Tutorial on

Electronic Transport

$$\frac{2e^2}{h}$$

Jesper Nygård

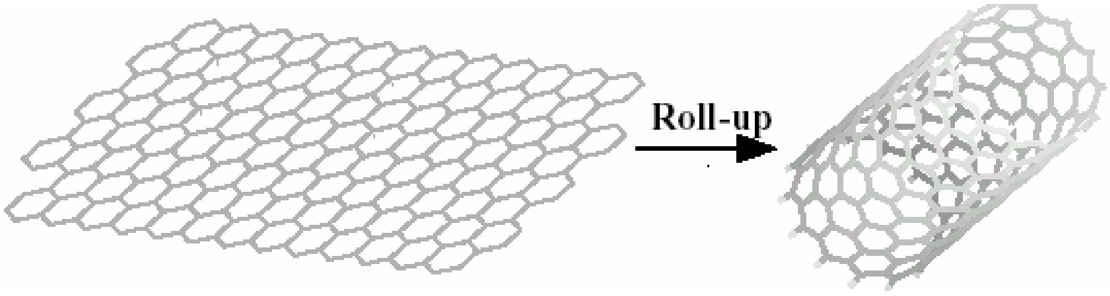
Niels Bohr Institute

University of Copenhagen

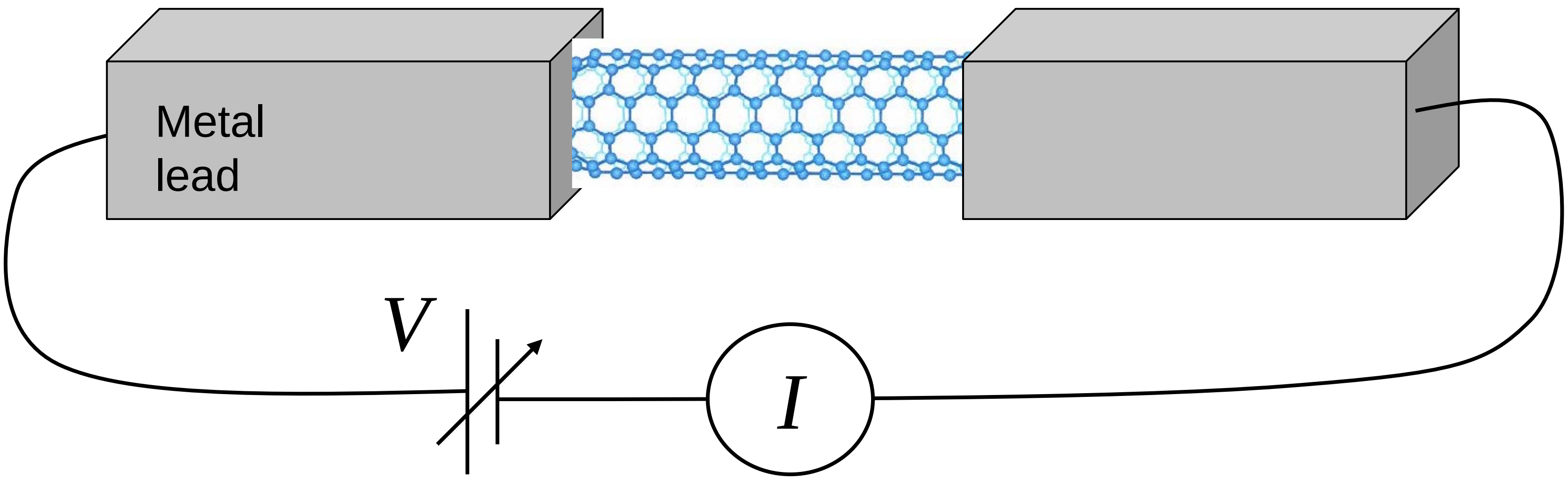
...for newcomers in the field...

Prior knowledge:

- What is a carbon nanotube
- (Some) nanotube band structure
- Ohm’s first law



Our aim: Understand the two-terminal electrical transport



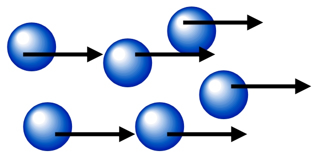
- **Rich on exciting physics and surprising phenomena**
- **Key for interpreting wide range of experiments**
- **Many possible variations over this theme:**
  - electrostatic gates
  - contact materials (magnetic, superconducting)
  - sensitive to environment (chemical, temperature...)
  - interplay with nano-mechanics, optics, ...

Outline

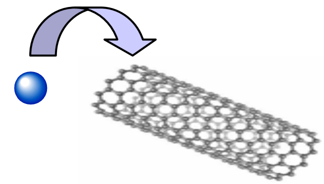
- Electronic structure (1D, 0D)
  - density of states
- Electron transport in 1D systems (general)
  - quantization, barriers, temperature
- Transport in nanotubes (1D)
  - contacts, field-effect,...
- Nanotube quantum dots (0D)
  - Coulomb blockade, shells, Kondo, ...
- Nanotube electronics, various examples
- Problem session
- Wellcome party

Nanoscale electrical transport

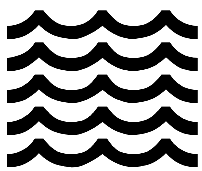
Electrons



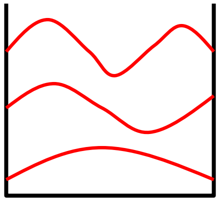
Charge -*e*



Single-electron effects

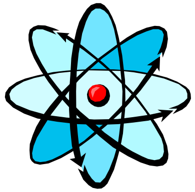


Wave function



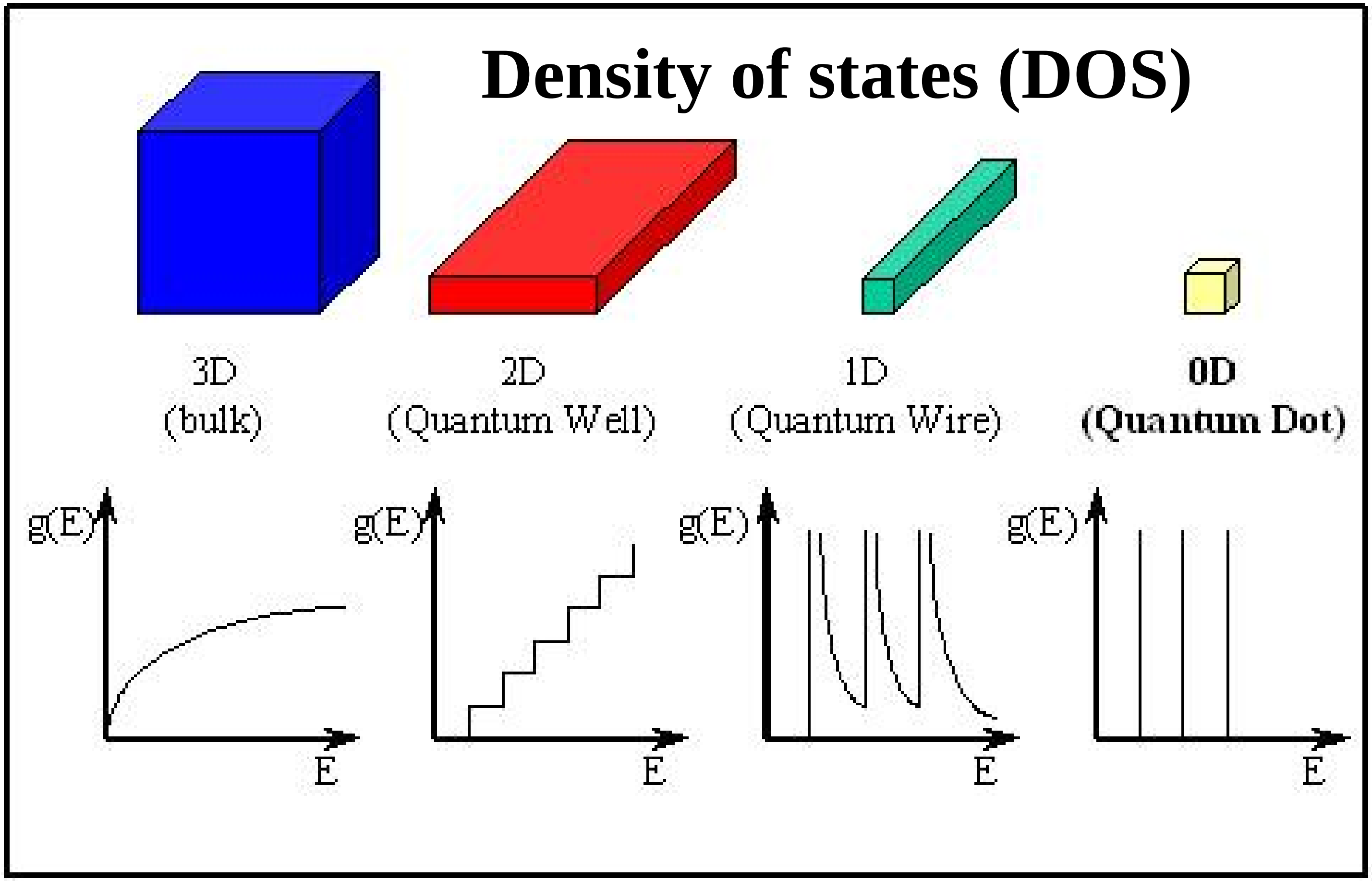
Size quantization

Mesoscopic transport; quantum transport ...



nm ? μm

Electronic structure



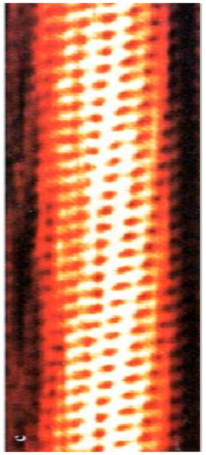
1D:
semiconductor quantum wires
conducting polymers
nanotubes

