Great Science versus Viable Technology?

Class goal is to prepare YOU to judge new NanoSCIENCE & NanoTECHNOLOGY

But it's not just a question of cold hard facts, the key word is **judgment**

And I realized that for this I really needed to adjust your level of skepticism

WHY? Science is generally taught in the PAST TENSE

But Nanoscience is PRESENT TENSE

It is going on right now!

Does that make it more exciting? Absolutely!

But it also means we lack the benefits of hindsight

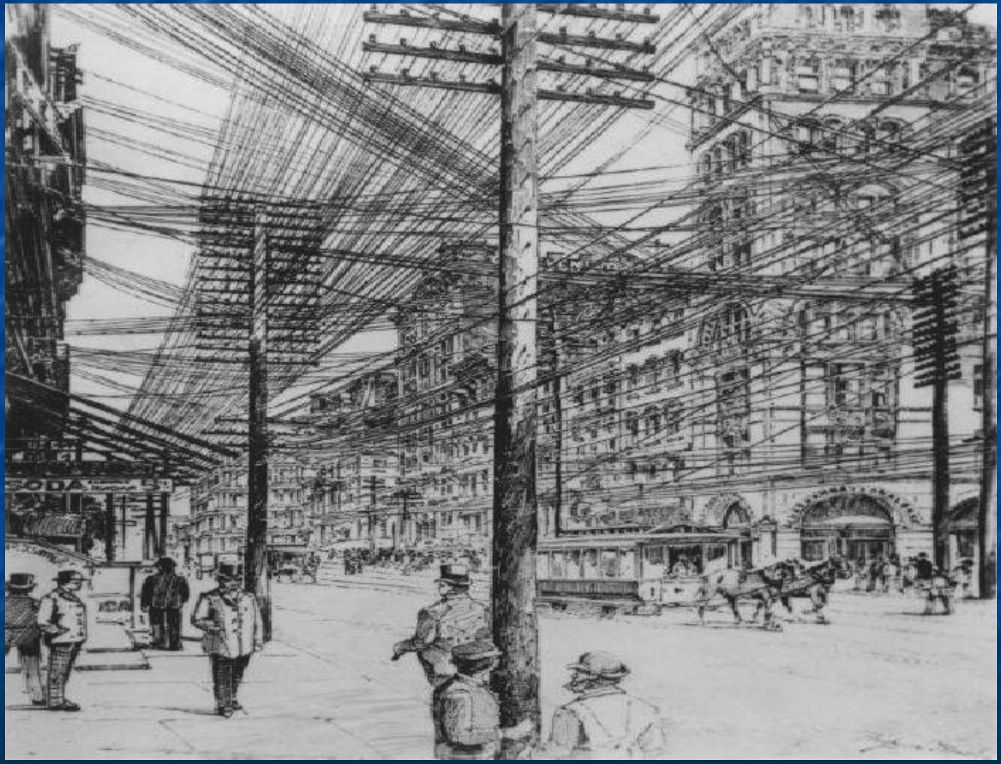
It's thus particularly important that we understand scientific process

I worked at Bell Labs: Largest most significant R&D lab of the 20th century

Bell Labs was set up after Bell System became a government sanctioned monopoly

Which was allowed because this is what 1890's New York City looked like

after unrestrained competition between new telephone companies:



Bell Labs factoids:

Bell Lab's entire budget was paid by surcharge on every customer's monthly telephone bill

Ma Bell's employee count reached just under 1,000,000 while I was there (1976-1996)

Bell Labs alone had almost 30,000 employees! Basic research alone had almost 1500!

Think ~ 10 university engineering schools, superbly funded, working on related problems

So Bell Labs' resources, scope, time horizons were unprecedented!!

Inventions: Transistor, Laser, CCD, UNIX, C, information theory, radio astronomy

Nobel Prizes:
1937 - Davisson - Demonstration of Wave Nature of Matter
1956 - Bardeen, Brattain & Schockley - Transistor
1977 - Anderson - Solid State Theory
1978 - Penzias & Wilson - Proof of the Big Bang
1997 - Steven Chu - Laser Cooling and Trapping of Atoms
1998 - Stormer, Laughlin & Tsui - Fractional Quantum Hall Effect
2009 - Boyle & Smith - CCD digital imaging sensors
2014 – Eric Betzig – PALM Microscopy

Patents: Over 26,000 (of which I contributed 14)

And at Bell Labs I had a rather unusual career path

First 16 years spent as basic researcher and research department head

But spent last 5 years supporting manufacturing plant, doing technology transfer

For Bell Labs, these were RADICALLY different roles:

Research & Manufacturing were deliberately located in separate STATES!

And my people and I didn't exactly volunteer for that switch:

After break up of the company in 1980's, it began to fail

They essentially pushed all researchers into development roles

(And, a few years after I left, Bell Labs collapsed)

Nevertheless, this experience:

Gave me rare insight into the differences between Researchers and Developers

Observation #1: Researchers vs. Developers

World class basic researchers MUST be wild-eyed optimists

Their GOAL is to do what no one has ever done before!

And to do this even if "conventional wisdom" says it can't be done!!

STOP - THINK about what this says about researcher's personality (ego . . .) !

Manufacturing people MUST be cynics

Gravitating toward known, well-proven (= OLD), methods and techniques

Or they would NEVER achieve high-yield production!

Heck, the Sales Dept. would be happy with only ONE NEW THING per product!

And with good enough advertising, ZERO new things could suffice!

Mindsets are so incompatible or even corrosive to one another that corporate R & D are often separated geographically

(So that researchers don't get TOO practical and developers don't get TOO spacey!)

Consequences?

Putting it bluntly:

Discussing commercial possibilities, researchers have a gaping blind spot

When discussing technology they combine innate optimism with ignorance

And yet researchers are often the public face of a corporation:

As scientists, part of their job is to publicly share results

And management encourages this to bolster technical stature of the company

However, this means that when basic researchers make technology predictions

Predictions should be taken with a HUGE grain of salt

(in ANY field of science!)

Observation #2: Quality of Nanoscience "Peer Review"

The **Scientific Method** is built around "peer review:"

Before publication, papers must pass review by peer experts

If paper is accepted and published, it's then further critiqued by all readers

This is normally done through very focused (scientifically narrow) publications

Where ~ ALL readers have SOME expertise in the subjects being written about

But Nanoscience is uniquely broad (because we don't yet know where it is going!)

GENERAL SCIENCE publications are therefore preferred (Nature, Science . . .)

All readers are NOT experts - Even all REVIEWERS may not be experts!

