Engineering Research Center for
Environmentally Benign Semiconductor Manufacturing

Manufacturing in Nano-Scale: Environmental Challenges and Opportunities

University of Utah
March 15, 2011

ERC Members and Participants

Founded in 1996 by NSF & SRC; now almost entirely industry funded

Founding Universities

- U Arizona
- U California – Berkeley
- MIT
- Stanford

Other University members

- Arizona State U (1998 -)
- Columbia (2006 - 2009)
- Cornell (1998 -)
- Georgia Inst. of Tech. (2009 -)
- U Maryland (1999-2003)
- U Massachusetts (2006 - 2009)
- U North Carolina (2009 -)
- Purdue (2003 - 2008)
- U Texas - Dallas (2009 -)
- Tufts (2005 - 2008)
- U Washington (2008-)
- U Wisconsin (2009-)

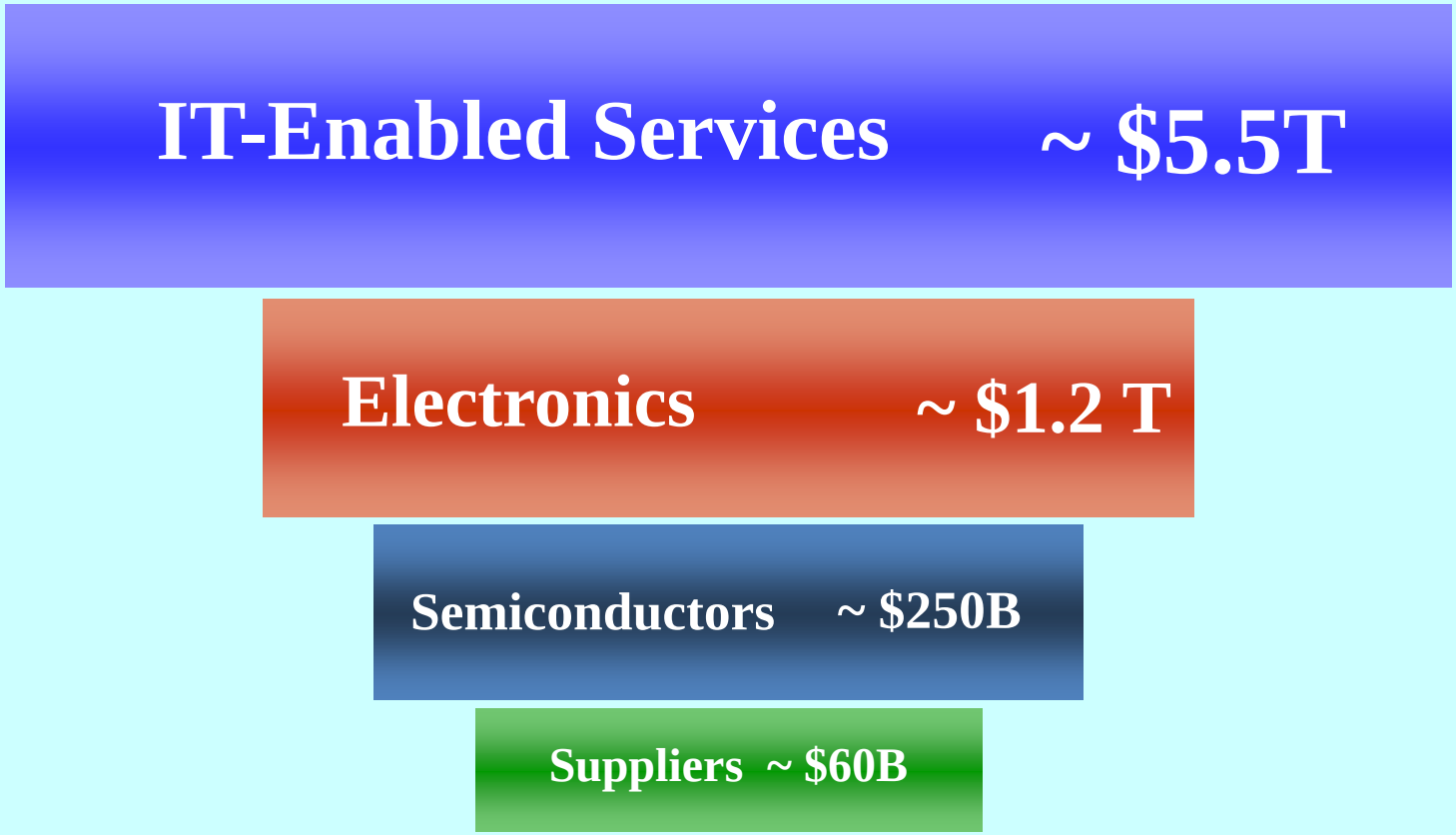
Cumulative Data:

16 Core member Universities
241 PhD and MS
205 Undergraduates (reported)
13 Academic disciplines

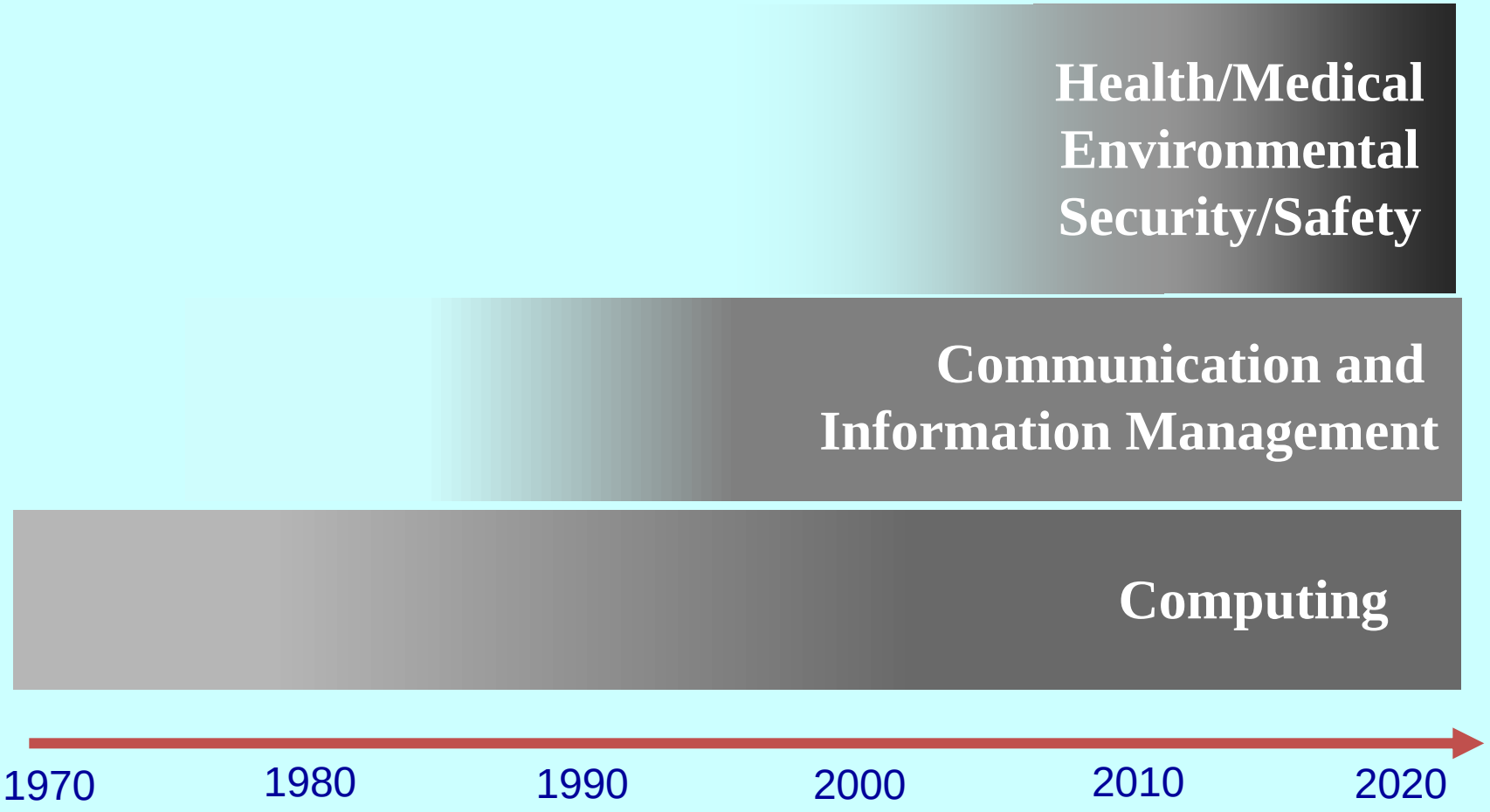
> 80% of graduates joined SC industry & suppliers (mostly ERC members)

10 Current member universities
28 Current PI/Co-PIs
37 Current graduate students

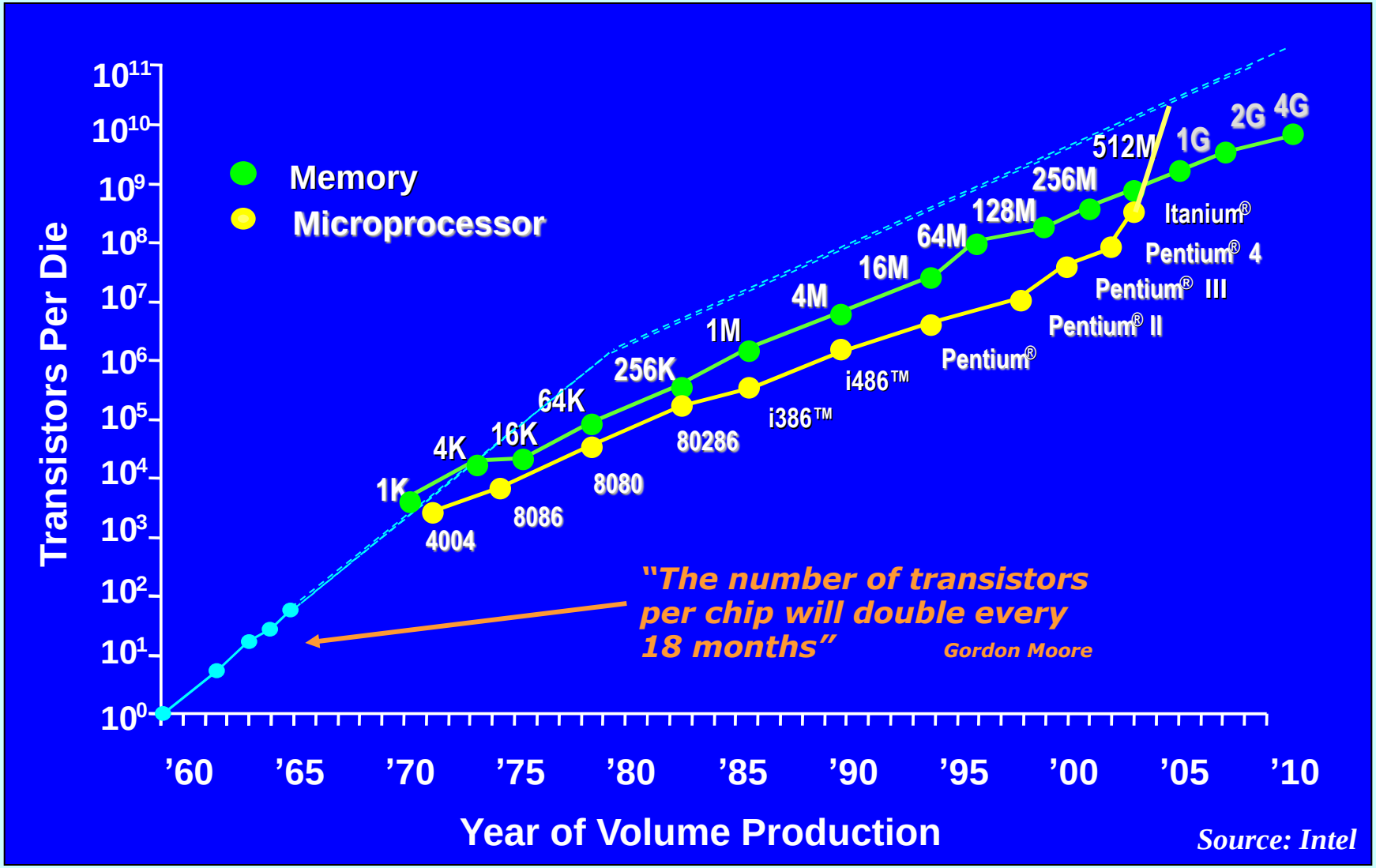
A Formidable Economic Ecosystem



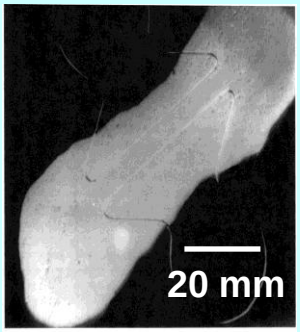
Applications that Have Changed Our World



