

NANOELECTRONICS beyond CMOS

David Pulfrey

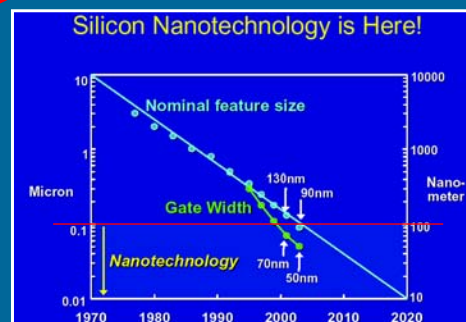


1

NNI definition of Nanotechnology

"Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to understand and create materials, devices and systems with fundamentally new properties and functions because of their small structure"-M. Roco, NNI

1- 10 nm is better
But Intel prefer ...



2 Bourianoff04

How did Microelectronics become Nanoelectronics?

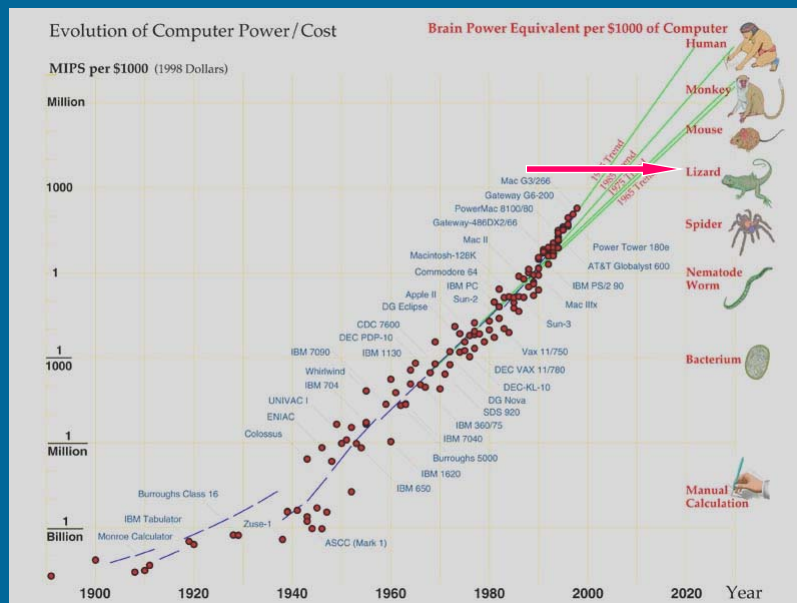
- Semiconductors have a natural synergy between cost and performance
- As semiconductor designs shrink, the cost drops, and the performance increases
 - Higher performance creates new markets
 - Cost reduction supports R&D, and capital investments

Microelectronics became Nanoelectronics because of a synergy between cost and performance!

