Nano-electronics

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CBSSS ‘04
Exploring and exploiting novel electronic properties of nanomaterials for computation
Microelectronics

Circuitry patterned on micron length scale

The basis for present-day information technology

Behavior of microelectronic devices well-described by classical physics, e.g. Ohm’s law
For nanometer-scale devices, as quantum mechanics (and other considerations unique to small structures) becomes important, we expect a rich variety of new transport phenomena to be observable.
Nanoelectronics:

Acessing the nanometer length scale

Lithographic techniques
“top down”

Chemical/biological Synthesis: “bottom up”

Length Scale (nm)

1000
100
10
1
0.1
Chemically/biologically Synthesized Nanostructures

- Nanocrystals
- DNA
- Cobalt ion + ligands
- Single-walled nanotubes
- Multi-walled nanotubes
Carbon Nanotubes

- Chemical/Biological
- Electronic
- Mechanical
Carbon

Diamond – sp³

Graphite – sp²
Nanotube rolled from graphite sheet
Nanotube Band Structure
Sample Fabrication

Locate nanotubes

Measure

Deposit Cr/Au leads
Operation of Single-walled Nanotube Devices

Nanotube device geometry

Band structure

G vs. $V_g$

Metallic SWNT

Semiconducting SWNT
Nanotubes: a One-Dimensional Electron Box

Low temperature behavior

$T=1.4\,\text{K}$
Energy spacing $\Delta E$ between discrete levels determined in principle by solving Schrödinger equation.

States are filled with electrons up to the Fermi level $E_F$ in accordance with the Pauli exclusion principle – two electrons per orbital assuming spin degeneracy.

Energy cost $\Delta E$ to add electron to empty orbital relative to Fermi level.
Nanotube electron box

Coulomb repulsion
Sets another energy scale

\[ U = \frac{e^2}{C} \]

Total energy to add electron: \( U + \Delta E \)

Gate voltage can tune the relative position of the energy gap to the Fermi level
Adding electrons one-by-one: single electron transistor
Nanotube Transport Spectroscopy

![Graph](image.png)
Nanotube Transport Spectroscopy

Can measure directly $U$ & $\Delta E$
Single electron transistors: potential applications

Classical & quantum Information storage & processing (see e.g., Likharev, Nakamura [cooper-pair box], Devoret & co-workers, etc.)

High bandwidth charge detection (e.g. Schoelkopf and co-workers)

Amplifiers

Nanoscale motion sensors (Schwab and co-workers)
Variable Conductance Nanotube Device

$V_g$ (Arb. units)

$V$ (Arb. units)

0

Conductance
Operation of a metallic Single-walled Nanotube Device

\[ G(e^2/h) \]

\[ V_g \ (V) \]

\[ T=4 \ K \]

\[ \text{SiO}_2 \]

\[ \text{Gate} \]

\[ \text{SWNT} \]
High Conductance Nanotube Transport Measurements

\[
\frac{dI}{dV} (\frac{e^2}{h})
\]

Graphs showing the variation of \(V_g\) (V) with \(V\) (mV) for different values of \(\frac{dI}{dV}\) (\(\frac{e^2}{h}\)).
High Conductance Nanotube Transport Measurements

\[ \frac{dI}{dV} = \frac{e^2}{h} \]

\[ V_c (\text{meV}) \]

\[ L = 500 \text{ nm} \]

\[ L = 250 \text{ nm} \]
Optical Resonator – Fabry-Perot Cavity

Overall transmission of light determined by the interference of partially reflected light waves

Transmission oscillates as a function of the round trip phase accumulation $\phi$
Electron resonator – Nanotube Cavity

- Potential energy of the electrons tunable by varying the gate voltage
- Kinetic energy tunable by varying the bias voltage
- This allows the tuning of the deBroglie wavelength of the electrons in the nanotube, resulting in the observed interference pattern
Comparison Between Data and Theory

Reproduces all the major features of the data

Gives energy period of oscillations with no free parameters

Nanotubes are ballistic, coherent electron waveguides!