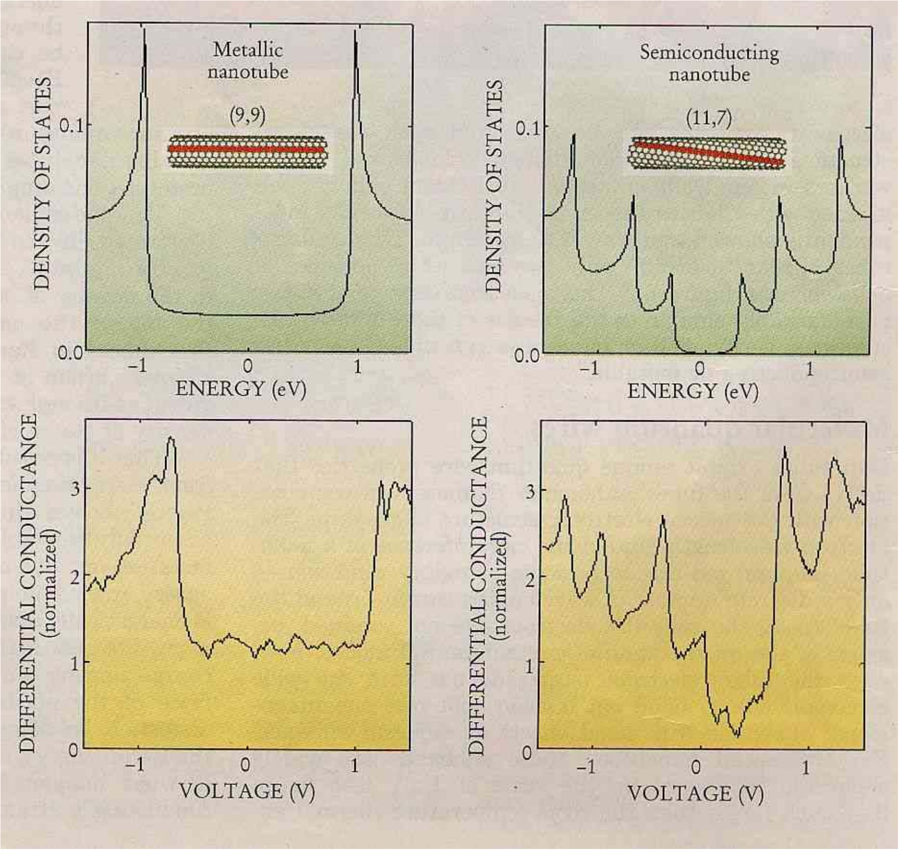
0D:
atoms
molecules
nanocrystals
metal nanoparticles
quantum dots
short nanotubes

1D density of states per unit length:

$$g_{1D}(E) = \frac{2}{h}\sqrt{\frac{2m}{E}} = \frac{2}{hv(E)} = \frac{2}{\pi}\left(\frac{dE}{dk}\right)^{-1} \qquad v_{\text{group}} = \frac{d\omega}{dk} = \frac{1}{\hbar}\frac{dE}{dk}$$

Tunneling spectroscopy (STM)





van Hove singularities:

dI/dV ~ DOS ~ $(E)^{-1/2}$

Cees Dekker, Physics Today, May 1999

Electronic transport

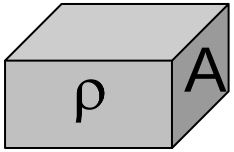
Resistance and conductance

Ohm's first law: $V = R \,.\, I$

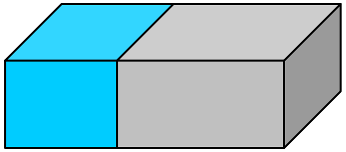
Ohm's second law: $R = V \,/\, I$ $[\Omega]$

Bulk materials; resistivity ρ:

$$R = \rho\, L \,/\, A$$



L



R is additive

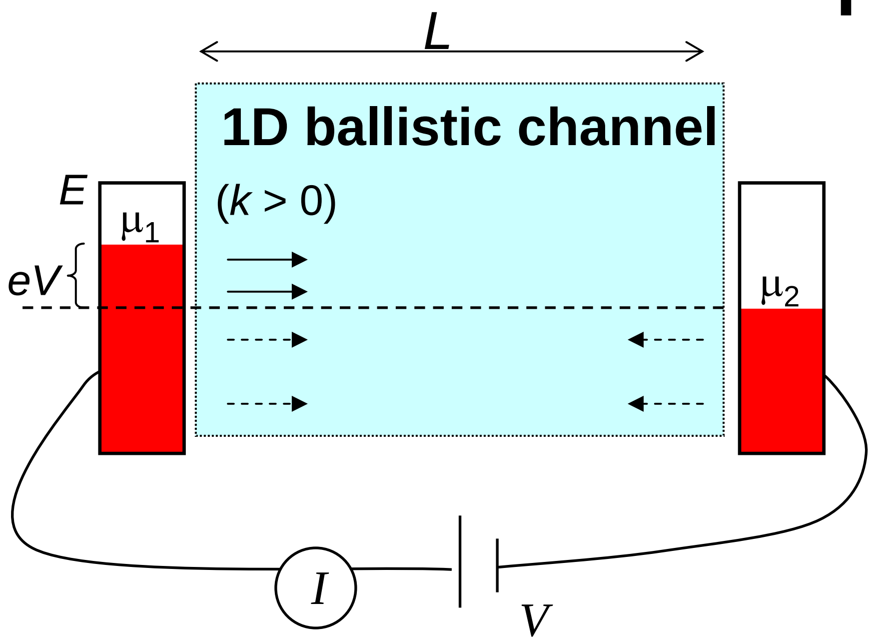
Nanoscale systems (coherent transport):

R is a **global** quantity, cannot be decomposed into local resistivities (see why later)

Conductance *G*: $G = 1 \,/\, R = I \,/\, V$ [unit e^2/h]

(Not *conductivity* σ)

Conductance of 1D quantum wire



Contacts: 'Ideal reservoirs'

Chemical potential $\mu \sim E_F$ (Fermi level)

Channel: 1D, ballistic (transport without scattering)

velocity

$$I = \int_{\mu_1}^{\mu_2} ev(E)\left(\overbrace{2\frac{1}{2}g_{1D}(E)}^{\text{1D density}}\right)\mathrm{d}E = \int_{\mu_1}^{\mu_2} ev(E)\left(\frac{2}{hv(E)}\right)\mathrm{d}E$$

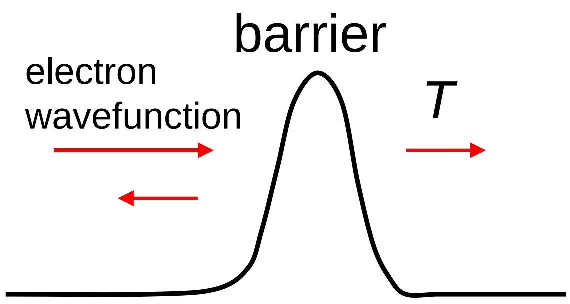
spin $\quad$ $k > 0$

$$= \frac{2e}{h}(\mu_2 - \mu_1) = \frac{2e}{h}(eV)$$

$$\boxed{G = I/V = \frac{2e^2}{h}}$$

Conductance is fixed, regardless of length *L*, no well defined conductivity σ

Conductance from transmission



Rolf Landauer (1927-1999);
- *G* controversial issue in 80'ies

Landauer formula:

$$G = \frac{2e^2}{h} T \quad (\text{transmission probability } T)$$

With *N* parallel 1D channels (subbands):

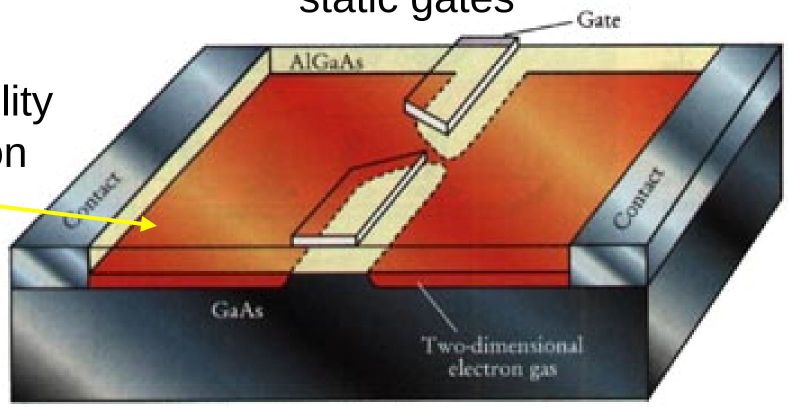
$$G(E_F) = \frac{2e^2}{h} \sum_n T_n(E_F) \ (T = 0)$$

Quasi-1D channel in 2D electron system

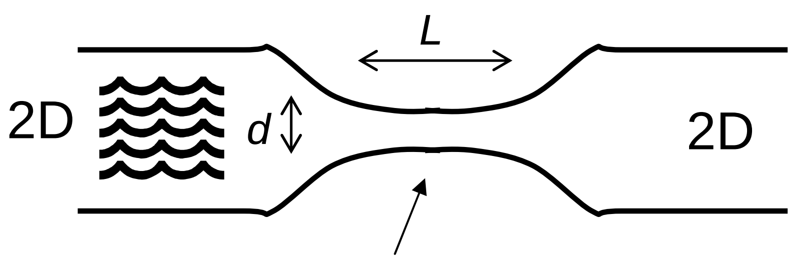
$$G(E_F) = \frac{2e^2}{h}\sum_n T_n(E_F) \approx \frac{2e^2}{h} N(E_F)\ (T = 0\text{K})$$