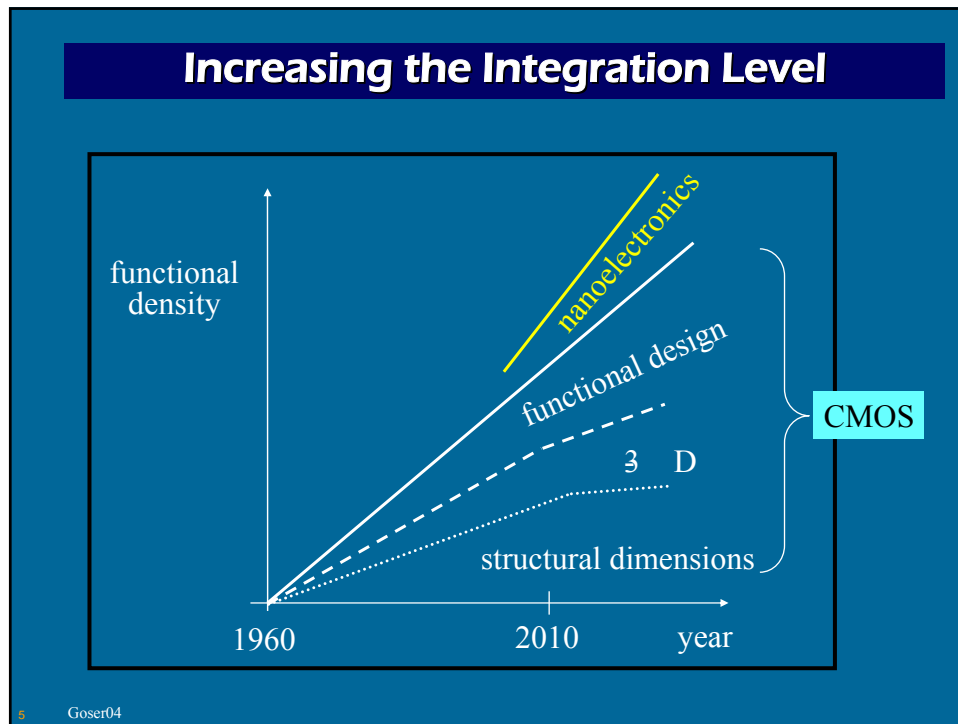
7



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Nanotransistors: the Candidates

- Molecular switches
- Spin FETs
- Single electron transistors
- Nanotube FETs
- Nanowire transistors

Molecular Electronics

- Use few molecules instead of multi material transistors
- *Gates scaleable to densities of greater than 10^{12} gates per cm^2 .

Approx 100 molecules

- Few electrons/bit- low power

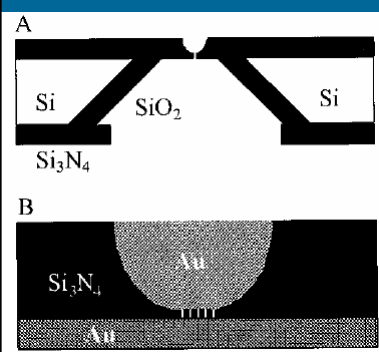
Compare: 1fF at 1V $\approx 10^4$ electrons

- Billions of identical molecules are easily formed
- “Natural” self assembly
- Compositional flexibility of organic molecules
- Tailor properties to achieve device functionality
- *Memory density of 10^{15} bits per cm^3 .

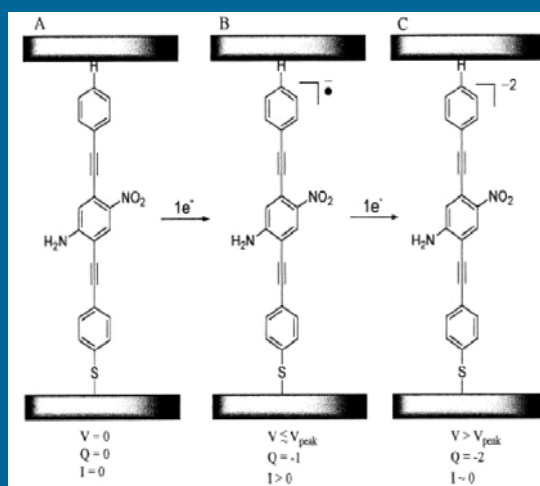
Human brain
 10^{13} bytes

*DARPA04

Self-assembled Molecular Switch



Self-assembly of molecule containing nitroamine redox centre in nitride nanopore



Neutral

Conductive anion

Insulating dianion

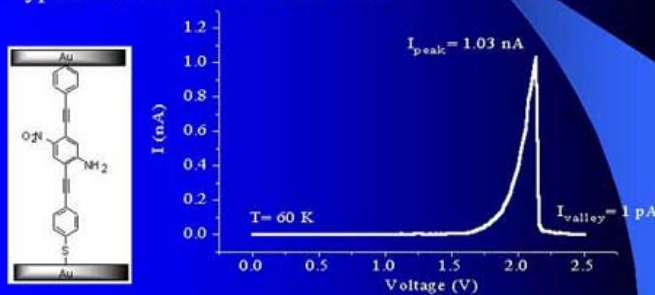
Chen99

2'-amino-4-ethynylphenyl-4'-ethynylphenyl-5'-nitro-1-benzenethiol

Self-assembled reversible switch

Self-Assembled Reversible Molecular Switch

The first demonstration of a reversible molecular switch.
Over 1000:1 on-to-off ratio in switching. (*Science*, 1999, 286, 1550)
Typical devices are ~30:1 on-to-off.



