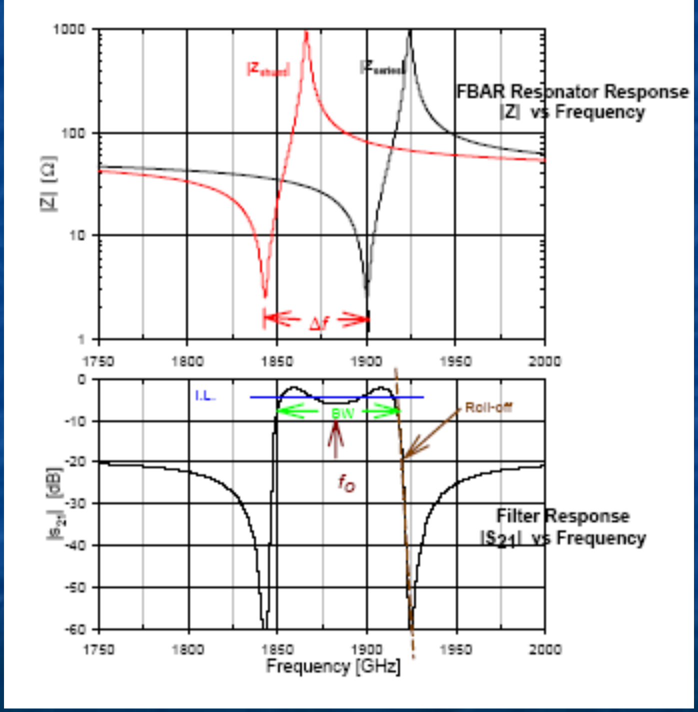




FBAR: Filter Design

- Thin film bulk acoustic resonator (FBAR)
- Single resonators can be used as notch filters
- Filters can be realized by connecting FBAR resonators in ladder configurations.

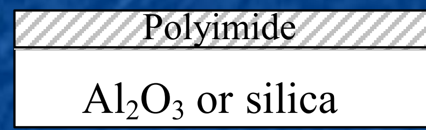




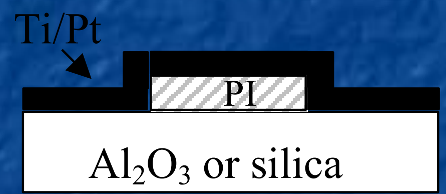
- Synthesis or optimization techniques still need to be developed.
- Tuning of response might be achieved with additional components such as MEMS tunable capacitors.

Fabrication: Carleton FBAR

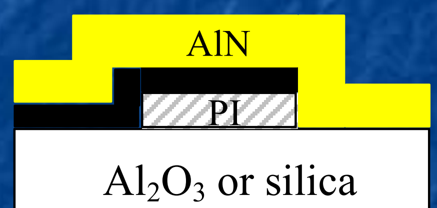
1. Sacrificial Layer:



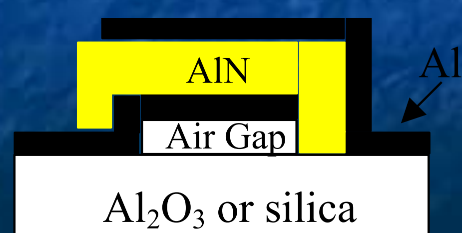
2. Metal 1:

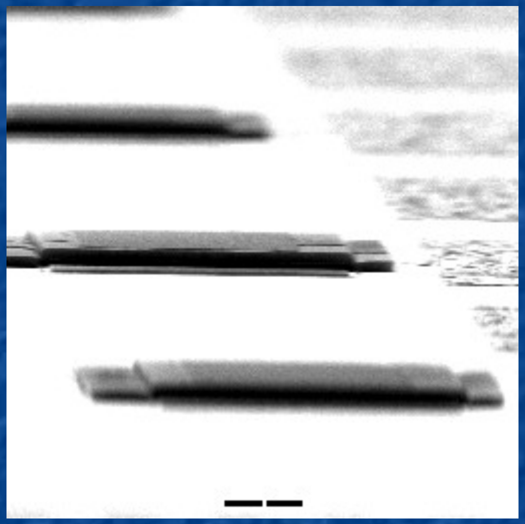


3. Piezoelectric:



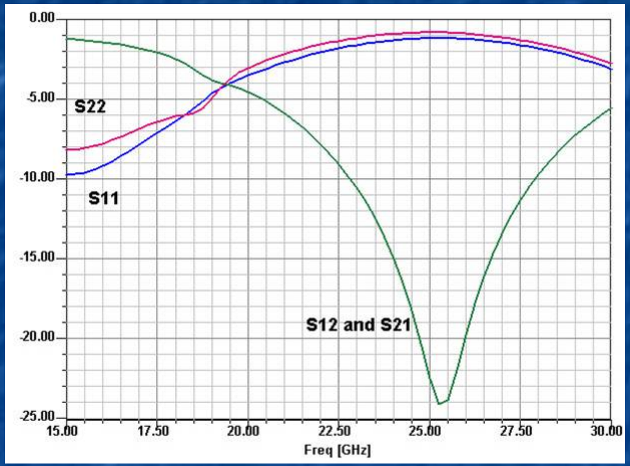
4. Metal 2:

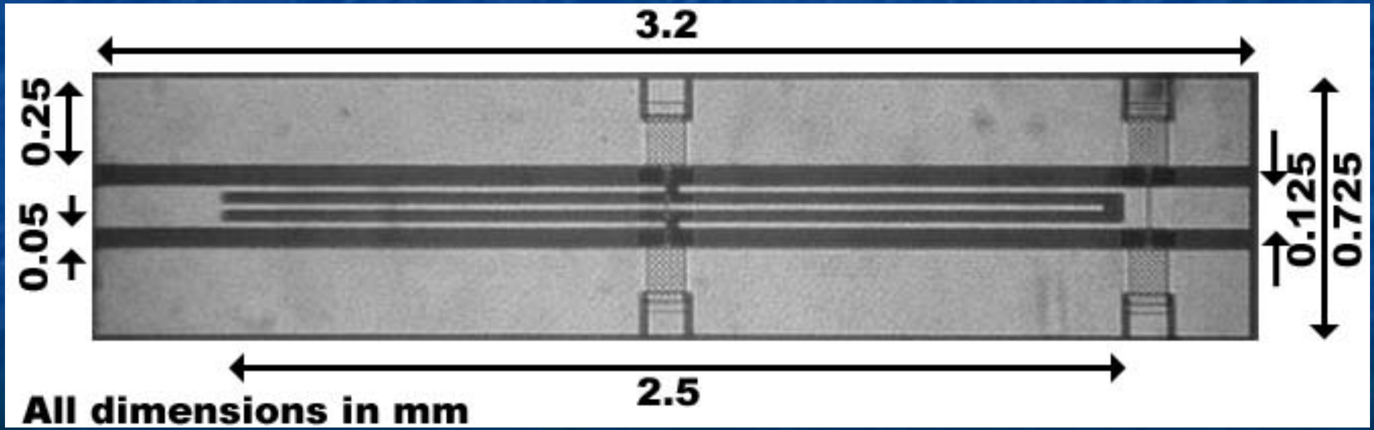




Microwave filter design

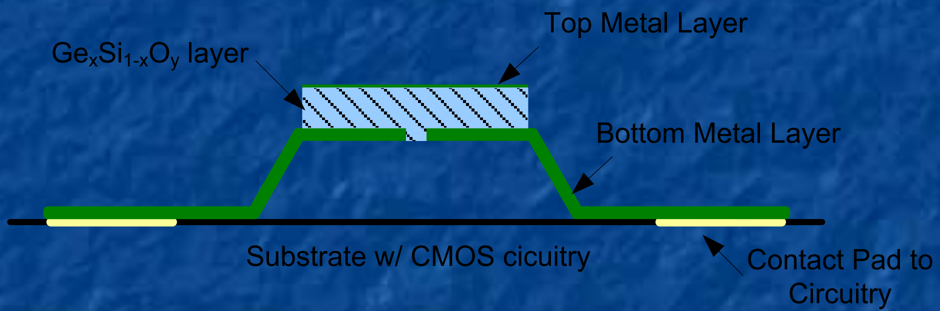
- Design is first scaled to a more easily measured frequency.
- A lumped element equivalent circuit helps in selecting location of tuning components.

