Nano Manufacturing Challenges

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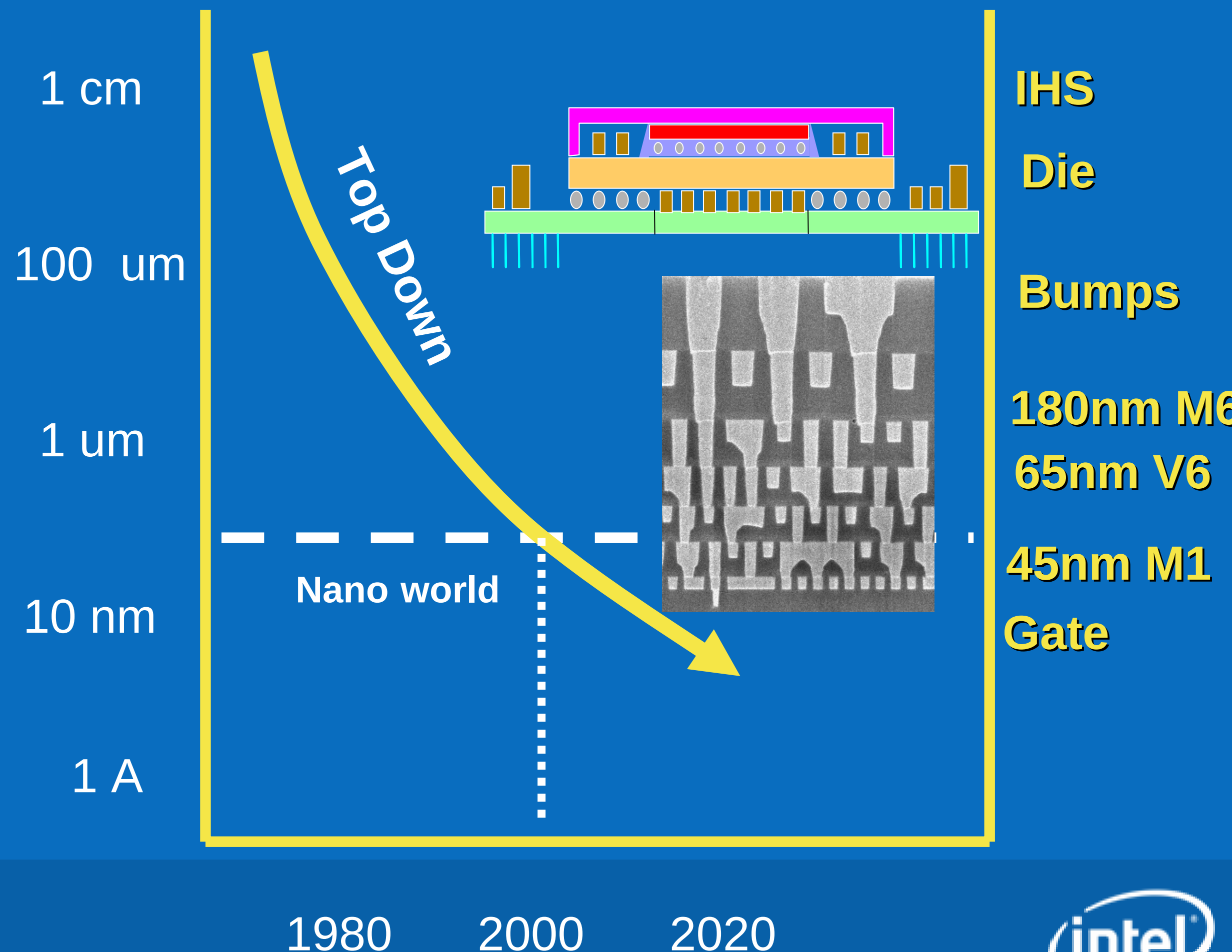
Not all Nano is created equal …

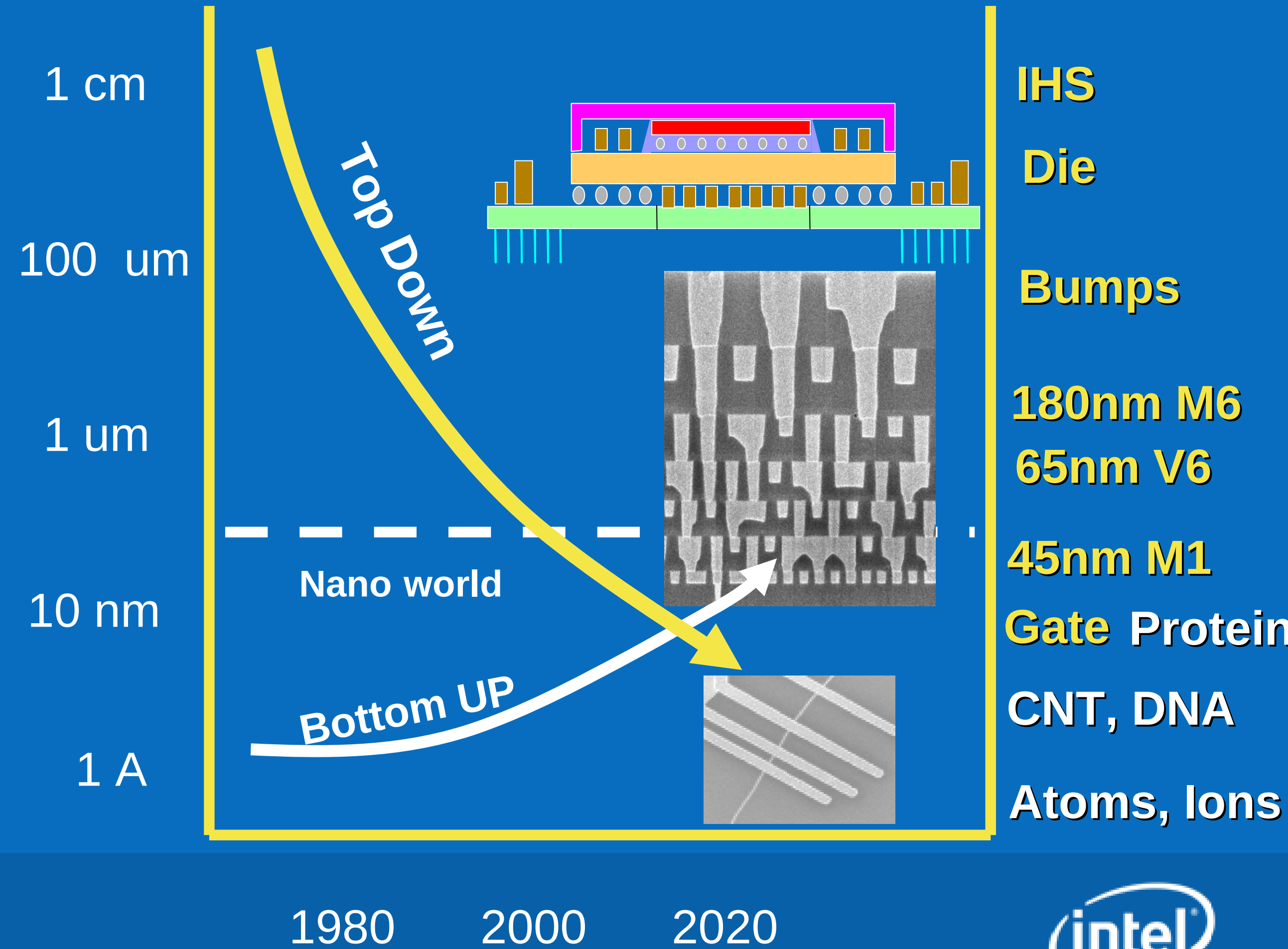
… while commonly defined as lengths below 100nm, how you get there matters

