Nanowires: A Platform for Nanoscience & Nanotechnology

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Outline of Presentation

- Why Nanowires
- Synthesis of Functional Nanowires
- Nanoelectronic-Biology Interface
- Conclusions & Future
Why Nanowires?

- Central importance of nanoscale wires in integrated nanosystems
- Fundamental scientific questions in 1-dimensional systems
- Synthetic challenge of controlling structure and composition on many length scales
- New/novel materials can make revolutionary vs. evolutionary changes in science and technology!
Nanoscale Wire-like Materials: Carbon Nanotubes

- Metals & semiconductors depending only on diameter and helicity (+/-)
- Carbon is carbon (+/-)


Functional Nanowires: A Beginning

Designed synthesis yields materials with diverse & predictable physical properties beyond that achievable with template

- Requires template & limited in classes of materials

History: Key Growth Concepts

\[ r_{\text{min}} = 2\sigma_{LV}V_L/RT\ln\sigma \]

\[ \sim 100 \text{ nm} \]

\( \sigma_{LV} \) is liquid-vapor interfacial free energy
\( V_L \) is the liquid molar volume
\( \sigma \) is the vapor phase supersaturation

Wagner & Ellis, *Appl. Phys. Lett.* 4, 89 (1964)
**Nanowires: A General & Predictable Approach**

- **Breaking symmetry for 1D growth.** Nanoscale wires can be prepared rationally by exploiting a catalyst to direct preferentially the addition of reactant.

- The key issue for controlled nanowire growth is the generation of nanometer scale ‘catalyst’ clusters.

- The growth process begins when the catalyst becomes supersaturated with reactant, and terminates when the nanowires pass out of the hot reaction zone.

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Nanocluster-Catalyzed Nanowire Growth: An Early Summary

- minimum diameters ~2 nm with single crystal structure
- controlled nucleation yields monodisperse diameters with controlled lengths
- surface properties tailed for assembly and device properties

### Table

<table>
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<tr>
<th>Material</th>
<th>Group IV</th>
<th>Group IV Alloys:</th>
<th>III-V</th>
<th>III-V Alloys</th>
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<td>Si, Ge</td>
<td>Si(<em>x)Ge(</em>{1-x})</td>
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<td>ZnS</td>
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<td>GaP</td>
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<td>Growth Conditions</td>
<td>330-1200 Fe, Ni, Au</td>
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<td>700-1000 Cu, Ag, Au</td>
<td>800-950 Au, Ag</td>
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<td>defined by starting composition</td>
<td>1:1</td>
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Nanowire Heterostructures & Superlattices

1-d growth nucleation

axial growth

axial heterojunction/superlattice

axial growth

radial growth

radial heterostructures

- Designed core/shell nanowire structure enables investigations of electron and hole gases confined in uniform 1D potential.
- Reduced scattering can yield higher mobility transistors and open up studies of fundamental quantum phenomena at low-temperatures!

Pushing Nanowire Transistor Limits

**Transconductance** = 26 $\mu$S/V

Max $I_{on}$ = 35 $\mu$A

Scaled values ($V_{dd}$=1V; 70/30 on/off):

$G_m = 1.4$ mS/µm

$I_{on} = 0.78$ mA/µm

**Transconductance** = 60 $\mu$S/V

Max $I_{on}$ = 91 $\mu$A.

Scaled values ($V_{dd}$=1V; 70/30 on/off):

$G_m = 3.3$ mS/µm

$I_{on} = 2.1$ mA/µm

*First demonstration that a nanowire transistor could exceed limits of top-down devices!!*

Nanowire FETs: How Good Are They?

- $L = 40 \text{ nm}$, 8x faster than Si p-MOSFET, and shows fundamental limit $> 2 \text{ THz}$
- $I_{on}$ is $\sim 100\%$ of the ballistic limit at low bias

Double Quantum Dot with Integrated Charge Sensor Based on Ge/Si Nanowires

- Fully control of interdot coupling and barrier height by local top gates
- Plunger gates control charge number
- Double dot capacitively coupled to sensor dot on adjacent nanowire
- Charge sensing critical for single-electron double dots and spin control

Core/Shell Architecture is Rich in Function: Photovoltaics

**p-i-n Core/Shell Nanowire Properties**

- Dark current-voltage ($I-V$) data demonstrate (i) ohmic contacts and (ii) good rectifying/diode behavior with quality factors, $n$, of ~2.

- Under 1-sun illumination, yield an open circuit voltage of 0.260 V, a short circuit current (density) of 0.503 nA (24 mA/cm$^2$), and stable operation of at least 8-months!

- 1-sun efficiency, ~3.5%, and current density exceed values achieved with nanoparticle & nanorod composite systems, although open circuit voltage is lower.