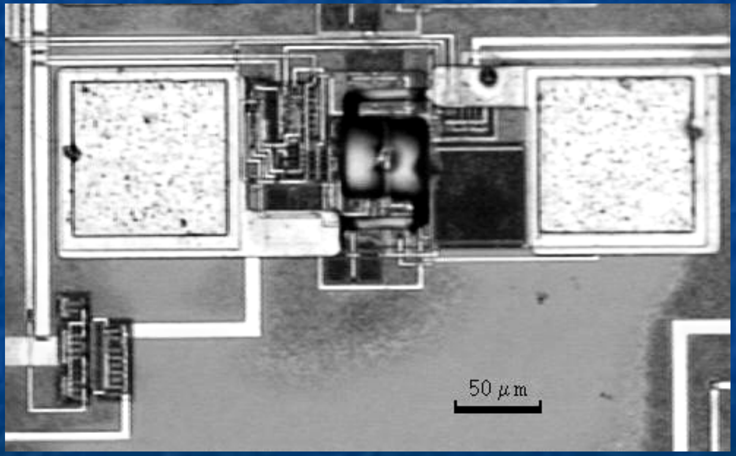




Sensors

- a-$Ge_xSi_{1-x}O_y$ bolometer developed for use in uncooled FPA.
- Monolithically integrated with 0.8 μm CMOS



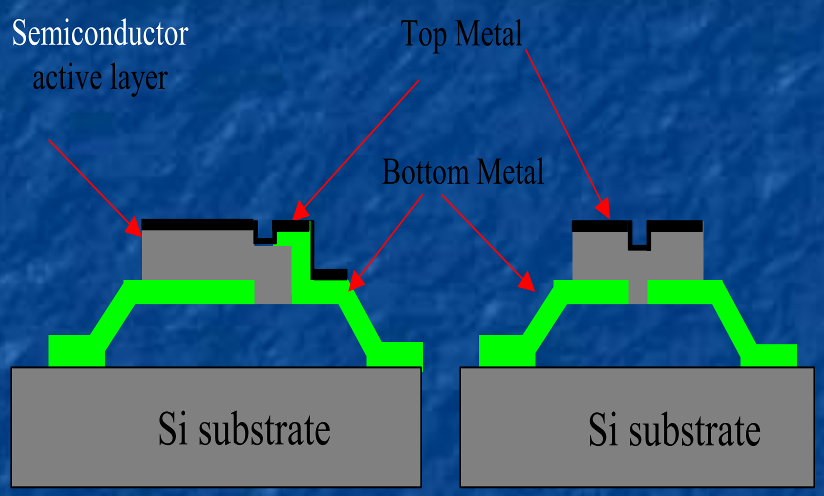


Detectors for thermal imaging

- Photon detectors
  - Fast (μs)
  - Low noise
  - High sensitivity
- Thermal detectors
  - Slow
  - Noisy
  - Low sensitivity

- Why pursue thermal detectors?
  - Silicon IC compatibility = low cost, highly integrated
  - Micromachining enables detectors suitable for many imaging applications.

Bolometer: Design

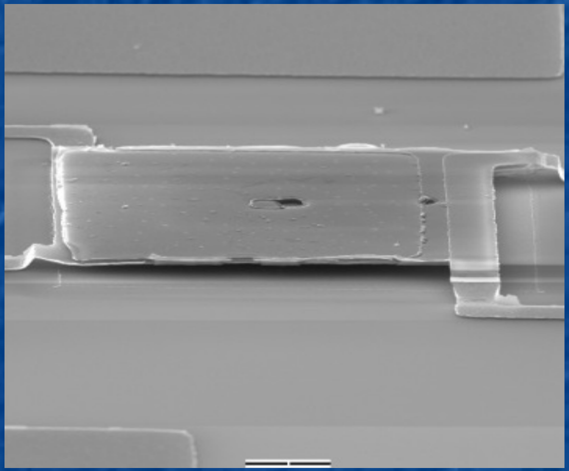


1)Sandwich structure   2)Sandwich-Gap structure

- **High absorption requirements:**
- 1)top metal sheet resistance =377 W /□ .
- 2)active layer optical thickness (nd) =2.5 μm for thermal imaging applications.
- 3)bottom metal sheet resistance <10 W /□ (trade off: mechanical strength , thermal capacitance).

