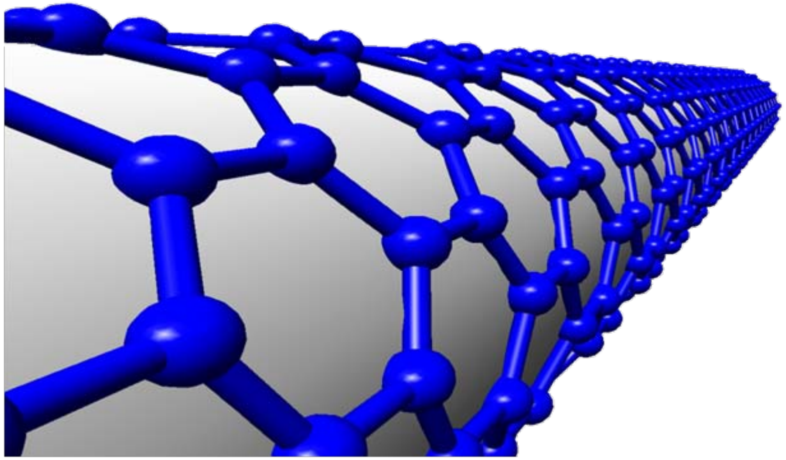
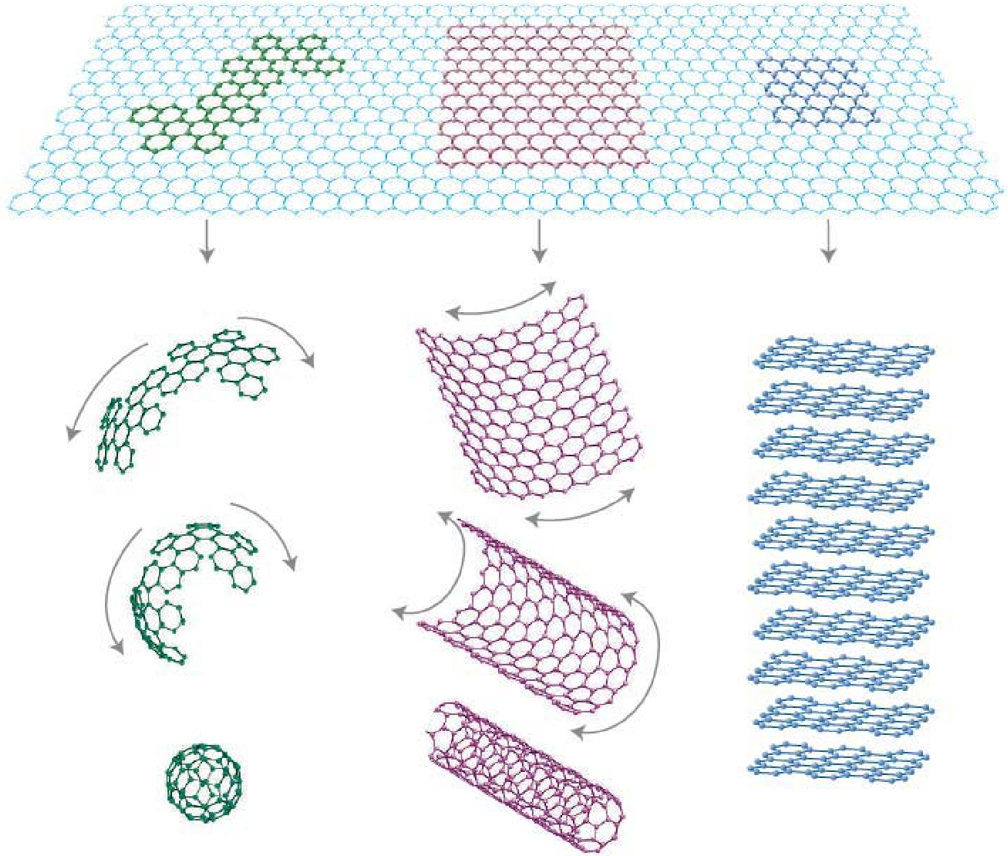
Carbon Nanotube & Graphene Electronics for RF and Bio Applications



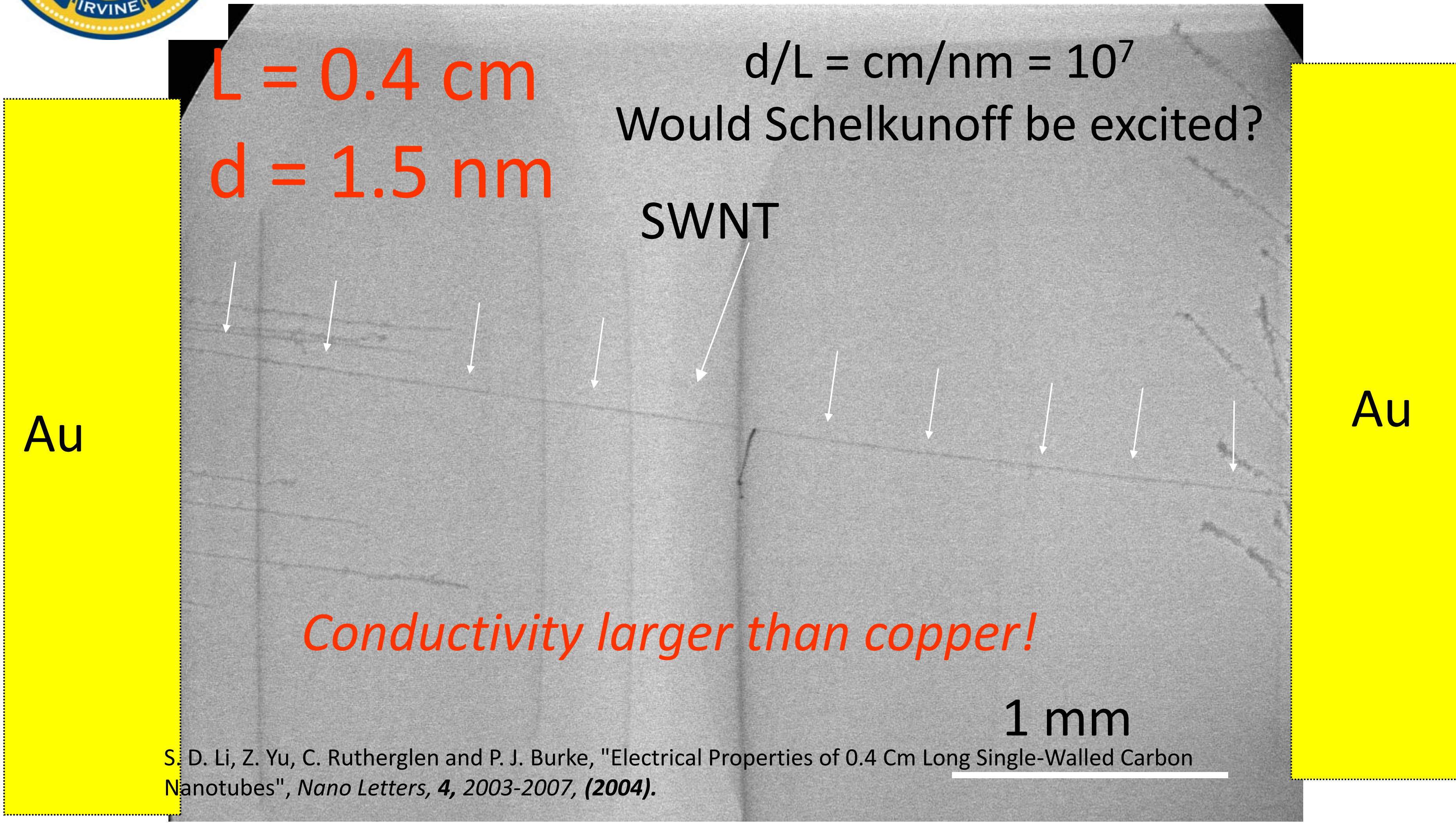
Peter Burke
EECS Department, University of California, Irvine, Irvine, CA, USA