Old News: Electronics has already entered the Nano Realm



Source: Intel

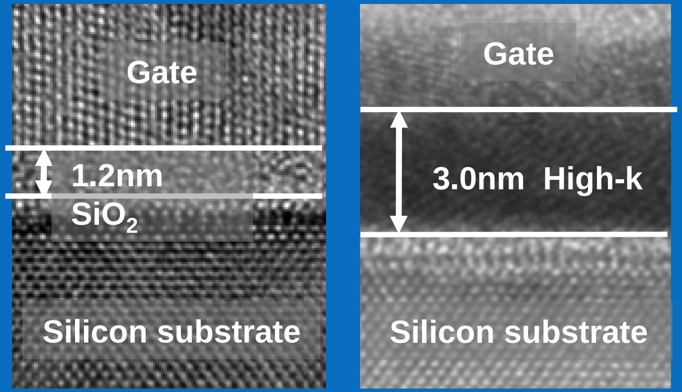
New News: Convergence between Top-Down Scaling and Bottoms-Up Construction

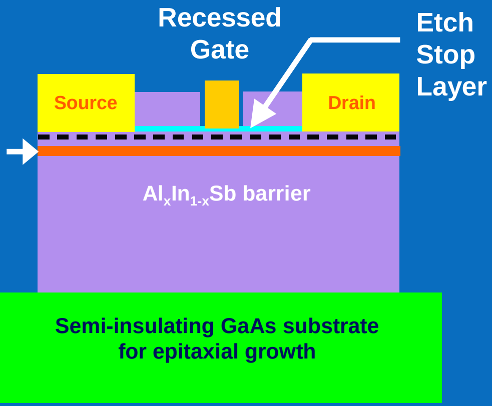


Source: Intel

1D Nano and 2D Macro

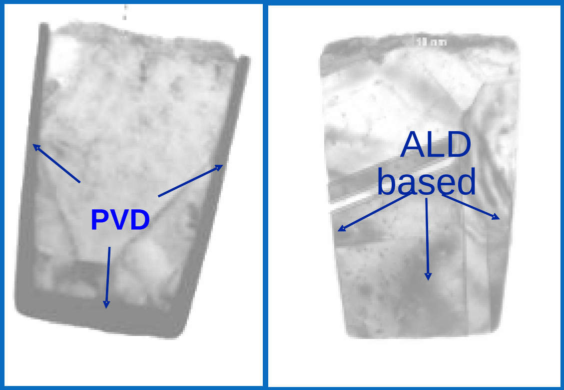
Source: Intel





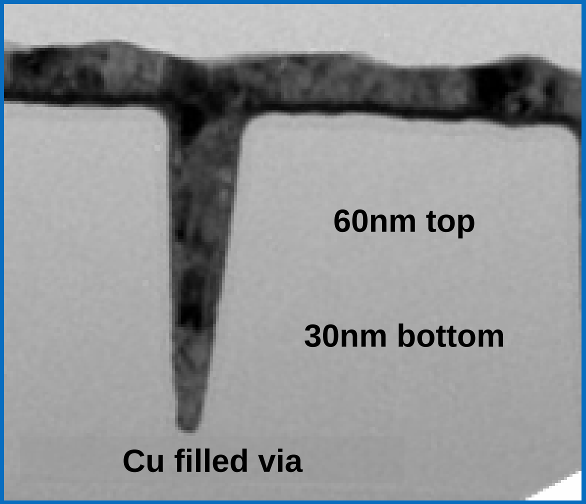
- Novel properties due to dimension, drives new materials
- Formed in place, attached to much larger structure
- Widely used in semi manufacturing

No Buzz



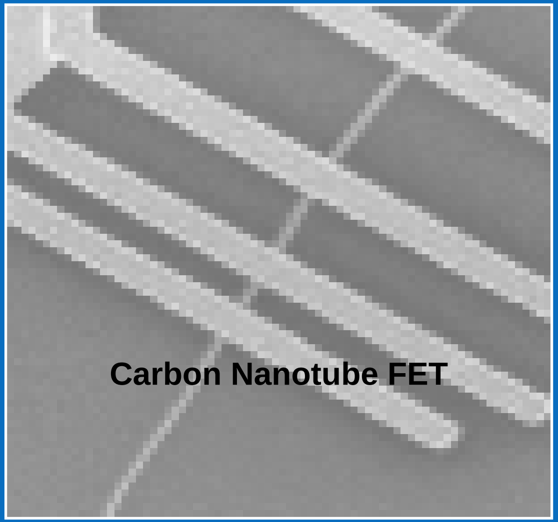
Source: Intel

2D Nano and 1D Macro



Source: Intel

- Novel properties due to dimension, drives new materials
- Formed in place, attached to much larger structure **No Buzz**
- … or formed separately and integrated **Buzz**



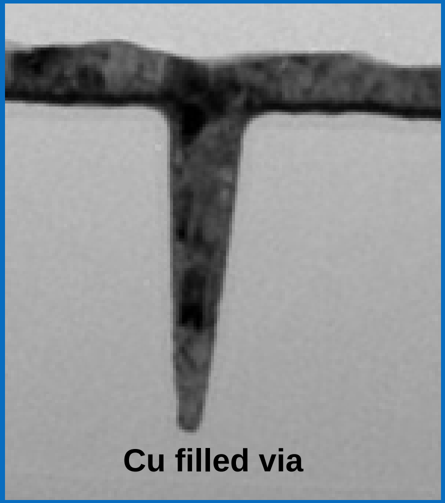
Source: Intel

Flow comparison

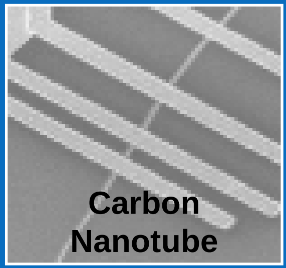
Surface Prep → Deposit → Pattern or Shape

Grow → Purify → Deposit

Surface Prep → Deposit → Align → Modify → Pattern or Shape



Source: Intel

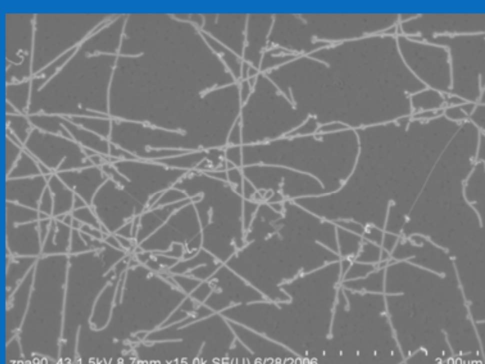


Source: Intel

It can be done … on lab scale

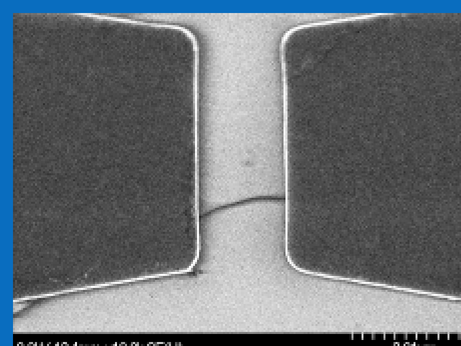
- Single wall CNT grown on catalyst
- Nanotube suspension
- Coupon application
- Dielectrophoresis to align
- Metallization for electrical contact
- High freq verification (20-50GHz, 2-5um)

