Developing the Quantum Wire

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“Making Buckytubes Be All They Can Be”

Launched 2003 as a division of CNST at Rice
Coordinates SWNT Research with 10 Faculty in 6 Departments

Prof. Richard E. Smalley – Founding Director
Dr. Howard K. Schmidt - Executive Director
Dr. Robert H. Hauge - Technology Director
CNI – Principal Commercialization Partner
Key Collaborators

- James Tour
- Ed Billups
- Andrew Barron
- Boris Yakobson
- Mateo Pasquali
- Bruce Weisman
- Lon Wilson
- Paul Engel
- Enrique Barrera

- Jack Fischer, Karen Winey, U Penn
- Satish Kumar, Ga Tech
- Len Yowell, NASA JSC
- Mike Meador, NASA Glenn

- $$ NASA, DARPA, DOE, USRL/ML, NSF, AFOSR, ONR
MOLECULAR PERFECTION & EXTREME PROPERTIES

- The Strongest Fiber Possible
- Thermal Conductivity of Diamond
- The Unique Chemistry of Carbon
- The Scale and Perfection of DNA
- Selectable Electrical Properties
  - Metallics Better Than Copper
  - Semiconductors Better Than InSb or GaAs
- *The Ultimate Engineering Material*
SWNT Quantum Wire Project

Expected Features
• 1-10x Copper Conductivity
• 6x Less Mass
• Stronger Than Steel
• Zero Thermal Expansion
• 30x Power Density vs. Cu/Al

Key Grid Benefits
• Reduced Power Loss
• Low-to-No Sag
• Reduced Mass
• Higher Power Density

SWNT Technology Benefits
• Type & Class Specific
• Higher Purity
• Lower Cost
• Polymer Dispersible
Conductivity of Metallic SWNT

- Measurements on individual metallic SWNT on Si wafers with patterned metal contacts
- Single tubes can pass 20 µA for hours
- Equivalent to roughly a billion amps per square centimeter!
- Conductivity measured twice that of copper
- Ballistic conduction at low fields with mean free path of 1.4 microns
- Similar results reported by many
- Despite chemical contaminants and asymmetric environment

An interesting feature of this junction is the sensitive dependence of conductance on the contact length, \( l \). Figure 2 shows the conductance values for armchair-armchair and

![Graphs showing conductance vs. energy and current vs. voltage](image)

FIG. 1. (a) A two-terminal nanotube junction can be formed by bringing two tubes’ ends together in parallel and pointing opposite directions (\( l \) is the contact length). (b) The transmission coefficient \( T \) of the two armchair tube [(10,10)-(10,10)] junction as a function of energy \( E \) for \( l=64 \text{ Å} \). Interference of electron waves yields resonances in transport. (c) Current-voltage characteristics of the (10,10)-(10,10) junction for \( l=46 \text{ Å} \).
Resonant Tunneling Evidence

- Indirect indication of conductivity by measuring lifetimes of photo-excited electrons
- Cooling mechanism is interaction with phonons – just like electrical resistivity
- Anomalously long life-times yield mean free path of 15 microns (10x single tubes)
- Based on bundles in ‘buckypapers’ – good local symmetry and clean, but still based on mixture of metals and semi-conductors
- Results imply 10 – 25x better conductivity than copper

Job One: Get The Right Tubes

- Need Single Type of Metallic SWNT
- Current Growth Inadequate
  - Mixtures of ~ 50 Types
  - Mixtures of Metals, Semi-Metals & Semiconductors
  - Impure & Inefficient
- N,M Control Critical
  - Quantum Wire
  - Electronics & Sensors
  - Biomedical Therapeutics
  - Energy Conversion Storage
- Seeded Growth Required
  - Separates Nucleation From Growth
  - Eliminate By-Products & Purification
  - Vastly Improved Efficiency
  - Sort Once at Small Scale
Rolling Graphite: n,m Vectors

- Of the 864 distinct types between 0.7 and 2.8 nm diameter,
- ~ 1/3rd are semi-metals
- ~ 2/3rd direct band-gap semiconductors
- Only 16 are armchair metals!
SWNT Amplifier Process Flow

- Cut
- Grow
- Disperse
- Attach
- Dock
Seeded Growth on HiPco Fibers

**nanozone news**

3 March 2005

**New life for nanotubes**

To become a technological material, nanotubes may have to be grown to any length and with controlled molecular structures. A new technique shows the way.