Validity of certain Nanoscience papers has been severely questioned

One produced best known case of scientific fraud in recent history!

Problem's exacerbated by modern publication via the web and/or press release

Consequences?

Again putting it bluntly:

Nanoscience publications have a particularly jaded history

They are prone to exaggeration

They often include overlooked omissions or errors

And, occasionally, outright fraud

Further, veracity is also affected by the nature of nanoscience businesses:

HUGE expense of **Microfabrication** => Big, old, well-established companies

With strong vested interest in protecting their reputation/credibility

Low cost of **Nanofabrication** => Hundreds of small start-up companies

Some of which may “bend truth” to raise capital and/or stock price

(in order for their start-up to survive a few more months!)

This sets the stage for my discussion of Science vs. Technology:

Researchers deliberately isolated from (and naive about) technology

+

Peer review weakened by breadth of field / self-publication trends / business promotion

=> It's very hard to distinguish valid science from questionable "technology"

And you shouldn't blindly accept "experts" word (including mine)

Yet distinction is essential if are to judge prospects of Nanoscience/technology

So, to sharpen our skills at making such distinctions, let's:

1) Identify boundaries for Microscience/technology (where they are more certain)

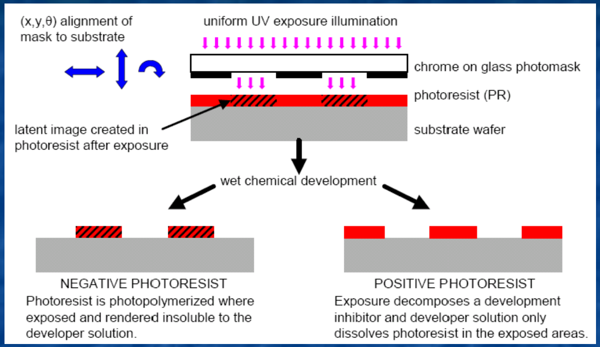
2) Then try to do the same for Nano

Drawing the distinctions in Microtechnology

Relevant example is "photolithography" - optical micro-patterning

Last class described it schematically:

(UV light through shadow mask
onto polymer "resist" coated wafer)



Source: R. Bruce Darling
University of Washington

But what do machines ("tools") really look like and what are they capable of?

Laboratory PHOTO-lithography tools don't look all that different from schematic

Mask and wafer below microscope

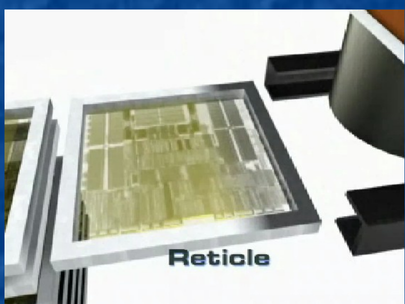
Arm at left and knobs below to move wafer to proper position

UV light source (at rear) then directed via mirror through stack

(Karl Suss MJB3-IR w/ thru wafer IR camera: www.bidservice.com)

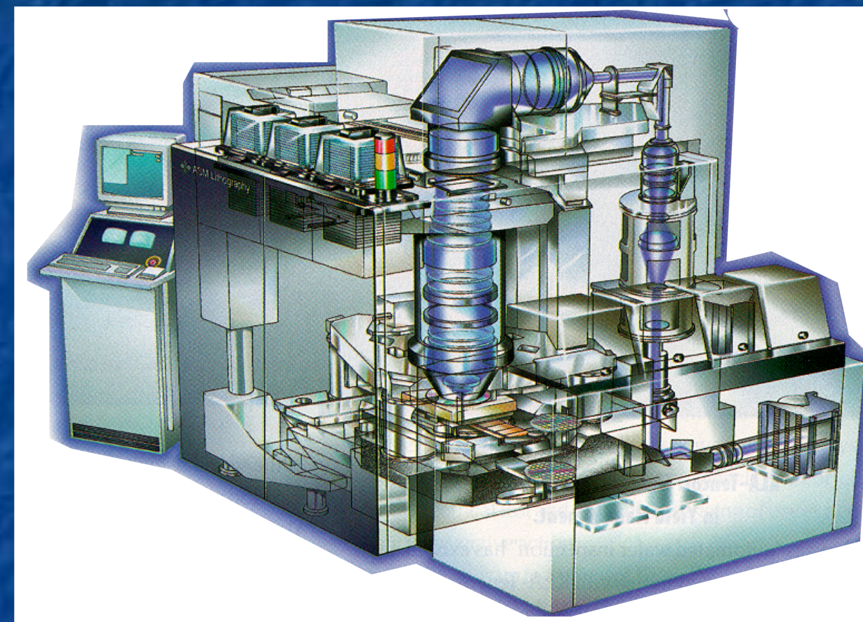
*More modern **production** photolithography tools:*

Nikon stepper recreated in virtual reality on WeCanFigureThisOut.org website:



(https://WeCanFigureThisOut.org/VL/Photolith.htm)

ASML stepper: 248 nm light, 20M$



(www.asml.com)

Both are capable of printing of entire integrated circuit in a single rapid step

Then precisely moving to next circuit and repeating process ("stepping")

Hands-off, fully automated!

Preceding is CLEARLY technology

But where does boundary get fuzzy?

How are the shadow masks for those tools patterned?

E-Beam Lithography (E stands for electron) - Derived from common SEMs!

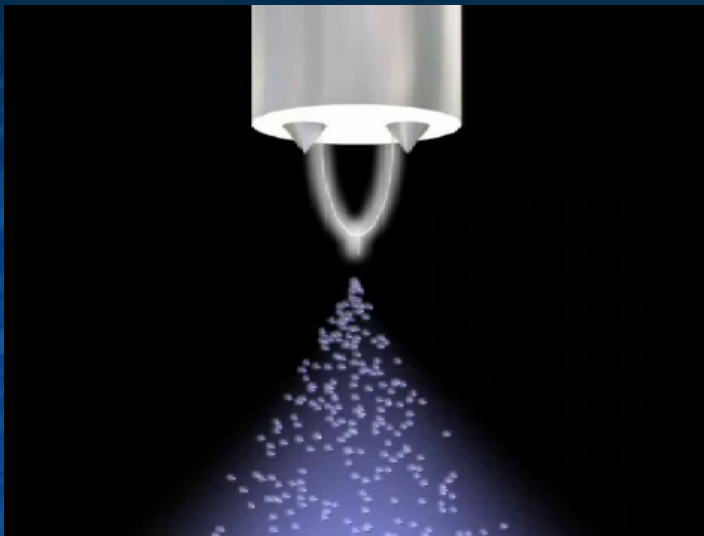
Scanning Electron Microscope:

Laboratory workhorse for seeing things

smaller than the wavelength of light

But how does it work?