Grow
Purify
Deposit
Align
Integrate
Verify



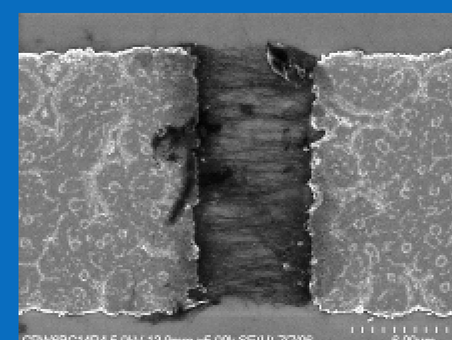
CNT as grown

Source: Intel



Aligned single CNT

Source: Intel



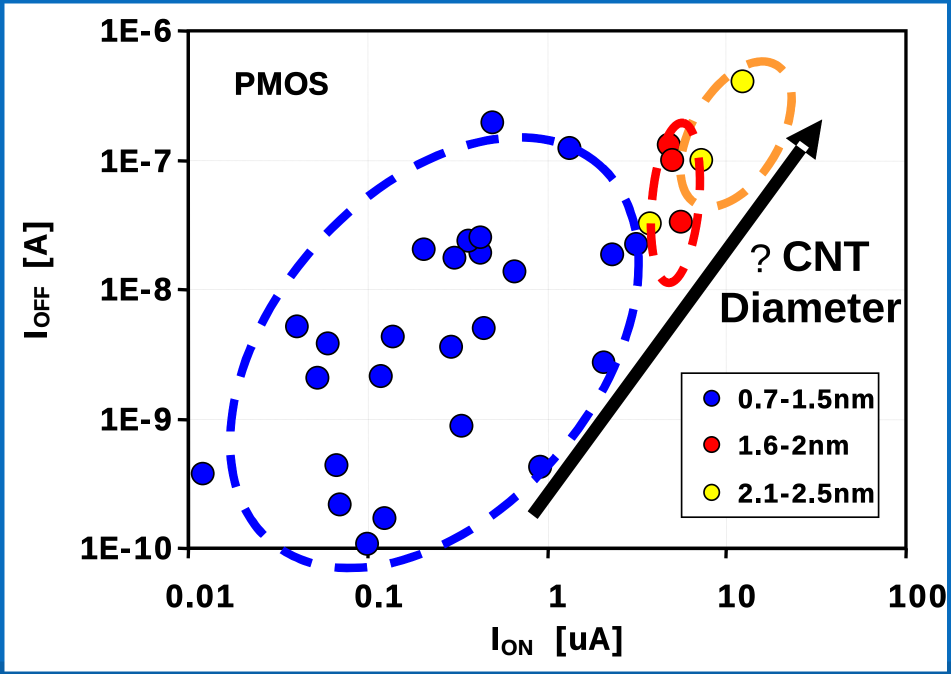
Aligned CNT bundle (few thousand CNT)

Source: Intel

Scaling up for Nanoelectronics

- Purification
  - Begin with clean starting materials
  - Control grow process to reduce variability
  - Remove undesirable contaminants

Possible



Source: Intel

Scaling up for Nanoelectronics

- Purification
  - Begin with clean starting materials
  - Control grow process to reduce variability
  - Remove undesirable contaminants

Possible

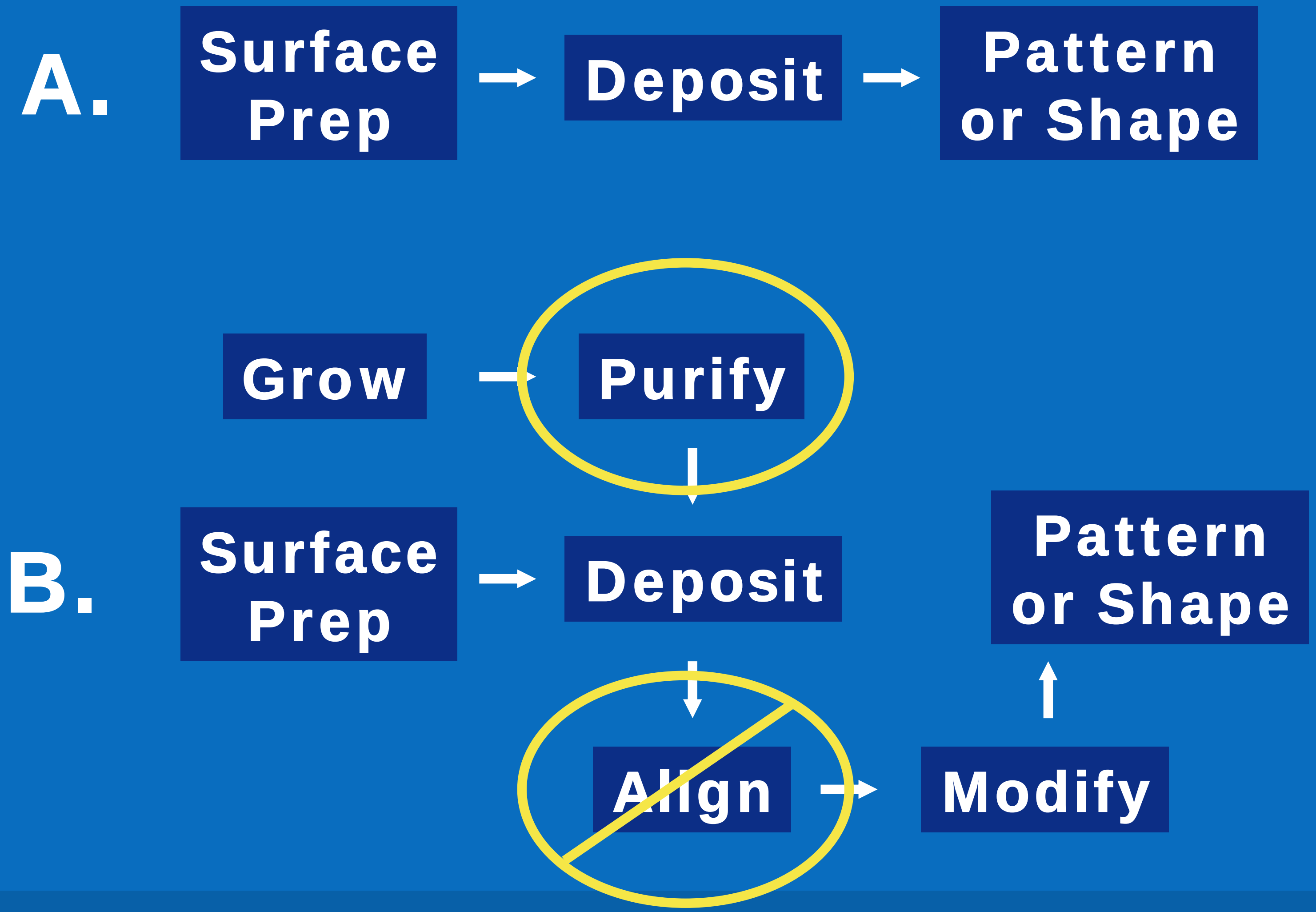
- Alignment
  - In 2015 a leading edge logic device might have >50B transistors
  - A critical layer might have 4 terabytes of pixels
  - Placement requirements of a few nm with error rates $\ll 10^{-14}$

Difficult to imagine a solution

What do you call a free floating 3D nanomaterial?

