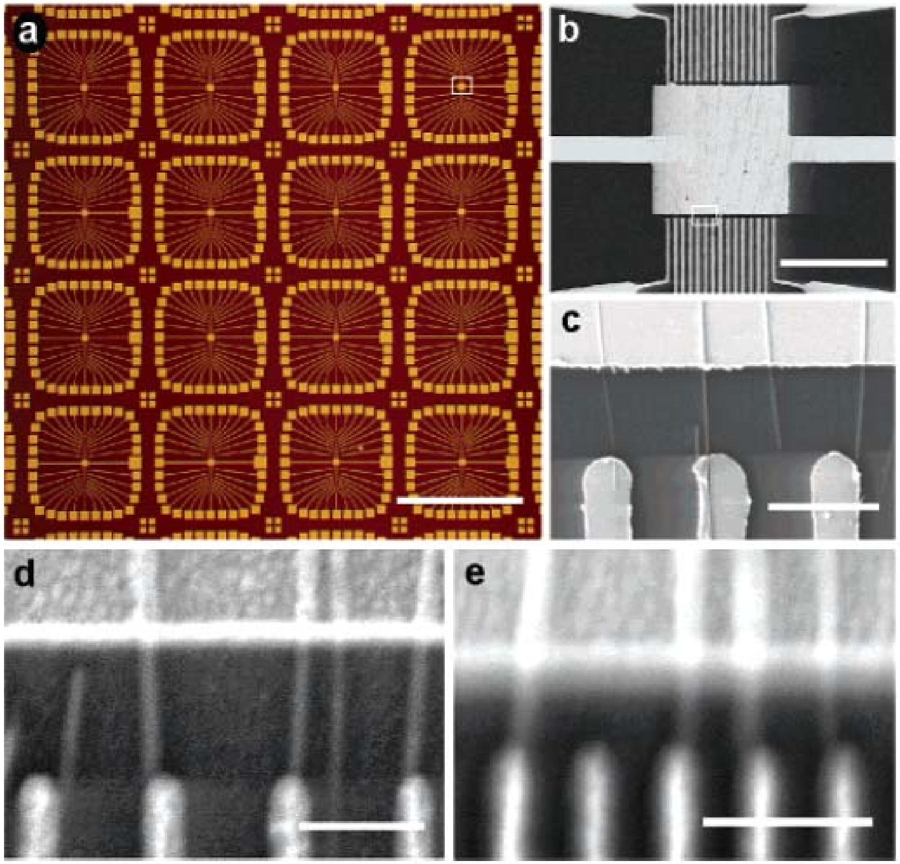
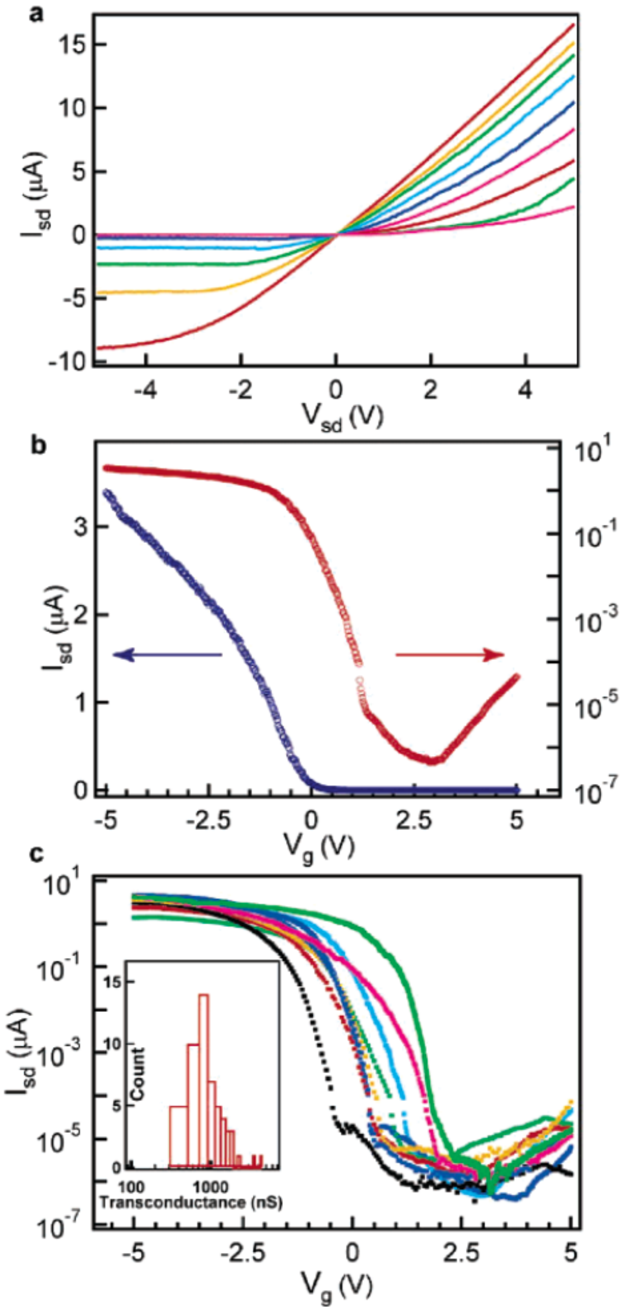
Semiconductor nanowires: 2
Electronic applications

11/10/2005

Si naowire devices



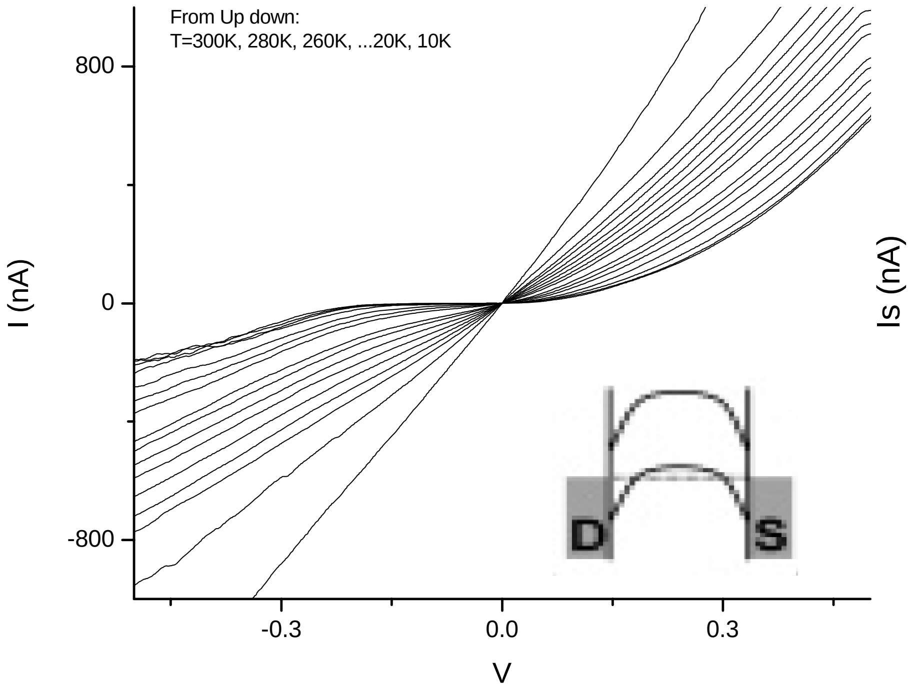


μ~300cm^2/Vs

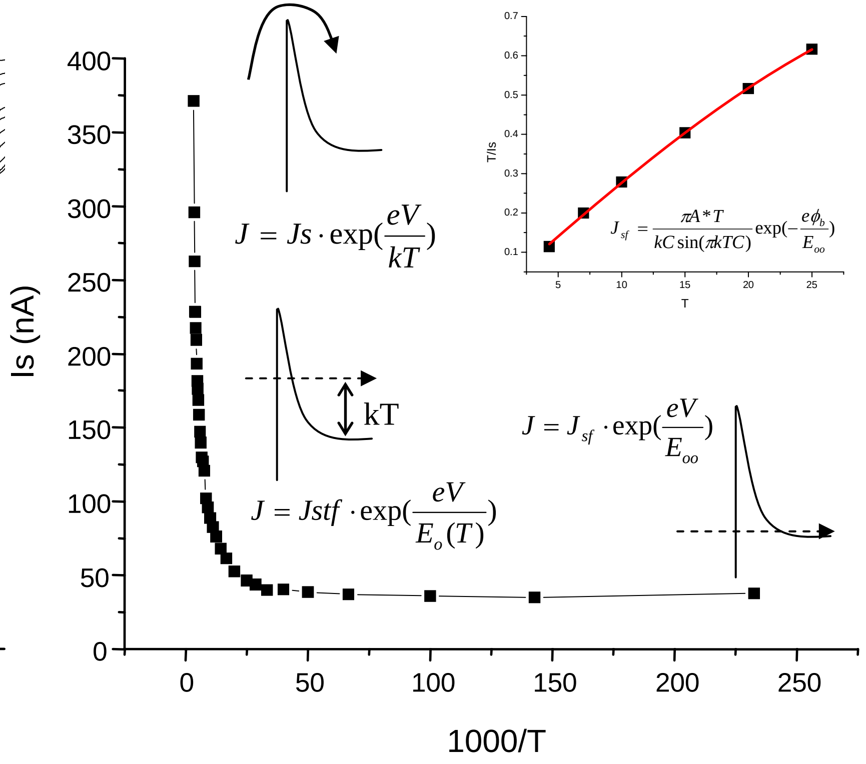
uniform behavior

Jin, Nano Lett. **4**, 915 (2004)

Shottky barrier formation at the contacts



From Up down:
T=300K, 280K, 260K, ...20K, 10K



$$J = Js \cdot \exp(\frac{eV}{kT})$$

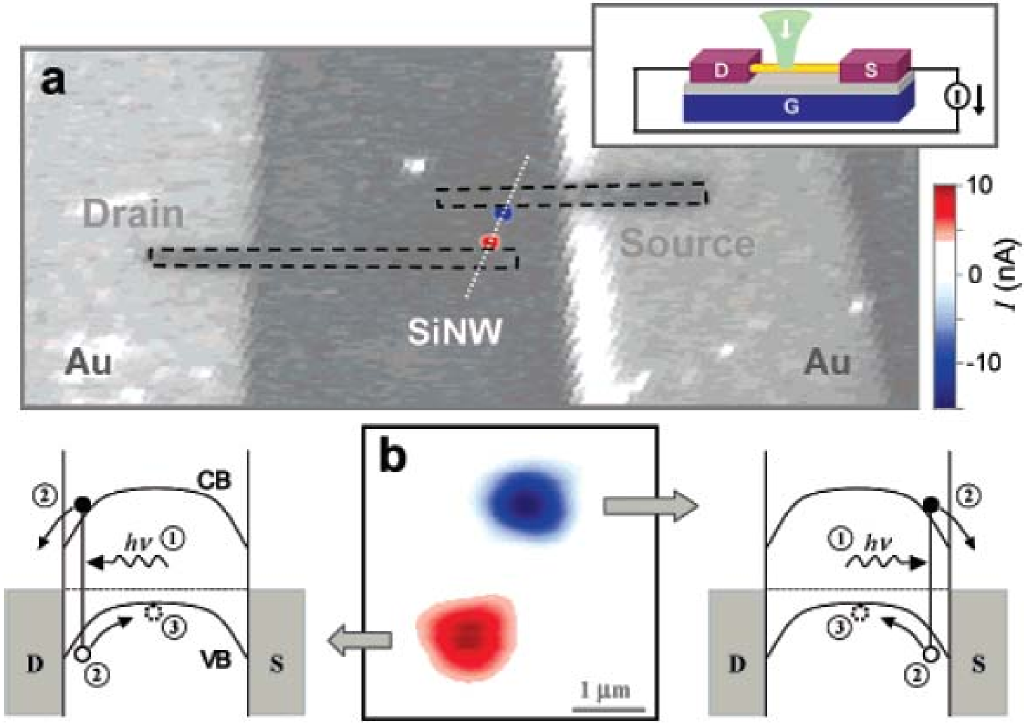
$$J = Jstf \cdot \exp(\frac{eV}{E_o(T)})$$

$$J = J_{sf} \cdot \exp(\frac{eV}{E_{oo}})$$

$$J_{sf} = \frac{\pi A^* T}{kC \sin(\pi kTC)} \exp(-\frac{e\phi_b}{E_{oo}})$$

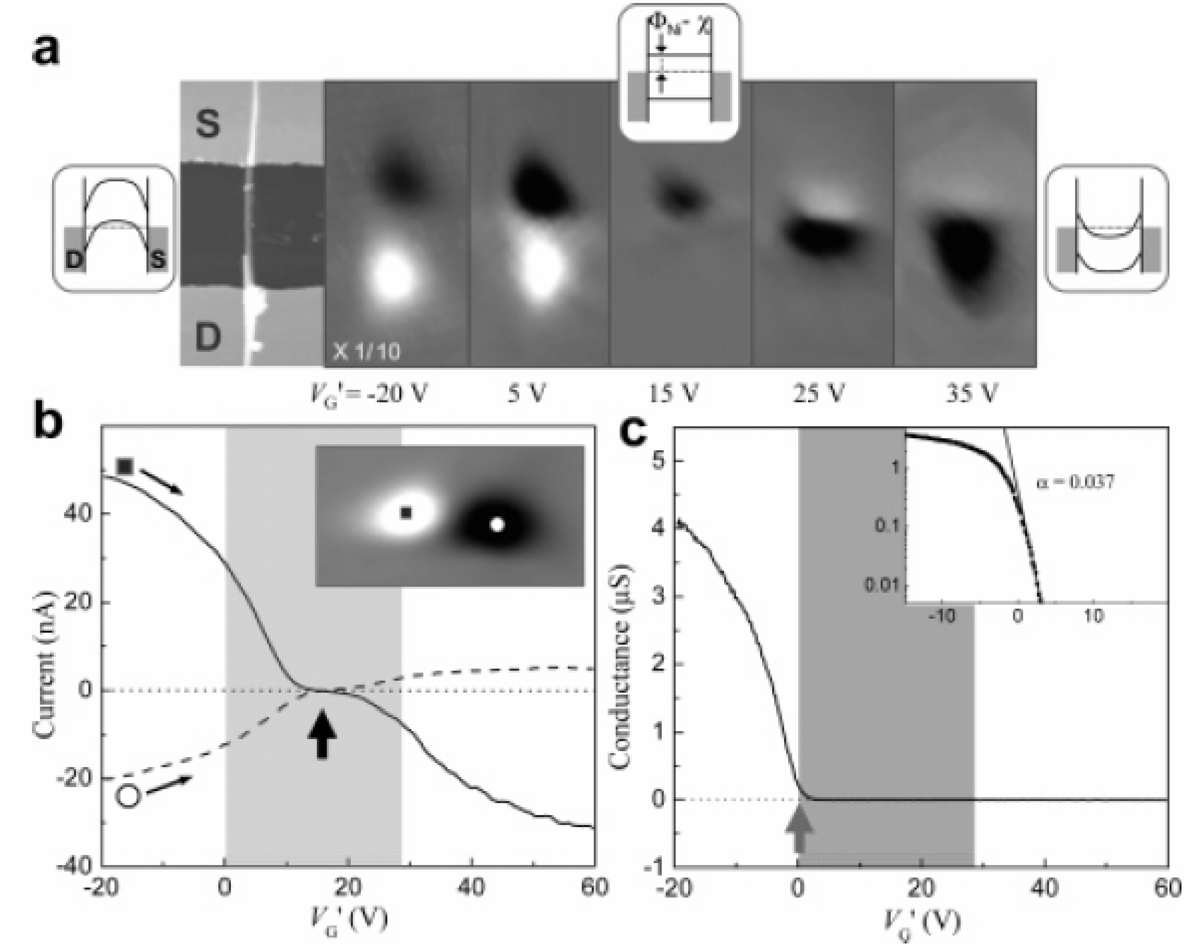
- •Ohmic-like contact at RT because of thermally assisted tunneling and thermal emission
- •Shottky barrier is obvious at low T.
- •Typical contact resistance ~ 100KΩ-1MΩ per wire

Measuring the Schottky barrier with photocurrent



Ahn, Nano Lett, **5**, 1367 (2005)

Measuring the Schottky barrier with photocurrent

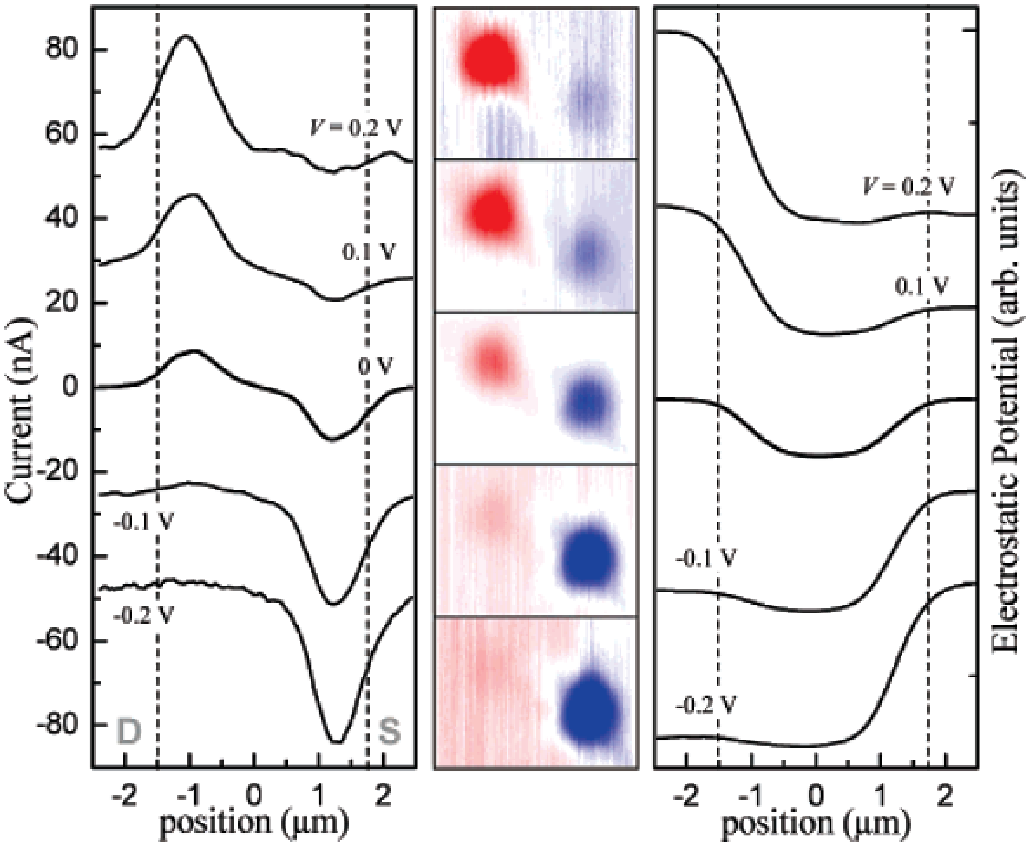


$$\alpha = |\Delta E / e \Delta V_G|$$

ϕ_b~0.57eV

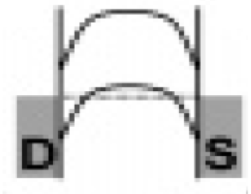
Ahn, Nano Lett, **5**, 1367 (2005)