Depletion by electro-static gates

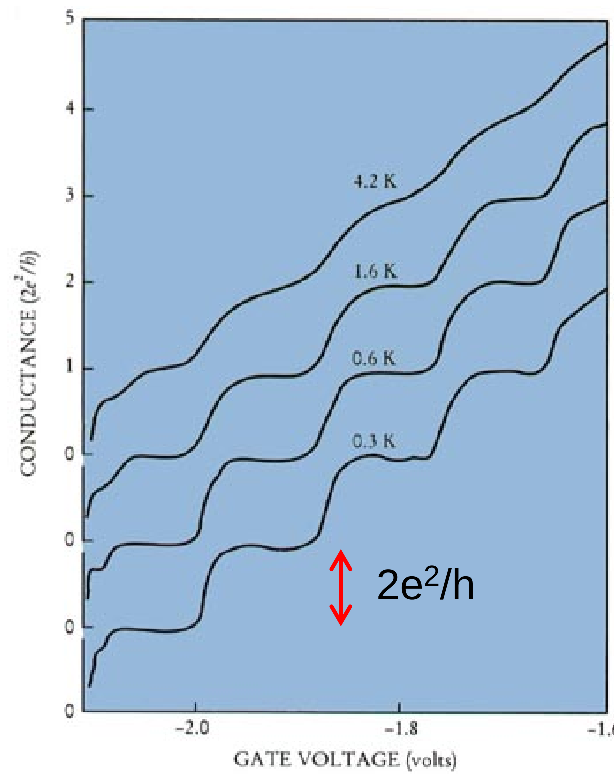
High mobility 2D electron gas ('ballistic')



'Quantum Point Contact'

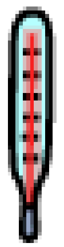


Narrow constriction; quasi-1D (width d ~ Fermi wavelength λ_F)

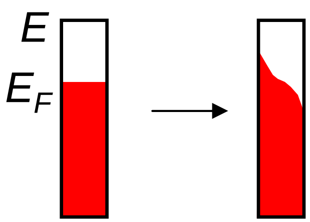


Limited conductance $2e^2/h$ even without scattering, regardless of length L: "contact resistance"

Finite temperature



- Electrons populate leads according to Fermi-Dirac distribution:



$$f(E, E_F) = \frac{1}{\exp\left(\frac{E-E_F}{k_B T}\right) + 1}$$

- Conductance at finite temp. *T*:

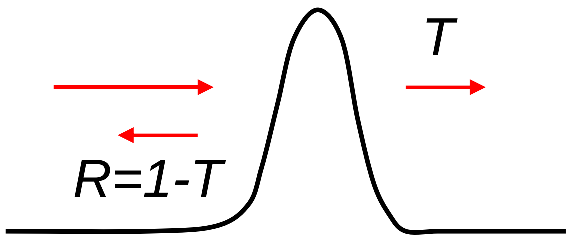
$$G(E_F, T) = \frac{2e^2}{h} \sum_n \int T_n(E) \left(-\frac{df}{dE}\right) dE \approx \frac{2e^2}{h} \sum_n f(E_n - E_F)$$

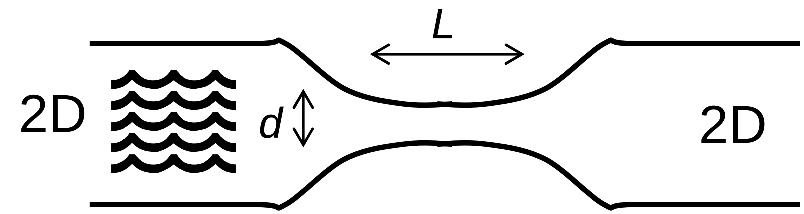
eg. thermal smearing of conductance staircase (previous slide)

- Higher *T*: incoherent transport
  (dephasing due to inelastic scattering, phonons etc)

Where's the resistance?

One-channel case again:





$$G = \frac{2e^2}{h} T \quad \text{(transmission probability } T\text{)}$$

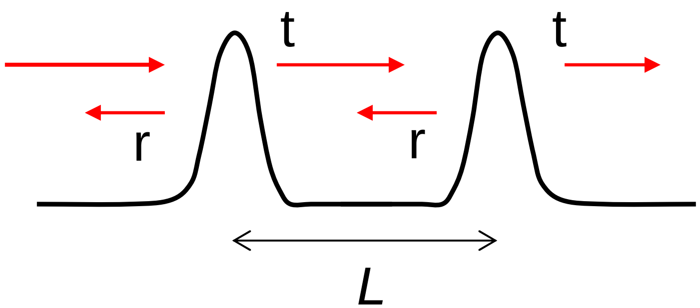
scattering from barriers
(zero for perfect conductor)

$$\text{Resistance} = \frac{h}{2e^2}\frac{1}{T} = \frac{h}{2e^2}\left(1 + \frac{1-T}{T}\right) = \boxed{\frac{h}{2e^2}} + \boxed{\frac{h}{2e^2}\frac{R}{T}} \quad (T + R = 1)$$

quantized contact resistance

Resonant transport

Two identical barriers in series:



Coherent transport; complex transmission and reflection amplitudes:

$t = |t|e^{i\phi_t}$
$r = |r|e^{i\phi_r}$

Total transmission:

$$T_{\text{total}} = \frac{|t|^4}{1 + |r|^4 - 2|r|^2\cos(\phi)}, \quad \phi = 2kL + \phi_{r1} + \phi_{r2}$$

Resonant transmission when round trip phase shift $\phi = 2\pi n$:

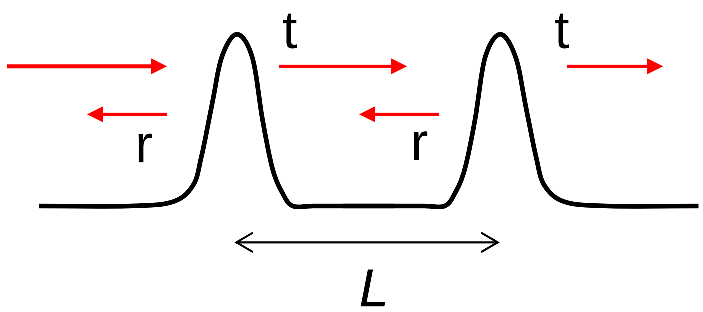
$$\text{For } \phi = 2\pi n: \quad T_{\text{total}} = \frac{|t|^4}{(1-|r|^2)^2} = \frac{T^2}{(1-R)^2} = \frac{T^2}{T^2} = 1$$

Perfect transmission even though transmission of individual barriers $T = |t|^2 < 1$!

Resonance condition (if $\phi_r=0$): $kL = \pi n$ ('particle-in-a-box' states, $n(\lambda/2)=L$)

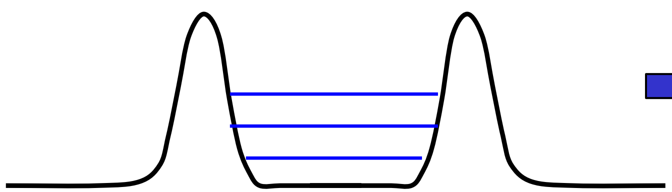
Resonant transport, II

Two identical barriers in series:



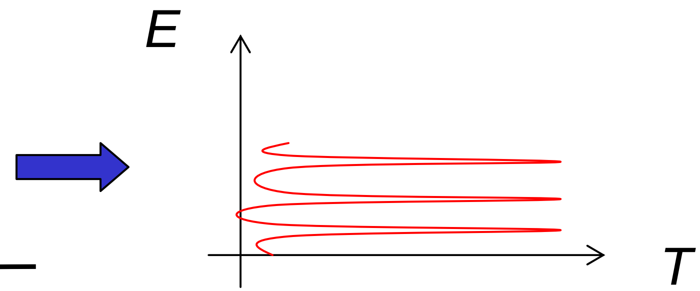
Quasi-bound states:
(‘electron-in-a-box’)

$kL = \pi n$



Spectrum
(0D system)

Resonant transmission:

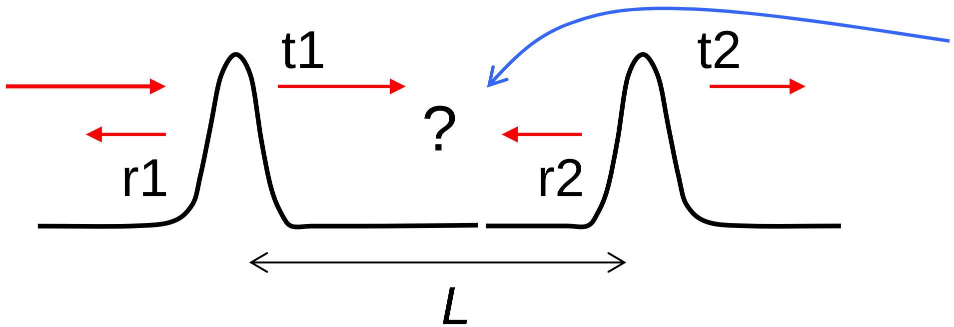


Transport measurement

...spectroscopy by transport...
(quantum dots, see later)

Incoherent transport

Separation L > phase coherence length L_ϕ:



Electron phase randomized between barriers

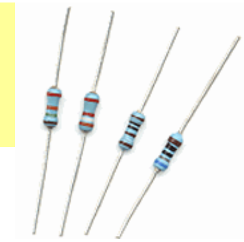
Total transmission (no interference term):

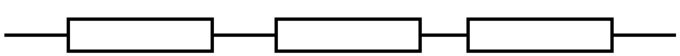
$$T_{\mathrm{total}} = \frac{|t_1|^2 |t_2|^2}{1 - |r_1|^2 |r_2|^2}$$

Resistors in series:

$$\mathrm{Resistance} = \frac{h}{2e^2}\left(1 + \frac{|r_1|^2}{|t_1|^2} + \frac{|r_2|^2}{|t_2|^2}\right)$$