PHILIP BALL

The dream of super-strong fibres made from carbon nanotubes is predicated on the notion of being able to grow these nanoscale carbon cylinders to any length. The idea of using such nanotubes as conductive wiring and semiconducting devices in nanoscopic electrical circuits, meanwhile, hinges on the ability to make nanotubes to order in either a metallic or a semiconducting form. Neither of these
Improved Growth on Fibers

A: Typ. FIB-cut Fiber
B: Typ. Cleaned & Catalysed Fiber
C: After CVD Growth

(FIB cut swnt fiber
Collaboration with WPAFB)
Iron/Molybdenum Nanocluster - FeMoC

\[ [\text{H}_x\text{PMo}_{12}\text{O}_{40} \subset \text{H}_4\text{Mo}^{\text{VI}}_{72}\text{Fe}^{\text{III}}_{30}(\text{CH}_3\text{COO})_{15}\text{O}_{254}(\text{H}_2\text{O})_{98}] \cdot \text{ca. 60 H}_2\text{O} \]

- 12 mg/mL solubility in ethanol
- distinct visible-NIR, FT-IR, and \(^{31}\text{P}\) NMR spectra
- easy to synthesize
- perfect size for attaching to nanotubes

2.1 nm

In-Solution Attachment

\[ \text{FeMoC} \text{ in CHCl}_3 \quad + \quad \text{FeMoC} \text{ in ethanol} \]

55°C
4 hours
In-Solution Attachment

<table>
<thead>
<tr>
<th>Sample</th>
<th>% SWNTs with FeMoC Attached</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temp</td>
<td>13</td>
</tr>
<tr>
<td>55°C, 4 hours</td>
<td>50</td>
</tr>
</tbody>
</table>

![Graph showing SWNTs with FeMoC Attached](image)
Reductive Docking

55°C In-Solution Attachment

Baked
500°C - 1 hour - 1 atm H₂
Seeded Growth on Surfaces

- From functionalized SWNT with end-linked Iron Oxide nano-particles

Before Growth

- 46 nm long
- 0.6 nm
- 1.8 nm

After Growth

- 120 nm long
- 0.6 nm
- 0.6 nm
- 1.0 nm
Ultra-Long SWNT Re-Grown From HiPco Felt
Fast (20 microns/sec) & “Immortal”

Collaboration with Jie Liu, Duke Univ.
Seeded Growth w/o Supports

- Partially Seeded Growth?
- Macroscopic, Immortal Tip-Growth
- Potentially Scaleable
- Potentially Continuous
- Current Density $\sim 10^4 – 10^5$ A cm$^{-2}$
- Stay Tuned!

SWNTcat Clusters Before Growth

After Growth Detail

MM-Scale SWNT Yarns
SWNTamp Production Concept

Hydro-carbon feedstocks → Seed Preparation. (1 lb/day)
Cut SWNT, Prep. Catalyst, Functionalize, Attach, Dock

— SWNT + FeMoC Catalyst

Seed Preparation. (1 lb/day)
Cut SWNT, Prep. Catalyst, Functionalize, Attach, Dock

→ “Inner Loop” Processing

Seeded Growth
500 < T < 700 C

Mono-Type SWNT
(1000 lb/day)

Bulk Output
Production Scale-Up Path

- Rice made 1 mg / day in 1997
- Lab-scale reactor at 1 gm / hour (2002)
- CNI Pilot plant at 20 lb / day (2004)
- CNI testing 100 lb / day reactor
Job Two: Forming SWNT Wires

