Challenges for Materials to Support Emerging Research Devices

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Key Messages

- **Silicon Nanotechnology is production reality and follows Moore's law**
- **New materials are needed for future technologies**
- **Materials research is crucial for revolutionary devices**
  - Synthesis
  - Metrology & Characterization
  - Modeling
- **New materials will require collaboration**

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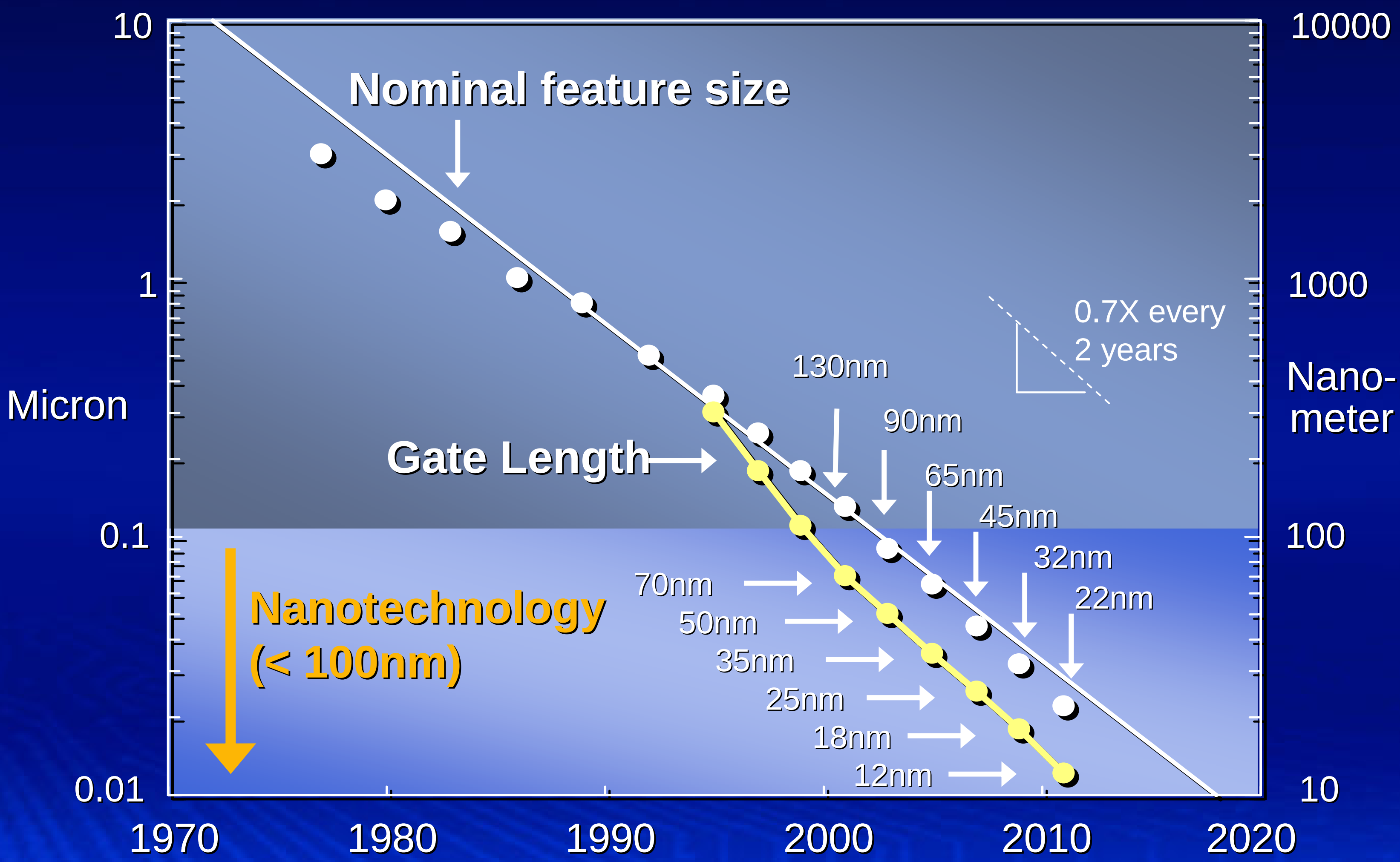
Agenda