Unprecedented Growth

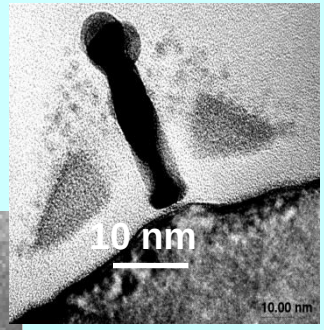


Shrinking of Device Dimensions



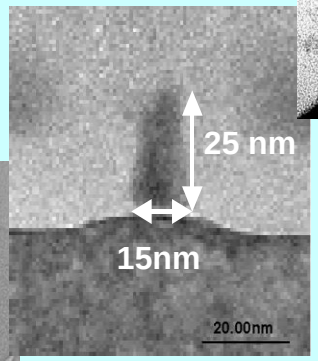
First MOSFET (1960)

10^{-7}

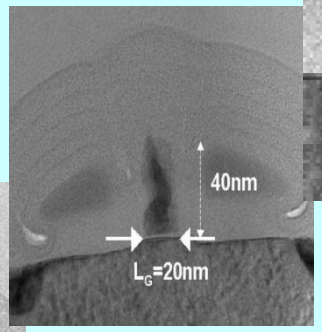


MOSFET in 2008

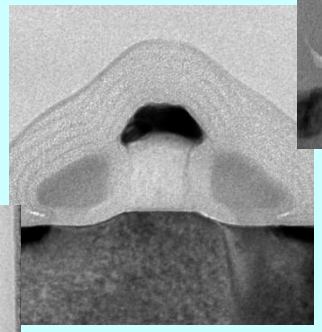
Gate thickness <1 nm
Channel Length <10 nm
Junction depth < 50 nm



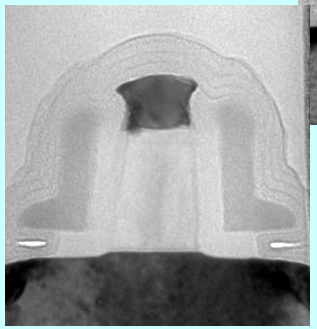
15 nm



20 nm



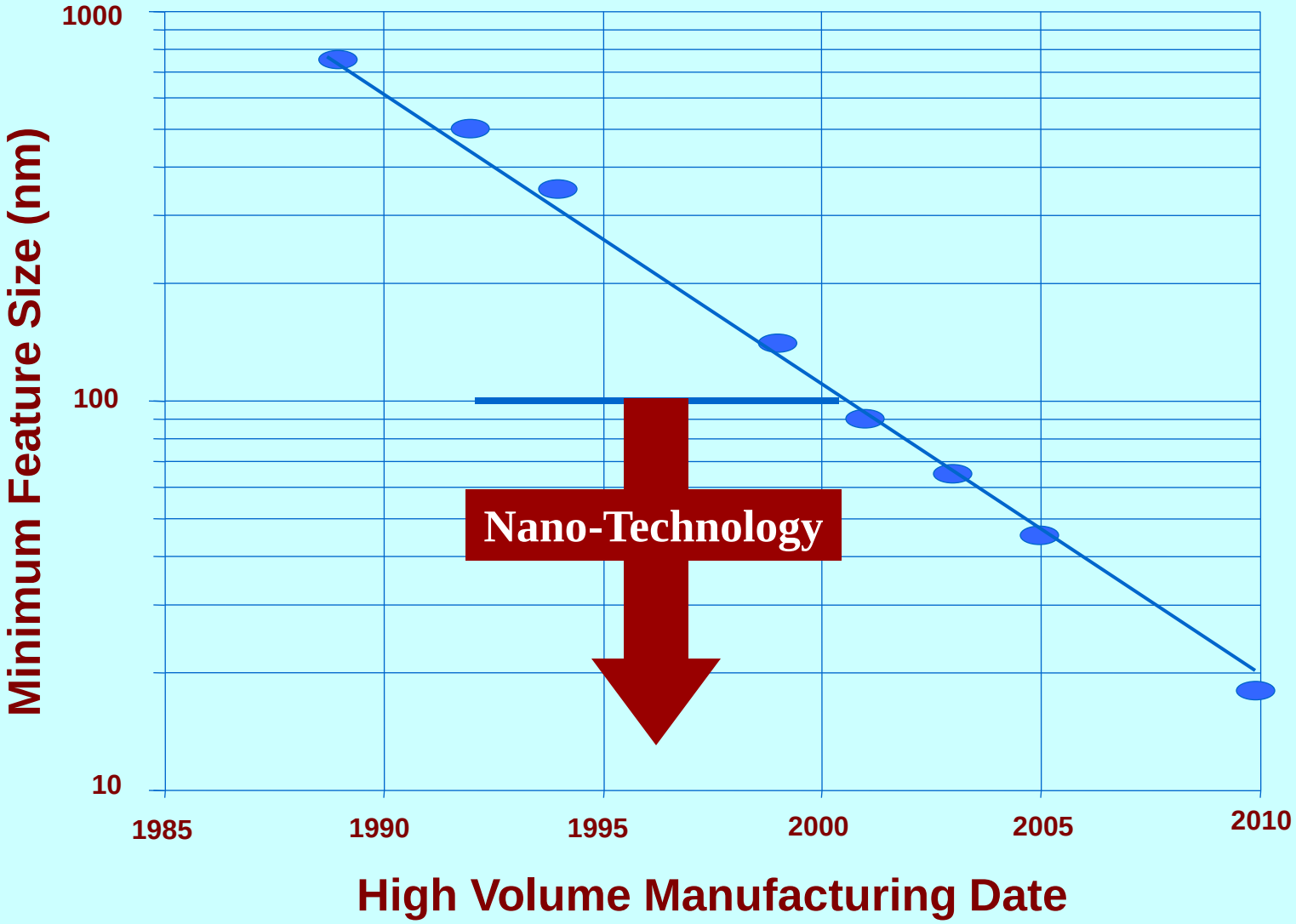
30 nm



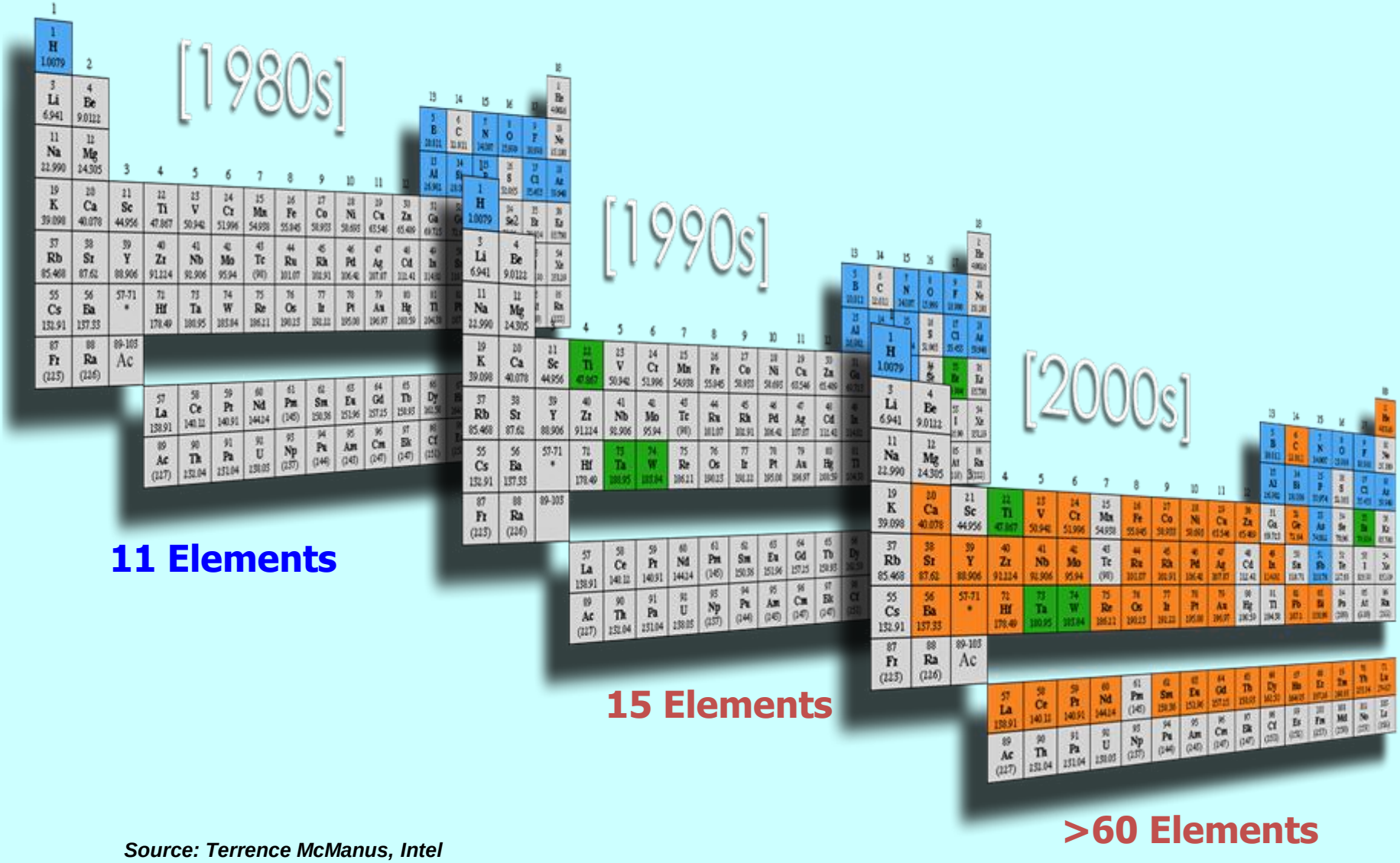
50 nm length

Size of an atom ~ 0.5 nm

Trends in Feature Size

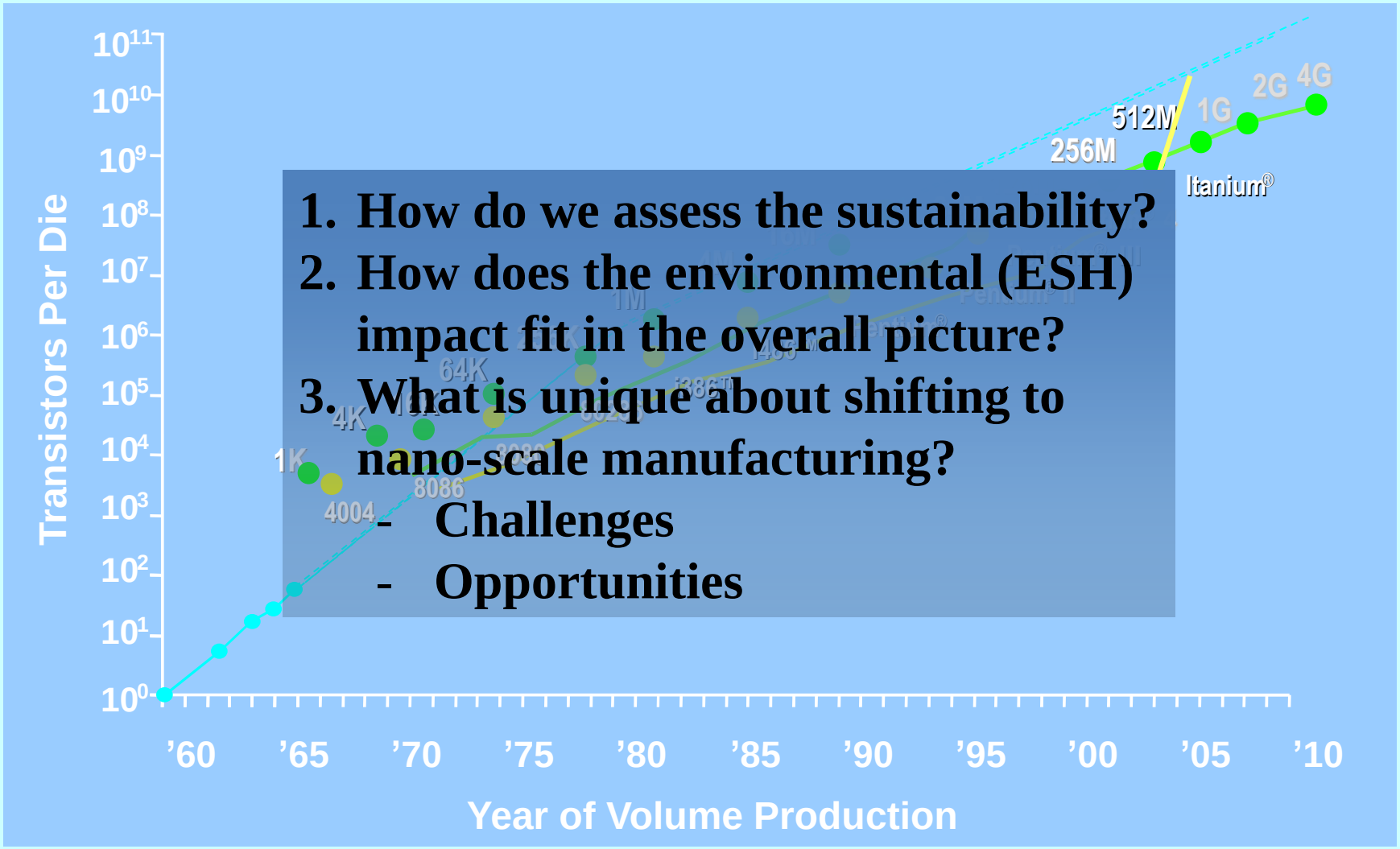


Introduction of New Materials



Source: Terrence McManus, Intel

Is this Growth Sustainable?



