Metrology For Emerging Research Materials And Devices

C. Michael Garner, Intel
Dan Herr, SRC

Key Messages

Silicon Nanoelectronics is production reality and follows Moore's law

Long term: Novel devices will be needed to enhance CMOS

Novel devices may use new physical principles

New materials would be needed

Novel devices & materials require new metrology

Increased collaboration between Industry, Universities & Gov't is essential!!!

Agenda

Moore's Law

ITRS Emerging Research Devices & Materials

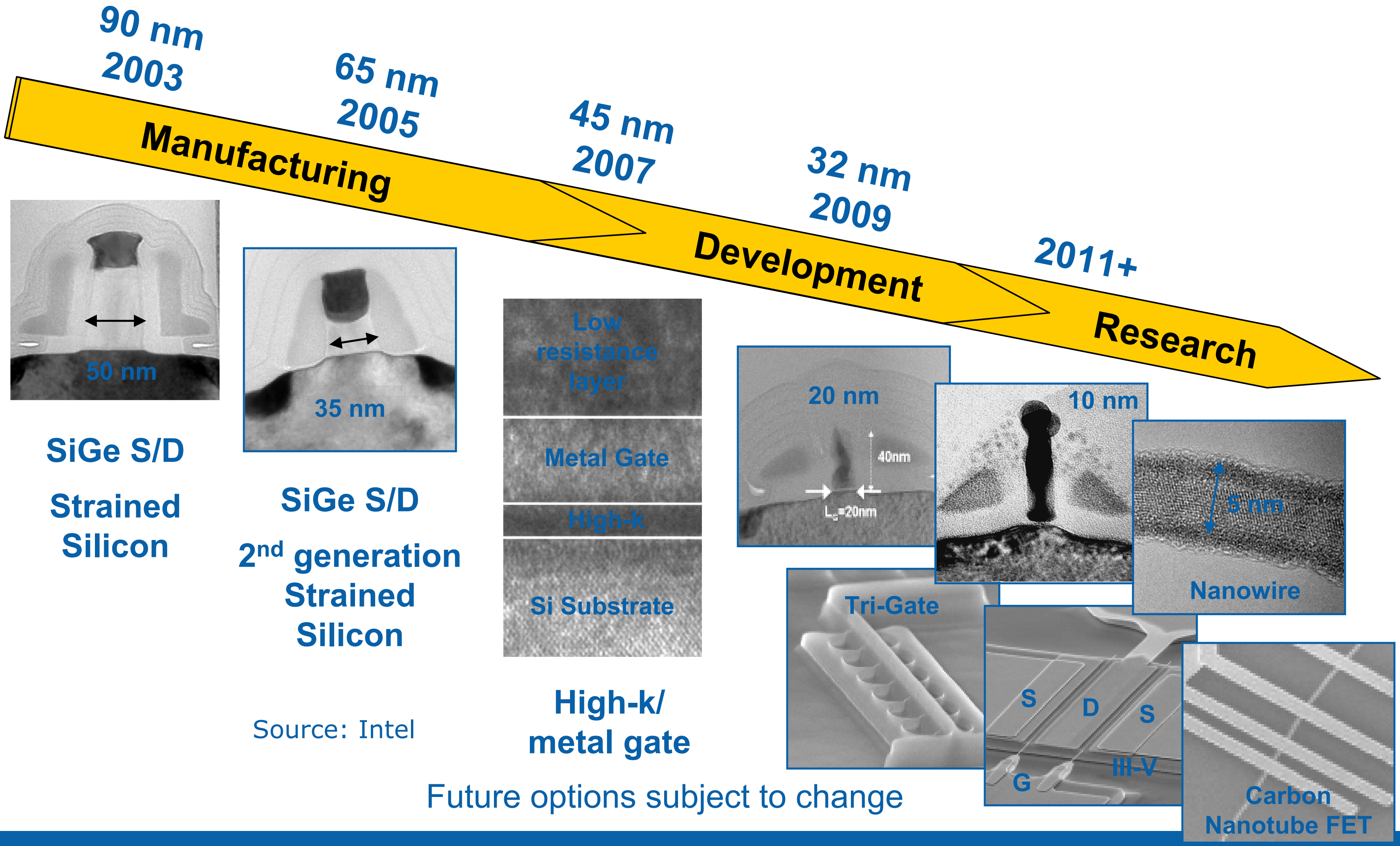
Revolutionary CMOS

Beyond CMOS Devices & Materials

Metrology & Characterization Challenges

Summary

Innovation-Enabled Technology Pipeline



90 nm
2003

65 nm
2005

45 nm
2007

32 nm
2009

2011+

Manufacturing

Development

Research

SiGe S/D

Strained Silicon

SiGe S/D

2nd generation Strained Silicon

High-k/ metal gate

Source: Intel

Future options subject to change

ITRS Emerging Research Devices & Materials

Beyond CMOS Memory Options

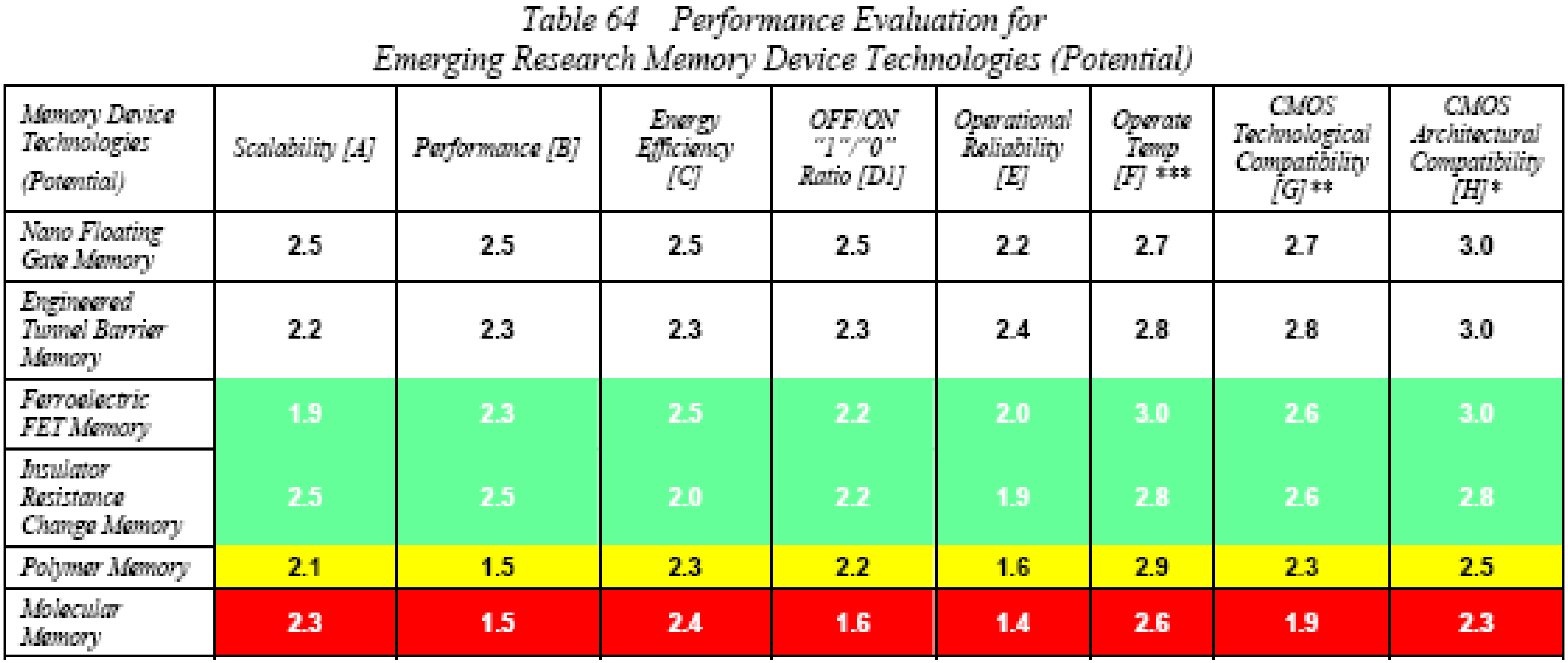


Table 64 Performance Evaluation for Emerging Research Memory Device Technologies (Potential)

Memory Device Technologies (Potential)	*Scalability [A]*	*Performance [B]*	*Energy Efficiency [C]*	*OFF/ON "1"/"0" Ratio [D1]*	*Operational Reliability [E]*	*Operate Temp [F] ****	*CMOS Technological Compatibility [G] ***	*CMOS Architectural Compatibility [H] **
Nano Floating Gate Memory	2.5	2.5	2.5	2.5	2.2	2.7	2.7	3.0
Engineered Tunnel Barrier Memory	2.2	2.3	2.3	2.3	2.4	2.8	2.8	3.0
Ferroelectric FET Memory	1.9	2.3	2.5	2.2	2.0	3.0	2.6	3.0
Insulator Resistance Change Memory	2.5	2.5	2.0	2.2	1.9	2.8	2.6	2.8
Polymer Memory	2.1	1.5	2.3	2.2	1.6	2.9	2.3	2.5
Molecular Memory	2.3	1.5	2.4	1.6	1.4	2.6	1.9	2.3

Semiconductor Industry Association
The International Technology Roadmap for Semiconductors, 2005 edition