- Moore's Law
- Extending CMOS
- Revolutionary CMOS
- Beyond CMOS
- Summary

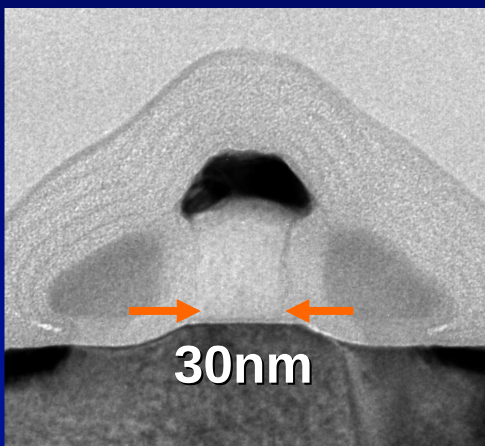
Silicon Technology Reaches Nanoscale



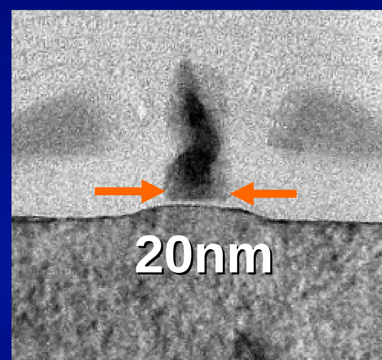
Source: Intel

Intel's Transistor Research in Deep Nanotechnology Space

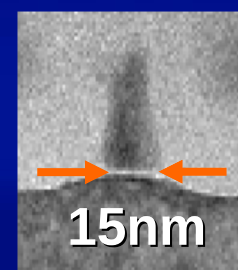
Experimental transistors for future process generations