Definition of Sustainability

"*SUSTAINABILITY*" is like "*PEACE*":

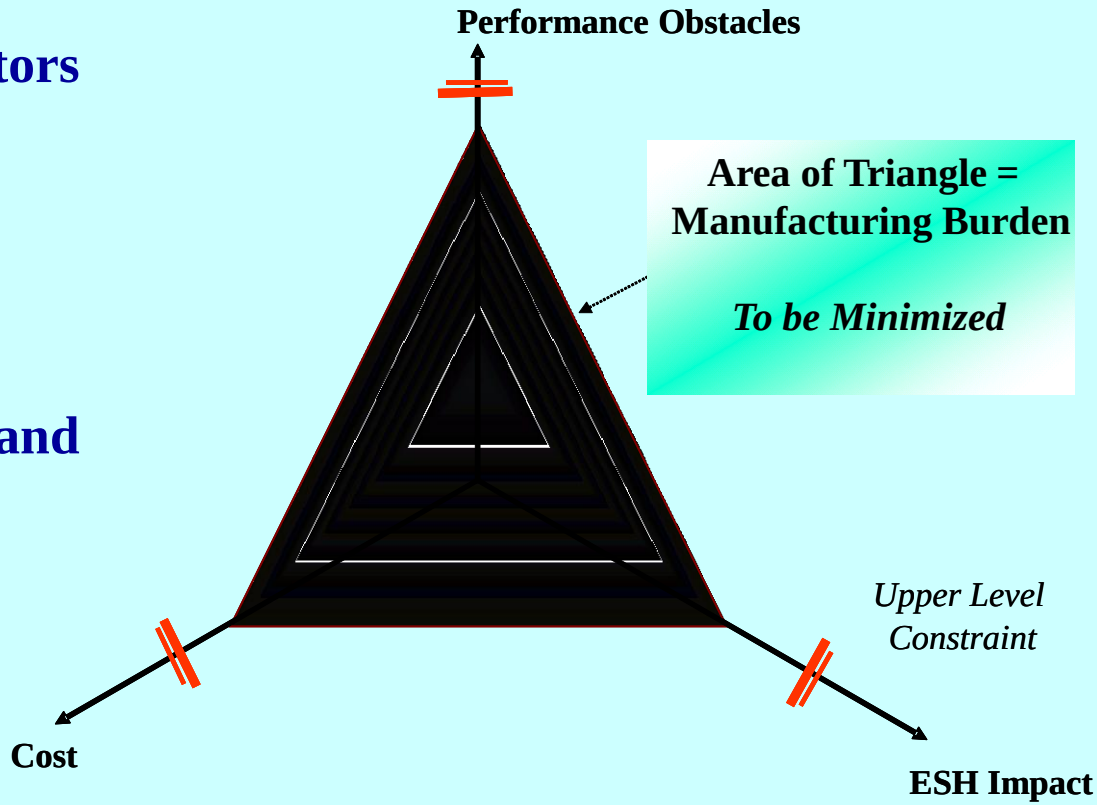
it enjoys a universal appeal and full agreement;

the disagreement in ONLY in what it means and how to implement it.

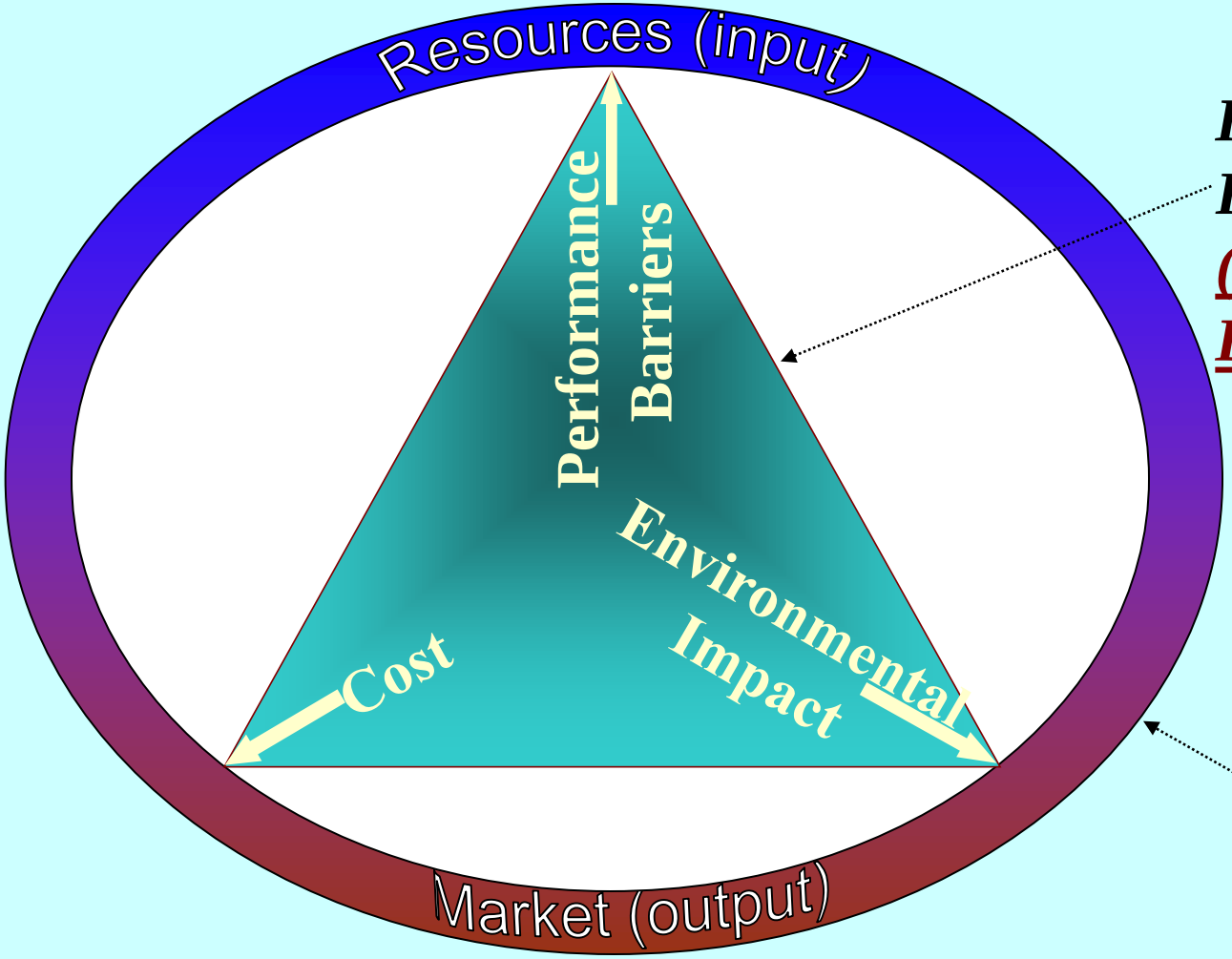
Sustainability Factors

Factors that determine the sustainability of *a product*, *a process*, *a manufacturing operation*, or *an industry:*

1. **Product performance**
2. **Cost and economic factors**
3. **Environmental impact**
   - **Safety and Health**
   - **Social factors and compatibility**
   - **Resource utilization and availability**



Sustainability Illustrated



Industry Footprint (Manufacturing Burden)

Sustainability Boundary

Sustainability Challenges
Environmental, Safety, and Health (ESH) Aspects of Nano-Manufacturing

1. **Nano-Particles in Manufacturing**
   - **Workers exposure to nano-particles in the fabs**
   - **Emission of nano-particles through fab waste streams**

2. **Impact on Resource Utilization**
   - **Increase is water, energy, and chemical usage**

3. **Introduction of New Materials**
   - **New device materials, new processing fluids, etc.**

4. **Positive Environmental Impact**
   - **Opportunities for major ESH gain**

Functionalized Fabricated Nano-Particles

New name for some old materials

Aerosil = fumed SiO_2

Particle size:

4-20 *milli-micron* (nanometers)

New additive for coating industry

Colorants & Coatings

(Farbe & Lack Journal; April 1949)

What is Unique About Nano-Particles?

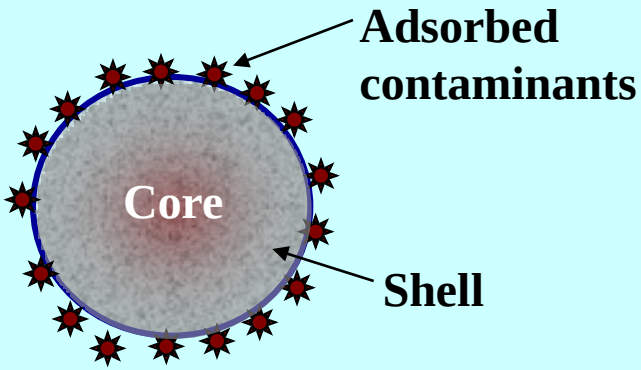
Treatment problem:

- **Nano-particles cannot be effectively removed by *agglomeration, settling, and filtration;* they also clog membranes.**

Synergistic ESH impact of nano-particles:

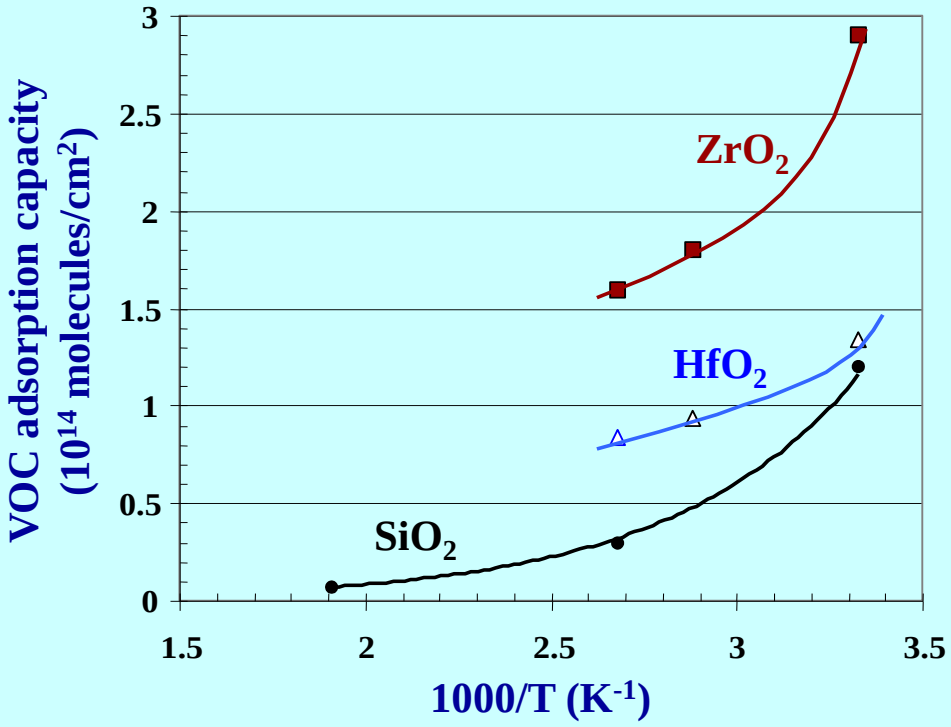
- ***Active surface***
- ***Selective adsorption***
- ***Pore condensation*** ***(Kelvin Effect)***

Consequence
- ***Concentration***
- ***Facilitated transport***
- ***Enhanced life-time***



Toxicity Enhancement in Nano-Particles

a) Nano-particles in the gas phase
15ppb VOC; 40 nm particles



b) Nano-particles in the wastewater

- **10 ppb of Cu^{++} in CMP wastewater results in $3x10^6$ ppb of adsorbed copper on 90 nm CeO_2 nano-particles**
- **10 ppb of PFOS in wastewater results in $2.8x10^4$ ppb of contaminated 10 nm carbon nano-particles**