Bockrath et al. Nature 2001
Nanomechanical machines and computers

Micromachine (from Sandia labs)

Nanotube bearing motor (Zettl group, Nature ’03)

Mechanical computing paradigm e.g., Babbage ‘analytical engine’

Nnaotube nanomechanical memory (Lieber group, Science ‘00)
Self-aligned nanotube linear bearings

Related work, P. Collins, J. Cumings et al.
Device current-voltage characteristics

From V. Deshpande

Devices show hysteresis!
Forces acting on inner tube:
Retraction  Electrostatic Adhesion

Electron Microscope images

100 nm
Potential applications of nanomechanical devices

High-frequency:
Logic gates
Memories
Oscillators
Mixers
Discriminators

See e.g. Roukes etc.
Molecule-based Electronics

- Ultimate limit of miniaturization
- Self-assembly → low fabrication cost
Attaining the ultimate limit of miniturization

Chemical synthesis of individual molecules allows construction of nanoscale objects with atomic precision

Liang et al. Nature (’02)
J. Park et al. Nature (’02)
Individual divanadium molecule transistors studied using electromigration-induced break-junction technique

Park et al., APL ('98)
Kondo Effect in a single Divanadium Molecule

- Coherent superposition of virtual spin flip events leads to a narrow Kondo resonance near the Fermi energy of the leads.
- The appearance of a Kondo resonance indicates spin degeneracy.

Schematic Diagram (S=1/2)

Kondo effect in GaAs quantum dots: Goldhaber-Gordon et al. Nature ('98), Cronenwett et al. Science ('98)
Tunable Kondo Effect

We can tune $\epsilon$ just by varying the gate voltage.

Additional energy scale $k_B T_K$
Tunable Kondo effect

Kondo temperature exponentially decaying in $\varepsilon$, in accordance with theoretical predictions (e.g. Haldane et al.)
Another Molecular Wire?

DNA similar in diameter to nanotubes

Its recognition capabilities may enable self-assembly of nanoelectronic circuits

But........
Does it Conduct?!

YES

Fink & Schonenberger Nature (1999)
Kasumov et al. Science (2001)
ETC.

NO

de Pablo et al., PRL (2000)
ETC.
Scanned Conductance Microscopy

Tip applies potential so as to induce local charge density

Presence of absence of charge determined by monitoring the cantilever resonant frequency
Minimum Detectible Wire Conductance

Charge motion takes a characteristic time equal to the $RC$ time constant of the wire. This time constant is $\sim 10^{-10}$ s for a 1 MΩ 10 µm long wire.

Tip scans over wire in characteristic time $\sim 10^{-3}$ s.

Can detect extremely low conductivity wires!
No signal from the $\lambda$-DNA in the scanned Conductance image

Bockrath et al. Nanoletters ('02)
Challenge: *addressing* individual nanodevices

Nanowire Crossbar array – potential for high integration density

Problem: Voltage applied to one wire acts on all the crossing wires in parallel
Making junctions behave differently

Crossed Si nanowires, one used as a gate electrode, the other as a MOSFET channel

With Lieber group

Treated with tetraethyl ammonium chloride

Untreated junction

With Lieber group
Can use this to make a decoder!

Junctions can be selectively treated to enable independently controllable function
Demonstration of Decoder with a 2x2 and 4x4 array
Project idea:

Design a system of logic gates based on single-electron transistors
Example: NOT gate

Design XOR, NAND gates

Also how about *single electron logic*?

What are some of the major challenges that must be overcome if SET logic is to be achieved? What are the issues associated with achieving room temperature operation?

From K. Likharev
Collaborators

Nanotube Transport
Wenjie Liang
Hongkun Park
Michael Tinkham
Jason Hafner
Charles Lieber

Nanotube Relay
Vikram Deshpande
Hsin-Ying Chiu

Molecule SET
Wenjie Liang
Matthew Shores
Jeffrey Long
Hongkun Park

Scanned Conductance Microscopy
Nina Markovic
Adam Shepard
Leonid Gurevich
Leo Kouwenhoven
Minshaw Wu
Lydia Sohn

Si nanowire wire decoder
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