- Power output is ~ 1 nW (ca. 100 W/m$^2$)

Axial $p-i-n$ Nanowire Photovoltaics

- Optical absorption and transport characteristics are unique compared to radial core/shell nanowires.
- Important point of comparison for studies of carrier generation, recombination and collection at the nanometer scale.
Axial p-i-n Nanowires: Synthesis & Properties

- Controlled modulation of p-, i-, and n-type diode regions
- Etching delineates different doped Si regions

- Good quality diodes (not Schottky) with quality factors for $i = 4\mu m$ of 1.2-1.3.
- $\Delta I_{sc}$ is proportional to $\Delta I_{length}$ implies that photocurrent is predominantly from i-region

Kempa, Tian, Zheng, Lieber & coworkers
Axial $p$-$i$-$n$ Nanowires: Tandem Cells

- Controlled nanowire synthesis enables integration of 2 (or more) $p$-$i$-$n$ diodes in series with independent control of all junctions.

- Substantial increase in open circuit voltage realized in ‘tandem’ single nanowire photovoltaic elements!
Assembly of Multi-Functional Structures: NW-Photovoltaic Powered Nanodevices

- Individual coaxial nanowires function as robust photovoltaic devices with sufficient power output to drive nanoelectronic devices ‘on chip’.

- A single photovoltaic nanowire integrated with a nanowire sensors is capable of powering the nanowire sensor device without external input.

Interfaces between nanoelectronic & biological systems

- Natural length-scale for electronic interfaces
- Create new tools for biophysics to healthcare

Nanoelectronic-Biological Systems

Hybrid materials that enable new opportunities in science & technology
Because the sizes of biological macromolecules are comparable to nanowire building blocks, these structures represent natural transducers for ultra-sensitive detection.
Nanowire Nanosensors: Beginning

- A nanotransistor is transformed into a nanosensor by modifying the surface with a receptor.
- Changes in the surface charge ‘gate’ the device and yield a conductance change.

Detection of Proteins

- Real-time label-free
- High-sensitivity and specificity

Cui, Wei, Park & Lieber, *Science* 293, 1289 (2001)
Nanosensor Chip for Real-Time, Label-Free Multiplexed Detection

- **Bottom-up/top-down hybrid fabrication yields large number of addressable nanowire elements**
- **Assemble distinct types of nanowires on single chip**
- **Personalize sensor elements with distinct receptors**

Multiplexed Cancer Marker Detection

- Multiplexed, real-time monitoring of cancer marker proteins.
- Quantitative & selective detection of protein concentration to femtomolar level.
- General platform for multiplexed, ultrasensitive, real-time detection of proteins and other species!

Undiluted Blood Serum Analysis

- Serum samples are characterized after single step ‘desalting’ purification.
- (1) buffer; (2) *Donkey Serum (DS)*, 59 mg/ml total protein; (3) DS + 2.5 pM PSA; (4) DS + 25 pM PSA
- (1) DS + 0.9 pg/ml; (2) DS

**Marker proteins are detected selectively in presence of ca. 100-billion-fold excess of serum proteins!**

Making Good on the Promise: Commercialization

- Vista combines nanowire devices and biotechnology to provide all the tools needed to measure **biomarkers over time**.

- Revolutionize monitoring of biomarkers of therapeutic response and toxicity in the clinic and lab for drug development through patient care.

Vista Therapeutics, Inc.
www.vistatherapeutics.org
Ultimate Sensor: Single-Particle Detection

Can nanoscience enable detection at ultimate limit of a single biological entity?

Can the sensitivity of nanowire sensors be pushed to enable true single molecule detection?

Consider the case of small oligonucleotides:

Fang, Zheng, Tian, Yan, Zhou & Lieber
Nanoelectronic-Cell Interfaces

An example:

Nanowire nanoelectronic devices can enable:
- Interface to cells at natural scale of biological communication
- Input/output of electrical signals
- Input/output of chemical/biological signals
Nanowire/Neuron Junctions

- Nanowire (NW) response correlated w/conventional measurements
- Multiplexed recording with flexible arrays is straightforward
- Nanowire/neuron junctions can be localized at level of individual neurites

Nondestructive, Real-time Neurotransmitter Detection

- Selective detection of neurotransmitter dopamine to at least 100 fM sensitivity
- Reversible & nondestructive
- Potential for high spatial and temporal resolution
- Potential for simultaneous neurotransmitter & action potential recording
Better Approaches for Building & Using These Tools?
Interfacing to Brain Slices

S. Pal & V. Murthy
Q. Qing, B. Tian, G. Yu & Lieber
Vision for Life Sciences

Nanoelectronic-Biological Interfaces Enable:

- Diagnostic devices for disease detection
- General detection & kinetics platform
- New tool for single-molecule detection/biophysics
- Powerful devices for electronic and chem/bio recording from cells, tissue & organs
- Potential implants for highly functional & powerful prosthetics, as well as hybrid biomaterials enabling new opportunities
Evaluating Research Motivation: Progress?

- Synthetic challenge of controlling structure and composition on many length scales
- Fundamental scientific questions in 1-dimensional systems
- Central importance of nanoscale wires in integrated nanosystems
- New/novel materials can make revolutionary vs. evolutionary changes in science and technology!

⇒ Many fundamental scientific questions remain, and will require bold researchers to address.
⇒ Pushing ourselves to identify and tackle these ‘big’ challenges, while difficult, offers the best opportunity to make revolutionary advances and benefit society!
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