From https://WeCanFigureThisOut.org/VL/SEM.htm:



Start by heating metal filament

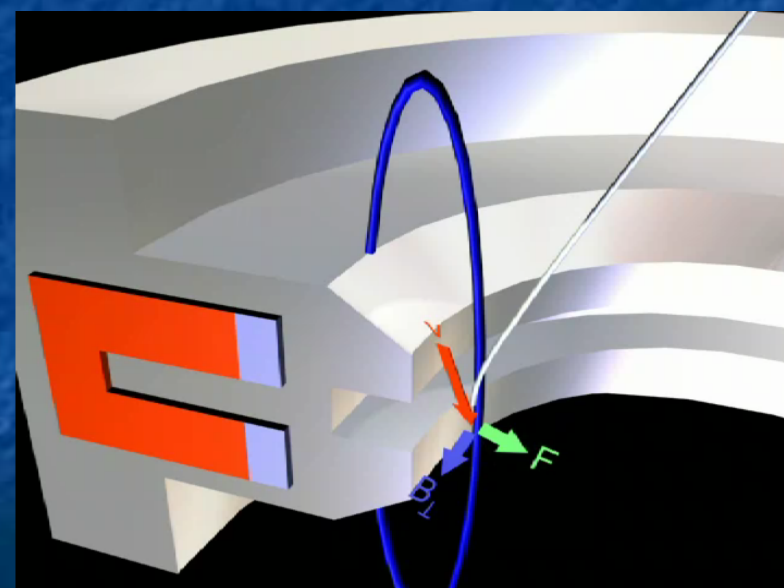
Then pull electrons off with positive electrode

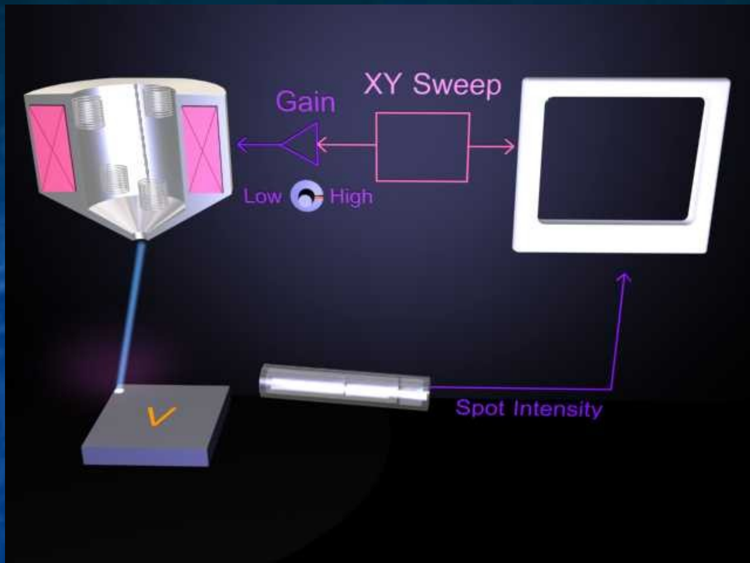
Diverging electrons pass through bore of cylindrical magnetic lens

$$Force_{magnetic} = q\ (v \times B)$$

Electrons spiral 1/2 turn around B field loops

Diverting back toward axis (= focusing)





Small electromagnetic coils in last lens cycle current up and down

AC magnetic field scans e-beam across sample

"Secondary" electrons are emitted from the sample

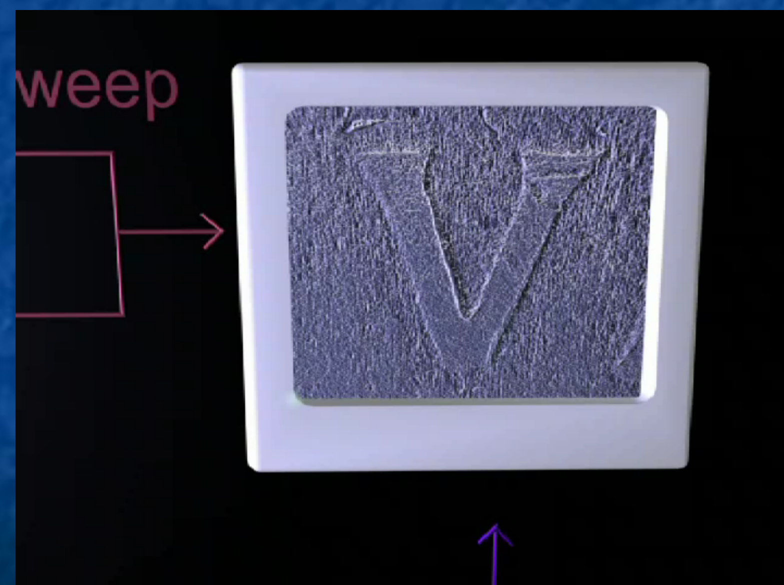
Electron multiplier (cylinder) amplifies their signal

Different materials emit different numbers of secondary electrons

Electrons from different shapes + slopes more or less likely to reach multiplier (huh? explain!)

Result: Get "contrasting" brightness point by point

Mapped into corresponding pixels on screen
(here real SEM image of 'V" on Virginia quarter coin)



To convert SEM to e-beam lithography, you only need to:

Add a "beam blanker" = Means of rapidly turning beam off and on

You can just apply voltage to two parallel metal plates to slam beam off to the side!

Then add a computer to decide when the beam is to be on or off

For instance, based on CAD drawing of desired mask

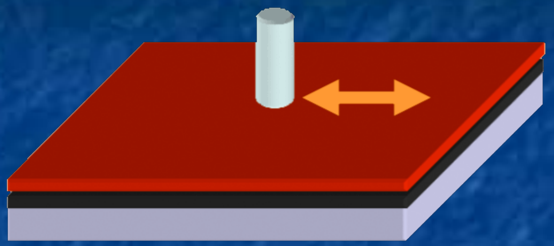
Not surprisingly, result is an instrument

that looks almost identical to SEM!

(UVA's e-beam lithography system)

What has this got to do with making masks?