Ohmic addition of resistances from independent barriers

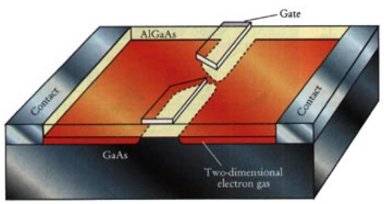




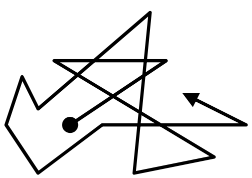
Transport regimes (simplified)

Length scales: λ_F Fermi wavelength
(only electrons close to Fermi level contribute to G)
L_m momentum relaxation length (static scatterers)
L_ϕ phase relaxation length (fluctuating scatterers)
L sample length

- **Ballistic transport**, $L \ll L_m, L_\phi$
  - no scattering, only geometry (eg. QPC)
  - when $\lambda_F \sim L$: quantized conductance $G \sim e^2/h$



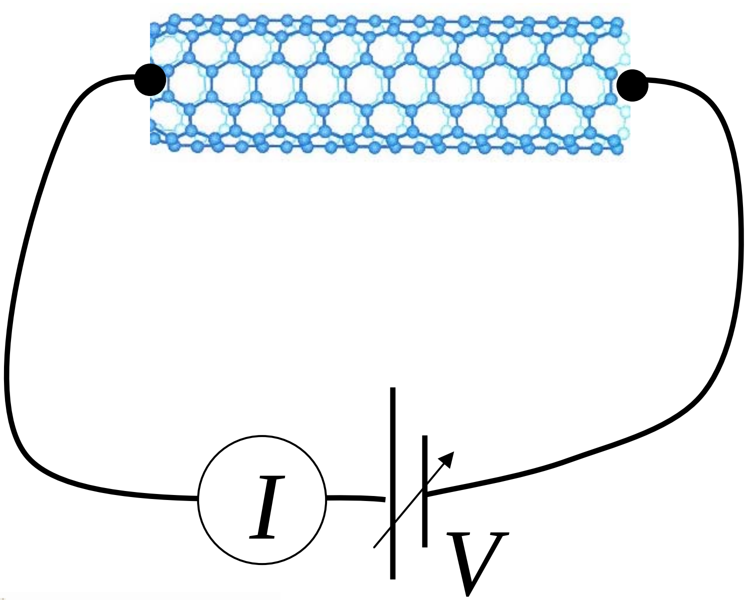
- **Diffusive**, $L > L_m$
  - scattering, reduced transmission



- **Localization**, $L_m \ll L_\phi \ll L$
  - $R \sim \exp(L)$ due to quantum interference at low T
- **Classical** (incoherent), $L_\phi, L_m \ll L$
  - ohmic resistors

Brief conclusion - prediction:

Conductance of one-dimensional ballistic wire is quantized:



With perfect contacts:

$$G = {}^{current}/_{voltage}$$
$$= 2*2e^2/h$$

(two subbands in NT)

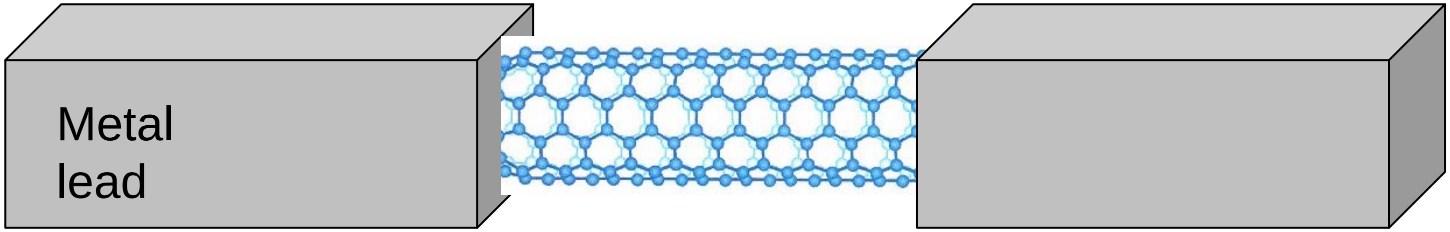
Quantum of resistance:
h/e^2 = 25 kOhm

Outline

- Electronic structure (1D, 0D)
  - density of states
- Electron transport in 1D systems (general)
  - quantization, barriers, temperature
- Transport in nanotubes (1D)
  - contacts, field-effect,...
- Nanotube quantum dots (0D)
  - Coulomb blockade, shells, Kondo, ...
- Nanotube electronics, various examples
- Problem session
- Wellcome party