Allotropes of Carbon



A. Geim and K. Novoselov, "The Rise of Graphene", *Nature Materials*, **6**, 183-191, (**2007**).

Single Walled Carbon Nanotube

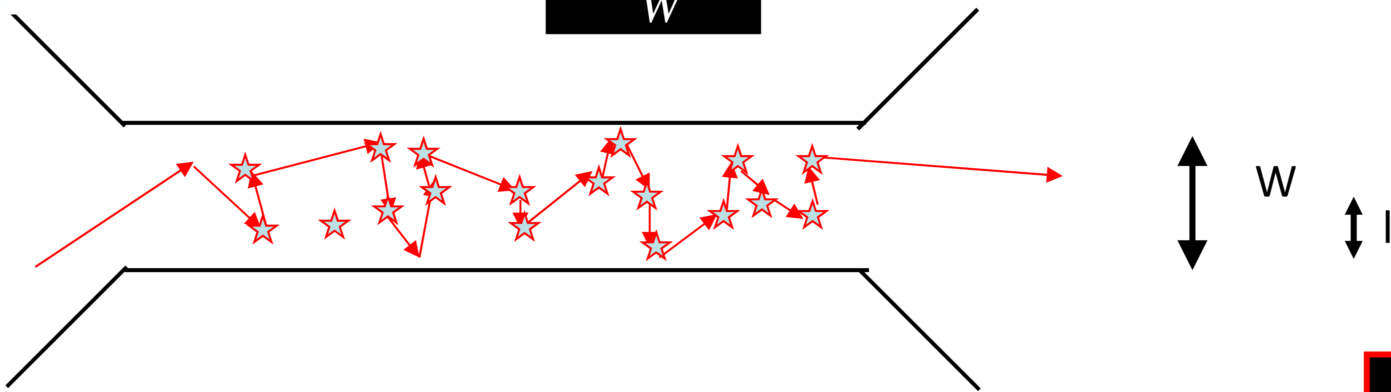


S. D. Li, Z. Yu, C. Rutherglen and P. J. Burke, "Electrical Properties of 0.4 Cm Long Single-Walled Carbon Nanotubes", *Nano Letters*, ***4,*** *2003-2007,* ***(2004).***