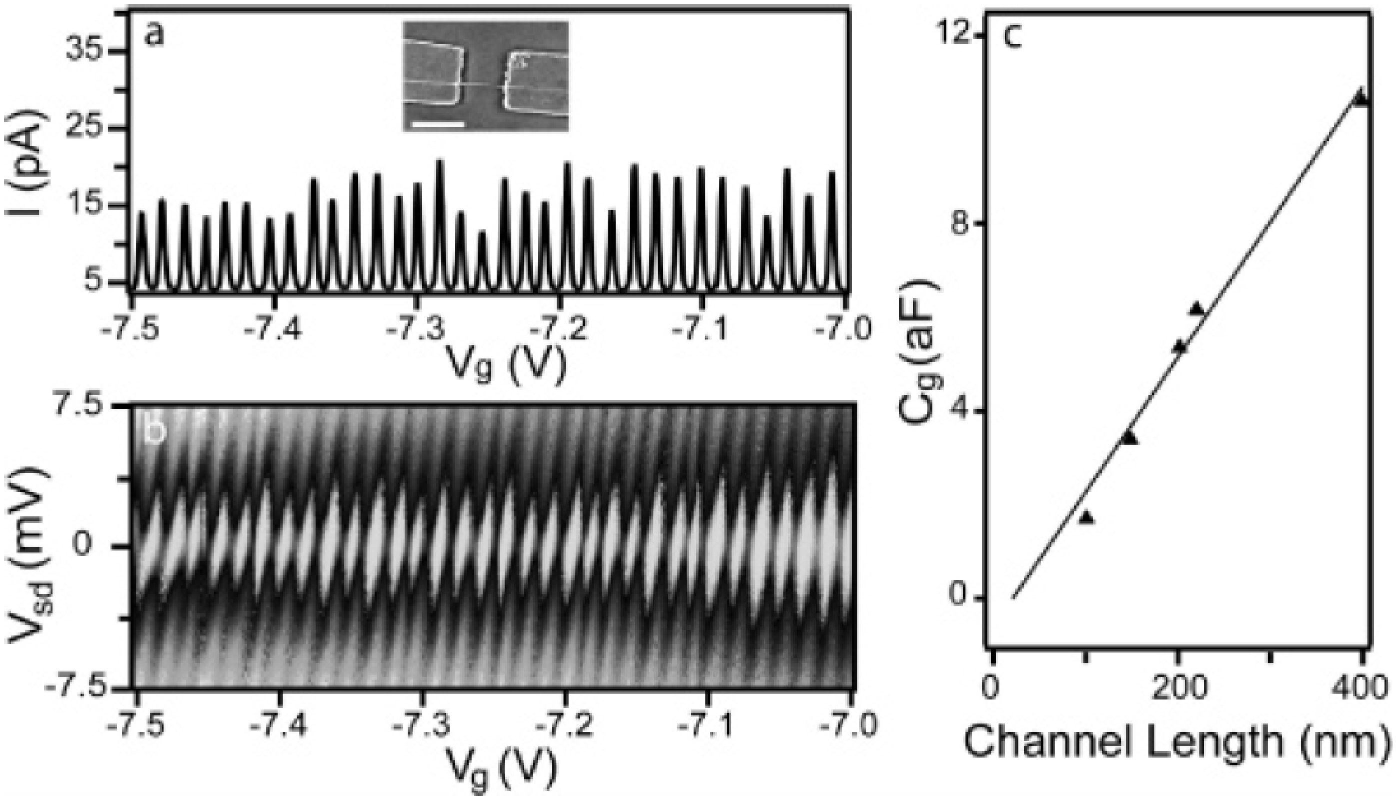
Measuring the potential inside the channel with photocurrent



Ahn, Nano Lett, **5**, 1367 (2005)

Schottky barrier formation at the source/drain contacts

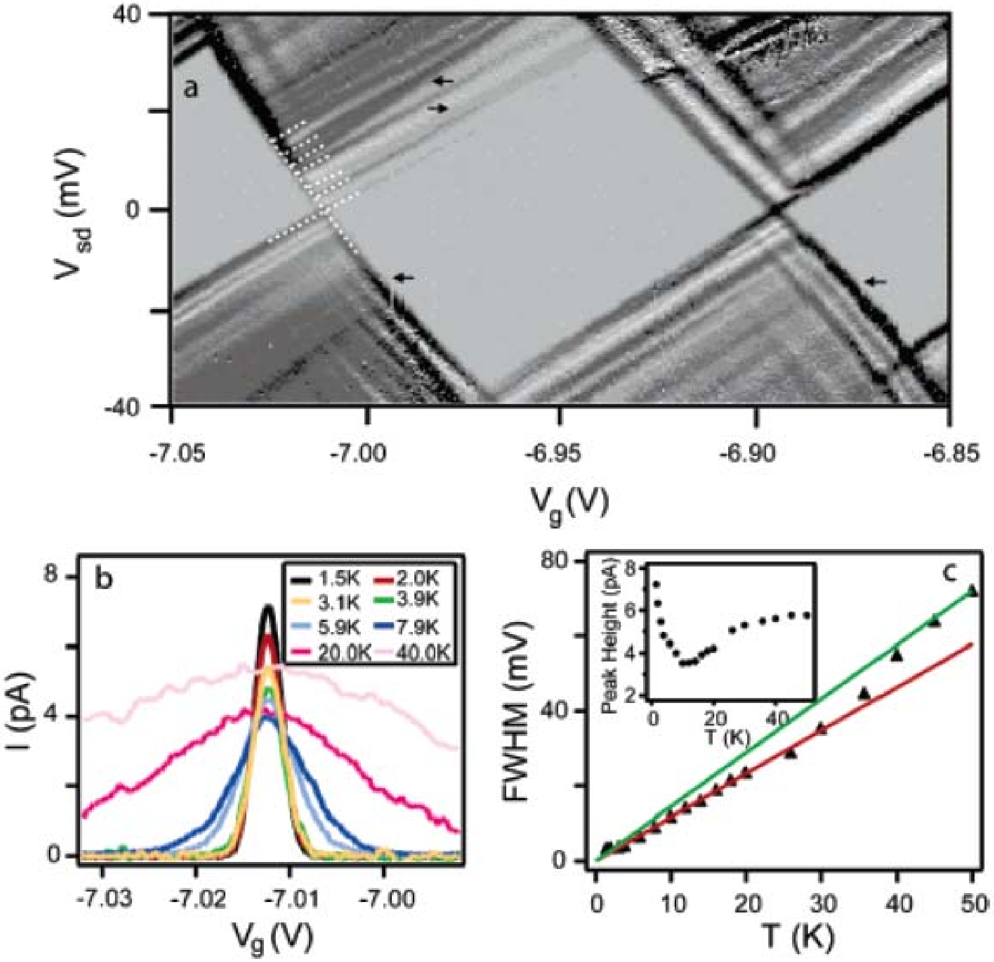




Zhong, Nano Lett, **5**, 1143 (2005)

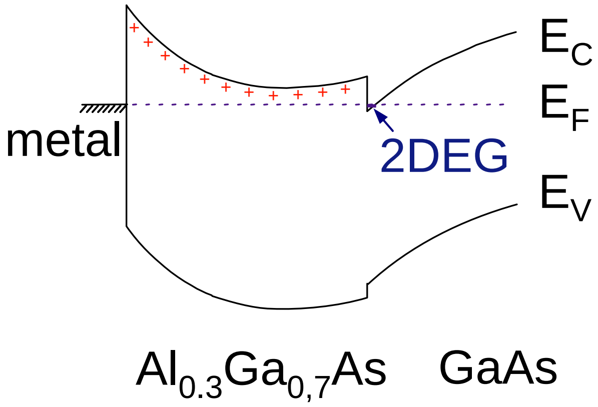
Schottky barriers as tunnel barriers
Quantum dot formed between the source/drain electrodes

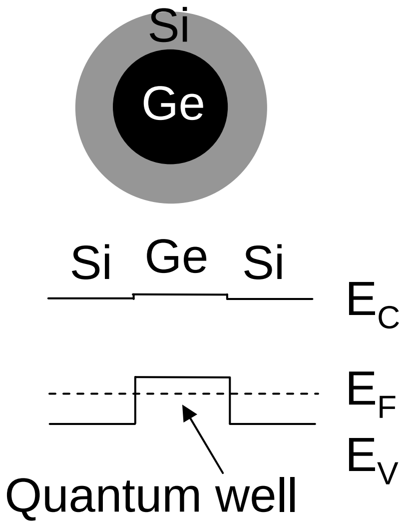
Schottky barrier formation at the source/drain contacts



Zhong, Nano Lett, **5**, 1143 (2005)

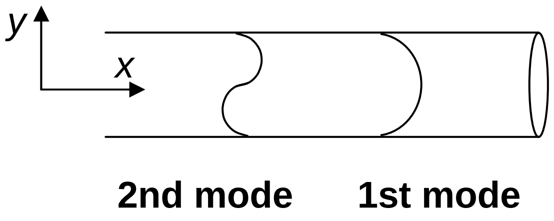
Elimination of Schottky barriers and dopants





~~dopants = impurities~~

~~Schottky barriers~~

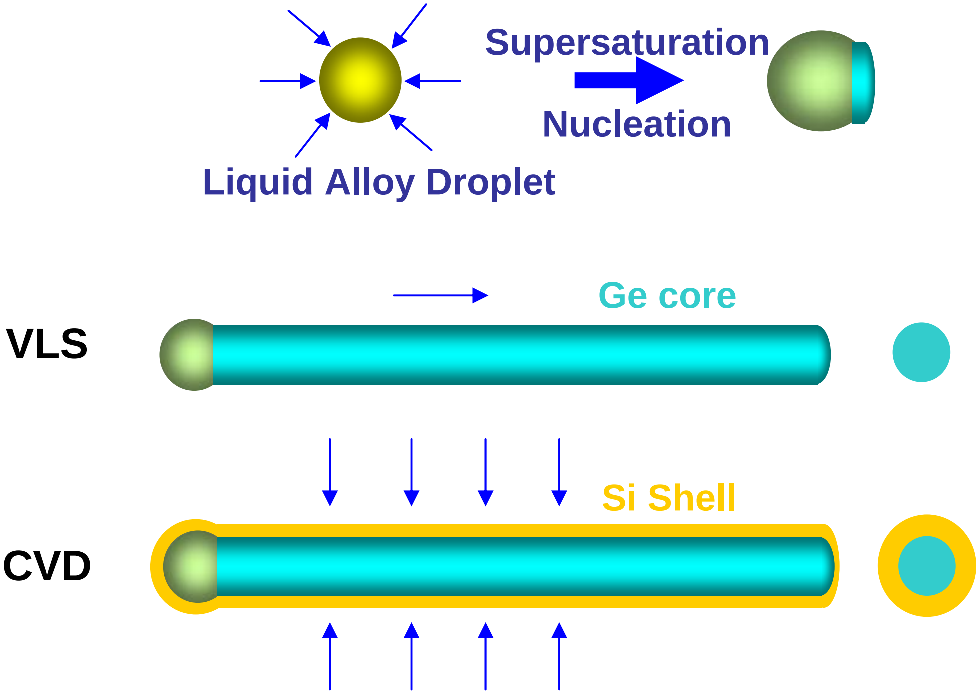


Band structure engineering

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

# of modes $n = \frac{k_y w}{\pi}$

Ge/Si core/shell nanowire growth



Supersaturation

Nucleation

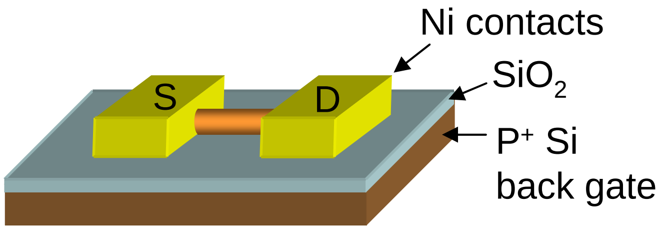
Liquid Alloy Droplet

VLS

Ge core

CVD

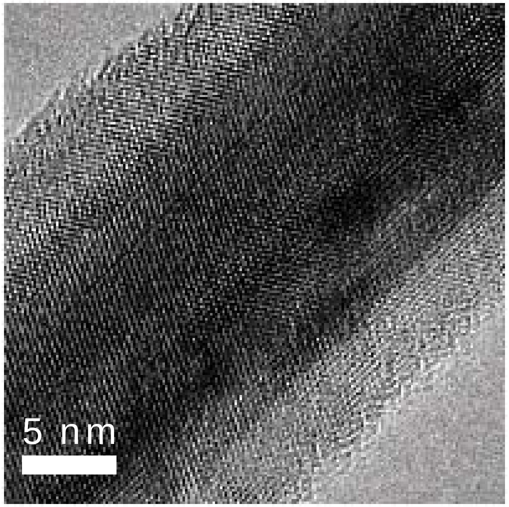
Si Shell

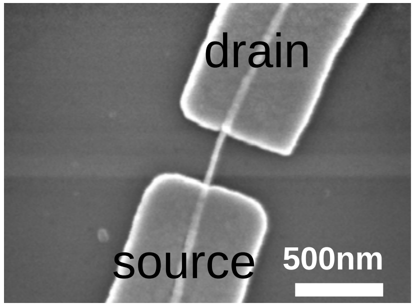


Ni contacts

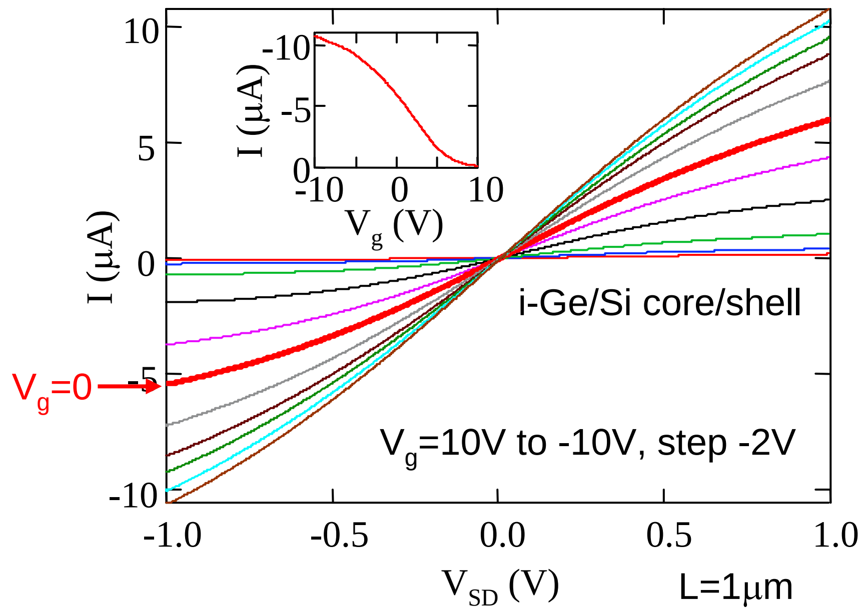
SiO_2

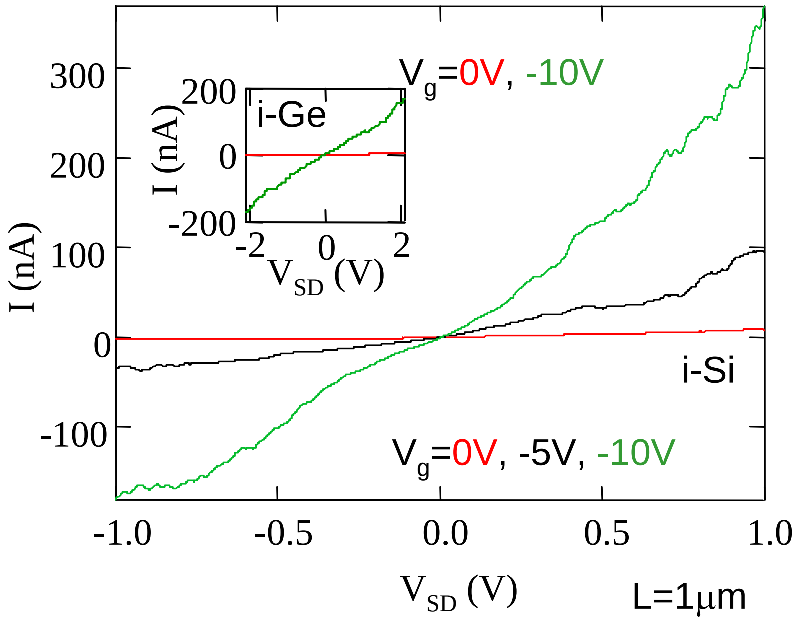
P^+ Si
back gate





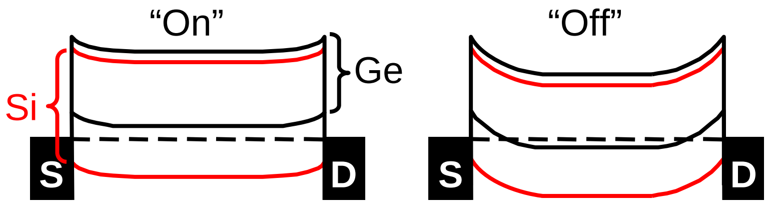
Room-T transport studies

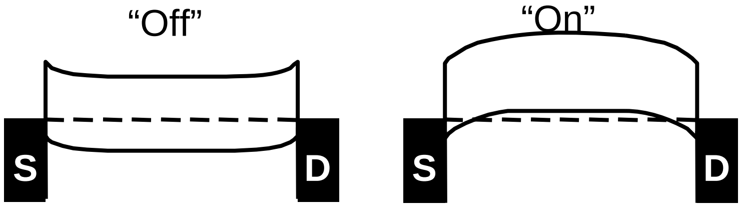




"Depletion mode"

