Nanotechnology Overview

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Nanoelectronics – Si CMOS

Courtesy of Intel Corp.
Nanotechnology

Figures courtesy of IBM Research
Nanotechnology

One day, it may replace Si CMOS…
Key Challenges

- Power / performance improvement and optimization
- Variability
- Integration
  - Device, circuit, system
Nanotubes and Nanowires

STM Image
1.0 nm

Nanotubes

Nanowire
CNT Families and Structure

\[ n,m=(10,10) \text{ -- metallic} \]

\[ n,m=(10, 0) \text{ -- semiconducting} \]

Diameter: \(~1\) nm
Length: several \(\mu m\)

1998 Carbon Nanotube FETs

Tans et al. Delft University
Nature 393, 49 (1998)

→ P-type, high contact resistance

Martel et al. IBM

→ P-type, high contact resistance
Carbon Nanotube FET
Carbon Nanotube FET

- Drain current normalized by gate capacitance

Drain Voltage $V_d$ [V] vs. Normalized Drain Current $|I_d| / C$ [mA/$\mu$m/µF]

Solid line = 2.5/3 µm CNFET
Dashed line = 50 nm Si FET

Data from:
Carbon Nanotube FET is Promising...

- CV/I, $G_{\text{msat}}/C$ are comparable to or better than Si nFET
- Chemical synthesis controls a key dimension
  - think of this as an ultra-thin body SOI with body thickness and device width controlled to atomic precision
- Band structure of CNFET:
  - Symmetric band structure
    - electron and hole transport should be identical
    - balanced nFET and pFET
  - Thermal velocity / source injection velocity of CNFET higher than Si FET
  - However, density of states is lower - lower gate capacitance
- Carrier transport is one-dimensional - reduced phase space for scattering
- Wrap-around (“double”) gate - thicker gate oxide possible
- All bonds are satisfied, stable, and covalent
- Device is not “wed” to a particular substrate - 3D plausible
- Circuit design infrastructure preserved - no need to reinvent circuits
CNFET vs. Si MOSFET


Si n-MOS data is 70 nm $L_G$ from 130 nm technology from Antoniadis and Nayfeh, MIT
Key Issue: Materials and Fabrication

- Right kind of tube (electronic properties) at the right places (placement, orientation), doping
- Low parasitic capacitance/resistance, compact device (including isolation) structure
- Process compatibility with Si CMOS

Si Nanowire Growth

- Catalyst size controls nanowire size

Nanowires – 3D Heterogeneous Integration Fabric

Formation of heterostructure interfaces between lattice mismatched materials, e.g. InAs/GaAs (7%) & InAs/InP (3.5%): a comparison between 2D epitaxial growth and wire growth.

Core-shell
Axial hetero-epitaxy
1D Channel FET:

- **1D semiconductors (nanotube, nanowire)**
  - Chemical synthesis controls the critical dimension (reduces variation due to quantum confinement)
  - Self-assembly or directed growth – new manufacturing methods
  - Nanowire (Si, Ge, III-V, II-VI) is the next logical step after Si FinFET
    - Bandgap engineering and strain engineering tricks still possible
    - Both lateral (along axis) and radial (core-shell) engineering possible
  - Excess noise for 1D conductors may be problematic – needs study
Nanotubes and Nanowires

- Net: basic science has progressed to a level where engineering work is feasible
Molecular Electronics

As defined by the conceptual creators Aviram and Ratner [1], molecular electronics is the “study of molecular properties that may lead to signal processing” [2]. However, making molecular electronics into a functioning, manufacturable technology will require revolutions in circuit architecture, fabrication, and design philosophy in addition to gaining a fundamental understanding of conduction and electronic interactions in single molecules.

Molecules = Small?

- All devices are governed by electrostatics and eventually limited by tunneling.
  - Difficult to be much smaller than 2 - 3 nm.

Si FET

Molecular Device

L > 2.5 – 3 nm

Molecules

Organic Systems

- Wires
- Donor
- Acceptor
- Bridges

Metal-metal bonded supramolecules

- $M = V, Nb, Cr, Mo, W, Tc, Re, Fe, Ru, Os, Co, Rh, Ir, Ni, Pd, Pt, Cu, Ag ...$

Ligands chosen to tailor:
- Electronic coupling between dimetal units
- Electrochemistry
- Solubility
- Structure ...

Nanotubes

STM Image 1.0 nm

Naphthalocyanine
- tailor metal center
- tailor ligands off peripherary
- link to form chains or onto surfaces
- stack vertically

Porphyrin

Phthalocyanine

Organo-metallic Akin to Biological Systems

Lower manufacturing cost
New functionality
Two-Terminal Electrical Measurements

NDR measurements

- Nanopore monothiol
- Nanowire monothiol
- CAFM dithiol
- Nanoparticle bridge dithiols
- Xbar monothiol
- Other similar
- Nanopore nitroamine
- Hg drop bilayer
- SIM Fe

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Hysteresis – A Dime a Dozen
Key Challenges

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Impact of Statistical Variations

![Graph showing the impact of statistical variations on normalized leakage and frequency. The graph illustrates a 30% variation and a 5X improvement in leakage for 130nm technology.]

Normalized Leakage vs. Normalized Frequency

- 30% variation
- 5X improvement

130nm

Frequency ~30%
Leakage ~5-10X

Courtesy of Intel Corp.

Can These be Fabricated for 10 nm FET?

Source: Toshiba, K. Uchida et al., *IEDM* 2003

Source: Samsung, J.-H. Yang et al., *IEDM* 2003
Nanomaterials

Courtesy of IBM Research
Nano for Si Technology – Nano, Now!

Use techniques that produce these:

To make these structures:

Source: Toshiba, K. Uchida et al., IEDM 2003

Source: Samsung, J.-H. Yang et al., IEDM 2003
Lithography Subdivision

- Templated assembly of nanostructures
- Combines top-down lithography with bottom-up assembly
- Provides feature registration with larger, irregular features

Diblock copolymer molecule

Metrology and Characterization

- Cannot manufacture if we cannot measure what we make

- Wish list
  - Fast AFM
    - The equivalent of the CD SEM
  - Defect recognition for new materials
    - nanotube, nanowire, organic molecules
  - Defect repair
  - Characterization methods for soft materials
A Possible Path

Transport-enhanced FET
Strained Si, Ge, SiGe, III-V

Silicon Substrate

Gate Voltage ($V_{GS}$)

Drain Current ($\log(I_D)$)

$S < kT/q$

Fine-grain FLA / PLA

Multi-Gate / FinFET

Source Drain

Molecular devices

Spintronics

Nanotube

Quantum cascade

Embedded memory

3D, heterogeneous integration

Nanowire

Time
Questions? Please contact:

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