Metrology and Characterization Challenges for Emerging Research Materials and Devices

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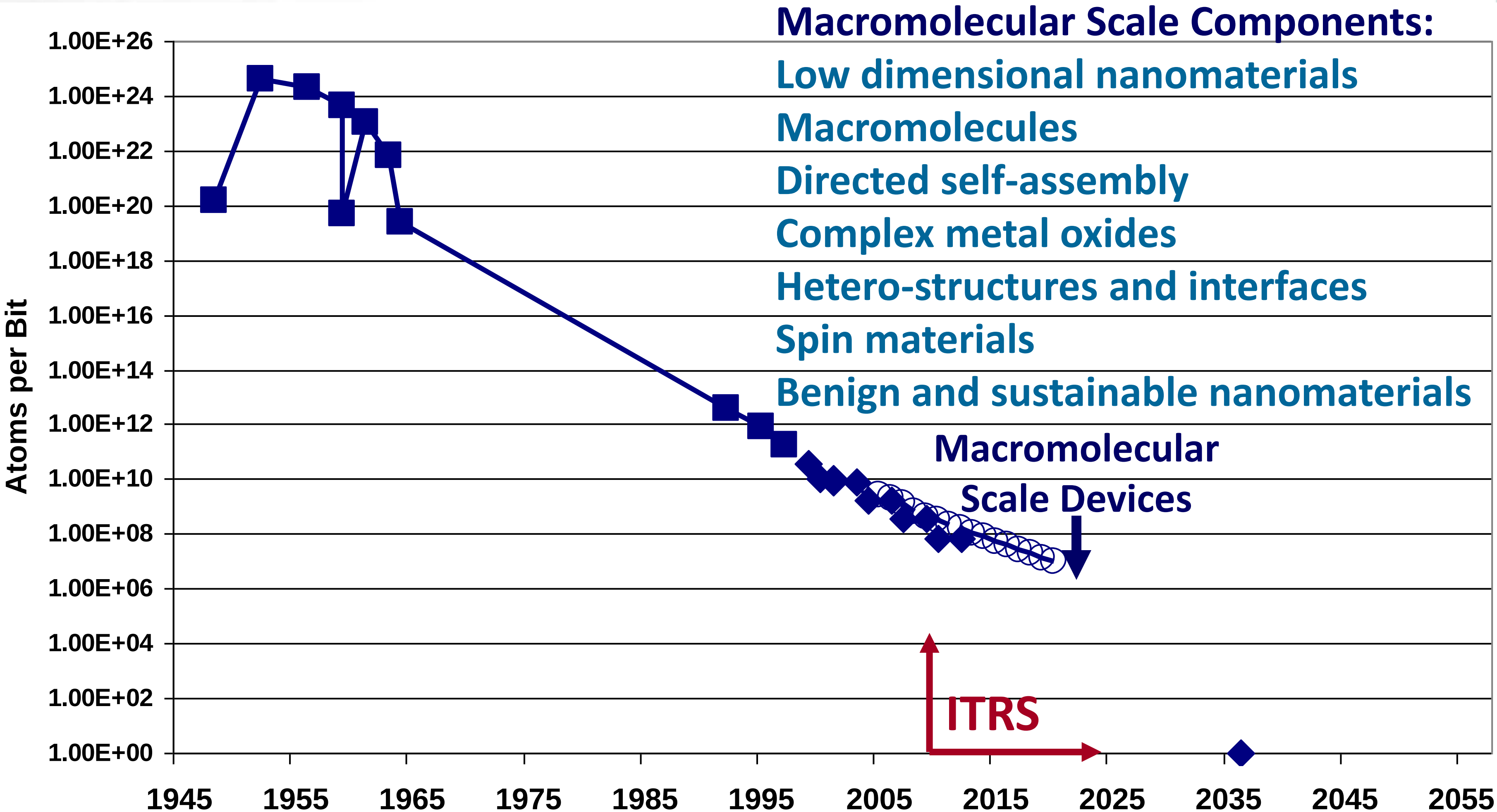
Outline

- ITRS Emerging Research Materials [ERM] Scope
- Materials metrology needs for ERM
- The emerging impact of More than Moore
- Impact of the technology cycle on ITRS ERM metrology needs
- Key messages

Towards Macromolecular Scale Devices: The trend in atoms per bit and material complexity



ITRS ≡ International Technology Roadmap for Semiconductors

Revised 2006 from: D. Herr and V. Zhirnov, Computer, IEEE, pp. 34-43 (2001).

Work in Progress: Not for Distribution

Emerging Research Materials Matrix

Mat. / TWG	Low Dimensional Materials	Macro-molecules	Spin Materials	Complex Metal Oxides	Hetero-structures & Interfaces	Directed Self-assembly	ESH	Metrol. & Model'g
ESH	Detailed	General				General	Detailed	General
ERD	Detailed	Detailed	Detailed	Detailed	Detailed	General	Detailed	Detailed
FEP	General		General	General	General	General	General	General
INT	Detailed	Detailed				General		General
LIT	General	Detailed		General		Detailed	General	Detailed
MET	Detailed	General	General	Detailed	Detailed	General	Detailed	Detailed
M&S	General	Detailed	Detailed	General	General	General		
PIDS	Detailed	Detailed	Detailed			General		
PKG	Detailed	Detailed	Detailed	General		General		General

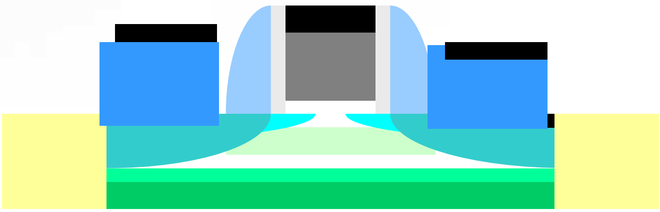
Detailed TWG requirements or alignment | General TWG interest or alignment | No TWG interest to date

Future Technologies Require New Metrology

- Extending CMOS Logic
  - Alternate channel materials
  - Deterministic doping
  - Novel structures
  - Carbon nanomaterials
- New Memory Technologies
- Beyond CMOS
- Novel Interconnects
- Extending Lithography

Extending CMOS Alternate Channel Materials

MOS



Need to assess:

Materials Performance

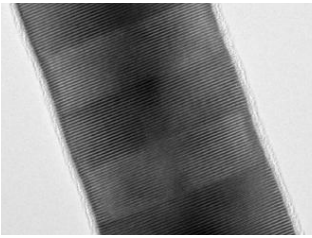
Gate materials

Contacts

Interfaces

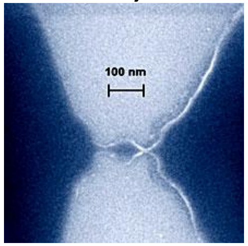
Alternate Channel Materials

- **Ge & III-V Compounds**
- **Nanowires**



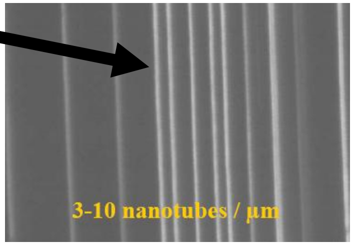
III-V Heterostructures (L. Samuelson, Lund Univ.)

