Semiconductor Research Corporation

PIONEERS IN COLLABORATIVE RESEARCH®

global GRC RESEARCH COLLABORATION

Challenges and Trends in Patterning and Materials by Design:

Emerging Research Material Requirements

Daniel Herr, Director

Nanomanufacturing Sciences Research

herr@src.org; 919-941-9431

- February 22, 2007

Agenda

- The bad news?
- Key messages and material-by-design opportunities
- The need for understanding the ESH impact of nanomaterials
- Summary

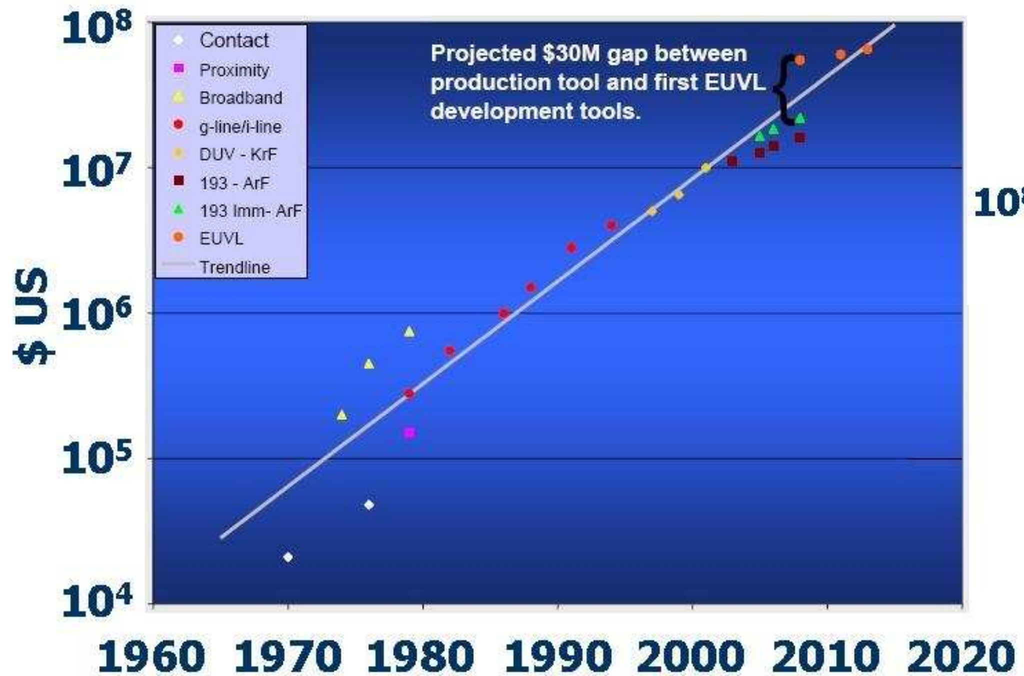
The Bad News?

Moore's Second Law

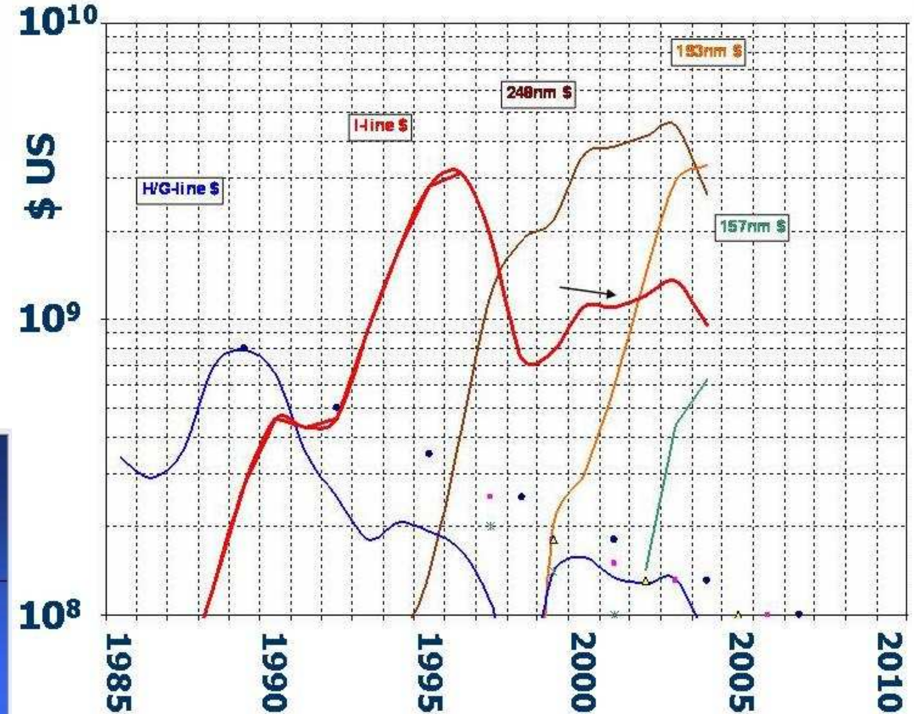
As chip density increases exponentially, the cost to set up manufacturing also increases exponentially.

Exposure Tool Trends

Exposure tool costs tend to increase exponentially



Frank Goodwin, Infineon, Trends in the Cost of Photolithography Development and an Outlook for the Future, Nov 7, 2005



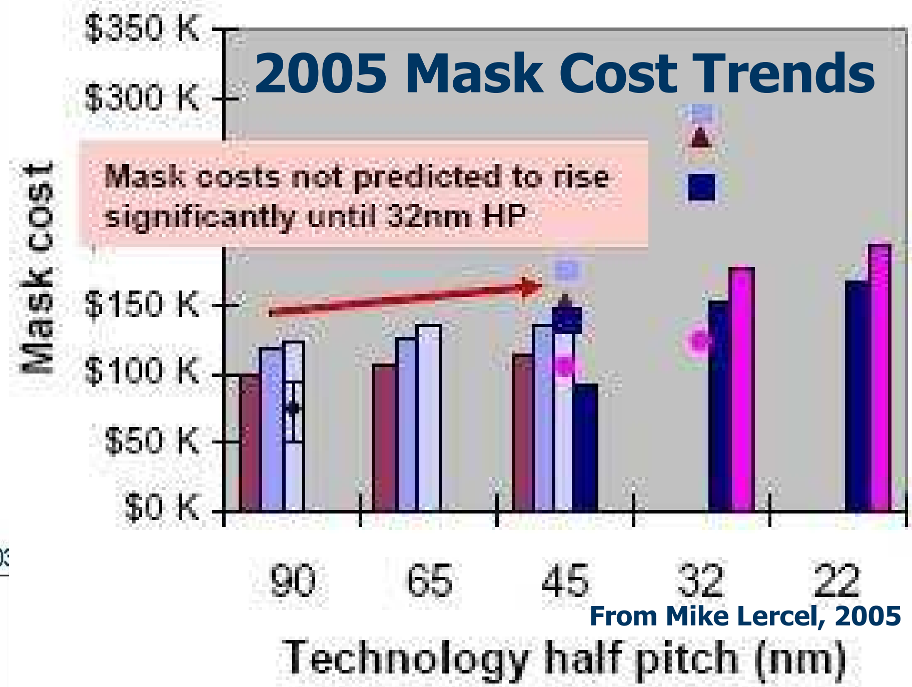
Revenue and units data from VLSI Research, 9/99 and 10/99

Cumulative exposure tool investment:
Tens of billions of dollars

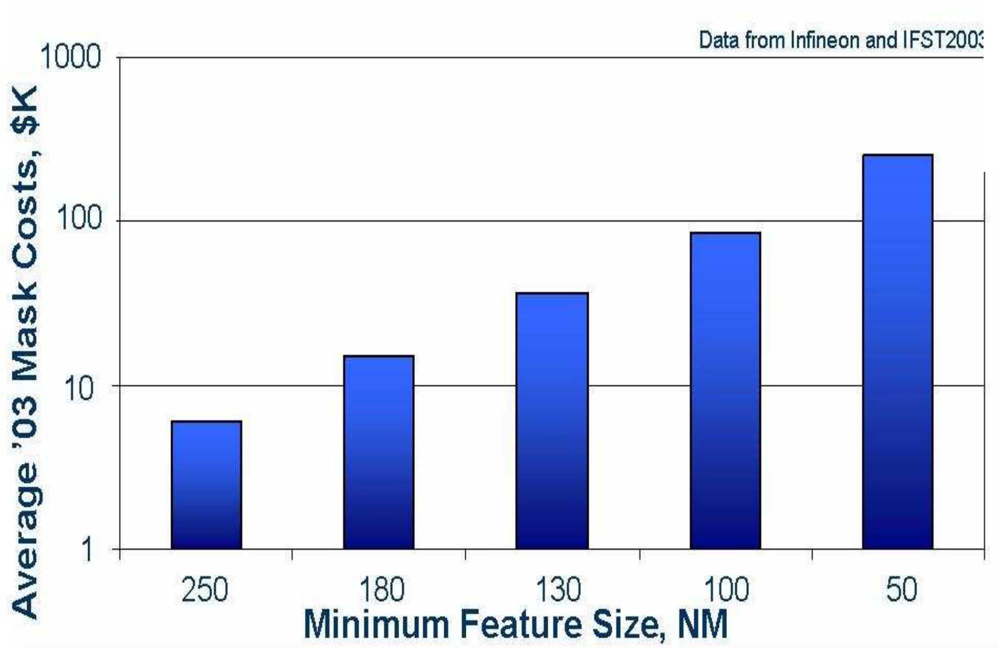
Mask Technology Trends

Projected 2003 Mask Set Costs:
100 nm: ~$1.2M; 50 nm: ~$3.2M

Projected Annual Cost @ 50 NM:
ASIC [~$1.2B]; IDM [~$0.2B/Tool]



From Mike Lercel, 2005



2005 mask cost trends suggest a cumulative mask investment of:

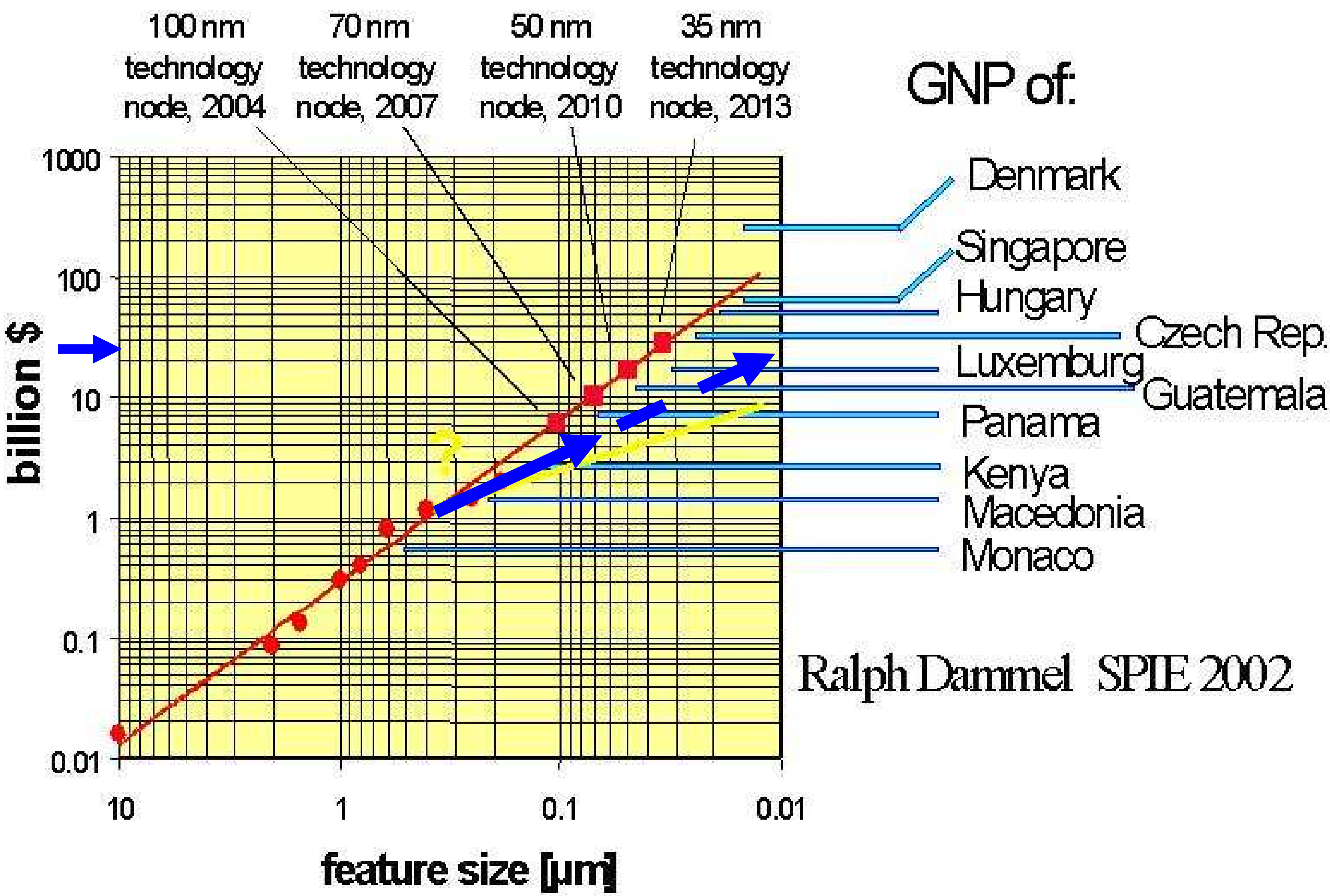
Several Billions of Dollars

Selected ITRS Litho Challenges: Dimensional and Placement Control

Selected 2005 ITRS lithography variability control requirements

Year of Production	*2005*	*2008*	*2011*	*2014*	*2017*	*2020*
MPU physical gate length (nm) [after etch]	*32*	*22*	*16*	*11*	*8*	*5*
MPU gate in resist length (nm)	53	38	27	19	13	9
Resist meets requirements for gate resolution and gate CD control (nm, 3 sigma)	3.3	2.3	1.7	1.1	0.8	0.6
Line width roughness: (nm, 3 sigma) <8% of CD	2.6	1.8	1.3	0.9	0.6	0.5
Overlay (3 sigma) (nm)	15	10	7.1	5.1	3.6	2.5

Rising Cost of Wafer Fabs Vs. GNPs



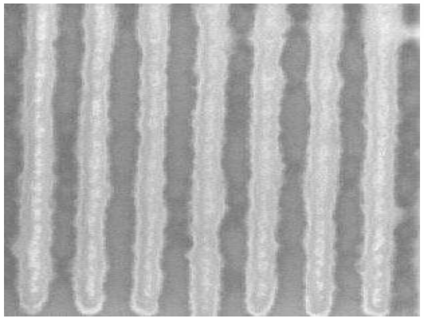
An Opportunity for Alternate Approaches?

Consider the Evolution of Imaging Materials

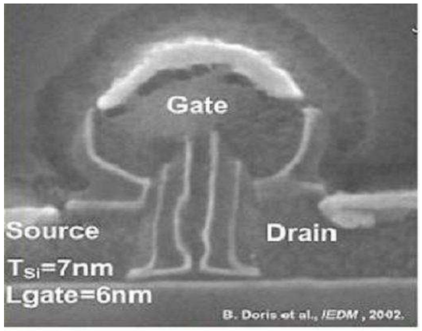
- 1725 - Information capture: Transient images
- 1826 - Image replication: 1st permanent photograph
- Photoresist: Image transfer **plus three functions**, i.e. **speed, resolution,** and **masking** ability:
  - 1935 – Negative tone poly(vinyl cinnamate) materials
  - 1940 – Positive tone diazoquinone-based photoresist
  - 1983/4 – Chemically amplified resists

Difficult Patterning Material Challenges

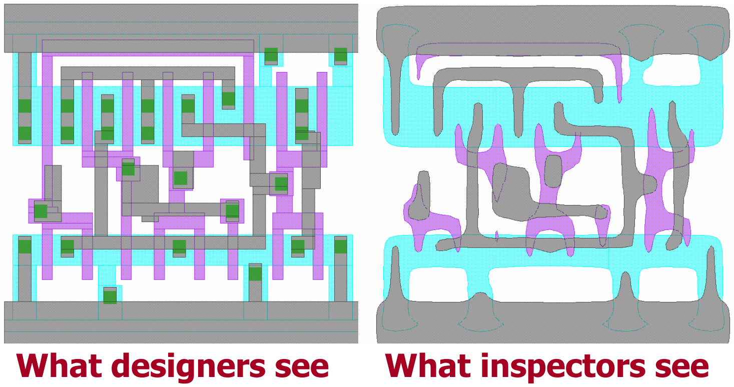
- Line edge roughness



- Long range dimensional control and repeatability



- Pattern fidelity
  - With current resists, at 65 nm there is no top down yield without RET



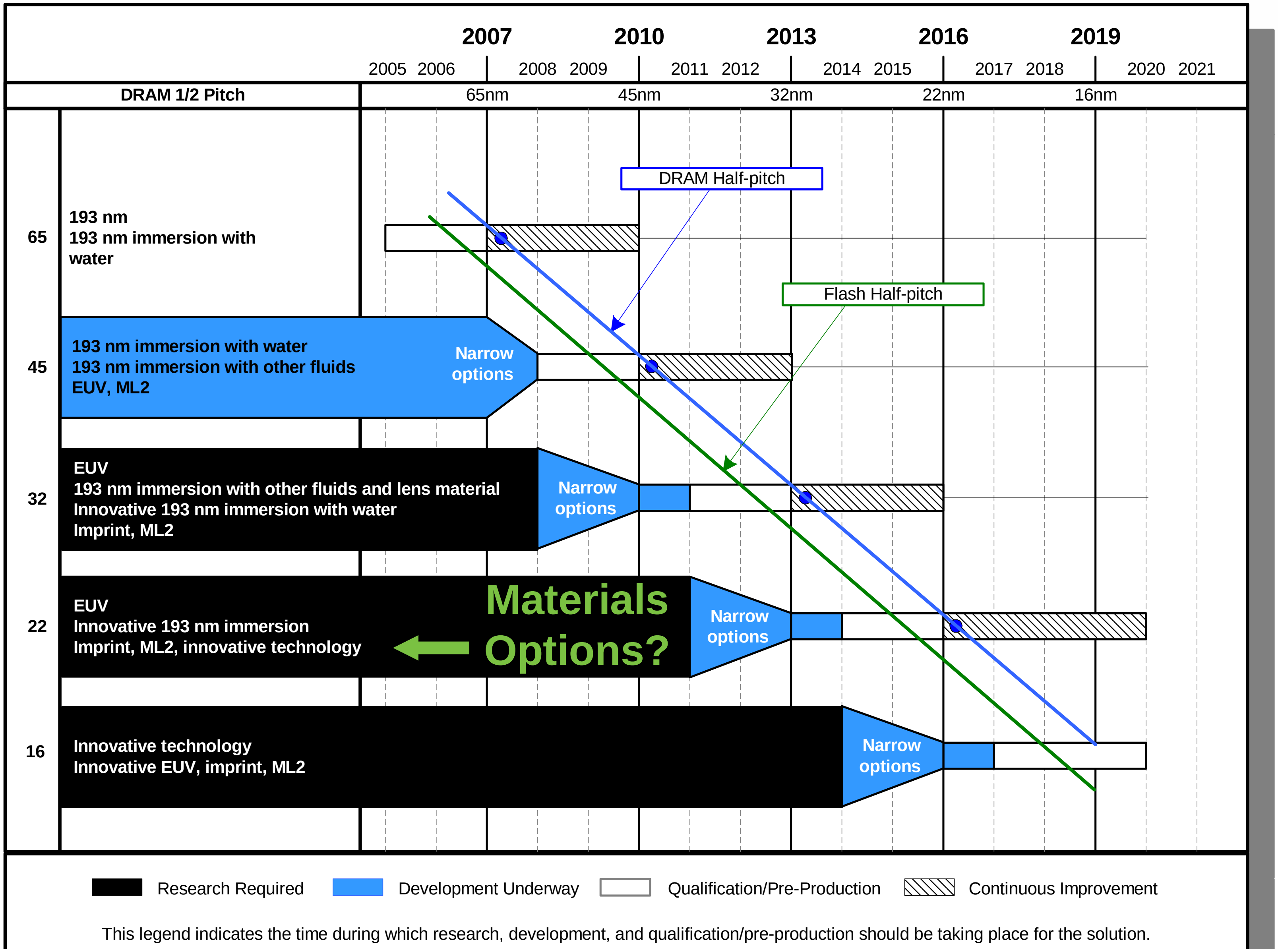
- Resolution: Catalytic blurring

Key Message(s): There is hope.

Perhaps we should view Moore's Second Law as an innovation driver for:

- **Directed assembly**, which may enable extensibility of **affordable CMOS fabrication to ~10 nm**.
- **Enhanced patterning functions**, beyond masking, such as **3D nanofabrication** and **deterministic placement** of electronically useful nanostructures.
- **Materials-by-design**, including **engineered interfaces** and the **heterogeneous materials integration** on CMOS.
- **Predictive nanomaterials models**, which concurrently **optimize nanomaterial performance and ESH impact.**

Innovation insertion windows



We need materials options that circumvent Moore's Second Law

What is the next evolutionary step?

Smart resists, with designed dimensional, placement, and alignment control?

With electronically useful functionality?