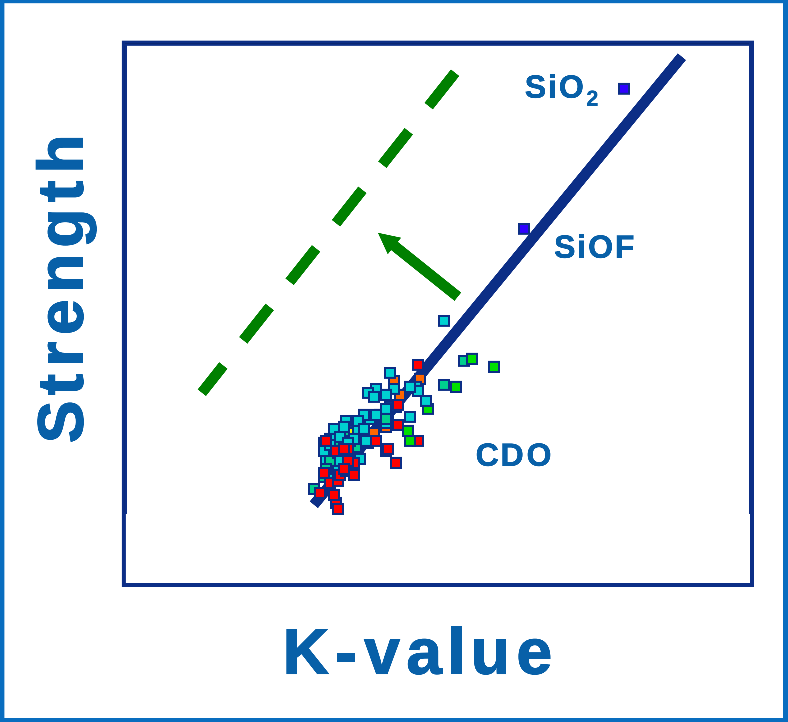
Answer: A particle

Opportunities for 3D Nano



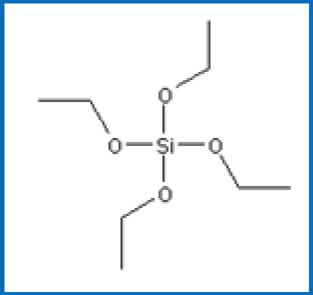
Defining Better Interconnect Dielectrics

- SiO_2 based dielectrics tend to follow same performance curve
  - Holds for a wide variety of precursor chemistries
  - How weak you tolerate determines low you can go for k effective
- Migration from SiO_2 to SiOF to CDO were all difficult but also only incremental k improvement
- Opportunity if there is a way to move off the curve



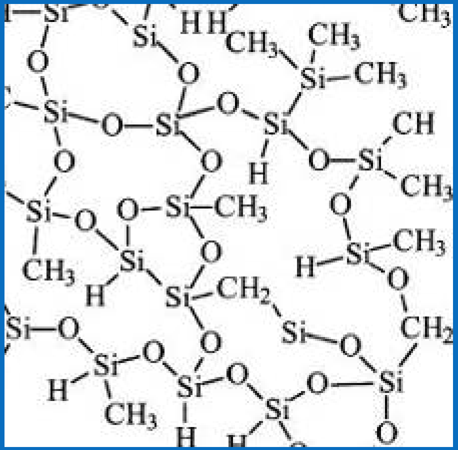
Porosity Options

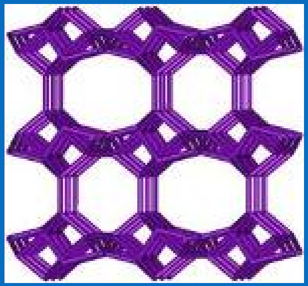
- Example porous ILD
  - About 25% porous (random)
  - Pore size ~2nm
  - At this level, pores are interconnected = extra integration challenges
- Ordered materials
  - Potentially higher porosity but lower interconnection, superior strength
  - Typically only available as spin-on coatings
- Polymers offer the potential of lower porosity <u>and</u> lower strength at equivalent k value

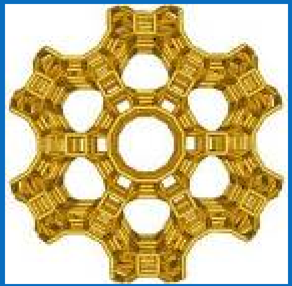


PECVD

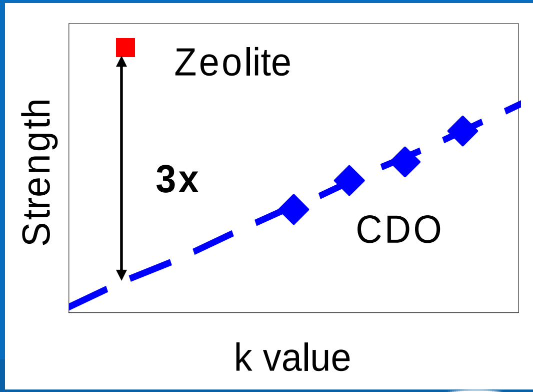
Spin-on

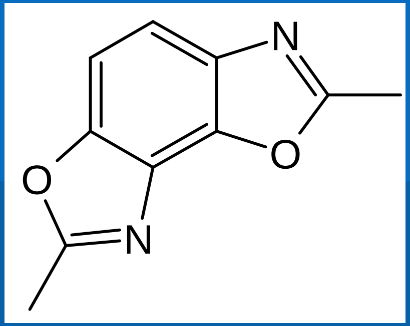






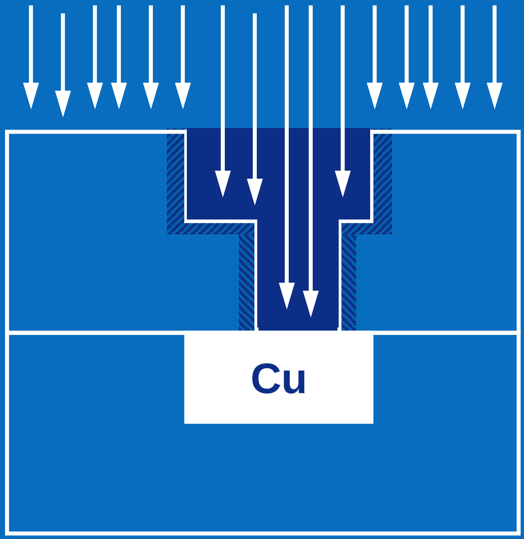
Source: Li et al, UCR, J Phys Chem, 2005