9 MEC01

Molecular electronics: prognosis

Chris Gintz, President, MEC
March 7, 2003

- *"It's simply too early to commercialize molecular memory technology at this point," he said.*
- *"The problem has turned out to be much more difficult than we anticipated.*
- *I think it is very unlikely that we are going to see hybrid molecular electronic and silicon systems anytime soon.*
- *It turns out that the processes are extremely difficult."*

10 Gintz03

SPINTRONICS

- **Generic & inflated term -implies use of spin for information storage and manipulation**
- **An extra degree of freedom**
- **Nonvolatile and increased data storage**
- **Faster data processing (10x) and low power (10-50x)**

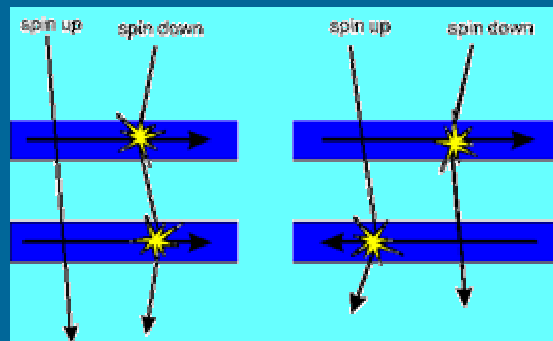
Perhaps not relying on transport

Addressing CMOS deficiency

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Giant Magnetoresistive Effect

- Scattering is energy and spin dependent

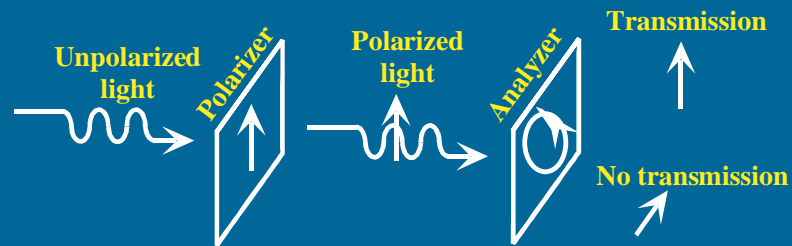


- R depends on: spin, and magnetization of medium (controllable by B).
- Effect is much larger in artificial thin films than in metals
- Used in hard disk read heads

12 Stoner04

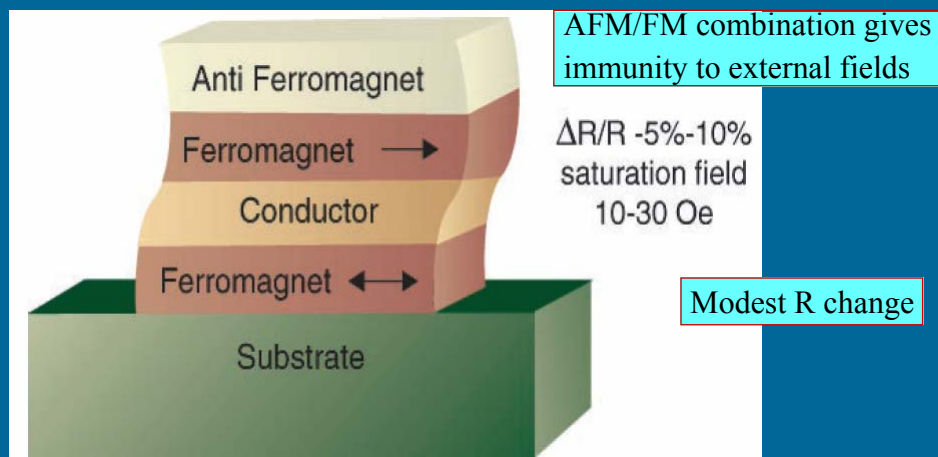
What is a Spin Valve?