Goals and a Timeline for Nanocomputing

L~30 nm

L~5 nm

Nanodevices

L~1 nm

Embrionic demonstrations

Needed: Information delivery to matter to provide assembly instructions

Nanofabrication

~10^{18} molecule/s
~10^{-20} J/molecule

Self-organization of complex structures

Understanding of fundamental limits of heat removal:~10^5 W/cm^2

Exp.: ~10^2 W/cm^2

Heat removal at ~10^3 W/cm^2

Heat Removal

Heat removal at ~10^5 W/cm^2

10^{16} bit/s
10^3 MIPS
~5 MIPS / W

10^{19} bit/s
10^5 MIPS
10-100 MIPS/W

Nanoarchitectures

Brain-inspired energy efficient computation

10^{22} bit/s
10^8 MIPS
10^6 MIPS / W

A two-way interface between neurons and transistors

Systems

Cognitive machines

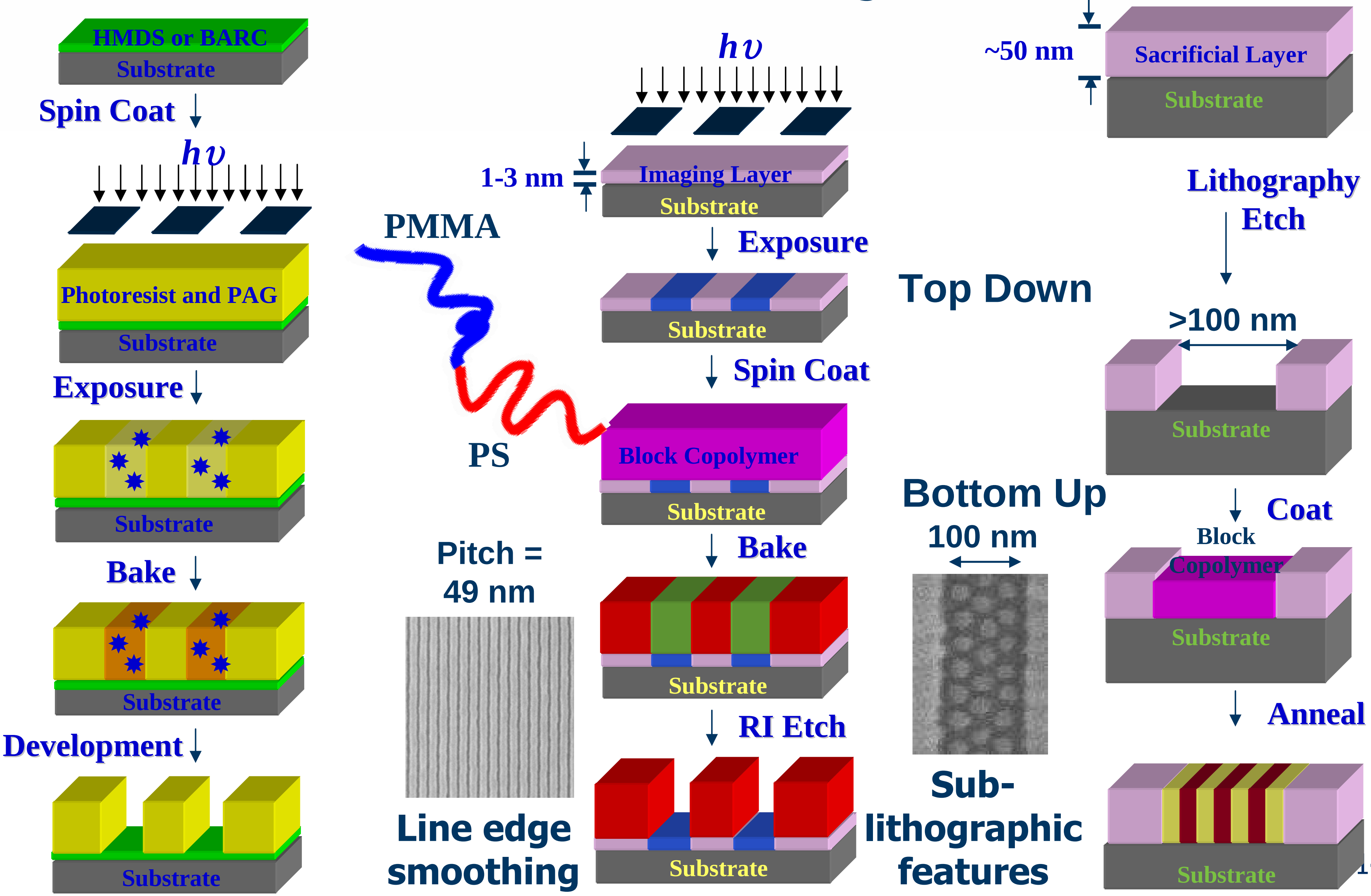
[Courtesy of Victor Zhirnov and Ralph Cavin III, ***2020 Computing Technologies: A Fundamental Physics Perspective,*** New York Academy of Sciences Meeting, 2/16/07]

2005 — *Time* — 2050

Hybrid assembly of block copolymers

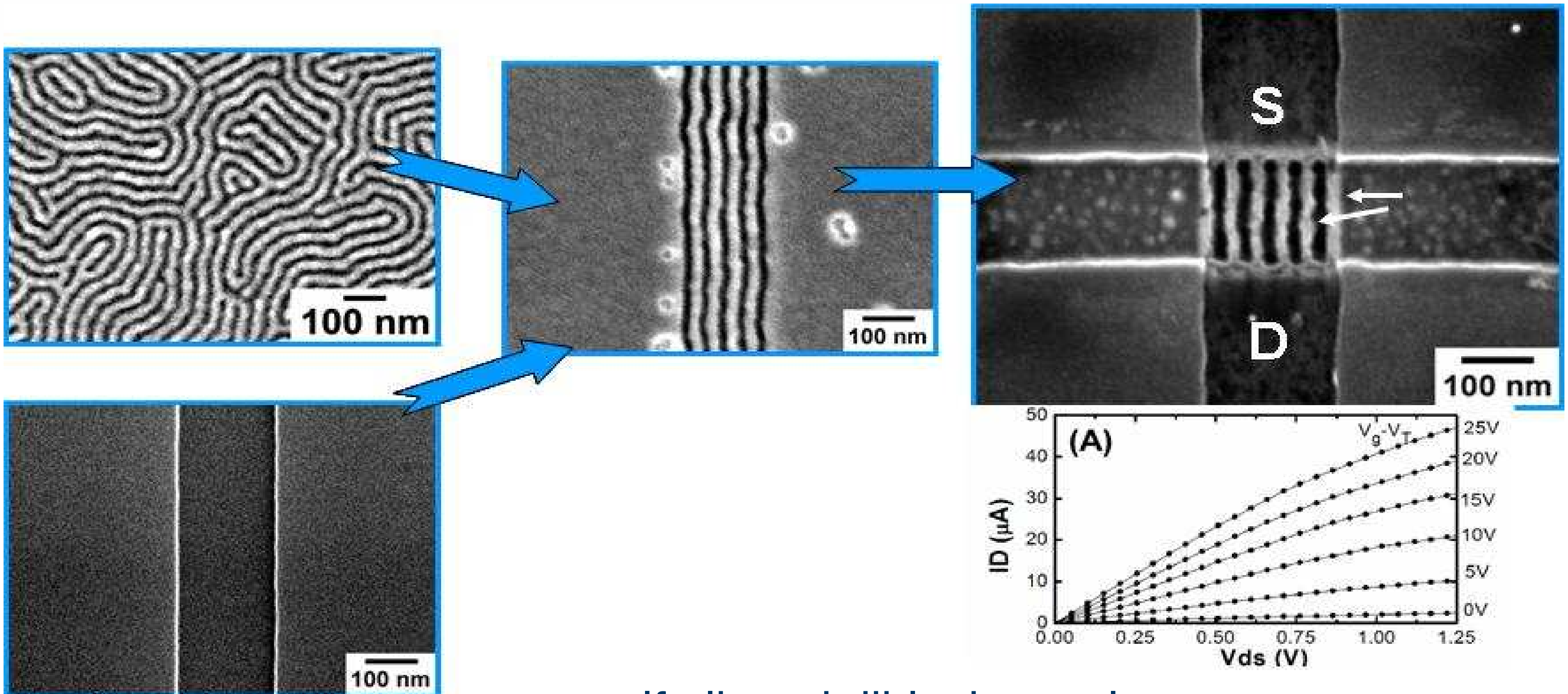
Potential Material Option to Extend Optical Technology

Photolithography | **1:1 Patterning** | **1:X , with X ≤ 1**



Silicon nanowire-array FET

C. T. Black, Appl. Phys. Lett., submitted (2005).



self aligned diblock copolymer process
integrated with multiple lithographic levels

- critical device dimensions defined by self assembly
- self assembly size uniformity, order, and registration

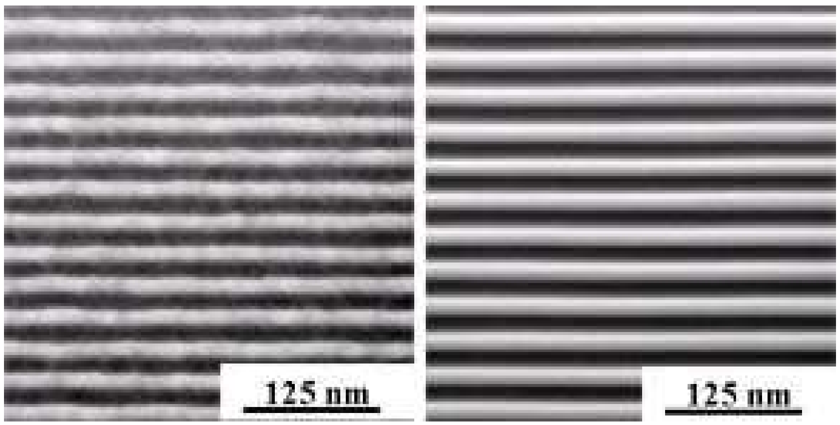
all important to device performance

C. Black/IBM

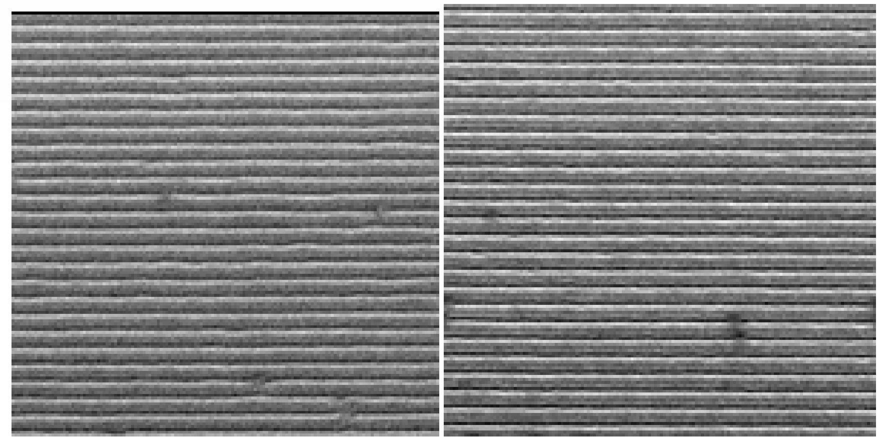
2011-2012 ITRS Emerging Research Material Requirements: Directed Self-Assembly

Metric	Requirement
Defects and defect management strategies	<0.02 20 nm defects/cm^2
Low Frequency LER	~2.1 nm 3 σ
Gate CD Control	~1.7 nm 3 σ
Resolution	11 nm
Essential shapes	Dense and Isolated L/S, circles, hexagonal arrays
Overlay and registration	5.1-7.1 nm 3 σ
Throughput	1 W/Min
Etch and pattern transfer	~CARs
Placement and orientation	Under development
Multiple Sizes-Pitches/Layer Overall Performance	2-3/layer
Other	ESH Impact?

