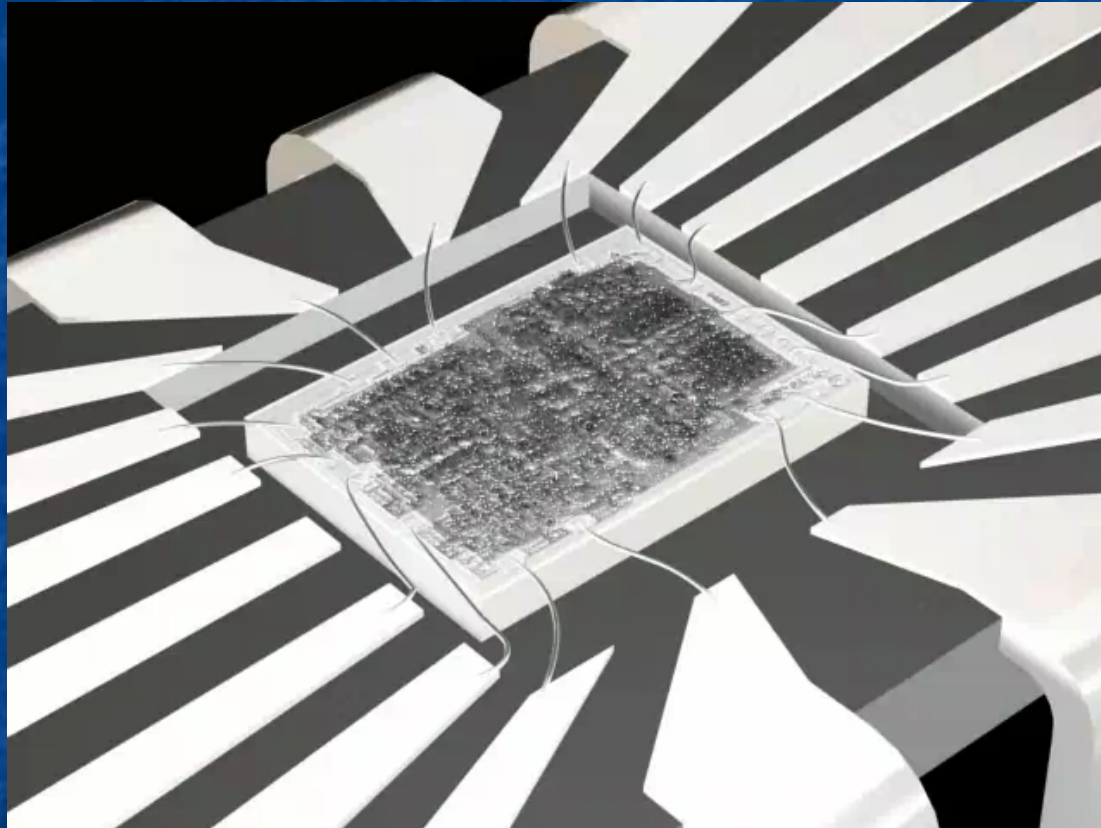
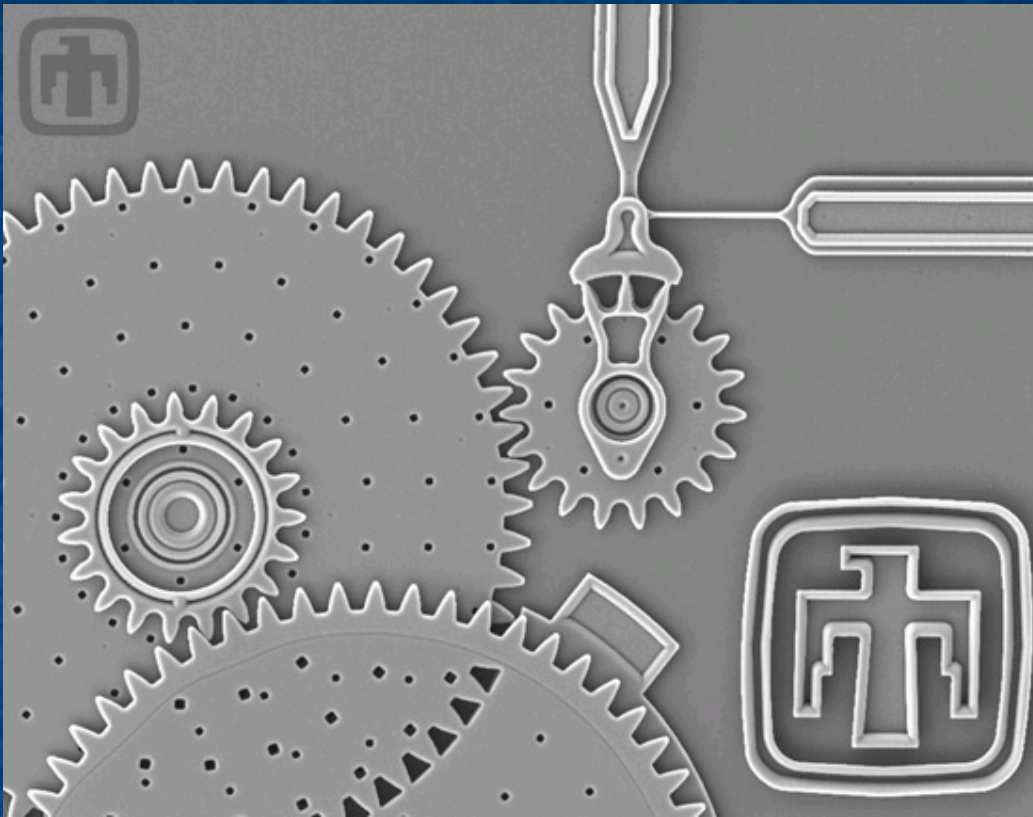


# *Microfabrication*

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



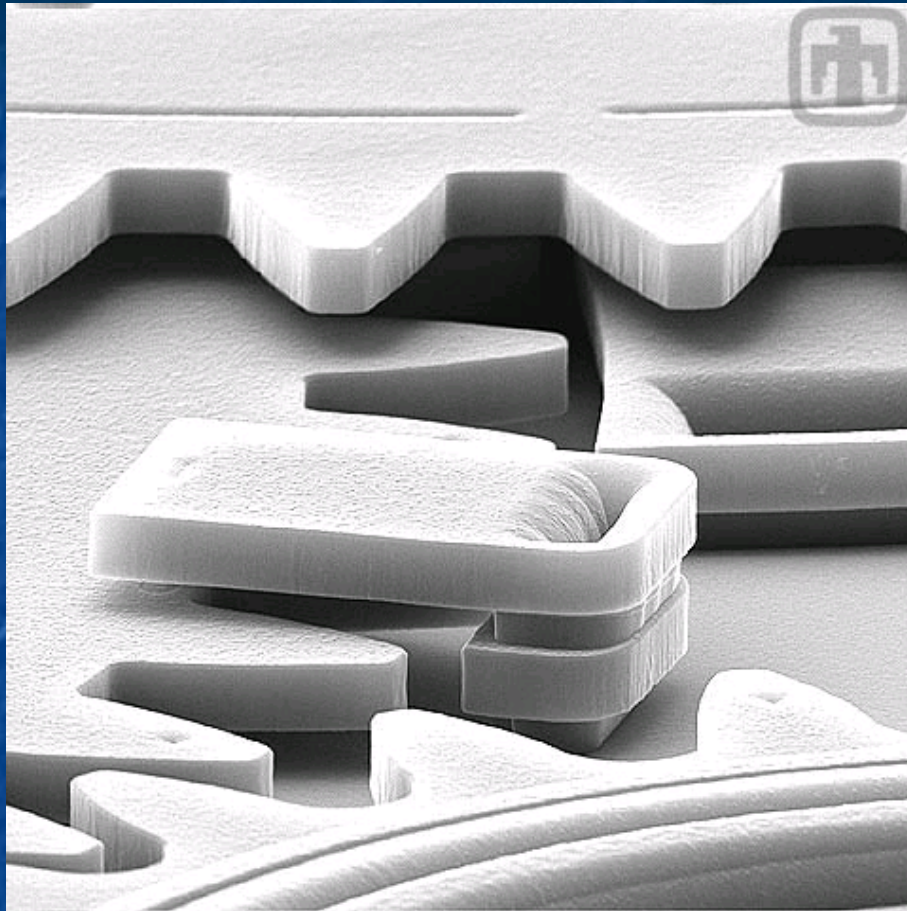
It's now about a lot more, including "Micro-electro-mechanical Systems (MEMS)



Multiple Gear Speed  
Reduction Unit

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





Courtesy of Sandia National Laboratories

## Alignment Clip

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

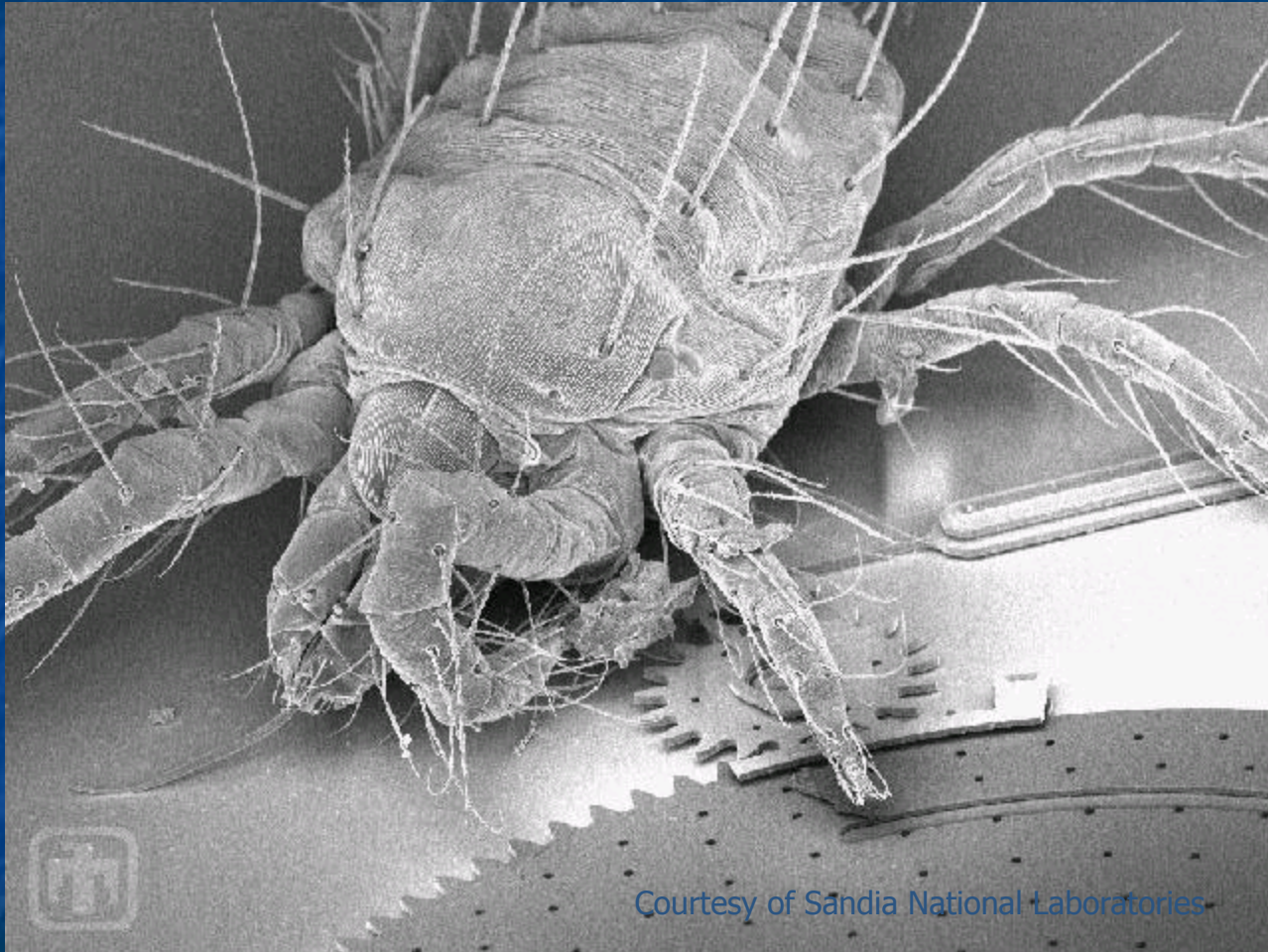
This complex device is entirely batch-fabricated, with no assembly required