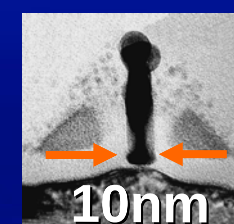
65nm process
2005 production



45nm process
2007 production



32nm process
2009 production

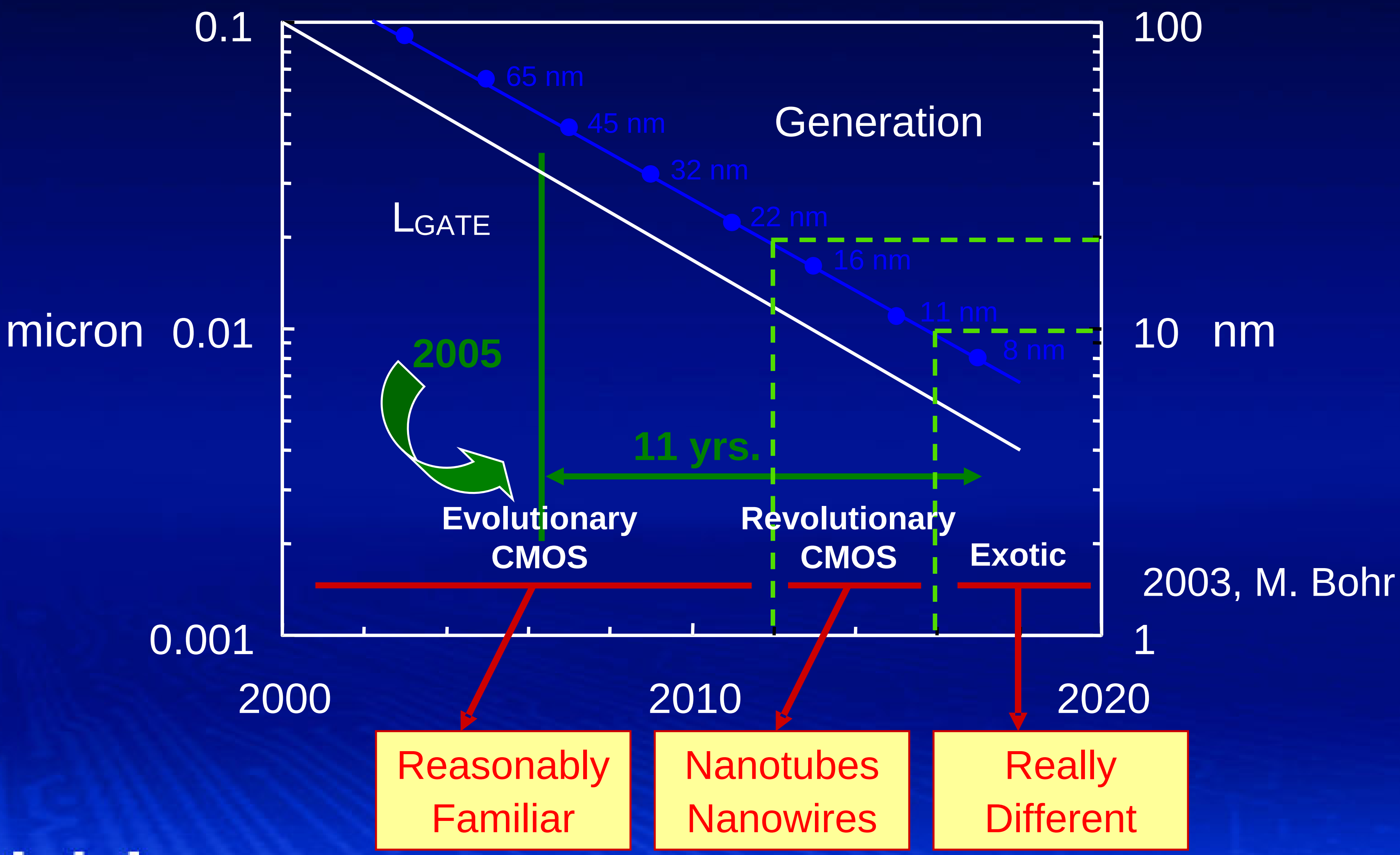


22nm process
2011 production

Transistors will be improved for production

Source: Intel

Nanotechnology Eras



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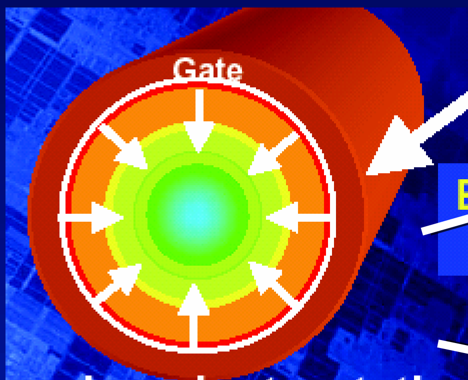
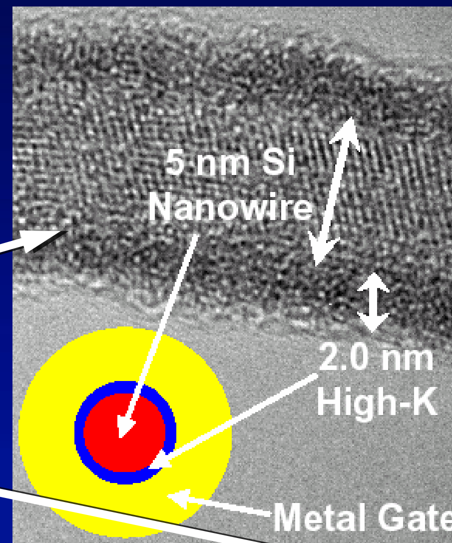
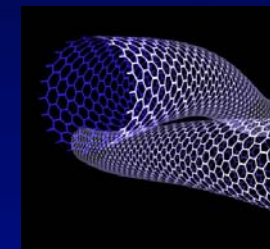
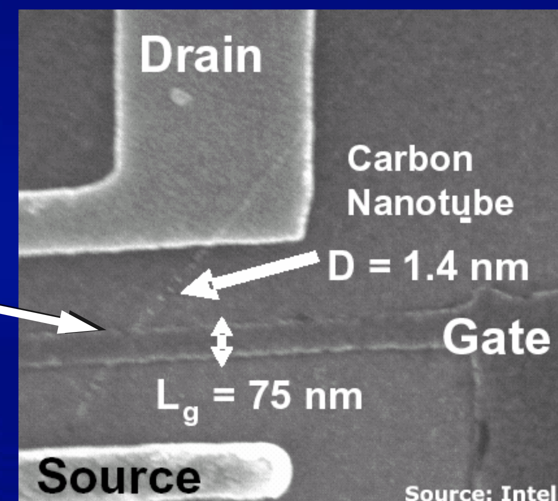
Revolutionary CMOS