Directed Self-Assembly for Enhanced Dimensional Control



LER(3σ) = 4.65 nm **LER(3σ) = 2.4 nm**



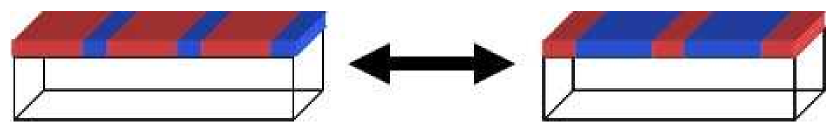
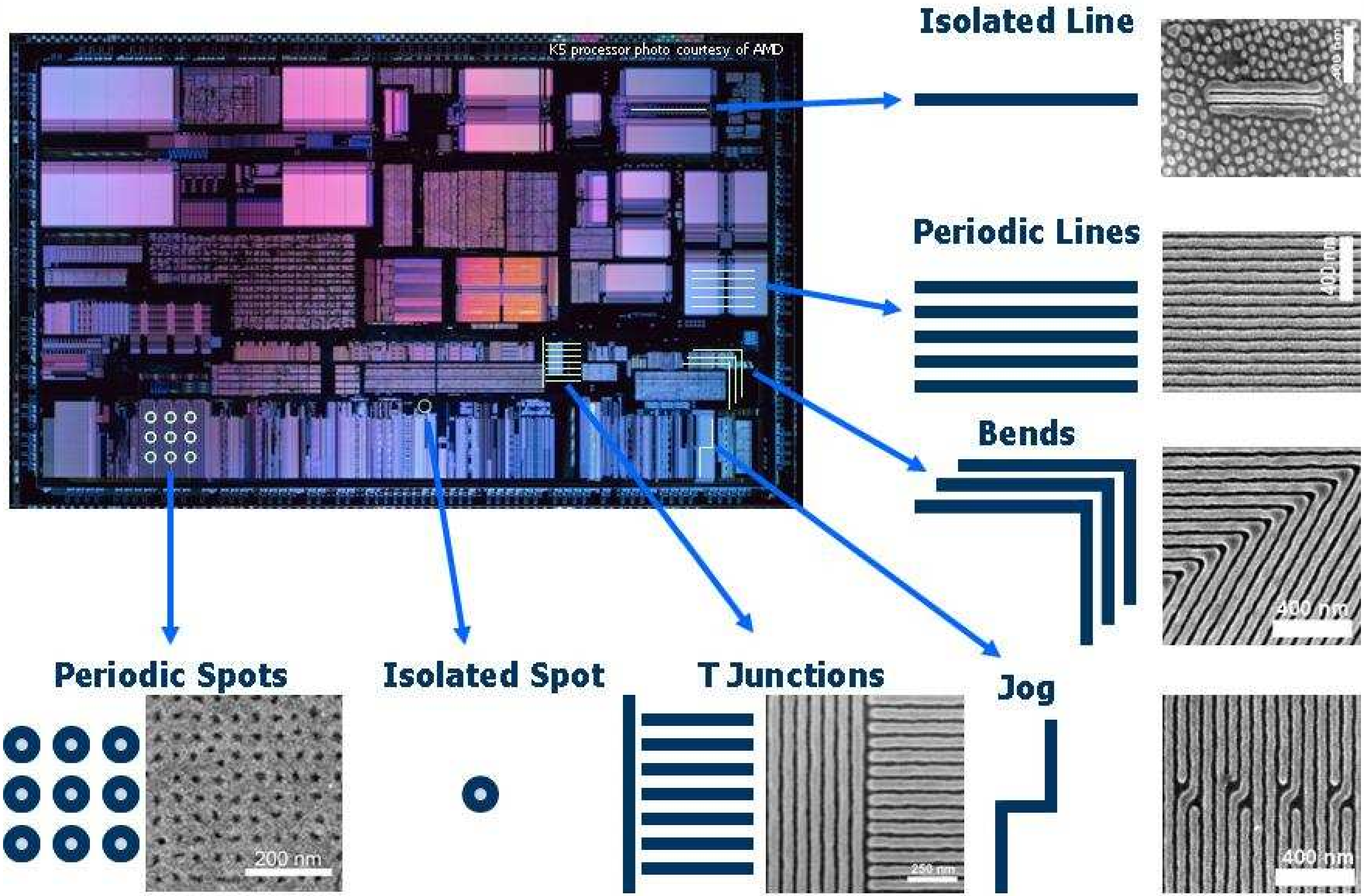


Figure 1. Post etched dense line/space structures in a) PMMA and in b) phase segregated PS-PMMA diblock copolymers.

Figure 2. **Long range CDs are controlled by block copolymer size** and relatively independent of lithographically defined lines of variable width and constant pitch.

Materials and Processes for Sub-32 nm Lithography [Nealey/UW-Madison]
New Architectures for Directing Assembly of High Resolution Resist Material [Ober/Cornell]

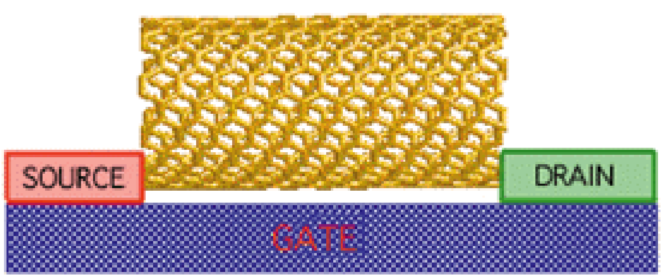
Essential Features for Integrated Circuits



Nanofabrication:
The Post-Masking Patterning Challenge

Research in Nanodevices will have a value if and only if

we can find a way to cost-effectively make working circuits by connecting together TRILLIONS of such devices

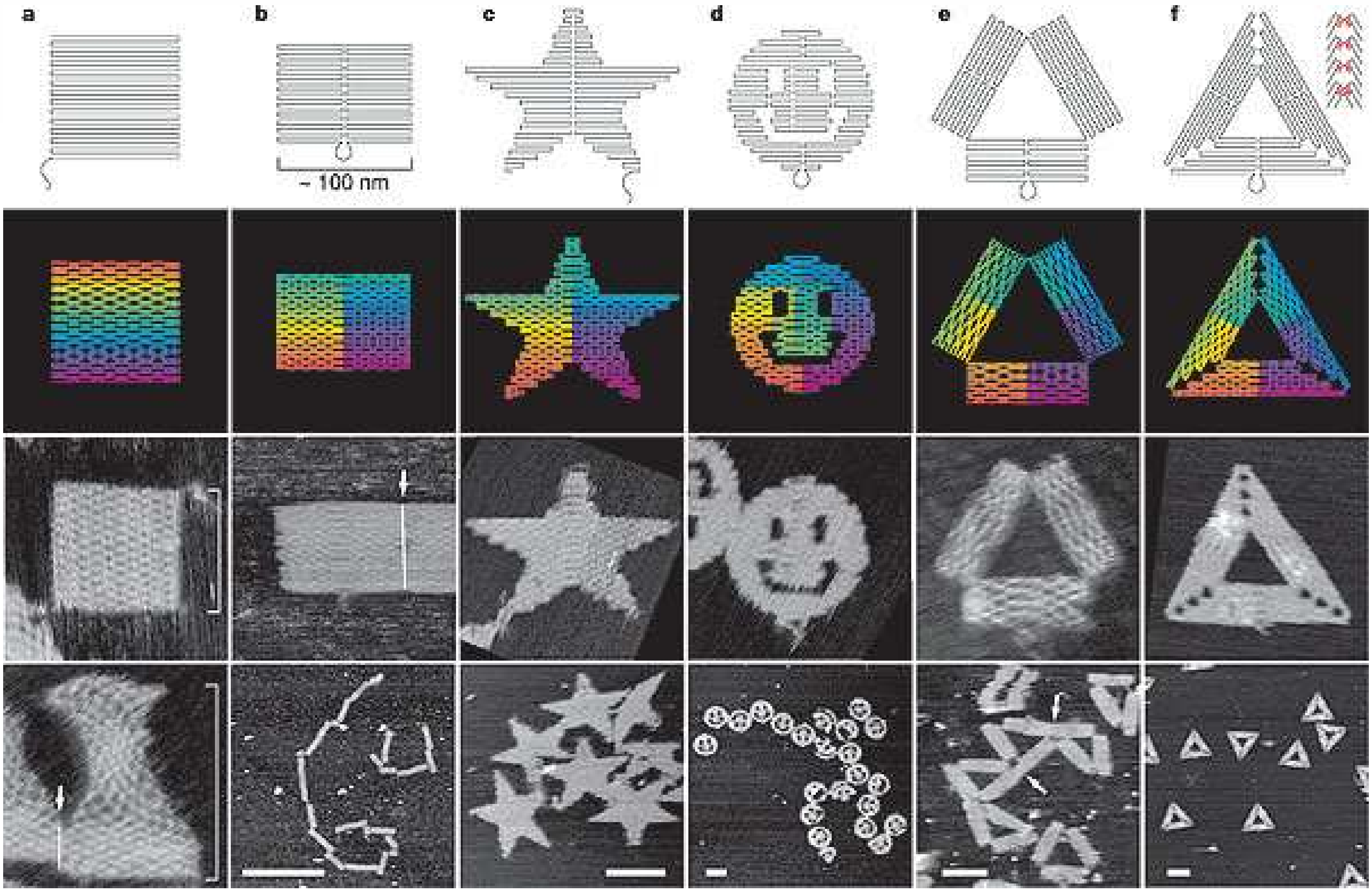


Can we 'teach' matter to organize into useful functional structures?

What can we learn from nature?