Magnetic analog of an optical polarizer/analyzer



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Spin valve



“Free” FM can be changed by external field

14 Wolf01

Magnetic Tunnel junction

Replace non- magnetic metal
with
thin insulating layer

5 10X higher R change

Lower I

15 Zorpette01

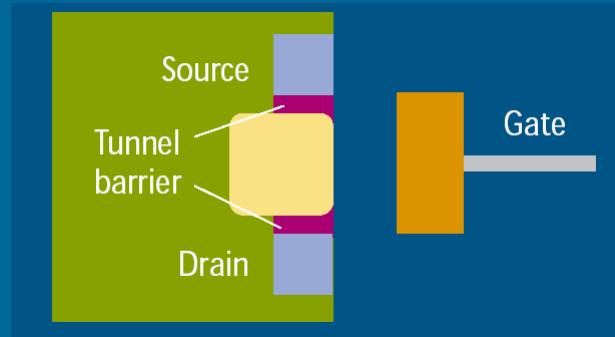
Spin FET

- Electrons move from S to D at high (relativistic) velocities
- Stationary E_{gate} appears to have a B component
- B causes spin-dependent band splitting and precession (Rashba Effect)
- Spin under gate is modulated by E_{gate} , e.g., a normally-on FET
- “Flipping” is a fast process requiring little energy.

This device has not yet left the drawing board!

16

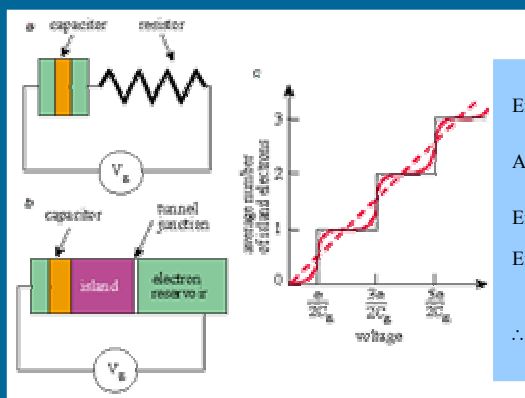
Single-electron Transistor



Principal motivation: greatly reduced power dissipation.
Also: increased speed (tunneling)

17 Geppert00

Coulomb Blockade



Energy of n electrons on capacitor : $E_n = \frac{1}{2} \frac{(nq)^2}{C}$

Add another electron : $E_{n+1} = \frac{1}{2} \frac{((n+1)q)^2}{C}$

Energy change : $\Delta E = \frac{1}{2} \frac{q^2(2n+1)}{C}$

Energy change of the electron is qV_G

\therefore Transfer only allowed if $V_G = \frac{1}{2} \frac{q(2n+1)}{C}$

Use 2 tunnel junctions and make a FET

Need : $\frac{q^2}{2C} \gg kT$
i.e. $C \approx \text{aF}$

18 Devoret98

Room temperature SET

STM tip, Island Region, Ti, SiO₂, Si, Formation of Island Region by STM, Anodization using water-coated tip as cathode, Drain, Source, SiO₂, Si, Formation of Source & Drain Ohmic Contact, TiOx Barrier, Source, Island, Drain, TiOx Barrier

Single Electron Transistor
 $T = 300 \text{ K}$
 $V_G = 2 \text{ V}$
 Drain Current ID (A), Drain Voltage VD (V), Conductance (S)

19 Matsumoto04

SETMOS: A Novel True Hybrid SET- CMOS High Current Coulomb Blockade Oscillation Cell for Future Nano-Scale Analog ICs