- **Graphene**



A. Geim, Manchester U.

- **Carbon Nanotubes**



D. Zhou, USC

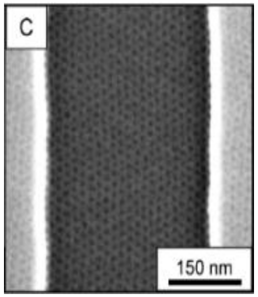
Identify Novel Metrology and Modeling Needs

Characterization Challenges for Nanoscale Alternate Channels

- Characterization of Mobility of Nanostructures
  - Separate interface traps and trapped charge from mobility
  - Lack of mobility test structures for nanowires, etc.
- Composition and dopants
- Embedded interfaces
- Statistical fluctuations in dopant concentration and location in nanoscaled devices

Deterministic Doping Characterization Needs

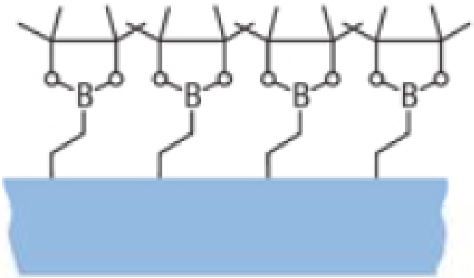
Patterning & doping via DSA



Bosworth, Ober, ACS NANO 2008

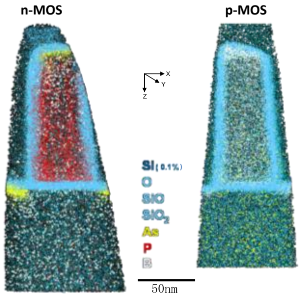
- DSA Produces Order
- Implant Delivers Dopants

Monolayer Doping



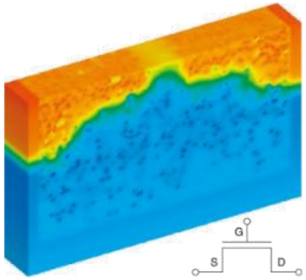
Ho, Javey, Nature Materials 2008

3D atom probe



Inoue, Ultramicroscopy 2009

3D simulation



Roy, Asenov Science 2005

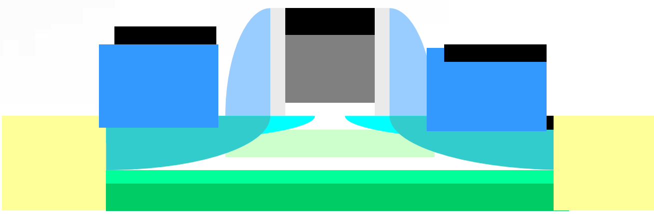
Massive Parallel Dopant Control

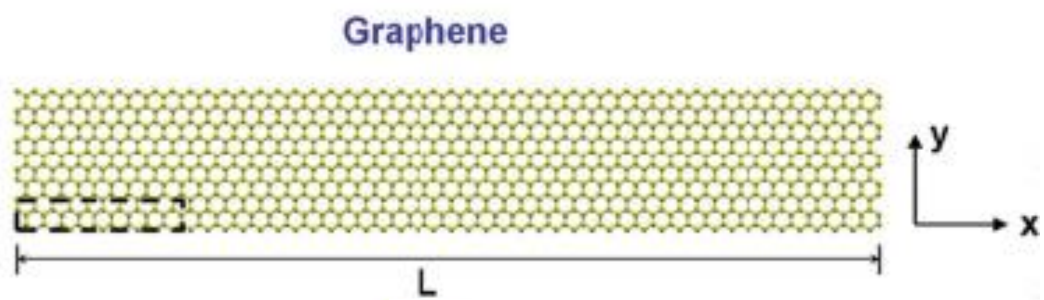
Metrology and Modeling Progress

- As devices shrink, fewer carriers will control device operation
- Need to control concentration and location

Extending CMOS
Nanoscale Carbon Channel Materials

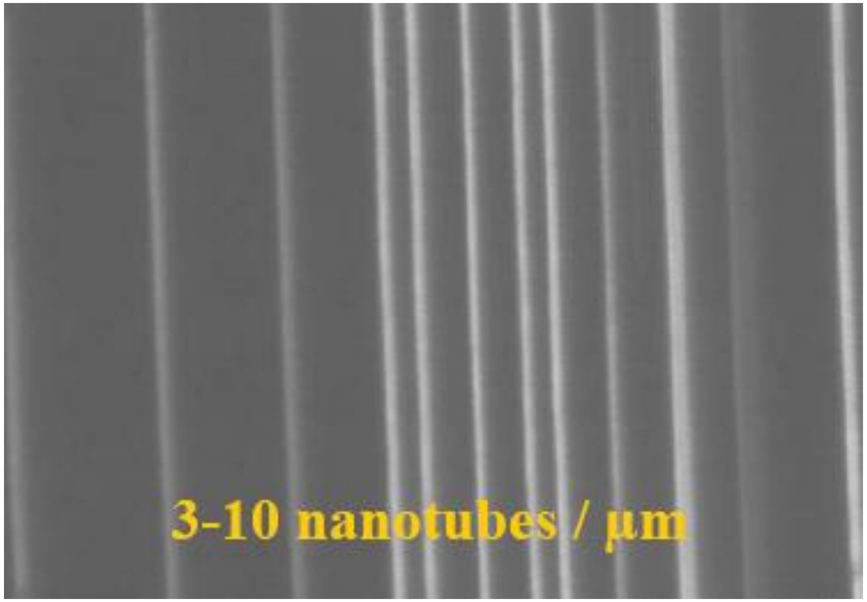
MOS





Challenges

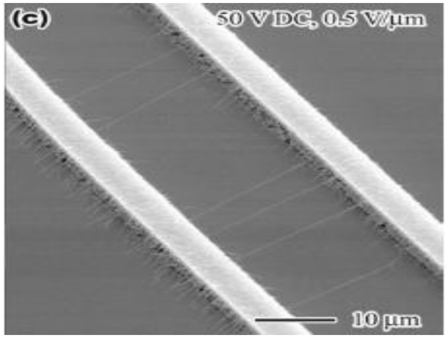
- **Location**
- **Alignment**
- **Defects**
- **Interfaces**
- **Bandgap**



C. Zhou, USC

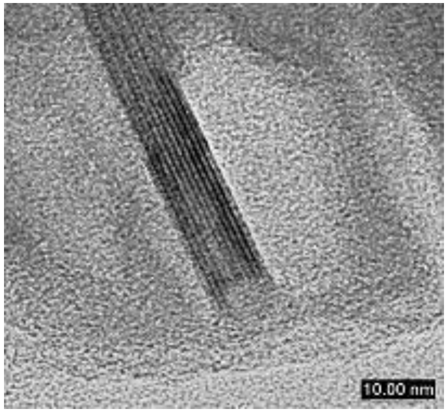
Carbon Nanotube Structural Characterization