Ballistic vs. diffusive transport

Diffusive

$$R = \frac{L}{W^2}\rho$$

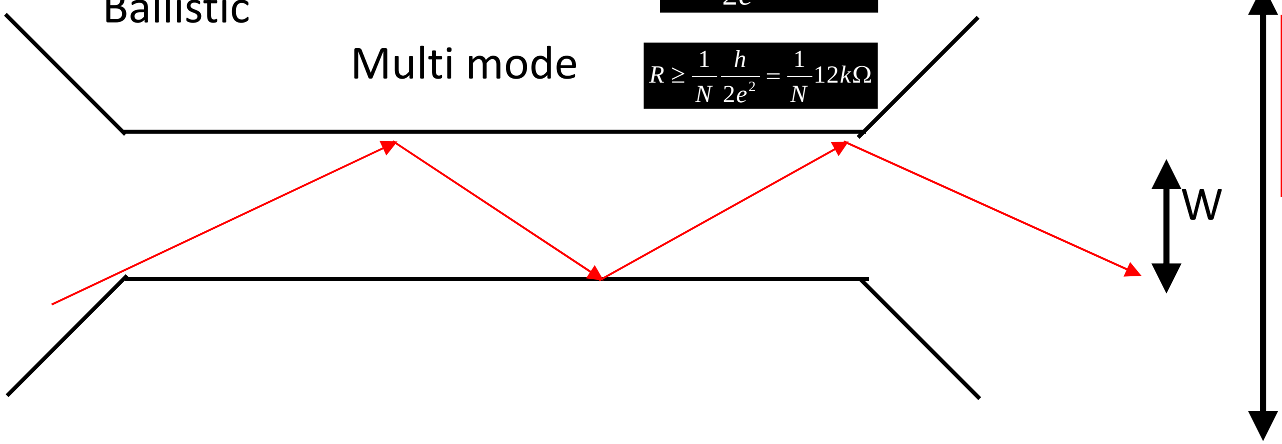


L

Ballistic

Single mode $R \geq \frac{h}{2e^2} = 12k\Omega$

Multi mode $R \geq \frac{1}{N}\frac{h}{2e^2} = \frac{1}{N}12k\Omega$



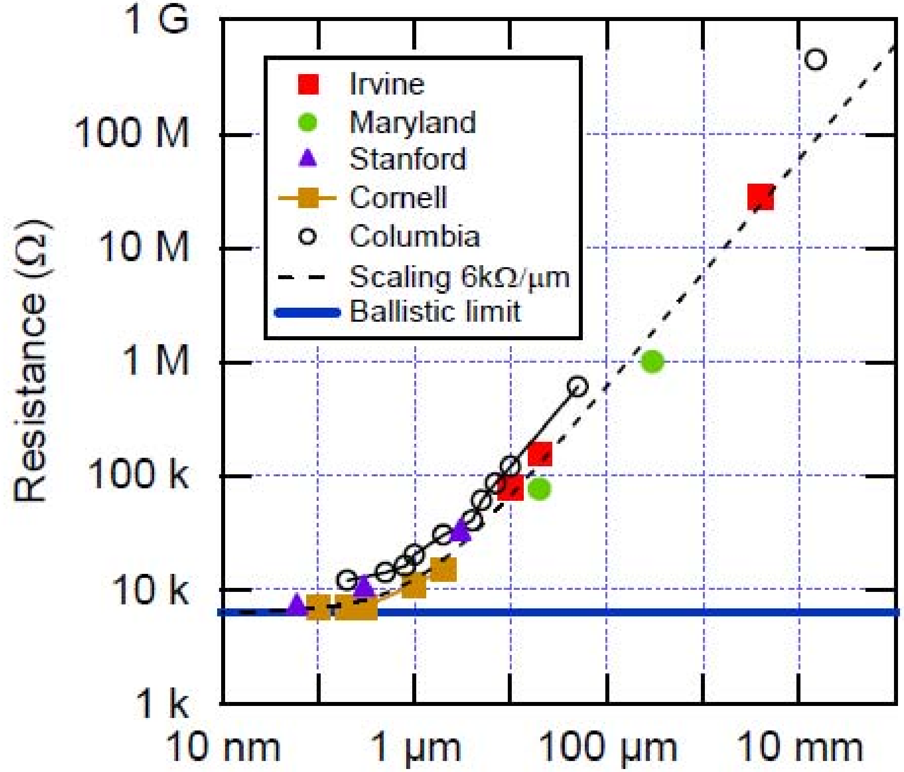
$$G = n\frac{2e^2}{h}$$

$$G = \frac{2e^2}{h}\sum T_n$$

l

Resistance vs. length

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

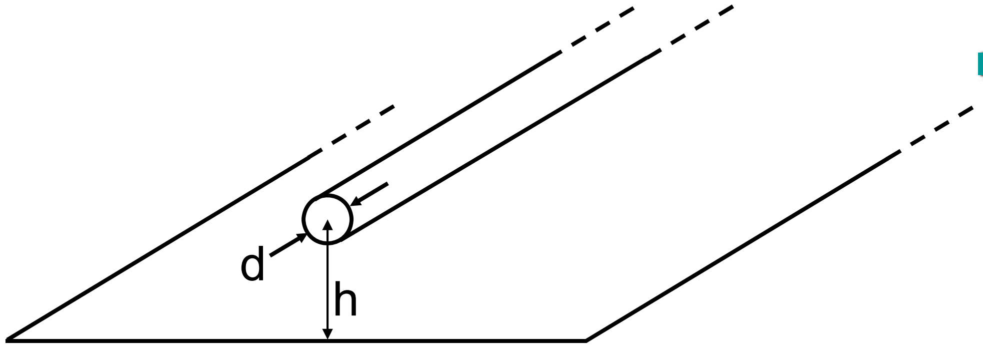


S. D. Li, Z. Yu, C. Rutherglen and P. J. Burke, "Electrical Properties of 0.4 Cm Long Single-Walled Carbon Nanotubes", *Nano Letters, **4,** 2003-2007, **(2004).***

C. Rutherglen, D. Jain and P. Burke, "Nanotube Electronics for RF Applications", *Nature Nanotechnology,* in press*, (**2009**).*

Nanotube RF Circuit Model

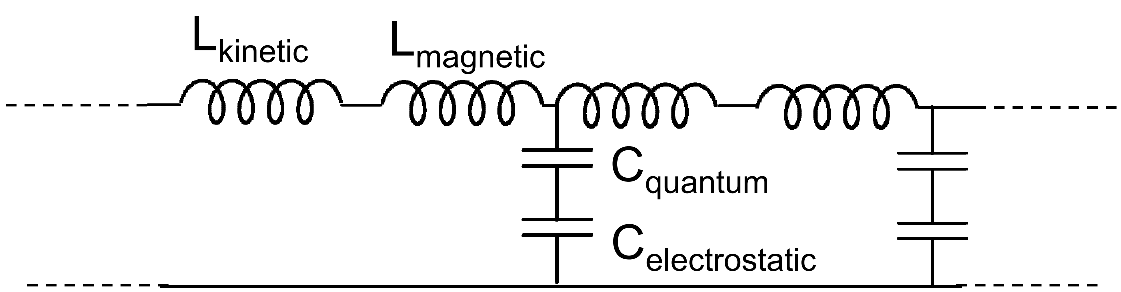
Geometry



- $L_{Kinetic}$ = 16 nH/μm
- $C_{Quantum}$ = 100 aF/μm
- $C_{Electrostatic}$ = 50 aF/μm

- Characteristic impedance = Sqrt(L/C) = $h/2e^2$ = 12.5 kΩ
- Wave velocity =Sqrt(1/LC) = v_{Fermi} = 8 10^5 m/s ~ c/100

RF circuit model: A transmission line

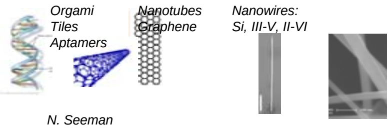


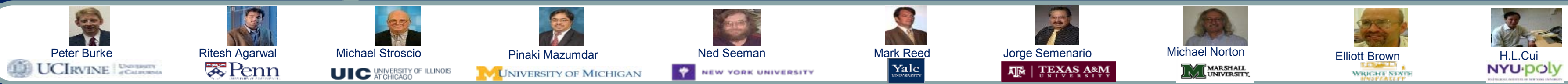
"An RF Circuit Model for Carbon Nanotubes", P.J. Burke *IEEE Transactions on Nanotechnology* 2(1), 55-58 (2003)

C. Rutherglen and P. Burke, "Nanoelectromagnetics: Circuit and Electromagnetic Properties of Carbon Nanotubes", *Small*, ***5, 884-906, (2009).***

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

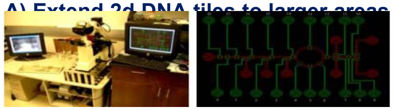
Lead P.I. : Peter Burke
Program Manager: Dwight Woolard
Program start Date: 11/1/2010



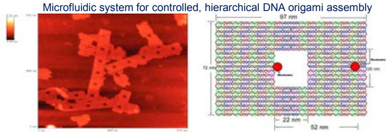


Thrust 1: Assembly

A) Extend 2d DNA tiles to larger areas

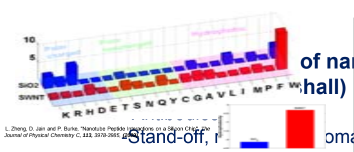


Microfluidic system for controlled, hierarchical DNA origami assembly



Rectangular Origami structure with biotinylated windows

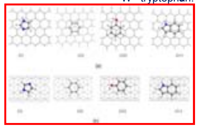
W. Shen, H. Zhong, D. Neff and M. L. Norton, "NTA Directed Protein Nanopatterning on DNA Origami Nanoconstructs", *Journal of the American Chemical Society*, **131**, 6660-6661, (2009).



Relative bonding efficiency of amino acids to nanotubes and SiO_2.