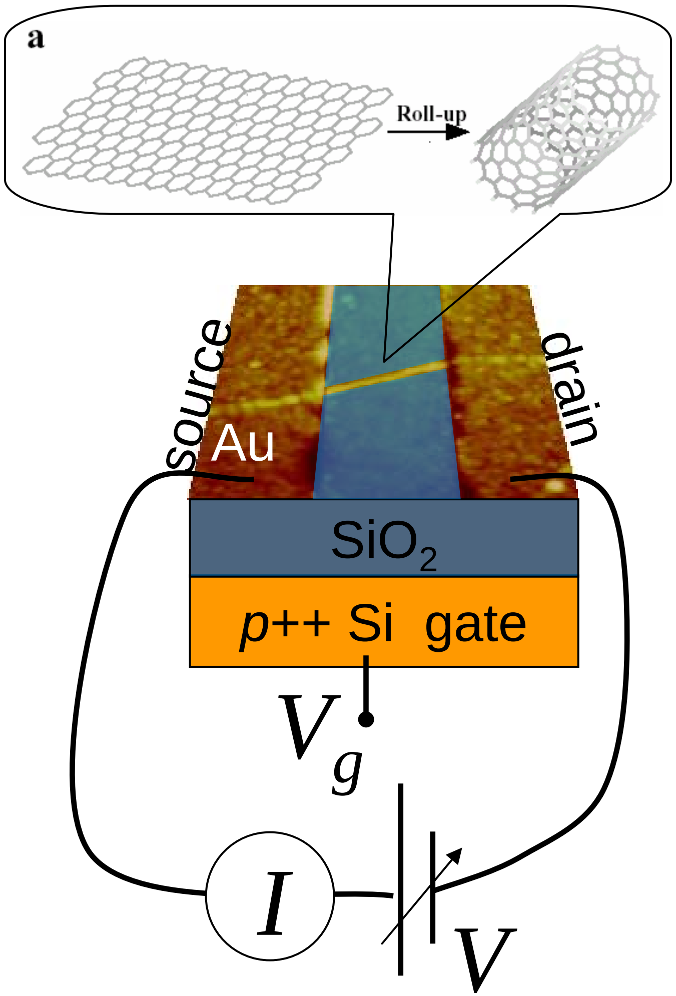
Tutorial on

Electronic Transport

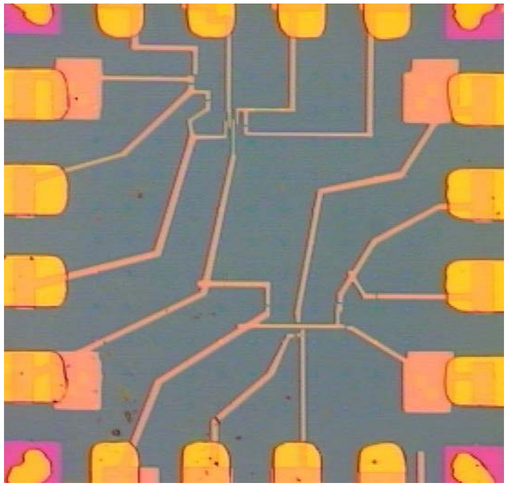


II. Electronic transport in nanotubes

Electrical measurements on *individual* tubes

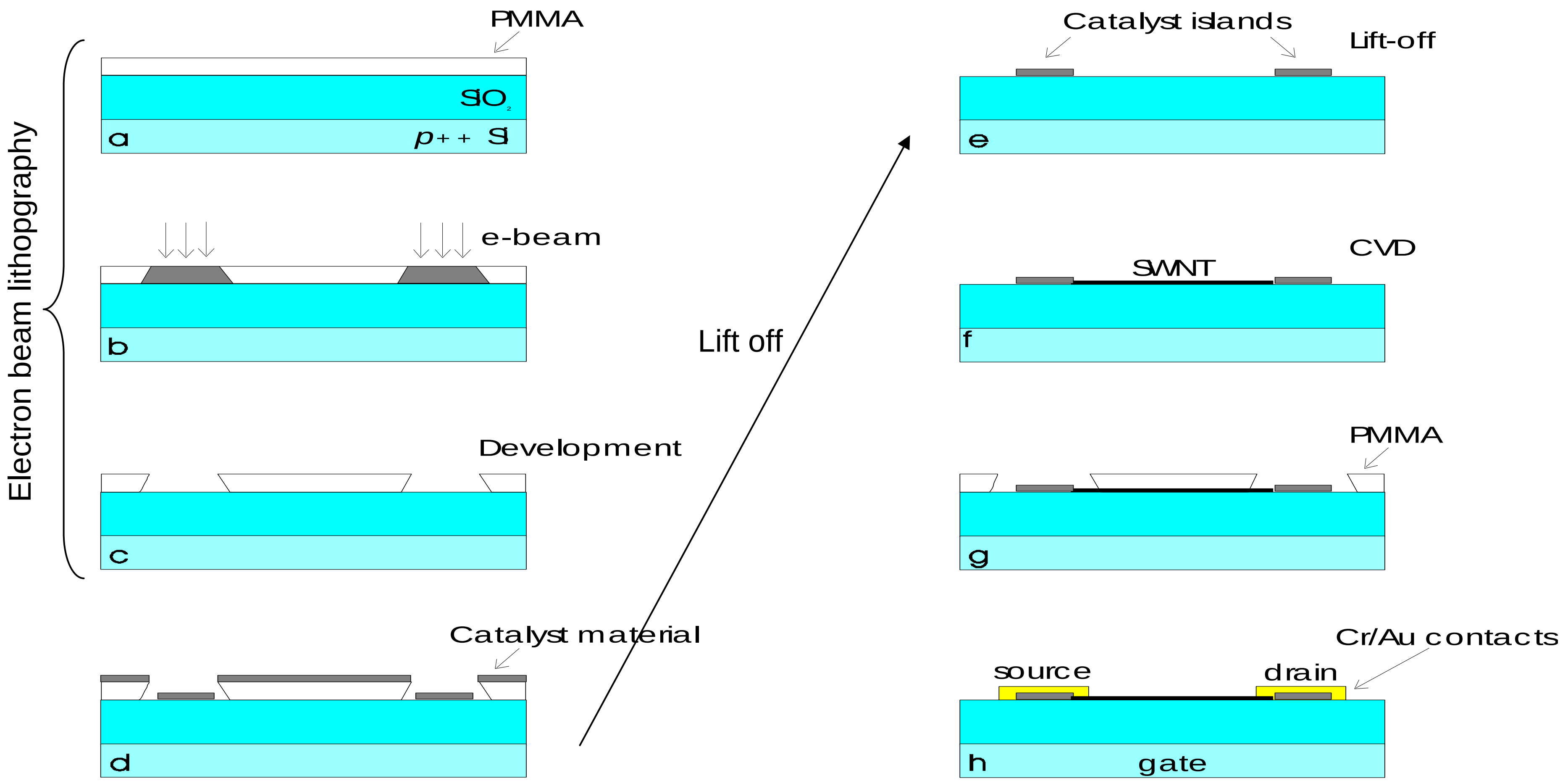


- Nanotubes deposited or grown (CVD)
- Localize nanotubes (AFM)
- Electron-beam lithography to define electrodes
- Evaporate metal contacts on top (Au, Pd, Al, Ti, Co, …)



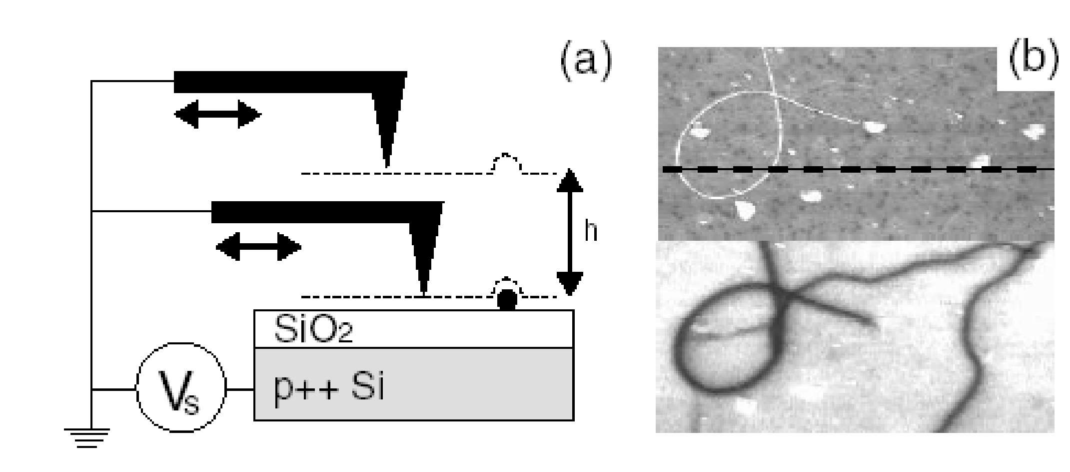
100 μm

Typical device fabrication



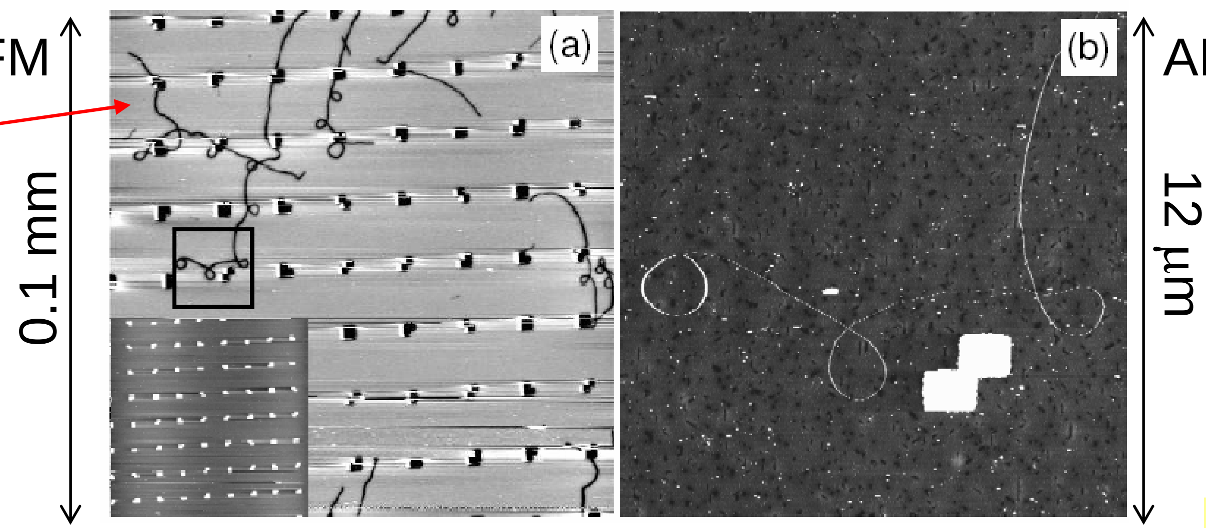
Another (UV) lithography step
for bond pads before mounting

AFM and alignment marks; EFM



Atomic Force Microscopy (AFM)

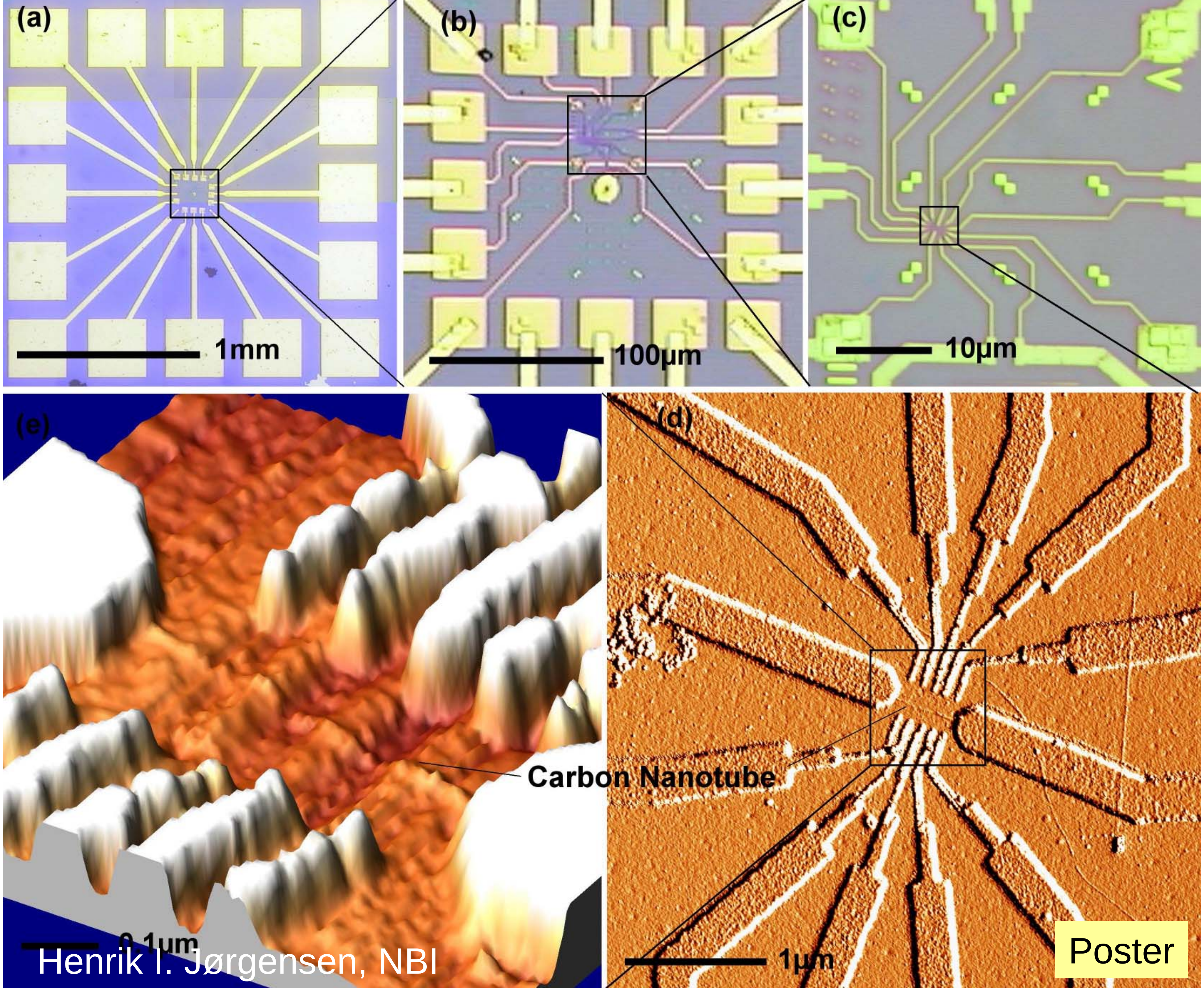
Electrostatic Force Microscopy (EFM)



Bockrath et al, NanoLetters (2002)
Jespersen et al, NanoLetters (2005)

