Challenges for Materials to Support Emerging Research Devices

C. Michael Garner*, James Hutchby+, George Bourianoff*, and Victor Zhirnov+

*Intel Corporation
Santa Clara, CA

++Semiconductor Research Corporation
Research Triangle, NC
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
Agenda

• Moore's Law
• Extending CMOS
• Revolutionary CMOS
• Beyond CMOS
• Summary
Silicon Technology Reaches Nanoscale

Nanotechnology (< 100nm)

Nominal feature size

Gate Length

Source: Intel
Intel’s Transistor Research in Deep Nanotechnology Space

Experimental transistors for future process generations

- 65nm process 2005 production
- 45nm process 2007 production
- 15nm process 2009 production
- 32nm process 2009 production
- 22nm process 2011 production

Transistors will be improved for production

Source: Intel
Nanotechnology Eras

Reasonably Familiar
Nanotubes Nanowires
 Really Different

2005

LGATE
Evolutionary CMOS
Revolutionary CMOS
Exotic

2003, M. Bohr
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 $E_g$, effective mass & $\mu$
  - 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!!!!
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
• Fabrication of contacts is challenging
• Need better understanding of mechanisms

Critical Material Properties
- Transconductance change
- Change in Tunnel distance
- Delocalization-Localized 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
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, $E_g$
  - 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

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

Critical Materials Properties
- 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??
• 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

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

- Orbitronics: Perovskite manganese oxides
  - $\text{RBaMn}_2\text{O}_6$
    - $R=$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

AFM, KPM, MFM, etc.
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
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  ▪ Synthesis
  ▪ Metrology & Characterization
  ▪ Modeling
• New materials will require collaboration
  ▪ Gov’t, Universities, Research Institutes, & Industry
For further information on Intel's silicon technology and Moore’s Law, please visit the Silicon Showcase at [www.intel.com/research/silicon](http://www.intel.com/research/silicon)