"Enhancement mode"



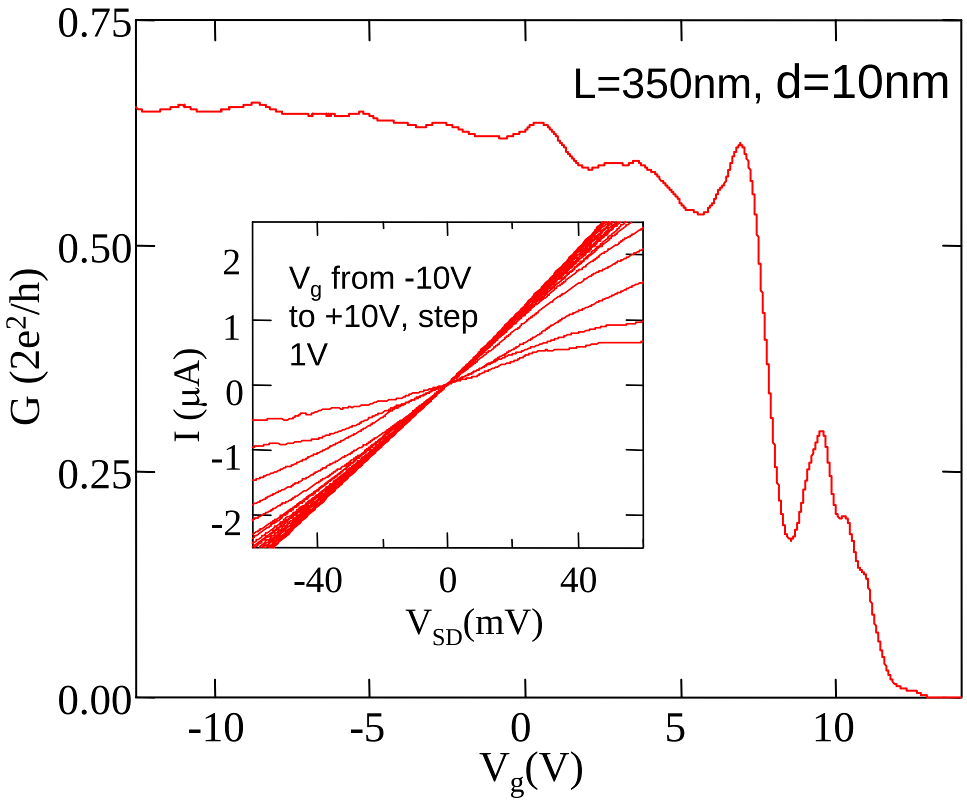


contact doping

Schottky barrier formation

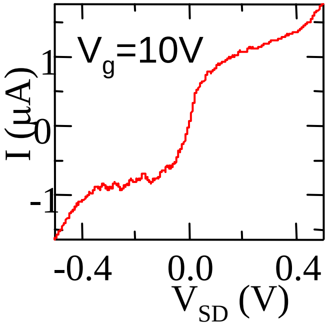
Low T- Conductance quantization

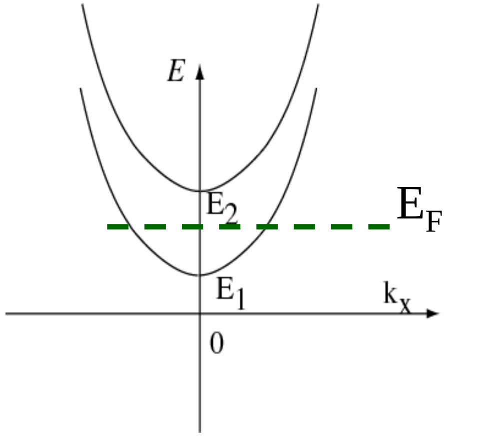
T=4.7K

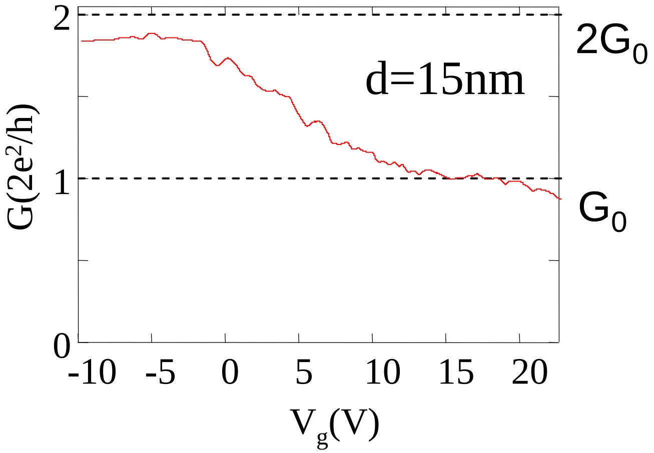


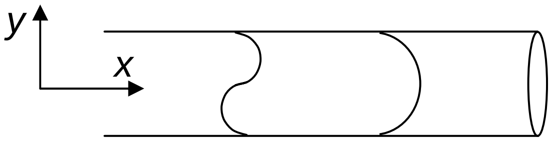
- Clear plateau formation at ~$0.65G_0$
- First subband occupied (1-D)

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





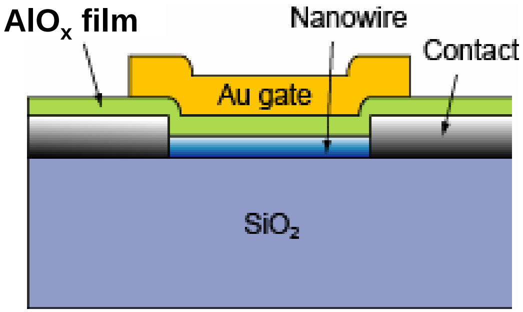


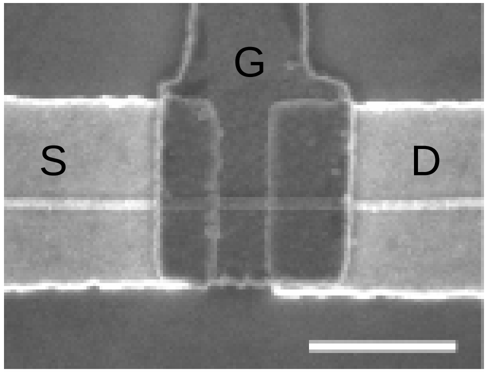


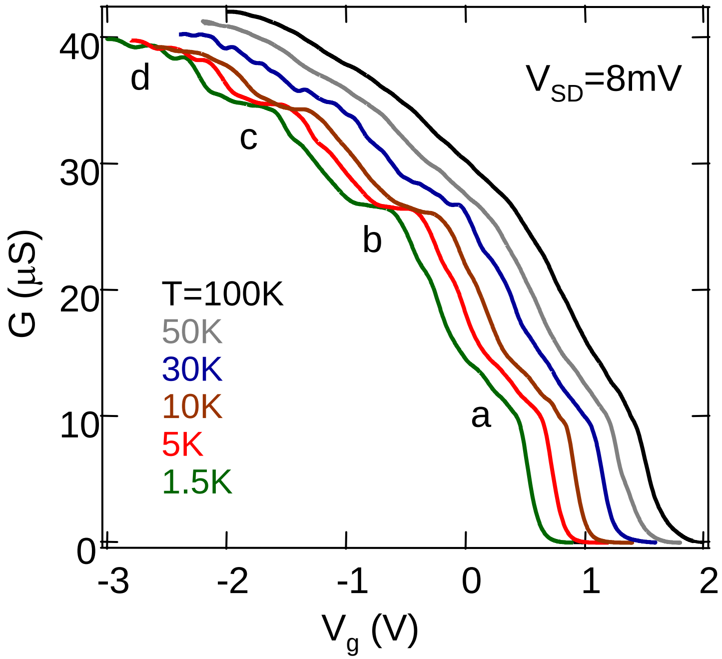
2nd mode **1st mode**

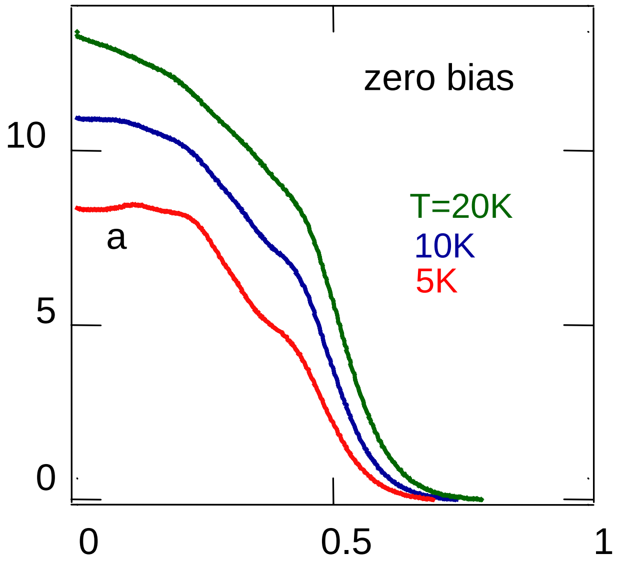
Top gate, multiple 1D channels

high-κ + metal gate



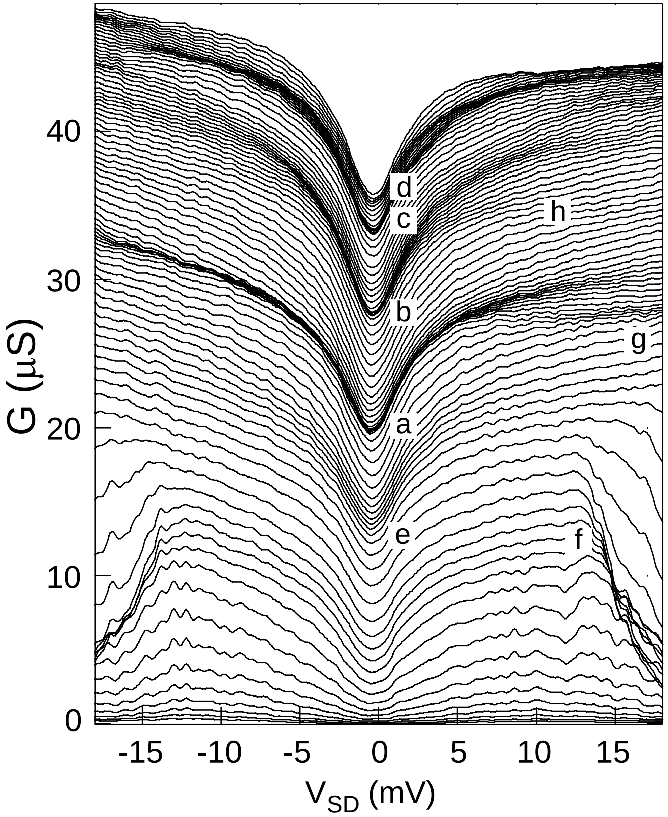




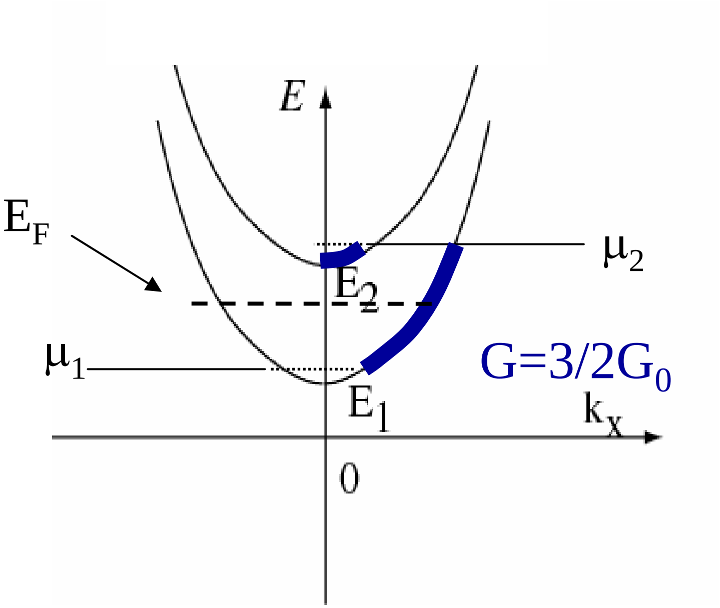


L~400nm, 10nm Ge core

Non-Equilibrium Studies, multiple subbands



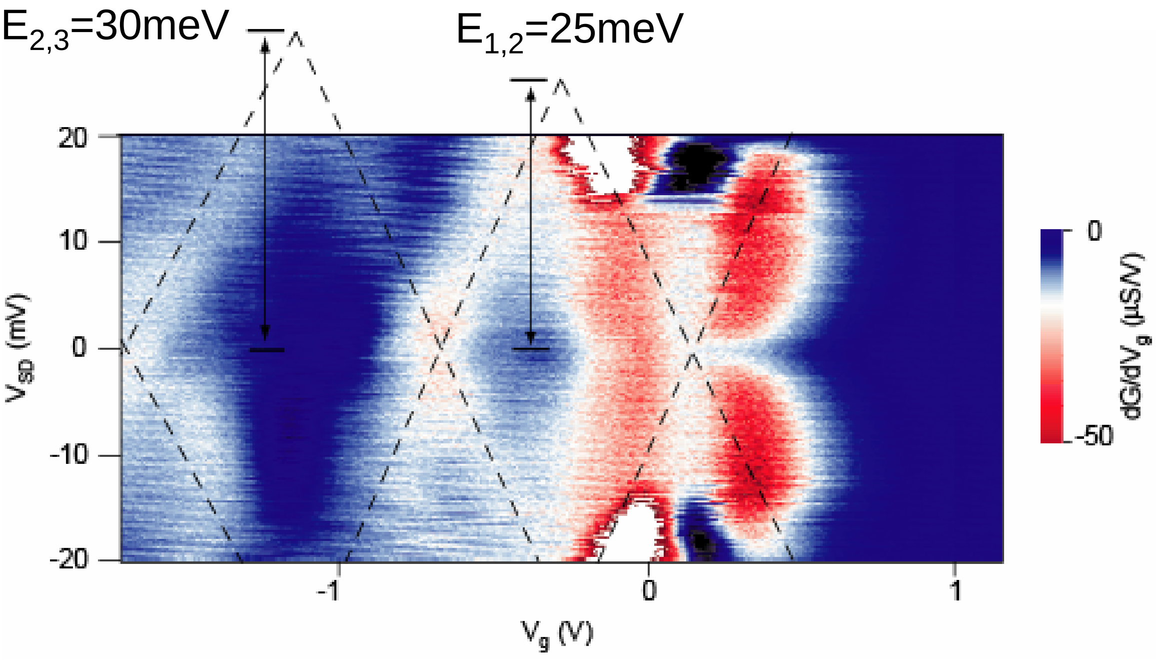
series of G-V_{SD} in V_g steps of 50 mV
no offset adjustment

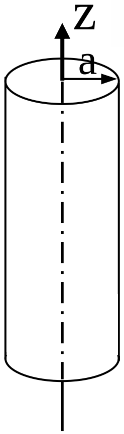


- plateaus ⟶ accumulation of curves, a-d
- half-plateaus at higher biases, f-h
- cusp ⟶ small potential fluctuations inside the channel

dG/dV$_g$ map, subband spacings

dG/dV$_g$-V$_g$-V$_{SD}$





$$-\frac{\hbar^2}{2m}\nabla^2\varphi(\vec{r})+V(\vec{r})=E\varphi(\vec{r})$$

$$\nabla^2=\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial}{\partial r})+\frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}+\frac{\partial^2}{\partial z^2}$$

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

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

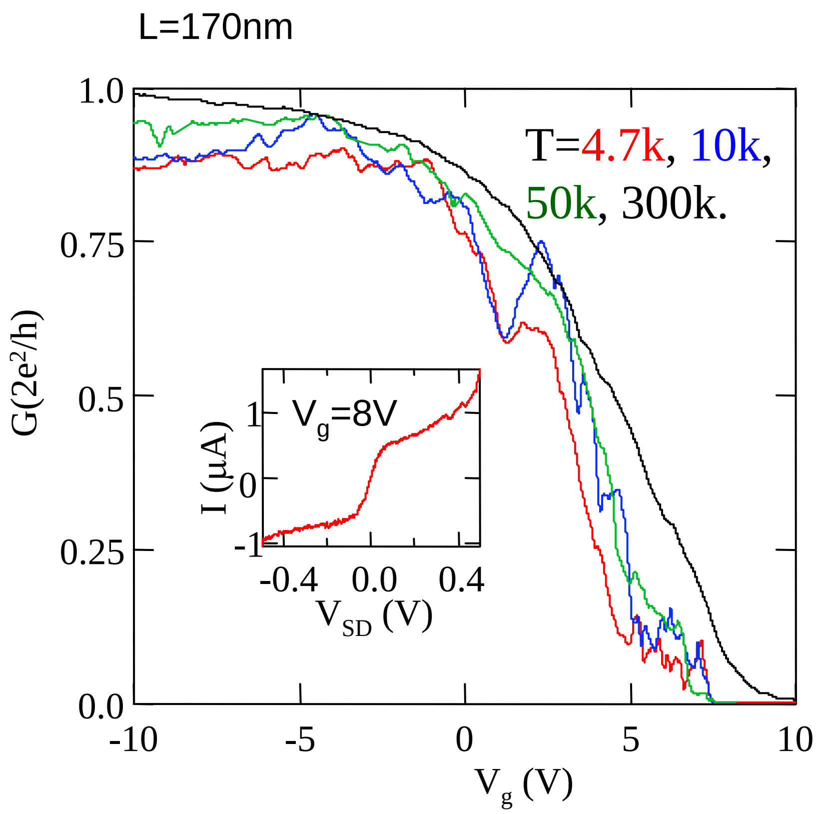
u_{mi}: J_m(x)'s *i*th zero point

$E_{1,2}$~25meV

$E_{2,3}$~32meV

for d=2a=14nm

Temperature dependence



Acoustic phonon scattering rate at room T

Following Fermi's golden rule $\frac{1}{\tau_{\mathrm{ap}}} = \frac{\pi k_{\mathrm{B}} T \Xi^2}{\hbar \rho v_{\mathrm{s}}^2} D(E_{\mathrm{F}})$