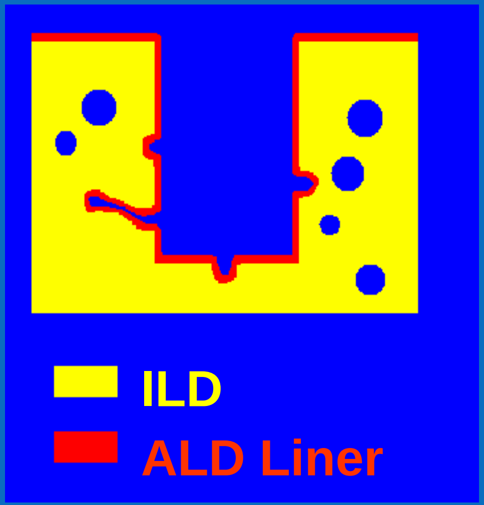




Integration

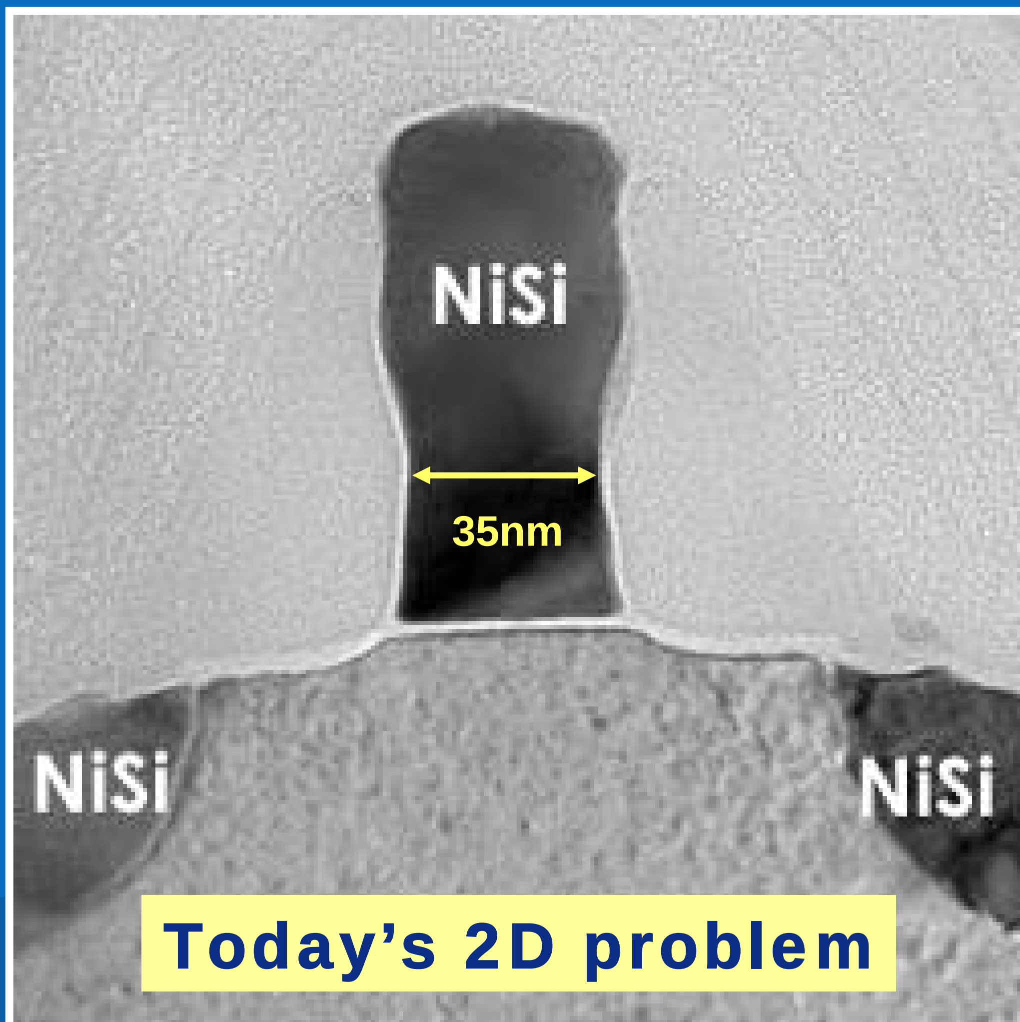
- Even if pores are unconnected as formed, subsequent patterning exposes a different surface
- Need to
  - Prevent damage to structure, particularly that affecting k_{EFF}
  - Smooth (seal) the surface for later conformal deposition
  - Good adhesion as deposited and over subsequent processing and also over a range of process conditions
- Could be accomplished with right combination of materials and surfaces