Multiple non-charge storage options look promising

Beyond CMOS Logic Options

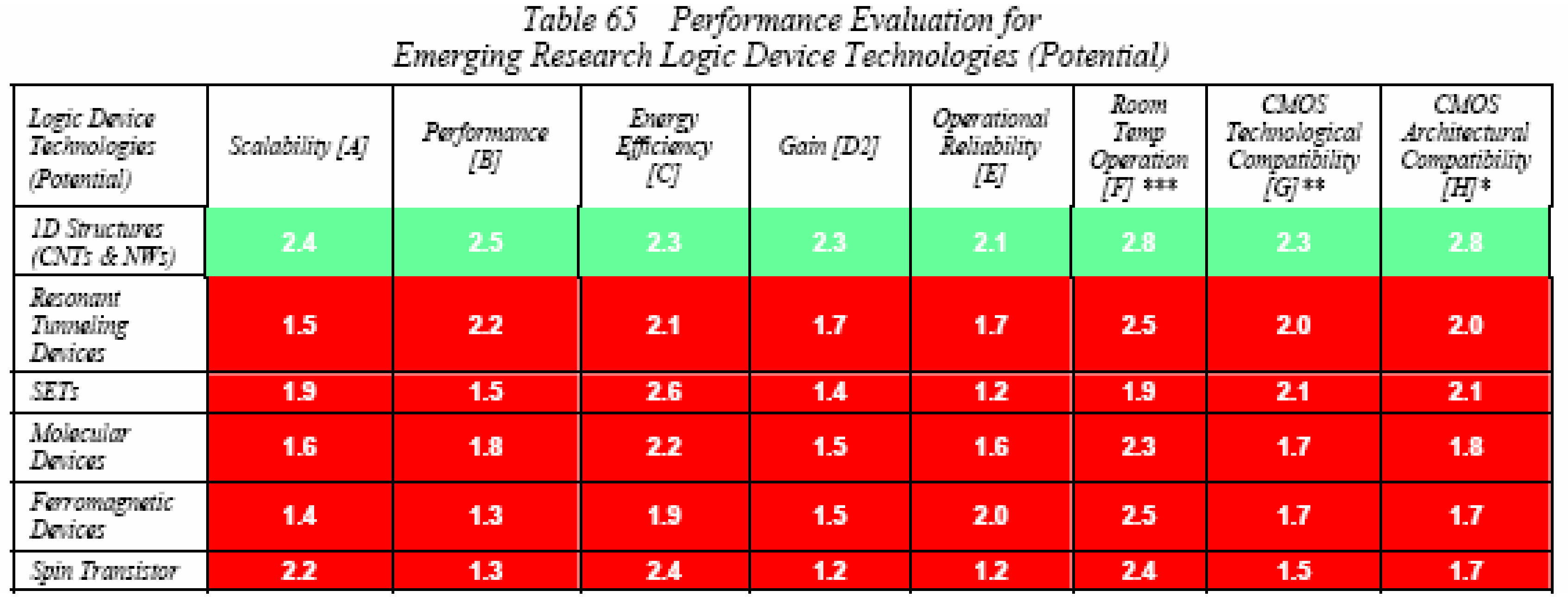


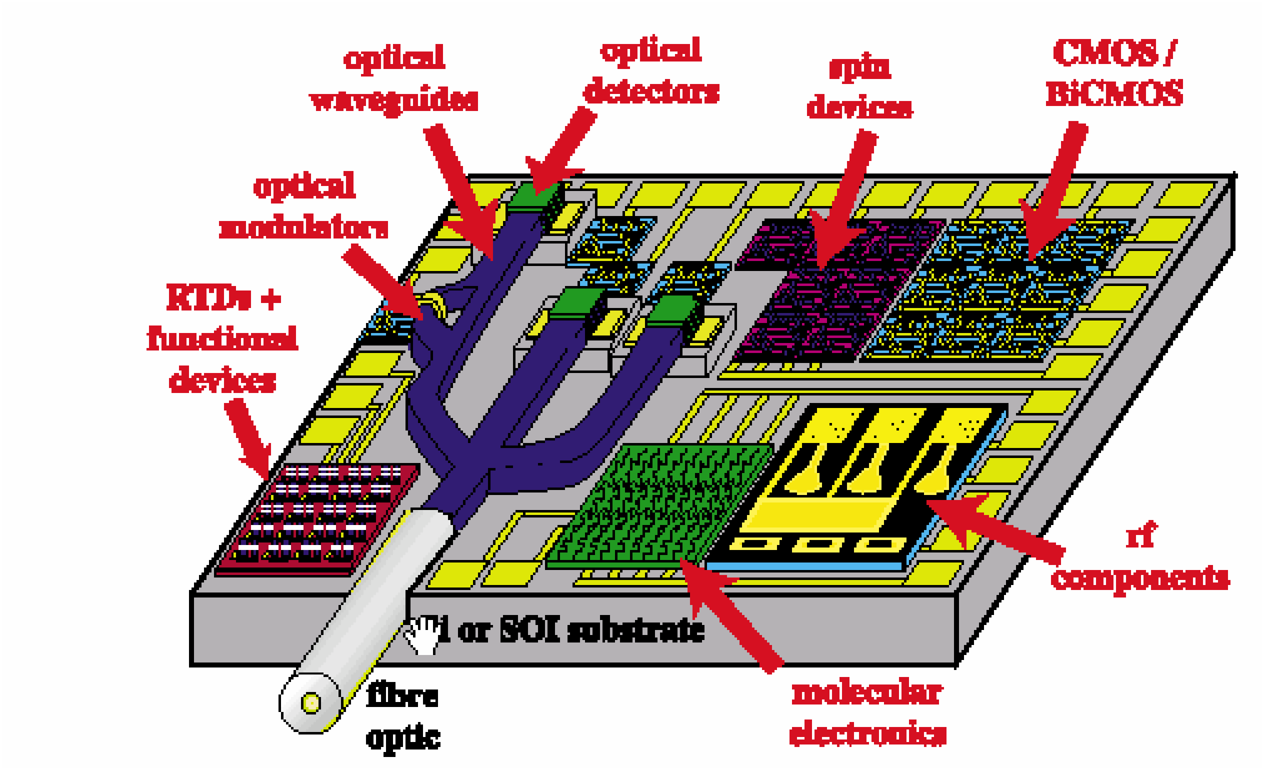
Table 65 Performance Evaluation for
Emerging Research Logic Device Technologies (Potential)

Logic Device Technologies (Potential)	Scalability [A]	Performance [B]	Energy Efficiency [C]	Gain [D2]	Operational Reliability [E]	Room Temp Operation [F] ***	CMOS Technological Compatibility [G] **	CMOS Architectural Compatibility [H]*
1D Structures (CNTs & NWs)	2.4	2.5	2.3	2.3	2.1	2.8	2.3	2.8
Resonant Tunneling Devices	1.5	2.2	2.1	1.7	1.7	2.5	2.0	2.0
SETs	1.9	1.5	2.6	1.4	1.2	1.9	2.1	2.1
Molecular Devices	1.6	1.8	2.2	1.5	1.6	2.3	1.7	1.8
Ferromagnetic Devices	1.4	1.3	1.9	1.5	2.0	2.5	1.7	1.7