Poster

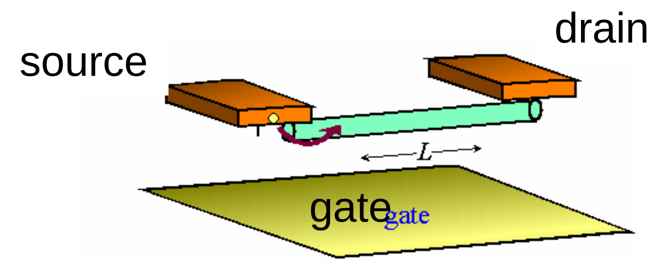
T.S. Jespersen

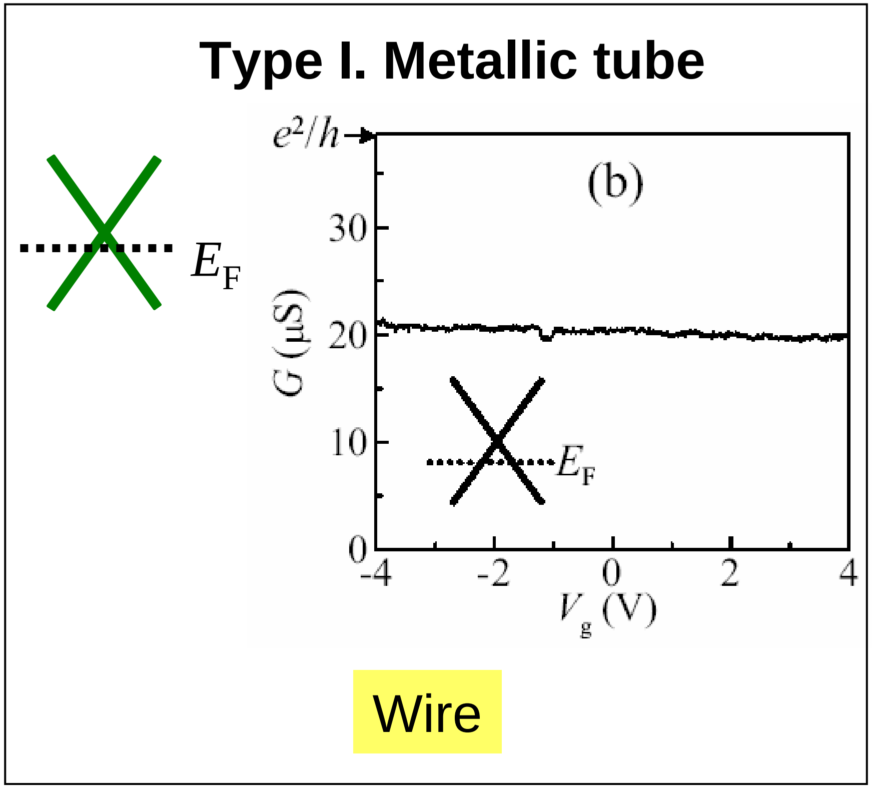


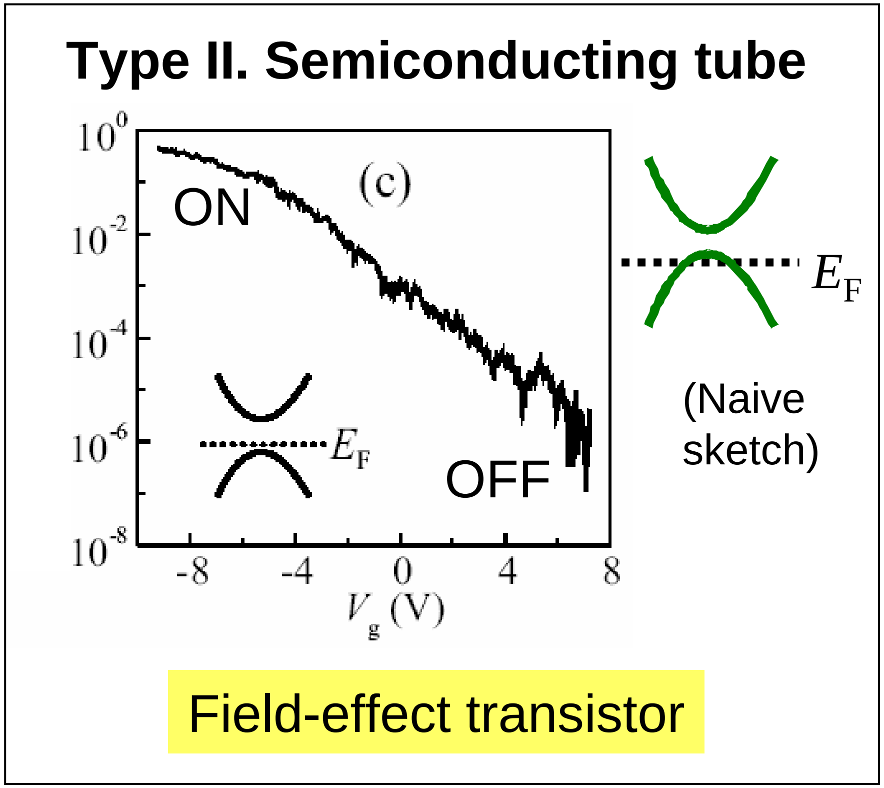
Henrik I. Jørgensen, NBI

Poster

Room temperature transport







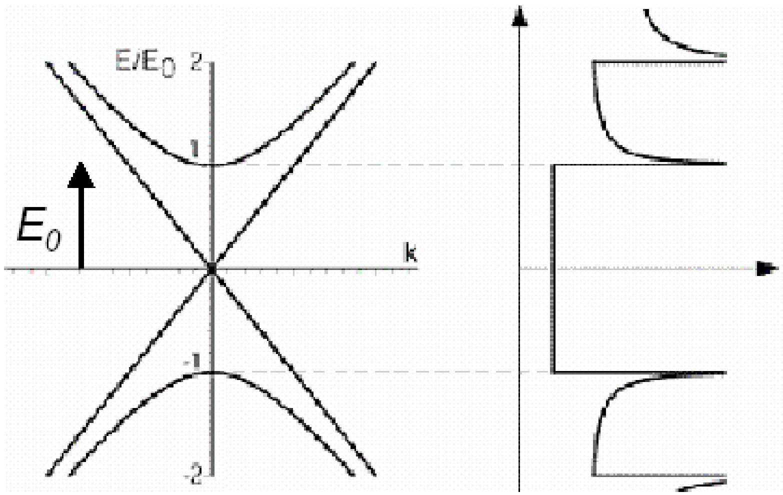
Seen first by Tans et al, Nature (1998)

Data from Appl. Phys. A 69, 297 (1999).

Chirality determines bandstructure

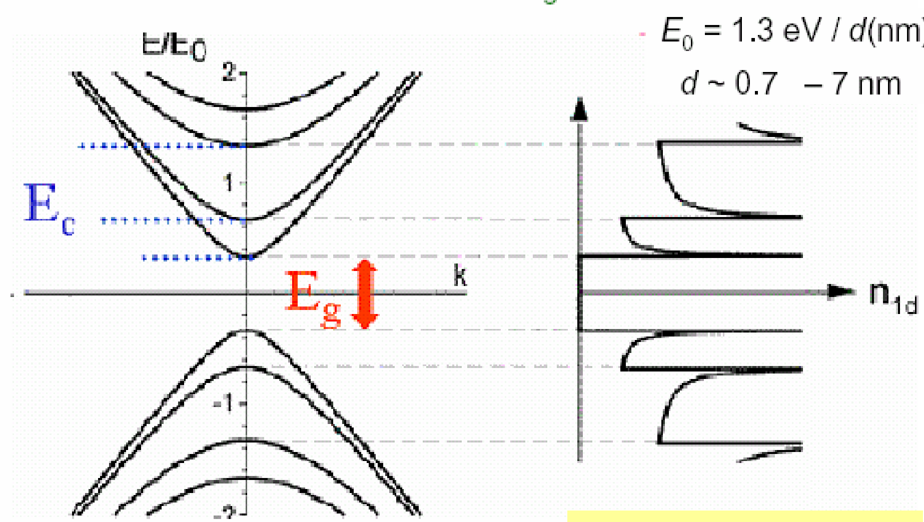
Type I. Metallic tubes

$M\text{-}N = 0$ $\quad$ $E_g = 0$

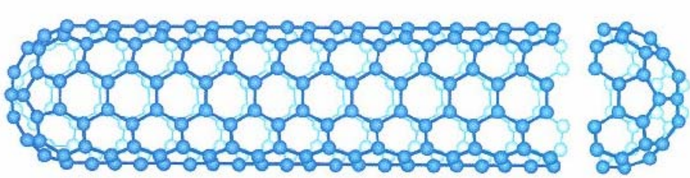


Type II. Wide-gap semiconducting tubes

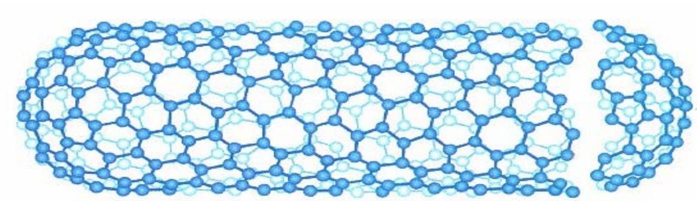
$M\text{-}N <> 3p$ $\quad$ $E_g = 2/3\ E_0$



E_g ~ 0.5-1 eV



(N, M) = (5, 5)



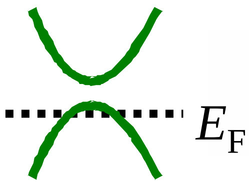
(N, M) = (10, 5)