Nanomaterial Transistors







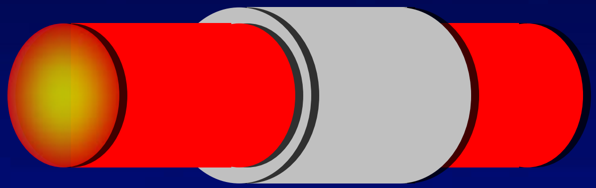


- **Options for sub 20nm technologies**
- **Challenges: Placement and property control**

1D Revolutionary CMOS Critical Properties

- **Critical Synthesis Issues**
- **Critical Materials Properties**
  - Device Material
    - **Density of States as manifest in Eg, effective mass & μ**
  - Gate Dielectric
    - **Dielectric constant**
- **Critical Interface properties**
  - Band Offset (Work function, fixed charge, trapped charge)
  - No Fermi level pinning
  - Lattice constant & coefficient of thermal expansion

Characterization & Modeling Challenges



- **How do you know the material is “good” ??**
- **Measurement of Properties**
  - Structure and composition (nm scale)
  - Electronic properties & interactions with interface materials
- **Impurities & Defects**
- **Modeling of Electronic Properties**
  - Density of States, effective mass, Eg
  - Models of interfaces, stress effects, etc

New Metrologies & Models Needed!!!!

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Exotic...

Exotic: 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**

Device Operation & Critical Properties

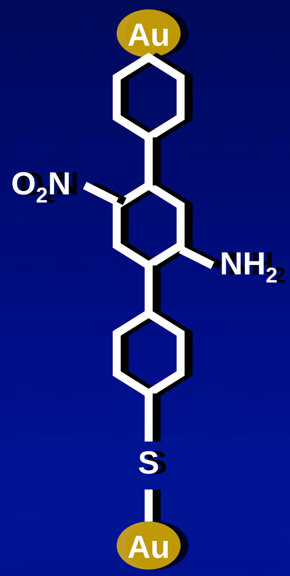
- **At least 2 "stable" states**
- **Mechanism to change states**
  - Communication with CMOS: Voltage or Charge
  - Logic:
    - **Ability to change the states of other identical devices**
    - **Gain**
- **Mechanism to read states**
  - Ability of CMOS to read the states (voltage or charge)
- **Material properties may limit mechanisms**

Alternate State Variable Examples

- **Molecular State**
- **Electron Spin**
  - Spin Injection in semiconductors
  - Ferromagnetic semiconductors
- **Orbitronics (Multiferroics)**

Molecular Materials

Molecular State



Critical Material Properties

Transconductance change

-Change in Tunnel distance

-Delocallization-Locallization of states

-Collective conformational changes

-Charge Storage

Critical Interface Properties

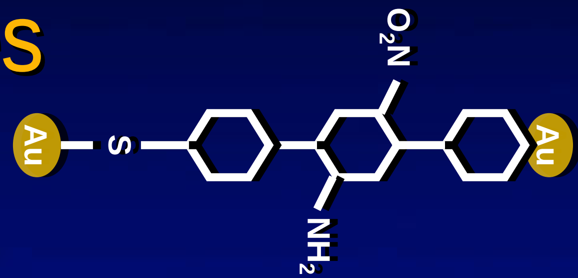
Atomic energy levels in resonance with the molecular energy states