SEM can locate nanostructures



E-Field Aligned Growth, H. Dai 2001

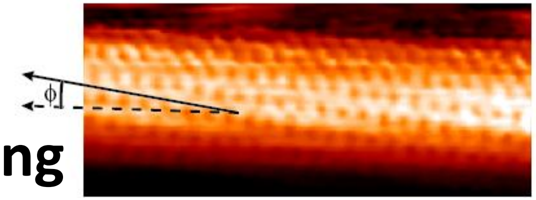
TEM has weak image contrast



E. Plonjes, J. W. Rich, et. al.2001

Scanning Tunneling Microscope

- Can resolve bonds, but is challenging



Smalley, et. al., 1997

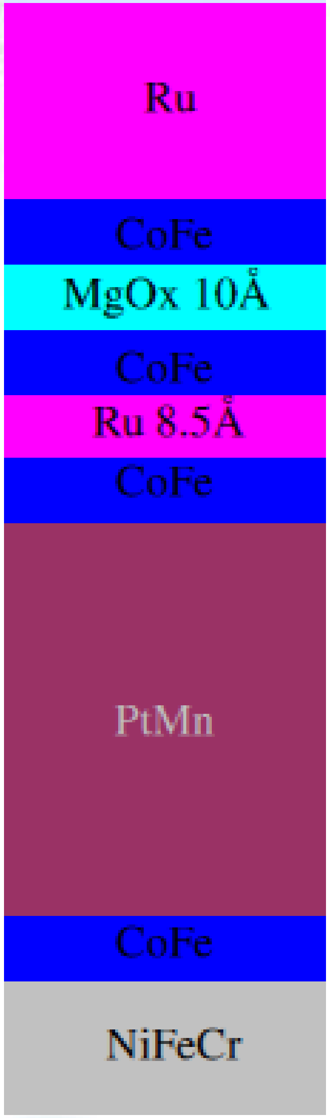
How much will aberration correction improve carbon imaging?

Work in Progress: Not for Distribution

Novel Memory Technology Options

- **Spin Transfer Torque RAM**
- **Redox RAM**
- Ferroelectric FET
- Electronic Effects Memory
- Nanowire Thermal Phase Change Memory
- Nanomechanical Memory
- Macromolecular Memory
- Molecular Memory

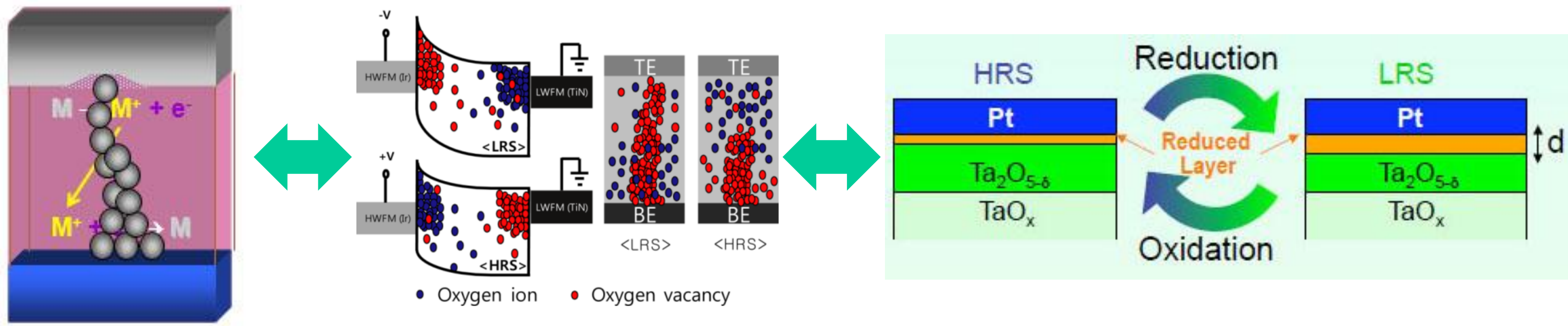
Spin Transfer Torque RAM Metrology Needs



- Characterization of embedded film thickness and uniformity
- MgO 10A +/- X%
- Properties of embedded interfaces with multiple thin films
- Detection of defects

Memory Devices and Materials

Redox RAM: How can we experimentally verify the Redox RAM operating mechanism?



Characterization Challenges:

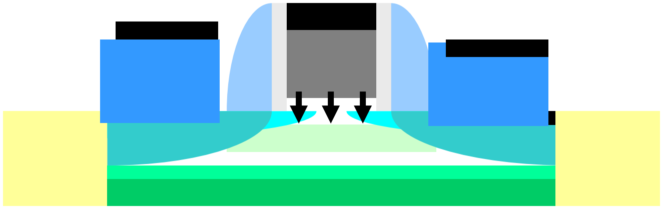
- Location and concentration of vacancies
- Atomic structure and electrical properties of “filaments”
- Movement of vacancies with applied fields

Beyond CMOS Materials and Interfaces

Switches that leverage new state functionality integrated with CMOS

Charge Based

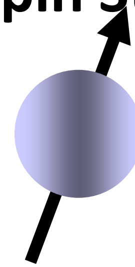
Ferroelectric Polarization



Negative Capacitance FET

States Other Than Charge Only

Spin State

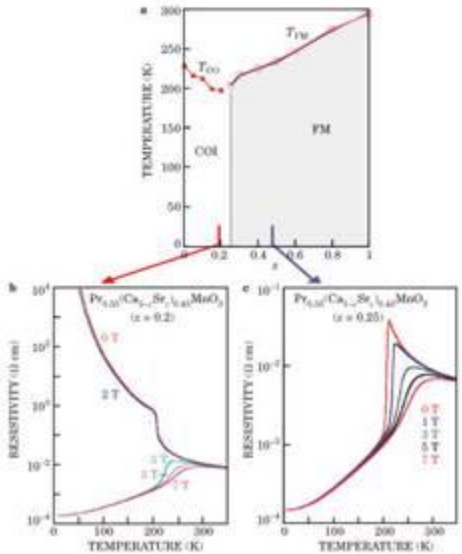


Individual or Collective

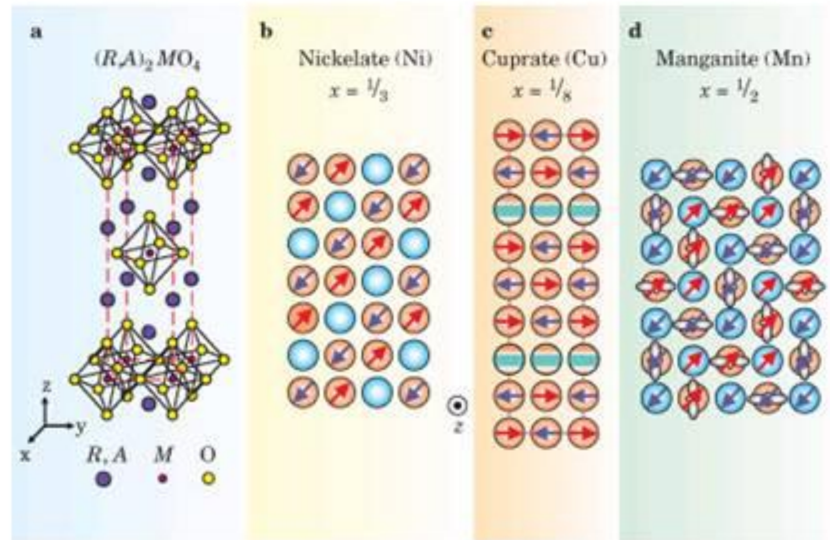
Need for room temperature assessment of:

- Ferromagnetic Materials, Dilute Magnetic Semiconductors
- Complex Metal Oxides
- **Strongly Correlated Electron State Materials (FE, FM, FE & FM)**
- Molecules
- **Interfaces [2D E Gases]**
- Native Interconnects

Strongly Correlated Electron State Materials



Tokura

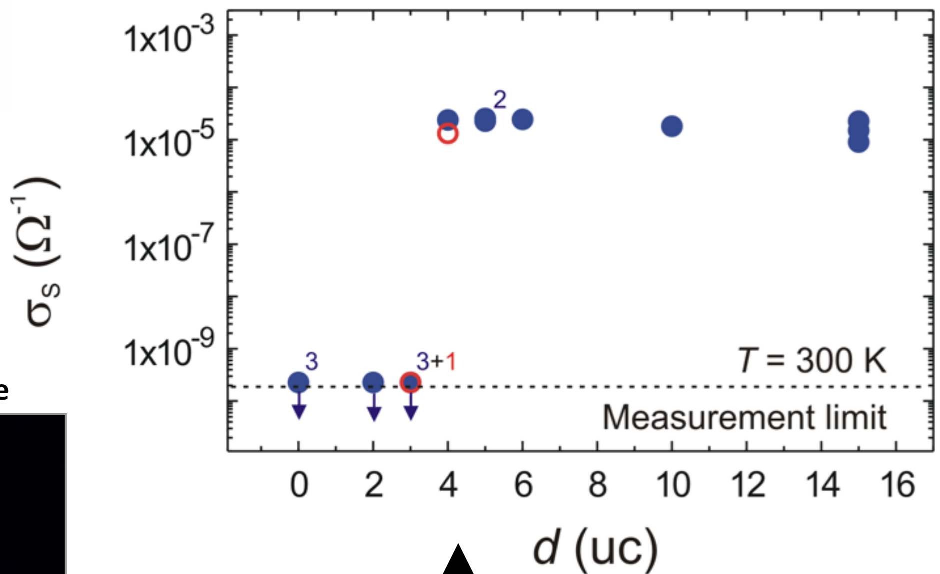


Tokura

- Materials exhibit complex phase relationships
  - Spin, charge, orbital ordering
- Phase transitions can be induced by small perturbations
  - Magnetic field, phonon, charge

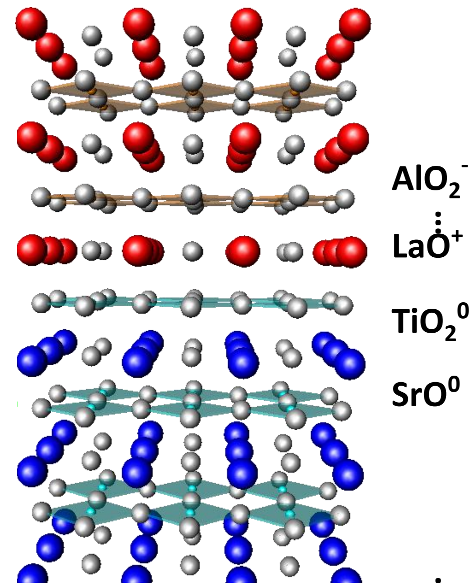
How do we probe phase change dynamics and kinetics?

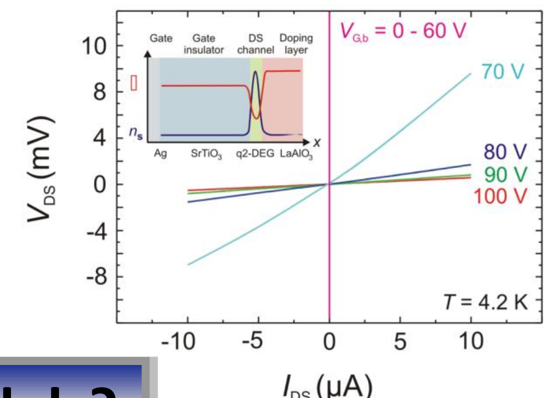
2D Electron Gas at SrTiO3-LaAlO3 Interface



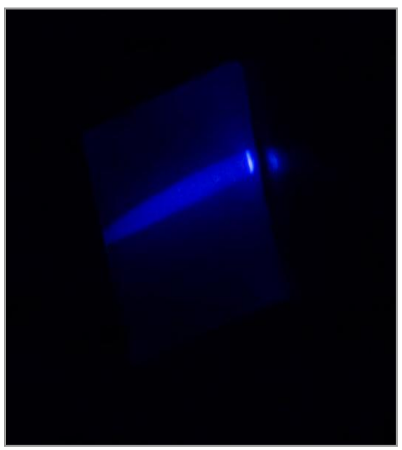
Critical thickness

J. Mannhart et. al. 2006





RHEED excited Cathodoluminescence

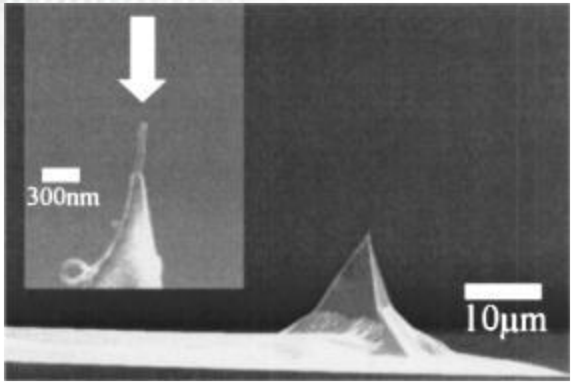


Oxygen Vacancies

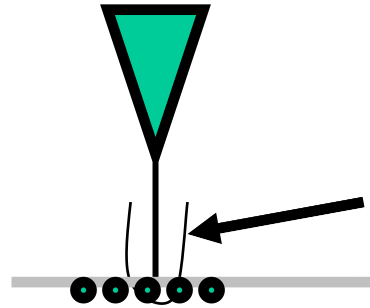
D. Winkler, et. Al. 2005

How do we validate the models?
What role do vacancies play?