### But How Big is This?

Sandia did not include scale markers  
I'd guess layers are  $\sim 0.1 \mu\text{m}$  thick

**For scale they did include this:**

A spider mite:

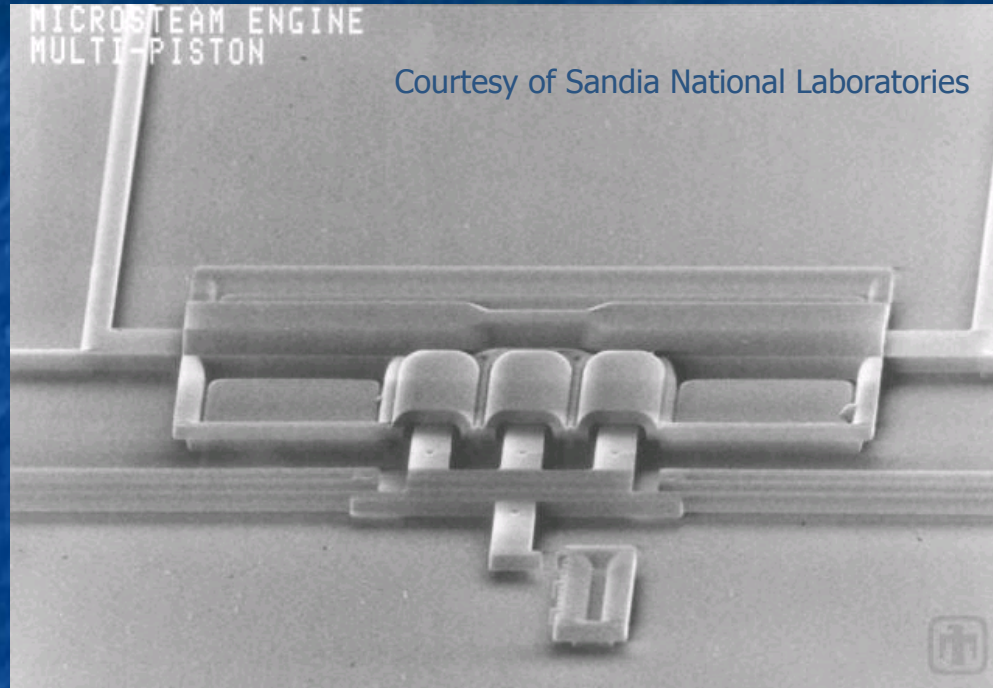


Courtesy of Sandia National Laboratories



# *What else can you make?*

How about a steam engine?



## **Triple-Piston Microsteam Engine**

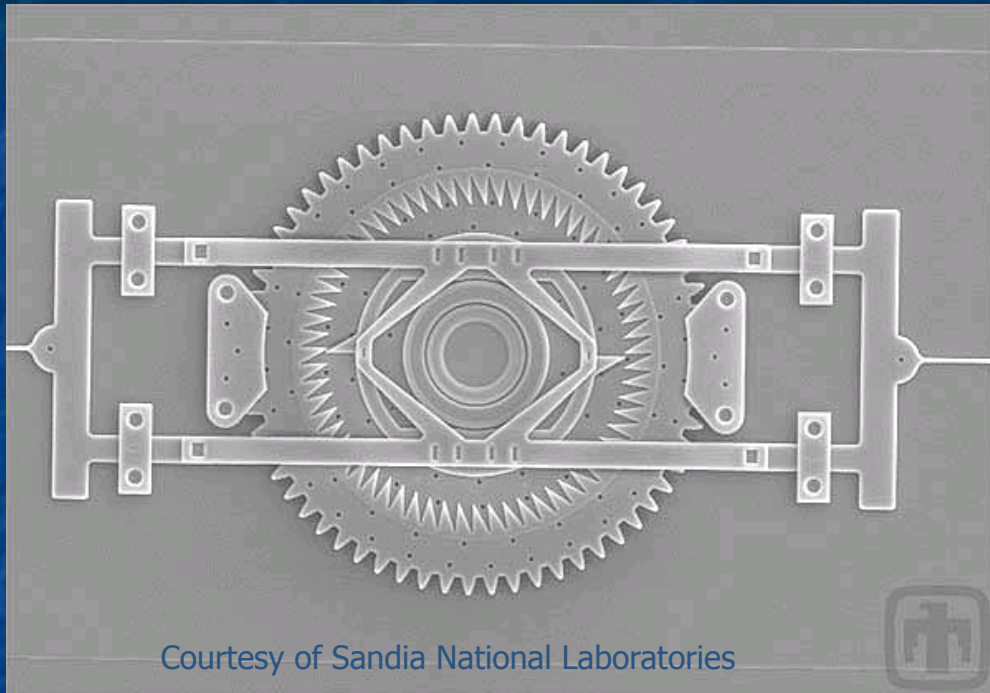
In a humid environment, water condenses inside three open-ended cylinders.

Which are then heated by electric current passing through adjacent wire.

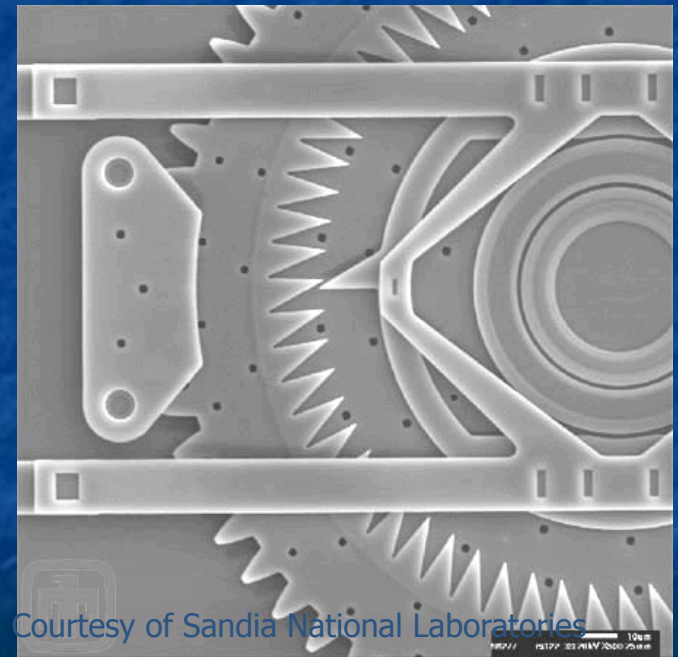
The water vaporizes, its expansion pushing the pistons out.

Once steam bubbles burst, capillary forces then pull pistons back into cylinders (etc.).

## *Or a ratchet indexing motor:*

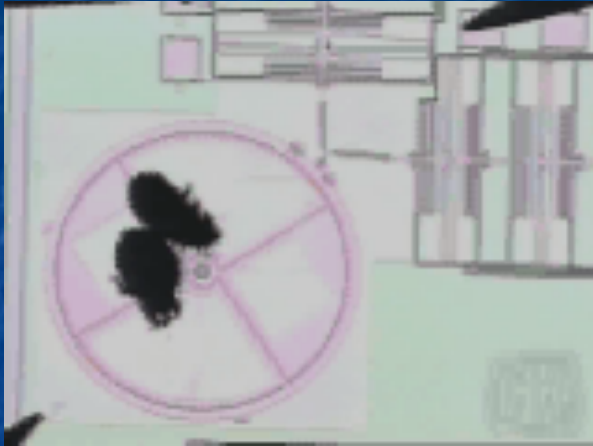


With side-to-side motion of frame possibly provided by steam engine of previous slide





# *Which can be used for . . . revenge!*



Spider mites helping to demonstrate motor:

Actuator (here possibly electrostatic) at top

Driving ratchet and pawl on gear

Yielding a "mite go round"

The spider mite really giving motor a work out:



Courtesy of Sandia National Laboratories

Supporting webpage with embedded animations:

[Microfabrication - Supporting Materials - Animations 1-2](#)

# *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

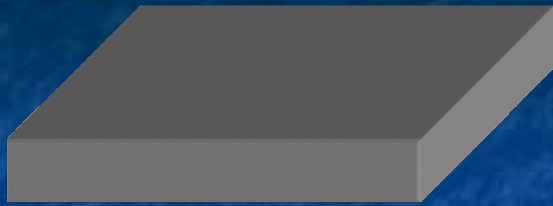
3) Apply, expose, develop pattern in photographic emulsion

4) Etch or blast away material not protected by emulsion

5) Strip off emulsion → Cycle back to step 2



# Schematically:



:Starting substrate



:Deposit layer of desired material

Deposit photographic emulsion:



Expose photographic emulsion:



# Schematically (cont'd):



:Develop photographic emulsion

Etch desired material:



Remove photographic emulsion:



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

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



# Or going over that a little more slowly:

## Step 1) Start with Silicon wafer

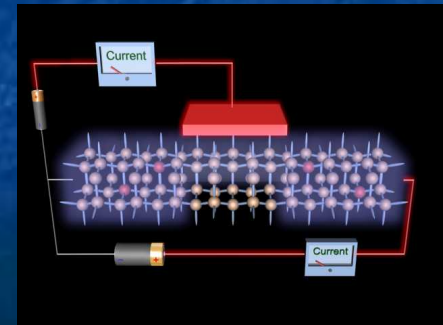
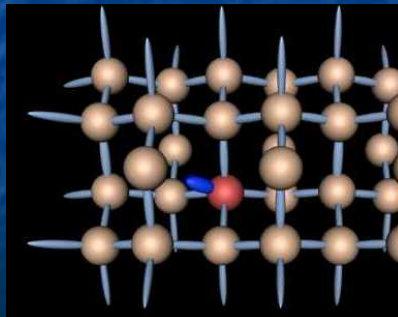
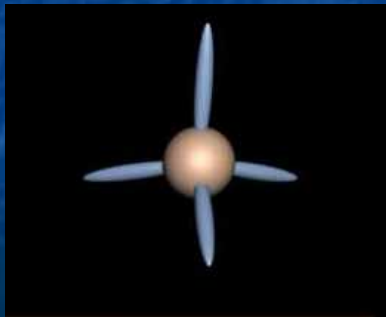
Silicon, element 14 in the periodic table, is known as a semiconductor:

- 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 my "Virtual Lab" webpage on [How Semiconductors and Transistors Work](#)



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

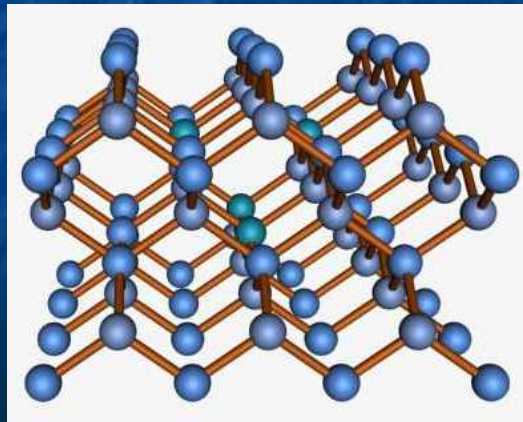
It is incredibly hard and strong!