Spin Transistor	2.2	1.3	2.4	1.2	1.2	2.4	1.5	1.7

Semiconductor Industry Association
The International Technology Roadmap
for Semiconductors, 2005 edition

All beyond CMOS Logic Options are **Very High Risk!!**

Heterogeneous integration of alternative technologies*

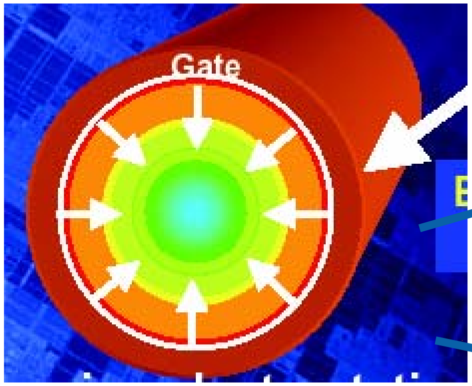


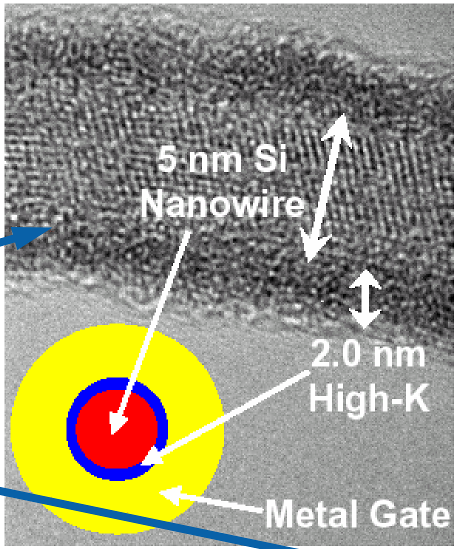
**European Technology Roadmap for Nanoelectronics*

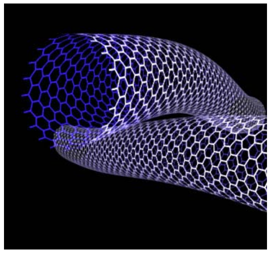
Silicon integration platform

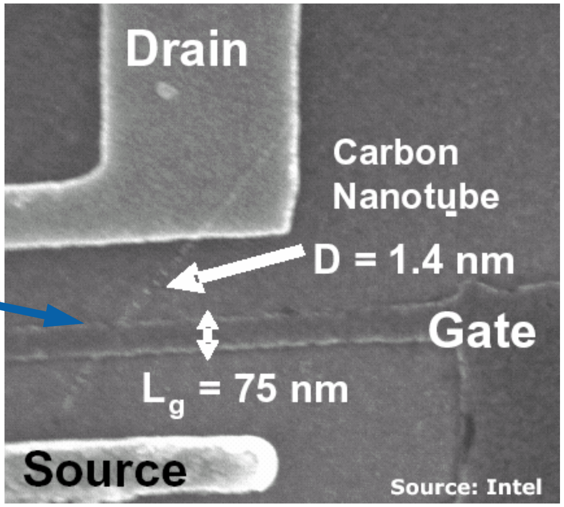
Revolutionary CMOS

Extreme CMOS Transistor Options









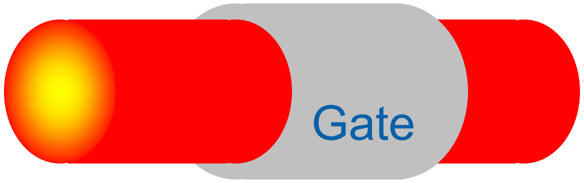
Superior performance required

Increased density

Many options and challenges….