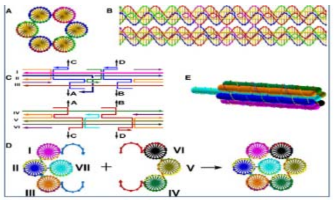
L. Zheng, D. Jain and P. Burke, "Nanotube Peptide Interactions on a Silicon Chip", *The Journal of Physical Chemistry C*, **113**, 3978-3985, (2009).

Nanotube-peptide docking



Equilibrium geometry of the rings of the aromatic amino acids on top of a) graphene, and b) 5,5 CNT : i Histidine, ii phenylalanine, iii tyrosine, and iv tryptophan.

C. Rajesh, C. Majumder, H. Mizuseki and Y. Kawazoe, "A Theoretical Study on the Interaction of Aromatic Amino Acids with Graphene and Single Walled Carbon Nanotube", *Journal of Chemical Physics*, **130**, 124911, (2009).



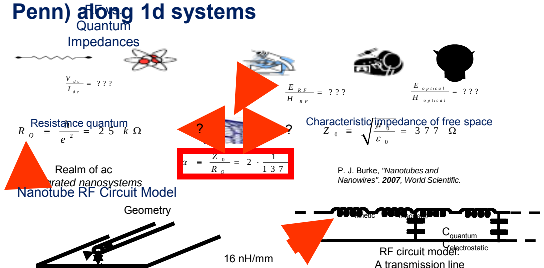
Schematic of the Motifs (A) The top view of DNA 6HB. (B) The side view of DNA 6HB. These drawings were rendered by GIDEON (Birac et al., 2006). (C) The BTX molecules. (D) Cross sectional views of the sheathing process. The guest duplex is connected to the BTX (I, II, and IV molecule). (E) oblique image to show the ...

C) Programmat... (NYU, Irvine, Marshall)

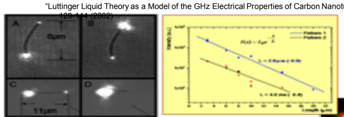
W. Y. Liu and N. C. Seeman, "Prototyping Nanorod Control: A DNA Double Helix Sheathed within a DNA Six-Helix Bundle", *Chemistry & Biology*, **16**, 862-867 (2009).

Thrust 2: Probes

A) Fundamental understanding of signal propagation from RF (Irvine) to light wave (Yale, Penn) along 1d systems

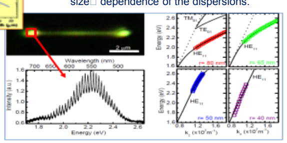


"An RF Circuit Model for Carbon Nanotubes", P.J. Burke *IEEE Transactions on Nanotechnology* 2(1), 55-58 (2003)
"Luttinger Liquid Theory as a Model of the GHz Electrical Properties of Carbon Nanotubes", P.J. Burke, *IEEE Transactions on Nanotechnology* 1(3), 129-144 (2002).



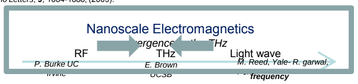
M. Reed, "Observation of Plasmon Propagation, Redirection, and Fan-out in Silver Nanowires", *Nano Letters*, **6**, 1822-1826, (2006).

Plasmon propagation along a Ag nanowire. (Right) Measurement of the propagation lengths of SPPs in microfabricated Ag waveguides, at a launching wavelength of 830 nm.



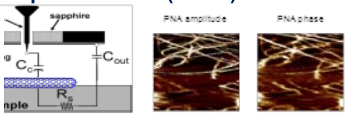
PL image of a ZnSeNW and the corresponding spectra from one of the ends. E-k dispersions for different ZnSe NWs of different radii showing very strong size dependence of the dispersions.

R. Agarwal, "Size-Dependent Waveguide Dispersion in Nanowire Optical Cavities: Slowed Light and Dispersionless Guiding", *Nano Letters*, **9**, 1684-1688, (2009).

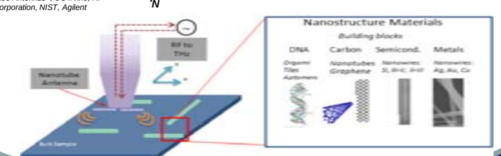


B) Demonstration of signal propagation measurement techniques In water (Irvine)

7.75 GHz non-contact imaging of carbon nanotubes



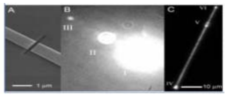
STTR #W911NF-07-C-0098
"Nanotube Antennas", UC Irvine, RF Nano Corporation, NIST, Agilent



MURI Proposal

C) Invention & demonstration of innovative, on-chip source/detector schemes of molecular probes (Yale, Penn, NYU, Irvine)

-Nano gap
-Nano fluidics

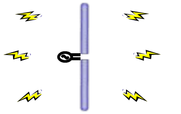


A) SEM image of a nanogap in a CdS. B) PL image of this wire when excited with a laser spot at position I. C) PL image under homogeneous illumination of the wire. This wire was cut at position V.

Agrawal, MURI Proposal

D) Far-field interrogation methods demonstrated and assessed

-Nano-antennas
-Meta-materials
-DNA-tiles

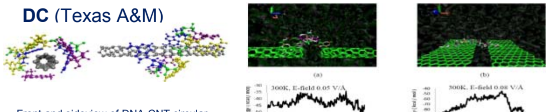


C. Rutherglen and P. Burke, "Nanoelectromagnetics: Circuit and Electromagnetic Properties of Carbon Nanotubes", *Small*, **5**, 884-906, (2009).

Thrust 3: Signals and Signatures

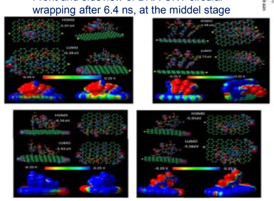
A) Simulation of Molecular Conductance

DC (Texas A&M)



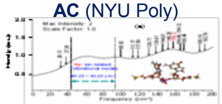
Front and sideview of DNA-CNT circular wrapping after 6.4 ns, at the middel stage

LAMMPS molecular dynamics of ssDNA junction on a) graphene and b) CNT electrodes. Van der Waals energy during application of electric field at 300K for c) DNA-CNT and d) DNA-graphene.