$D(E) = \frac{\sqrt{2m^*}}{\pi \hbar \sqrt{E}} \frac{1}{\pi r^2}$ density of states in 3D form

ρ mass density, 5.3 g/cm^3

Ξ deformation potential, 3.81 eV

v_{s} velocity of sound, 5400 m/s

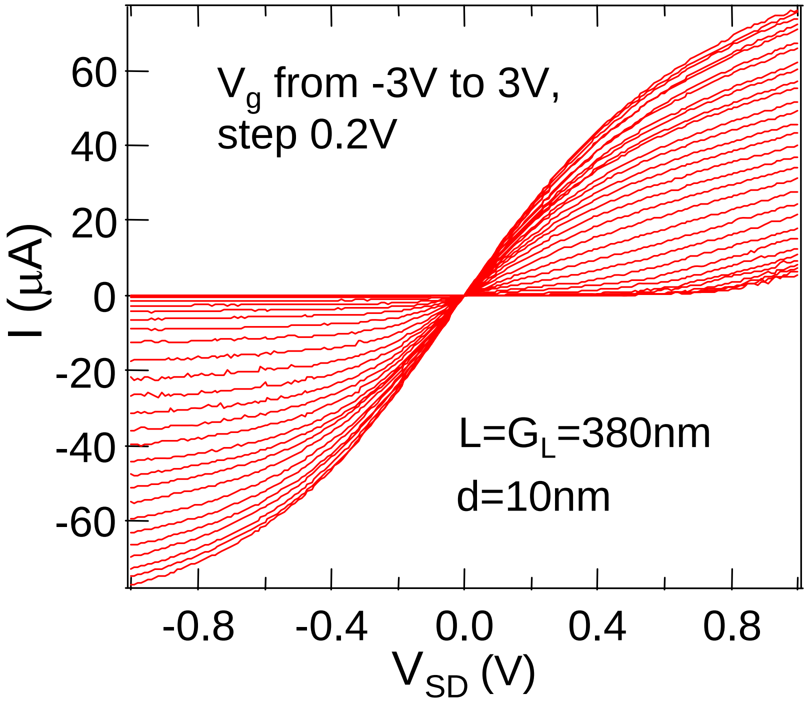
acoustic phonon scattering rate $\tau_{\mathrm{ap}} \sim 4.5 \times 10^{-12}\,\mathrm{s}$

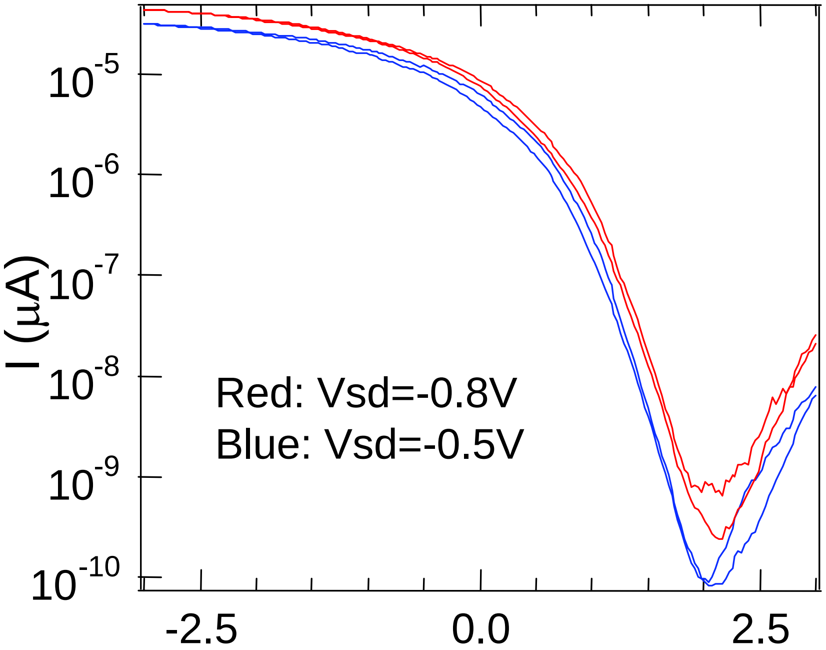
$$v_{\mathrm{F}} = \frac{\hbar k_{\mathrm{F}}}{m^*} \sim 1.1 \times 10^5\,\mathrm{m/s} \quad \Longrightarrow$$

mean free path *l* ~ 492 nm

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

Top gated Ge/Si nanowire devices, room T

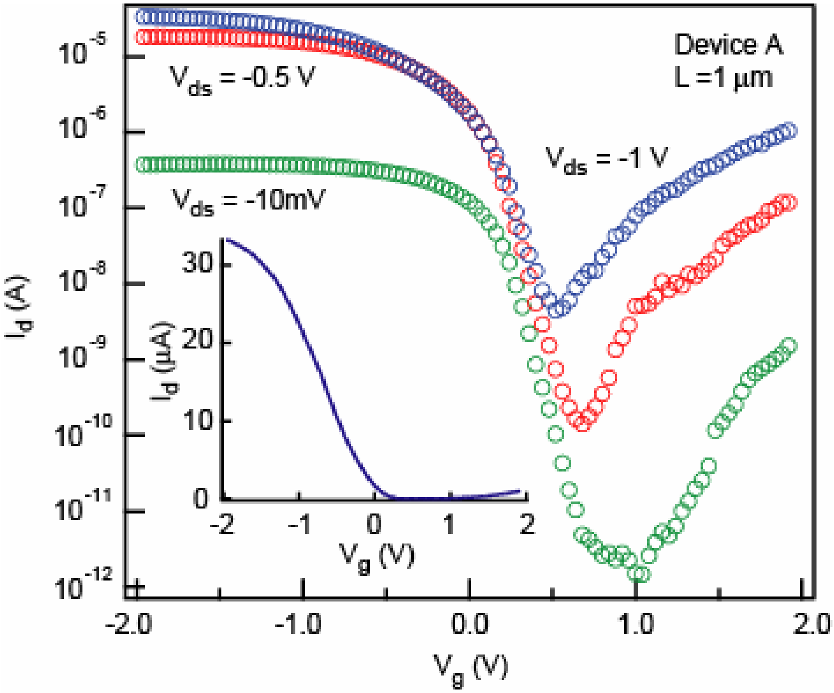


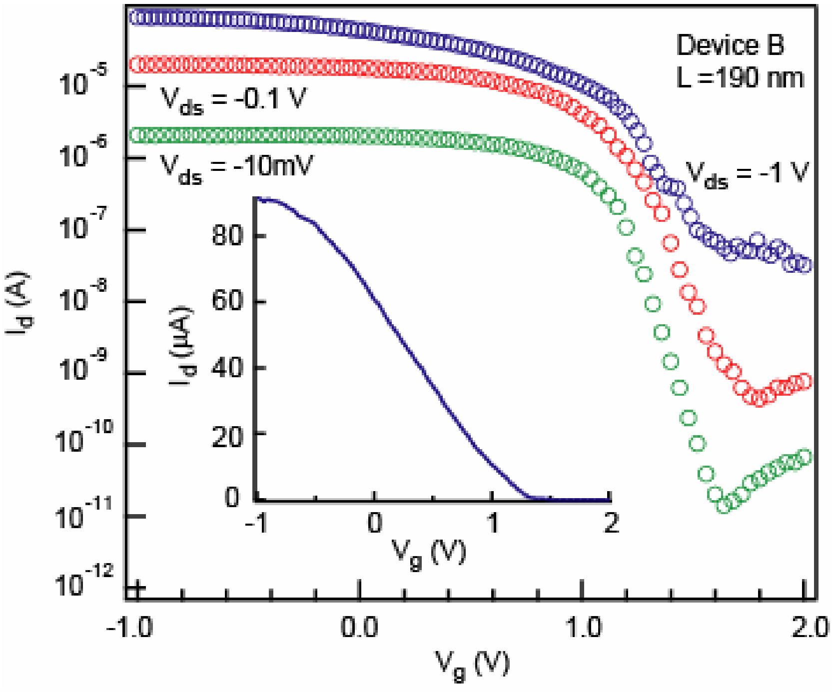


With AlO_x dielectric

- •I_{on}> 70 μA
- •G_m>20 μS, among highest achieved (~1mS/μm), at -1V
- •on/off > 10^5
- •Uniform behavior (100% yield)

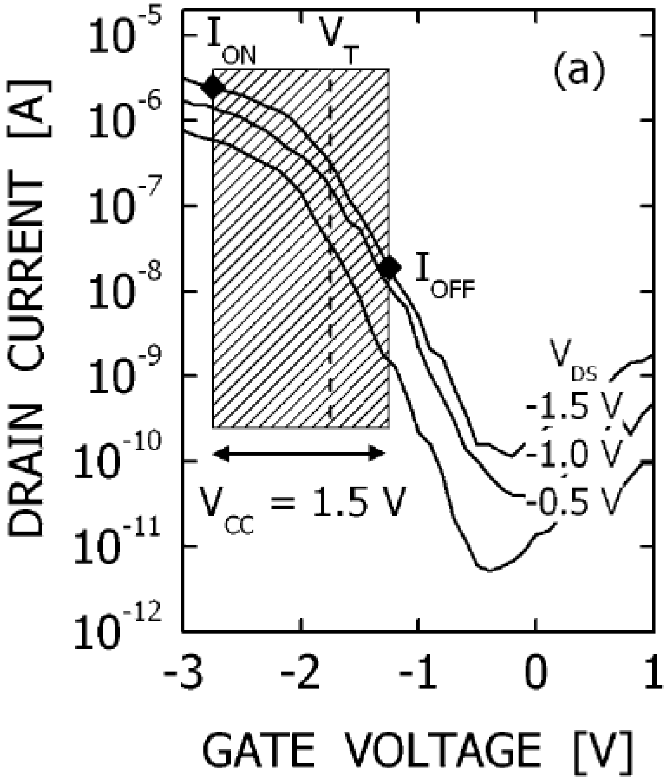
Top gated Ge/Si nanowire devices, room T

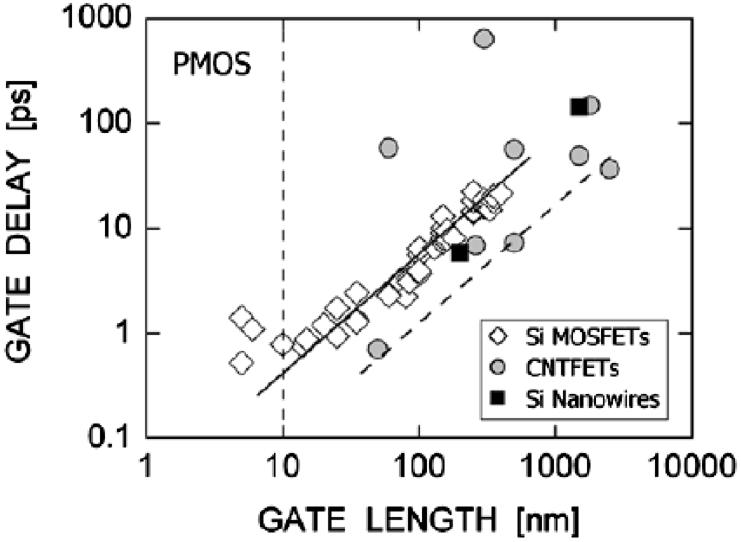


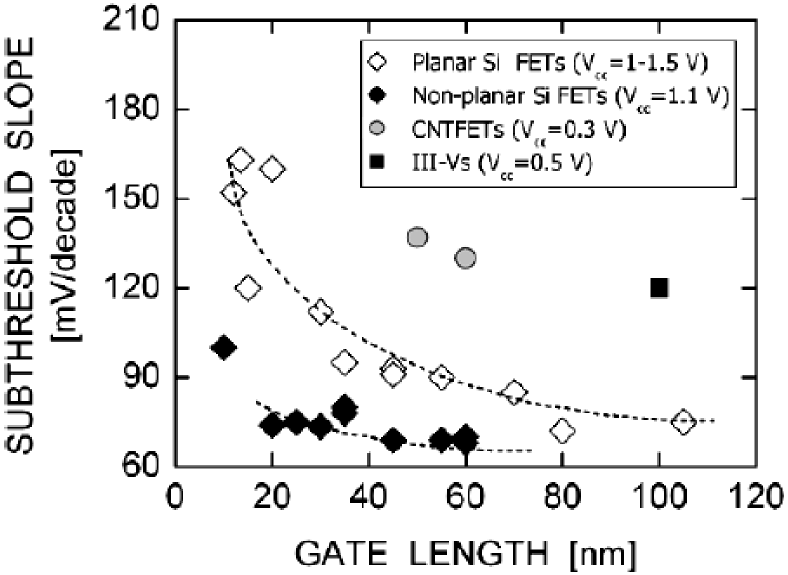


- 3X improvements achieved using better high-k dielectrics (HfO_2)
- G_m=3.3 mS/µm
- I_{on}=5 mA/µm
- CV/I=3.8ps with V_{dd}=1V

Benchmarking of nanoFETs

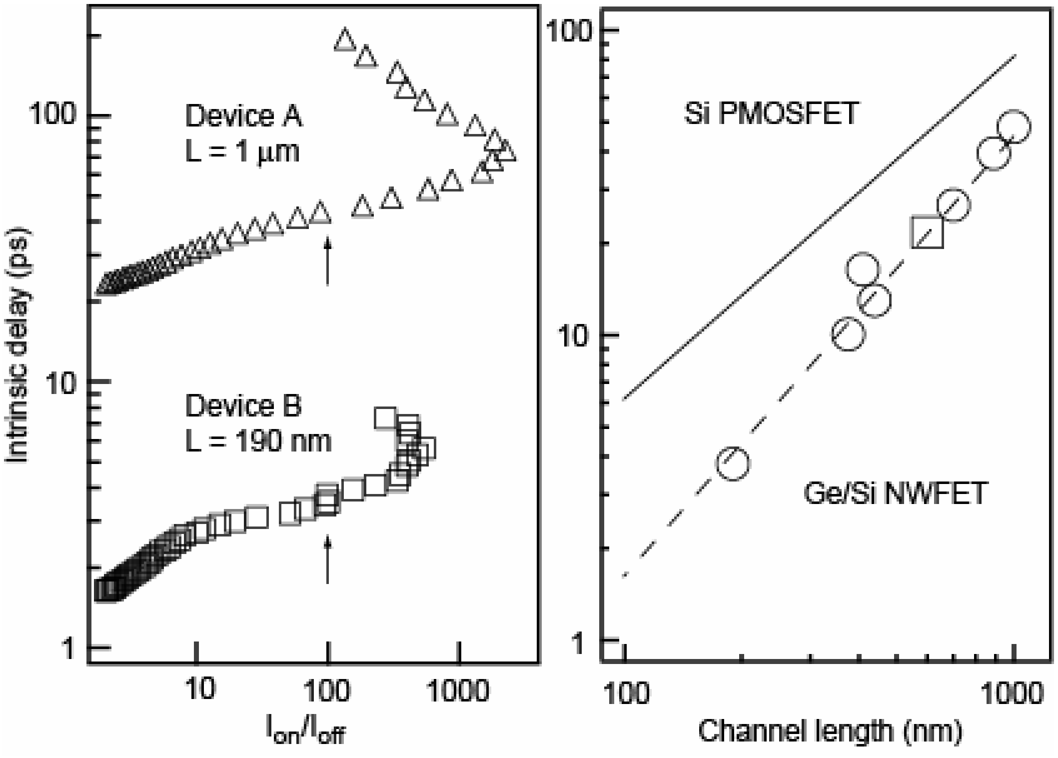






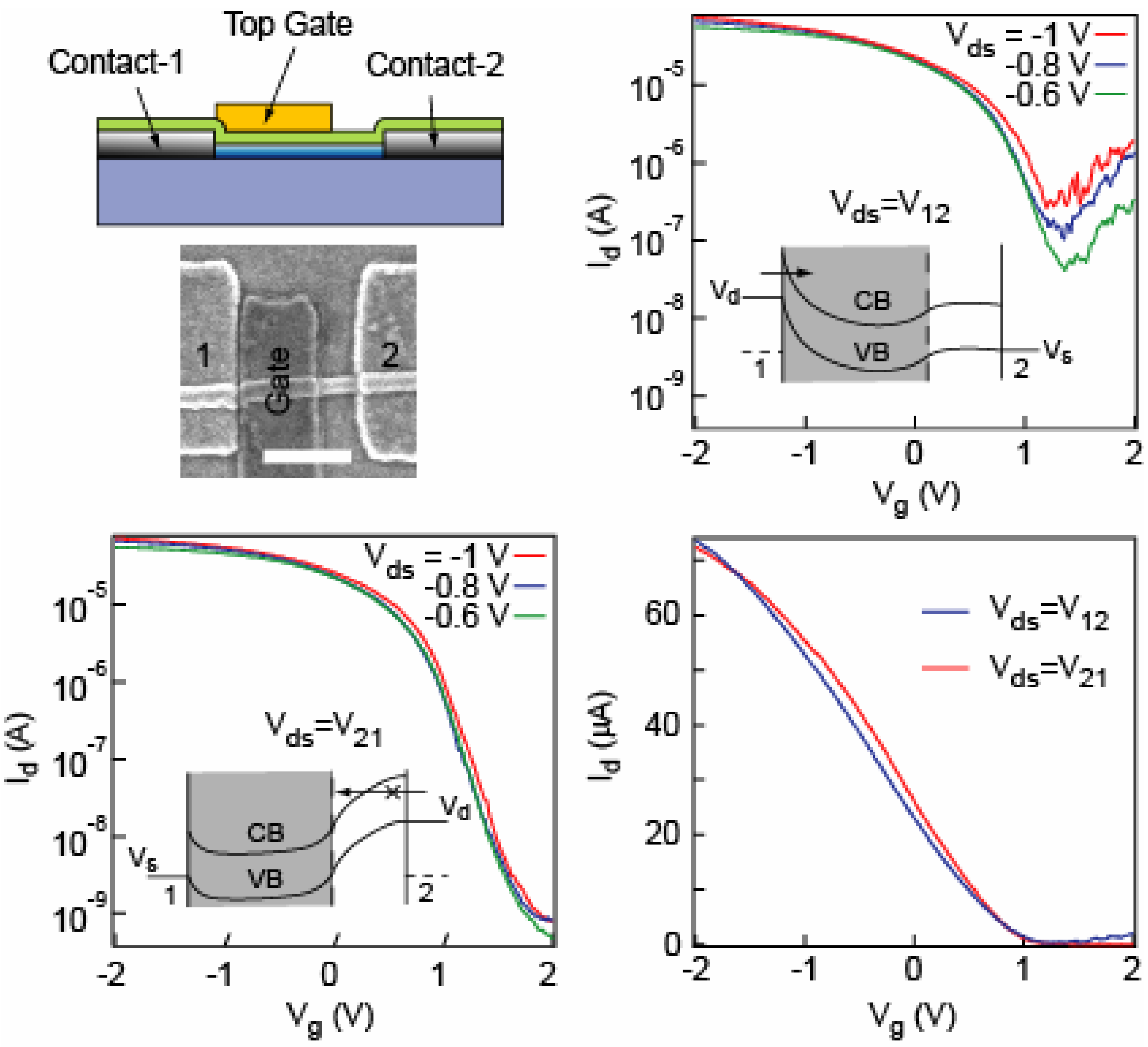
Chau, IEEE Trans Nano, **4**, 1536 (2005)