	Knoop Hardness Index (kg/mm <sup>2</sup> )
Diamond	7000
Silicon Carbide	2480
<b>Silicon</b>	<b>1150</b>
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):





## A (significant) digression pertaining to **Silicon**:

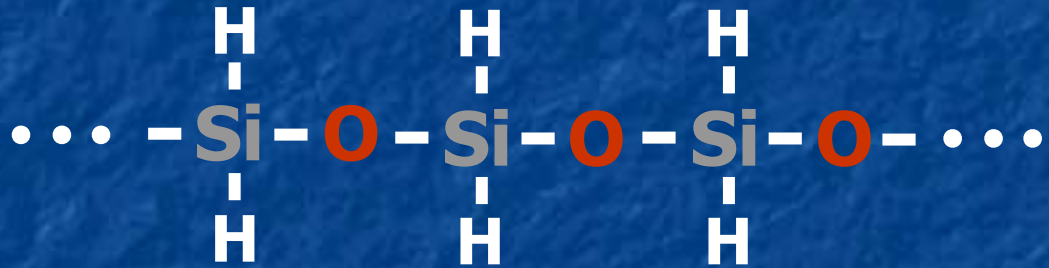
It is pronounced (in the U.S. Pacific Coast dialect) as "sil-ah-cun"

Similar to state of Oregon which is pronounced "Or-ah-gun"

### Reasons for using this pronunciation:

- 1) N. California IS the birthplace and spiritual center of the associated industry
- 2) **Silicone** (common mispronunciation of silicon) is **VERY** different:

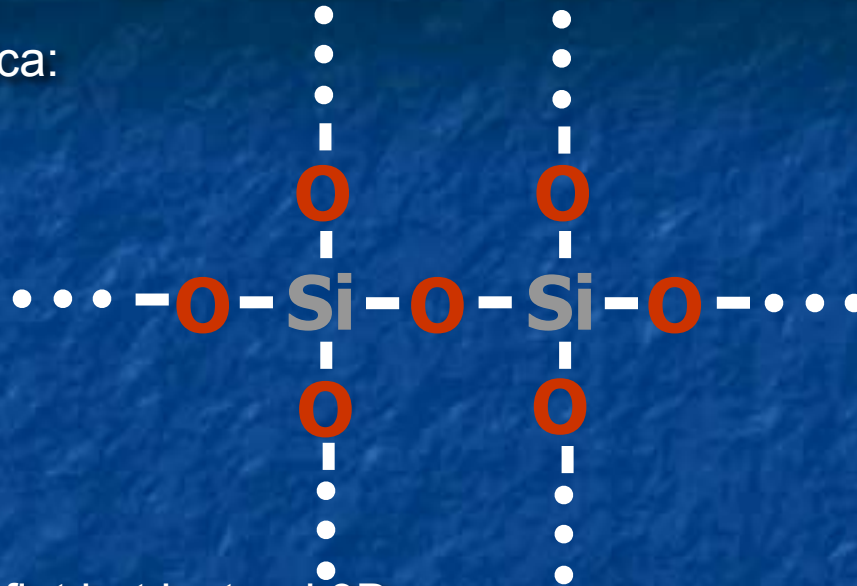
Silicone (a.k.a. "siloxane"):



- Strongly cross-linked => Rubber w/ exceptional heat and chemical resistance
- More weakly cross-linked + H<sub>2</sub>O => Silicone Gel (of breast implant fame)
- Change H's to methyl groups => Polydimethylsiloxane ("PDMS")

And both **Silicon** and **Silicone** are VERY different from **Silica**

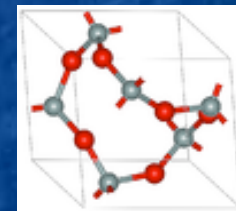
Bonding structure of silica:



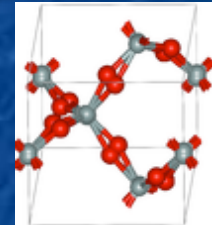
But real structure is not flat but instead 3D:

a) Organized 3D crystal = "**quartz**"

(from Wikipedia webpage on silicon dioxide)



"alpha quartz"



"beta quartz"

b) Disorganized (amorphous) 3D = "**glass**"

So now you understand **Silicon** vs. **Silicone** vs. **Silica** – onward!



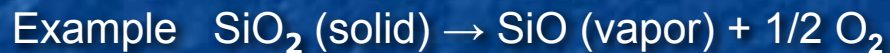
## Step 2) Spray on or grow on additional layer

### Alternative i) Spray via evaporation:

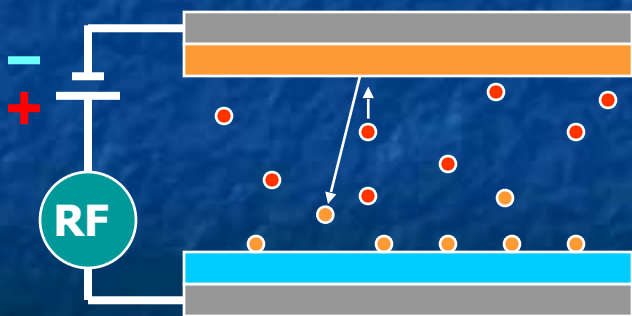
Heat up the material you want to deposit until it starts to fall apart

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



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



**Gas** is excited and ionized by oscillating RF field

Driven by DC Voltage, **gas ions** crash into top plate

Blasting atoms of **desired material** off top plate

To condense on other plate (covered with **wafer**)

## Alternative iii) "Grow" a layer of what you want via surface chemical reactions

Sort of like rusting iron:  $2 \text{Fe (solid)} + 3/2 \text{O}_2 \text{ (gas)} \rightarrow \text{Fe}_2\text{O}_3 \text{ (solid)}$

Except that where iron oxide is a crumbly porous mess,

Silicon oxide is . . . glass!  $\text{Si (solid)} + 1/2 \text{O}_2 \text{ (gas)} \rightarrow \text{SiO}_2 \text{ (solid)}$

Chemically, glass is 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:

$\text{SiH}_4 + \text{O}_2 \rightarrow \text{SiO}_2 \text{ (solid)} + 2 \text{H}_2$  (Disclaimer: Goes "boom" if don't carefully dilute!!)

And works for other related insulators

$3 \text{SiH}_4 + 4 \text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 \text{ (solid)} + 12 \text{H}_2$

***Once you've added that layer  
(via one of these techniques):***



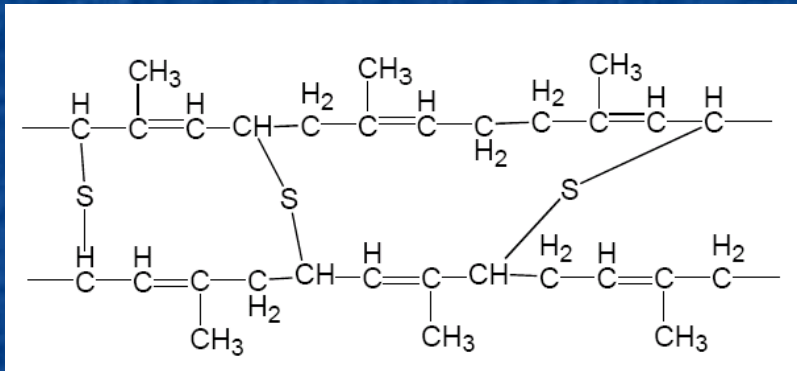
Step 3) Apply, expose, develop desired pattern in a photographic emulsion

Emulsion is also called "resist" because we want it to resist 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:

[Microfabrication - Supporting Materials - Darling](#)

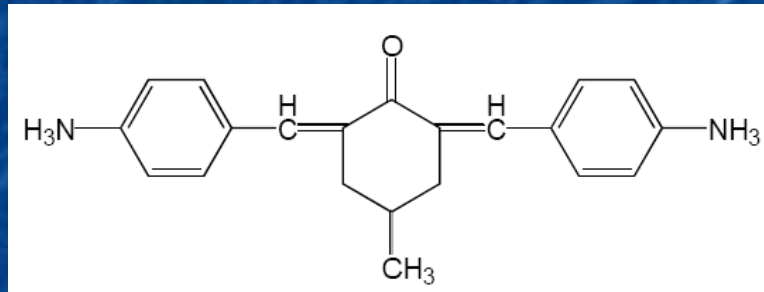
Hydrocarbon monomers (long carbon-based chains) can be very chemically resistant

Here they're held together by sulfur atoms - **But sulfur linking is induced by heat not light!!**

We need different LIGHT-stimulated way of linking/unlinking monomers

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

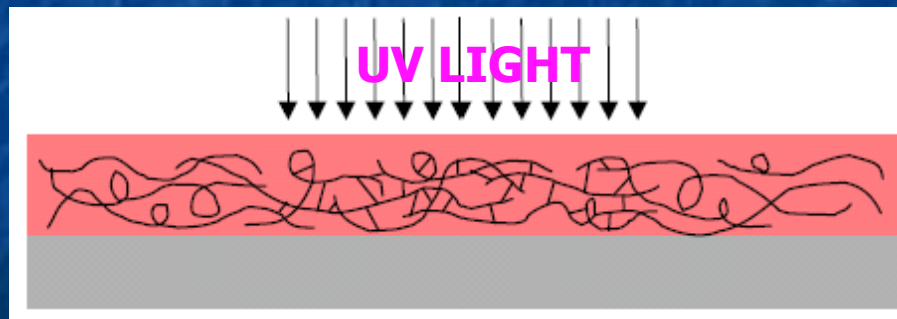
2,6-bis(4-azidobenzal)-4-methylcyclohexanone or just "ABC" (I didn't make this up!)