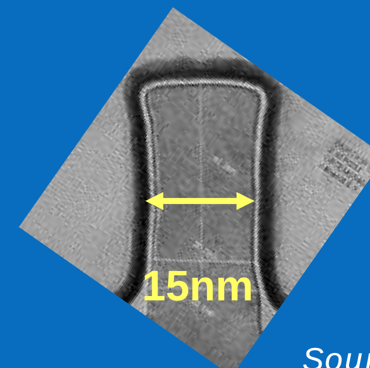
Lithography at Nanoscale

193nm light



Source: Intel

13.5nm light

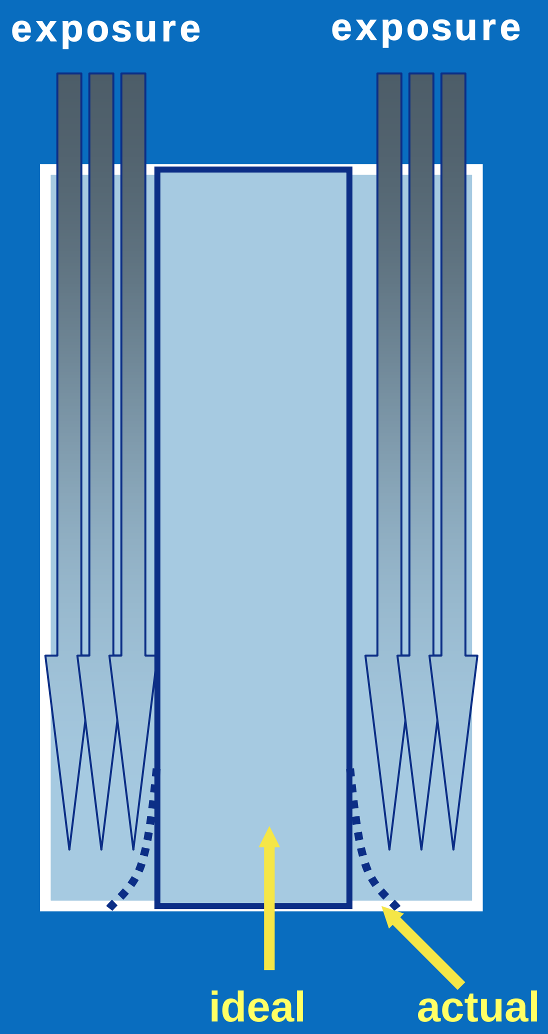


Source: Intel

2nm resist molecules

Tomorrow's 2D problem

Lithography at Nanoscale



Tomorrow's 1D problem

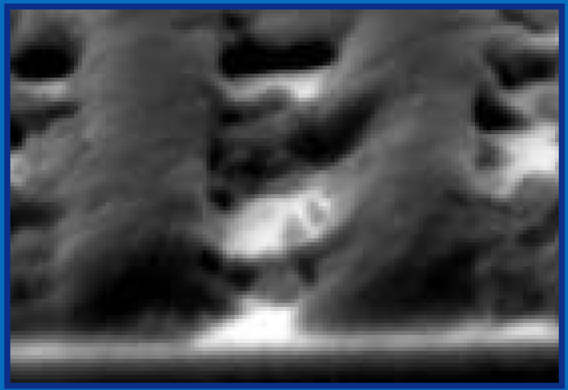
- Resist thickness >> feature size
- Absorption through resist changes effective dose and exposed profile
- Function of dose, contrast, diffusion, …
- Accentuated as scale shrinks

Designing Material Solutions

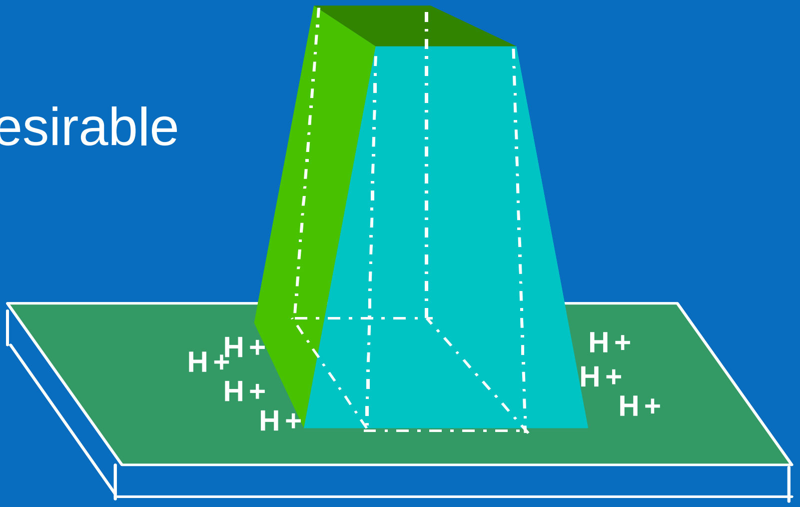
Solutions

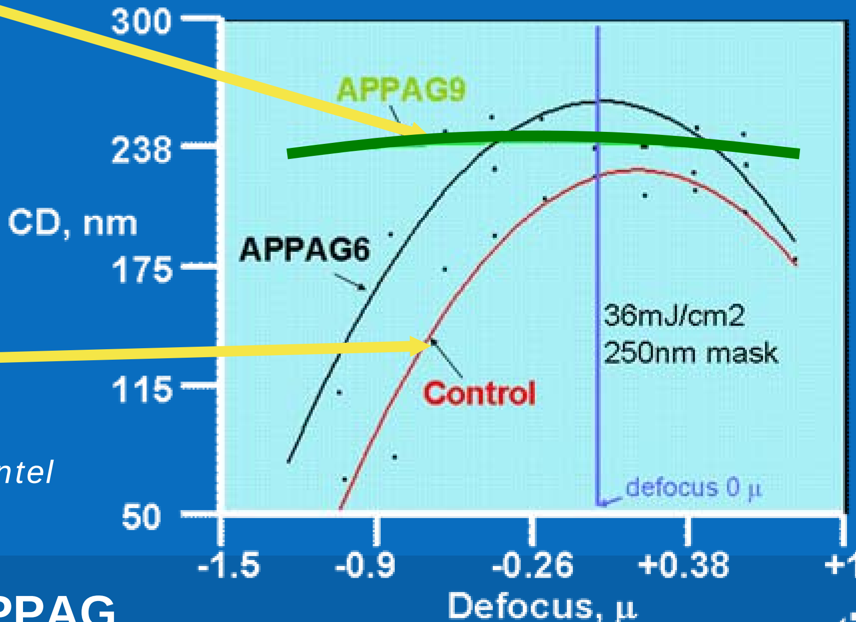
- Increase intensity or thin resist – not desirable
- Modify surface to improve sensitivity