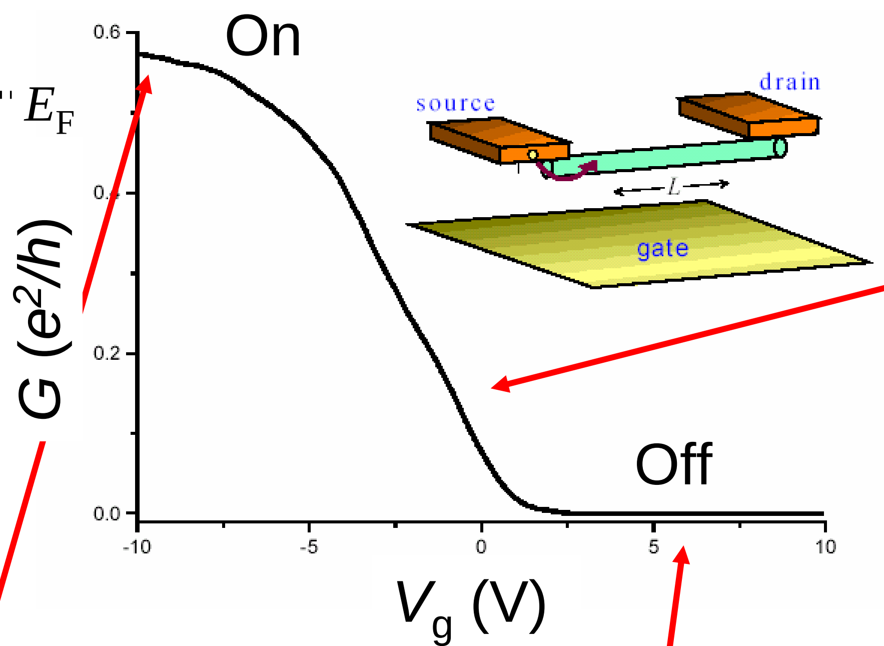
In reality, also Type III: Small-gap semiconducting tubes (zigzag metals)

First interpretation of

Semiconducting nanotube FET

[Field Effect Transistor]





Linear increase in G-V_g ie limited by mobility (diffusive transport)

Slope: $dG/dV_g = \mu C_g/L^2$

(from Drude $\sigma = ne\mu$)

$\Rightarrow \mu \approx 10{,}000$ cm^2/Vs

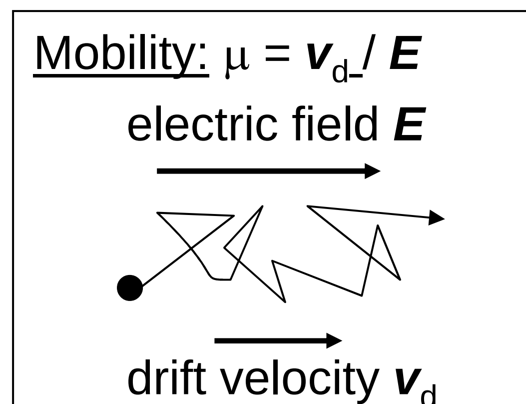
(For silicon $\mu \approx 450$)

Saturation due to contact resistance, ~ e^2/h

"Off" at positive V_g

$\Rightarrow$ *p* type FET

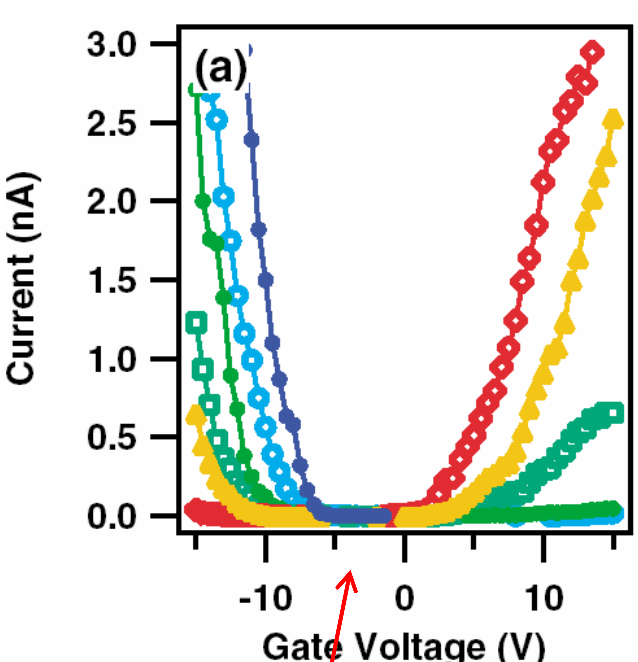
(intrinsic *p* doping?)



Later work showed importance of (Schottky) contacts!

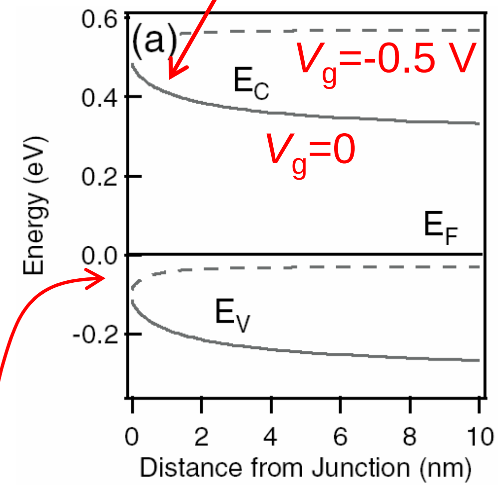
Schottky barriers in nanotube FETs

Oxygen exposure

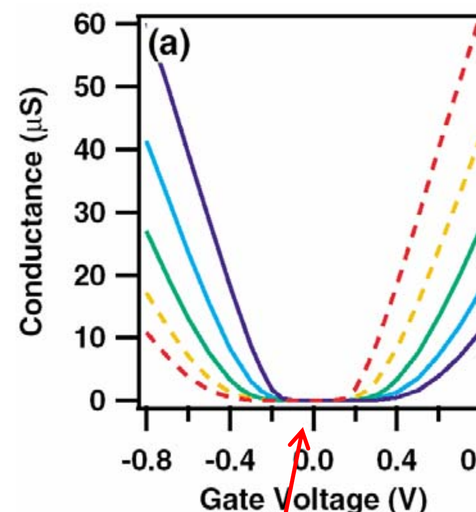


Band structure

Schottky barrier



Different workfunctions (eg due to O_2 exposure)



Barriers thinnest for *V*g < 0, ie largest current when p type

No change of gap

No shift of mid gap; contacts (shape) modulated

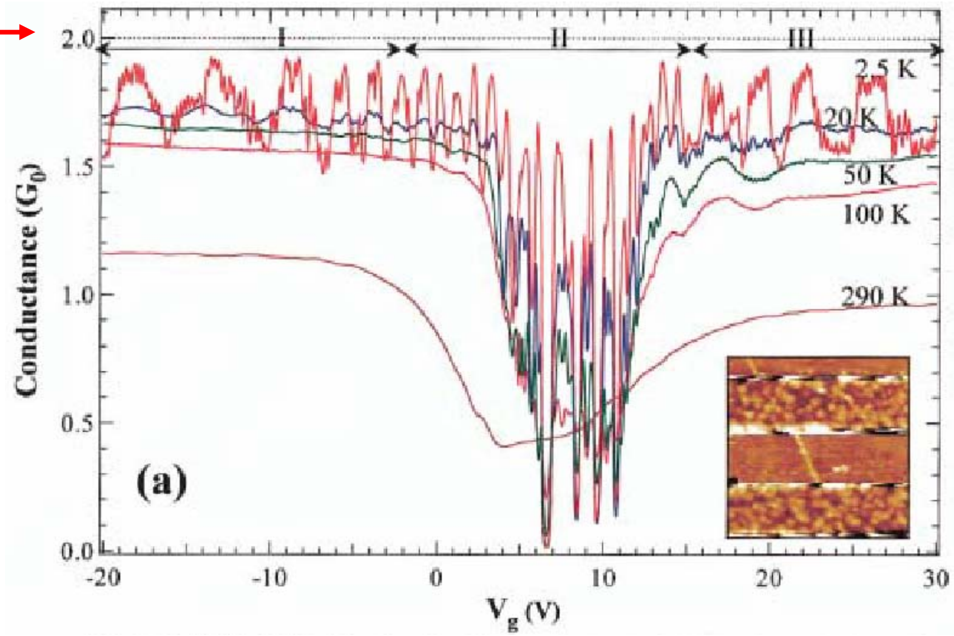
Asymmetry due to modulation of contact Schottky barriers

Heinze et al (IBM), PRL 89, 106801 (2002)

(Gas sensors)

Ballistic transport in metal tubes

$4e^2/h$ ✓



1D conductor

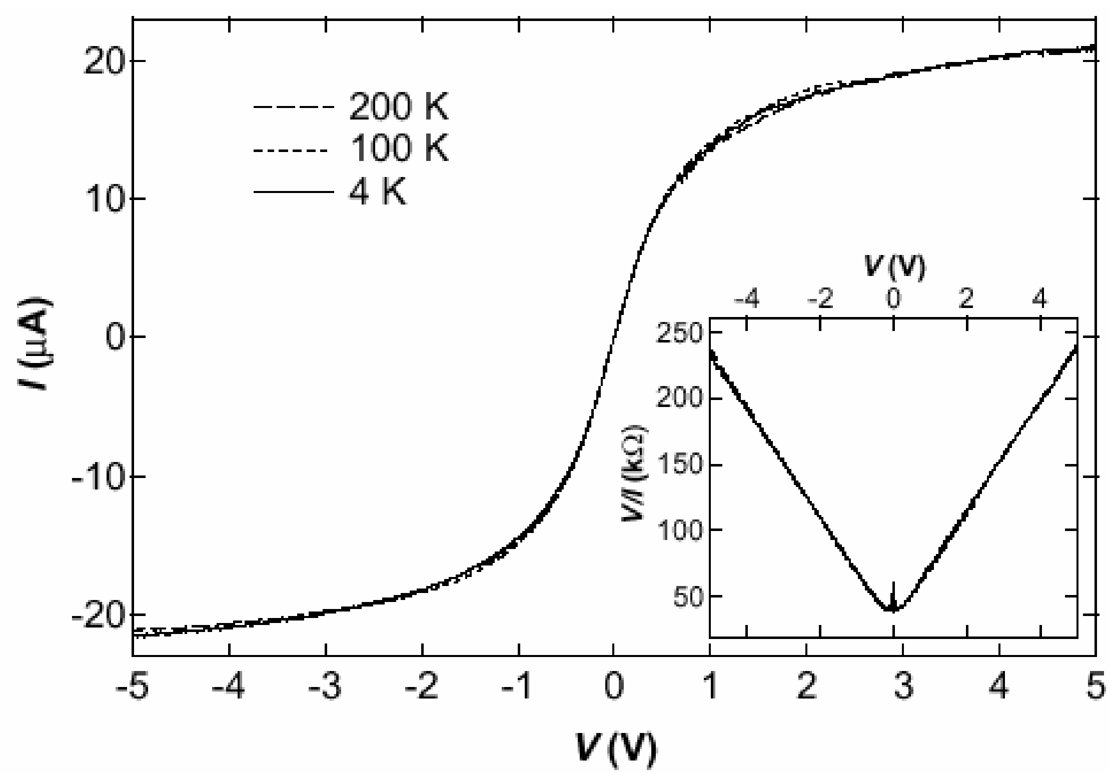
- Near the theoretical limit $4e^2/h$ (with two subbands)
- Close to Fermi level backscattering is suppressed in armchair (metal) tubes by symmetry