CV/I scaling of Ge/Si nanowires



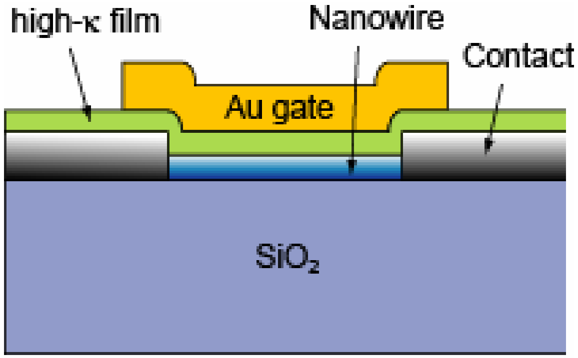
- CV/I data points picked at I_{on}/I_{off}=100
- Better than state-of-the-art p-Si devices
- Sharper slope obtained, due to suppression of mobility degradation.

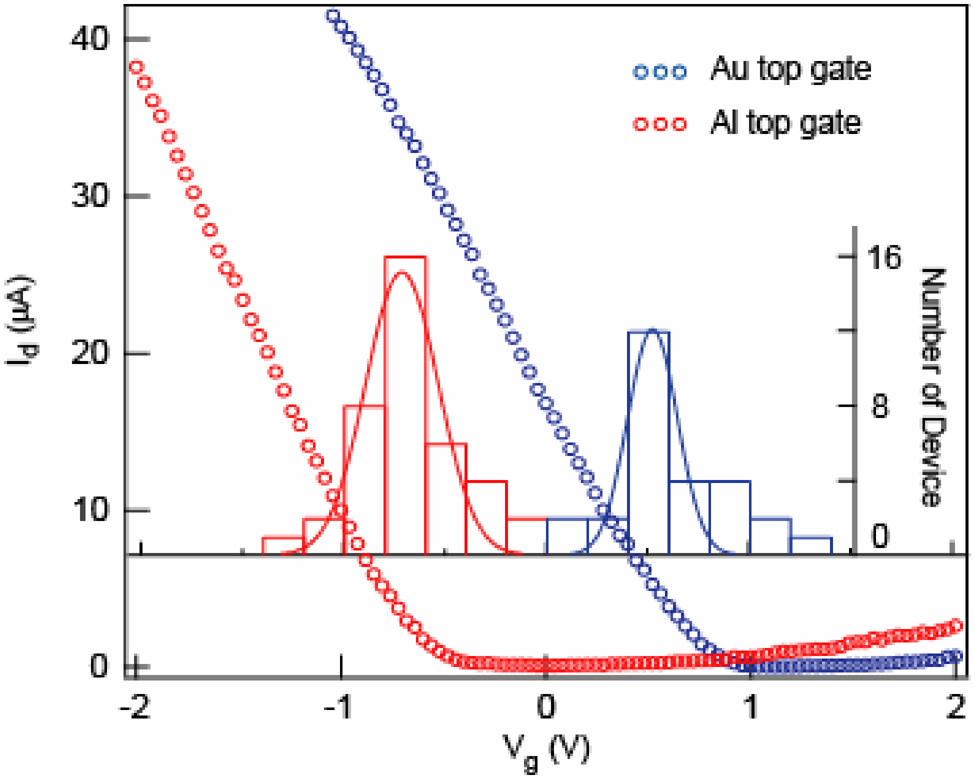
Ambipolar suppression



- •Metal contacts results in pronounced ambipolar behavior.
- •Ungated region as local contacts instead.

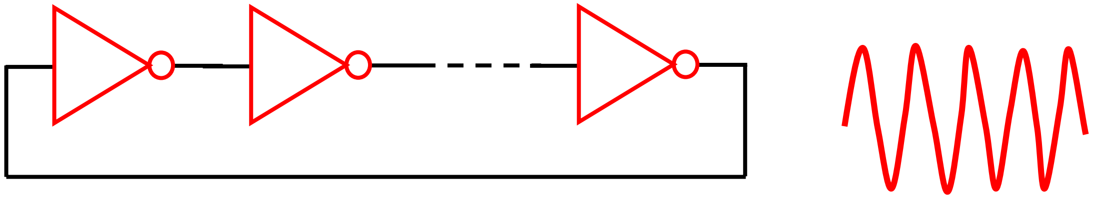
Threshold engineering



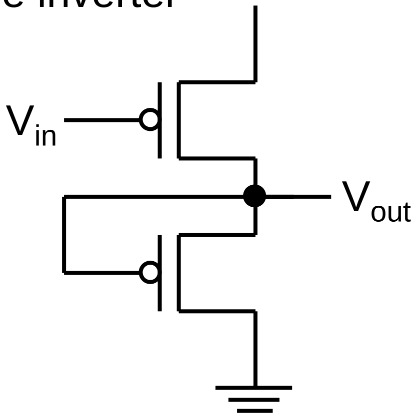


- •Both depletion mode (V_T>0) and enhancement mode (V_T<0) devices can be obtained via selection of top gate materials.
- •High uniformity

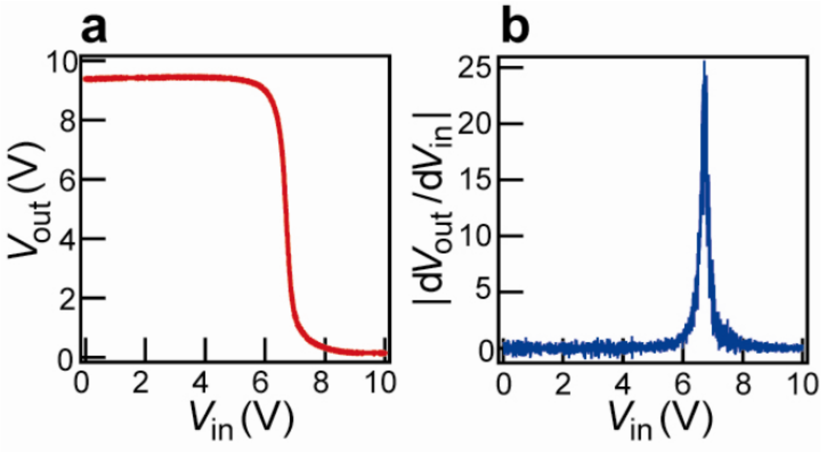
Nanowire ring oscillators



nanowire inverter



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”

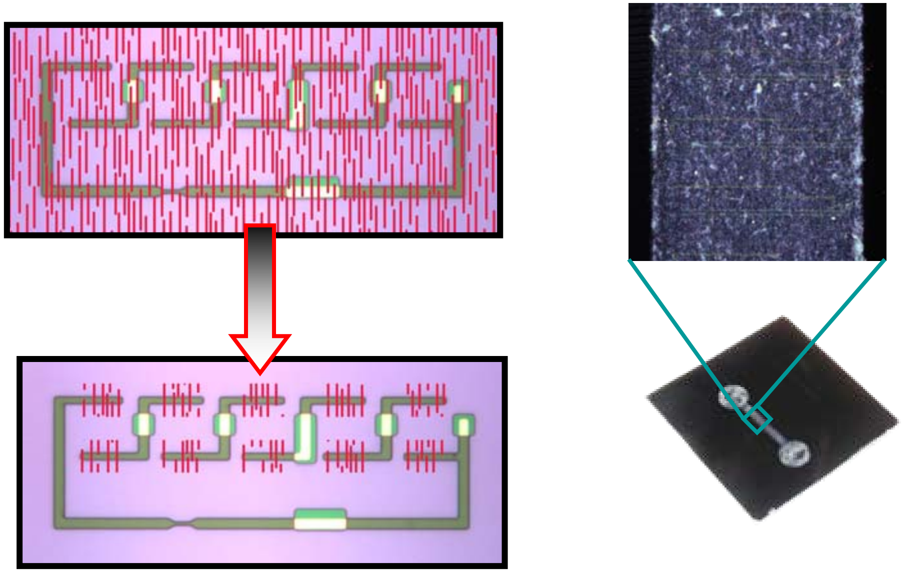


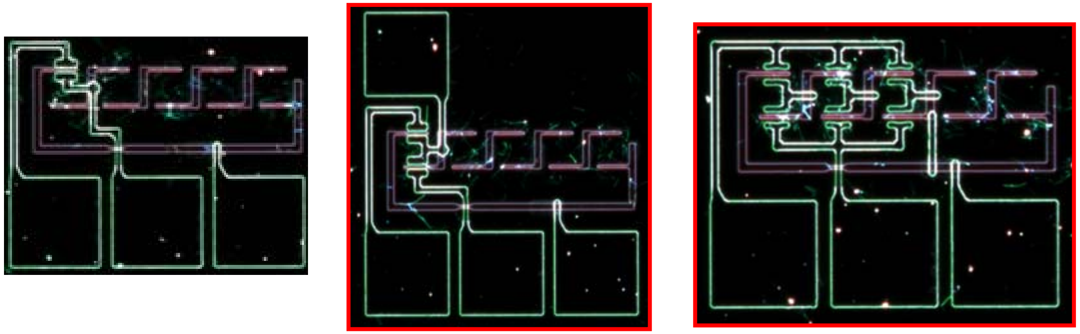
Si nanowire inverter response

Nanowire ring oscillators

Friedman, Nature **434**, 1085 (2005).

Deposit wires by flow-alignment and pattern via photolithography





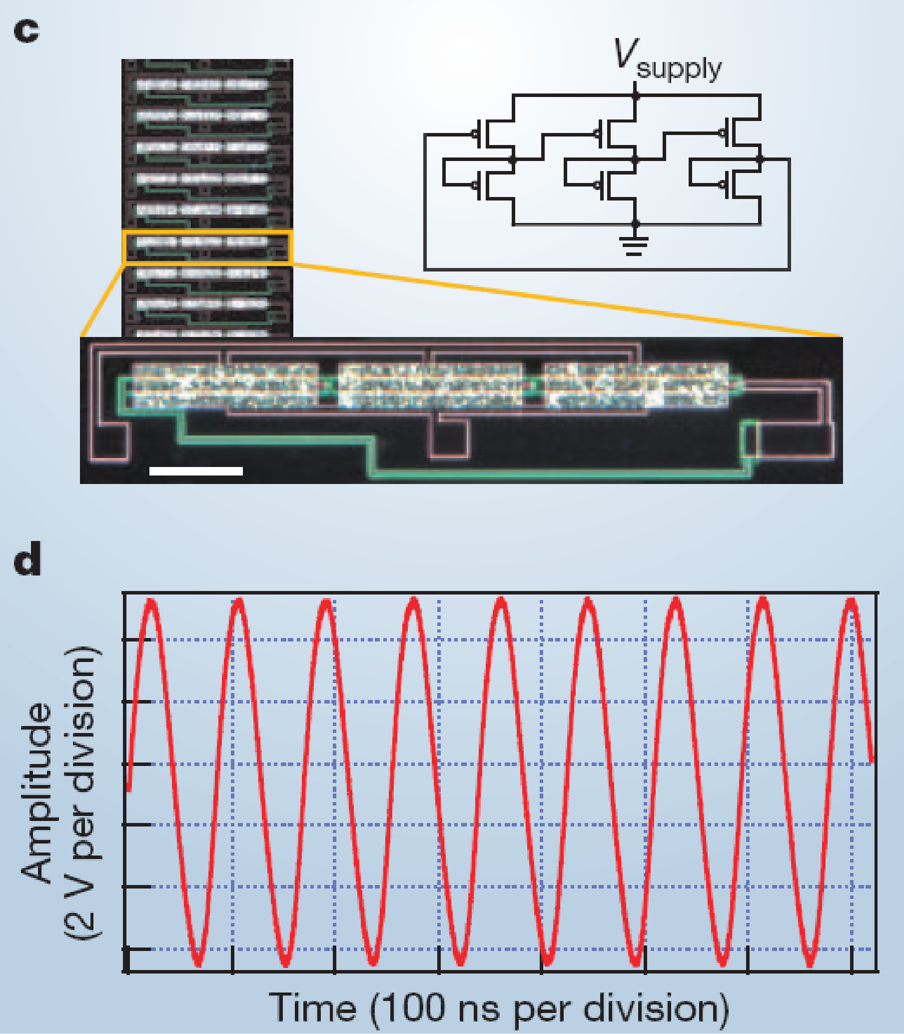
Uniformity critical in these multiple wire devices

Si nanowire ring oscillators

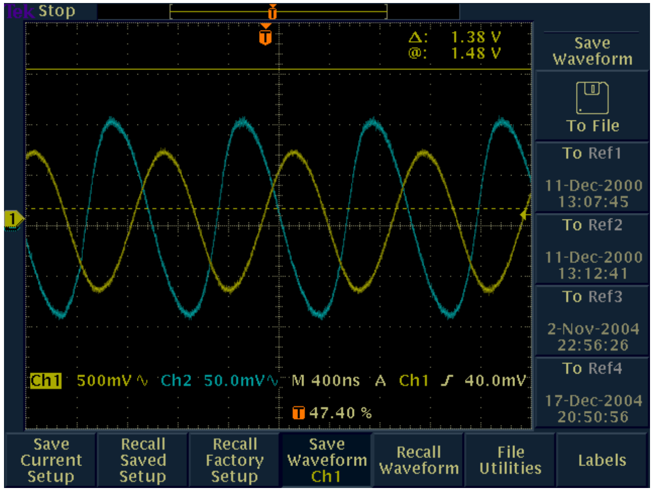
Friedman, Nature **434**, 1085 (2005).