-Work Function

-Contact material DOS

- **Fabrication of contacts is challenging**
- **Need better understanding of mechanisms**

Characterization & Modeling Challenges

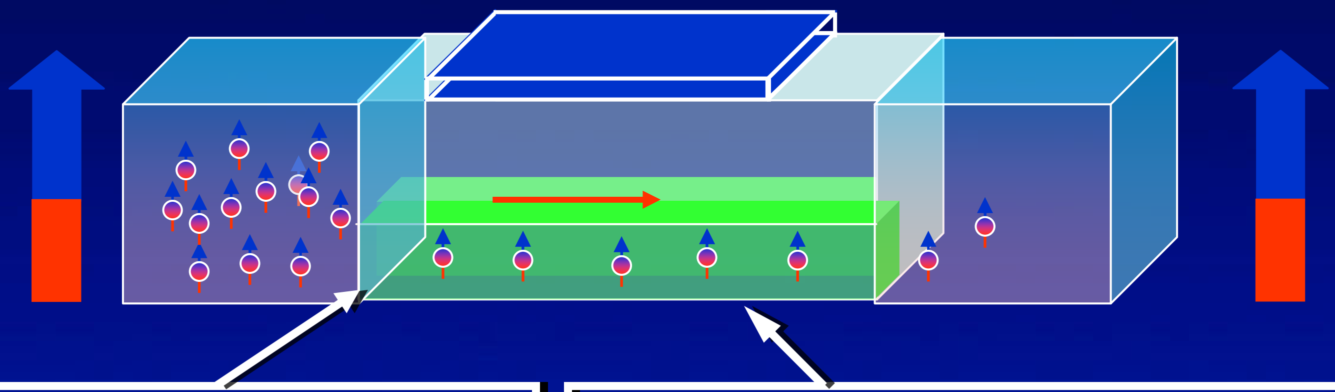


- **How do you know you have a "good" device??**
- **Measurement of Properties**
  - Structure & contact interaction
  - Electronic energy levels & interactions with interface materials
- **Modeling of Electronic Properties**
  - Density of States, effective mass, Eg
  - Models of interface electronic interactions
  - Charge storage, excited local states, conduction mechanisms
  - Accurate prediction of energy levels for molecular structures

New Metrology & Models Needed!!!!

Spintronic Materials

Semiconductor Spintronics



<u>Interface Critical Properties</u>

- Interface Band Structure Matching [energy & symmetry] (as manifest in spin injection efficiency)
- No band-bending

<u>Critical Materials Properties</u>

Semiconductor:

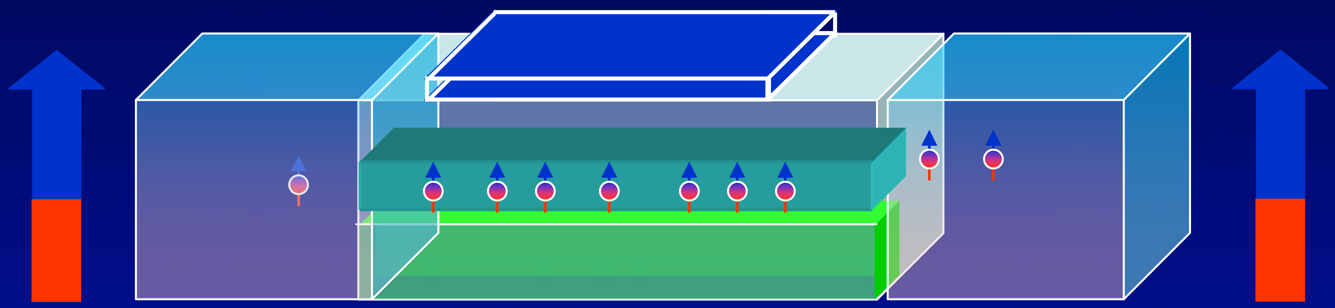
- Spin Orbit Coupling (As manifest in spin lifetimes, and diffusion lengths)
- g-Factor

Ferromagnetic contact source:

- Coercivity

How can we separate materials issues??