Source: Intel



Source: Intel

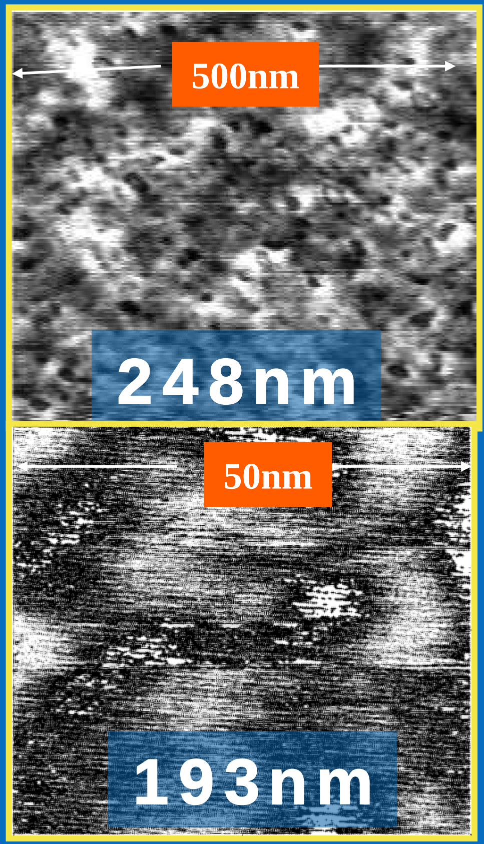




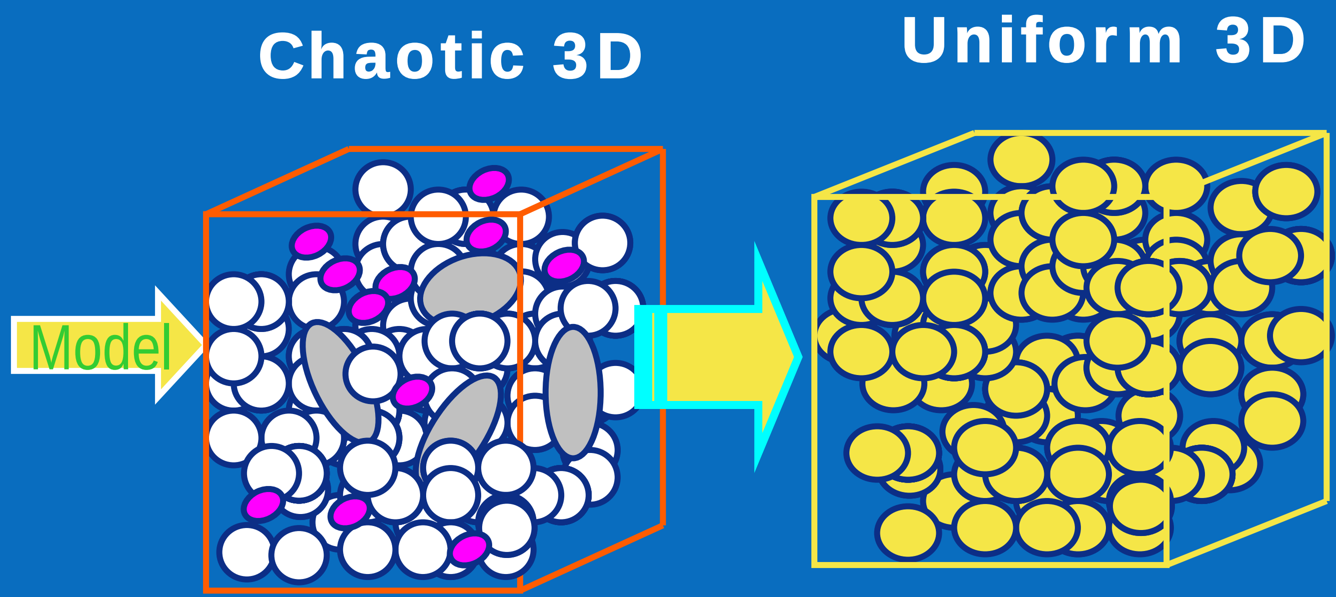
DUV @ 0.8 µ defocus

Experiment replaces BARC with APPAG

Resist pixel evolution



chaotic anisotropy by AFM

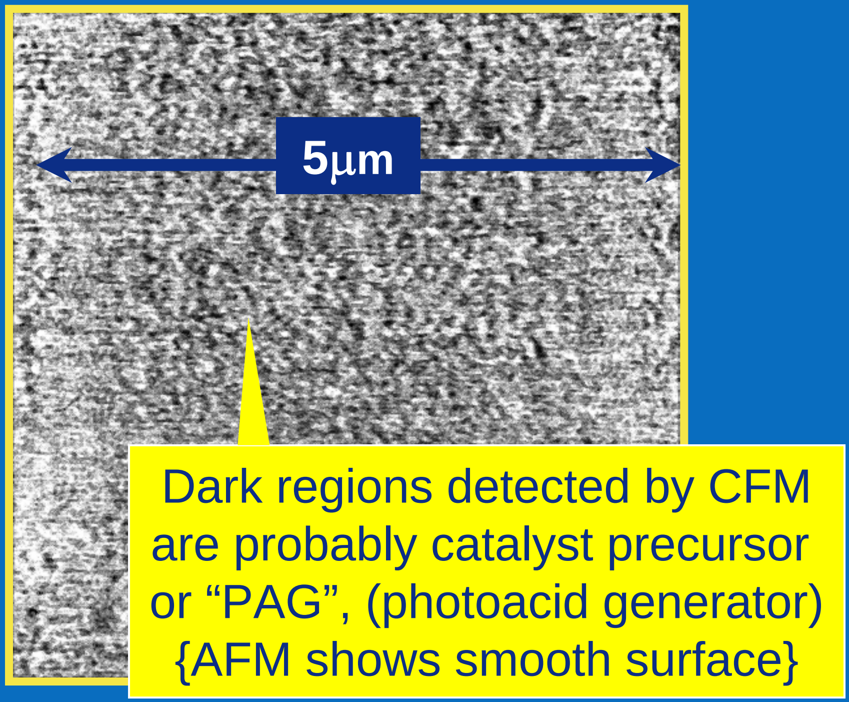


Source: Intel

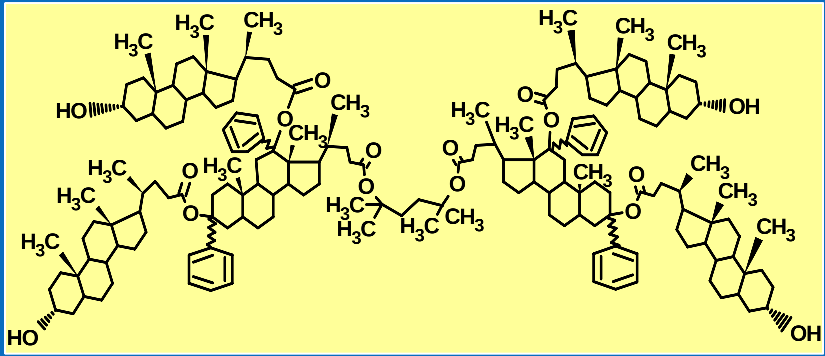
Designing Material Solutions

Resist solutions

- Improvement in uniformity
- Molecular size
- Self-assembly
- Designing active molecules

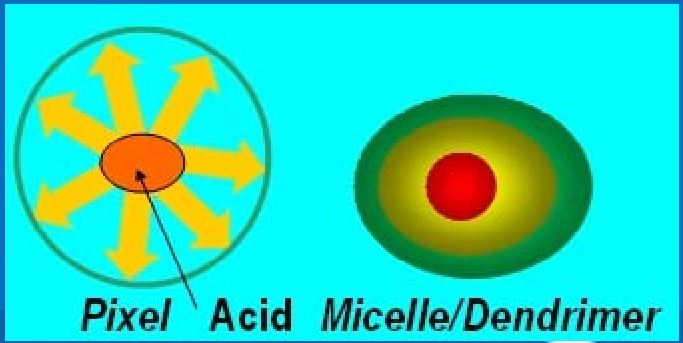


Source: NIST



“G1” Dendrimer

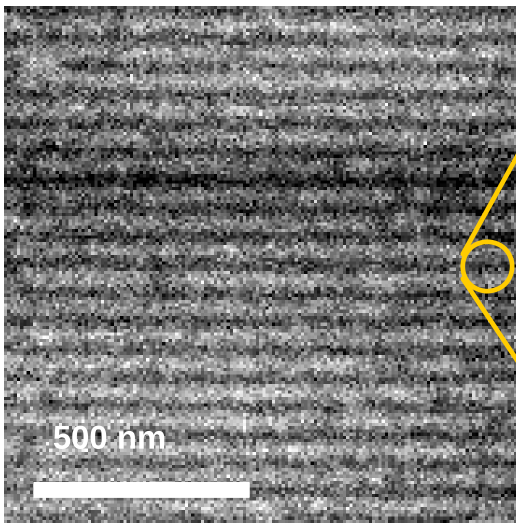
These are small (1to 2nm) tree-shaped molecules that modulate host-guest chemistry by using different steroids and terminal functionality. When exposed, the dendrimeric host-guest system is ripped apart. This disruption in structure encourages the fragments to dissolve. Thus, it is an architectural approach to a preorganized nanometer sized lithographic pixel using a branched design