Scan e-beam across photoresist (polymer) covered, metal-coated, glass plate



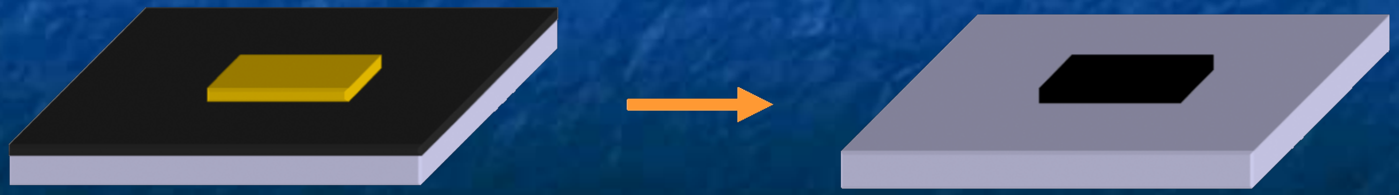
Where beam was on, photoresist polymer is "exposed" (i.e. its bonding altered)

Works as well or better than UV:

e-beam has more energy!

Then "develop" photoresist pattern:

The etch away unprotected metal:



But did you spot key difference from earlier photolithography?

Photolithography printed entire integrated circuit at once!

All elements were printed "in parallel" across full circuit area:

E-beam lithography printed point by point

As e-beam was scanned "sequentially" or "serially" across mask:

But HERE serial e-beam write is OK:

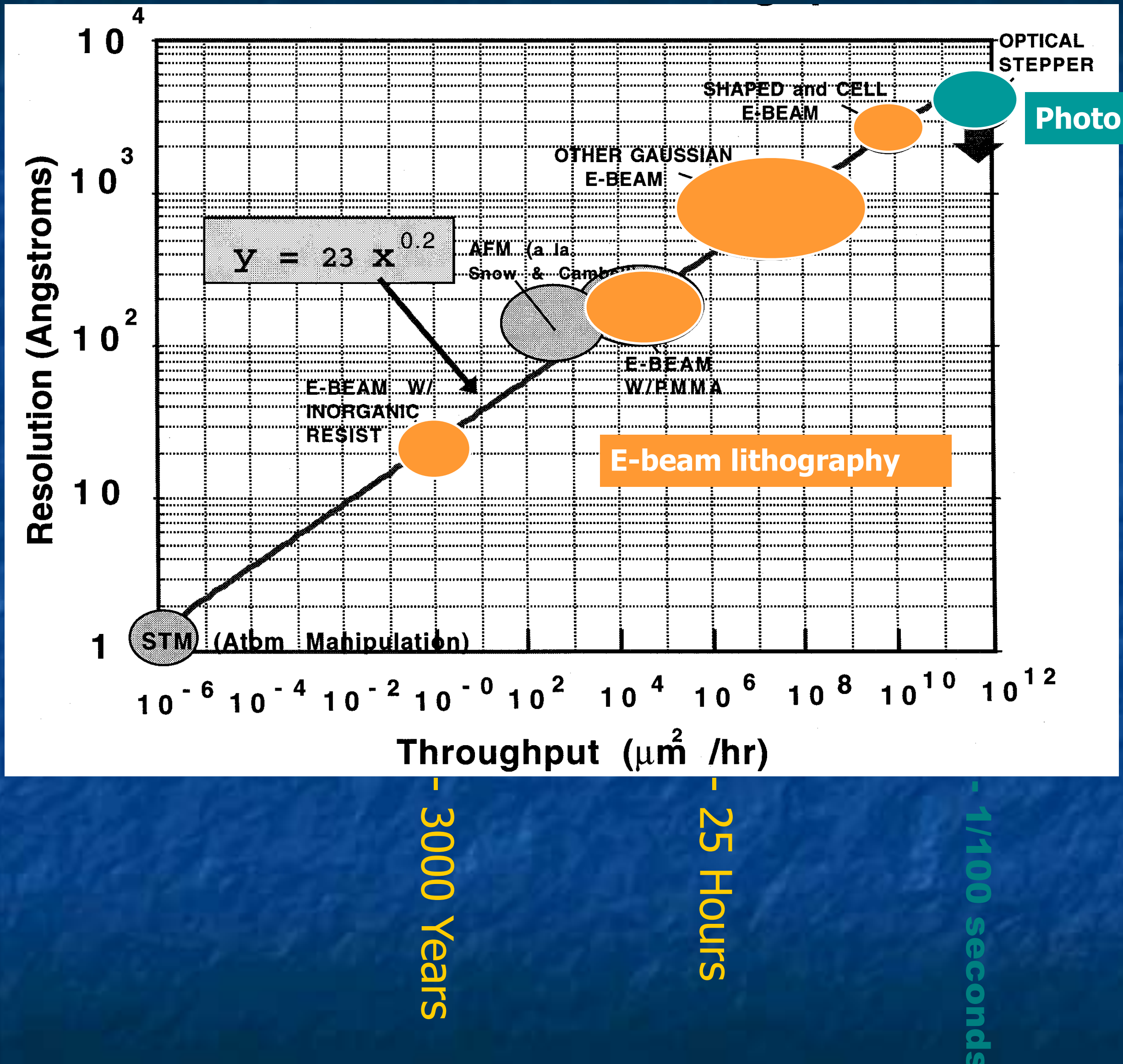
Mask is created once, lasts a long time, is used to print 1000's of wafers!

E-beam → Computer programmed, ultra-fine patterning (to ~ nanometer scale)

So slow e-beam mask creation is still economically viable technology

Because we can afford slow expensive process for production of <u>reusable</u> masks!

Photo vs. E-beam lithography patterning rates?



Source: Don Tennant
(then at) Bell Labs
Assumes printing 50% of area

5x5 mm² =2.5 x 10⁷ um²
(~ single small circuit)

← Time to print that area

So both techniques = technology, right?

Applied as described above, YES   But as often applied in nanoscience, NO!

E-beam lithography, with its resolution of ~ 1 nm is often used in nanoscience

I attended presentation on semiconductor nanowires:

Heard about clever techniques for growing these nanometer diameter wires

And new approaches for trying to float wires into position on circuit

Then speaker quickly mumbled "contacts made by high-resolution lithography" **OOPS!!!**

→ Slow serial e-beam, likely going into SEM imaging mode to FIND end of each wire!!

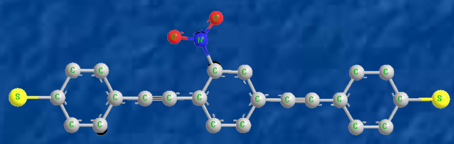
Was murmur through conference room as his "technology" crashed and burned!!!

Further examples?

Rattner & Aviram 1974: Single organic molecules might = nano-electrical switch!