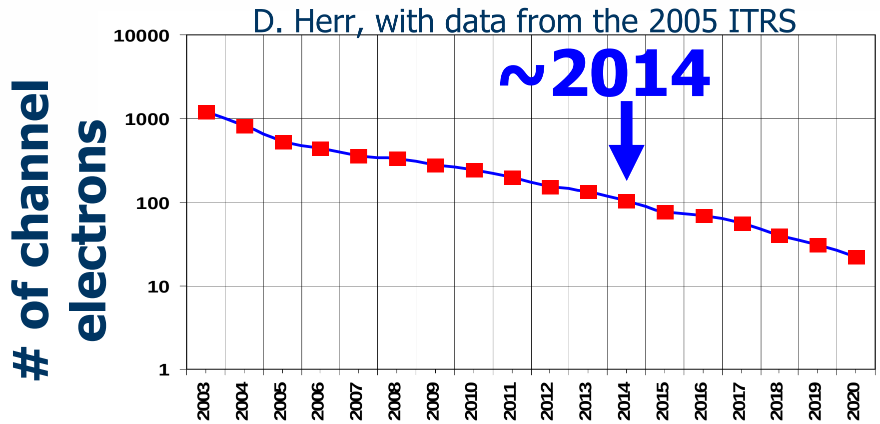
	EUV Lithographic Patterning [Subtractive Patterning 32 nm]	Growth of a Baby [Bio-Assisted Self-Assembly]	Assisted Assembly Advantage
Bits patterned per second	8.6E+09 bits/s/masking layer	7.5E+17 amino acid equivalents/s	~9E+07
Energy required per bit	>1.5E-12 J/bit/masking layer	~1.3E-20 J/amino acid equivalent [4.6 KTLn(2)]	>9E+7

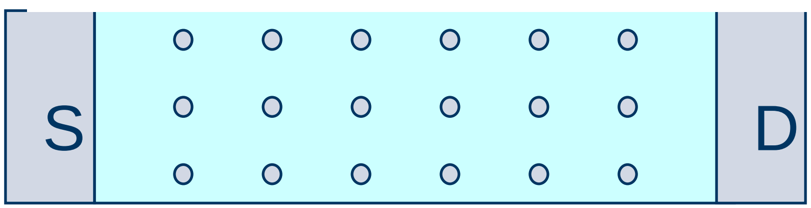
Designed DNA origami & healable tiles with deterministic positional control



From: Folding DNA to create nanoscale shapes and patterns, Paul W. K. Rothemund, Nature 440, 297-302 (16 March 2006)

Extreme CMOS Patterning Challenges: Dopant No., distribution, and roughness

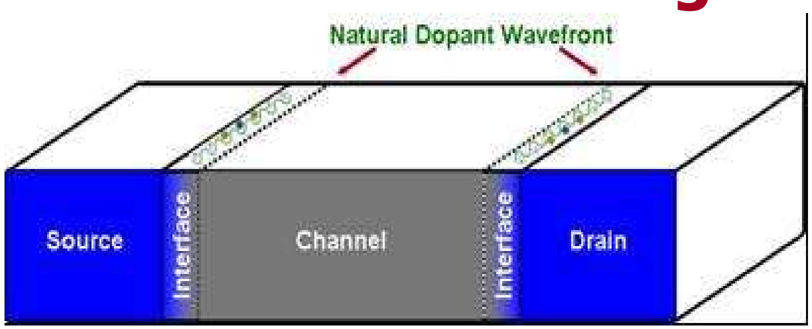


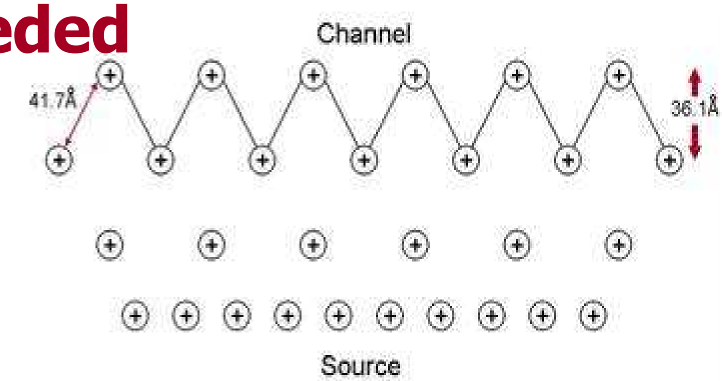


- Conductance variability reduced from 63% to 13% by controlling dopant numbers and roughly ordered arrays;
- Conductance due to implant positional variability within circular implant regions of the ordered array ~13%.

From Shinada et. Al., "Enhancing Semiconductor Device Performance Using Ordered Dopant Arrays", Nature, **437** (20) 1128-1131 (2005) [Waseda University]

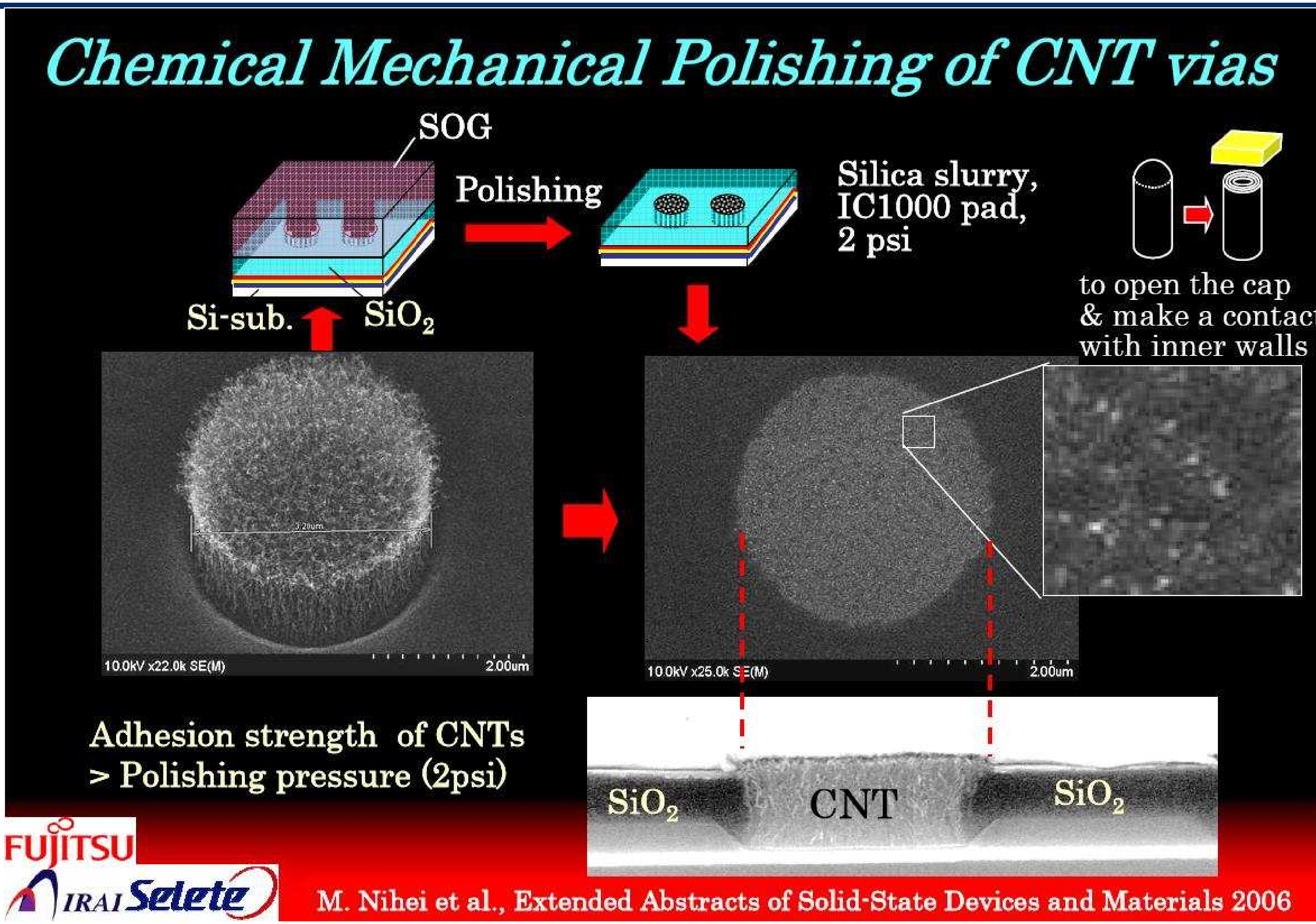
Deterministic Patterning Needed





D. Herr, The Potential Impact of Natural Dopant Wavefront (NDW) Roughness On High Frequency Line Edge Roughness Requirements II, Cavin's Corner: SRC June 2006.

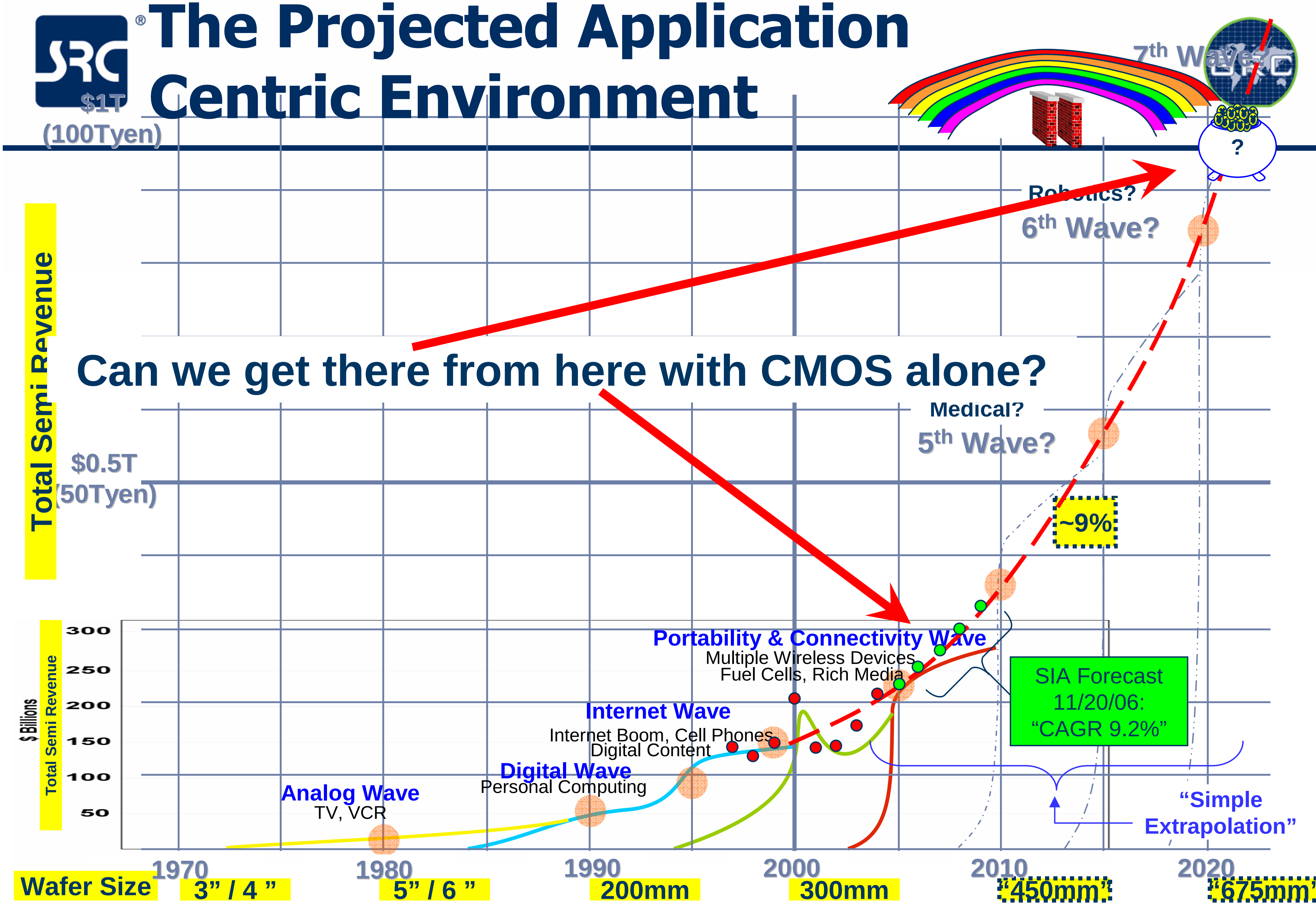
Emerging Research Materials: Low Dimensional Materials