Decoupling nm-Scale Probe-Sample Interactions



Dai, Moler, et al (2004)



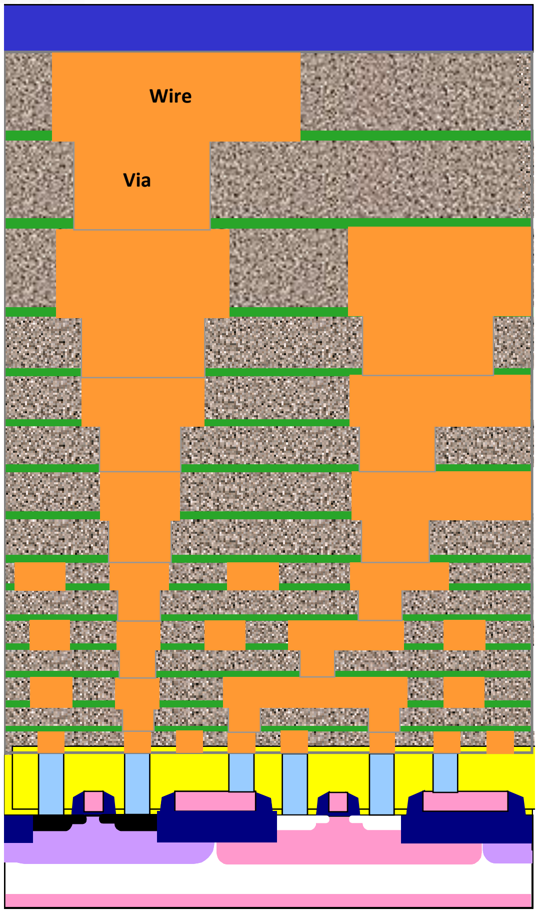
Probe discrete nanostructures:

- Apply multiple spectroscopic techniques to characterize the materials and interface properties and interactions
- Need models and algorithms to separate probe-sample interactions
- Understand the impact of the uncertainty principle

How do the probe fields perturb the "state"?
Can the probe perturbation be minimized?
What algorithms can extract the "state"?

Interconnect Materials

Interconnects



Native Interconnect

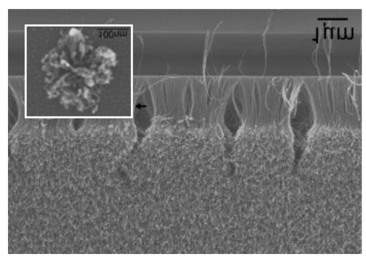
Ultra-thin Barrier Layers

- Transition Zr Barriers to Interconnect TWG
- Novel sub 5nm materials
- SAMs

Ultra low κ ILD

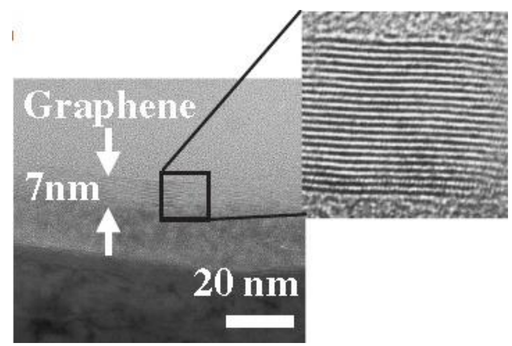
Novel Interconnects and Vias

- Carbon Nanotubes



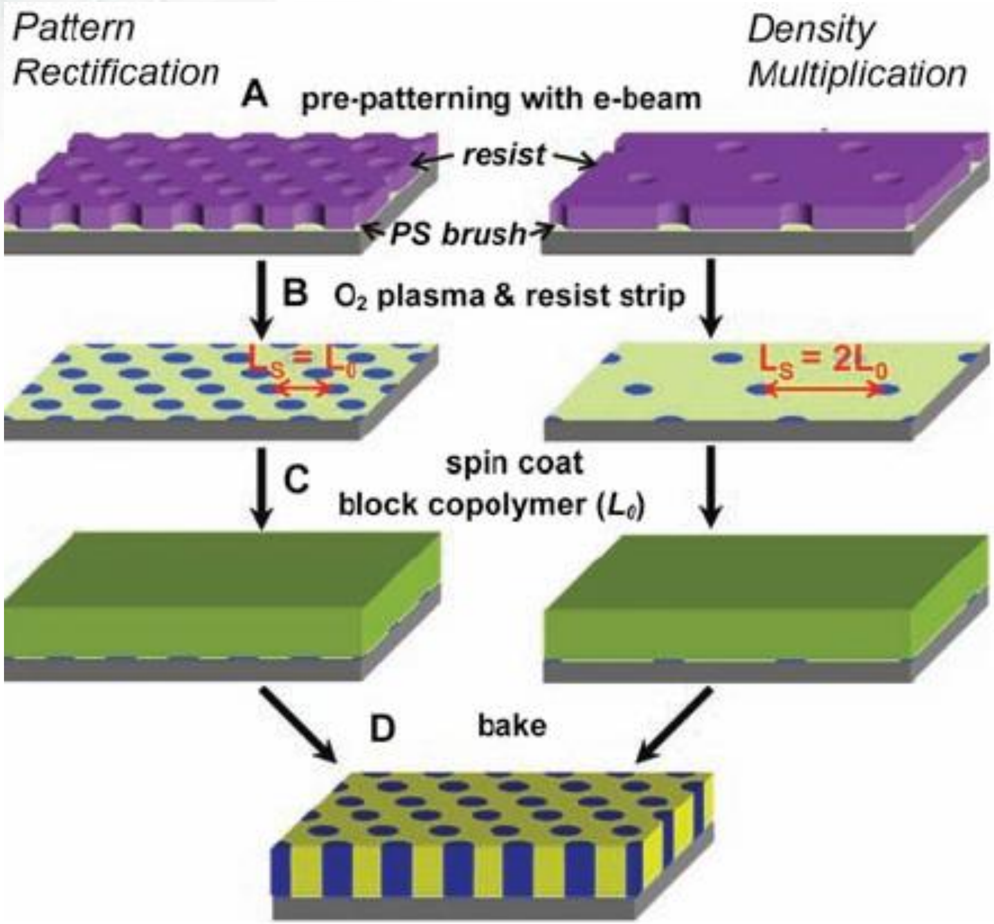
MIRAI-Selete / TOSHIBA, APEX 3 (2010) 055002

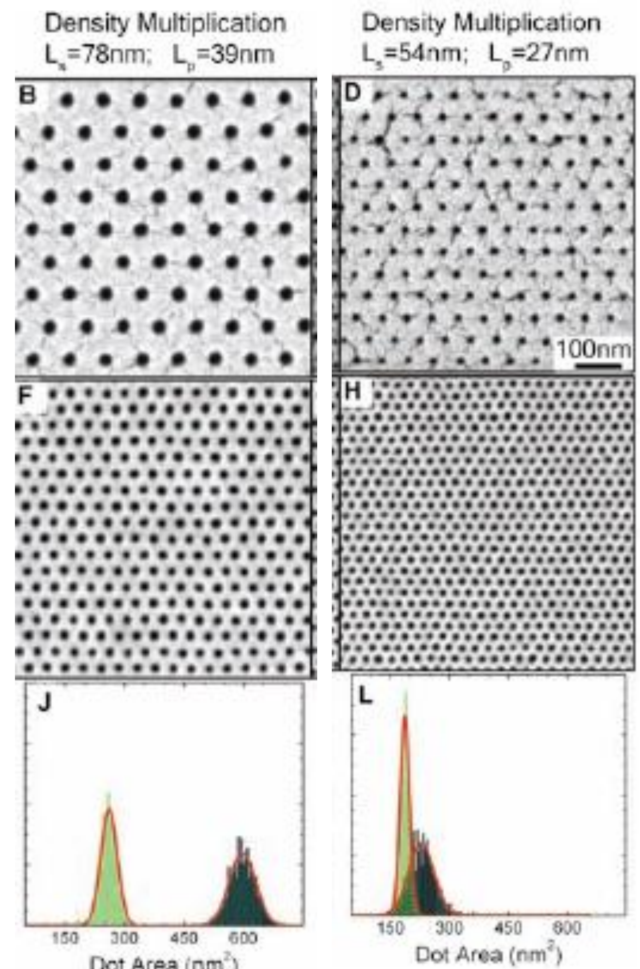
- Graphene



Fujitsu Lab / CREST, APEX 3 (2010)