Source: R. Bruce Darling  
University of Washington

Light reacts with "azide"  $\text{NH}_3$  end units, converting them to reactive radicals

So that they chain themselves to other monomers ("cross-linking" them):



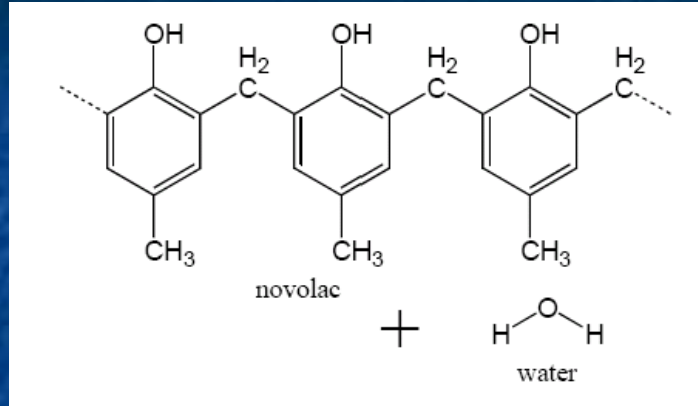
Source: R. Bruce Darling  
University of Washington

Unlinked | Linked | Unlinked



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

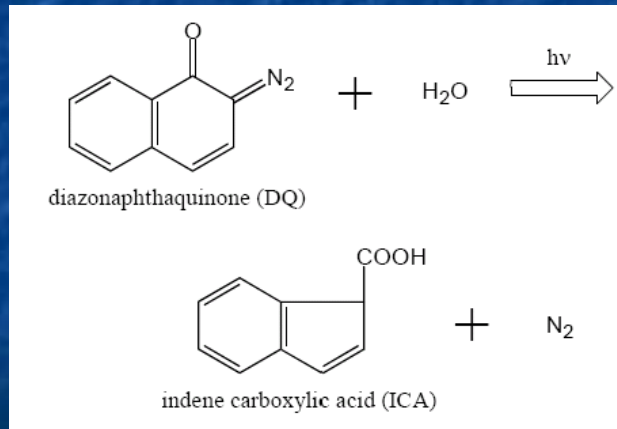
Phenolic "resin" (monomer):



Source: R. Bruce Darling  
University of Washington

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

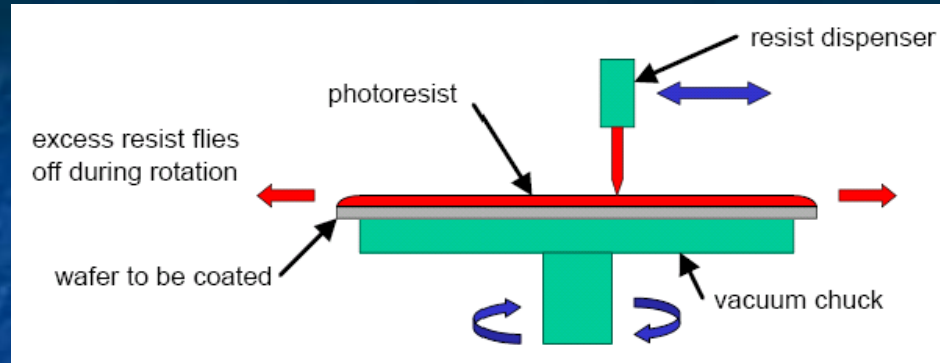
Where not struck by light →  
Sheds water-based remover  
(and thus everything stays put)



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

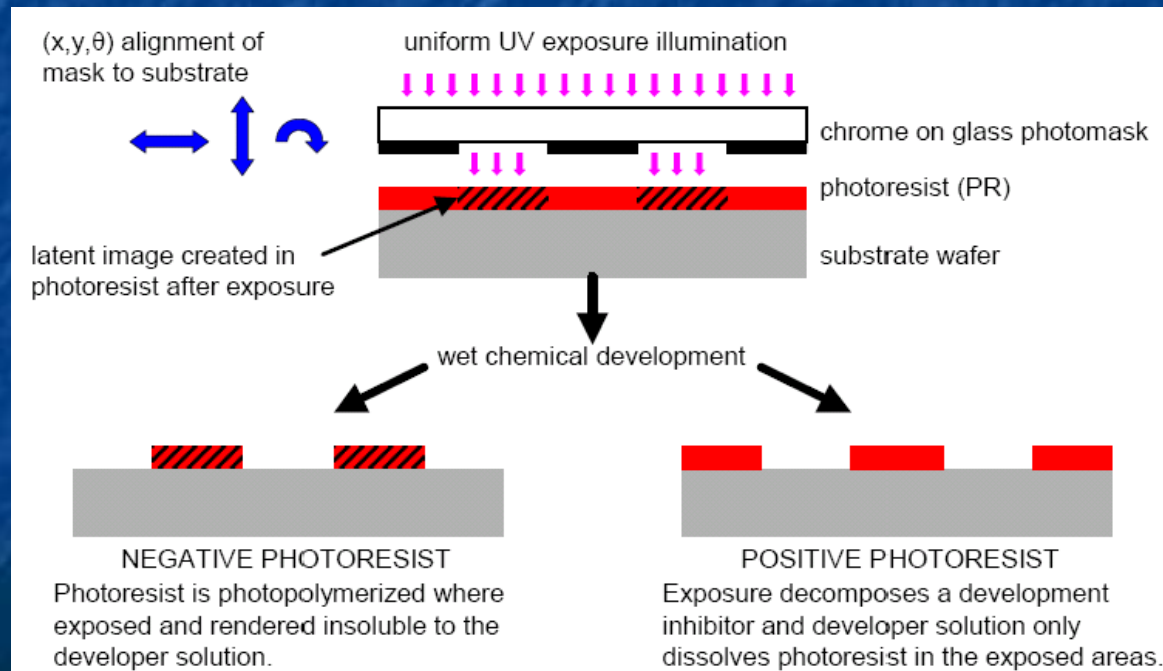
Source: R. Bruce Darling  
University of Washington

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



Source: R. Bruce Darling  
University of Washington

Then expose pattern through photographic shadow "mask (also called a "reticle"):"



Source: R. Bruce Darling  
University of Washington

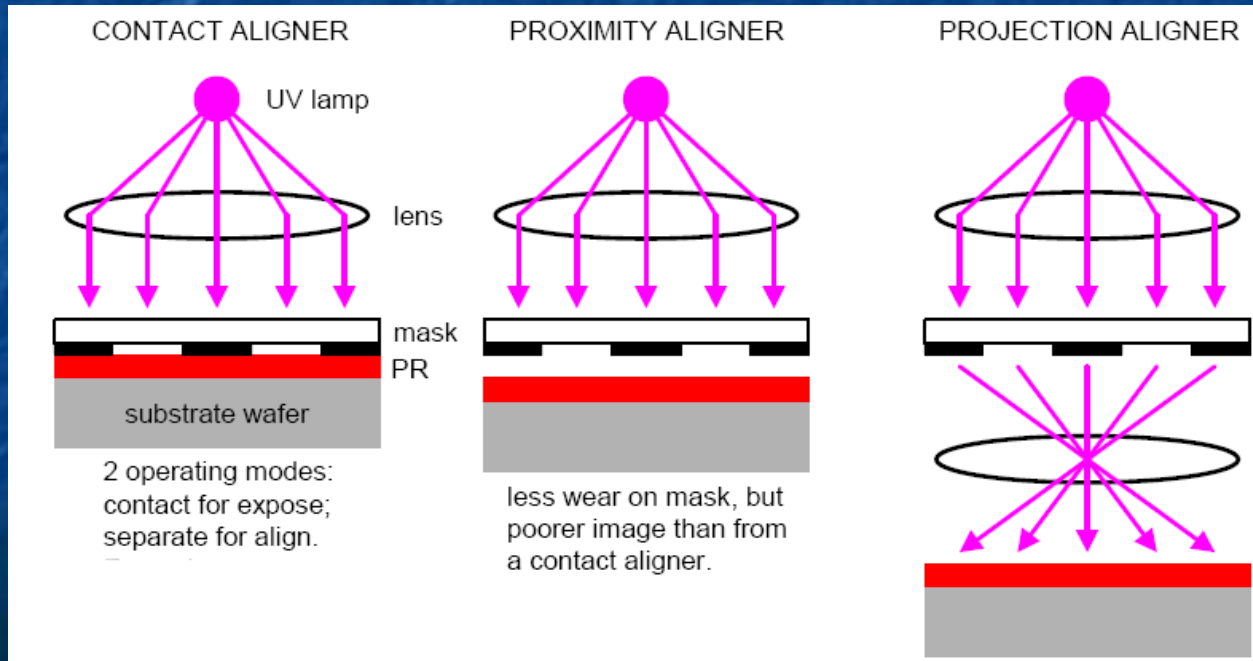


It's actually done in a tool called a “mask aligner” which (in older non-automated versions):

- 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

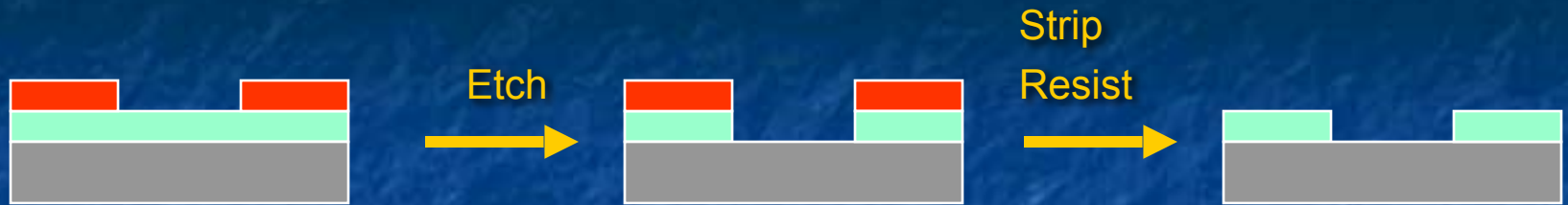
UV light then passes through transparent regions of mask onto resist/wafer

- 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

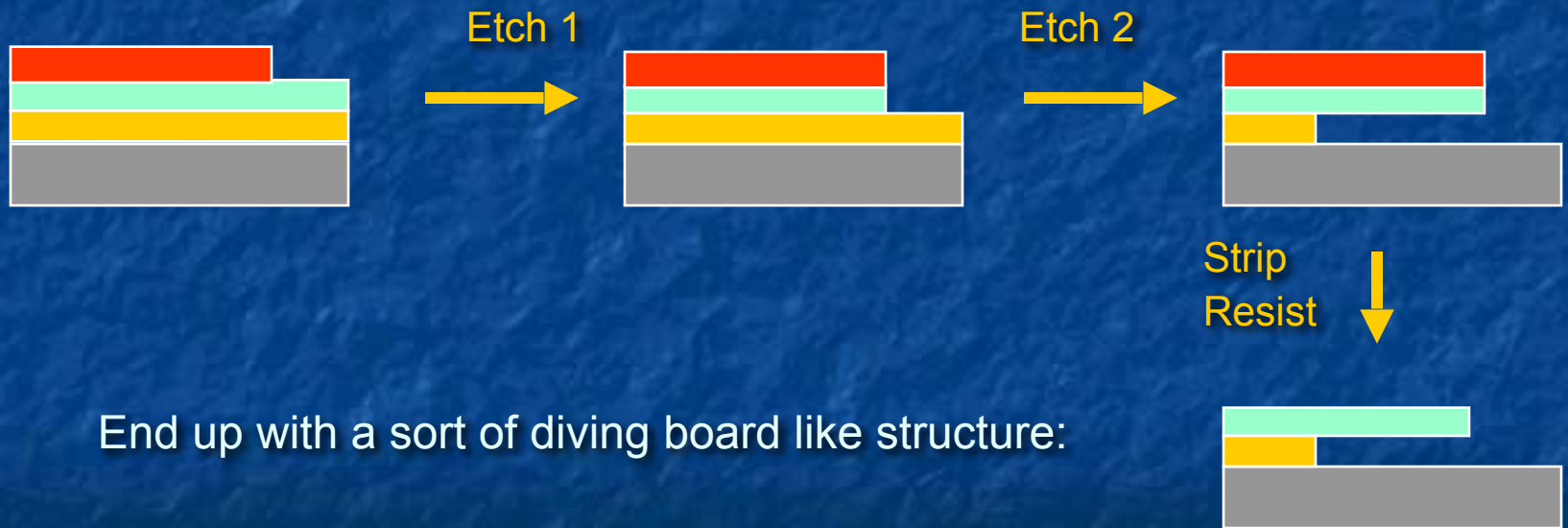


Source: R. Bruce Darling  
University of Washington

Step 4) Etch or blast away material no longer protected by photoresist



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



End up with a sort of diving board like structure:

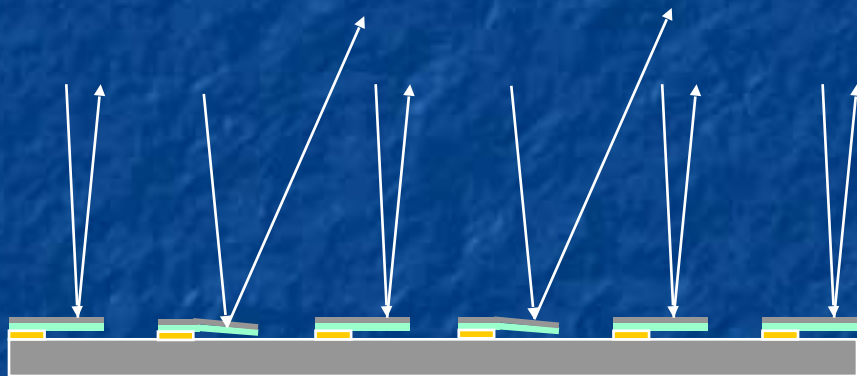


*What if "diving board" were metallic (or covered by metal)?*

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

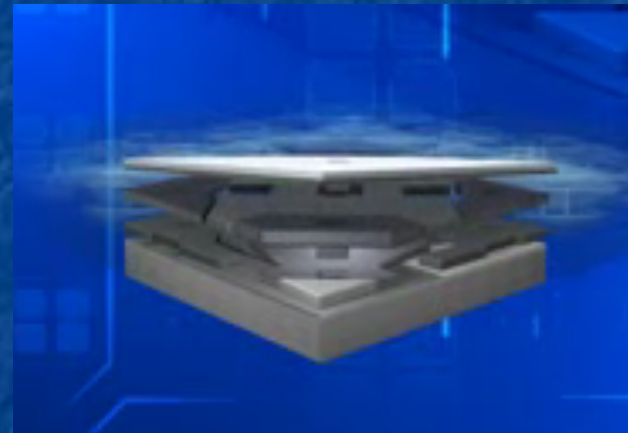
2) We **MAY** be using it at this very moment

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

From the DLP.com / Texas Instruments Website:



Voltage applied at front

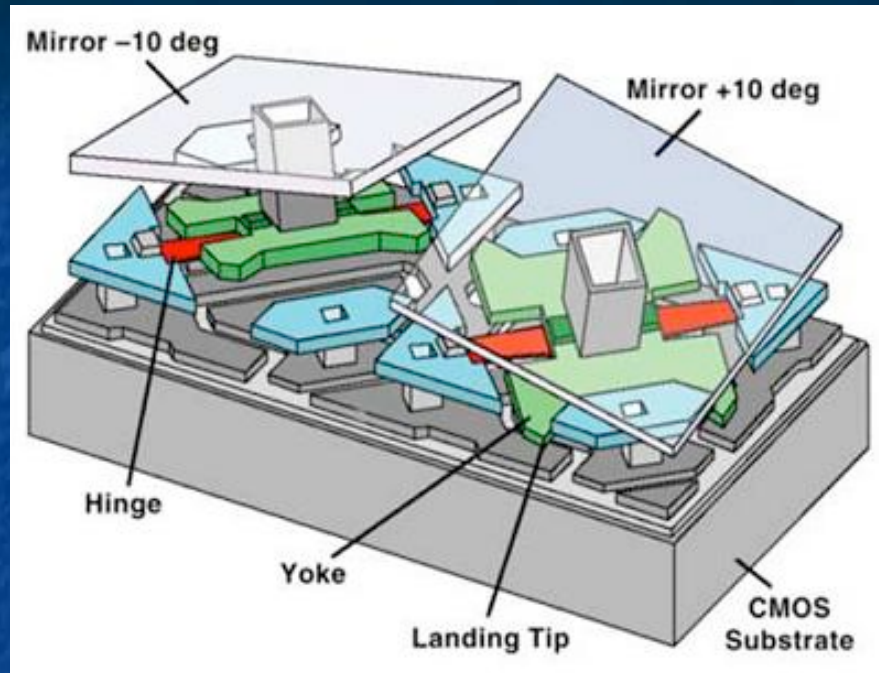


Voltage applied at rear:

Supporting webpage with embedded animations:  
[Microfabrication - Supporting Materials - Animation 3](#)



*Here is a more detailed look at two pixels in the device:*



(Image found on a Japanese language blog  
– original probably from TI.com)

**KEY POINT:** Pieces were not made and brought together to yield this assembly!

**INSTEAD:** Uniform layer was deposited, photoresist pattern exposed and developed.

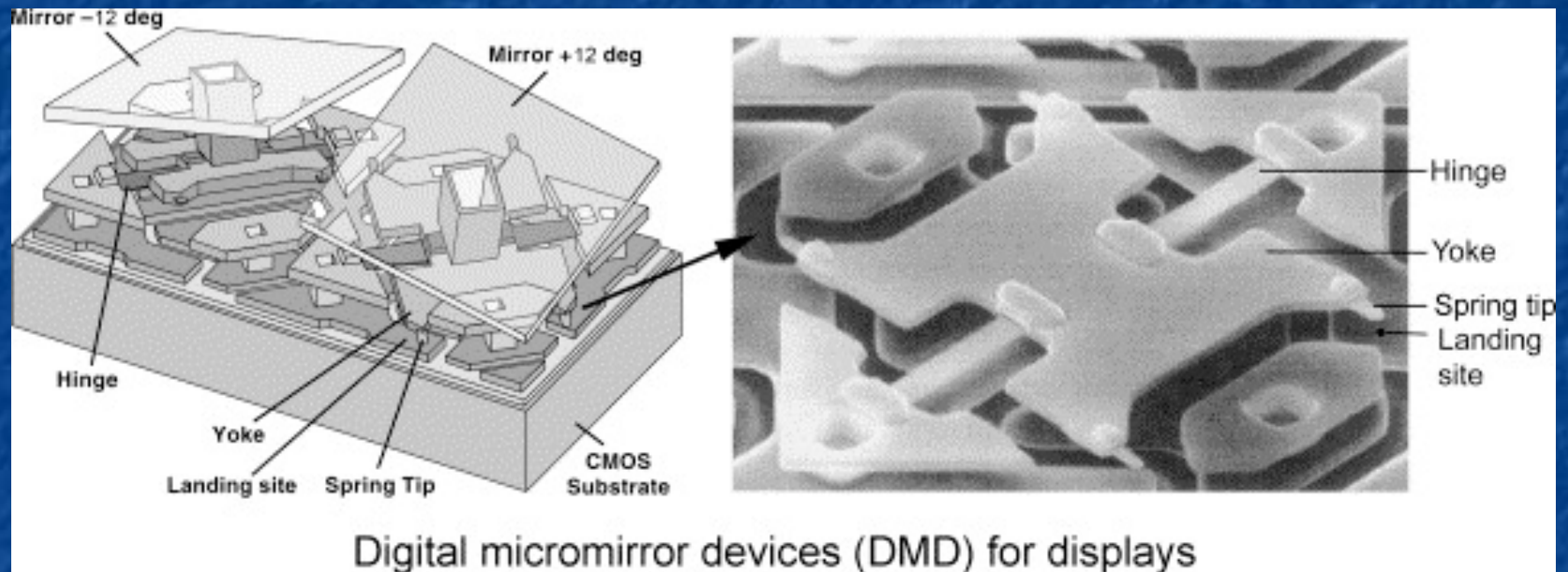
Pattern protected parts of layer against removal (transferring pattern to layer).

Then steps were repeated over and over again to build up structure

And this was done, simultaneously, at millions of different points!

## Comparing schematic with direct SEM image:

("Nanomechanical characterization of multilayer thin film structures for digital micromirror devices," Wei, Bhushan and Jacobs, Ultramicroscopy 100(3-4), pp. 375-389 (2004))



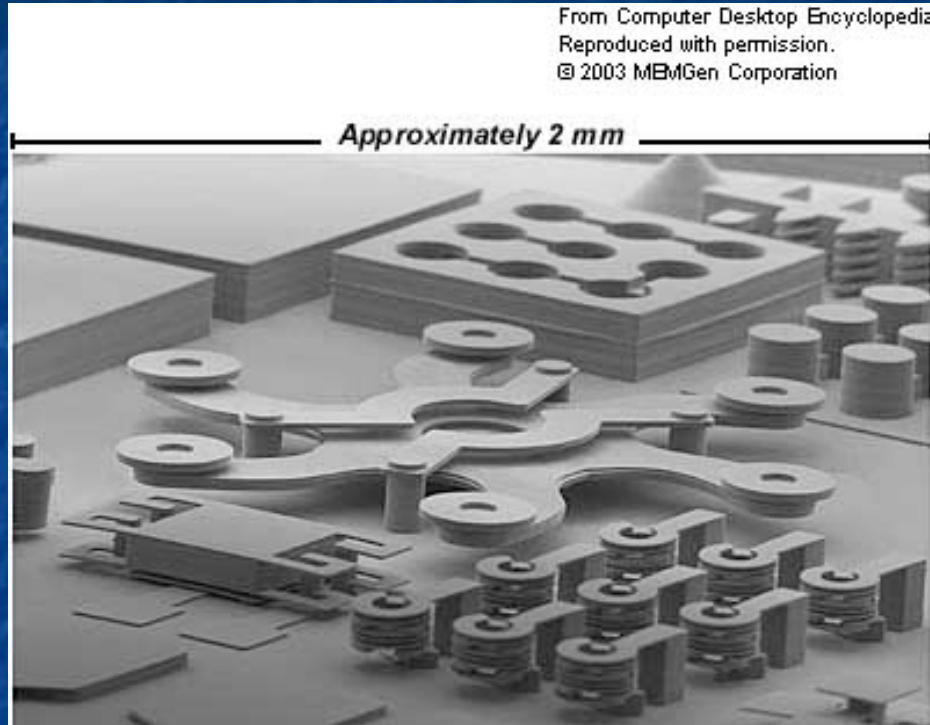
**See how the whole thing is made up of layer upon layer upon layer?**

(Note: Drawing at left shows mirror up on post not seen in SEM image of real structure at right. Missing or does real device just use understructure as mirror?)