ITRS Emerging Research Materials: ERM ITWG Workshops

	Nano-particles 0D & 1D 09/06	Macro-molecules 10/06	Metrol. & Model'g 10/06	Directed Self-assembly 12/06	Dielectrics & Multiferroics for Int/Pkg 11/06	Hetero-structuresIn terfaces 01/07	Spin Materials 03/07	ESH 2/07
ESH	✓	✓	✓	✓	✓	✓		✓
ERD	✓	✓	✓	✓	✓	✓	✓	✓
FEP LL/RJ	✓	✓	✓	✓	✓	✓		✓
INT	✓		✓	✓	✓	✓		✓
LIT Kameyama-san	✓	✓	✓	✓				✓
PIDS	✓	✓	✓					✓
PKG Bill Bottoms	✓	✓	✓	✓	✓	✓		✓

The Projected Application Centric Environment



Source: Semico Research Corp, May'04 [+ "Simple Extrapolation"]; plus added SIA, Nov'06 Forecast

Beyond Scaling: Pursuing the race for added value for the end customer by combining on-chip ULSI and off-chip integration

Perhaps one technology cannot do it all alone.

There may be synergistic computational benefits from leveraging the collective action of several functional elements.

A key challenge is to develop nanoscale fabrication methods for enabling heterogeneous integration on CMOS.

Hair receptor cells of the inner ear

[From: http://www.neurophys.wisc.edu/h&b/textbook/chap-5.html]

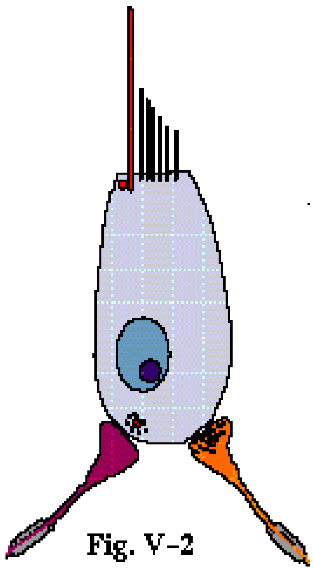


Fig. V-2

A schematic illustration of the major structural features of an inner ear hair cell.

Note the filaments, stereocilia, of differing lengths that stimulate input into this single cell.

Different regions of the basilar membrane respond maximally to different sound frequencies based on the local physical properties.

This figure shows the relationship between cochlear structure and the regions of greatest frequency sensitivity.

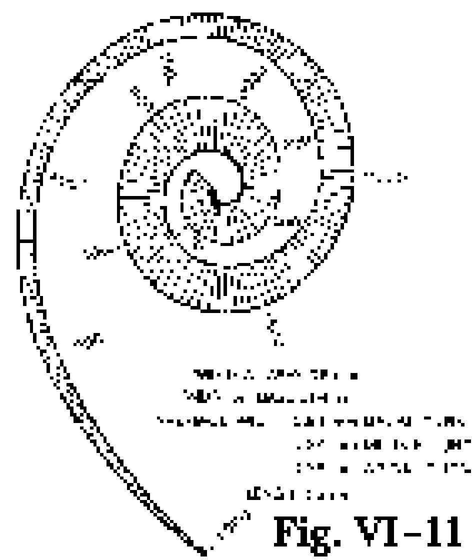
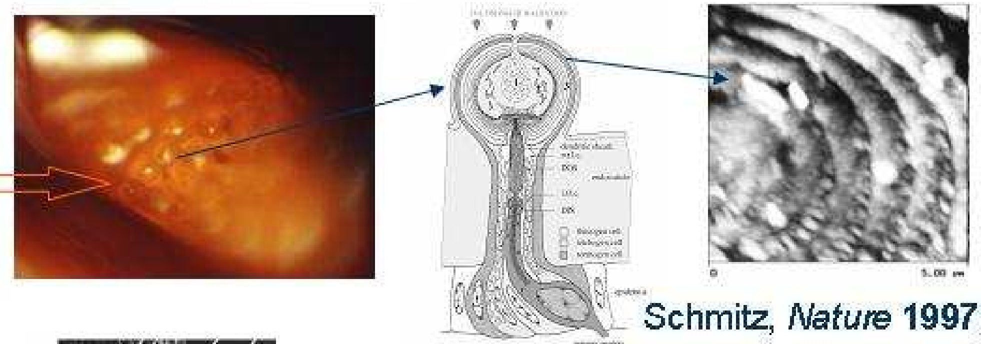


Fig. VI-11

Other examples of biological sensing: thermal, chemical, and mechanical

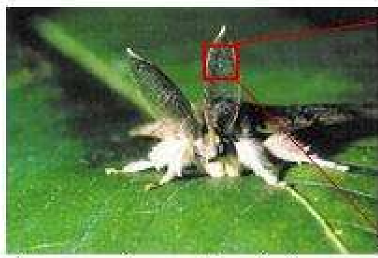
Thermal and odor (?) via thermal expansion

Melanophila acuminata beetles

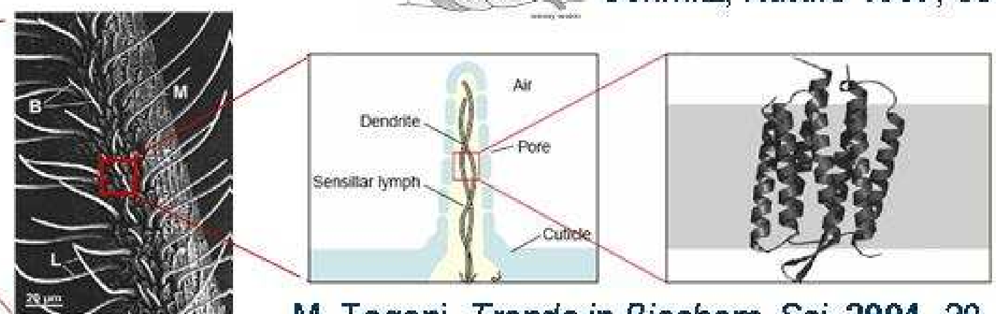


Schmitz, *Nature* **1997**, 386, 773

Odor (e.g., sex) via protein gating



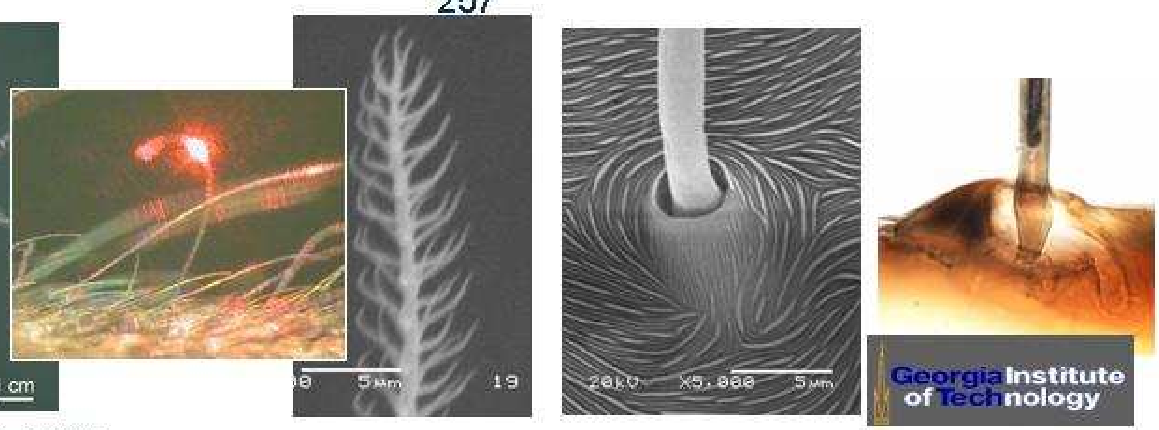
Odor sensing proteins in the antennae of moth, *Lymantria dispar*.



M. Tegoni, *Trends in Biochem. Sci.* **2004** ,29, 257

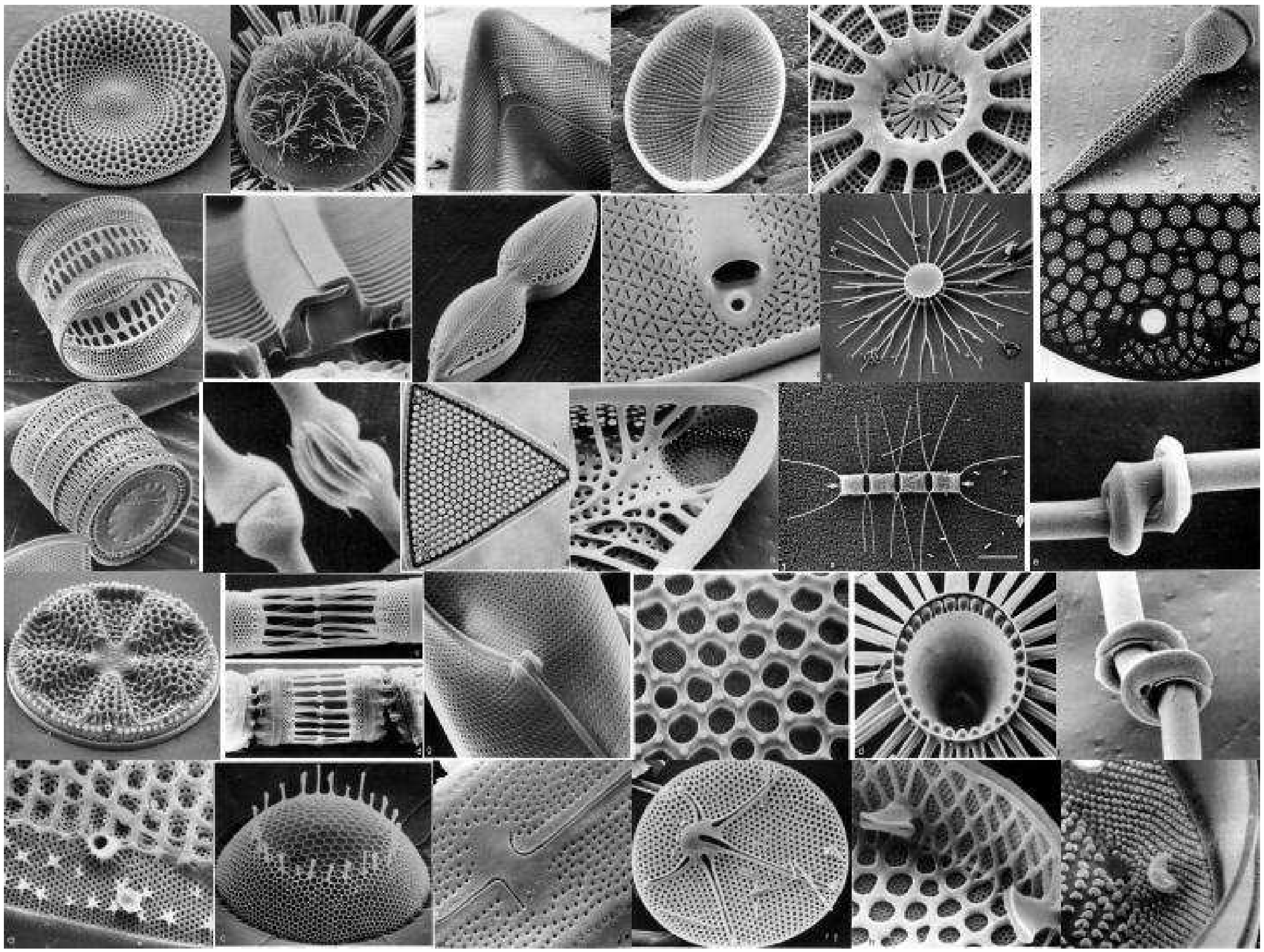
Vibration and odor via hair arrays and shaft-like mechanical motion