Directed Self Assembly for Extending Lithography



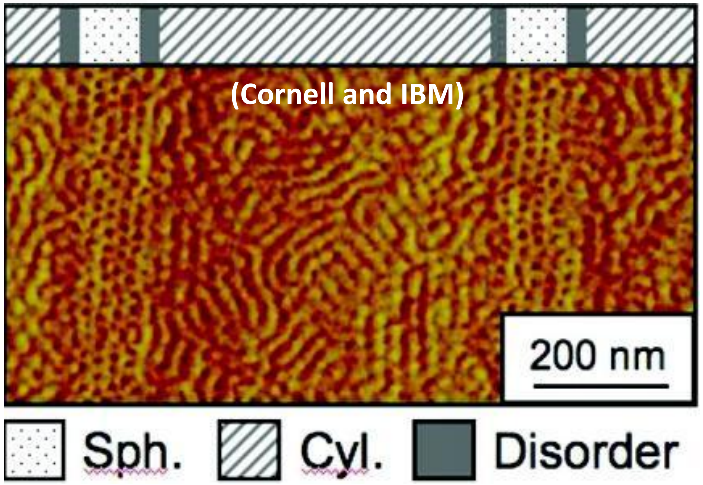


Ruiz, Nealey, et. al, Science, 2008

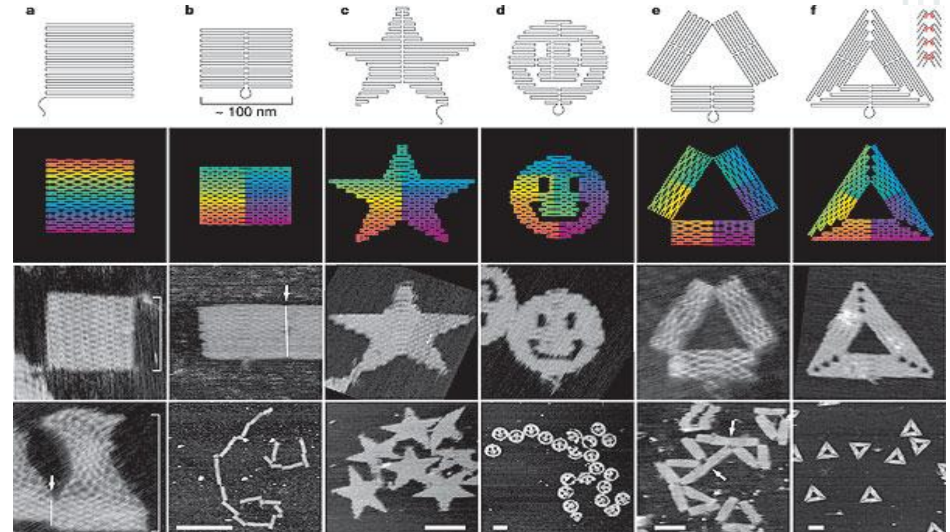
Defect density characterization is needed over large areas.

Resolution and Complexity

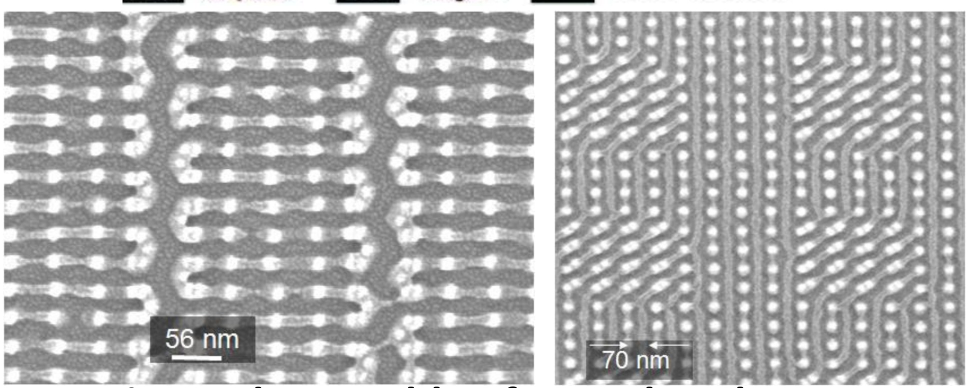
Due to unique crosslinking ability of PaMS-b-PHOST, multiple morphologies on one wafer are possible



Size of Molecular Scaffolds

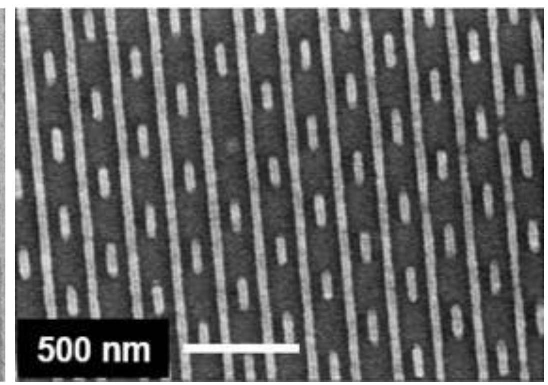


Folding DNA to Create Nanoscale Shapes and Patterns, Paul W. K. Rothemund, Nature 440, 297-302 (16 March 2006)



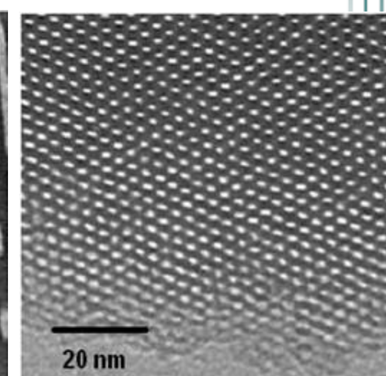
Directed Assembly of Complex Shapes

(MIT)



Trimmed DSA patterns

(MIT LL)



3 nm Silicate pores

(UMA-A)