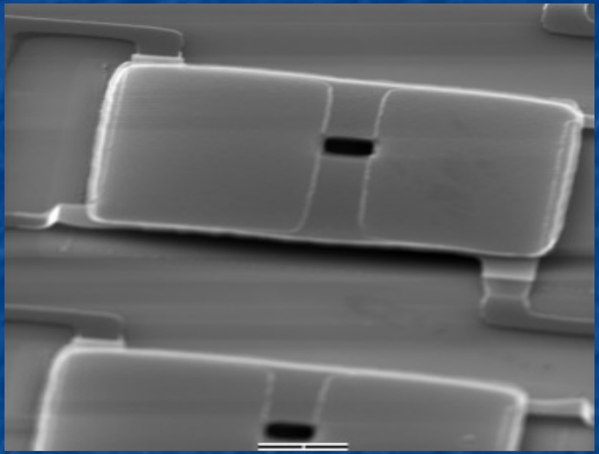
Bolometer: Release

O_2 plasma release using a downstream microwave plasma (NRC IMS)



Sandwich design

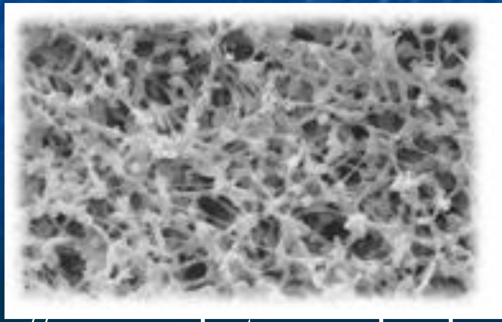
Completed release



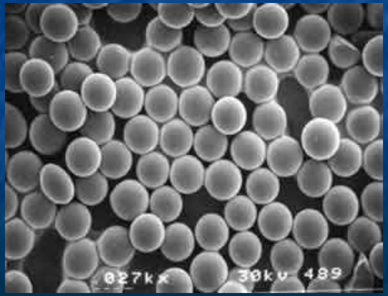
Sandwich-Gap design

Porous Media for Microfluidics

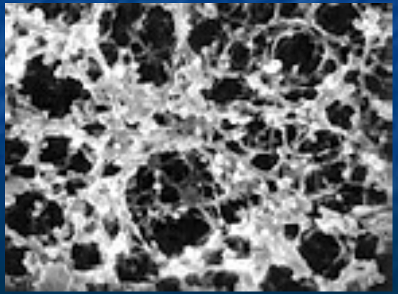
- This work will consider the use of electroosmotic flow in porous materials, for use in microfluidic devices.
- Porous materials:
  - provide a larger surface area for chemical reactions
  - can reduce dispersion of an analyte due to flatter velocity profiles
  - can be used to enhance separation of analytes via surface effects (chromatography applications)



http://www.whatman.plc.uk



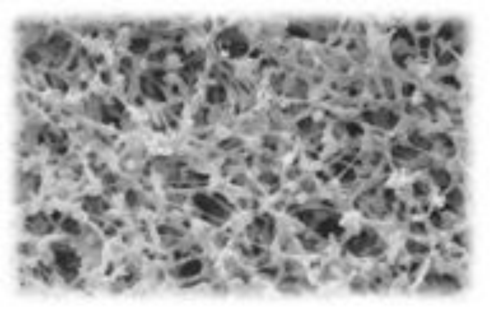
http://www.colorado.edu/ceae/environmental/



http://www.membrapure.de/

Microfluidics

- Porous materials:
  - provide a large surface area for reactions
  - minimize dispersion with flat velocity profiles
  - generate large electro-osmotic pressures
- A generalized model:
  - includes viscous effects near boundaries
  - Allows simulation of flow at interfaces between porous and open regions