Cupiennius salei Keys spider



Barth, *A Spider's World: Senses and Behavior.* 2002

Natural Nanostructured 3-D SiO_2 Micro-assemblies: Microshells of Diatoms



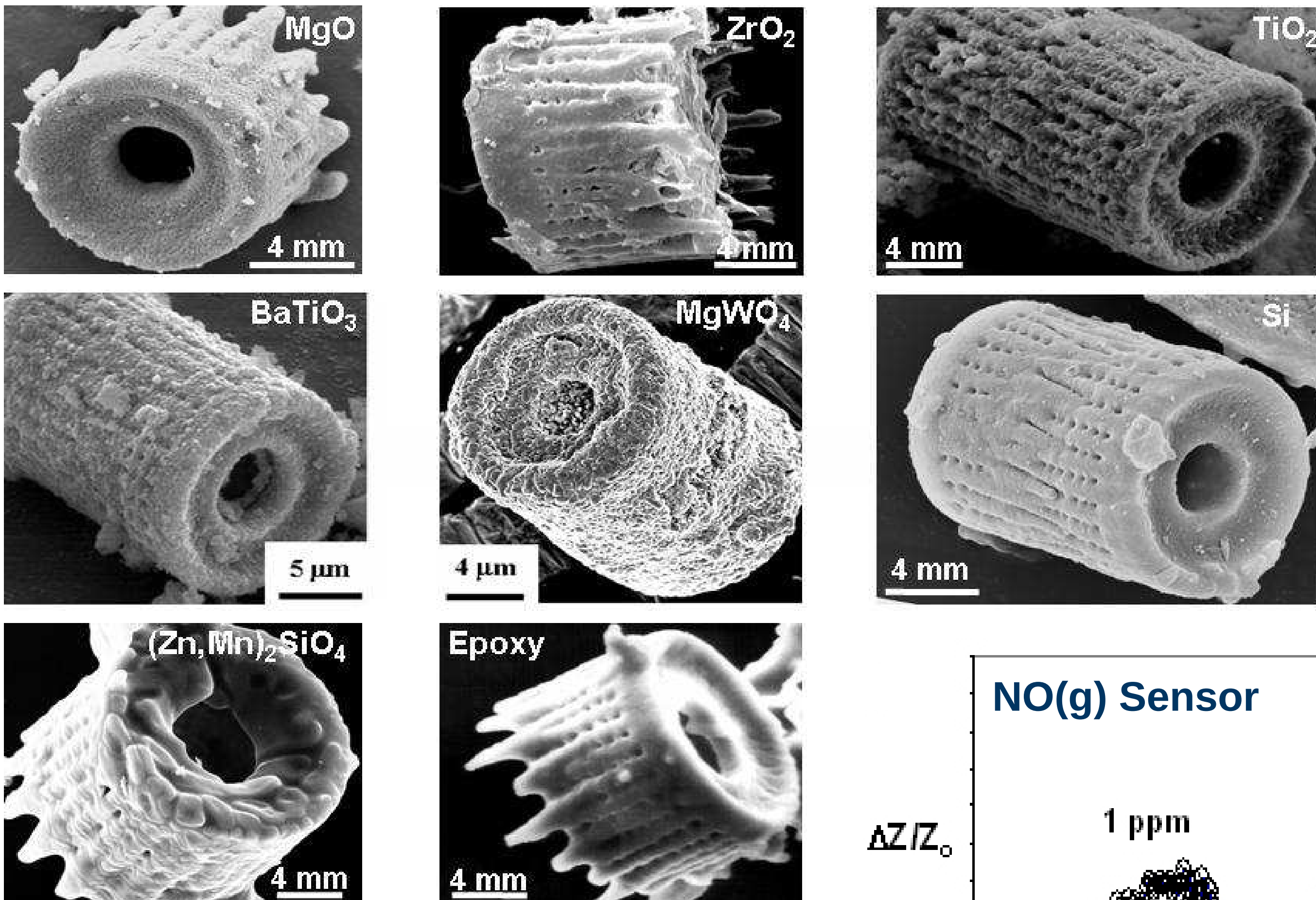
10^5 diatom species

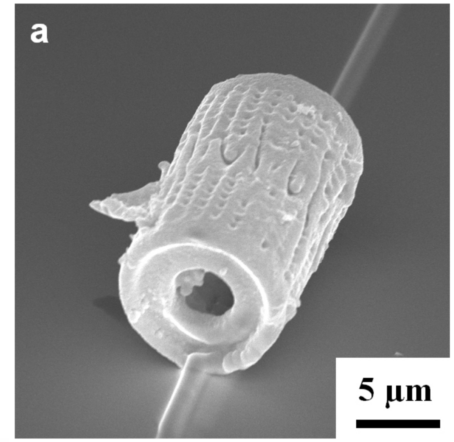
Each species forms a specific and unique 3-D shape: *genetic precision @ ambient temperature*

Sustained culturing can yield enormous numbers of copies (80 cycles = 2^{80} = 10^{24}): *massively parallel self-assembly*

F. E. Round, R. M. Crawford, D. G. Mann, The Diatoms: Biology and Morphology of the Genera, Cambridge University Press, 1990

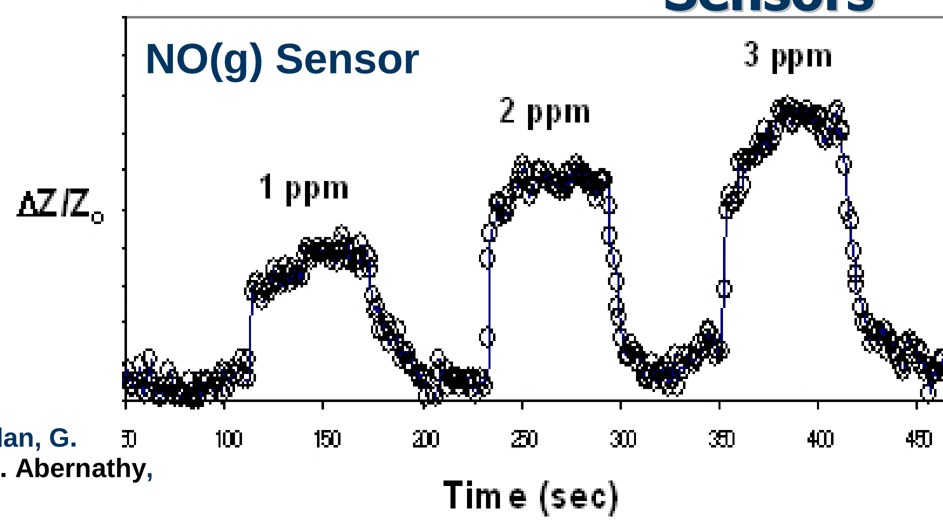
Chemically-converted Diatomic Replicas for Functionality





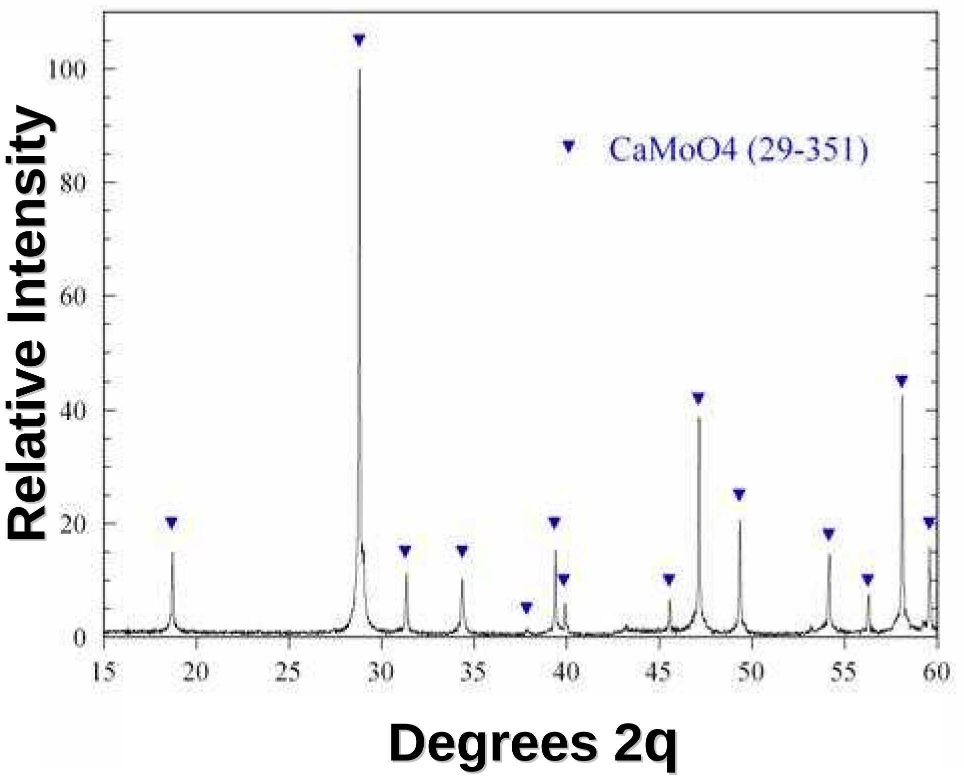
"Shaped Microcomponents via Reactive Conversion of Biologically-derived Micro-templates," *U.S. Patent No. 7,067,104*, June 27, 2006.