ETH, TI, UCSB

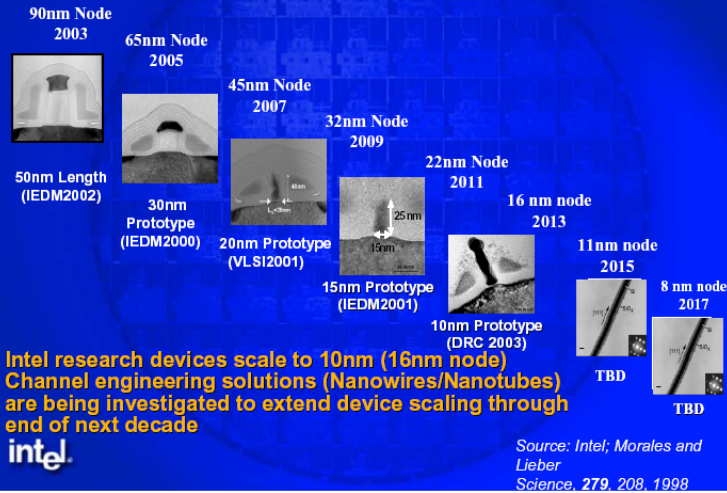
CMOS (high speed drive, voltage gain)
 + SET (ultra low power consumption)
 = SETMOS (dense, low- power, analog circuits, e.g., NDR, NN, ADC)
 Coulomb blockade oscillations and operation at- 100C

$T = 173 \text{ K}$, $V_{ds} (V) = 0.45$, $e/C_2 = 0.32 \text{ V}$
 Drain to Source Current, I_{os} (nA), Gate to Source Voltage, V_{gs} (V)

20 Mahapatra03

Nanotubes and Nanowires

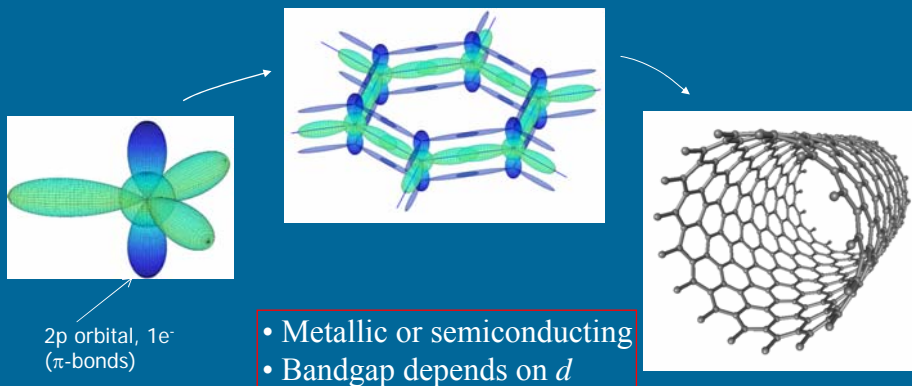
CMOS Device Scaling Demonstration



21 David04

Single-Walled Carbon Nanotube

Hybridized carbon atom \rightarrow graphene monolayer \rightarrow carbon nanotube



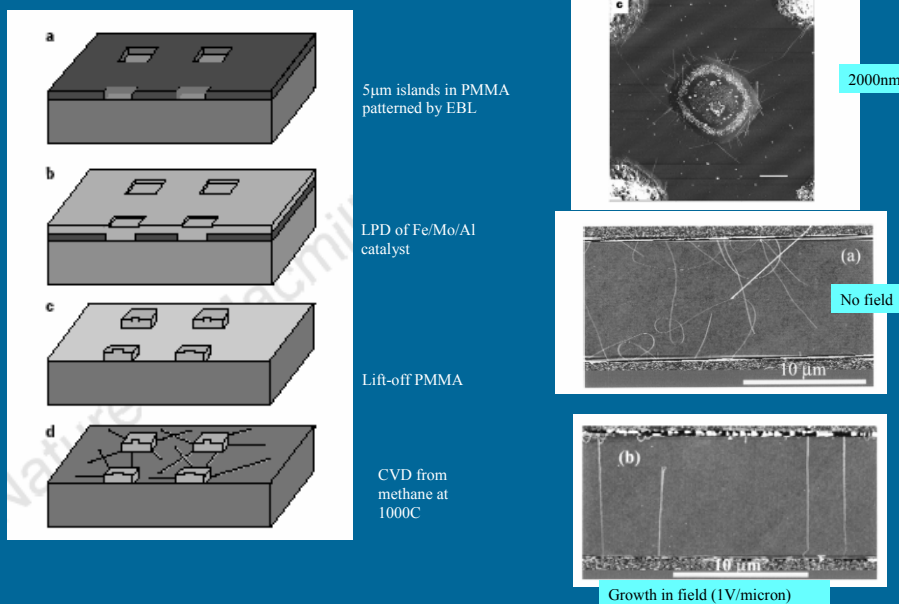
22 UBCnano (Castro)