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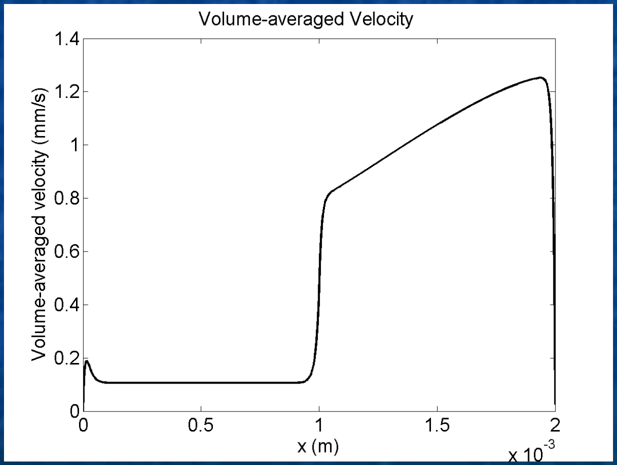
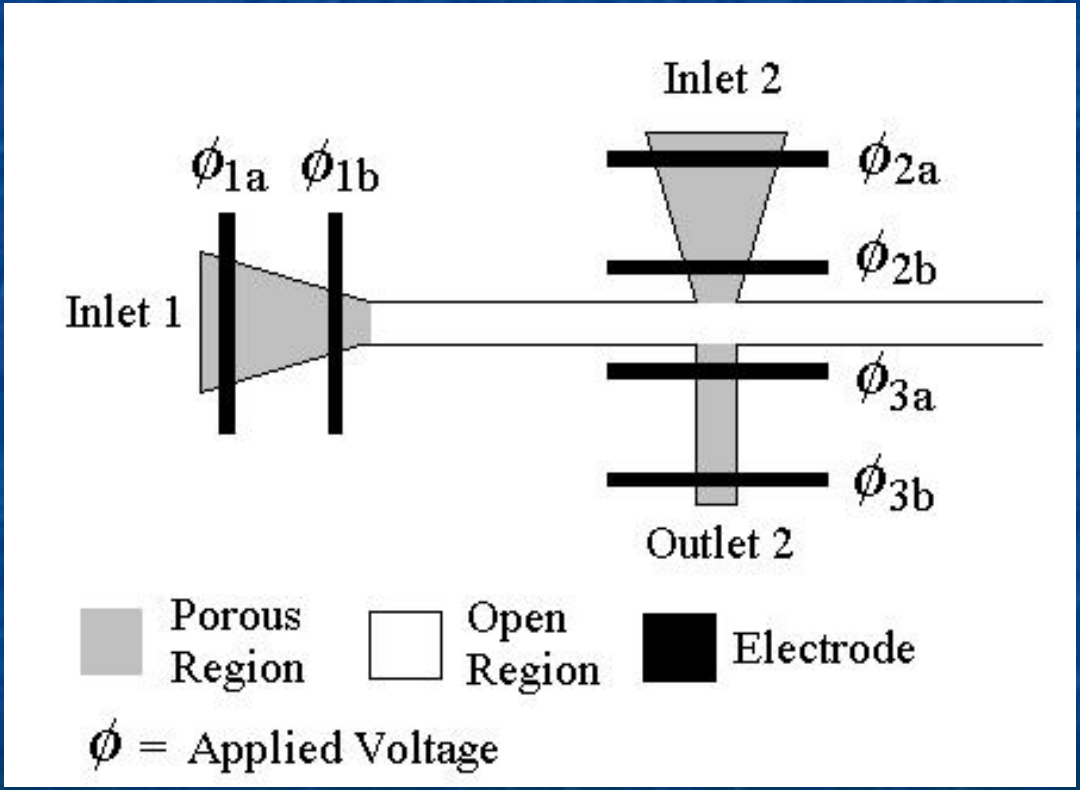


Advantages of Porous Materials

- Porous electroosmotic pumps can generate high pressures, allowing fluid to be pushed through areas not exposed to electric fields.

- Regions without electric fields can be beneficial if electrophoretic effects must be minimized.



Credits / Acknowledgements

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This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.

Many of those figures (and much of the material to be used for this class) are drawn from the "UVA Virtual Lab" (www.virlab.virginia.edu) website developed under earlier NSF grants.