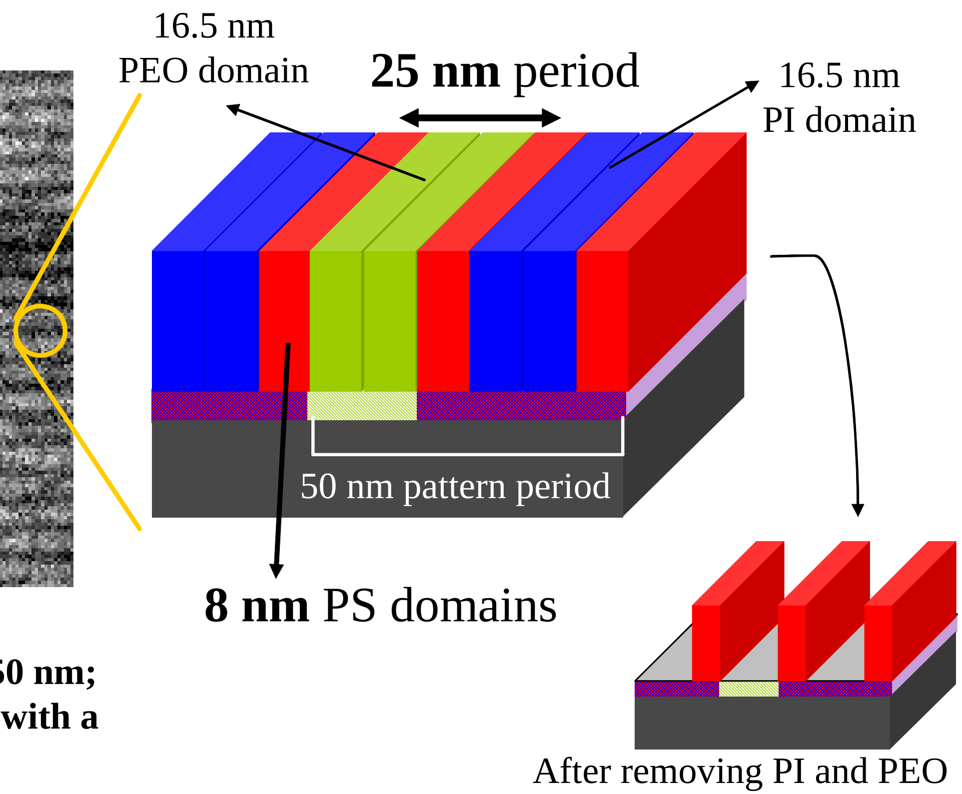


Pattern Assisted Self-Assembly

Perfectly assembled triblock copolymer (PISO) on binary surface pattern

Assembled PISO





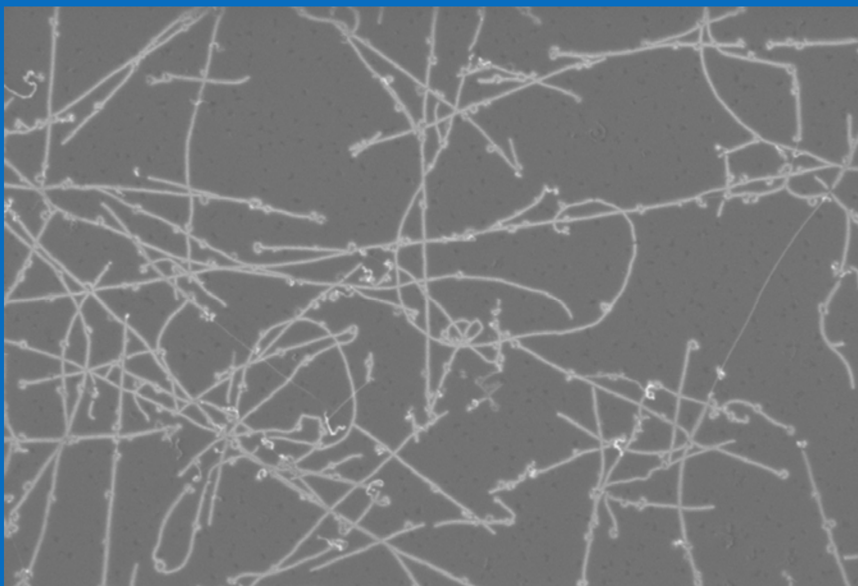
The possibility: Pattern at 50 nm; manufacture 8 nm features with a 25 nm period!

Welander, Chatterjee, Bates, de Pablo, Nealey

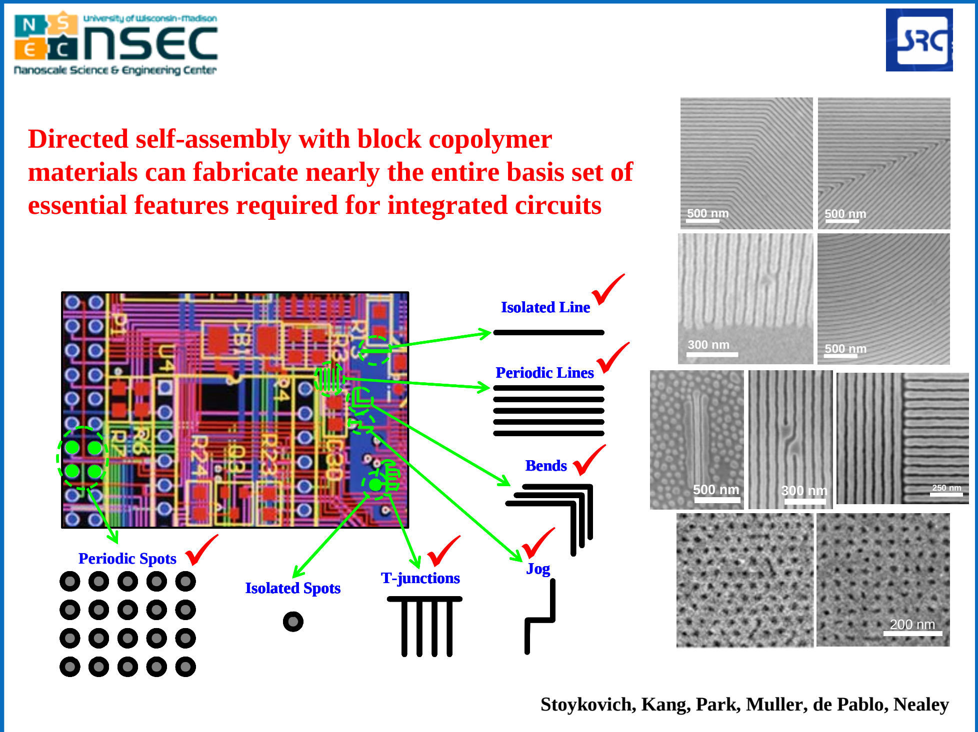
Source: Nealey et al, University of Wisconsin / Funding: SRC, NSF

Daunting

Possible



Source: Intel



Source: Nealey et al, University of Wisconsin
Funding: SRC, NSF

Less buzz here

Need more here

Summary: Moving to Manufacturing

- Nanomaterials which can be formed in place are inherently easier to integrate and have fewer side concerns
  - 1D and 2D nano grown in situ are already used in production
- Applications which ease alignment requirements can more readily incorporate nanomaterials where advantageous
  - Example: spin on coatings incorporating 3D nano
  - Example: ordered arrays created by directed self-assembly
- Far more research work is needed to utilize 2D and 3D nanomaterials which are not formed in situ
  - Purification of starting materials and prevention of contamination
  - Environmental, health, and safety evaluations
  - Alignment of billions of individual elements – a daunting task

Closing Thought

Thomas Edison:

Opportunity is missed by most people because it is dressed in overalls and looks like work.