Source: Intel

1D Revolutionary CMOS Challenges



Control of Critical Materials Properties

- Device Material
  - Control of diameter & chirality (Synthesis conditions)
  - Doping & carrier concentration

Placement & orientation of nano-materials

- Sub nm placement accuracy and alignment

Interface properties

- Low contact resistance
- Passivation of Nano-surfaces & interfaces

Metrology & Characterization Challenges

Metrology for Process Control & Interface Characterization

Nanotube Characterization

Structure & Interface Properties

- SEM
- TEM
- Electron Energy Loss
- Scanning Tunneling Microscopy

Electronic Properties

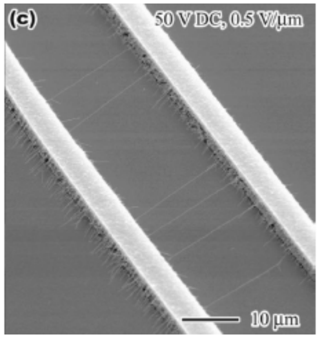
- Fluorescence*
- Optical Absorption*
- Raman Spectroscopy*
- Rayleigh Spectroscopy

*Complicated by bundling & chemical state

- Need improved imaging of structure and defects
- Need metrology to map bandgap distribution

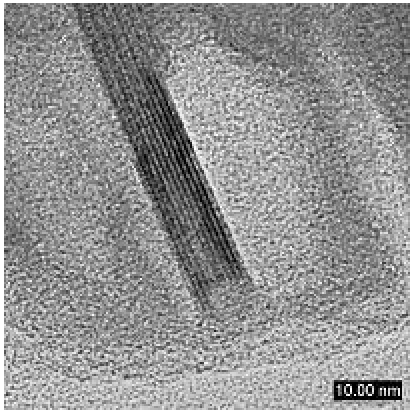
Carbon Nanotube Structural Characterization

SEM can locate nanostructures



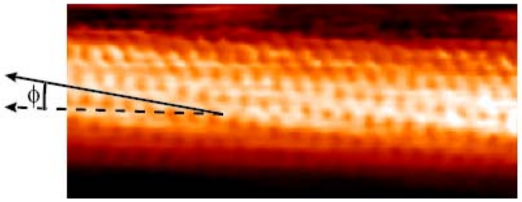
E-Field Aligned Growth, H. Dai 2001

TEM has weak image contrast



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

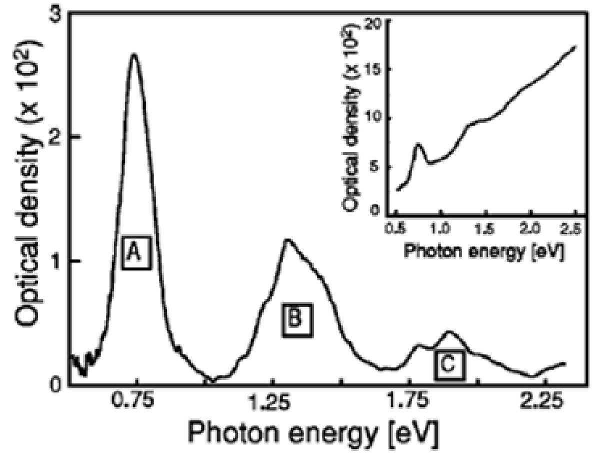
- Scanning Tunneling Microscope
  - Can resolve bonds, but is challenging



Smalley, et. al., 1997

Will Aberration Correction Improve Carbon Imaging?

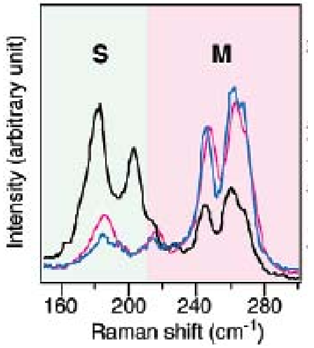
Carbon Nanotube Electronic Property Characterization



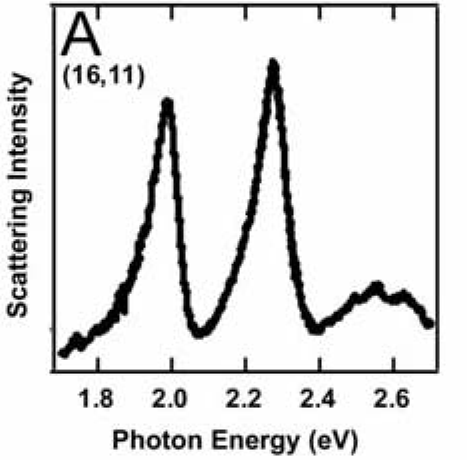
J. Fink, et. Al., 1999

Raman Spectroscopy

Chemical Separation Of Metallic and semiconductor CNTs, N. Minami, 2005

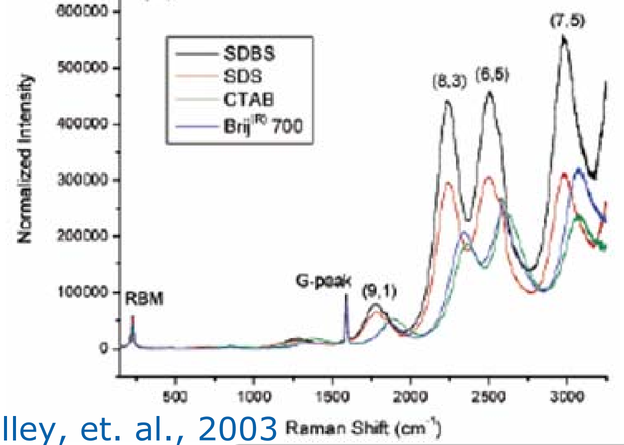


Raleigh Scattering



L.E. Brus, et. al. 2004

Fluorescence



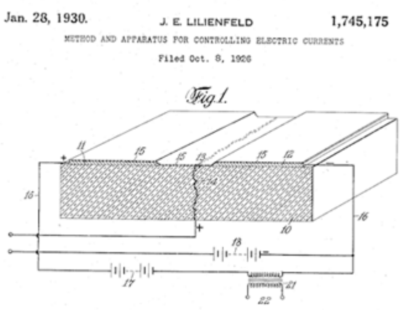
Smalley, et. al., 2003

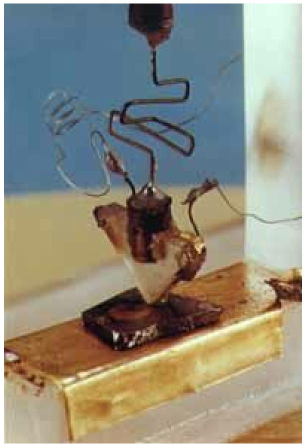
Need High Volume Bandgap Map

Beyond CMOS

Vision: Devices with new functionality integrated with CMOS

Beyond CMOS Challenge


Jan. 28, 1930. J. E. LILIENFELD 1,745,175
METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS
Filed Oct. 8, 1926



Identify viable alternate state device options

- Invent new device concepts
- Identify critical properties to optimize
- Optimize new materials, interfaces & integration
- **Metrology to characterize properties & interfaces**

What are we looking for?