Proof? Mark Reed's 1997 "Break Junction:"

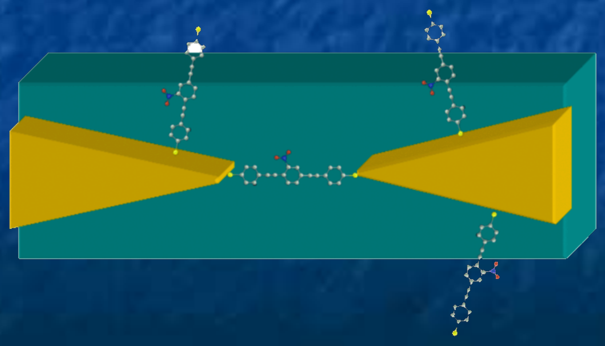
- Solution containing candidate molecules (yellow S atoms like Au):



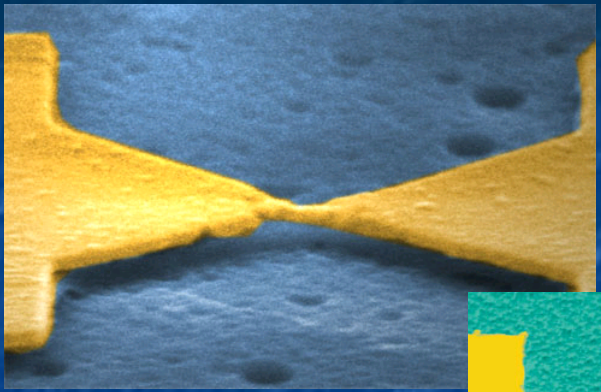
- Plus nano-patterned gold line:

- Expand substrate (by heating, bending, or piezoelectric crystal) until gold is drawn apart

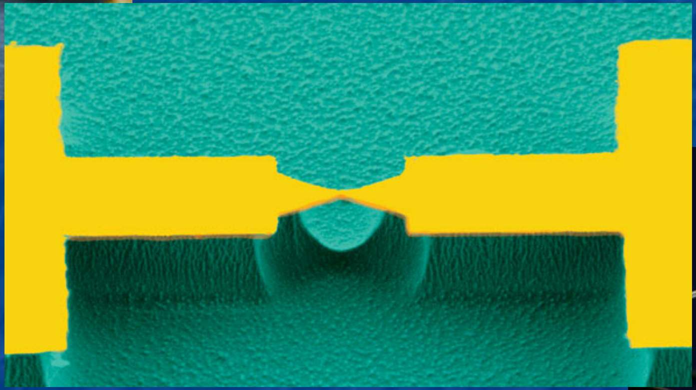
Continue until just ONE molecule fits in gap:



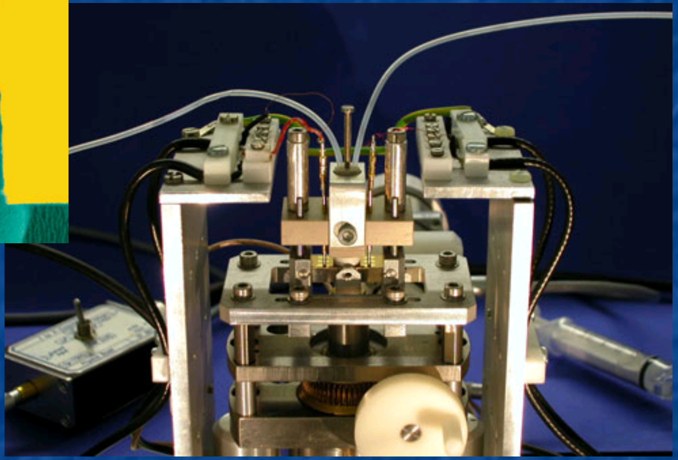
Photos of an actual break-junction setup:



High and low magnification SEM images of unbroken break-junctions (left/center respectively)



Mechanism for pulling break-junction apart:

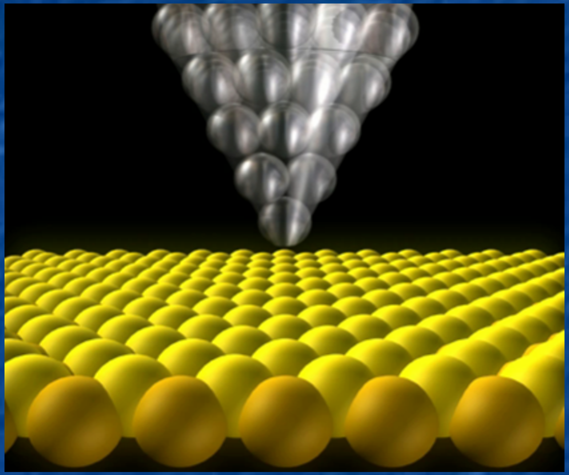


University of Basel: http://pages.unibas.ch/phys-meso/Pictures/pictures.html

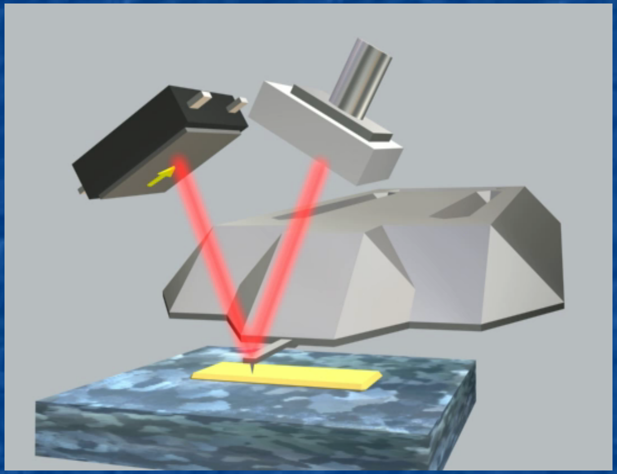
INCREDIBLE SCIENCE! But is it technology? Absolutely not!

Investigators noted similar configuration in nanoscale tips of:

Scanning tunneling microscopes (STMs)



Atomic Force Microscopes (AFMs)



Some inserted molecules into gaps (even as AFM tip bounced!) to study molecules

No problem - It's still great, powerful, science!

Some proposed memory cells based on STM Tips + Atoms/Molecules

Push atom/molecule into place for digital 1, remove it for digital 0

Others explored direct use of STM or AFM for lithography:

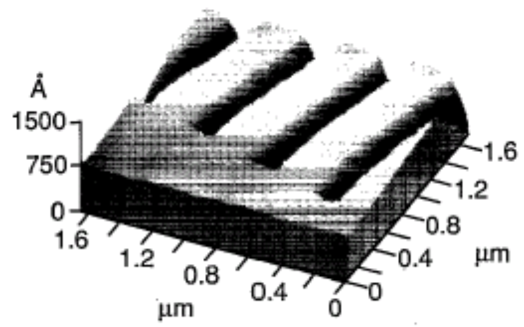


FIG. 1. 1.6 μm$\times$1.6 μm AFM image of a pattern fabricated by direct chemical modification of the H-passivated Si (100) surface and a subsequent etch in hydrazine. The total etch depth is 120 nm.