Compelling Properties of Carbon Nanotubes

- NANOSCALE -- no photolithography
- BANDGAP TUNABILITY -- 0.5-1.5eV
- METALS AND SEMICONDUCTORS -- all-carbon ICs
- BALLISTIC TRANSPORT -- 20-300nm
- STRONG COVALENT BONDING
 - strength and stability of graphite
 - no surface states (less scattering, compatibility with many insulators)
- HIGH THERMAL CONDUCTIVITY
 - almost as high as diamond (dense circuits)
- SELF ASSEMBLY -- biological, recognition-based assembly

23 UBCnano

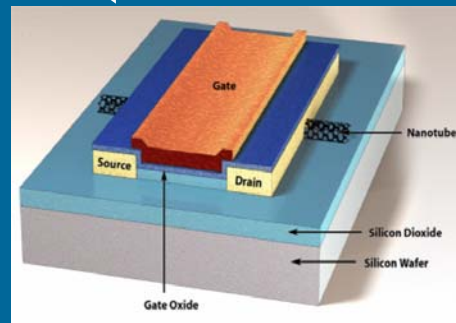
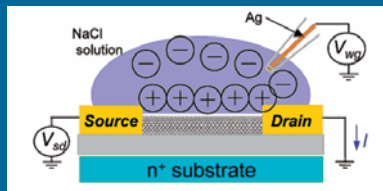
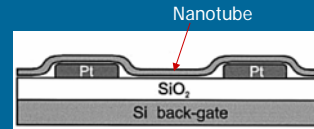
CNT formation by catalytic CVD



24 Kong98, Ural02

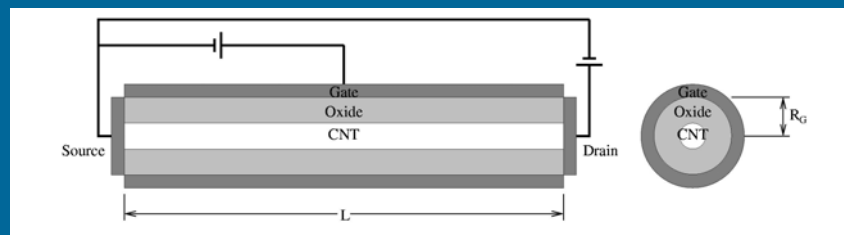
Fabricated Carbon Nanotube FETs

- Few prototypes
 - [Tans98]: 1st published device
 - [Wind02]: Top-gated CNFET
 - [Rosenblatt02]: Electrolyte-gated



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The Ultimate "Multi-gate" FET



chirality: (16,0)
 radius: 0.62 nm
 bandgap: 0.63 eV
 length: 15 - 100 nm
 oxide thickness: $(R_G - R_T)$: 2 - 6 nm