Required characteristics:

- **Scalability**
- **Performance**
- **Energy efficiency**
- **Gain**
- **Operational reliability**
- **Room temp. operation**

Preferred approach:

- **CMOS process compatibility**
- **CMOS architectural compatibility**

Alternative state variables

Spin–electron, nuclear, photon

Phase

Quantum state

Magnetic flux quanta

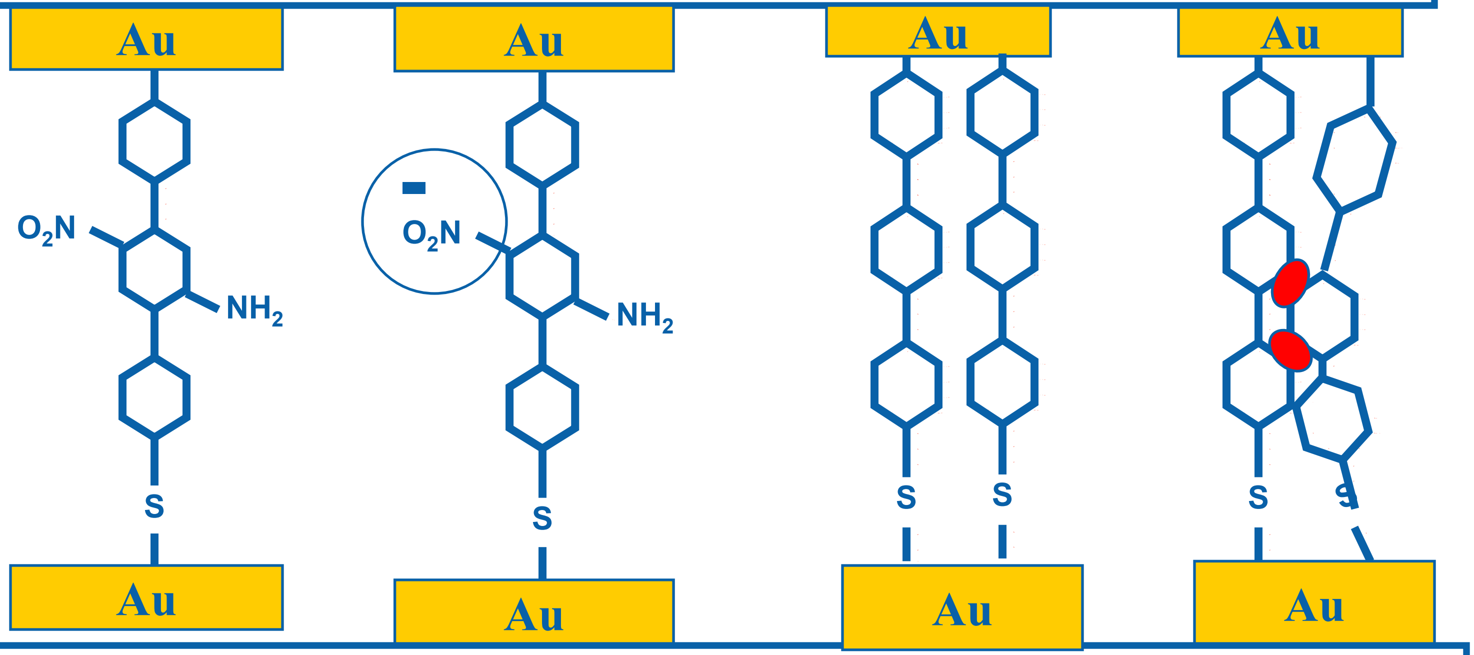
Mechanical deformation

Dipole orientation

Molecular state

Molecular State Challenges

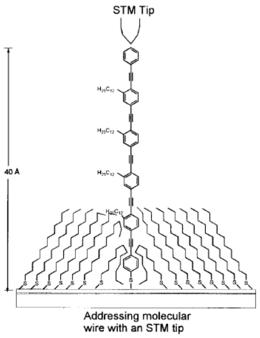
Device State	0	1	1	0
Molecular State	Neutral State	Charge Storage State	Neutral State	Collective Conformational State



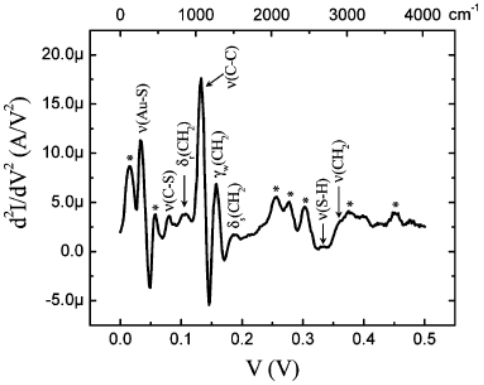
- Need to understand the transport & switching mechanism
- Does the top contact deposition change the molecule?

Molecular State Characterization Progress

Understand Transport & Switching Mechanisms

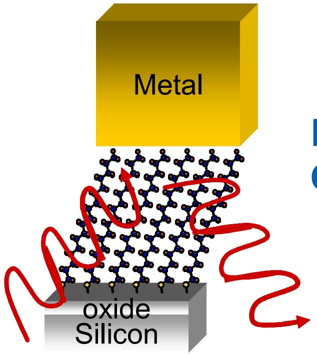


STM Molecular Switching, M. Reed 1996



Inelastic Electron Tunneling Spectroscopy, M. Reed 2004

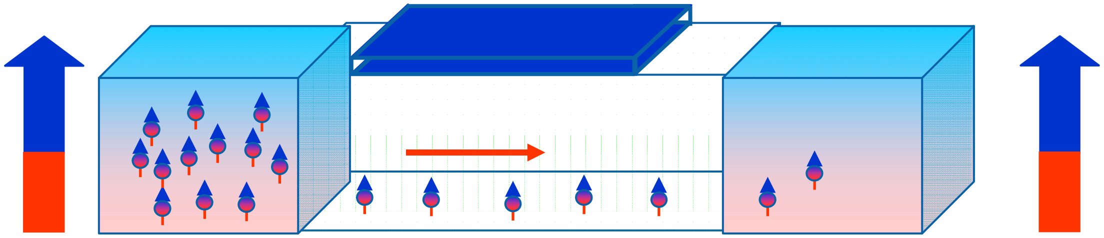
Understand Contact Formation & Interactions



Backside FTIR C. Richter, 2005

Multiple Techniques Required to Characterize Molecular State

Spin State Challenges



Room temperature ferromagnetic semiconductors (T curie)