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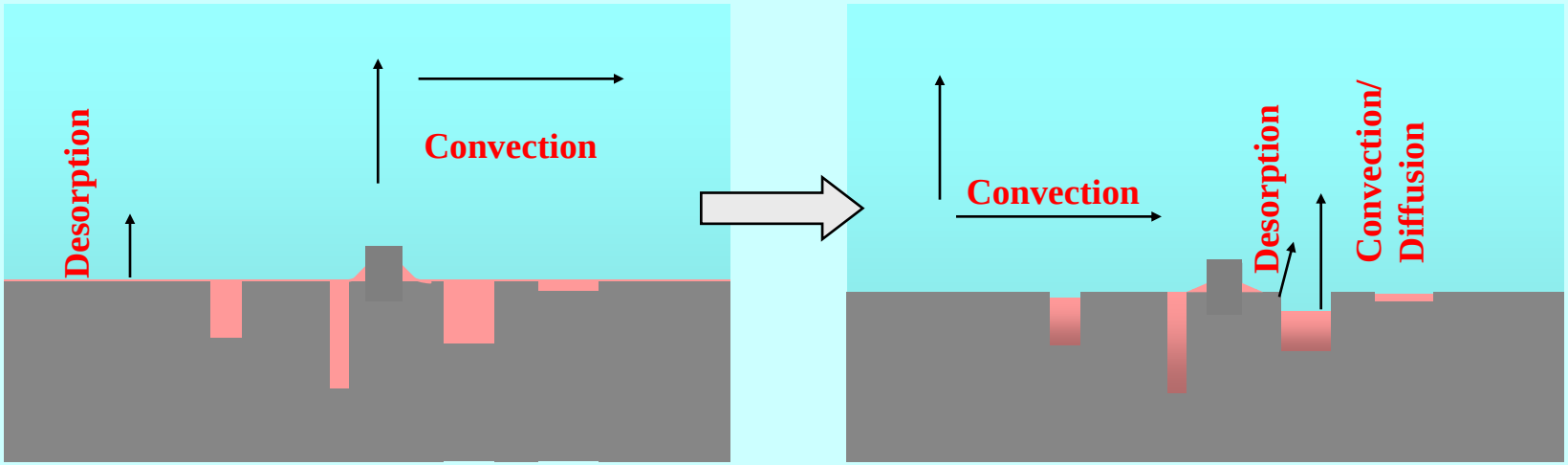
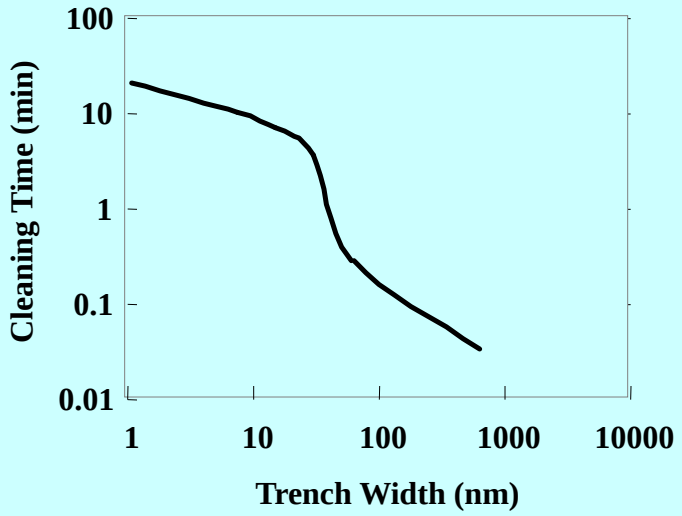
Issues in Cleaning of Nano-Structures

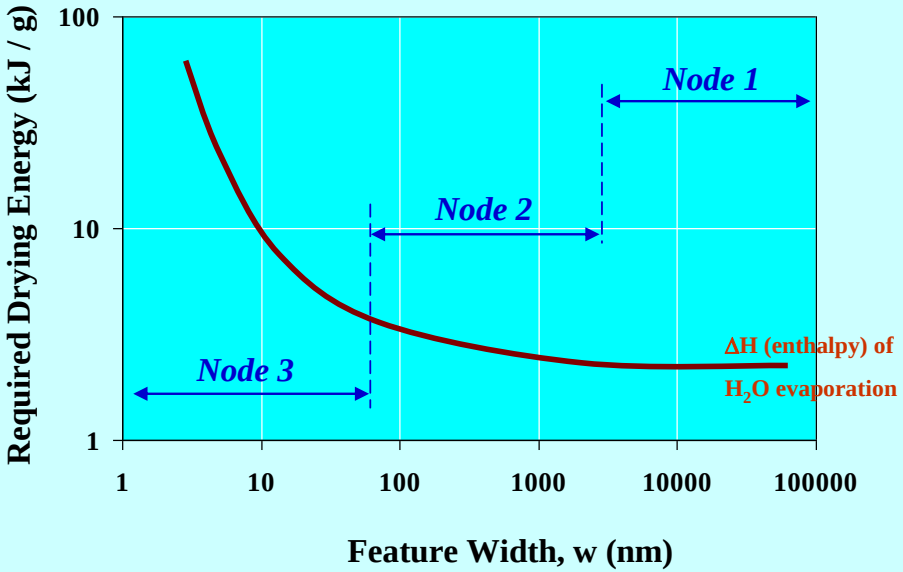


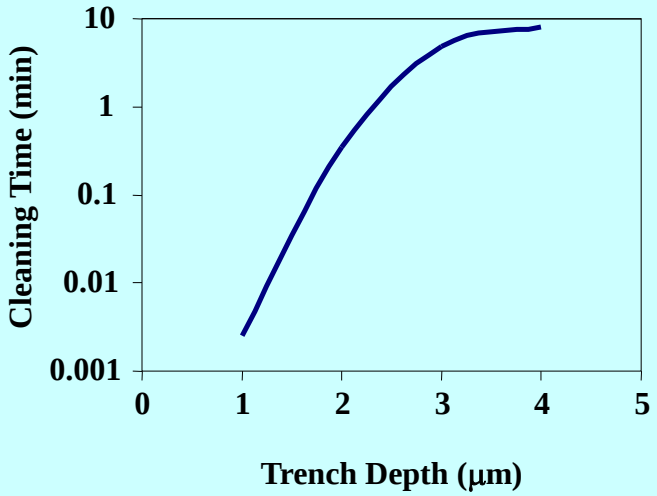
Mechanism	Time Scale	Flow Effect
Boundary Diffusion	$d^2/D \sim 10$ s	Indirect, mild
Convection	$d/u \sim 1\text{-}3$ s	Direct, strong
Desorption	$1/k_d \sim 0 - 10^5$ s	No effect

Needs: New metrology methods
New cleaning chemistries

Large Wafers and Small Features
ESH Challenges



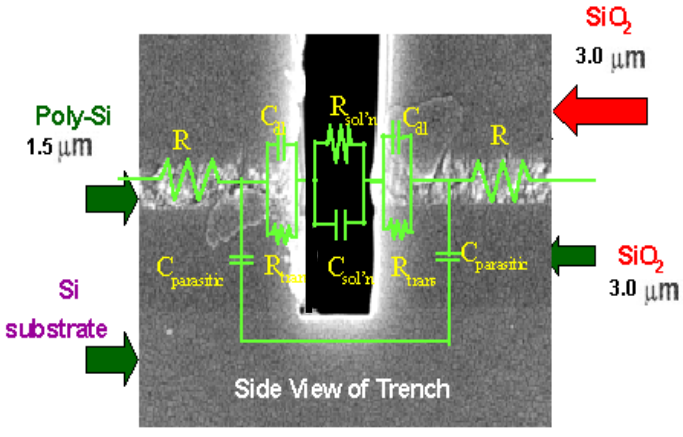


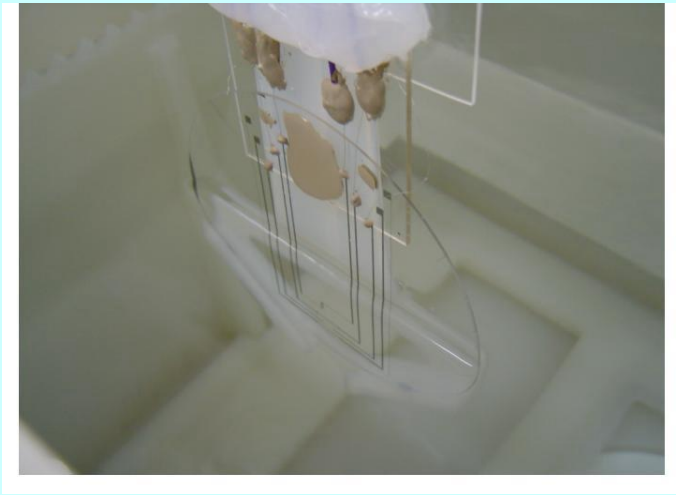


ERC results show large increase in *water, chemicals, and energy usage* in various nano-manufacturing processes as feature size decreases and wafer size increases.

A Novel Metrology Technology:

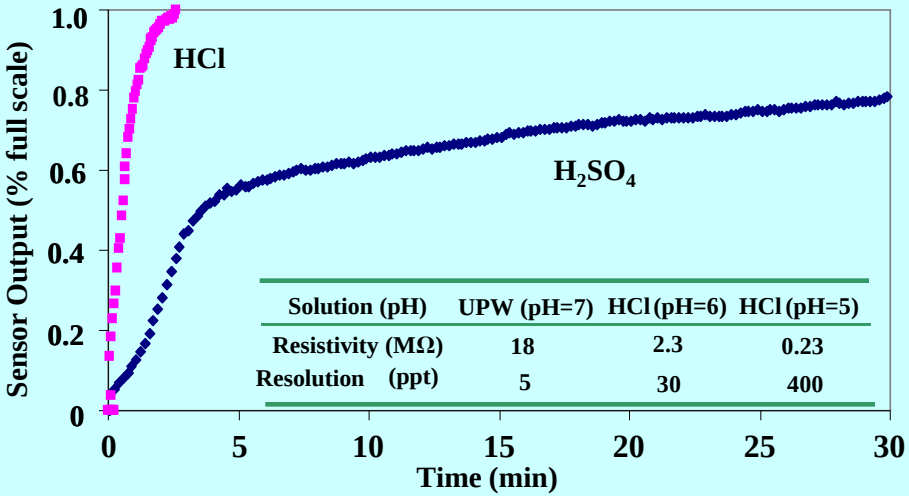
Electro-Chemical Residue Sensor (ECRS)





Unique Characteristics:

- In-situ
- Real time
- On-line
- High sensitivity for small feature sizes
- Very short response time
- Total integration



ECRS: Winner of *2009 Product of the year* Award

YAHOO! FINANCE

Semiconductor International Editors' Choice Best Product 2009

Semiconductor International Announces 2009 Editors Choice Best Product Award Winners

Wed Jul 15, 8:32 AM

Email Story | IM Story | Printable View

OAK BROOK, Ill.--(BUSINESS WIRE)--*Semiconductor International* bestowed its 2009 Editors' Choice Awards for excellence in semiconductor manufacturing on 15 commercially proven industry products. These awards will be presented at a ceremony in San Francisco on Wednesday, July 15, during SEMICON West. The 2009 winners exemplified state-of-the-art equipment and materials installed and used in numerous fabs around the world.

The 2009 Editors' Choice Best Product Award winners are:

AMEC	Primo D-RIE dielectric etcher
Applied Materials Inc.	SEMVision G4 defect review platform
ASM Technology Singapore	IDEALcompress encapsulation system
ATMI Inc.	AutoClean ion implant cleaning process
ATMI Inc.	Safe Delivery Source (SDS) cylinder
Cabot Microelectronics Corp.	Epic D100 CMP pad
Carl Zeiss SMT AG	ULTRA plus field-emission SEM
CI Semi	WetSpec200 in-line chemical analyzer
Environmental Metrology Corp.	Electro-Chemical Residue Sensor (ECRS)
Linde Group	Generation-F 80 on-site fluorine generator
Nikon Precision Inc.	NSR-S610C ArF immersion scanner
Nova Measuring Instruments Ltd.	NovaMARS optical CD software
Qcept Technologies	ChemetriQ 3000 inspection system
Tec-Sem AG	Pr@ctor 300 mm single wafer management s
W.L. Gore & Associates Inc.	GORE ultrapure water filters

"The Editors' Choice Best Products awards program acknowledges products, materials and services that are proven in the manufacturing environment," said Laura Peters, Editor-in-Chief of *Semiconductor International* (*SI*). In the evaluation process, *SI*'s editors consider the products based on feedback from

Press Release

Semiconductor International Announces 2009 Editors' Choice Best Product Award Winners

07.15.09, 08:30 AM EDT

BusinessWire - Semiconductor International bestowed its 2009 Editors' Choice Awards for excellence in semiconductor manufacturing on 15 commercially proven industry products. These awards will be presented at a ceremony in San Francisco on Wednesday, July 15, during SEMICON West. The 2009 winners exemplified state-of-the-art equipment and materials installed and used in numerous fabs around the world

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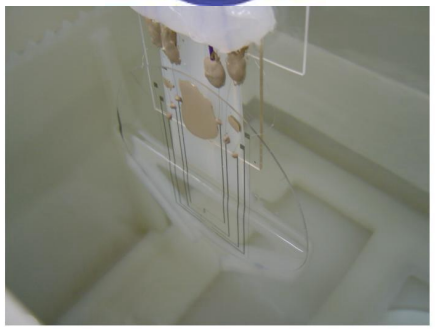
For more information about the Editors' Choice Product Awards program, go to www.semiconductor.net/awards.