2D and 3D materials characterization is needed

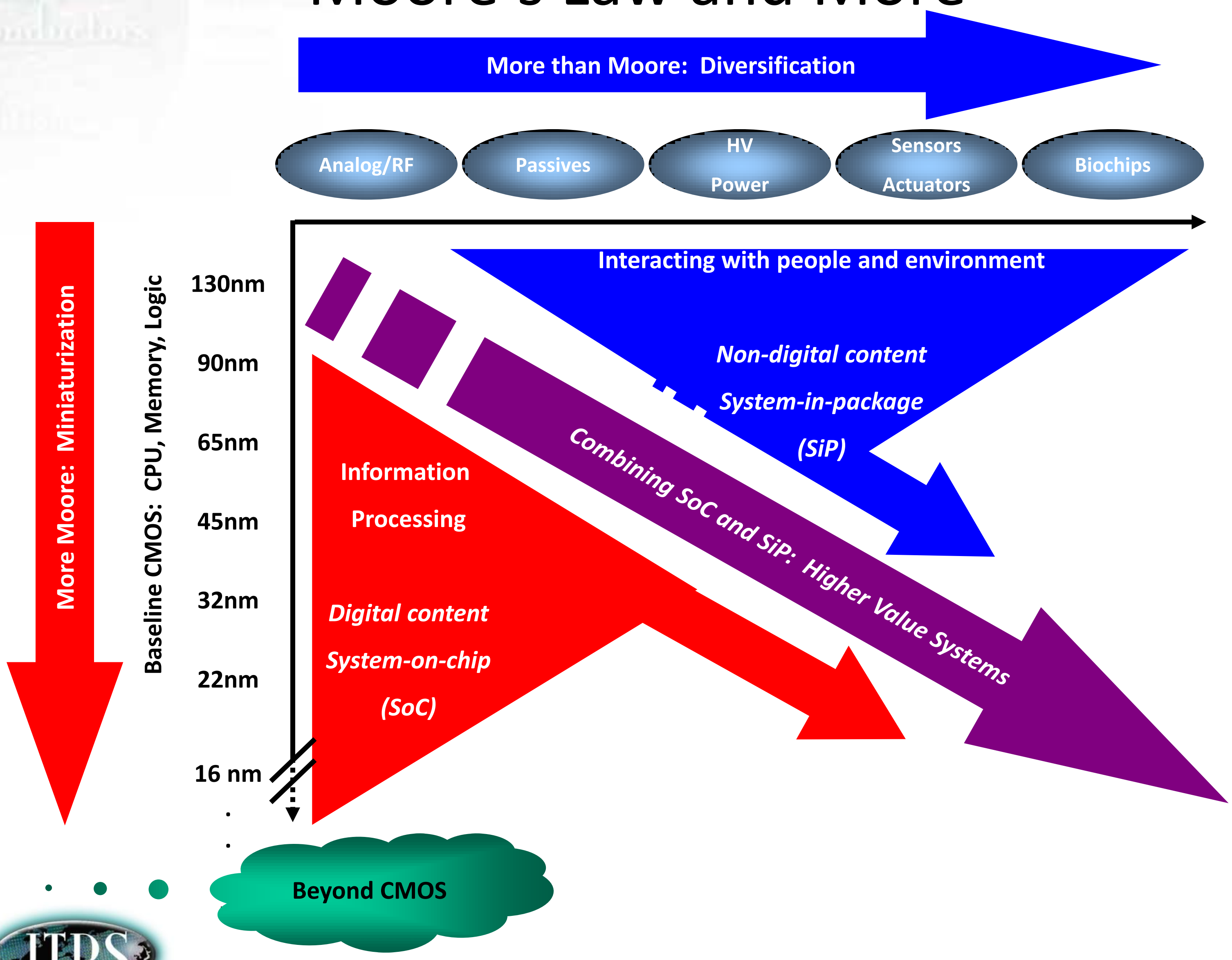
Summary of ERM Metrology/Characterization Needs

- Properties and composition of nanoscale structures and materials
- Nondestructive characterization of embedded interfaces and nanostructures
- Vacancies and defects in nanoscale structures
- Directed self assembly morphology and defect densities over large areas
- Simultaneous characterization of spin and electrical properties

2010 Update/2011 Renewal MtM Graphic Proposal from Europe IRC

Moore's Law and More

2010 White Paper IS



Work in Progress: Not for Distribution

ITRS More than Moore Directions

- ITRS is introducing Wireless More than Moore in 2011 and evaluating More than Moore for:
  - Energy
  - Smart Lighting
  - Automotive
  - Security
  - Medical and Health

- Too early to identify specific materials and metrologies

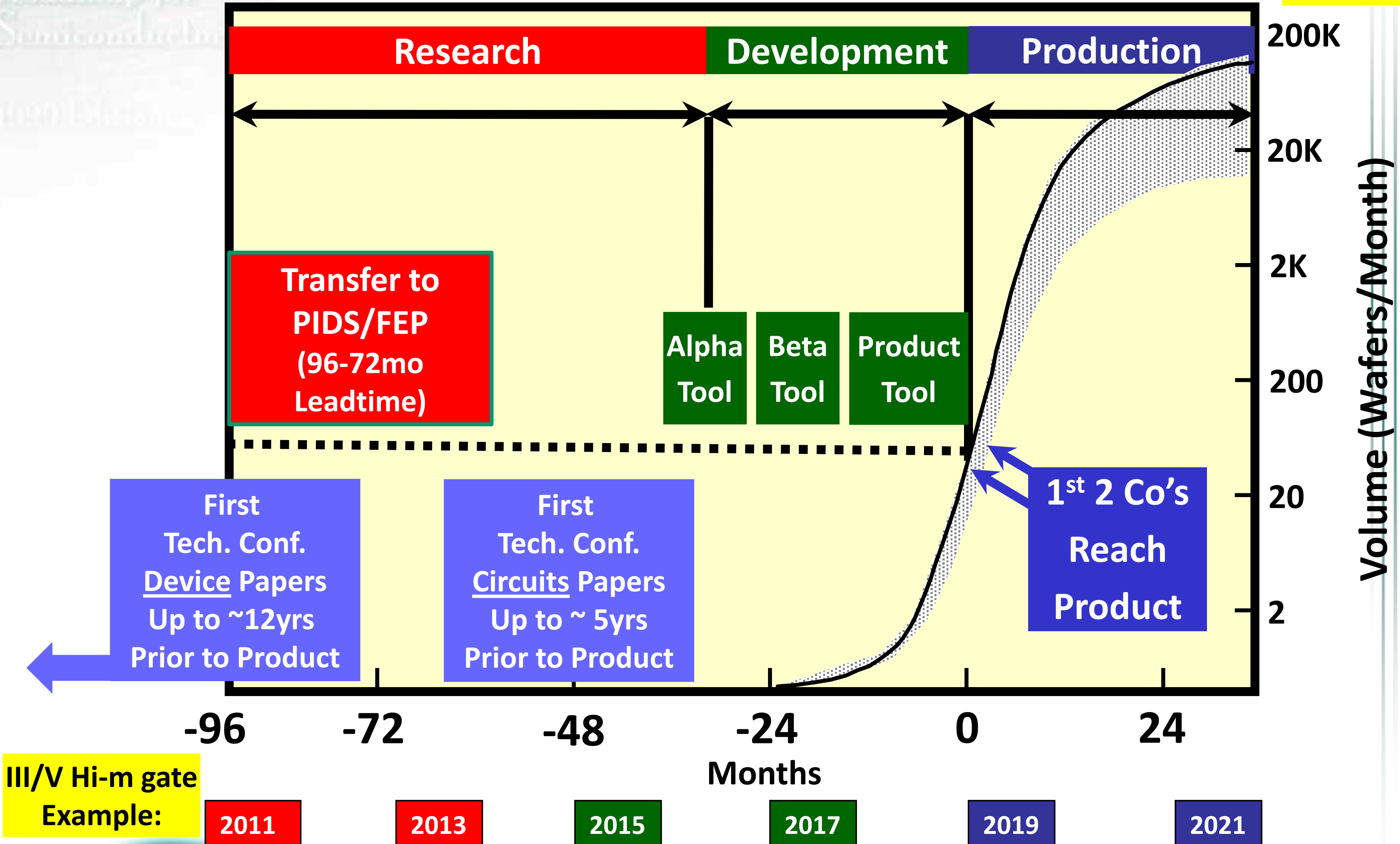
Impact of the Technology Cycle on ITRS ERM Metrology Needs

- **Research:** Needs characterization to determine and validate mechanisms.
- **Development:** Needs characterization and metrology to optimize materials, interfaces and device operation.
- **Manufacturing:** Needs metrology to control the process and validate control.