- Need macro-crystalline SWNT fiber/wire
- Starting material is tangled at several scales
- Starting material has variety of diameters and types
- Enormous Van der Waals forces make it hard to separate SWNT bundles
Dispersion in Super-Acids

- VDW interactions defeat SWNT dispersion in normal solvents
- Superacids protonate & intercalate SWNT bundles


W.-F Hwang and H. Fan
Prototype Wire - SWNT Fibers

Current Oleum Spinning Results

- Producing Neat SWNT Fibers
- Dry-Spun from Oleum
- 6 to 14 Wt. % SWNT Dope
- Extruded as 50 µm Dia. Fibers
- $10^9$ Tubes in Cross Section
- 100 Meters Long
- *Working On Alignment & Density*
Condensation Progress

9/2004

3/2005

9/2005
Expectations: AQW On The Grid

Key Benefits

- Eliminate Thermal Failures
- Reduce Wasted Power
- Reduce Urban R.O.W. Costs
- Enable Remote Generation
Current Grid Overload

The U. S. electric grid has become more unstable since 1998, with more failures that affect large populations of customers than the previous 50 years would predict. Current Impact ~ 100B / Annum.

Sources: DOE, Roger Anderson & Amin, IEEE Computer Applications in Power, 2001
Currently, power is generated close to population centers.
Renewable Resource Maps

Renewable sources generally remote from major population centers

Source: NREL
Remote Solar Base-Load Power

Also...

- Clean Coal
- Nukes
- Hydro
- Wind
- Space
- Lunar
- ??
AQW: Grid Applications

- **Eliminate Thermal-Sag Failure**: Now a $100B+ a year problem.

- **Short-Distance AC**: AQW could increase throughput up to ten-fold without increasing losses while using only existing towers and rights-of-way. Avoid new construction in congested urban areas – estimated over $100M per mile.

- **Medium-Distance AC**: AQW could decrease resistive losses and voltage drop ten-fold if amperage were not increased. This would improve grid dynamics significantly in the range between 100 and 300 miles, where voltage stability limits deliverable power.

- **Long-Distance HVDC**: AQW could permit amperage throughput ten fold or reduce losses ten-fold. New conventional lines cost $1M to $2M per mile, plus about $250M per AC/DC converter station.

- **Enables Remote Power**: Could enable utilization of large-scale renewables and remote nuclear.
Additional Research Areas

• Hydrogen Storage Materials
• Composites
  – SWNT Loaded Composites (ESD, strength, weight)
  – SWNT Molecular Composites (replace metals entirely)
• Energy Systems Components
  – Fuel Cells
  – SuperCapacitors
  – Batteries
  – Photovoltaic & Photocatalytic Systems
• NanoElectronic Devices
  – Chemical Sensors
  – THz Transistors
  – Digital Devices
The biggest single challenge for the next few decades:

ENERGY
for $10^{10}$ people

- At MINIMUM we need 10 Terawatts (150 M BOE/day) from some new clean energy source by 2050
- For worldwide peace and prosperity we need it to be cheap.
- We simply can not do this with current technology.
- We need Boys and Girls to enter Physical Science and Engineering as they did after Sputnik.
- Inspire in them a sense of MISSION (BE A SCIENTIST - SAVE THE WORLD)
- We need a bold new APOLLO PROGRAM to find the NEW ENERGY TECHNOLOGY
A Modest Proposal

- For Honoring Richard Smalley,
- Making The Vision Concrete, and
- Generating Practical Benefits…

- Some “Smalley Challenges” in Energy
  - Similar to Ansari X-Prize
  - Roughly Twenty-Year Goals
  - Drive Accomplishment in Ten Years

- **Generation**
  - 10x better TCO solar electric power
  - Make fossil fuels obsolete
  - Demonstrate at MW-Hr level

- **Transmission**
  - 10x better TCO in transmission
  - Enables remote renewable power
  - Demonstrate at 10 MW-Mile level

- **Storage**
  - 10x better TCO & energy density w.r.t.
    chemical batteries
  - Enables the Store-Gen Grid
  - Demonstrate at 1 MW-Hour level

Aim High!