Semiconductor nanowires: 2
Electronic applications

11/10/2005
Si nanowire devices

$\mu \sim 300 \text{cm}^2/\text{Vs}$

uniform behavior

Shottky barrier formation at the contacts

- Ohmic-like contact at RT because of thermally assisted tunneling and thermal emission
- Shottky barrier is obvious at low T.
- Typical contact resistance ~ 100KΩ-1MΩ per wire
Measuring the Schottky barrier with photocurrent

Measuring the Schottky barrier with photocurrent

\[ \phi_b \approx 0.57 \text{eV} \]

\[ \alpha = \frac{|\Delta E|}{e\Delta V_G} \]

Measuring the potential inside the channel with photocurrent

Schottky barrier formation at the source/drain contacts

Schottky barriers as tunnel barriers
Quantum dot formed between the source/drain electrodes

Schottky barrier formation at the source/drain contacts

Elimination of Schottky barriers and dopants

- Carrier injection w/o dopants in the channel
- Valence band offset between Ge and Si
- Cylindrical confinement, quantum size effects

Band structure engineering

\[ n = \frac{k_y w}{\pi} \]
Ge/Si core/shell nanowire growth

VLS

CVD

Ni contacts

SiO$_2$
P$^+$ Si

back gate

source

drain

500nm

5 nm

Nucleation

Supersaturation

Liquid Alloy Droplet

Ge core

Si Shell

S D
Room-T transport studies

"Depletion mode"

"Enhancement mode"

contact doping

Schottky barrier formation
Low T- Conductance quantization

T=4.7K

L=350nm, d=10nm

- Clear plateau formation at $\sim 0.65G_0$
- First subband occupied (1-D)

Landauer formula: $G = \frac{2e^2}{h} \sum_i T_i$

$V_g$ from -10V to +10V, step 1V

$V_g=10V$

$d=15nm$

2nd mode 1st mode
Top gate, multiple 1D channels

high-κ + metal gate

[Diagram of a nanowire device with labels: Au gate, AlO$_x$ film, Nanowire, Contact, SiO$_2$.]

$V_{SD}=8\text{mV}$

$T=100\text{K}$, $50\text{K}$, $30\text{K}$, $10\text{K}$, $5\text{K}$, $1.5\text{K}$

$L\sim400\text{nm}, 10\text{nm Ge core}$

zerobias
Non-Equilibrium Studies, multiple subbands

- plateaus $\longrightarrow$ accumulation of curves, a-d
- half-plateaus at higher biases, f-h
- cusp $\rightarrow$ small potential fluctuations inside the channel

series of $G-V_{SD}$ in $V_g$ steps of 50 mV
no offset adjustment
\[ \frac{\partial}{\partial E} - \frac{\hbar^2}{2m} \nabla^2 \varphi(r) + V(r) = E \varphi(r) \]

\[ \nabla^2 = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2} \]

\[ E_{mi} = \frac{\hbar^2 u_{mi}^2}{2m^* a^2} + \frac{\hbar^2 k^2}{2m^*} \]

\[ V(r) = \begin{cases} +\infty, & r \geq a \\ 0, & r \leq a \end{cases} \]

\[ u_{mi}: J_m(x)'s \ ith \ zero \ point \]

\[ E_{1,2} = 25 \text{meV} \]

\[ E_{2,3} = 30 \text{meV} \]

\[ \text{dG/dV}_g \text{ map, subband spacings} \]

\[ \text{dG/dV}_g - V_g - V_{SD} \]

\[ E_{1,2} \sim 25 \text{meV} \]

\[ E_{2,3} \sim 32 \text{meV} \]

for \( d=2a=14\text{nm} \)
Temperature dependence

- Little temperature dependence
- Reduction of phonon scattering
- Room temperature ballistic devices

Acoustic phonon scattering rate at room $T$

Following Fermi’s golden rule

$$\frac{1}{\tau_{ap}} = \frac{\pi k_B T \Xi^2}{\hbar \rho v_s^2} D(E_F)$$

$$D(E) = \frac{\sqrt{2m^*}}{\pi \hbar E} \frac{1}{\pi v_s^2}$$

- $\rho$ mass density, 5.3 g/cm$^3$
- $\Xi$ deformation potential, 3.81 eV
- $v_s$ velocity of sound, 5400 m/s

Acoustic phonon scattering rate $\tau_{ap} \sim 4.5 \times 10^{-12}$ s

$$v_F = \frac{\hbar k_F}{m^*} \sim 1.1 \times 10^5 \text{ m/s}$$

mean free path $l \sim 492$ nm

![Graph showing temperature dependence with markers at T=4.7k, 10k, 50k, 300k.](image)
Top gated Ge/Si nanowire devices, room T

$V_g$ from -3V to 3V, step 0.2V

$L=G_L=380\,\text{nm}$
$d=10\,\text{nm}$

With $\text{AlO}_x$ dielectric

- $I_{on} > 70\,\mu\text{A}$
- $G_m>20\,\mu\text{S}$, among highest achieved (~1mS/µm), at -1V
- $\text{on/off} > 10^5$
- Uniform behavior (100% yield)
Top gated Ge/Si nanowire devices, room T

• 3X improvements achieved using better high-k dielectrics (HfO₂)
• \( G_m = 3.3 \text{ mS/\mu m} \)
• \( I_{on} = 5 \text{ mA/\mu m} \)
• \( CV/I = 3.8 \text{ps with } V_{dd} = 1 \text{V} \)
Benchmarking of nanoFETs

CV/I scaling of Ge/Si nanowires

- CV/I data points picked at $I_{on}/I_{off}=100$
- Better than state-of-the-art p-Si devices
- Sharper slope obtained, due to suppression of mobility degradation.
Ambipolar suppression

• Metal contacts results in pronounced ambipolar behavior.
• Ungated region as local contacts instead.
Both depletion mode ($V_T>0$) and enhancement mode ($V_T<0$) devices can be obtained via selection of top gate materials. 

