Carbon Nanotube & Graphene Electronics for RF and Bio Applications

Peter Burke
EECS Department, University of California, Irvine, Irvine, CA, USA
Allotropes of Carbon

Single Walled Carbon Nanotube

$L = 0.4 \text{ cm}$

$d = 1.5 \text{ nm}$

$d/L = \text{cm/nm} = 10^7$

Would Schelkunoff be excited?

SWNT

Conductivity larger than copper!

Ballistic vs. diffusive transport

Diffusive

\[ R = \frac{L}{W^2 \rho} \]

Ballistic

\[ R \geq \frac{h}{2e^2} = 12k\Omega \]

Multi mode

\[ R \geq \frac{1}{N} \frac{h}{2e^2} = \frac{1}{N} 12k\Omega \]

\[ G = n \frac{2e^2}{h} \]

\[ G = \frac{2e^2}{h} \sum T_n \]
Resistance vs. length

\[ R = R_{\text{contact}} + L \cdot 6 \text{k}\Omega/\mu\text{m} \]


Nanotube RF Circuit Model

Geometry

- $L_{\text{Kinetic}} = 16 \text{ nH/\mu m}$
- $C_{\text{Quantum}} = 100 \text{ aF/\mu m}$
- $C_{\text{Electrostatic}} = 50 \text{ aF/\mu m}$

- Characteristic impedance = $\sqrt{L/C} = h/2e^2 = 12.5 \text{ k}\Omega$
- Wave velocity = $\sqrt{1/LC} = v_{\text{Fermi}} = 8 \times 10^5 \text{ m/s} \sim c/100$

MURI Center:
Near and Far-Field Interfaces to DNA-Guided Nanostructures from RF to Light wave: Exploiting the Spectrum

Lead P.I.: Peter Burke
Program Manager: Dwight Woolard
Program start Date: 11/1/2010

Ned Seeman
Michael Norton

MURI Center:
Nanowires: Si, III-V, II-VI
Building blocks
DNA Organo Tioi Aptamers
Carbon Semicond. Metals
DNA Carbon Semicond. Metals

Nanoscale Electromagnetics
A) Fundamental understanding of signal propagation from RF (Irvine) to light wave (Yale, Penn) along 1d systems
B) Demonstration of signal propagation measurement techniques In water (Irvine)
C) Invention & demonstration of innovative, on-chip source/detector schemes of molecular probes (Yale, Penn, NYU, Irvine)
- Nano gap
- Nano fluids
- Nano-antennas
- Meta-materials
- NA-tiles

Thrust 2: Probes
A) Extend 2d DNA tiles to larger areas

Rectangular Origami structure with biotinylated windows


RF circuit model: Q = \alpha \equiv \frac{RF}{\mu \epsilon_0} = \frac{377}{h}


PL image of a ZnSeNW and the corresponding spectra from one of the ends. E-k dispersions for different ZnSe NWs of different radii showing very strong size dependence of the dispersions.

A) Simulation of Molecular Conductance
B) Functionalization of nanostructures
C) Demonstration of innovative, on-chip source/detector schemes of molecular probes
- Nano gap
- Nano fluids
- Nano-antennas
- Meta-materials
- NA-tiles

Thrust 3: Signals and Signatures
A) Simulation of Molecular Conductance
DC (Texas A&M)

Front and sideview of DNA-DNT circular wrapping after 5.4 min at the middle stage

LAMBDR molecular dynamics of ssDNA junction on a) graphene and b) CNT electrode. Volt-der Gauss energy along application of electric field at 20KeV for c) CNT substrate.

AC (NYU Poly)

Calculated IR spectra for DNA Codon GGT

B) Arbitrary Plasmon Dispersion Design
Principle: (Optics, UV) Extension to THz (Michigan)

AC (NYU Poly)

Calculated IR spectra for DNA Codon GGT
Nano-Antenna Concept

Peter J. Burke, Shengdong Li, Zhen Yu
"Quantitative theory of nanowire and nanotube antenna performance"
Nanotube Radios

**Nanotube Radio: UC Irvine**

![Image of a man with a device]

<table>
<thead>
<tr>
<th>TX</th>
<th>RX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sig. Gen. w/ mod</td>
<td>Diff. Amp</td>
</tr>
<tr>
<td>[Diagram of TX and RX]</td>
<td></td>
</tr>
</tbody>
</table>


**University of Illinois UC**

A

Resonant Antenna

RF Amp.

RF Amp. / Mixer

Audio Amp.

6V

cut

gnd


**UC Berkeley**

![Diagram of a device and electron flow]

E_{rad} \sin(\omega t)

Press Coverage


Barnaby Feder. *Radio Nano Calling.. Testing 1,2,3,4* (Oct. 17, 2007)

‘*World’s smallest radio’ unveiled* (Oct. 18, 2007)


Jessica Thomas. *Carbon nanotubes: Turn the radio up (if you can find it).* Nature Nanotechnology 2, 744 (2007)


J. Scott Orr. *Dust Gets Smart* (Dec. 03, 2007)
Metabolism & Bioenergetics

- Diabetes
- Alzheimer’s
- Aging
- Cancer
- Heart disease

Microchip assays
Mitochondria are known as the powerhouses of the cell.

- Energy conversion
- Heat production
- Storage of calcium ions
- Apoptosis: programmed cell death

Crucial biological marker for cellular functions.

Source: http://remf.dartmouth.edu/imagesindex.html
Unique State of Mitochondria in hESC

- Small population with low mtDNA copy #
- Peri-nuclear localization
- Small round morphology
- Poorly developed cristae
- Low levels of ATP and ROS production
- Anaerobic respiration
  - Upregulated HKII, PFK
  - Upregulated Pentose Phosphate Pathways enzymes
- Higher Lactate production
Current Technology and Challenges

• **Current technology**
  - Chamber volume: ~ 1 to 5 mL
  - Sample concentration: 0.5 ~ 3 mg/mL
  - Several hundred µg of mito protein needed

• **Motivations**
  - No miniaturized and chip based-sensor
  - Waste a great deal of precious sample
  - Challenging to assay mitochondria from small samples
  - Reduce cost

*Oxyview, Hansatech Inc.*

*Oxygraph 2k, Oroboros Inst.*
Our Goal: Developing chip based technology for interrogating mitochondria

First Gen. mitochips

Chamber Volume: 80μL, Sample concentration: 0.3 μg/mL, mito protein needed: 30 ng

Second Gen. mitochips

- High yield
- Low Device variation
- Life-time & stability: ≥3 months
- Response time: 60% faster

More Devices under development.