Semiconductor International Editors' Choice Best Product 2009



Cleaning of Nanostructures

Process Simulation

Multi-component species transport equations :

$$\frac{\partial C_i}{\partial t} = \nabla \cdot (D_i \nabla C_i + z_i F \mu_i C_i \nabla \varphi)$$

Change in tank concentration :

$$V \frac{\partial C_b}{\partial t} = Q(C_{in} - C_b) + A \cdot Flux$$

Surface adsorption and desorption:

$$\frac{\partial C_{S2}}{\partial t} = k_{a2} C_2 (S_{02} - C_{S2}) - k_{d2} C_{S2}$$

Poisson equation: $\nabla^2 \varphi = -\frac{\rho}{\varepsilon}$

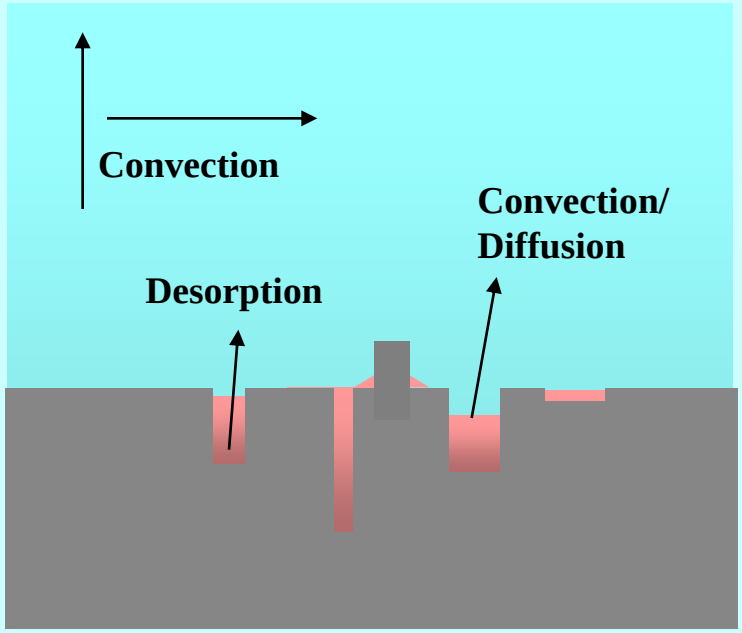
where charge density: $\rho = F \sum_i z_i C_i$

Ohm's law: $\vec{J} = \sigma \vec{E}$ $\quad \nabla \times \vec{E} = 0$

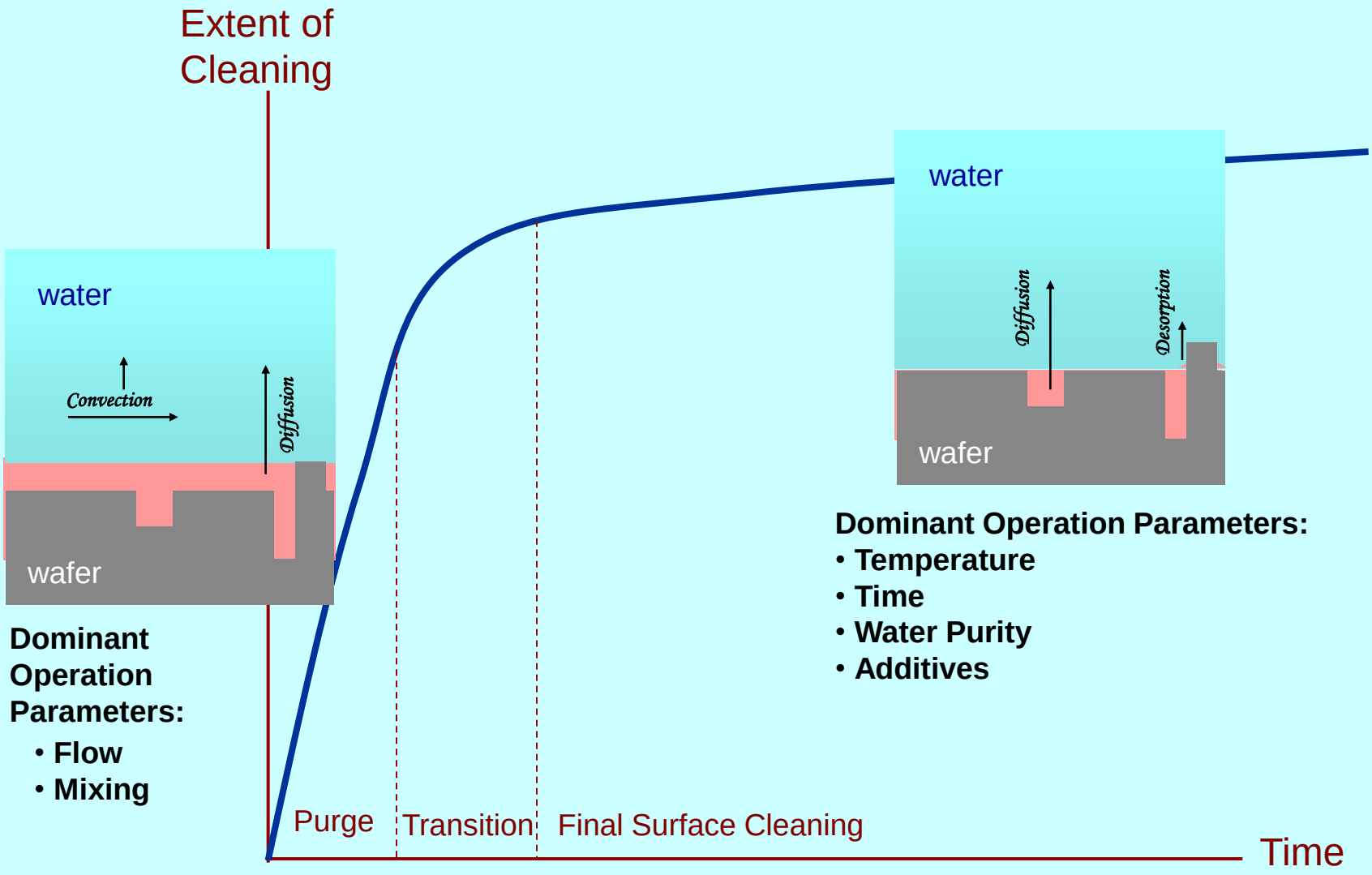
where electrical conductivity:

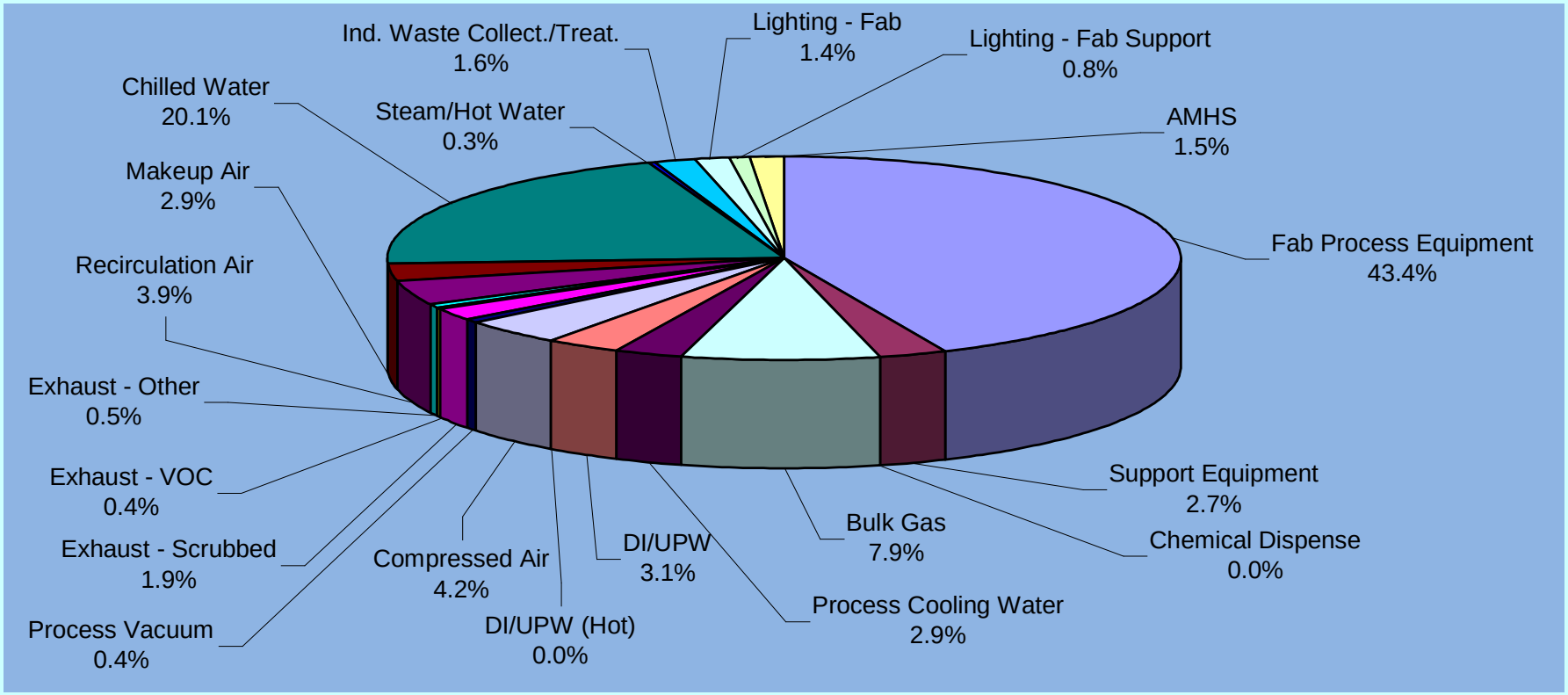
$$\sigma = \sum_i \lambda_i C_i$$

- **Surface Charge**
- **Diffusion**
- **Surface reaction**
- **Ionic transport**



A Novel Staged Rinse Process




Ind. Waste Collect./Treat.
1.6%
Lighting - Fab
1.4%
Lighting - Fab Support
0.8%
Chilled Water
20.1%
Steam/Hot Water
0.3%
AMHS
1.5%
Makeup Air
2.9%
Fab Process Equipment
43.4%
Recirculation Air
3.9%
Exhaust - Other
0.5%
Exhaust - VOC
0.4%
Support Equipment
2.7%
Exhaust - Scrubbed
1.9%
Bulk Gas
7.9%
Chemical Dispense
0.0%
Compressed Air
4.2%
DI/UPW
3.1%
Process Vacuum
0.4%
DI/UPW (Hot)
0.0%
Process Cooling Water
2.9%

ESH Aspects of Nano-Manufacturing

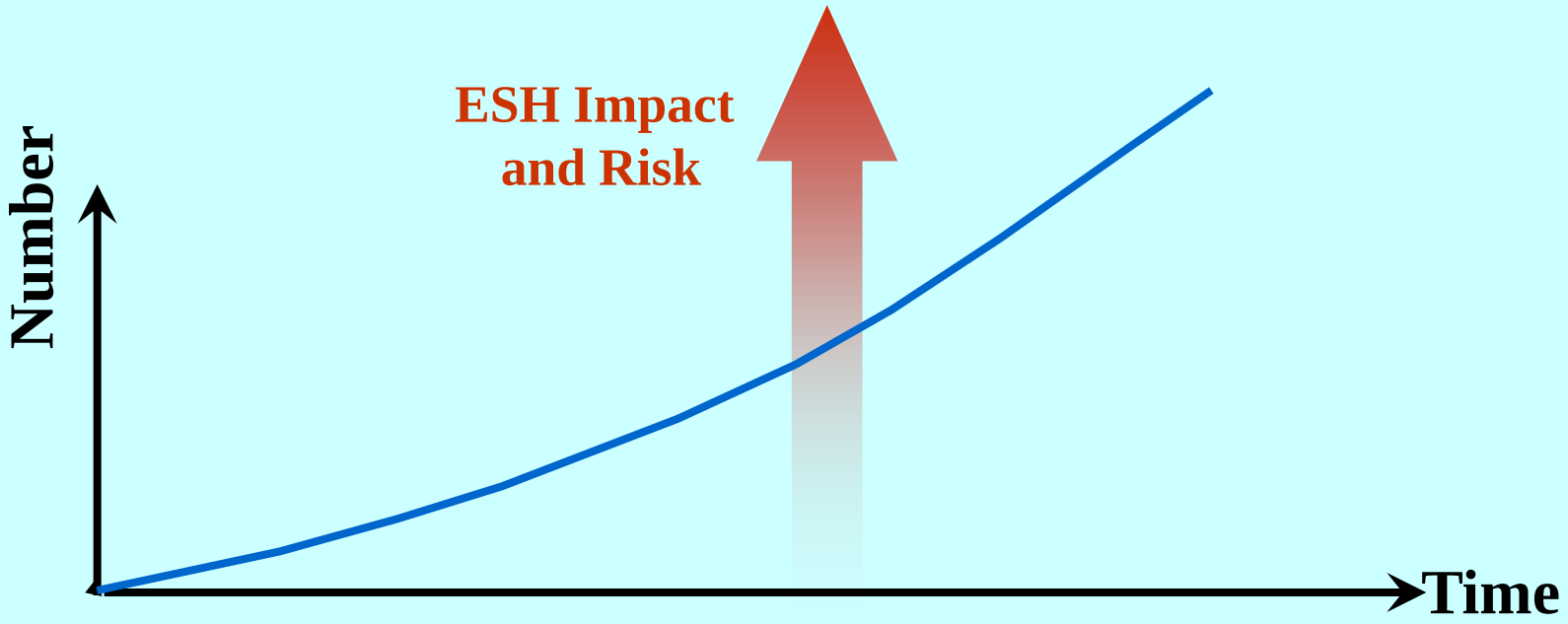
1. Nano-Particles in Manufacturing
   - Workers exposure to nano-particles in the fabs
   - Emission of nano-particles through fab waste streams

2. Impact on Resource Utilization
   - Increase is water, energy, and chemical usage

3. **Introduction of New Materials**
   - **New device materials, new processing fluids, etc.**