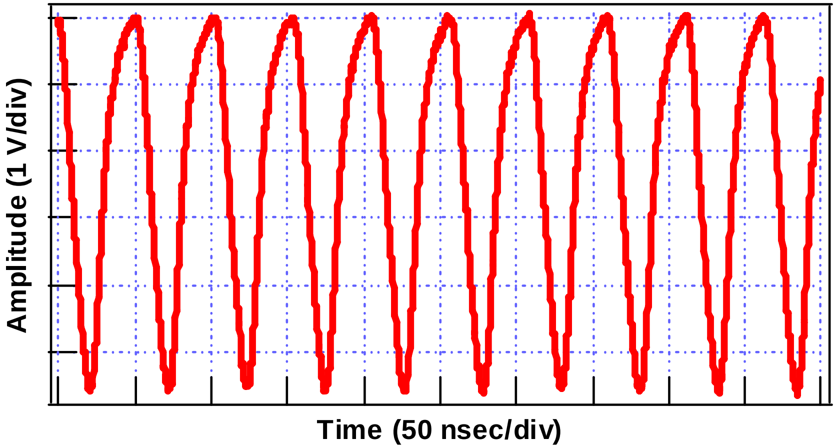
f>4MHz on oxidized Si substrate

f>10MHz on glass substrate



Ge/Si nanowire ring oscillators





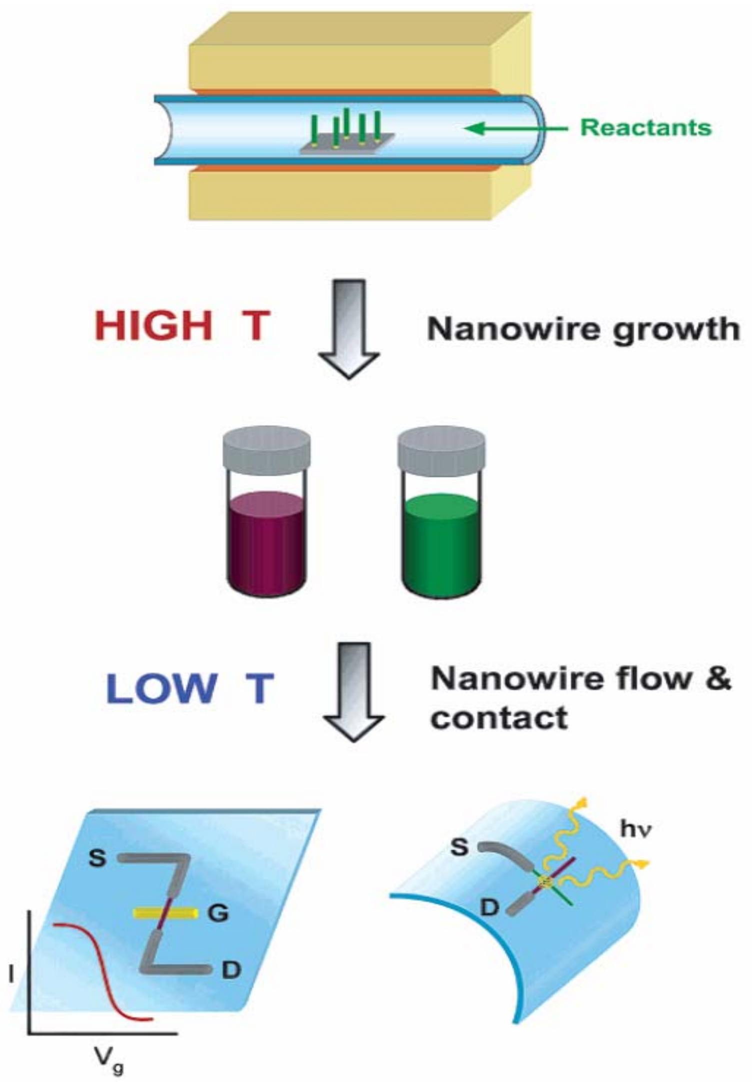
f~20MHz

Inverter response

Ring oscillator response

- Initial attempt on Si substrate already yields *f*~20MHz
- 3-4 times faster on insulating substrate, eg, glass
- Further optimization

Nanowire devices on flexible substrates



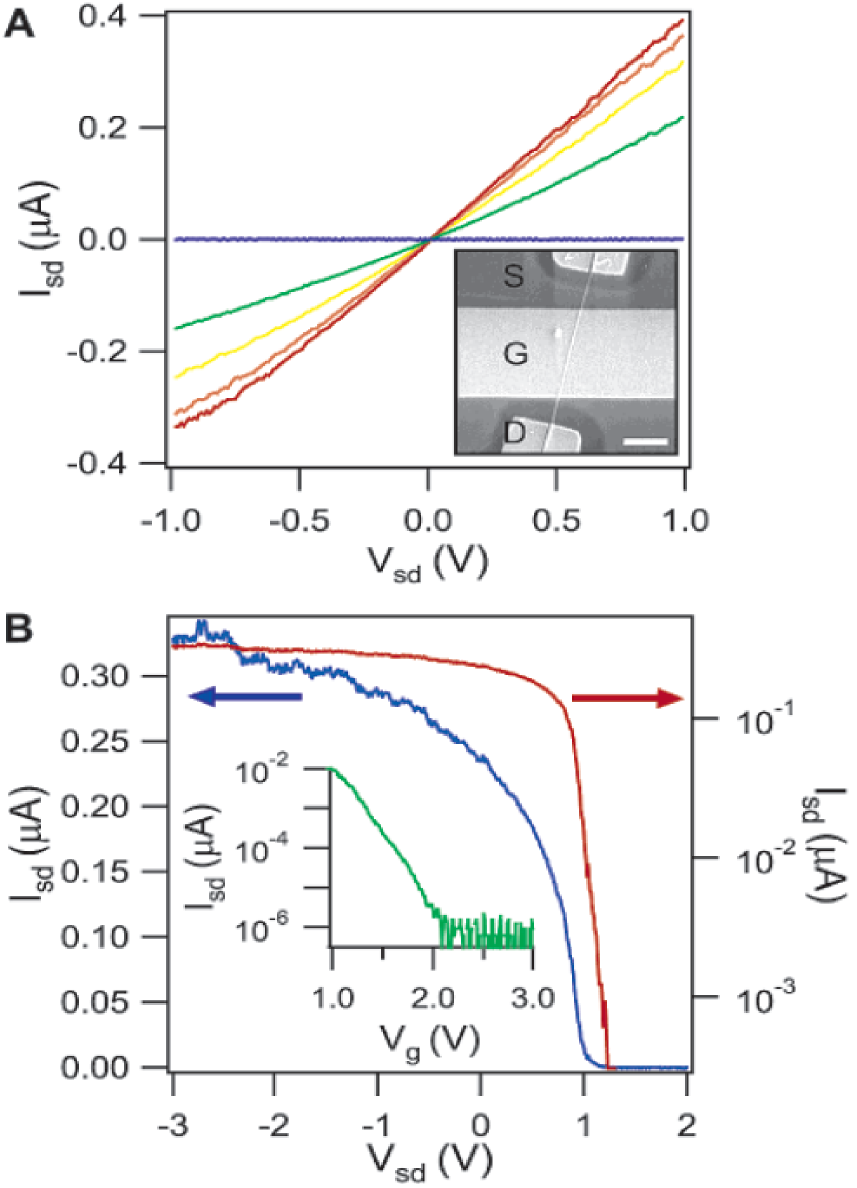
- Separation of high temperature material growth and low temperature device fabrication processes.

- High performance electronic and photonic devices on plastics

McAlpine, Nano Lett. **3**, 1531 (2003)

Nanowire devices on flexible substrates

McAlpine, Nano Lett. **3**, 1531 (2003)



μ~200cm^2/Vs, 2-3 orders higher than amorphous Si and organic semiconductors

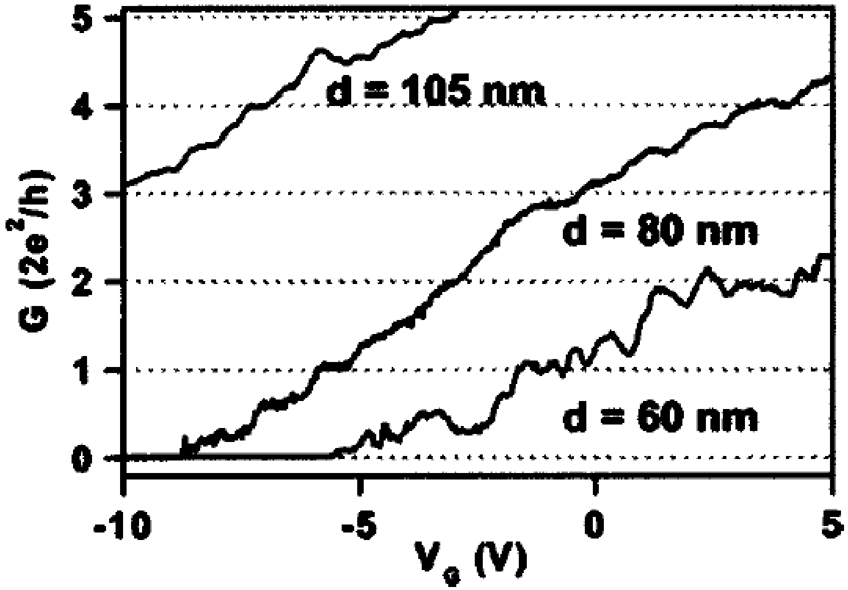
InAs nanowires and axial heterostructures

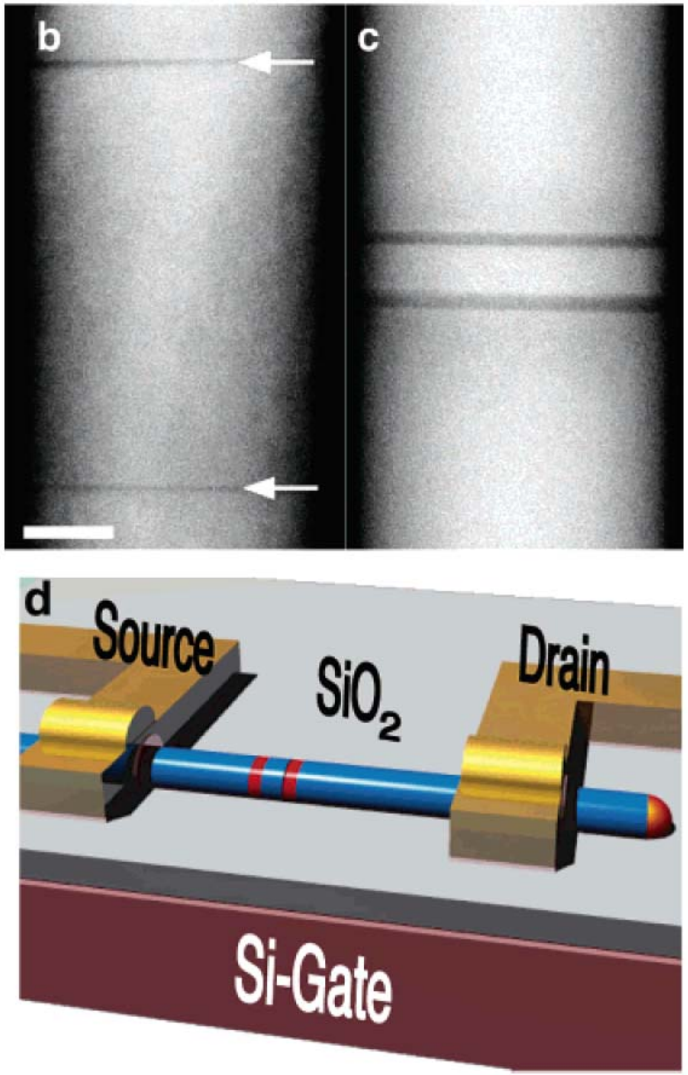
Samuelson group, Lund Univ

Bjork, Nano Lett **4**, 1621 (2004)

Thelander, APL, **83**, 2052 (2003)

InAs wire, n-type



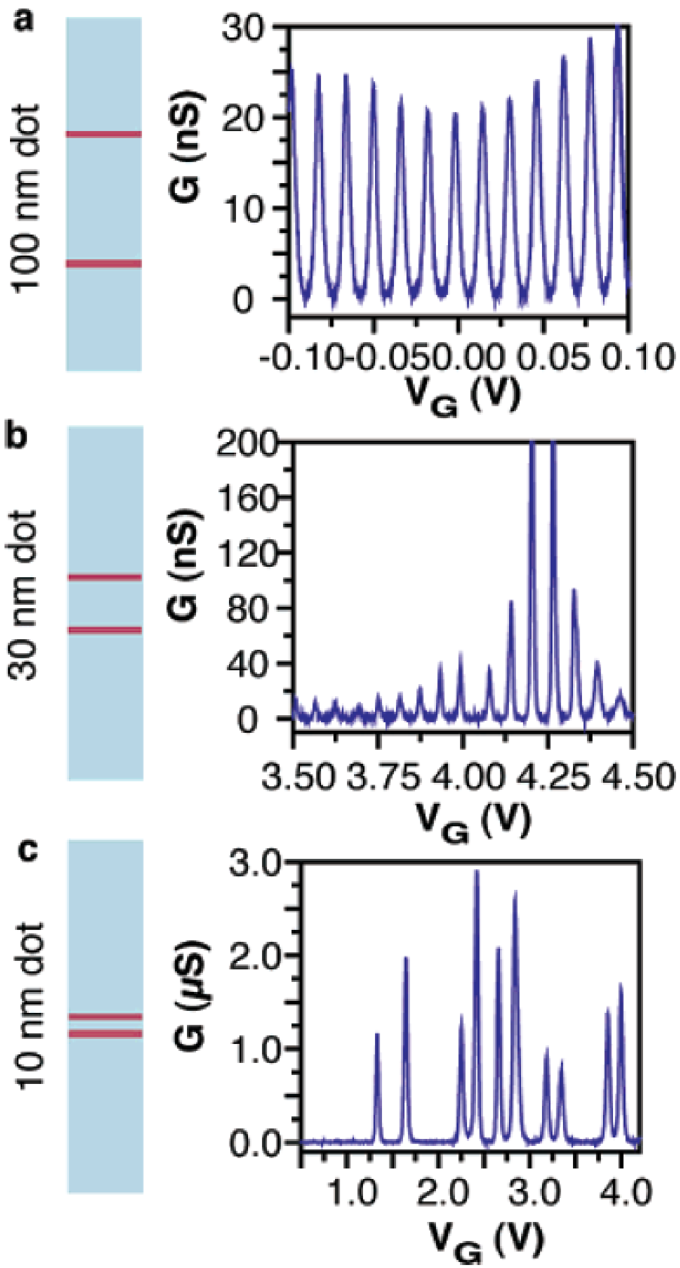


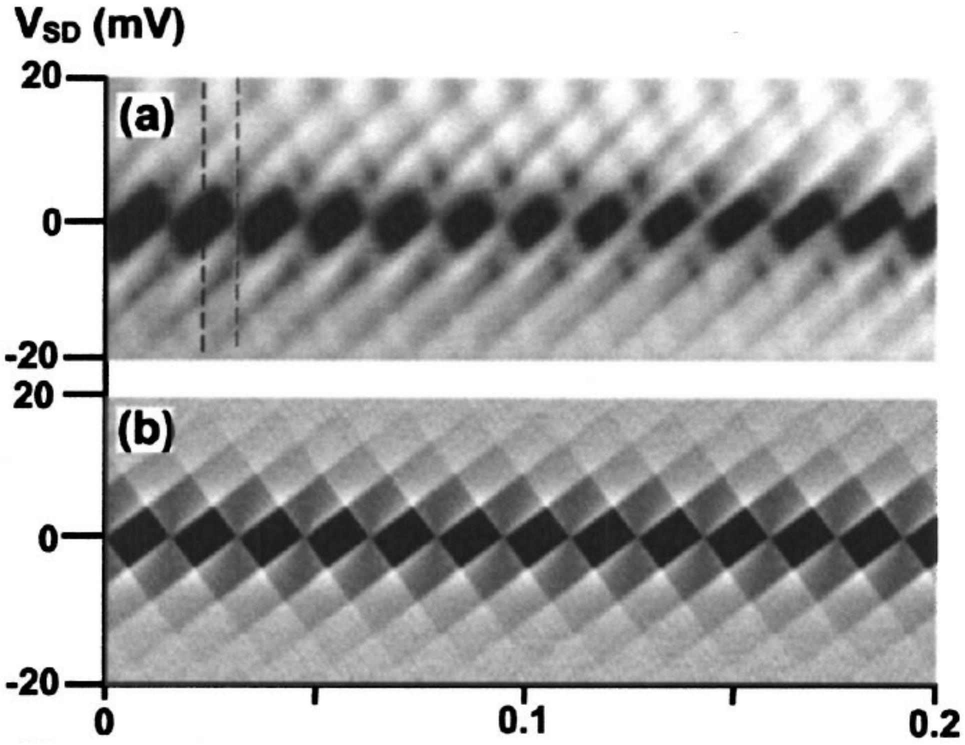
Diameter dependence of the threshold

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

Axial heterostructures, controlled growth of tunnel barriers

Bjork, Nano Lett **4**, 1621 (2004)



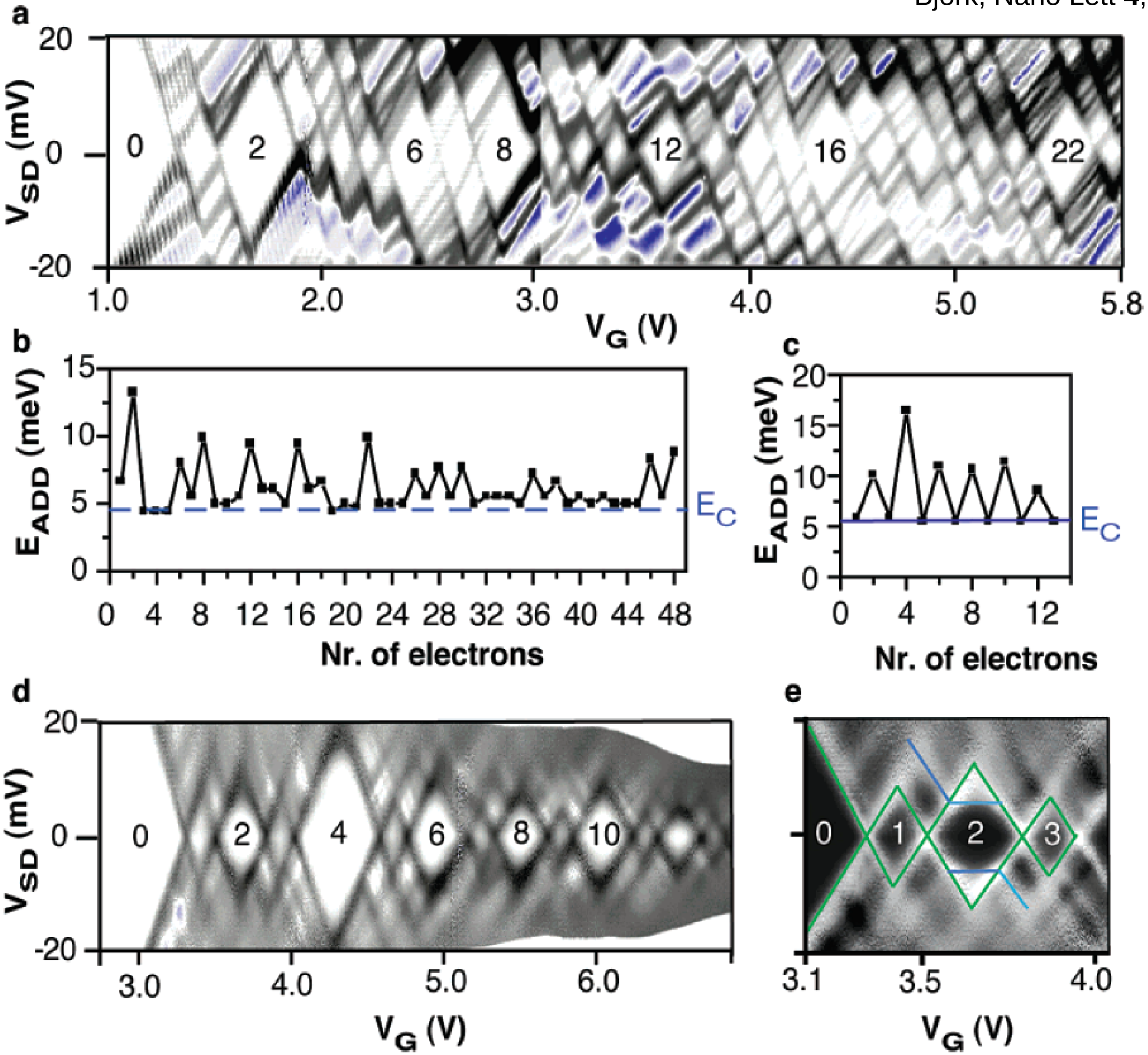


Well defined SET behavior

Thelander, APL, **83**, 2052 (2003)