## Other possible applications – Accelerometers:

(from: <http://encyclopedia2.thefreedictionary.com/Accelerometer>)



As built into:

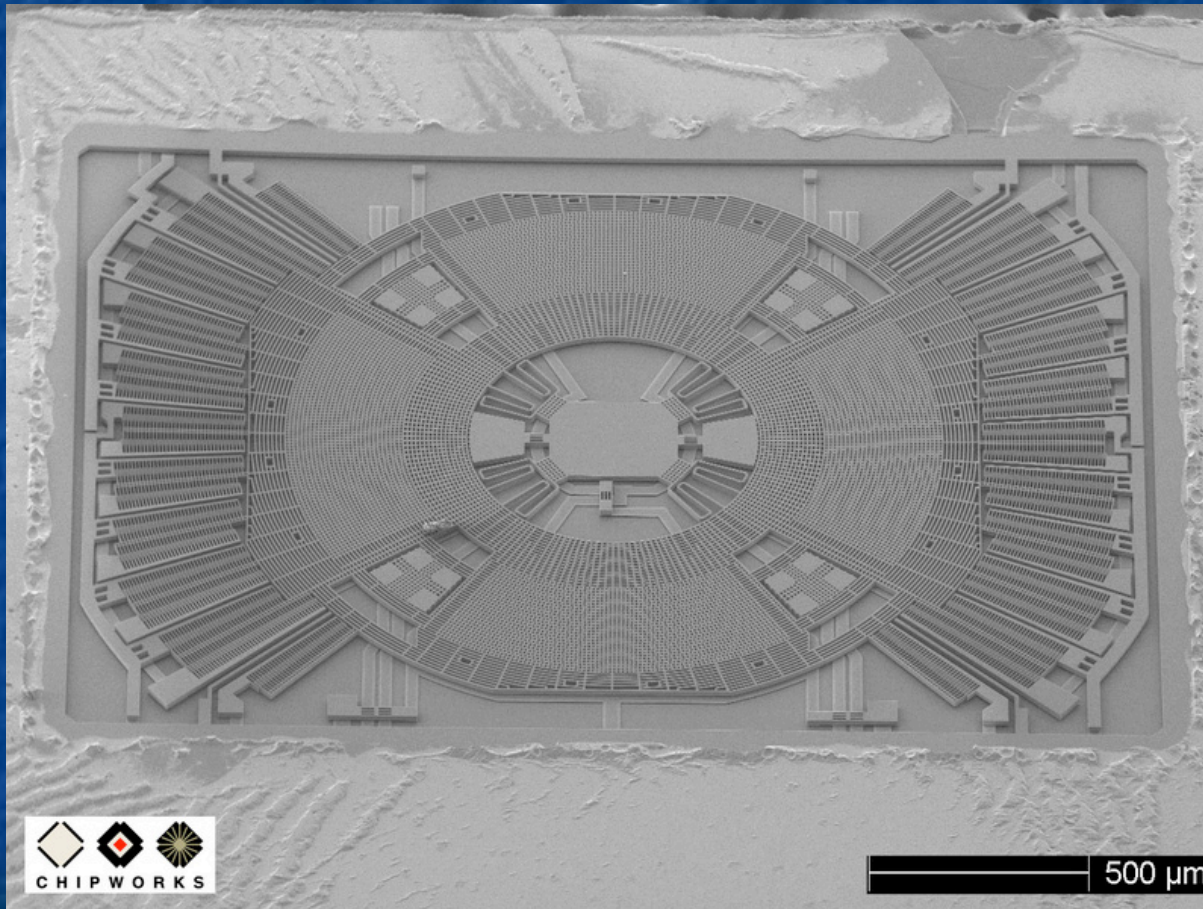
The airbag sensors in your car

Your Nintendo Wii game

Your cell phone . . .

# Or Gyroscopes:

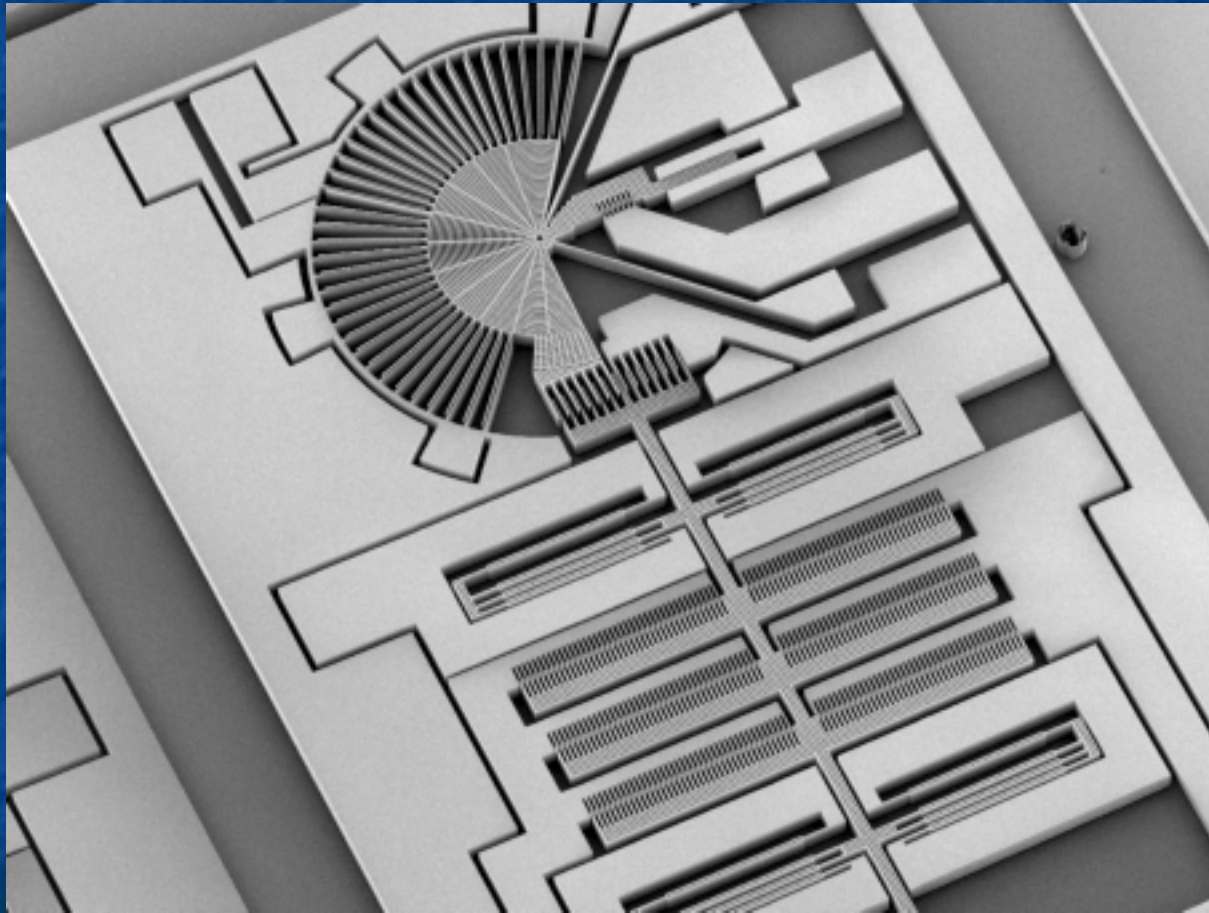
(<http://www.livenano.org/technologies/techniques/mems-gyroscopes/>)





## *Or Position Sensors (ultra-precise capacitive sensor):*

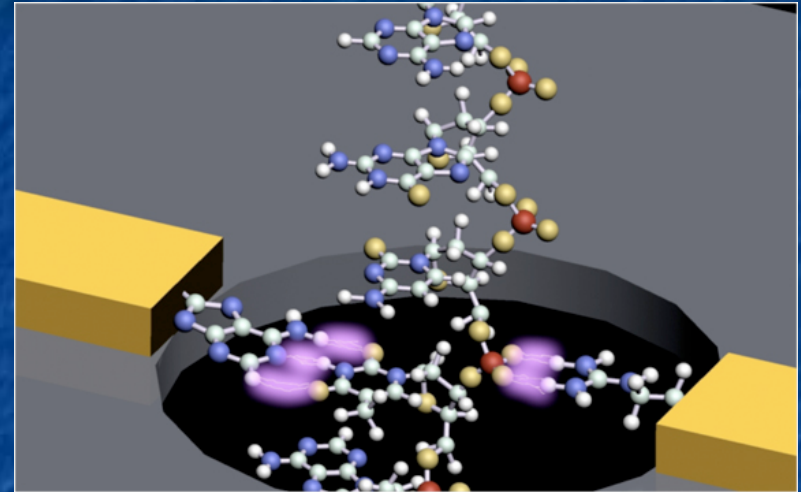
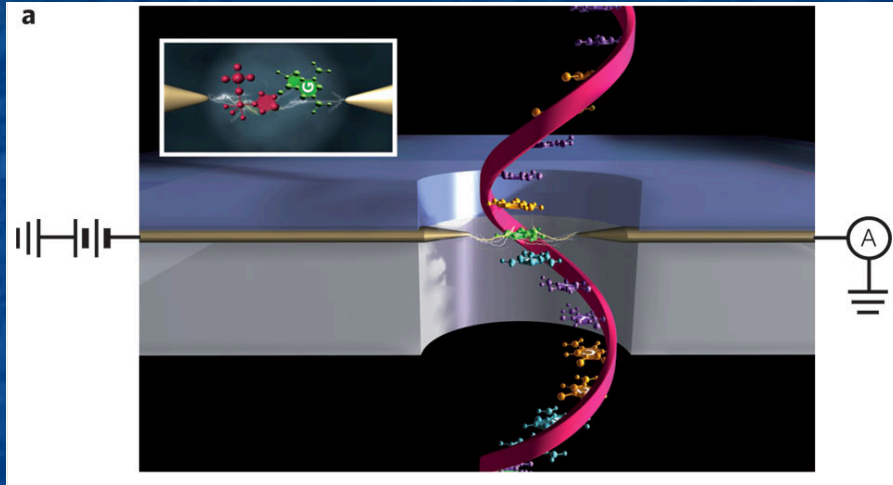
([http://www.utwente.nl/ewi/tst/education/assignments/bachelorassignments/Bachelor\\_CapacitiveSensor.doc/](http://www.utwente.nl/ewi/tst/education/assignments/bachelorassignments/Bachelor_CapacitiveSensor.doc/))



# And eventually, maybe even a Microchip DNA Sequencer:

([www.nature.com/nnano/journal/v6/n10/full/nnano.2011.129.html?WT.ec\\_id=NNANO-201110](http://www.nature.com/nnano/journal/v6/n10/full/nnano.2011.129.html?WT.ec_id=NNANO-201110))

(<http://researchmatters.asu.edu/stories/race-develop-cheap-rapid-dna-sequencing-753>)



## The Dream:

Separate DNA into single strands

Draw ONE strand through a nanopore by applying positive voltage below

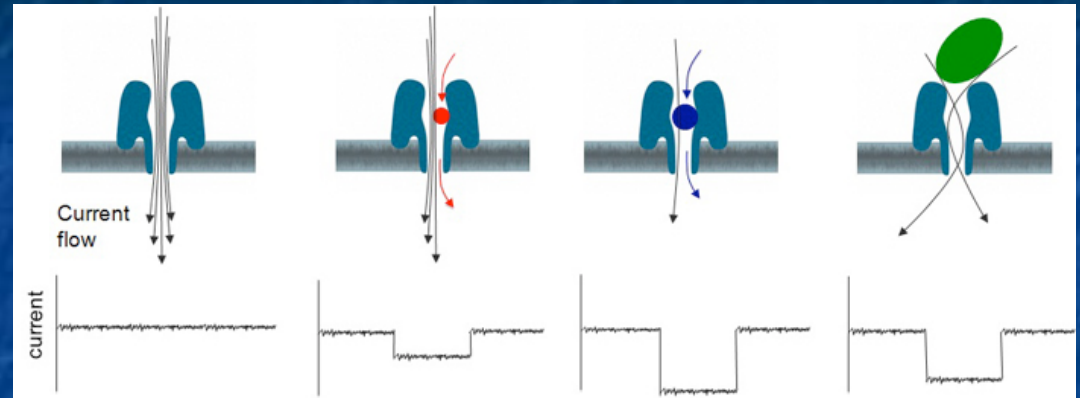
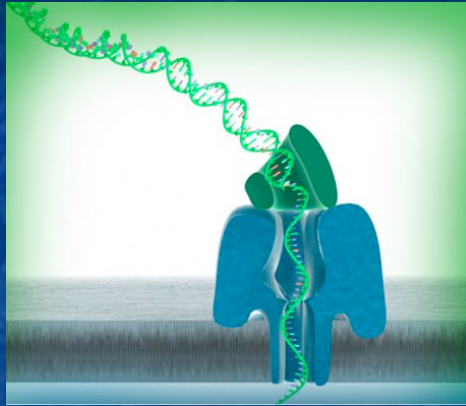
Sense what type of base is passing through pore at given moment