Efficient Spin Injection

Materials Properties to Support Spin Gain

Spin State Characterization

Spin Alignment

Faraday Rotation

Kerr Shift

Neutron Diffraction

Potential Spin Concentration Mapping

SQUID

Magnetic Force Microscopy

Hall Probe

Magnetic Resonance Force Microscopy

Device Functions

Injection Efficiency: Test Structures

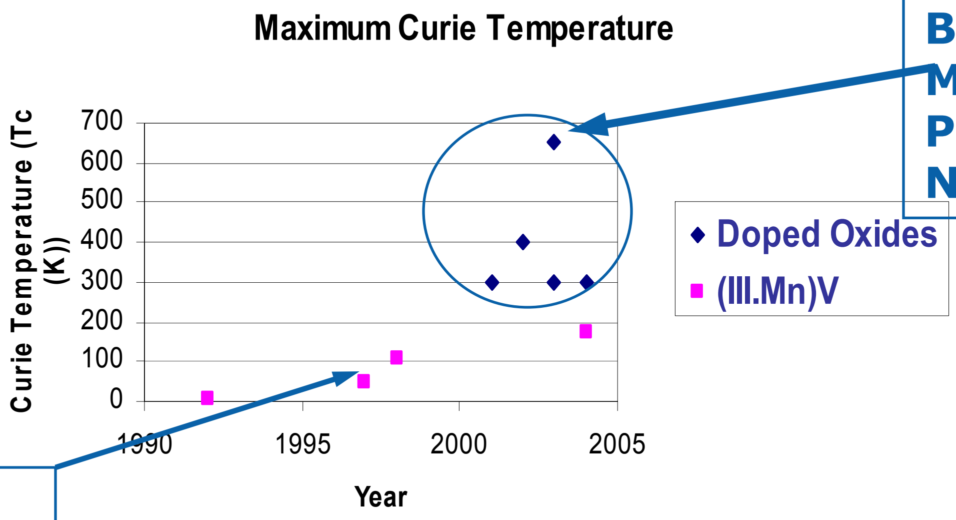
- Spin polarized photon emission
- LED, Lasers, etc.

Carrier Mediated Exchange

- Gated device structures required

Spin State Material Progress

Room temperature ferromagnetic semiconductors (T curie)



Overlapping Bound Magnetic Polarons, Coey, Nature 2005

Carrier mediated exchange

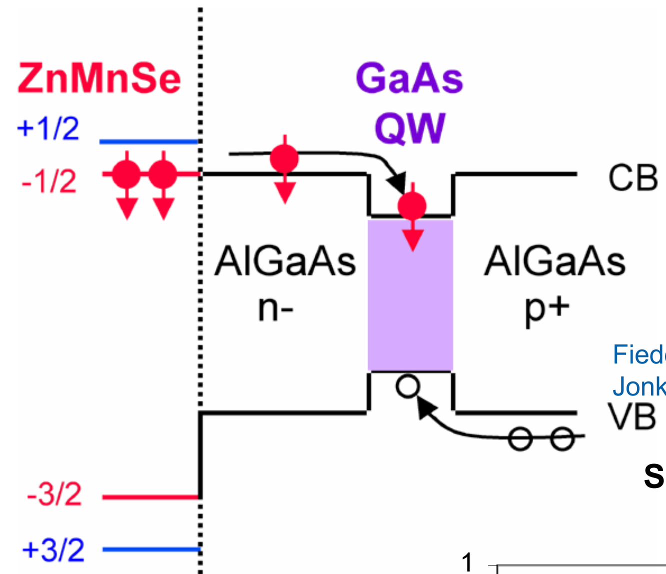
- Ferromagnetism can be detected with multiple techniques
  - Neutron Diffraction, SQUID, MFM, etc.
  - Will ferromagnetic properties change in nanometer structures?
- Carrier exchange requires fabrication of device test structures
  - How to measure in quantum dots?

Need Room Temp FM Semiconductor

Spin Injection Test Structures

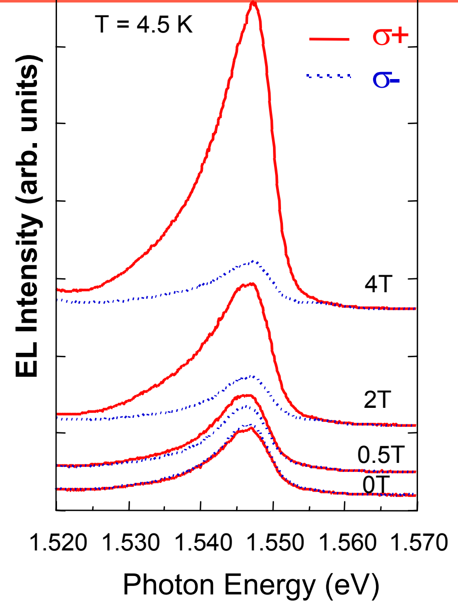
P_{circ} ~ 75-85%

ZnMnSe - Brillouin paramagnet



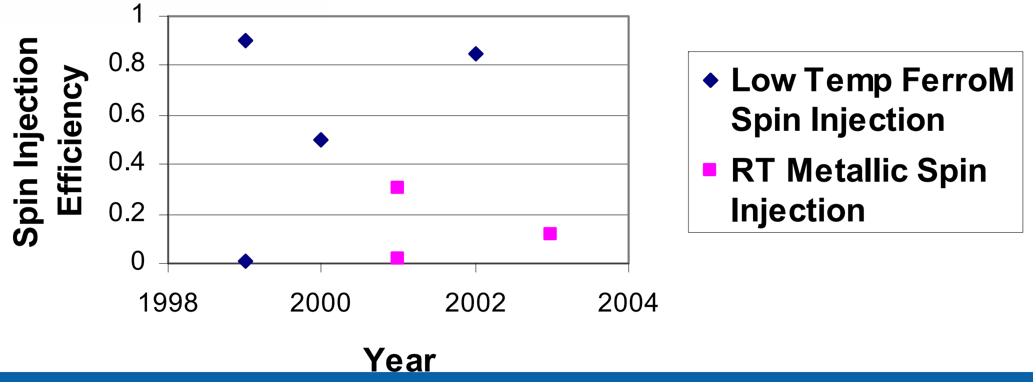
$\Delta E = gu_BH$

g ~ 100

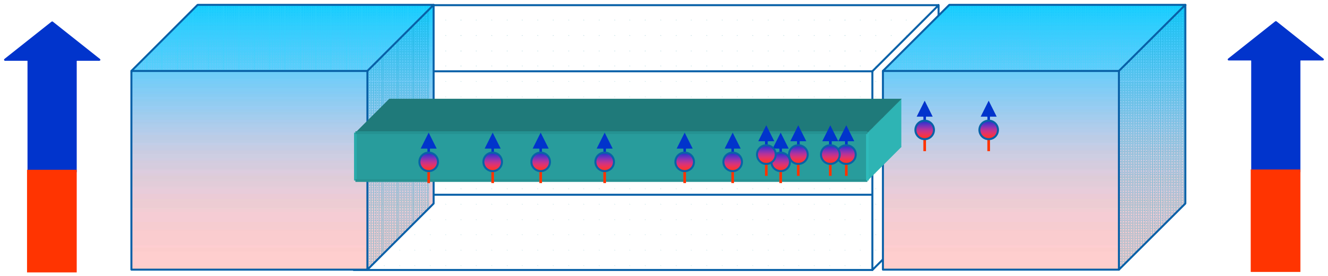


Fiederling et al, Nature 402, 787 (1999)
Jonker et al, PRB 62, 8180 (2000)