HOMO, LUMO and MEPs for single strand DNA placed over graphene sheet in four ways

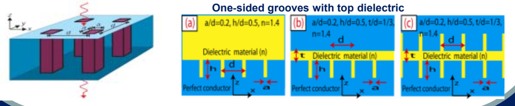
AC (NYU Poly)



Calculated IR spectra for DNA Codon GGT

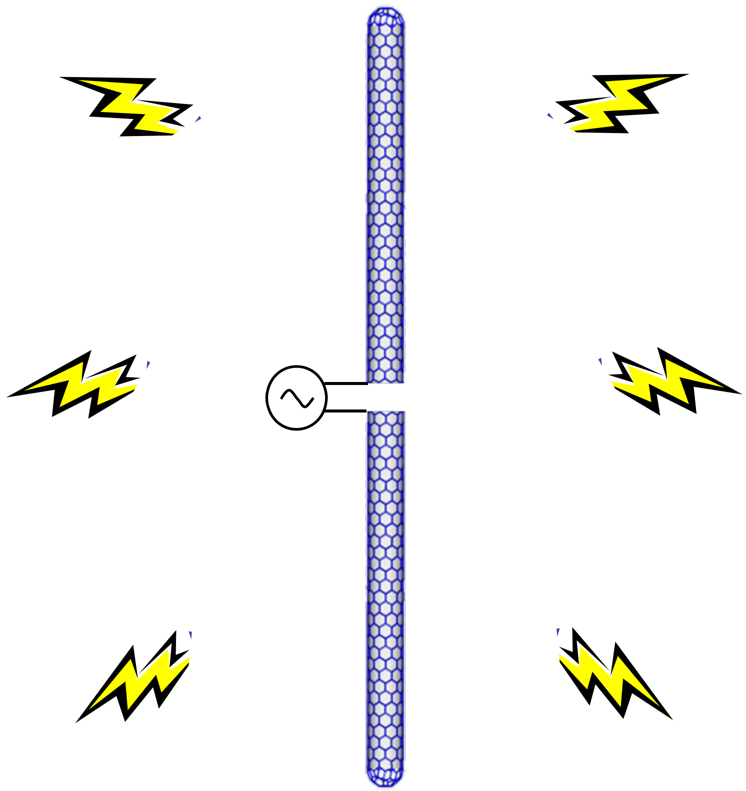
B) Arbitrary Plasmon Dispersion Design

Principle: (Optics, UV) Extension to THz:(Michigan)



Pendry, J. B., L. Martin-Moreno, et al. (2004). "Mimicking surface

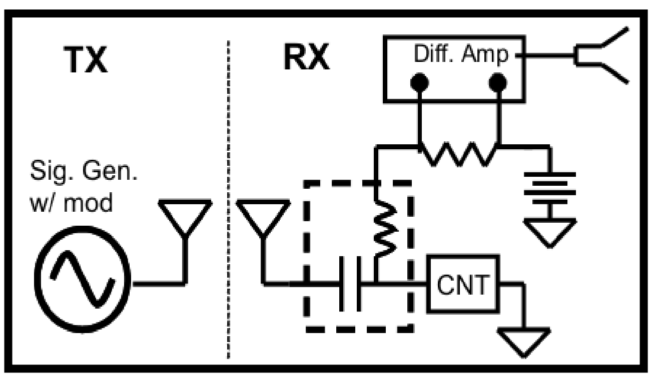
Nano-Antenna Concept



Peter J. Burke, Shengdong Li, Zhen Yu
"Quantitative theory of nanowire and nanotube antenna performance"
IEEE Transactions on Nanotechnology **5**(4), 314-334 (**2006**).

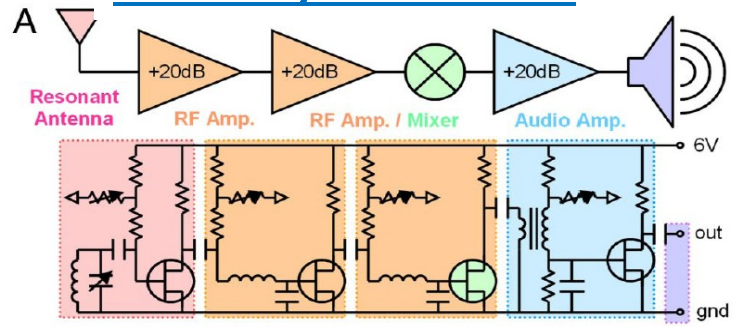
Nanotube Radios

Nanotube Radio: UC Irvine



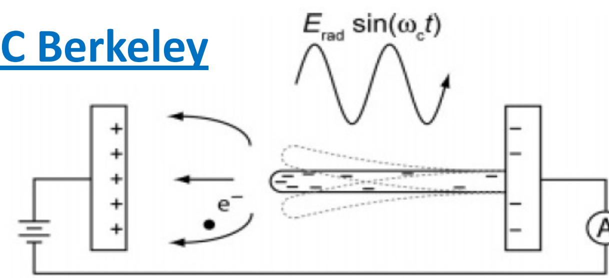
Rutherglen, Burke, et.al.. Nanoletters.7, 3005. (2007)

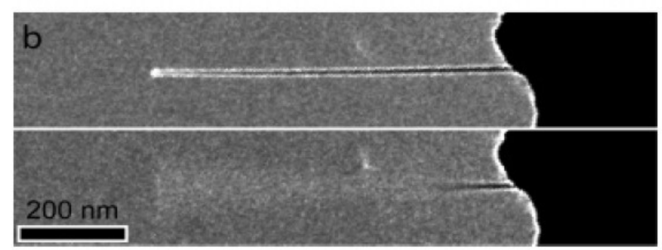
University of Illinois UC



J. Rogers, et.al.. PNAS. 105, 1405. (2008)

UC Berkeley





Zettle, et. al.. Nanoletters. 7, 3508 (2007)

Press Coverage

GIZMODO — Wilson Rothman. ***World's Smallest Radio Is Just Atoms Wide, Still Needs AAA Battery*** (Oct. 18, 2007)

The New York Times — Barnaby Feder. ***Radio Nano Calling.. Testing 1,2,3,4*** (Oct. 17, 2007)

BBC NEWS — ***'World's smallest radio' unveiled*** (Oct. 18, 2007)

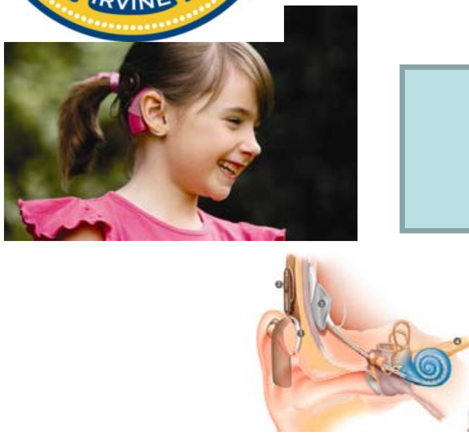
WIRED — Alexis Madrigal***.*** ***Nano Electronics Researcher Decodes Radio Signals Using Atom-Sized Components***(Oct. 17, 2007)