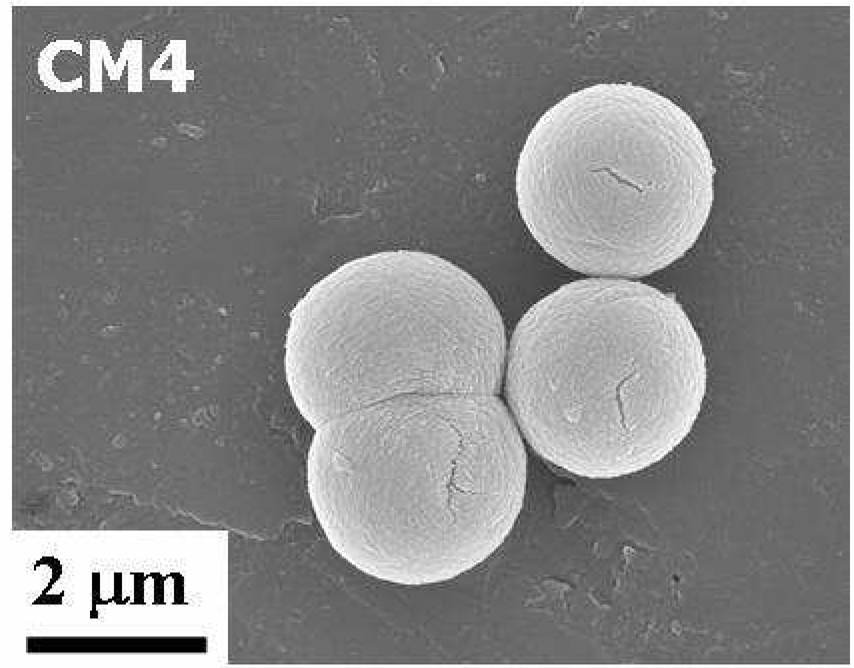
Miniature, Rapid, Low-voltage Sensors



***Z. Bao, M. R. Weatherspoon, Y. Cai, S. Shian, P. D. Graham, S. M. Allan, G. Ahmad, M. B. Dickerson, B. C. Church, Z. Kang, C. J. Summers, H. W. Abernathy, III, M. Liu, K. H. Sandhage, Nature, accepted, in press.**

Pure Multicomponent Oxides with Peptides as Mineralizing Agents
(No firing with protein catalyzed growth!)





G. Ahmad, M. B. Dickerson, B. C. Church, Y. Cai, S. E. Jones, R. R. Naik, J. S. King, C. J. Summers, N. Kroger, K. H. Sandhage, Adv. Mater., 18, 1759-1763 (2006).

Room temperature fabrication of complex materials.

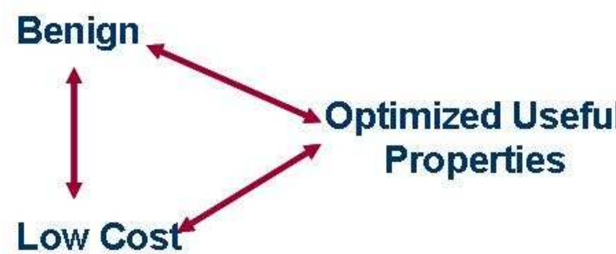
GRC ESH Thrust: High Priority Challenges

	Year N+1	Year N+2	Year N+3	Year N+4	Year N+5
Thrust: Environment, Safety, and Health [ESH]					
ESH Impact of New Materials for CMOS	**Mat.**	**Mat.**	**Mat.**	**Decr.**	**Decr.**
Water/Energy	**Mat.**	**Mat.**	**Mat.**	Decr.	**Decr.**
Design for ESH Methodology	**Mat.**	**Mat.**	**Mat.**	**Mat.**	**Mat.**
Additive & Wasteless Processes	**Mat.**	**Mat.**	**Mat.**	**Mat.**	**Mat.**
ESH Impact of Nanomaterials	**Start**	**Start**	**Start**	**Start**	**Start**

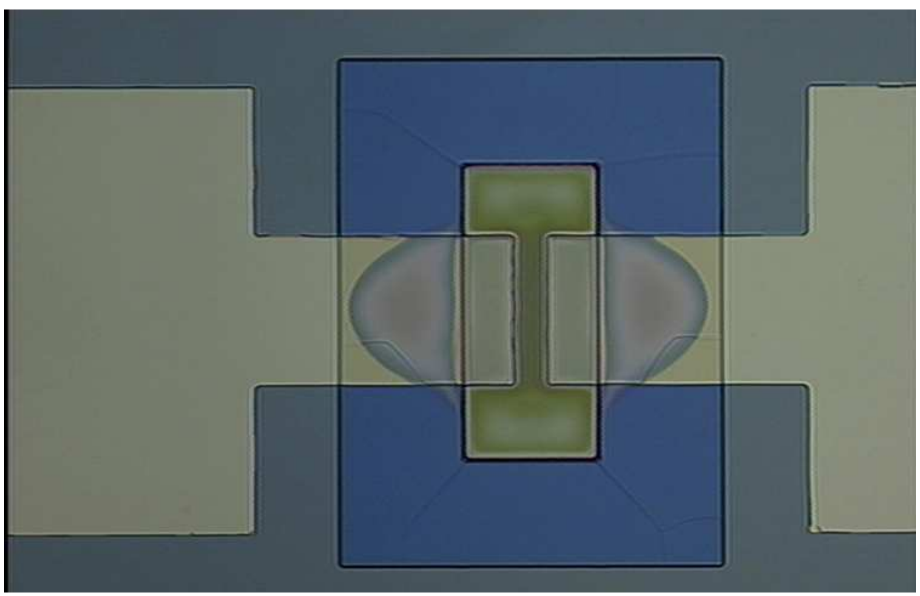
Strategic Gap

Joint ESH Research Challenges

- Metrics for nanoscale particle toxicity
- Exposure monitoring methodologies
- Hazard assessment methodology
- Testing strategy for toxicity



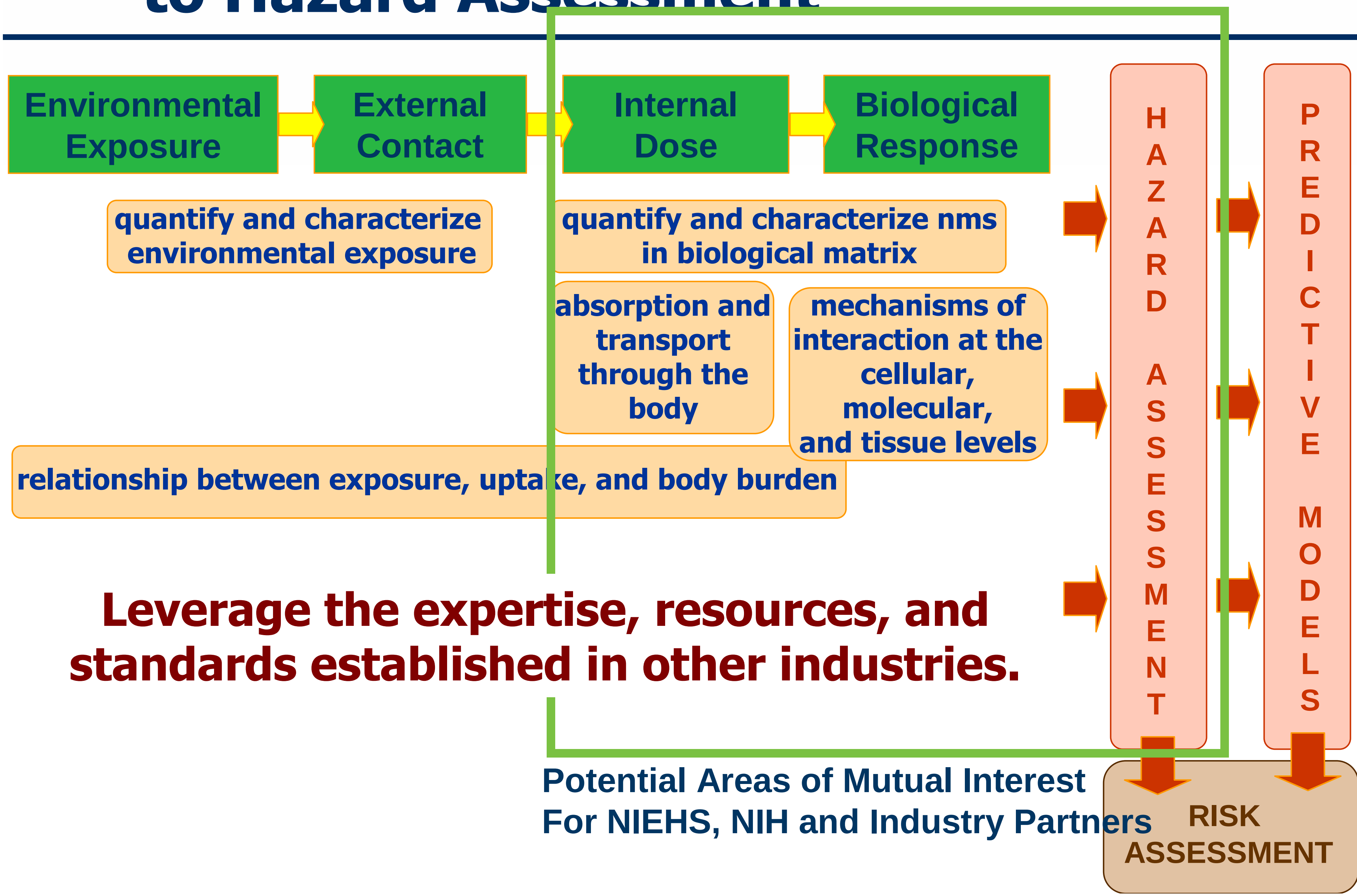
- Societal communication and education



Ex. Droplet on Demand Patterning enables low temperature [130C] Cu sintering and enhanced conductivity.

What is the ESH impact of 5 nm Cu particles?

Need for an Hierarchical Approach to Hazard Assessment



Leverage the expertise, resources, and standards established in other industries.

Key Message(s): There is hope.

- **Directed assembly** may extend **affordable CMOS fabrication to ~10 nm**.
- **Enhanced patterning functions** exhibit promise for **3D nanofabrication** and **deterministic placement** of electronically useful nanostructures.
- **Materials-by-design** identifies potential routes to **engineered interfaces** and **heterogeneous nanomaterial integration** on CMOS.
- Robust **predictive nanomaterials models** enable concurrent **optimization of nanomaterial performance and ESH impact.**

Summary

- **Dimensional scaling of CMOS will continue**
  - Enabled by new materials and assembly methods
- **New functionality will be added to CMOS**
  - Through CMOS compatible heterogeneous nanomaterials and integration methods.
  - What can we leverage from natural processes?
- **Need materials-by-design to concurrently optimize peformance – ESH attributes**
  - What is the ESH impact of nanomaterials?
  - Need a predictive and hierarchical ESH framework for assessing emerging nanomaterials

Thank You