• High uniformity
Nanowire ring oscillators

Ring oscillators:
- Excellent circuit for demonstrating reliable integration
- Excellent circuit for demonstrating gain/driving capabilities
- Excellent circuit for demonstrating high freq performance/limitations
- “An oscillator of some sort is an essential ingredient in electronics”

Si nanowire inverter response
Nanowire ring oscillators

Deposit wires by flow-alignment and pattern via photolithography

Uniformity critical in these multiple wire devices

Si nanowire ring oscillators


$f > 4\text{MHz}$ on oxidized Si substrate

$f > 10\text{MHz}$ on glass substrate
Ge/Si nanowire ring oscillators

- Initial attempt on Si substrate already yields $f \sim 20$MHz
- 3-4 times faster on insulating substrate, e.g., glass
- Further optimization

Inverter response

Ring oscillator response

$f \sim 20$MHz
Nanowire devices on flexible substrates

• Separation of high temperature material growth and low temperature device fabrication processes.

• High performance electronic and photonic devices on plastics

Nanowire devices on flexible substrates


$\mu \sim 200 \text{cm}^2/\text{Vs}$, 2-3 orders higher than amorphous Si and organic semiconductors
InAs nanowires and axial heterostructures


InAs wire, n-type

Diameter dependence of the threshold

InAs wires with InP tunnel barriers
Controlled growth via the CBE method

Samuelson group, Lund Univ

Axial heterostructures, controlled growth of tunnel barriers

Well defined SET behavior


InAs nanowire quantum dots

Few charge quantum dot obtained by reducing the dot size (separation of the InP barriers)

Nanowire based single electron memory

- Individual electrons added/removed via tunneling through the InP barriers
- Au nanoparticle as the charge storage node
- A second nanowire SET detects number of charges on the Au nanoparticle

Thelander, Nano Lett. 5, 635 (2005)
Nanowire based single electron memory

\[ N: \text{number of electrons on the Au particle} \]
\[ M: \text{number of electrons on the SET} \]

Thelander, Nano Lett. 5, 635 (2005)
Decoder: bridging the nanoscales wires with micro scale wires

Coding achieved via modulation doping (gatable regions vs. ungatable regions)

$2^N$ nanowires can be addressed by N microwires with perfect registry

Stochastic decoding


Unique addressing of all $N$ nanowires can be obtained via stochastic decoding with large coding spaces without registry.
Coding via modulation doping of Si nanowires

Yang, Science, 2005
Mechanical resonators

Cleland, APL, 69, 2653 (1996)

Application: passive RF filters, oscillators for wireless communications. (eg, prof. Nguyen’s group).

Fundamental interest (flexural modes):
\( hf \sim 50 \text{ mK for } f=1\text{GHz}, \) quantum mechanical system.
\( hf \sim 4\mu\text{eV}, \) comparable to energy scales of electrical systems. Entangled mechanical/electrical systems.
**Magnetomotive actuation**

Cleland, APL, 69, 2653 (1996)

In plane magnetic field.
AC current creates Lorentz driving force.

Other actuation methods

- Electromotive (AC signals applied to coupling electrodes, driven by electric forces)
- Piezoelectric forces (AC bias causes mechanical driving force)
GHz resonators

Doubly clamped SiC beam

f~1GHz, Q~500

For samples produced via the etching process, surface induced losses dominates the quality factor.

Such loss may be avoided in devices produced by single-crystalline nanowires.

Piezoelectric actuation possible with (AlN) nanowires without magnetic fields and 3rd electrode.

\[ f \approx 1\,\text{GHz} \] for a resonator based on Si nanowires with \( d=20\,\text{nm} \) and \( l=400\,\text{nm} \).
Comparing nanowires and nanotubes

Nanotubes:

Pros:
- truly 1D system
- interesting properties (orbital degeneracy, electron-hole symmetry)
- Small diameter (~1-2nm)
- Large mean free path (~1 μm at low bias, 30 nm at high bias)
- High mobility (~3000*d) (Zhou, PRL, 95, 146805 (2005))

Cons:
- Little control over metallic/semiconducting, chirality
- Hard to functionalize.

Nanowires:

Pros:
- Uniformity (large scale application possible, devices on plastic substrates)
- Flexible (core/shell heterostructures, axial heterostructures)
- Heterostructure design greatly enhances mean free path and mobility
- Vertical FET with conformal gating?
- Can be easily functionalized for alignment and biosensing purposes
- Other applications (photonics, solar cells and gas sensing due to large surface area).
- High freq, high Q resonators?

Cons:
- Larger size (~10-20 nm, but still small compared to top-down approach)
- Transport diffusive in most cases (may still be better than bulk materials due to confinement and smoother surface),