Fabrication of silicon nanostructures with a scanning tunneling microscope

E. S. Snow, P. M. Campbell, and P. J. McMarr[a)]
Naval Research Laboratory, Washington, DC 20375

STM inducing point-by-point oxidation of silicon

→ Oxide pattern → Subsequent etch mask

(Applied Physics Letters 63, 749 (1993))

Same process applied using AFM to fabricate

prototype nano field-effect transistor

(Applied Physics Letters 66, 1338 (1995))

Fabrication of nanometer-scale side-gated silicon field effect transistors with an atomic force microscope

P. M. Campbell,[a)] E. S. Snow, and P. J. McMarr[b)]
Naval Research Laboratory, Washington, DC 20375

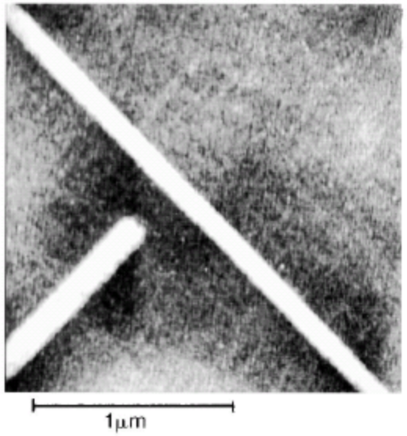


FIG. 1. AFM image of a latent oxide device pattern (prior to etching) imaged with the same tip used to write the pattern immediately after it was written. The source-drain channel pattern is the diagonal line. The side gate oxide line approaches from lower left. Vertical scale (black to white) is 2 nm. The oxide pattern height is ~1.5 nm.

Above was also great, even visionary, Nano<u>science</u>

NRL authors never claimed that STM or AFM writing was basis for Nano<u>technology</u>

But others HAVE suggested this . . . repeatedly . . . to this very day!!

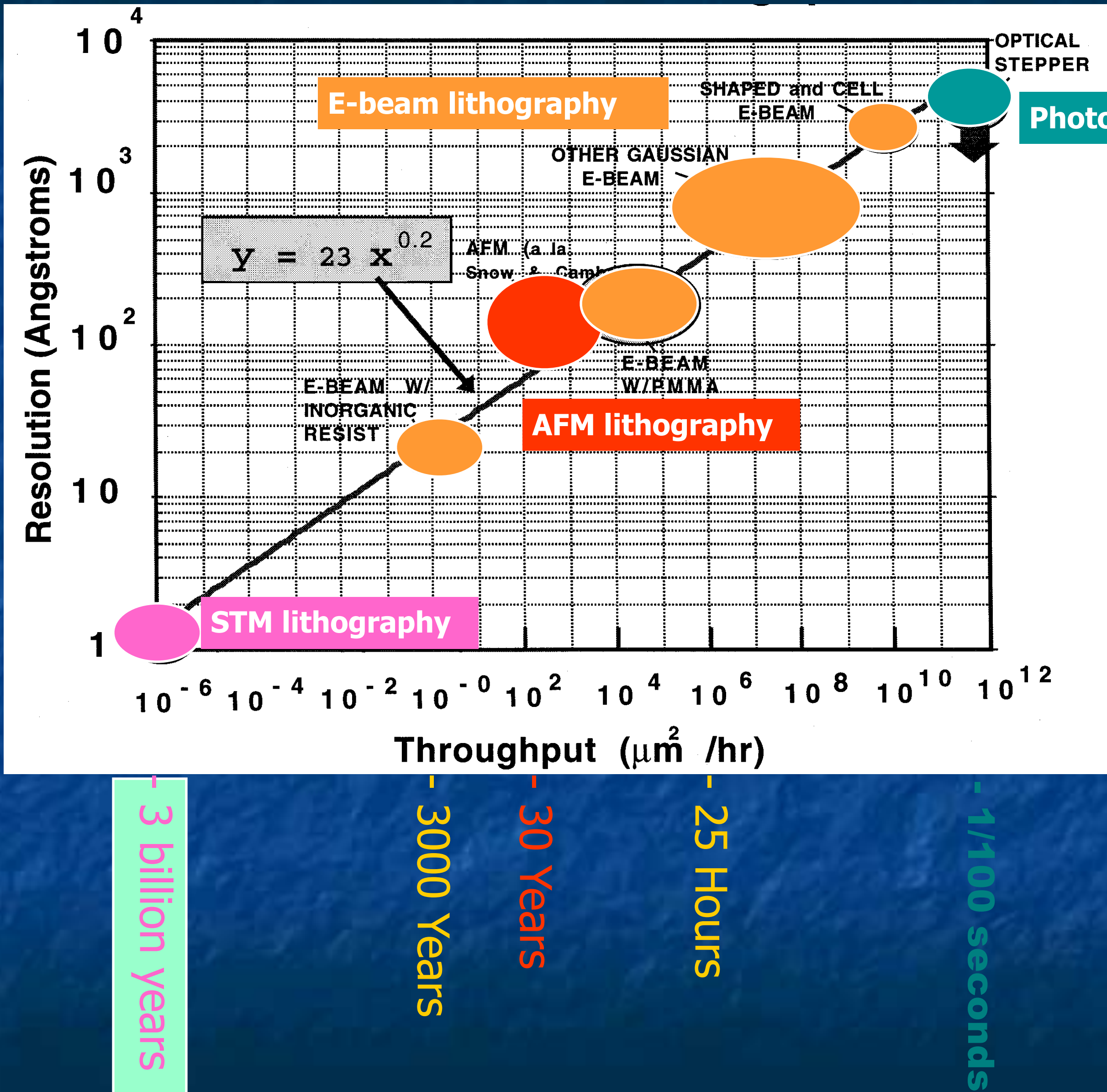
Pushing atoms is also suggested as technology . . . repeatedly . . . to this very day!!

Saw another such paper + corporate press release in recent months!!

What is the exact problem?