Ferromagnetic Semiconductor Spintronics



Critical Interface Properties

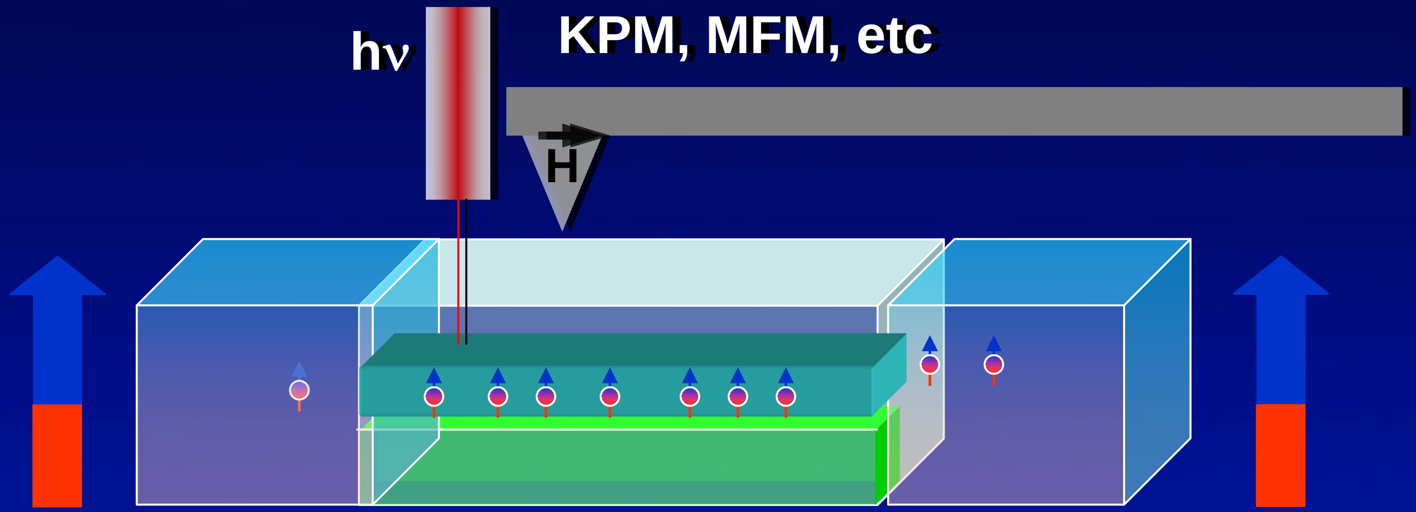
- Spin Orbit Coupling as manifest in (Interface Magnetic Anisotropy)
- Minimal band bending

Critical Material Properties

- Spin Exchange Interaction
- Exchange Splitting Energy
- T curie
- Moment per atom

How can we separate materials issues??

nm Scale Material Diagnostics



- **Need new metrology to measure spin properties & interactions at nm scale**
  - Spin polarization, lifetimes, diffusion lengths
  - Spin interaction with interface band bending, roughness, states
  - Local electric & magnetic fields
  - Stress interactions with spin lifetimes

Spin Material Modeling Needs

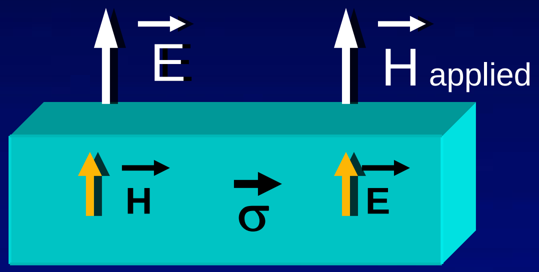
- **Interaction of spin lifetime and diffusion lengths with:**
  - Defects
  - Band bending
  - Stress
  - Interfacial roughness
  - Interface states and defects
  - Spin injection processes