4. Positive Environmental Impact
   - Opportunities for major ESH gain

Introduction of New Materials



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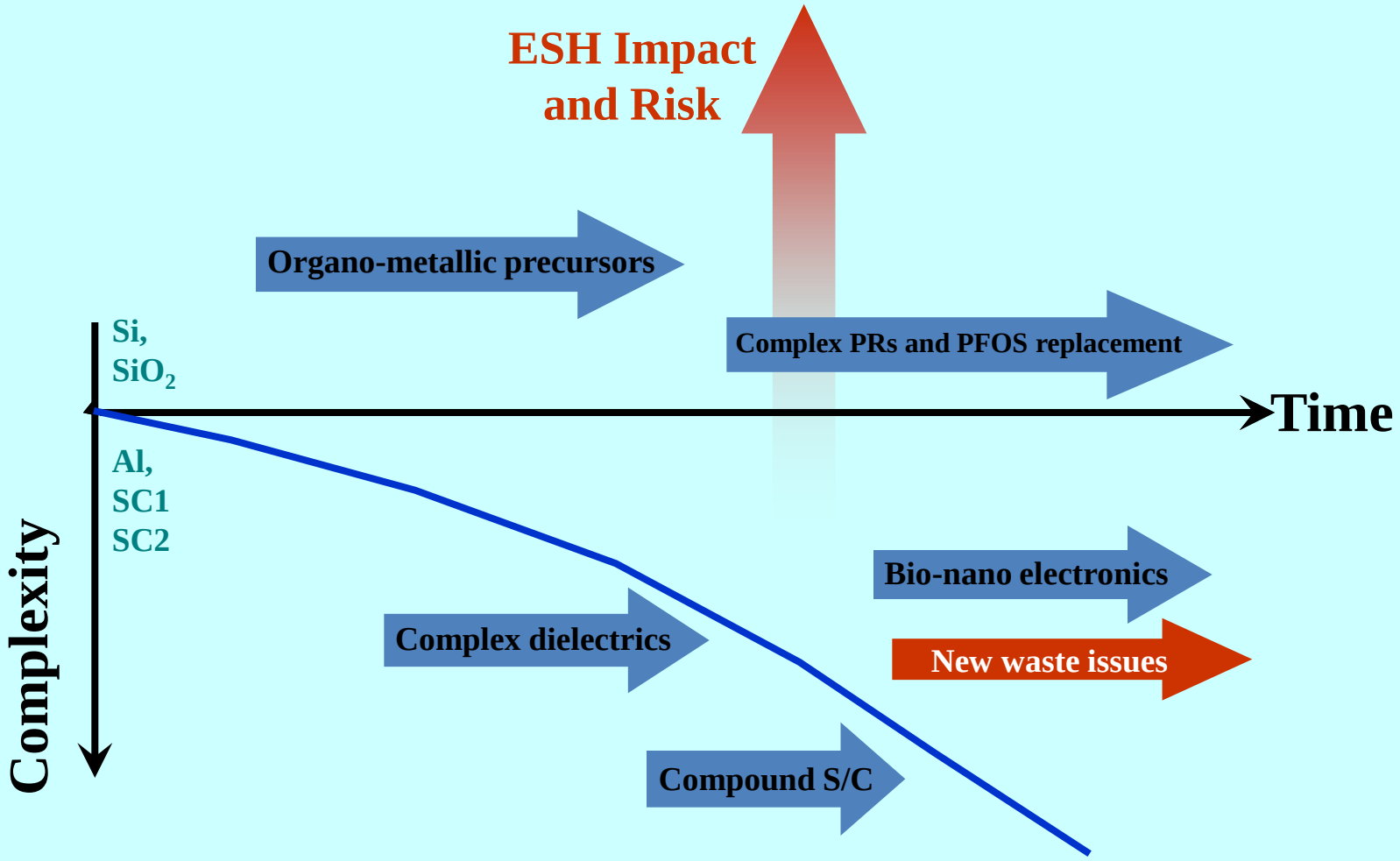
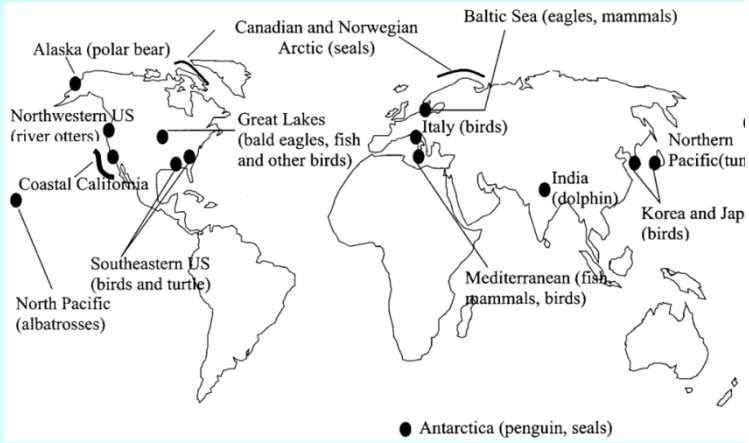


Example: Challenge of Replacing PFOS

Global Distribution of PFOS in Wildlife



Environ. Sci. Technol. 2001, *35*, 1339.

PFOS in human blood

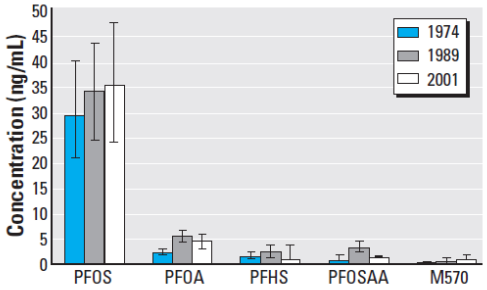


Figure 1. Median fluorochemical concentrations and IQRs for blood samples collected in Washington County, Maryland, from adults living in proximity in 1974 (n = 178 serum samples) and 1989 (n = 178 plasma samples) and in the county in 2001 (n = 108 serum samples; Olsen et al. 2003c).

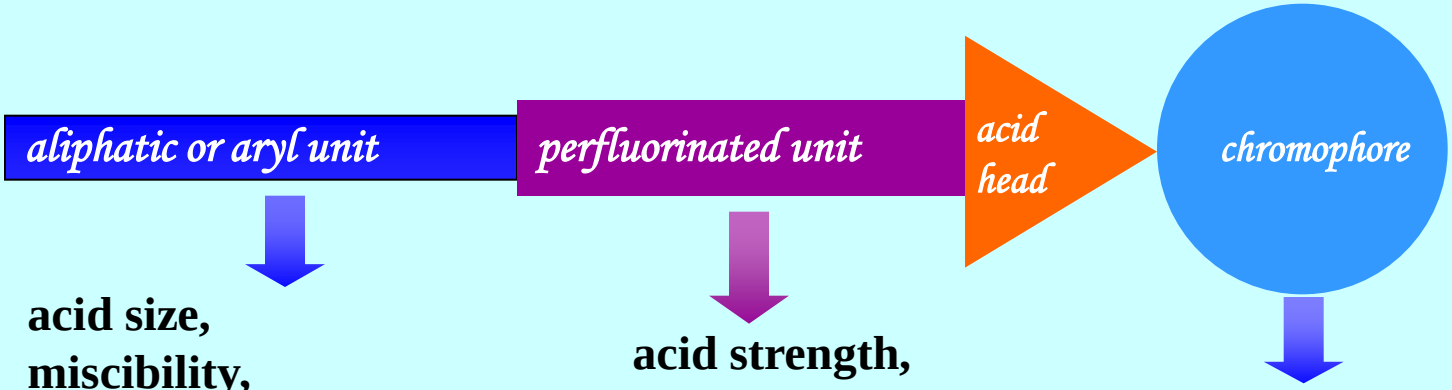
Environ. Health Perspect. 2005, *113*, 539.

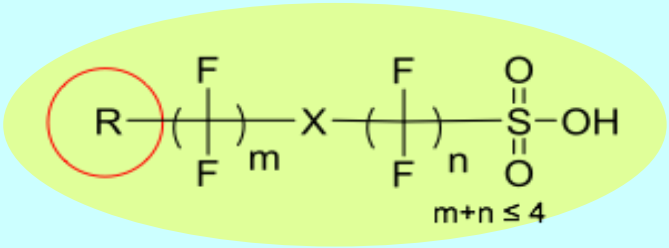
PFOS in drinking water

PFOS and other PFCs detected in drinking water resources worldwide

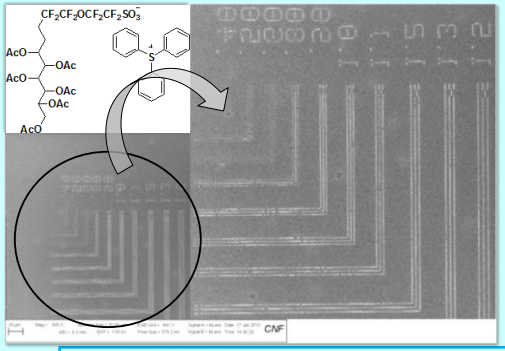
- **PFOS banned for most application is the US and EU.**
- **PFOS listed as chemical for regulation within the Stockholm Convention on Persistent Organic Pollutants (POPs)**
- **EPA Provisional Health Advisory Levels for PFOS 200 ng L^{-1}**

Molecular Design of PFOS-Free PAGS





Polar Nonpolar	Hydrophilic Hydrophobic	Aromatic Aliphatic	Linear branch ring



Sugar based
"Sweet" PAG

Natural molecules based
Biocompatible/
Biodegradable PAG

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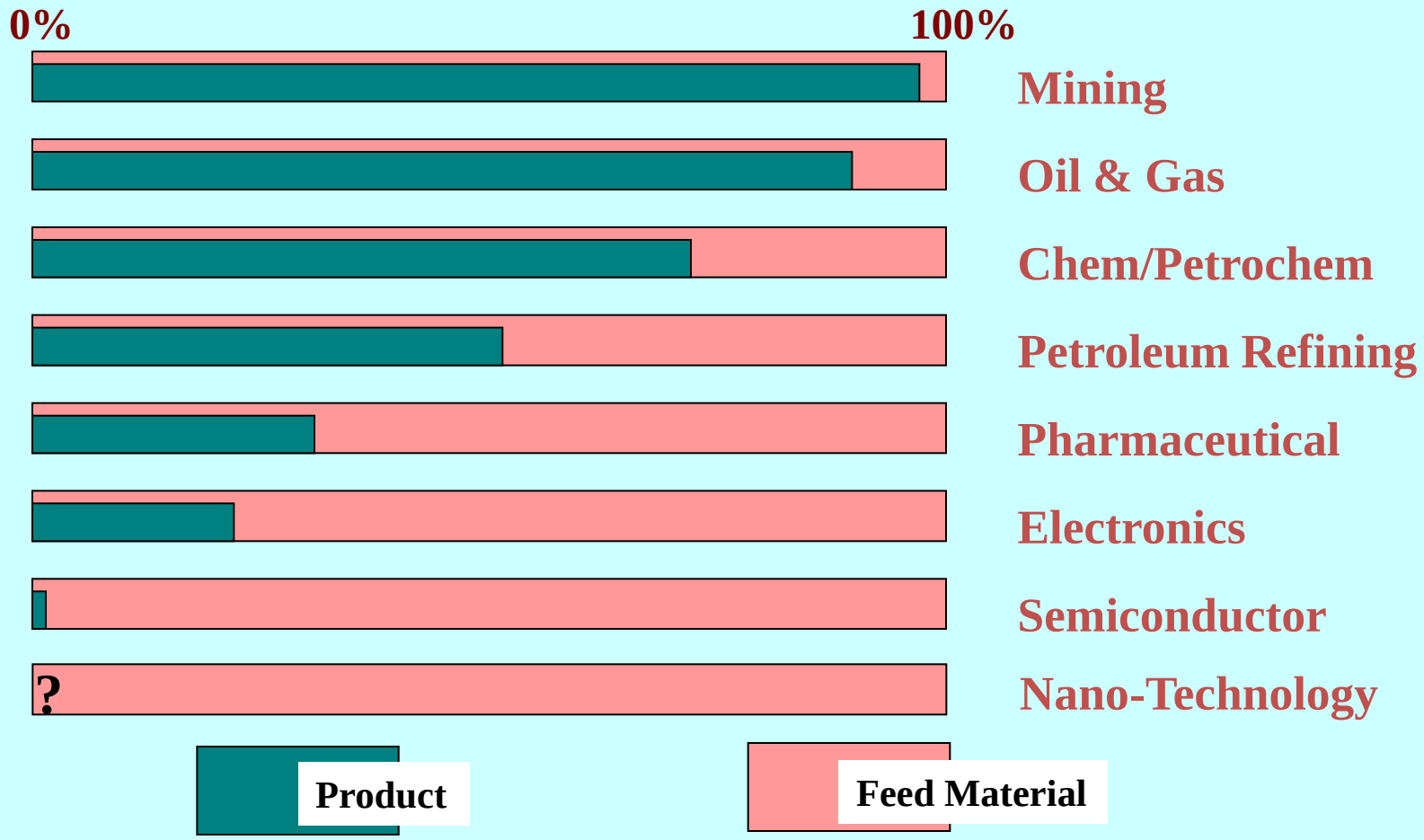
Material Usage Index in Various Industries