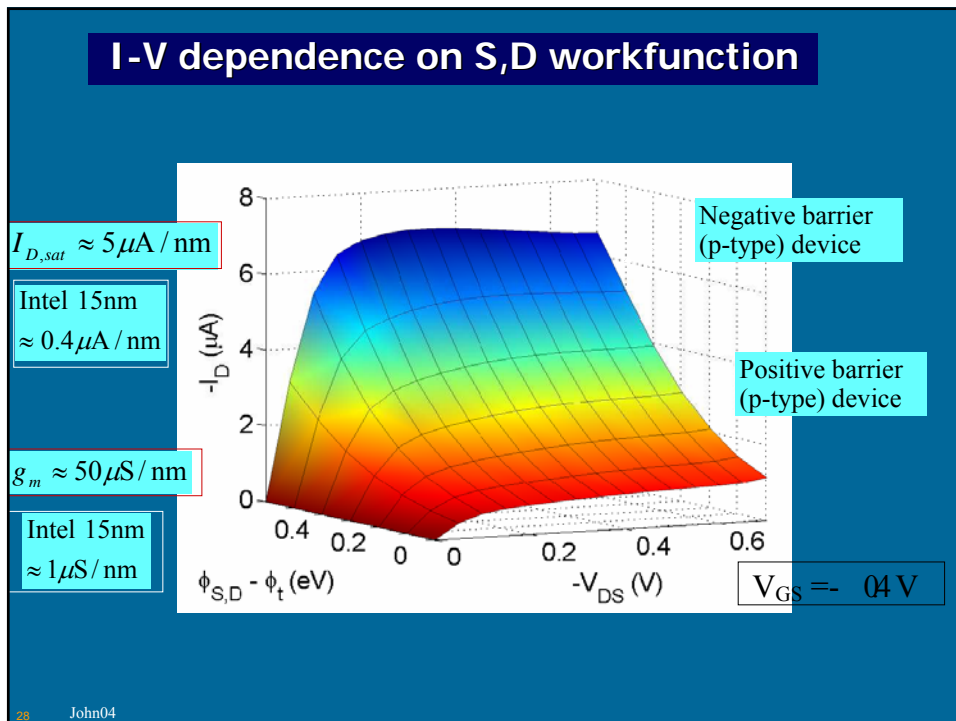
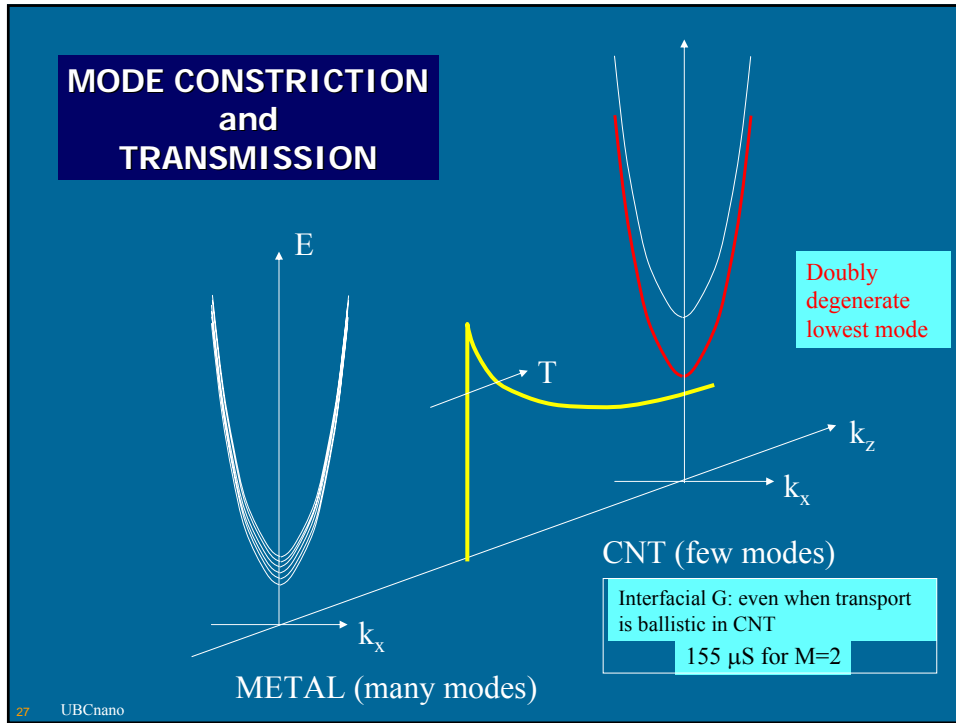
Boundary Conditions :

$$V(R_G, z) = V_{GS} - \frac{\Phi_G}{q}$$

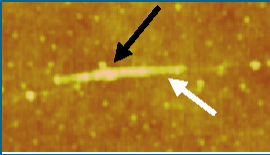

$$V(\rho, 0) = -\frac{\Phi_S}{q}$$

$$V(\rho, L) = V_{DS} - \frac{\Phi_D}{q}$$


26 UBCnano




Self-assembly of DNA-templated CNFETs


(i) RecA Polymerization



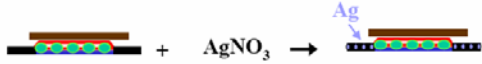
(ii) Homologous recombination



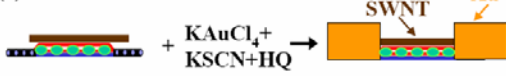
(iii) Localization of a SWNT using antibodies