Orbitronics & Multiferroics

Perovskite Materials

- Ferroelectrics
- Ferromagnetics
- Multiferroics (Ferroelectric & Ferromagnetic)
- Colossal Magnetoresistance
- Semiconductors
- High-T Superconductors
- Promising optical properties
- Phononic properties

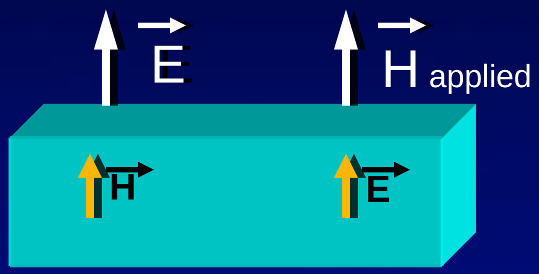
Multiferroics



Conceptual

- Interplay between charge, orbital, and spin degrees of freedom
- Magnetic field control of ferroelectric polarization
- Switching of magnetic polarization induced by electric fields

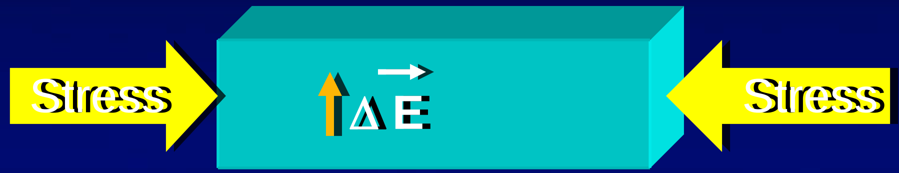
Orbitronics



Conceptual

- **Orbitronics: Perovskite manganese oxides**
  - RBaMn2O6
    - **R=Sm, Eu, Gd, Tb, Dy, Ho, Y**

Challenges

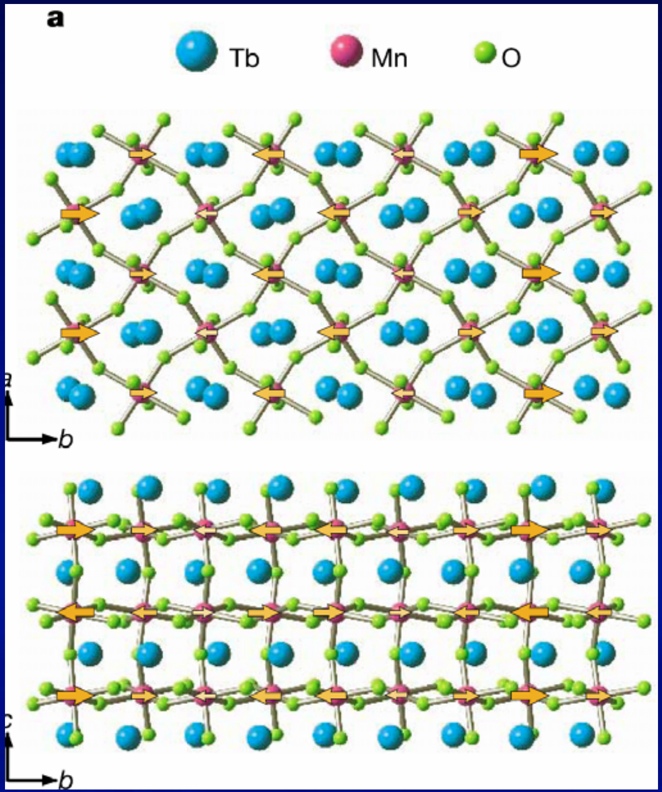


- **Key Properties**
  - Piezoelectric, Multiferroic, Colossal Magnetoresistance
  - Stress can interact with multiferroic properties
- **Good News: Multiferroic & CMR**
- **Bad News: Piezoelectric (Properties Depend on stress)**
- **Material unknown**
  - Vacancies, interstitials and impurities can cause local stress
  - How pure and defect free do the materials need to be?
  - Integration Issues: Coefficient of Thermal Expansion (CTE)