To answer, must finally go to left end of figure I used earlier:

Processing times for ALL lithographies:



5x5 mm² (=2.5 x 10⁷ um²):

TIMES FOR ONLY 5x5 mm²

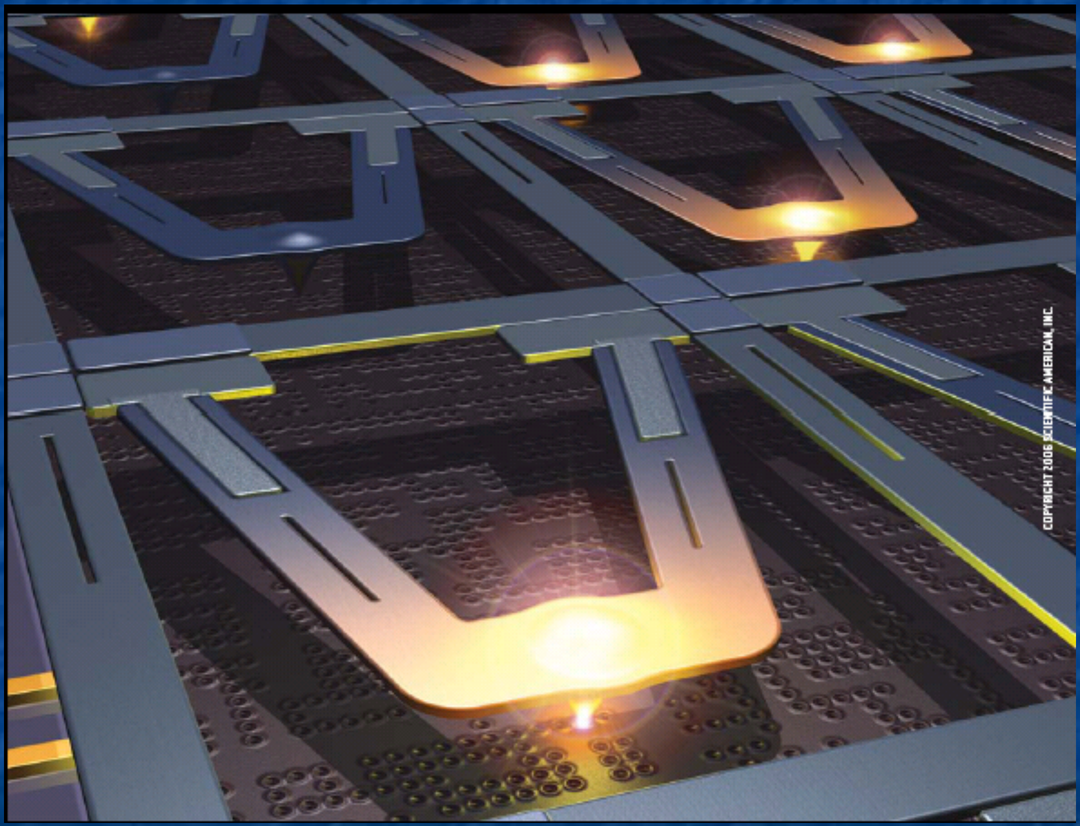
Wafers now 300 mm across! (~70,000 mm²)

→ 9000 billion years

Universe ~ 14 billion years!

We're now experts at distinguishing good science from viable technology

So try this proposal on for size:



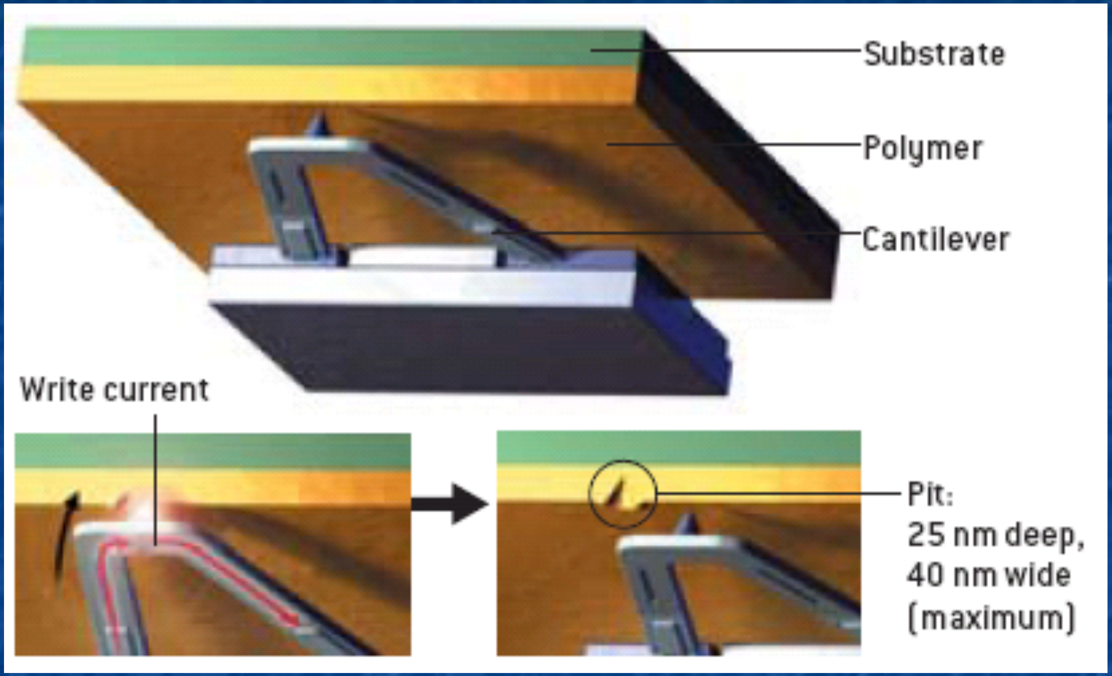
Proposed by IBM

Here described in Scientific American:

"The Nanotech Revolution" (2006)

Which works (upside down) by:

1) Writing a bit by passing heat through cantilever to melt pit in polymer



Scientific American "The Nanotech Revolution" (2006)