For instance, by putting complementary bases (A, T, C or G) to sides of nanopore (right)



# How far they have gotten to date:

(<http://www.nanoporetech.com/technology/introduction-to-nanopore-sensing/introduction-to-nanopore-sensing>)



Protein-based DNA separator / nanopores embedded in membrane (left)

Which can discriminate between different types of molecules based on electrical current (right)

And can distinguish between DNA having all one base or all another base (e.g. all A vs. all T)

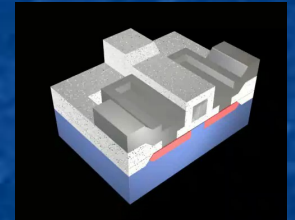
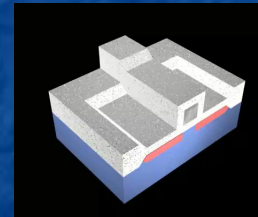
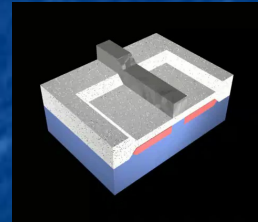
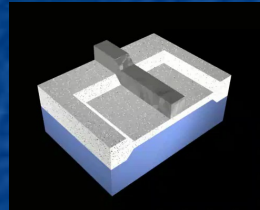
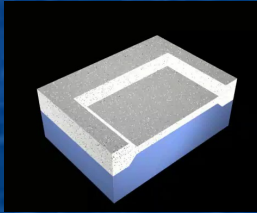
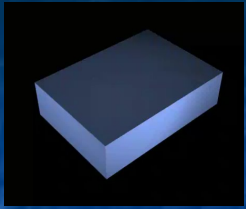
Further, did see one report of being able to identify AAA vs. TTT triplet sequences

But above was not yet able to identify individual bases in an arbitrary sequence

Nor had it yet been mass produced via microfabrication (but that was a couple of years ago!)

*And let's not forget microfabrication's original and still biggest application*

## *Transistors in Integrated Circuits:*



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:”

[https://WeCanFigureThisOut.org/VL/IC\\_process.htm](https://WeCanFigureThisOut.org/VL/IC_process.htm)



## *But how exactly do they make those more mechanical (MEMS) things?*

I've searched and searched for full pictorial description of MEMS process – and failed

Reason #1) To this point, most people doing MEMS got started building integrated circuits

Which is already well depicted in many textbooks (and on my website)

So they now use a sort of pictorial shorthand that leaves out most of the steps

Correctly assuming that others with similar training can figure it out for themselves

Reason #2) It is EXTREMELY hard to create complete drawings of process

New layers naturally **conform** with shape of patterned layers already there

But CAD/animation tools don't have a "deposit conformal layer" button

So you have to draw conformal layer as **sum** of huge number of sub shapes

As I DID (painfully) in transistor animation linked to in preceding slide!

*But here is one depiction giving start to finish process of making gears:*

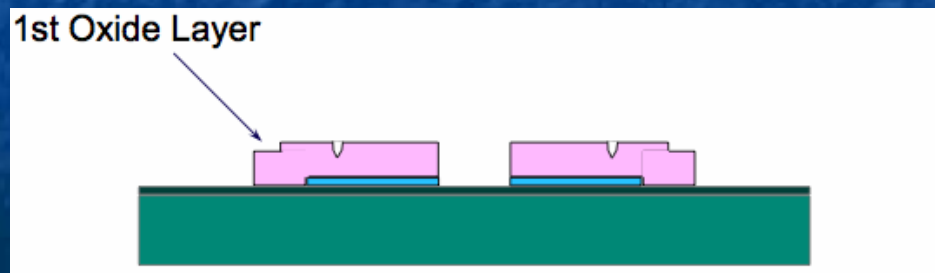
Even though it does still jump forward 5-10 steps between images

Source: Prof. LaVern Starman, Wright State University  
[http://www.cs.wright.edu/people/faculty/kxue/mems/MEMS\\_3FabricationM06.pdf](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):

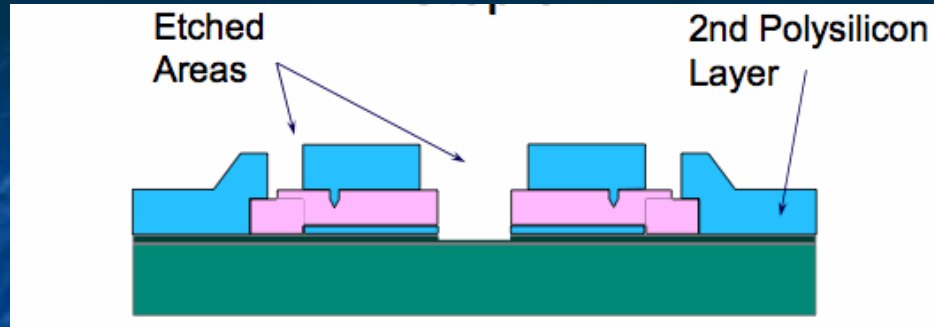


Deposit and pattern a thick oxide layer (pale purple), and then actually pattern and etch it twice:

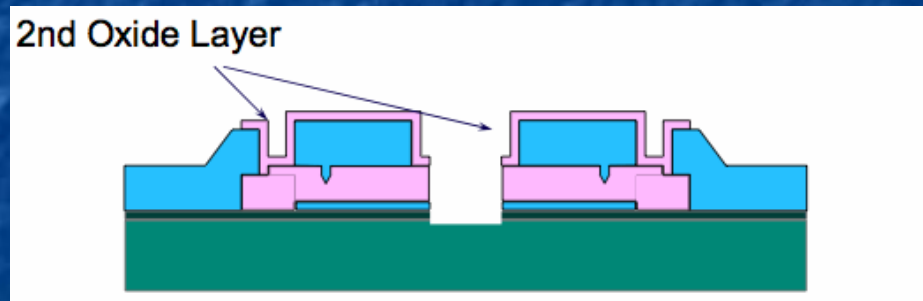




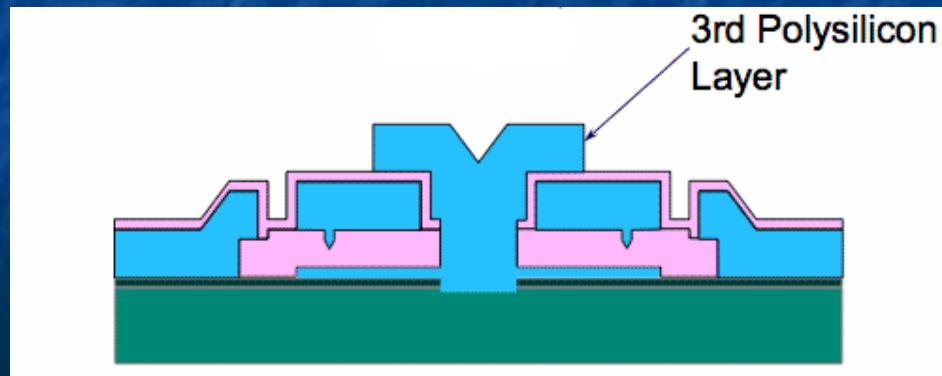
Deposit and pattern a second polysilicon layer (pale blue):



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



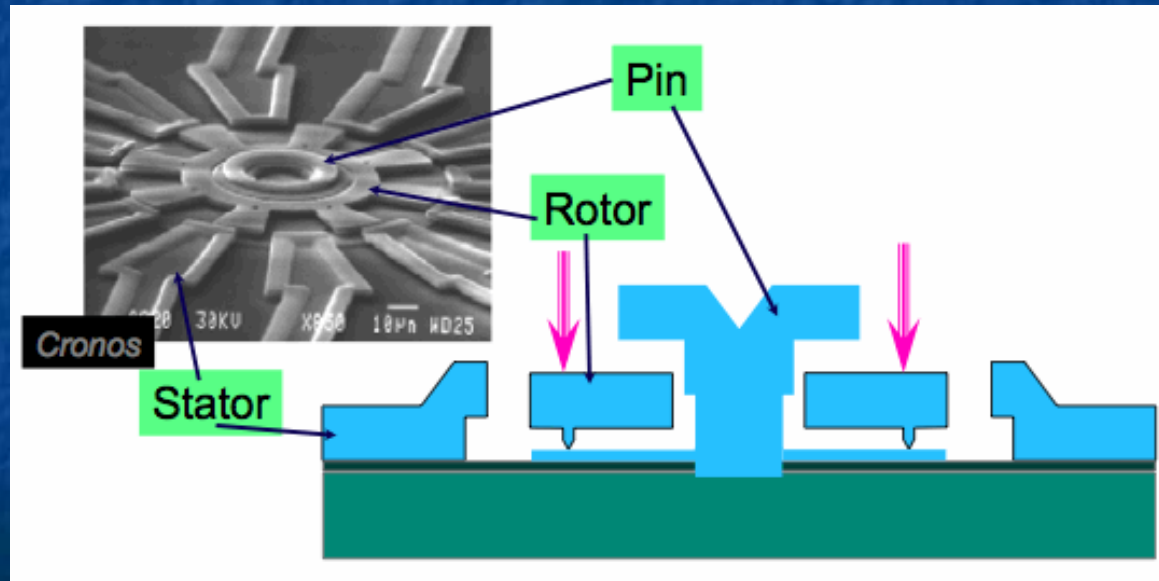
Deposit and pattern a third polysilicon layer (pale blue):



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



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





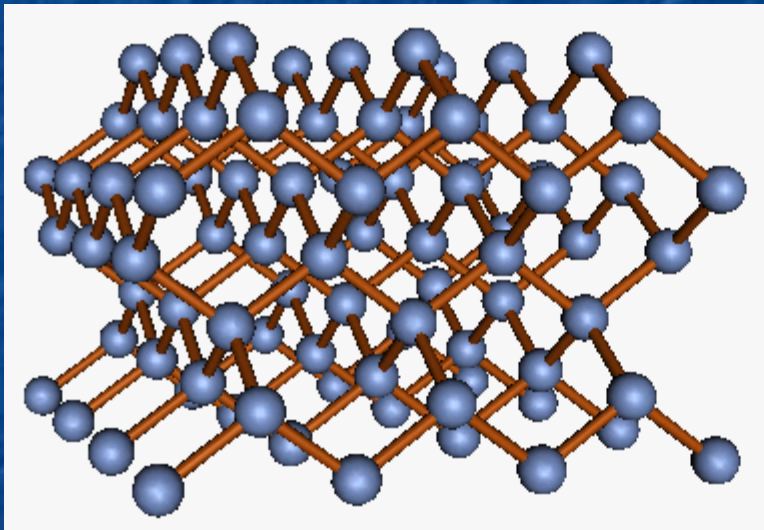
*To complete Microfabrication's bag of tricks, need one more thing:*

*"Anisotropic Etching"*

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

But, Crystals + Very Special Etches  $\rightarrow$  Direction dependent (anisotropic) etching

It depends on the bonding of atoms at the 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:

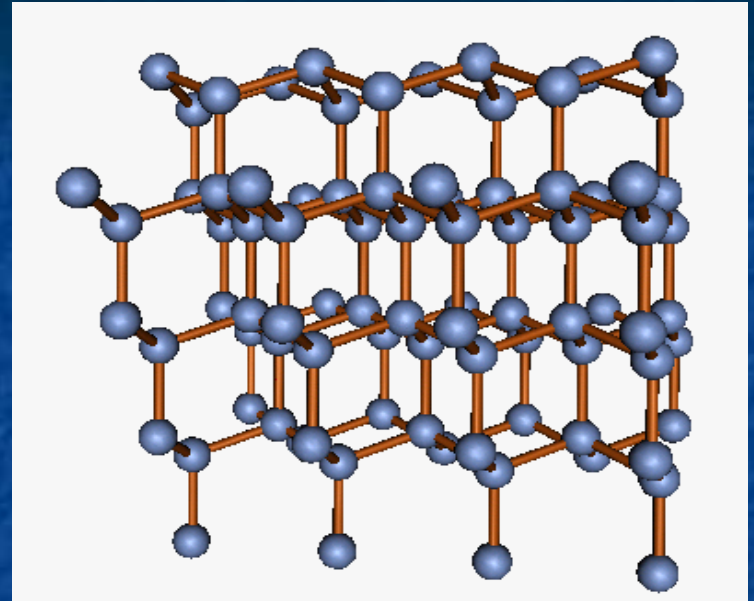
[https://WeCanFigureThisOut.org/VL/Semiconductor\\_crystals.htm](https://WeCanFigureThisOut.org/VL/Semiconductor_crystals.htm)

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

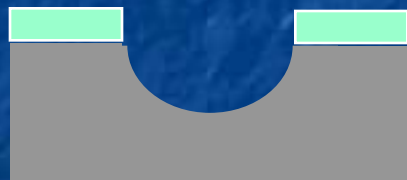
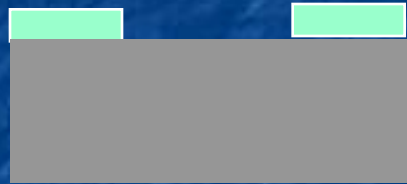
2 bonds = harder to break

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

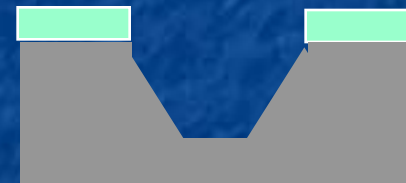
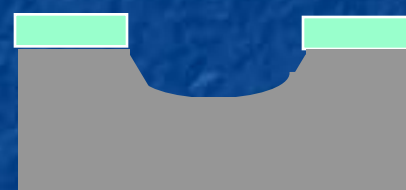
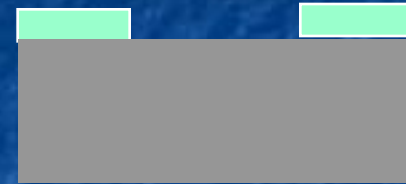


# Normal vs. Anisotropic Etch:

Normal (isotropic):



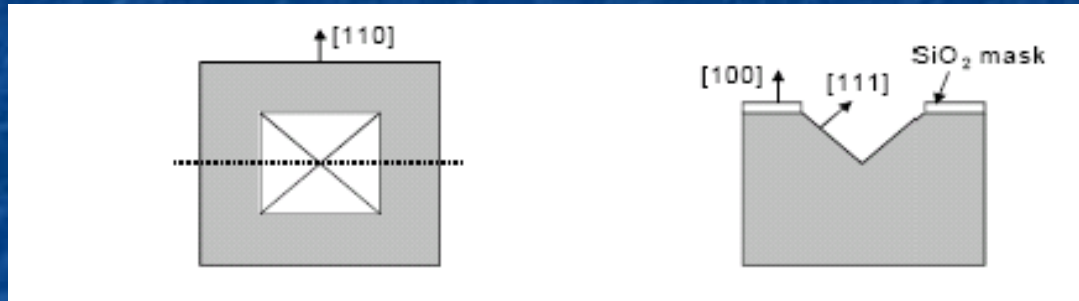
Anisotropic:



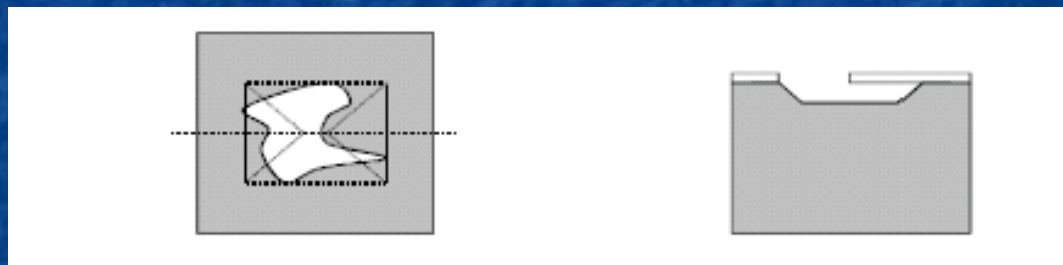
Anisotropic etched surface develops (111) facets !!!

## *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!*

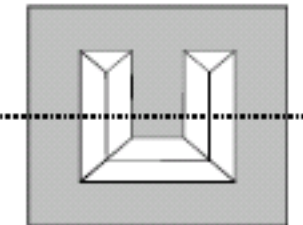
Figures again from Professor R. Bruce Darling's Microfabrication Notes - University of Washington <http://www.ee.washington.edu/research/microtech/cam/PROCESSES/NEWtutorial.html>



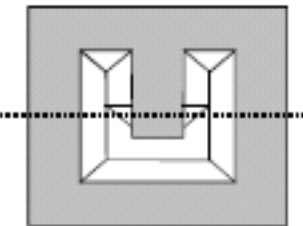
## Or to make (nearly) free-standing structures:

Start with "U" shaped hole in masking layer:

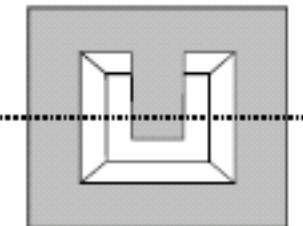
First - Faceted trench in Si



Trenches begin to undercut mask



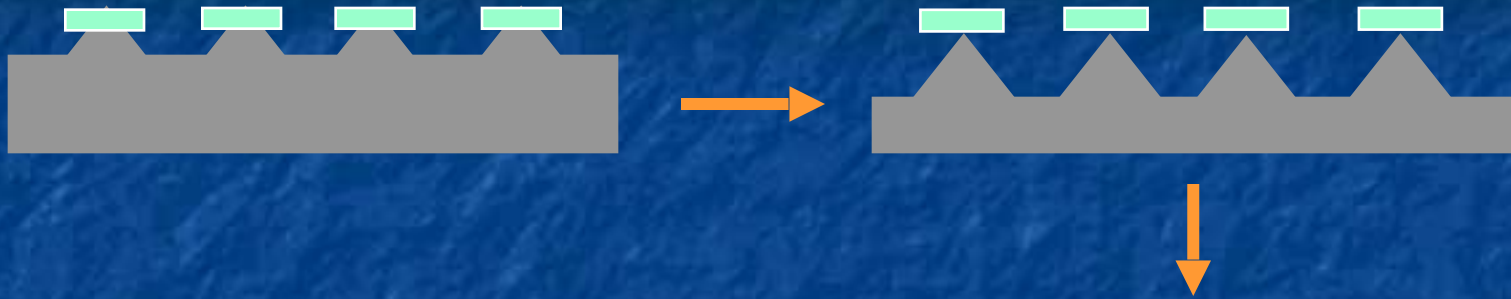
Finally part of mask left free-standing



Diving board over swimming pool!

Source: R. Bruce Darling  
University of Washington

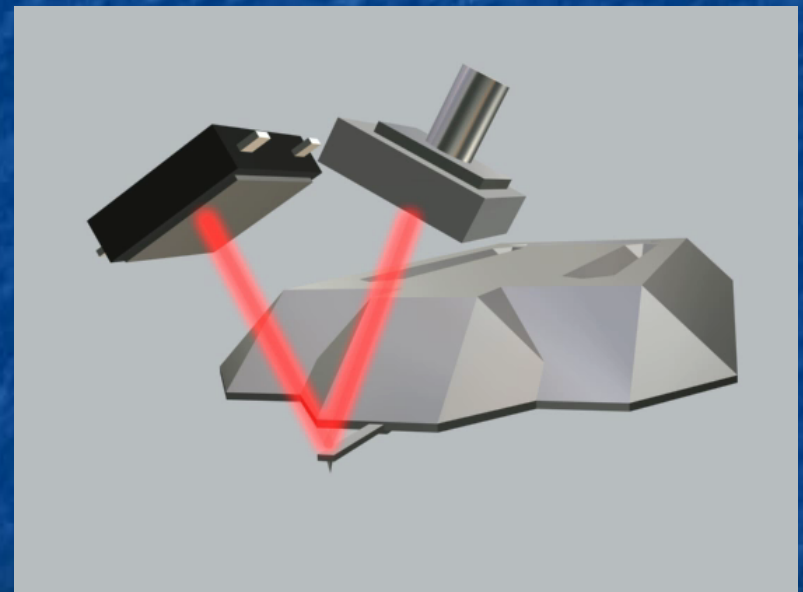
*Or if leave islands of masking layer on top of the silicon:*



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

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

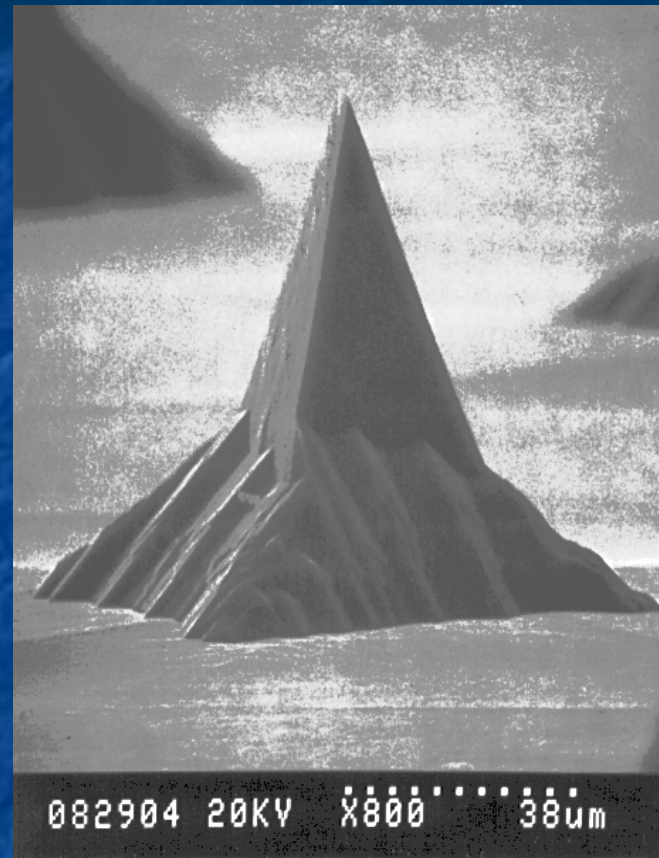


From UVA "Virtual Lab" webpage on "Atomic Force Microscope"

[https://WeCanFigureThisOut.org/VL/easyScan\\_AFM.htm](https://WeCanFigureThisOut.org/VL/easyScan_AFM.htm)



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



*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



# *Credits / Acknowledgements*

Funding for this class was obtained from the National Science Foundation (under their Nanoscience Undergraduate Education program).

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

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