(iv) RecA protects against silver reduction



(v) Gold metallization



29 Keren03

Carbon Nanotube Summary

- CNs have excellent thermal and mechanical properties.
- High DC currents and transconductances are feasible.
- CNFETs can be self-assembled via biological recognition.
- CNFETs are promising molecular transistors.
- But:
- Presently, cannot pre-determine conductivity type.
- Presently, coaxial FETs have not been made.

Coaxial Nanowires

a Au nanocluster catalyst

b Core
Axial growth from Au by CVD

c Shell
Radial growth on nanowire surface by changing T and C

d Shell

Cross section

●

●

●

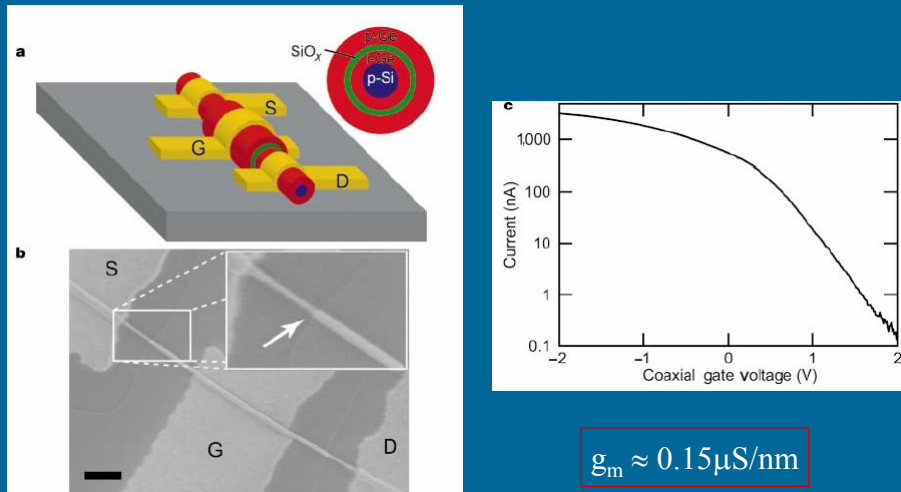
31 Lauhon03

Multi-shell Crystalline Heteronanowires

e.g., p-Si/Si

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Ge Nanowire coaxial FET



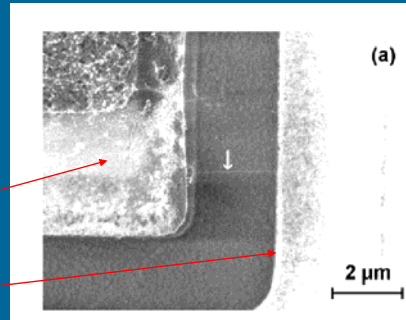
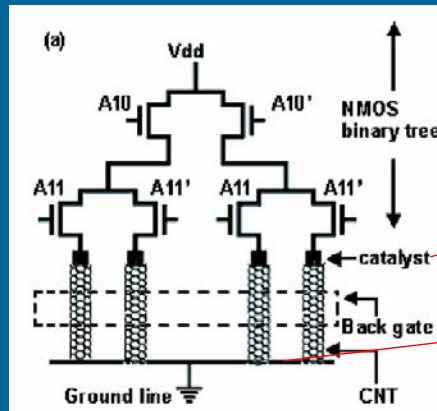
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Conclusions

- Molecular electronics, spintronics: **far future**.
- SETs: simulations of dense, low power circuitry, fabrication of single FETs: **future**.
- Carbon nanotubes: fabrication of devices and circuits, integration with Si: **near future**.
- Nanowires: fabrication of devices: **near future**.
- Complementing CMOS will be the key.

34

Carbon nanotube on Si IC



Proof of concept : decoder

Possibilities: massive memory, dense sensors.

35 Tseng04

Complementing CMOS



36

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