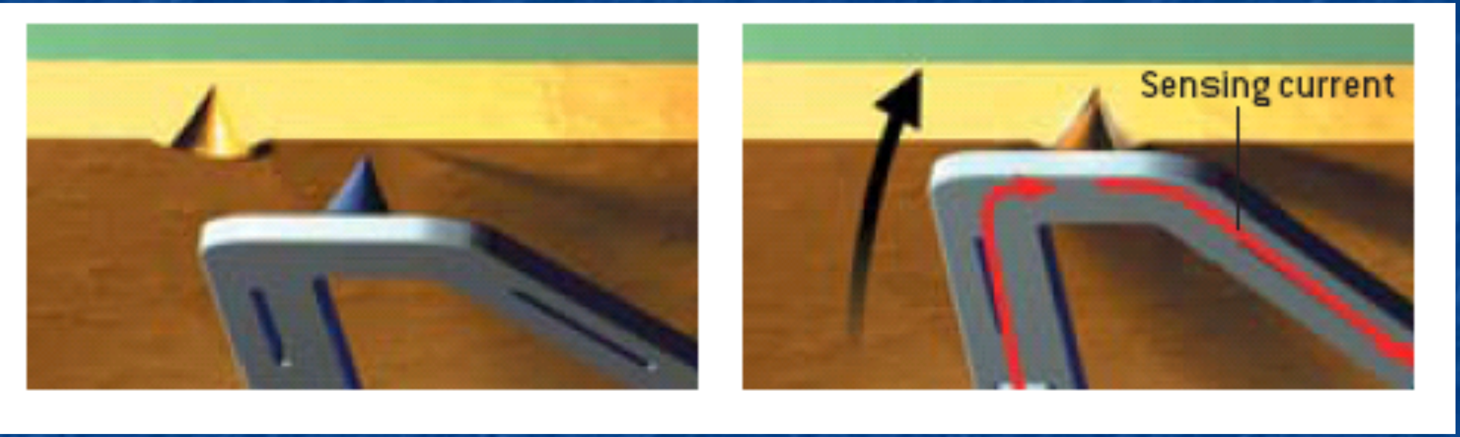
Presumably upside down so dust/particles can’t fall on surface

Even though nanoparticles <u>can</u> "fall" upward when electrostatics overcome gravity!

(So really could have been done right side up with ~ same results)

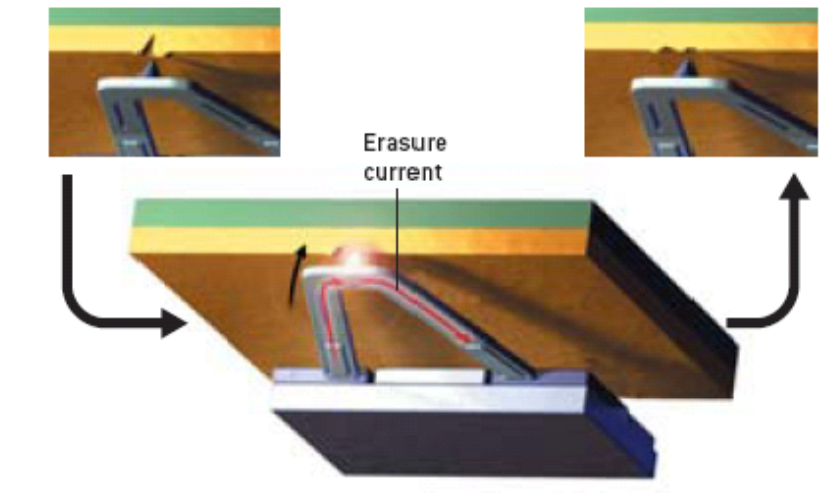
2) Read a bit by sensing when cantilever is cooled by falling into pit

By sensing the decrease in the heating element's resistance as it is cooled



Scientific American
"The Nanotech
Revolution" (2006)

3) Erasing a bit by melting polymer adjacent to pit to ~ fill it in



Scientific American
"The Nanotech
Revolution" (2006)

And using a heck of a lot of these cantilevers in parallel

My take as a fellow **researcher***:*

Their plan is to use slow "serial" point-by-point writing in "parallel" manner

That is, to use a glacially slow process

That I above calculated would take **30 YEARS** to write one circuit

But to do this **simultaneously** at a **WHOLE LOT** of points

Detailed comments:

Basic write / read / erase idea for each cantilever seems sound

Microfabrication techniques are suitable for making cantilever arrays

Article stated that array of 1024 levers already fabricated!

But what if polymer sticks to a point?

So find a better polymer!!

Will points erode? (AFM probes erode after hours of continuous use)

Would limit lifetime number of read-write-erase cycles

*My take having once hung with **development engineers**:*

Generally, for an entire "circuit" to work, all devices in that circuit must work

Unless we use much more complex and costly "fault tolerant" designs

Say we wanted a really simple circuit involving only three devices

If there's 90% chance each device works, what is chance of whole circuit working?

$(0.9)\,(0.9)\,(0.9) = (0.9)^3 = 0.72$ => 72% "yield" of working circuits

But "getting real" I'd guess Intel wants circuit yields of at least 90%

And these days their circuits can easily have 100,000,000 devices per circuit

$(X)^{100,000,000} = 0.9$ => $X = 1$ => 100% according to my calculator

Indicating that 90% circuit yield requires ~ 100% device yield

Again, trying to outsmart my calculator's rounding:

Put in explicit single device yields and calculate whole circuit yield:

Single device yield:	100,000,000 device circuit yield:
0.99	$(0.99)^{100{,}000{,}000} = 0 \Rightarrow 0\%$
0.9999	$(0.9999)^{100{,}000{,}000} = 0 \Rightarrow 0\%$
0.999999	$(0.999999)^{100{,}000{,}000} = 3.7\text{x}10^{-44} \Rightarrow \sim 0\%$
0.99999999	$(0.99999999)^{100{,}000{,}000} = 0.368 \Rightarrow 36.8\%$
0.999999999	$(0.99999999)^{100{,}000{,}000} = 0.905 \Rightarrow 90.5\%$

So EACH device must work with a 99.999999% probability for 90% circuit yield

Above is calculation every circuit development engineer knows well

It is WHY development engineers tend to be so cynical and pessimistic

But it is not a calculation most researchers truly appreciate

Unless some development engineer once **hammered** it into their head

As one such development engineer once did to me!

But it looks to me as if these IBM researchers **have not had that experience**

Because they are, in essence, still saying:

"But I got 1000 devices to work, why not 100,000,000?"

But YOU should now see that, while it is not impossible, is extemely improbable

Indeed, Intel and industry took FIFTY YEARS to get that good!

Evidence one way or the other?

In 2006 IBM authors gave it: 50-50 odds of working within 3 years (i.e. by 2009)

2008: "I'm skeptical . . . But not sure I'd bet against IBM (co-inventors of AFM)"

2009: No news from IBM

2010: My private conversation with an IBM developer

Since: Absolutely nothing new on the web – draw your own conclusion

Summary

Researchers have developed excellent nanoscience tools & techniques

Some of these are also suitable for limited nanotechnology roles

Prime example: E-beam lithography

Other tools are superb for nanoscience - but hopeless for nanotechnology

Prime examples: STM and AFM probes (at least as <u>normally</u> used)

But question of practicality can get REALLY MUDDY

As in visionary "Nanodrive Project"

So stay excited about nanotechnology - But also stay skeptical!

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.