Spin Injection Efficiency



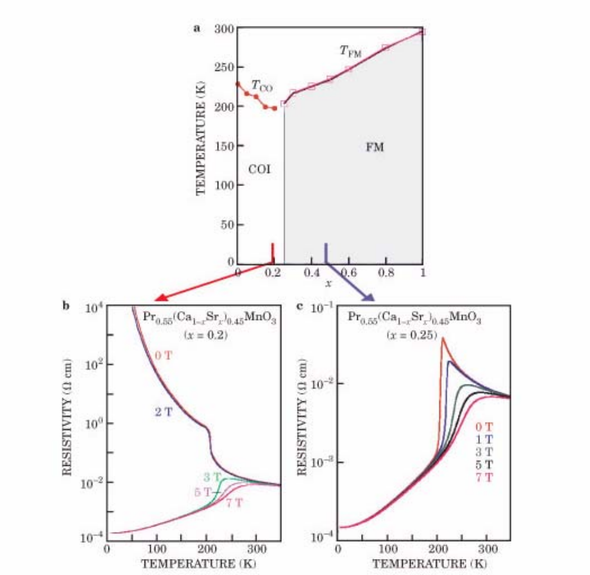
nm Scale Spin-Charge Characterization Challenge



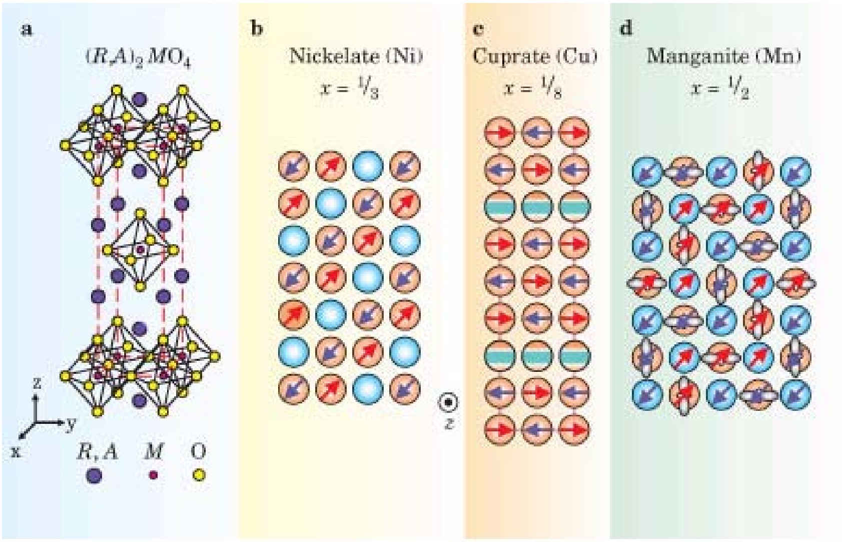
Need metrology to measure spin concentration & interactions at nm and atomic scales

- **Spin vs. electron concentration**
- **Spin interaction with interfaces**
- **Local electric & magnetic fields**
- **Stress interactions with spin**

Strongly Correlated Electron State Materials



Tokura

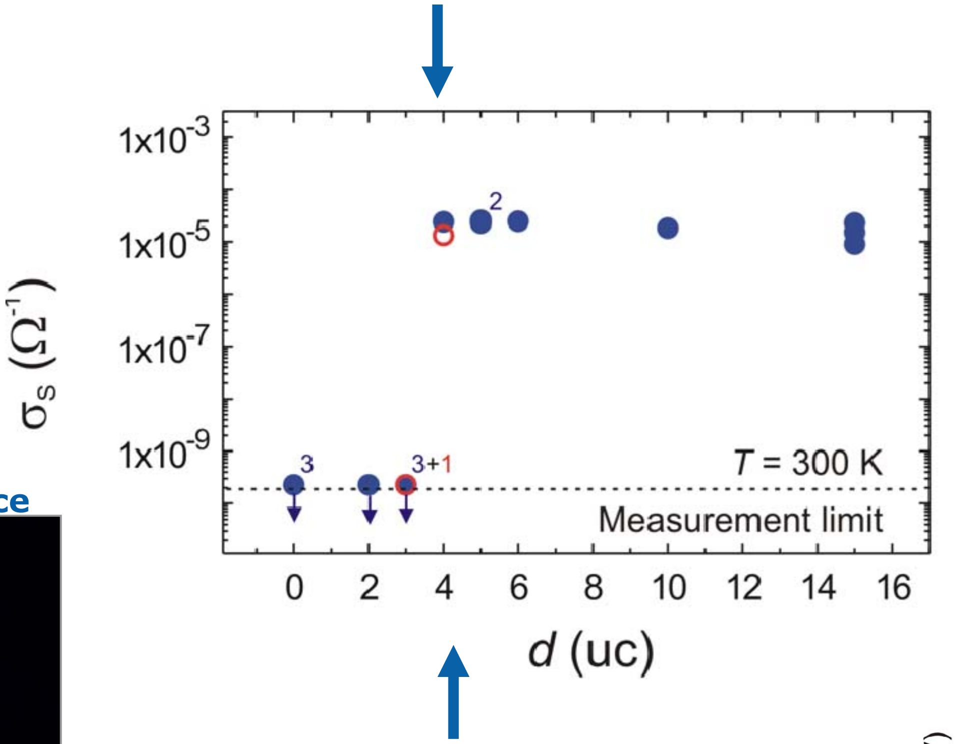


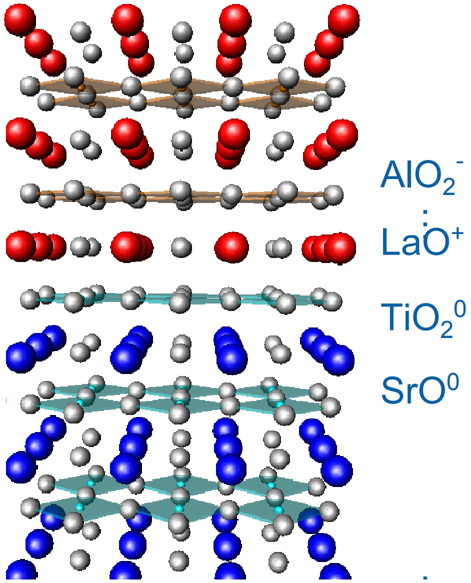
Tokura

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

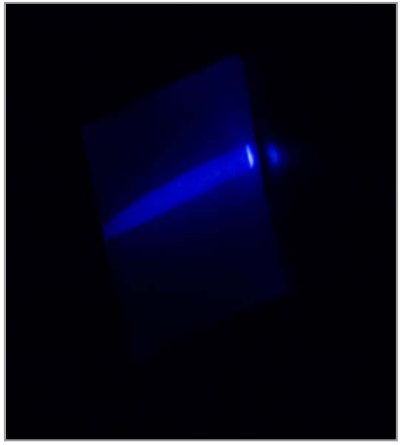
Can these materials enable new device functions?