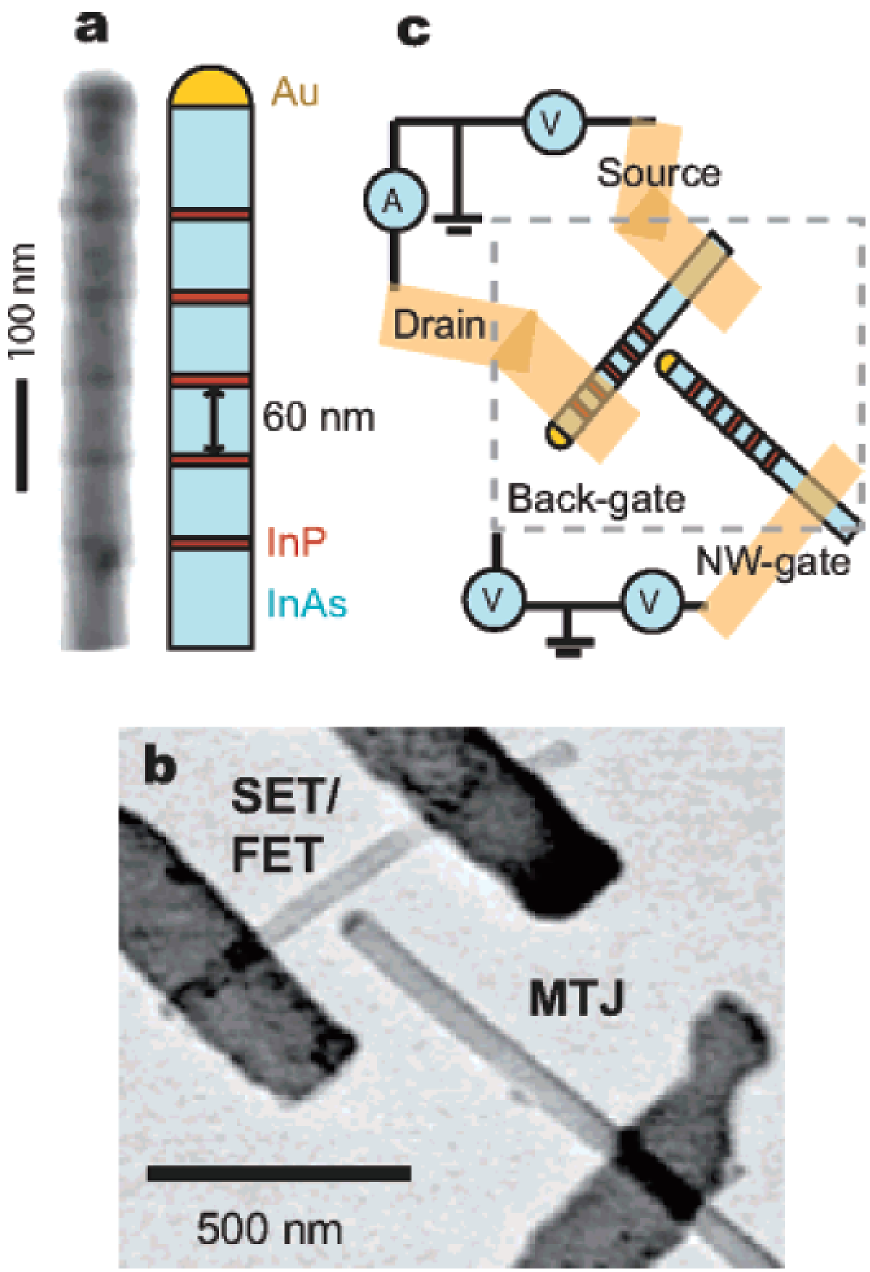
InAs nanowire quantum dots

Bjork, Nano Lett **4**, 1621 (2004)



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

Nanowire based single electron memory



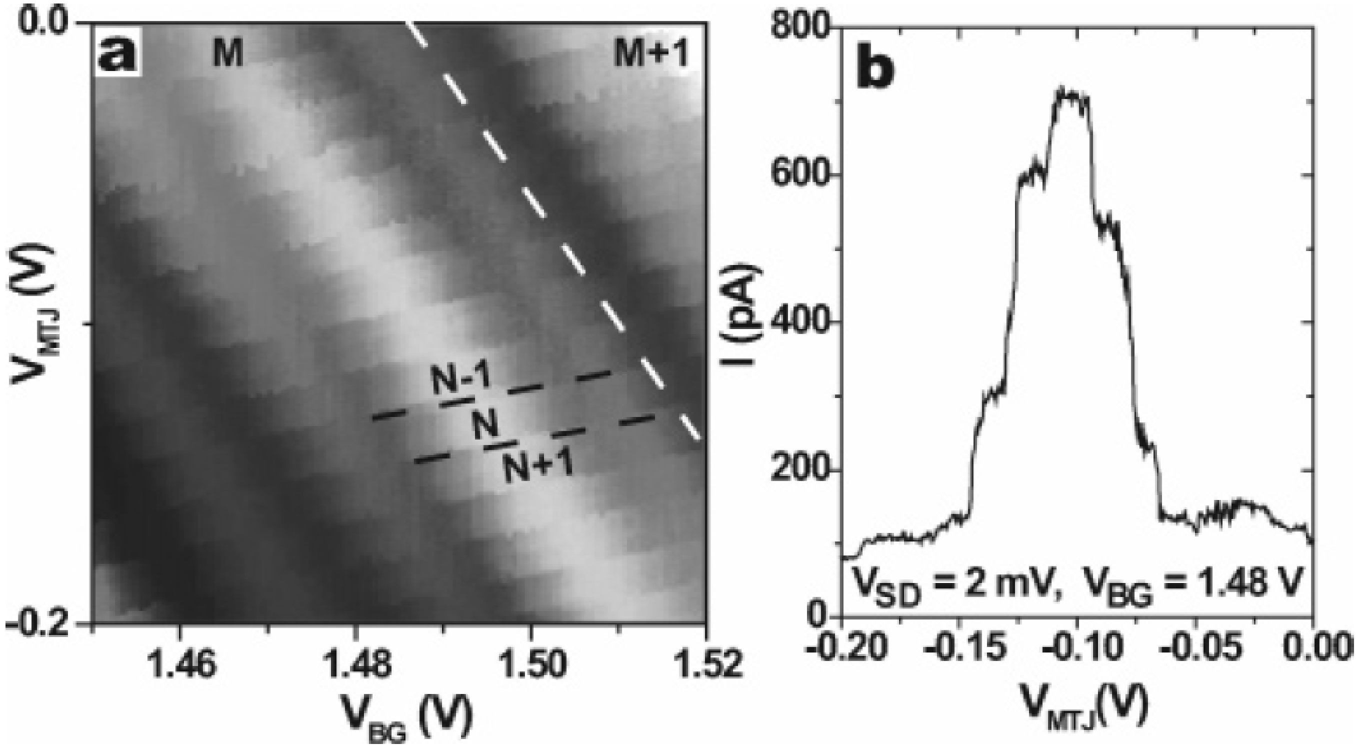
- Individual electrons added/removed via tunneling through the InP barriers

- 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



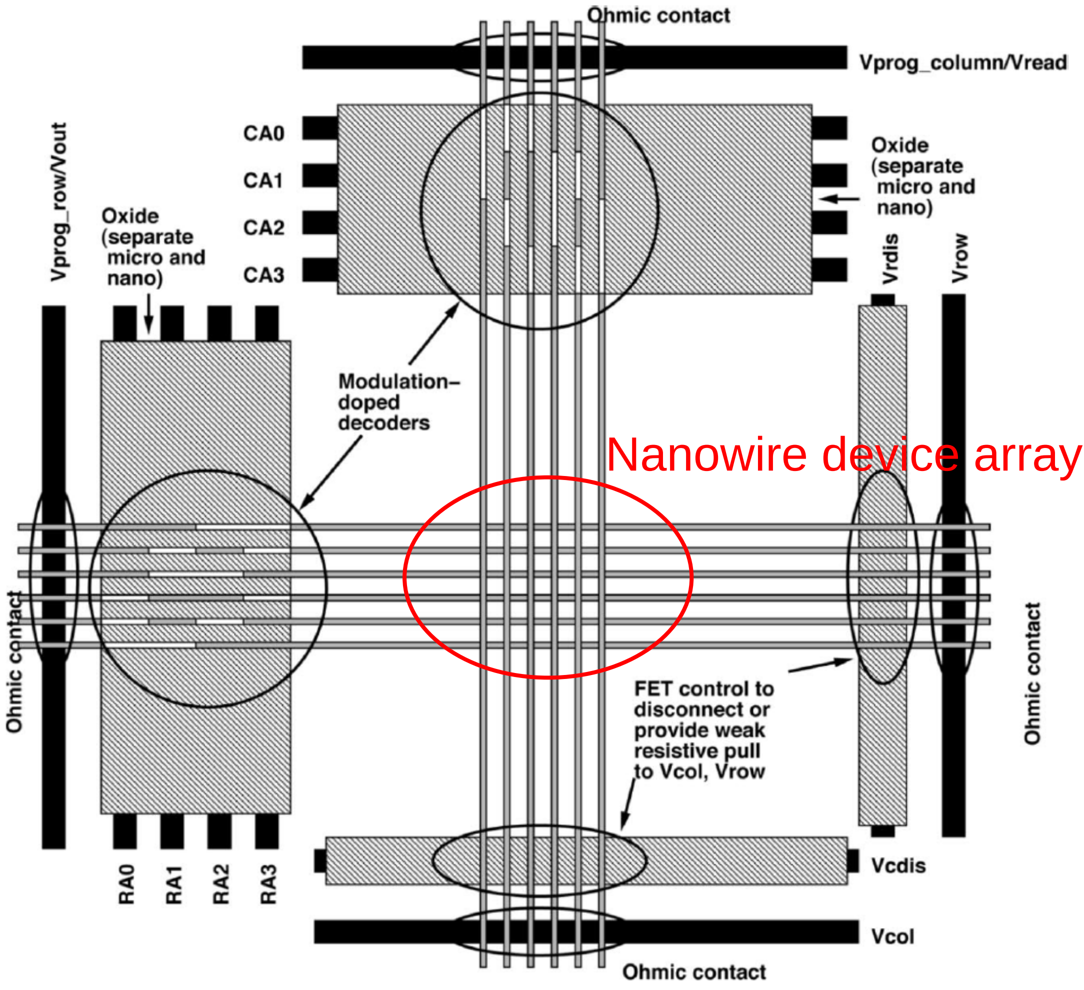
T=4.2K

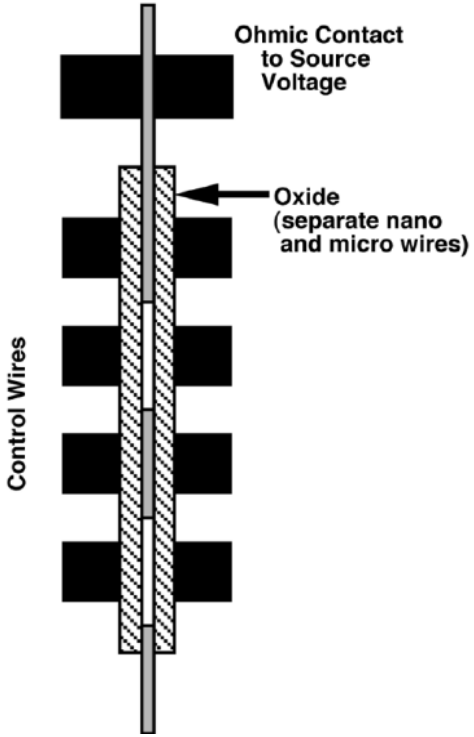
N: number of electrons on the Au particle
M: number of electrons on the SET

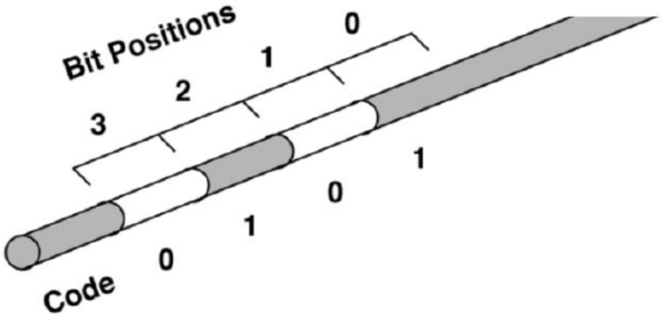
Thelander, Nano Lett. **5**, 635 (2005)

Decoder: bridging the nanoscales wires with micro scale wires

DeHon, IEEE Trans Nano, **2**, 165 (2003)





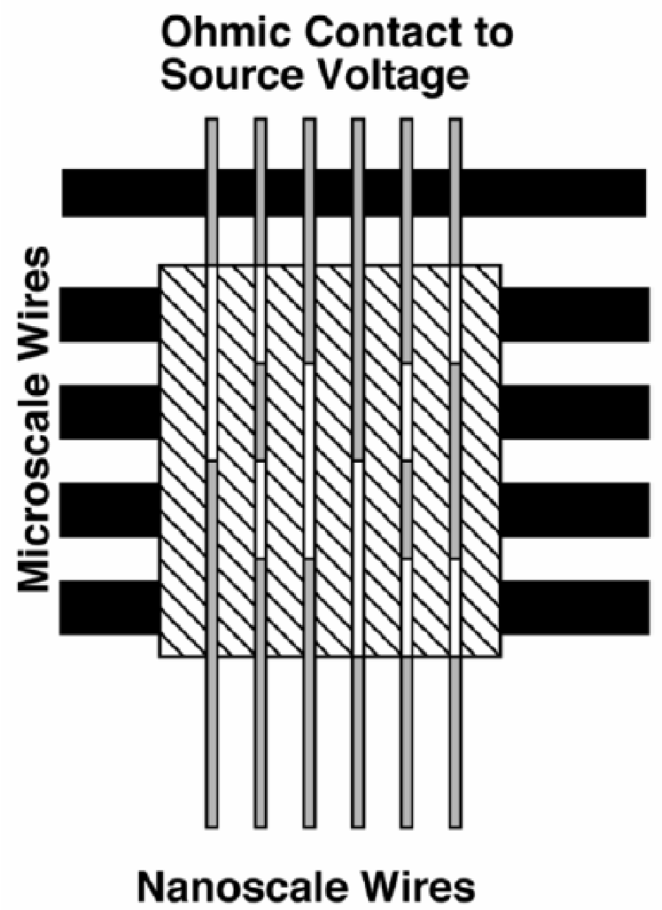


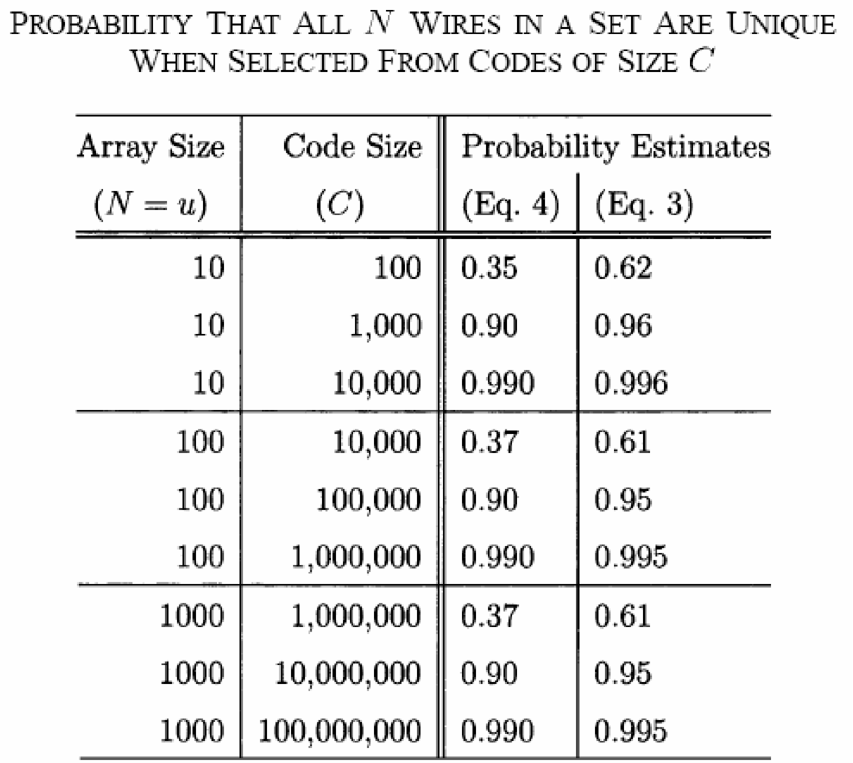
Coding achieved via modulation doping (gatable regions vs. ungatable regions)

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

Stochastic decoding

DeHon, IEEE Trans Nano, **2**, 165 (2003)