New Metrologies Needed

- **Nanometer characterization of:**
  - Piezoelectric properties
  - Electro & Magneto-optical properties
  - Ferroelectric and Ferromagnetic properties
  - Vacancy, defect, impurity interactions
  - Local stress effects
  - Interface properties

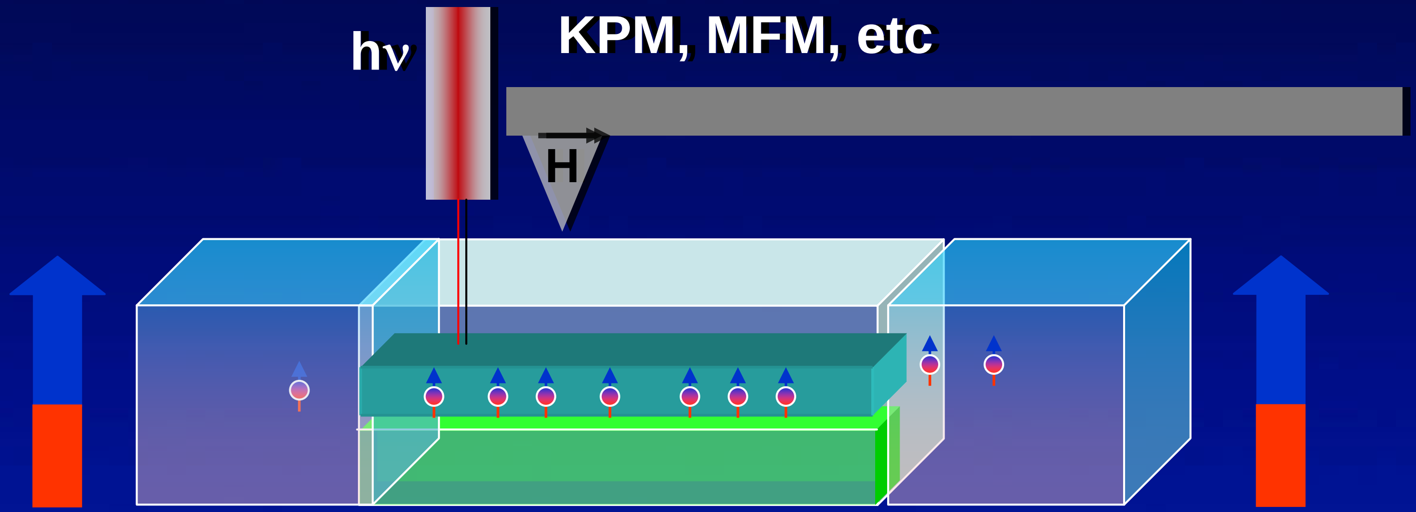
Multiferroic Modeling Needs



- **Basic models of the relationship between structure, bonding, and the resulting properties**
  - Extend from local structure to extended properties
  - Models of defect and vacancy impact on structure and properties

Special nm Metrology Needs

nm Scale Material Diagnostics



- **Atomic structure of carbon based materials**
  - Low energy TEM
- **Modeling of nm probe interactions with materials**
  - Improve analysis of signals from AFM based and multi-probe metrologies

Summary

- **Silicon Nanotechnology is production reality and follows Moore's law**
- **New materials are needed for future technologies**
- **Materials research is crucial for revolutionary devices**
  - Synthesis
  - Metrology & Characterization
  - Modeling
- **New materials will require collaboration**
  - Gov't, Universities, Research Institutes, & Industry

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For further information on Intel's silicon technology and Moore’s Law, please visit the Silicon Showcase at www.intel.com/research/silicon