ERD/ERM Long-Range R&D and PIDS Transfer Timing Model Technology Cycle Timing

Example: III-V MOSFET High-mobility Channel Replacement Materials

New for 2009



Source: 2009 ITRS - Executive Summary Fig 2b

Work in Progress: Not for Distribution

Earliest Intercept for New Materials in Technologies

Application Opportunities	Ge and III-V	Carbon Nanotubes and other Metal Nanotubes	Nanowires	Graphene	Oxide Nanoparticles	Metal Nanoparticles	Novel Macromolecules	Self-Assembled Materials	Complex Metal Oxides/ Transition Metal Oxides	Spin Materials [Fe, Co, Mn, Ni, etc.]
Process Materials	Not on Roadmap	Not on Roadmap	Not on Roadmap	Not on Roadmap	Current Application	Not on Roadmap	3-5 yrs.	10-15 yrs.	Not on Roadmap	Not on Roadmap
Lithography	Not on Roadmap	Not on Roadmap	Not on Roadmap	Not on Roadmap	Resist nD (3-5 yrs.)	Not on Roadmap	3-5 yrs.	10-15 yrs.	Not on Roadmap	Not on Roadmap
Device: Memory	5-10 yrs.	10-15 yrs.	10-15 yrs.	10-15 yrs.	Not on Roadmap	Not on Roadmap	10-15 yrs.	Not on Roadmap	5-10 yrs.	* MRAM (Current Application)
Device: Logic	5-10 yrs.	10-15 yrs.	10-15 yrs.	10-15 yrs.	Not on Roadmap	Not on Roadmap	10-15 yrs.	Not on Roadmap	5-10 yrs.	15+ yrs.
Interconnect	5-10 yrs.	10-15 yrs.	10-15 yrs.	10-15 yrs.	Not on Roadmap	Not on Roadmap	5-10 yrs.	5-10 yrs.	Not on Roadmap	15+ yrs.
Packaging	Not on Roadmap	3-5 yrs.	5-10 yrs.	Not on Roadmap	Current Application – 3-5 yrs.	3-5 yrs.	5-10 yrs.	< 2 yrs.	5-10 yrs.	Not on Roadmap

Earliest Potential Insertion Horizon	Current Application	3-5 yrs.	5-10 yrs.	10-15 yrs.	15+ yrs.	Not on Roadmap

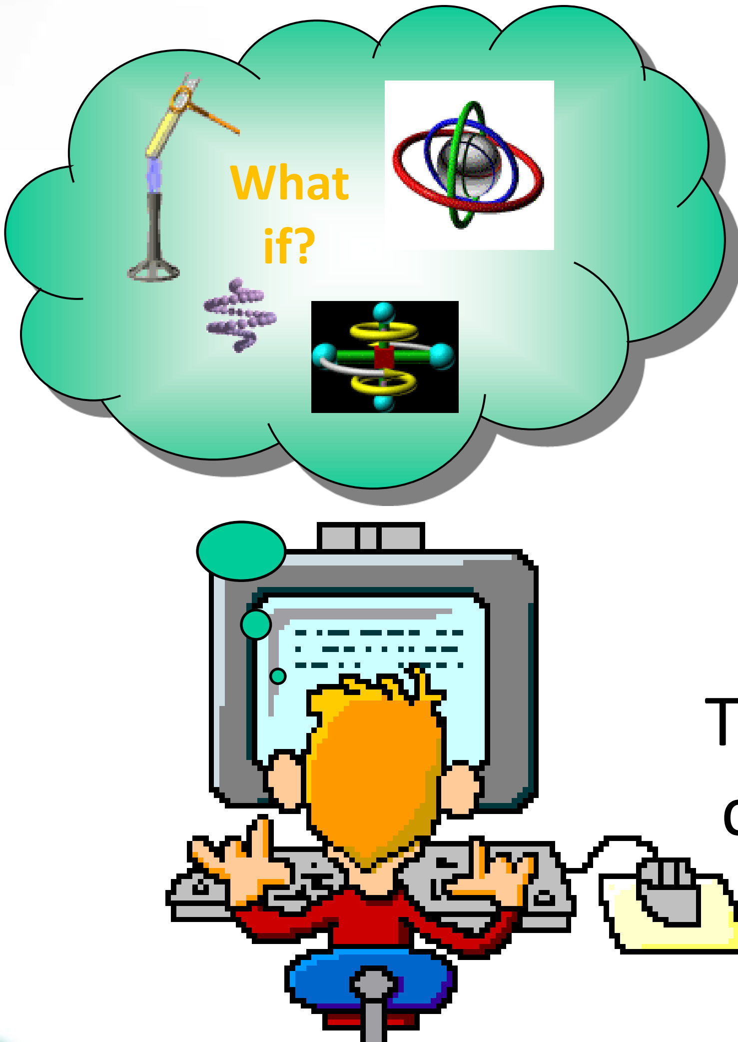
Metrology needs to support research, development & manufacturing

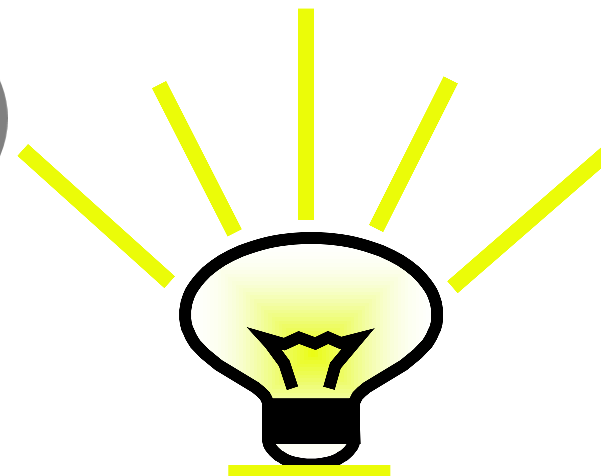
Key Messages

- Emerging materials, devices and interconnects:
  - Will be needed to extend and enhance CMOS.
  - May use new physical principles and state functions and may represent convergent opportunities, e.g. native interconnects.
  - Require new characterization and metrology options, with a new focus on atomic scale and nanoscopic material properties.
- The projected earliest insertion horizons highlight the need for a focus on developing new metrologies.

“If you can’t measure it, you can’t manufacture it.” Mike Postek

Thank You





The real voyage of discovery consists not in seeking new landscapes but in having new eyes. Marcel Proust

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