2D Electron Gas at SrTiO3-LaAlO3 Interface





RHEED excited Cathodoluminescence

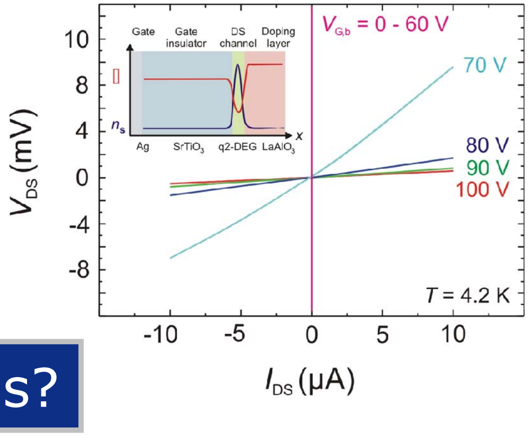


Oxygen Vacancies

D. Winkler, et. Al. 2005

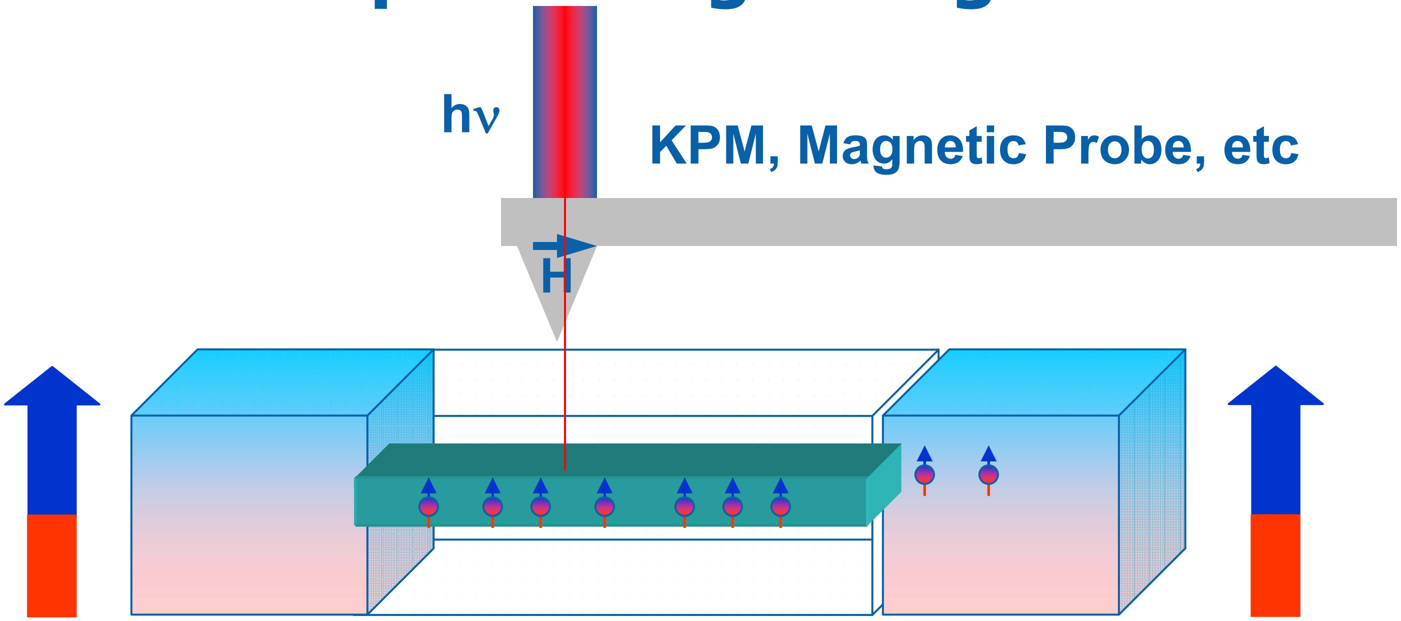
Critical thickness

J. Mannhart et. al. 2006



How do we validate the models?

nm Scale Spin-Charge Diagnostics



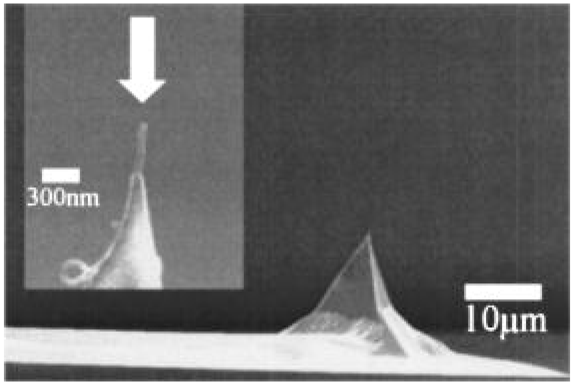
Concurrently Characterize

- Spin Density
- Electron Density
- Electric & Magnetic Fields

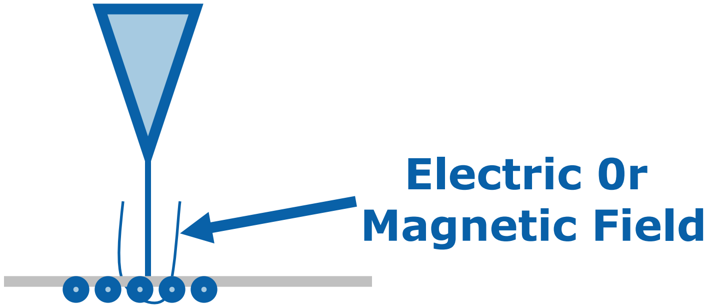
Combine Magnetic Probe with Kelvin Probe and NSOM or Scanning Microwave, etc?

- Magnetic probes that don’t alter the state or predictably alter…
- Algorithms to extract multiple properties

Decoupling nm-Scale Probe-Sample Interactions



Dai, Moler, et al (2004)



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

- Need to apply multiple spectroscopic techniques to characterize the materials and interface properties and interactions
- Need models & algorithms to separate probe-sample interactions

Summary

Summary

Silicon Nanoelectronics is production reality and follows Moore’s law

Long term: Novel devices will be needed to enhance CMOS

Novel devices may use new physical principles

New materials would be needed

Novel devices & materials require new metrology

Increased collaboration between Industry, Universities & Gov’t is essential!!!