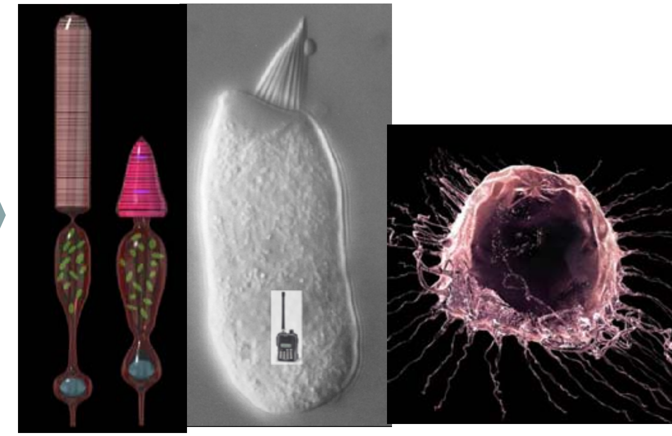
nature nanotechnology — Jessica Thomas***.*** ***Carbon nanotubes: Turn the radio up (if you can find it).*** Nature Nanotechnology 2, 744 (2007)

Science AAAS — ***Micromini Radio.*** *Science* 9 November 2007: Vol. 318. no. 5852, p. 893

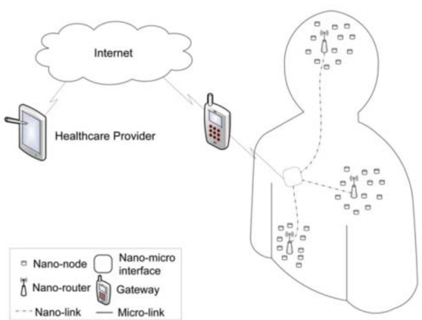
The Star-Ledger — J. Scott Orr. ***Dust Gets Smart*** (Dec. 03, 2007)