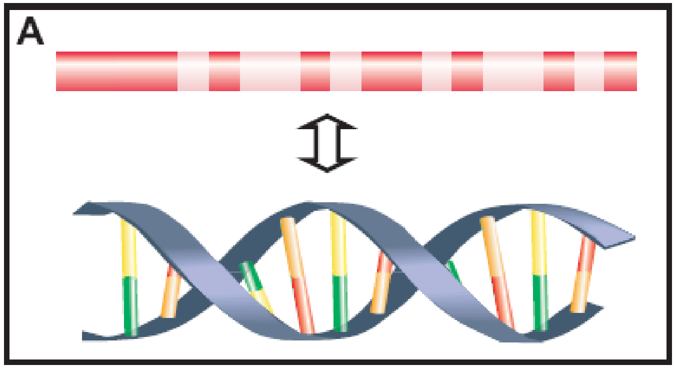


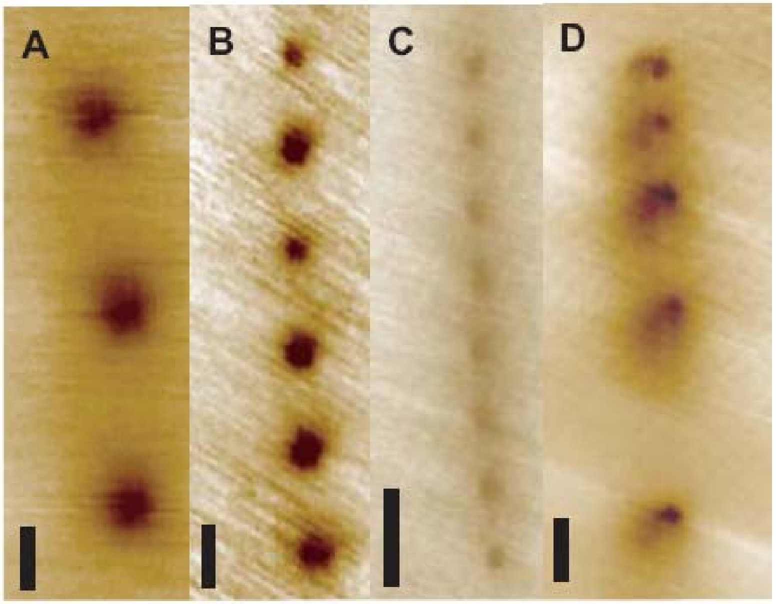

PROBABILITY THAT ALL N WIRES IN A SET ARE UNIQUE WHEN SELECTED FROM CODES OF SIZE C

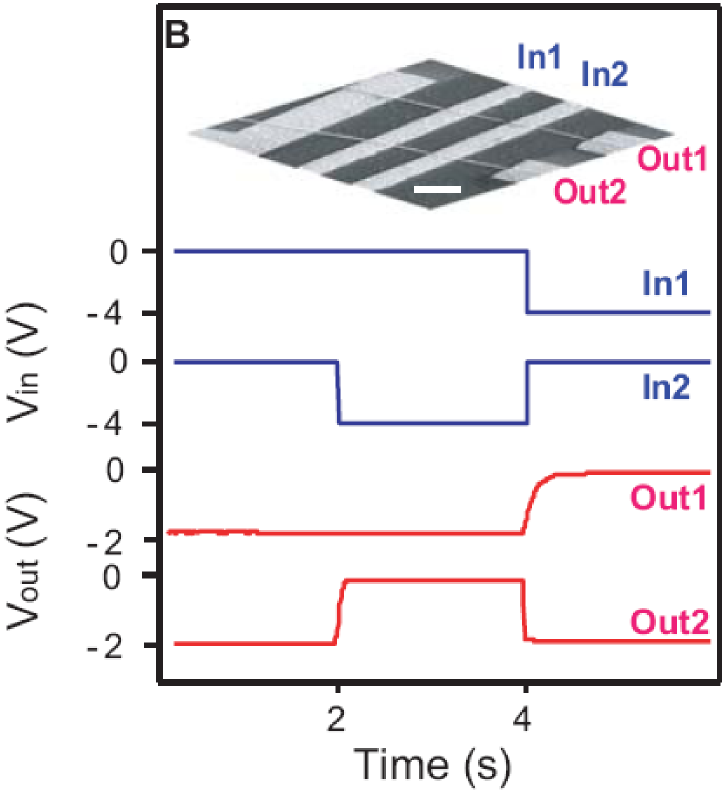
Array Size ($N = u$)	Code Size (C)	Probability Estimates (Eq. 4)	(Eq. 3)
10	100	0.35	0.62
10	1,000	0.90	0.96
10	10,000	0.990	0.996
100	10,000	0.37	0.61
100	100,000	0.90	0.95
100	1,000,000	0.990	0.995
1000	1,000,000	0.37	0.61
1000	10,000,000	0.90	0.95
1000	100,000,000	0.990	0.995

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



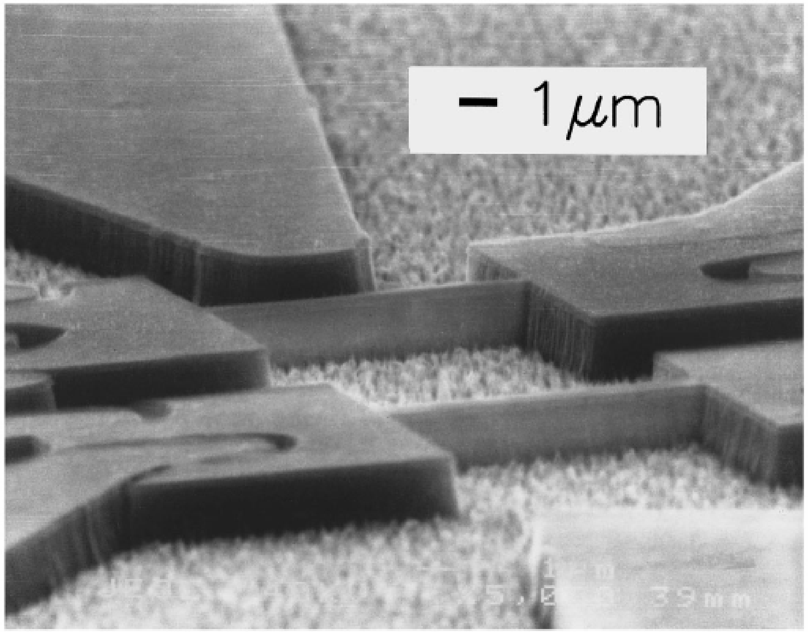


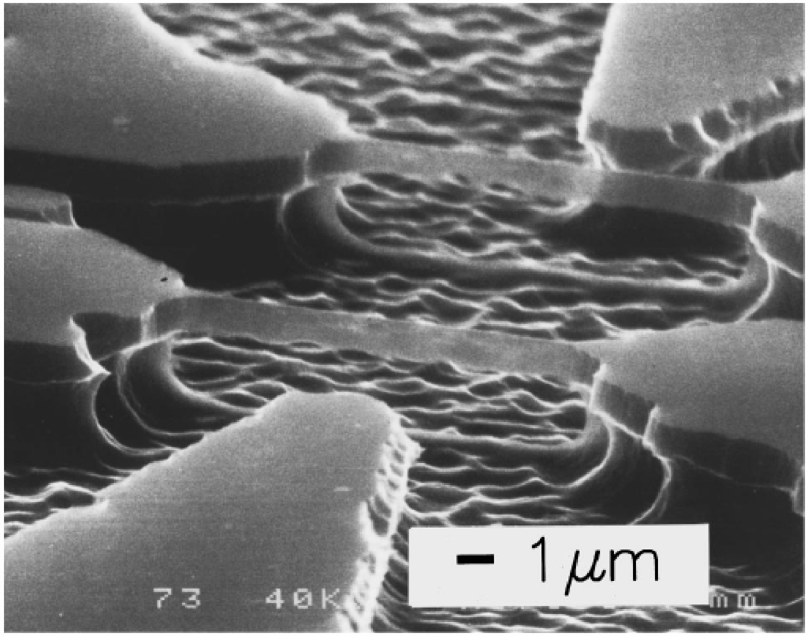


Yang, Science, 2005

Cleland, APL, **69**, 2653 (1996)

Mechanical resonators





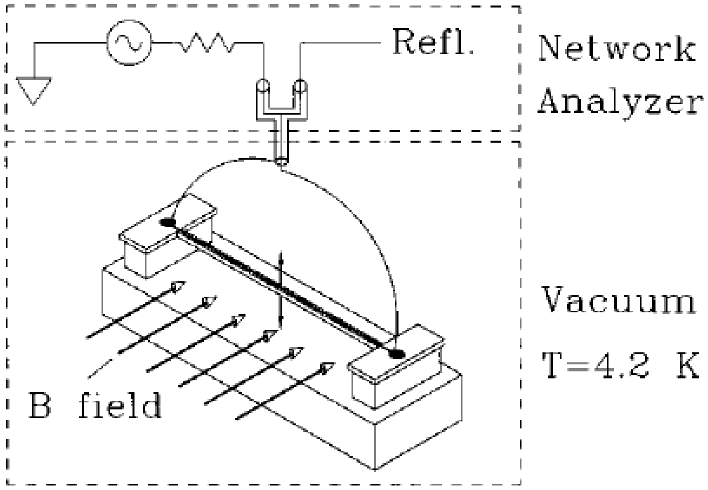
$$\omega = \left(\frac{4.73}{l}\right)^2 \left(\frac{EI}{\rho A}\right)^{1/2},$$

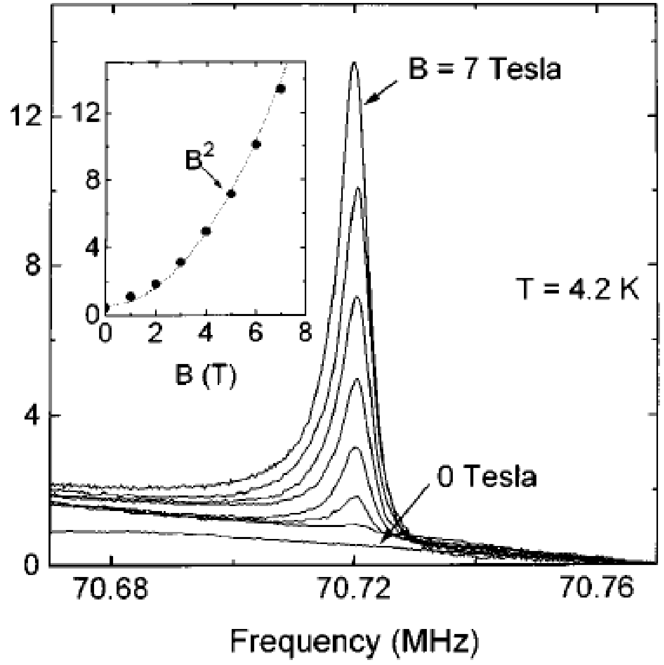
Application: passive RF filters, oscillators for wireless communications. (eg, prof. Nguyen’s group).

Fundamental interest (flexural modes):
hf~50 mK for f=1GHz, quantum mechanical system.
hf~4μeV, comparable to energy scales of electrical systems. Entangled mechanical/electrical systems.

Cleland, APL, **69**, 2653 (1996)

Magnetomotive actuation



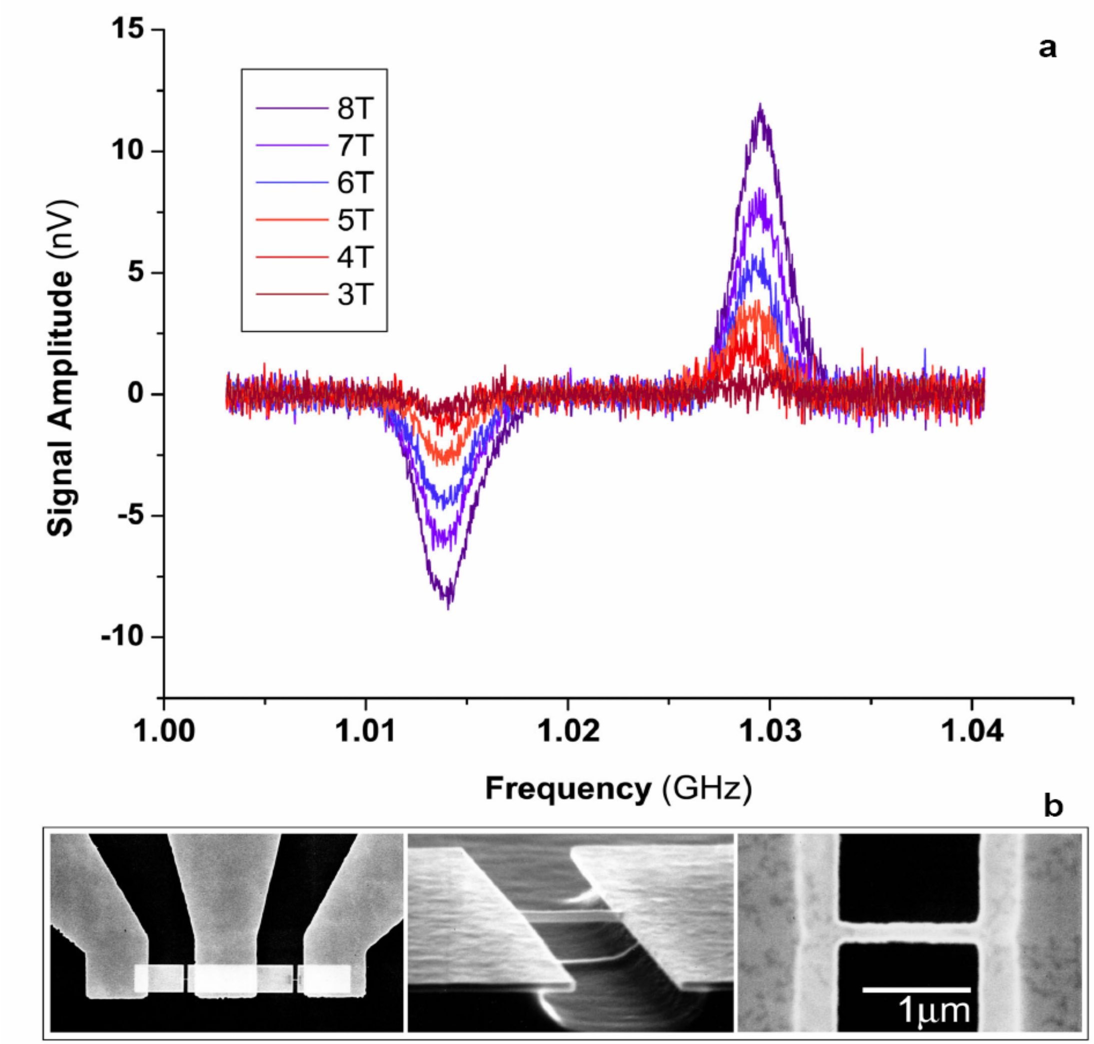


In plane magnetic field.
AC current creats Lorentz driving force.

Other actuation methods

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

GHz resonators



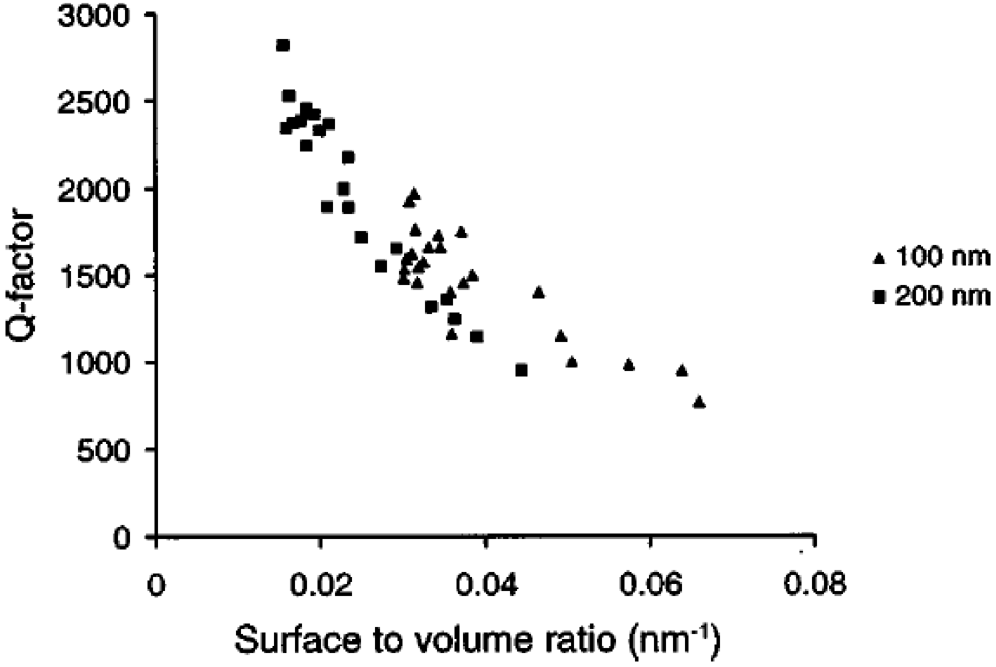
Doubly clamped SiC beam

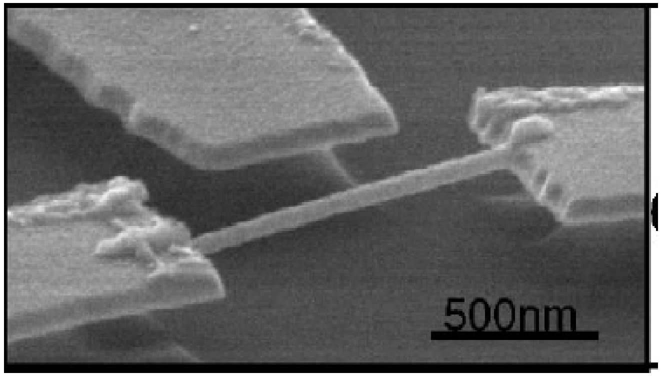
f~1GHz, Q~500

Huang, *Nature* **421**, 496 (2003).

Surface roughness induced losses

Carr, APL, **75**, 920 (1999)





f~1GHz for a resonator based on Si nanowires with d=20nm and *l*=400nm.

- 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

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),