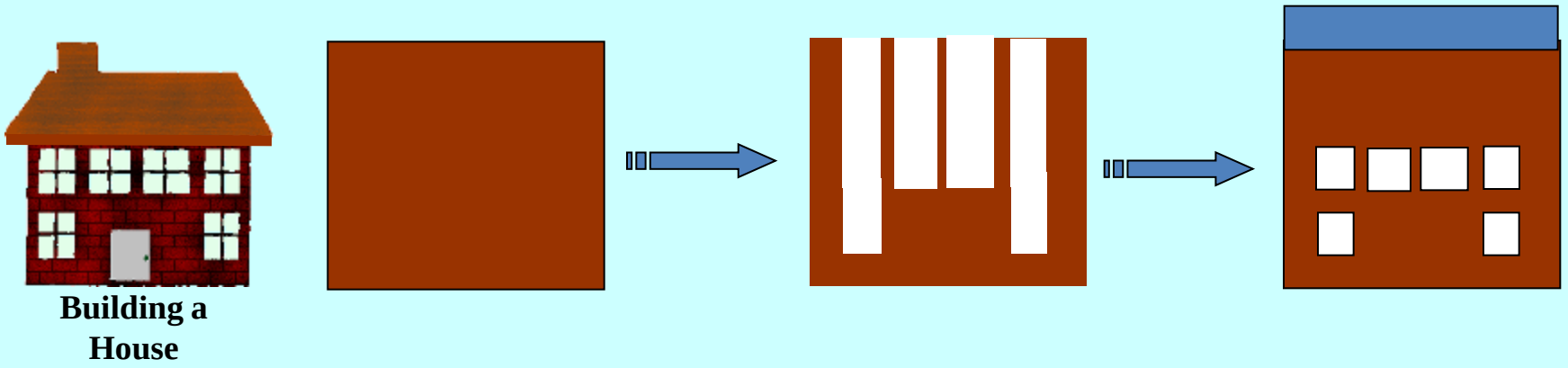


Two Basic Approaches to Manufacturing Structures

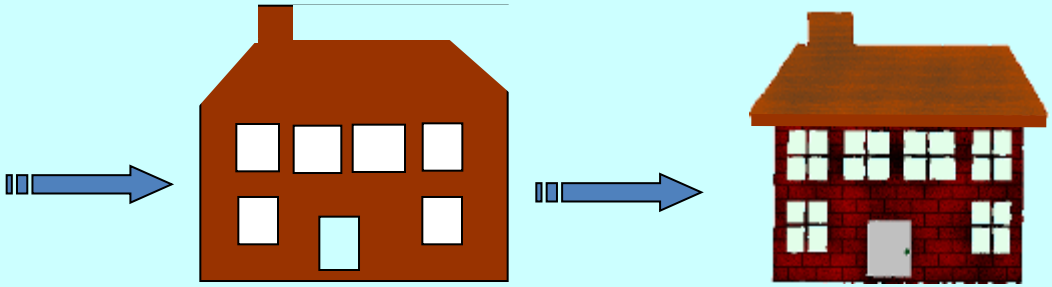
1. ***Subtractive:*** **Carve the structural details in a solid block or solid deposited layers**

2. ***Additive:*** **Place the final materials only in places where they are needed.**

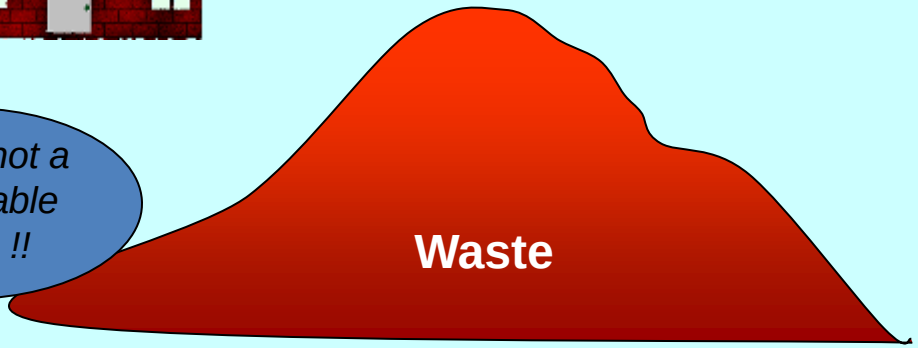
Subtractive Fabrication *(where it does not work)*



Building a House

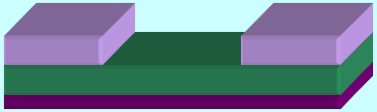
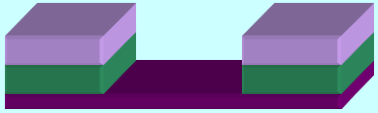


This is not a sustainable process !!



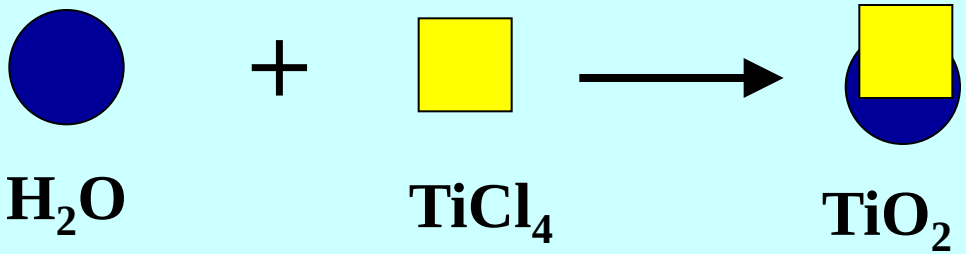
An Example of Subtractive Processing

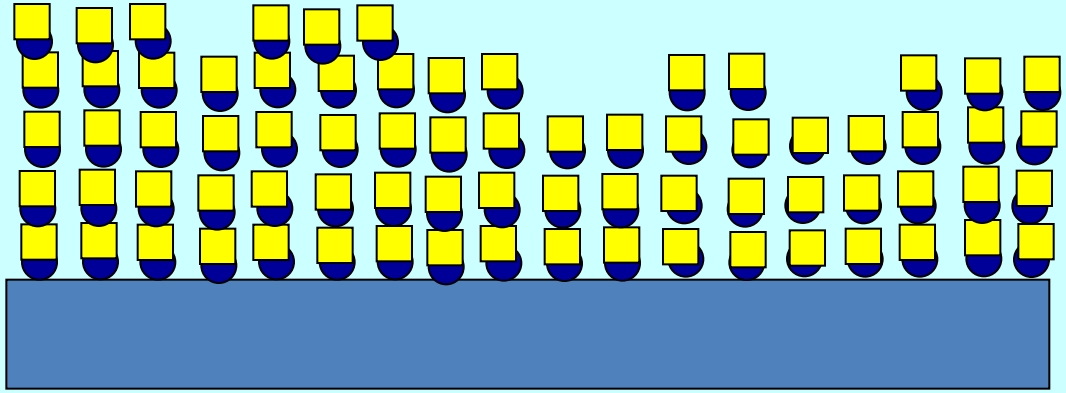
Deposition and Patterning of Dielectrics

Conventional Lithography		ESH Issues
dielectric deposition		Precursors, HAPs, wastes
spin-on imaging layer		VOCs, waste
selective irradiation		VOCs, radiation
development in aqueous base		VOCs, HAPs
dielectric patterning		HAPs, PFCs
resist strip		A/B chemicals, solvents
imaging layer strip		A/B chemicals, UPW