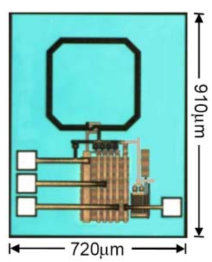
Nano-Radio Communications Technology

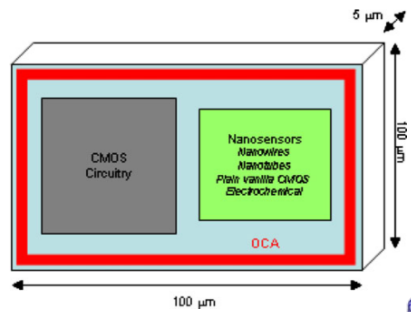


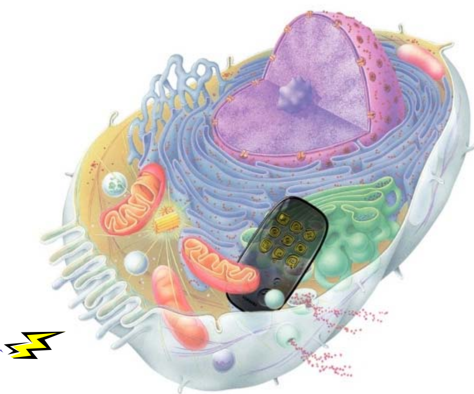


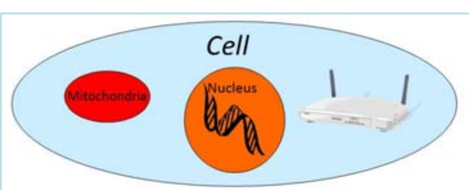
(30-50)x(1-5)um

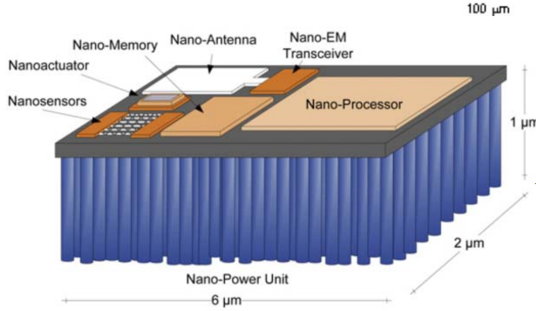


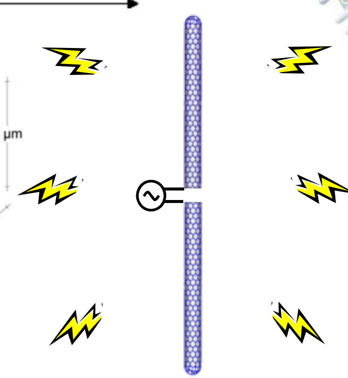


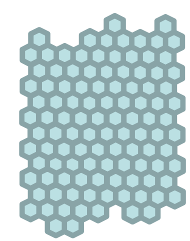












Metabolism & Bioenergetics

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

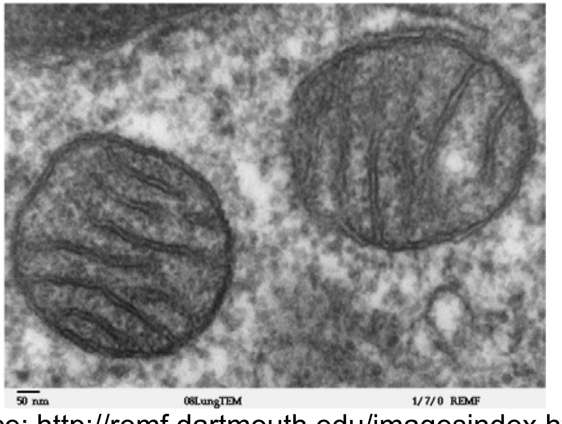
Microchip assays

Mitochondria

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

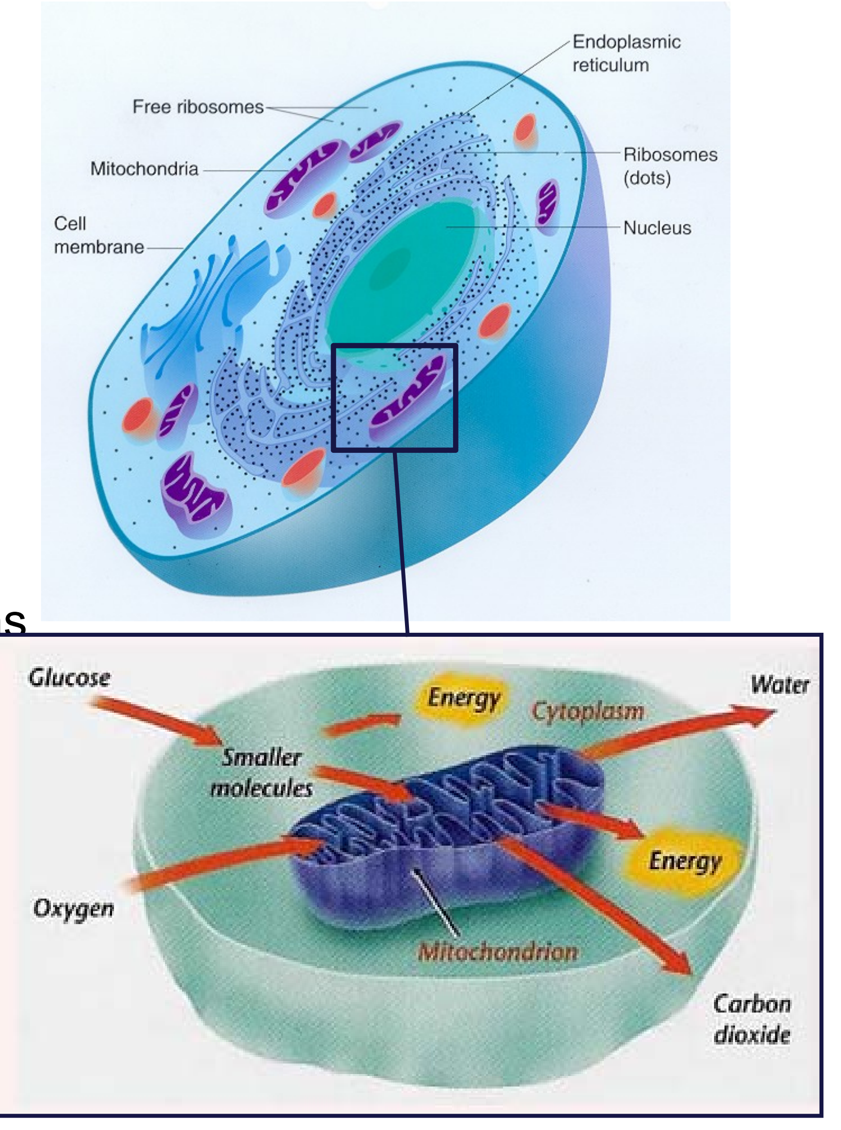
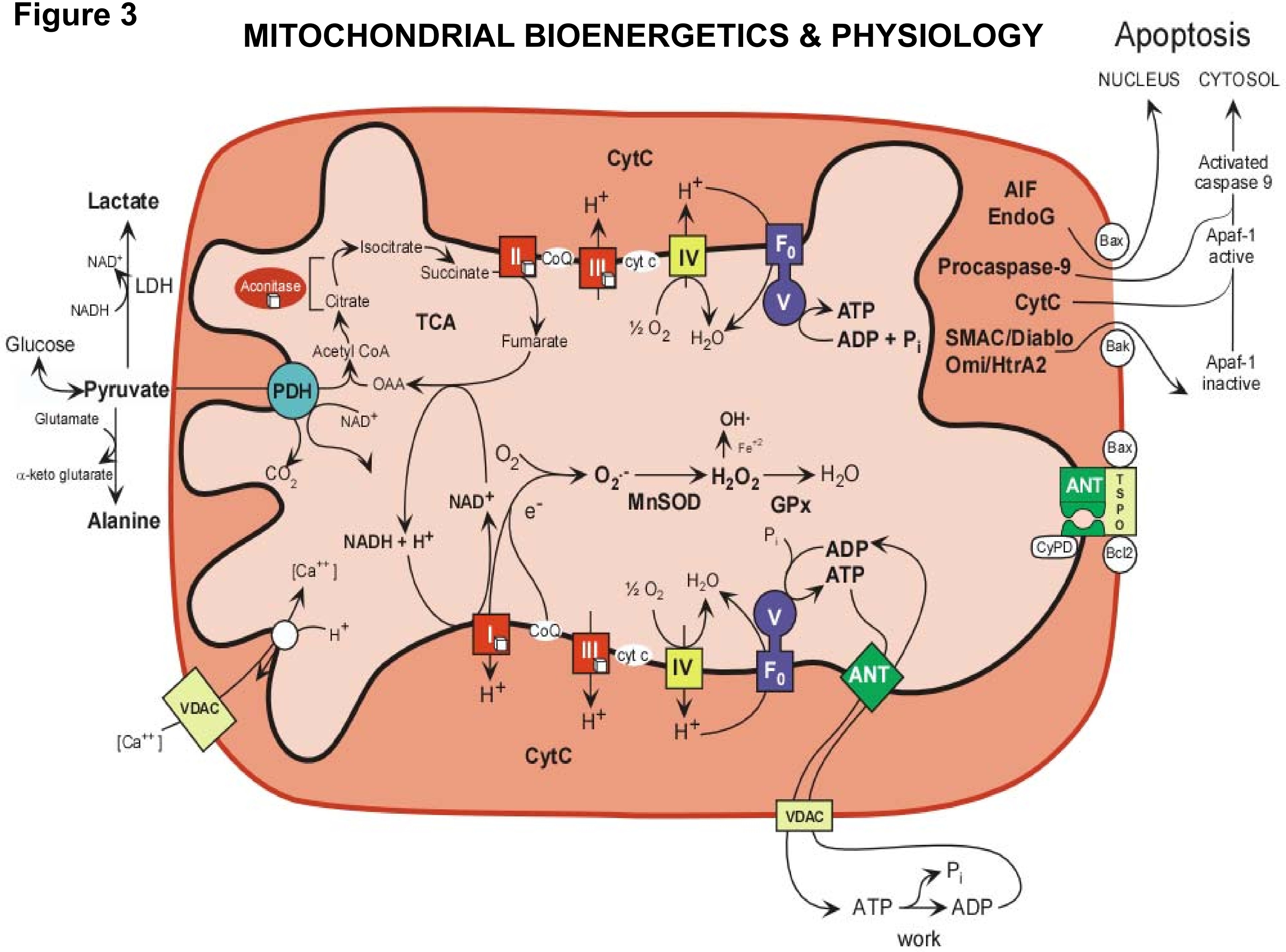
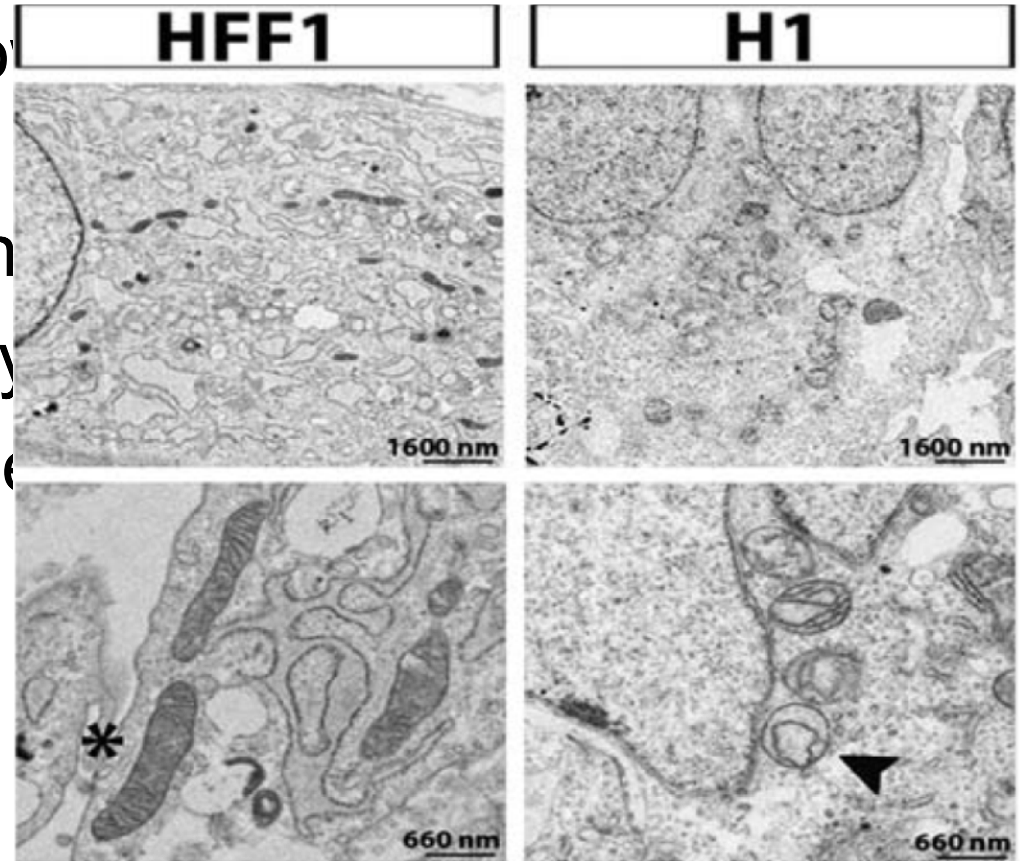