Conventional Subtractive Processing

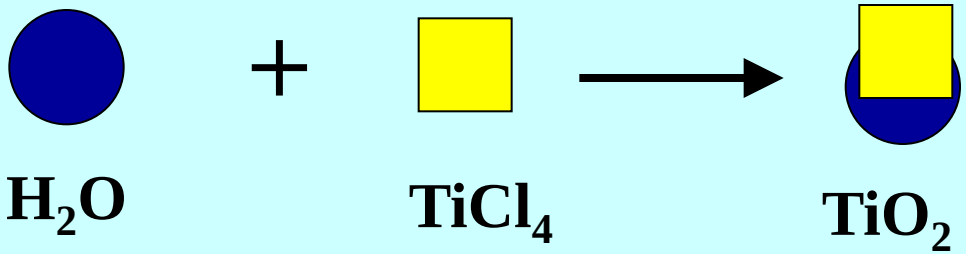
Deposition



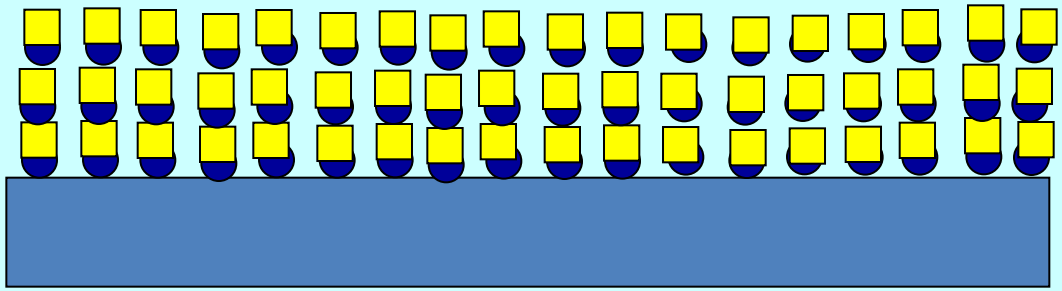


Conventional Subtractive Processing

Planarization

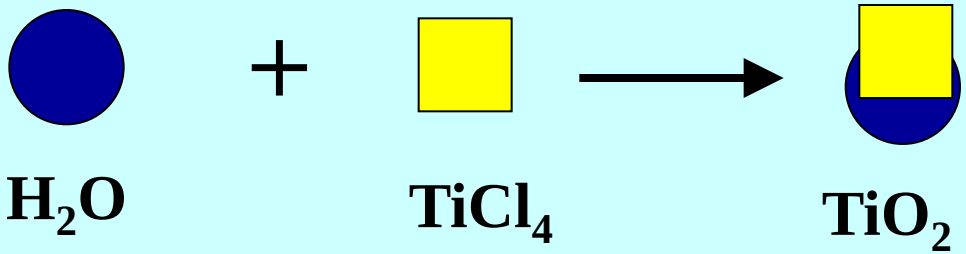


Waste

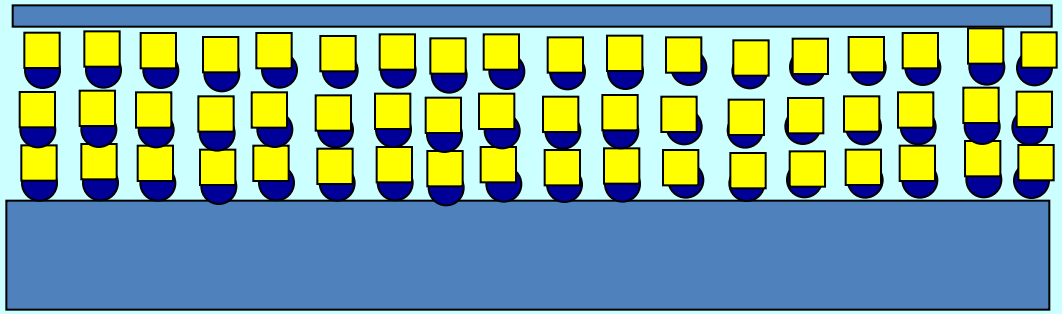


Conventional Subtractive Processing

Photo-Resist

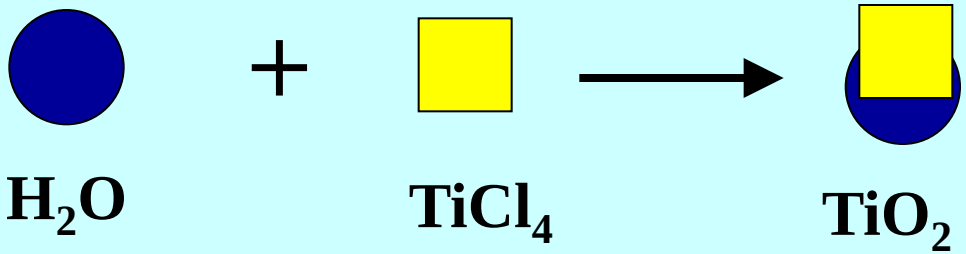


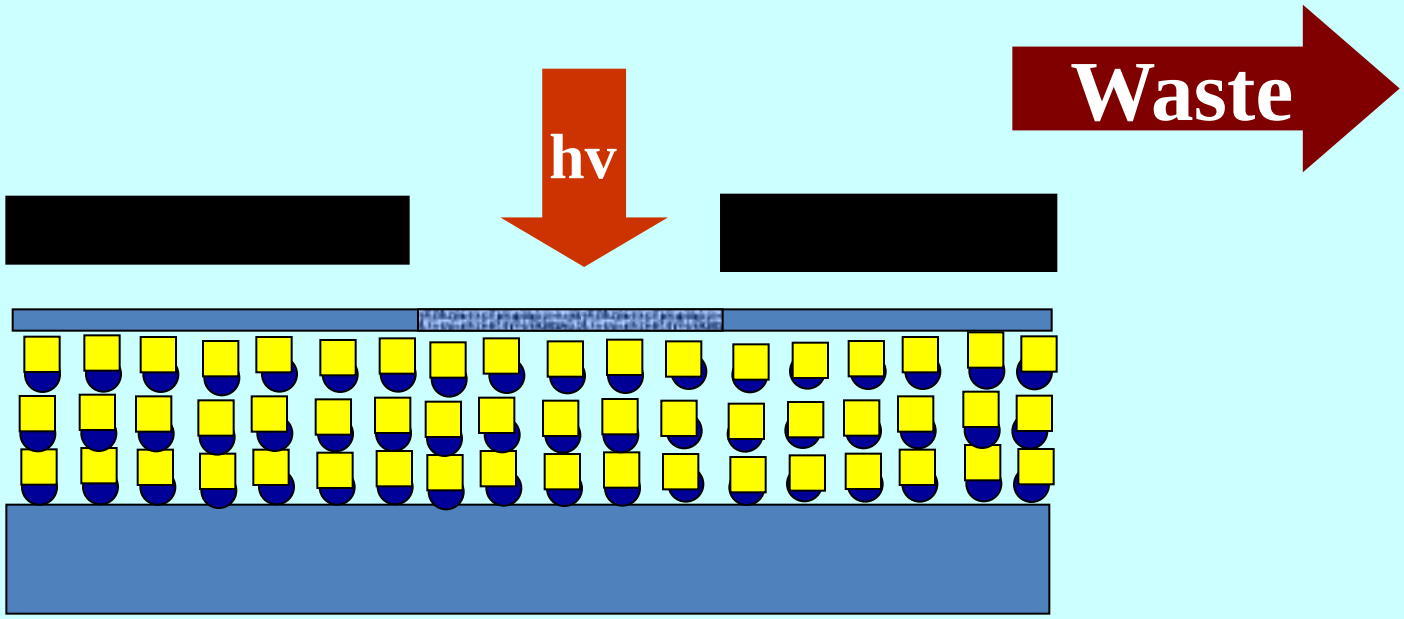
Waste



Conventional Subtractive Processing

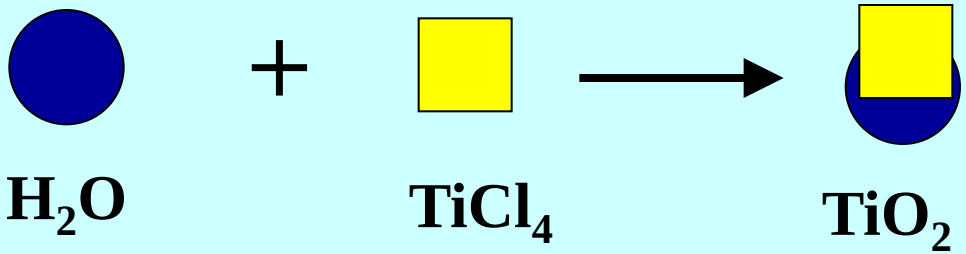
Lithography





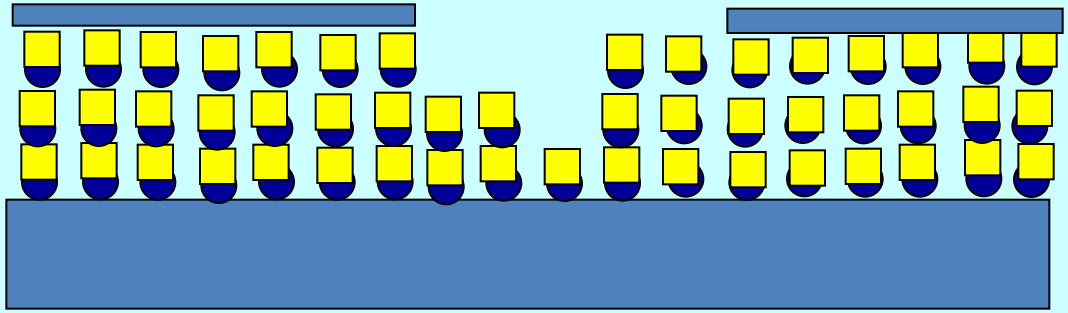
Conventional Subtractive Processing

Etch



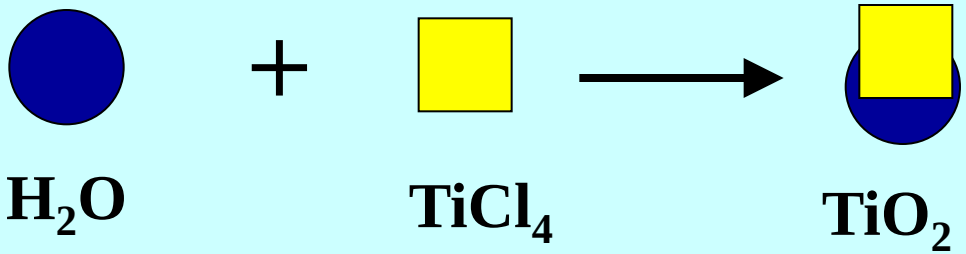
Etch

Waste

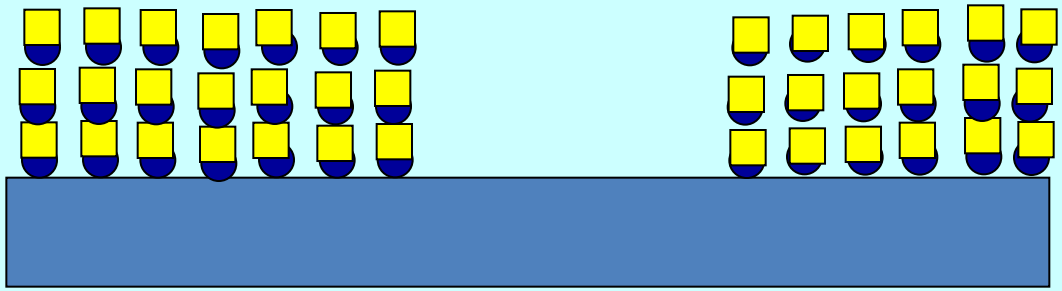


Conventional Subtractive Processing

Cleaning

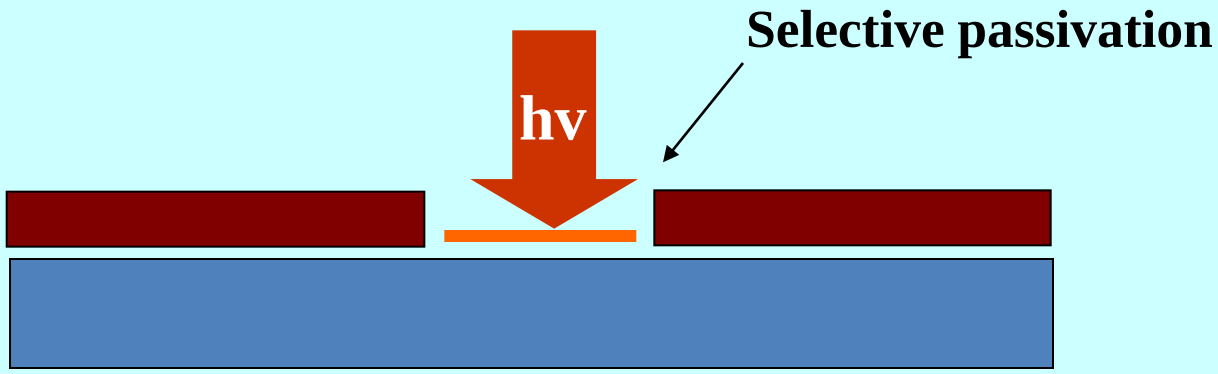


A lot of water and chemical waste



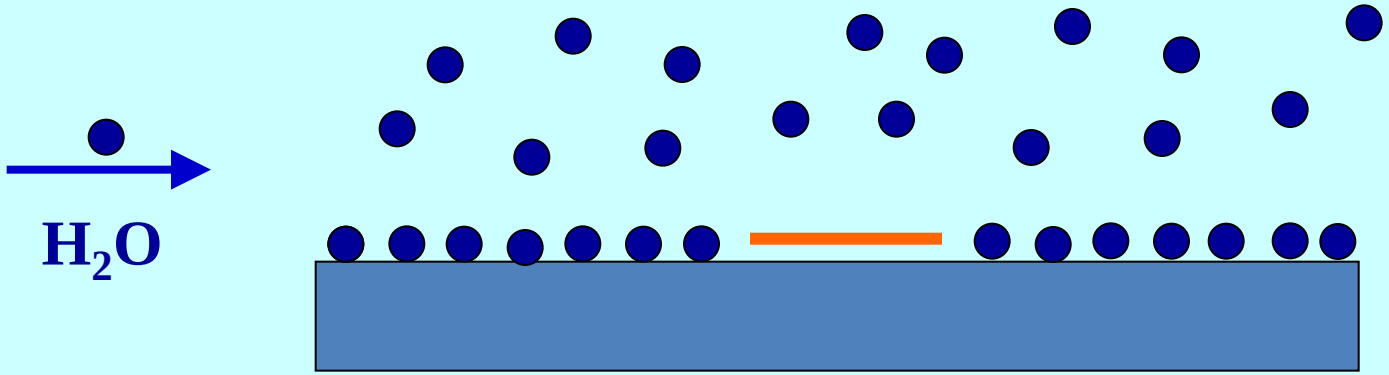
Additive Processing:

Patterning and Selective Passivation



Additive Processing:

Selective Atomic Layer Deposition (ALD)

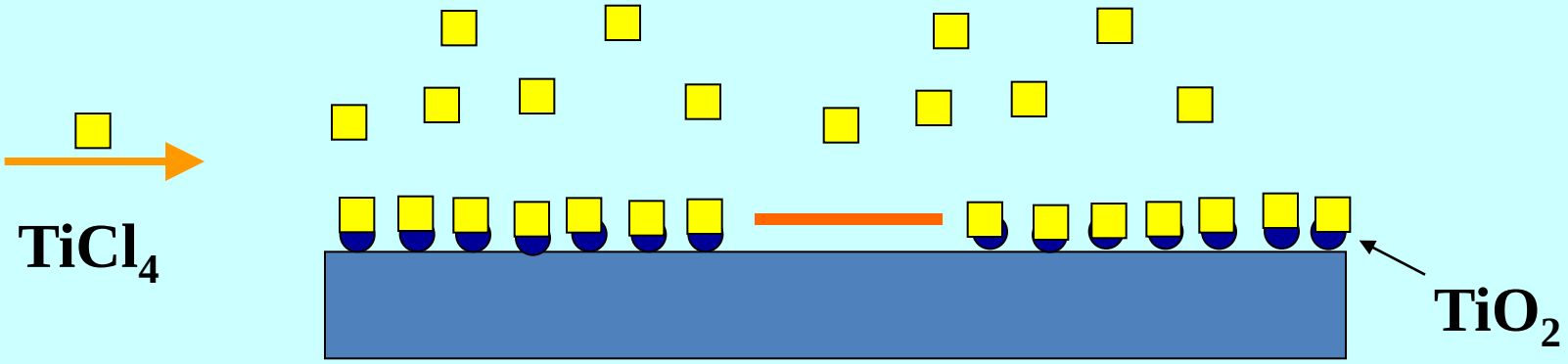


Additive Processing:

Selective Atomic Layer Deposition (ALD)

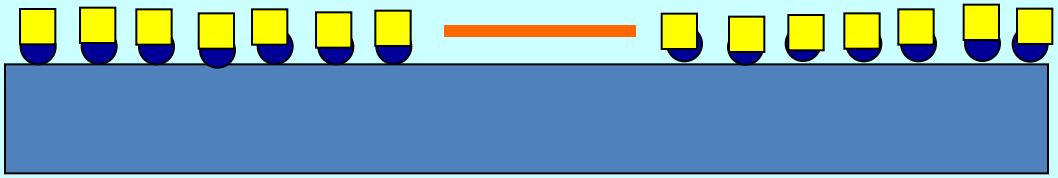
Additive Processing:

Selective Atomic Layer Deposition (ALD)



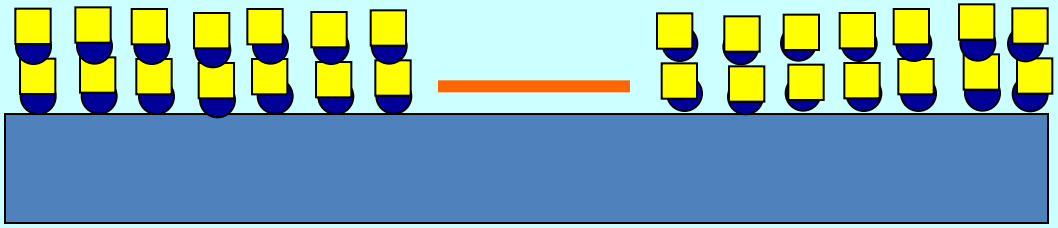
Additive Processing:

Selective Atomic Layer Deposition (ALD)



Additive Processing:

Selective Atomic Layer Deposition (ALD)



Best Examples of Additive Processing

Dan Herr and Victor Zhirnov (SRC)

	EUV Lithographic Subtractive Patterning 32 nm	Growth of a Baby [Bio-Assisted Self-Assembly]	Bio Advantage
Bits patterned per second	8.59E+09 bits/s/masking layer	7.53E+17 amino acid equivalents/s	8.77E+07
Energy required per bit	1.46E-12 J/bit/masking layer	1.29E-20 J/amino acid equivalent	1.13E+8

A Lot to Learn from Nature

Thank you

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