Figure 3


MITOCHONDRIAL BIOENERGETICS & PHYSIOLOGY
Apoptosis
NUCLEUS
CYTOSOL
Activated caspase 9
Apaf-1 active
Apaf-1 inactive
AIF
EndoG
Procaspase-9
CytC
SMAC/Diablo
Omi/HtrA2
Bax
Bak
Bcl2
CyPD
ANT
TSPO
CytC
Lactate
NAD+
LDH
NADH
Glucose
Pyruvate
Glutamate
α-keto glutarate
Alanine
PDH
Aconitase
Isocitrate
Succinate
Citrate
TCA
Acetyl CoA
Fumarate
OAA
NAD+
CO2
II
CoQ
III
cyt c
IV
F0
V
H+
½ O2
H2O
ATP
ADP + Pi
OH·
Fe+2
O2
O2·-
H2O2
H2O
MnSOD
GPx
NAD+
e-
NADH + H+
[Ca++]
Pi
ADP
ATP
I
ANT
VDAC
work

que State of Mitochondria in hESC

- population with lo
  mtDNA copy #
- Peri-nuclear localization
- Small round morpholog
- Poorly developed crista
- 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

***Oxyview*, Hansatech Inc.**

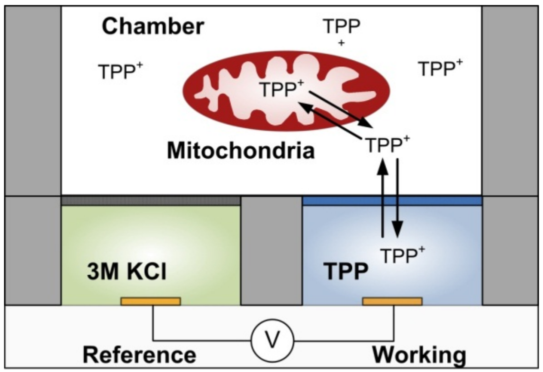
- **Motivations**
  - No miniaturized and chip based-sensor
  - Waste a great deal of precious sample
  - Challenging to assay mitochondria from small samples
  - Reduce cost

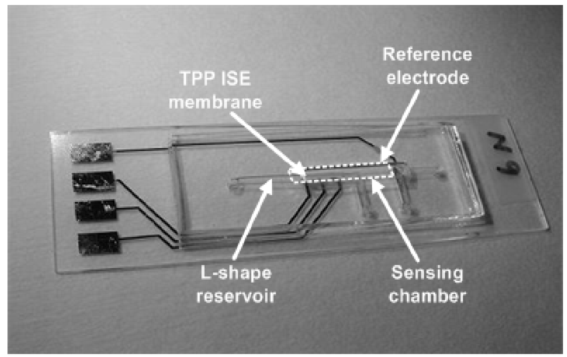
Oxygraph 2k, Oroboros Inst.

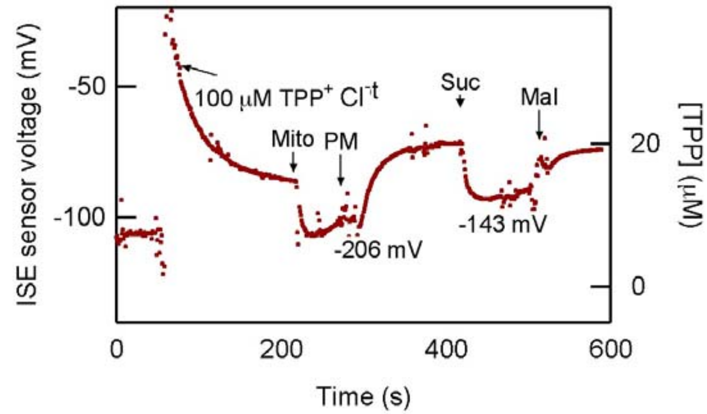
ur Goal:Developing chip based nology for interrogating mitochondria

First Gen. mitochips

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

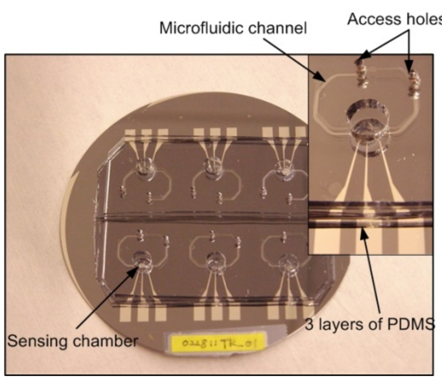


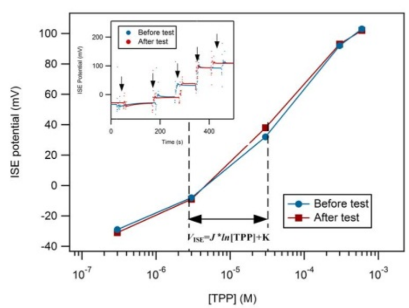


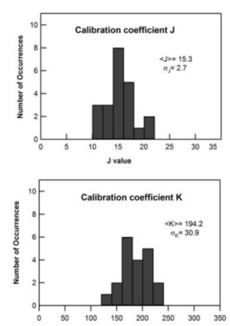


Tae-Sun Lim, Antonio Dávila, Douglas C. Wallace and Peter Burke
Lab on a Chip, (2010)

Second Gen. mitochips







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

More Devices under development.