Kong et al, PRL 87, 106801 (2001)
McEuen et al, PRL 83, 5098 (1999)

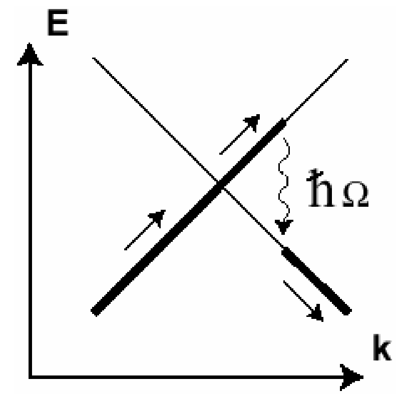
(Ballistic transport also possible in very short semiconducting tubes, otherwise mostly diffusive)

Quantized current limiting

Metallic tube with good contacts



$I_0 \sim 25$ μA



High electric field transport
- electrons are accelerated
- emit (optical) phonons when $E \sim E_{phonon}$
- electron-phonon scattering for high bias

Steady state current:

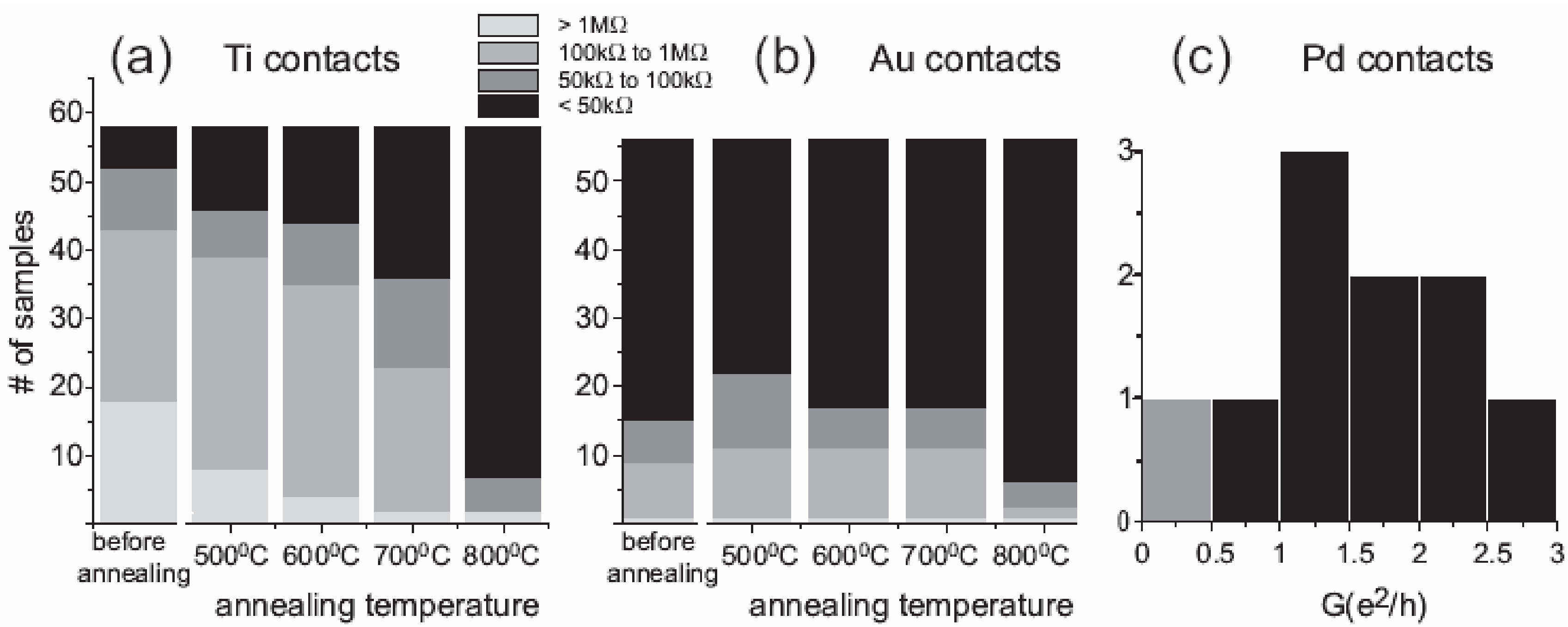
$I_0 = 4e/h \, E_{phonon}$

$\sim 4e/h * 160$ meV

$\sim 15\text{-}30$ μA

Z. Yao, C. Kane and C. Dekker
PRL 84, 2941 (2000)

Metal contacts; rarely ideal



Room temperature resistance of CVD grown SWNT devices

Babic et al, AIP Conf. Proc. Vol. 723, 574-582 (2004); cond-mat

Room temperature transport

- Ballistic transport possible (near $4e^2/h$)
  - ideal wires
  - current limiting ~ 25 μA

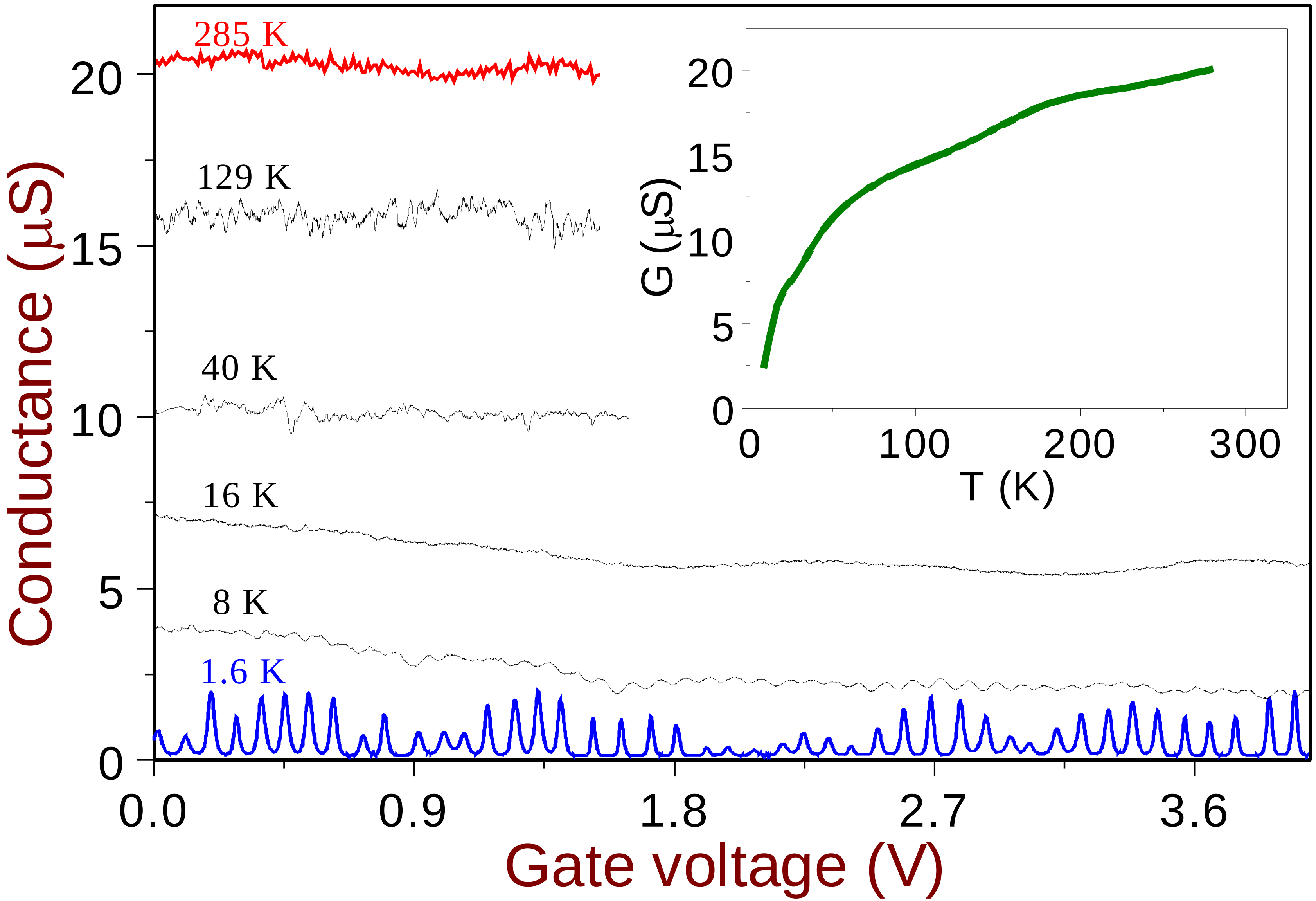
- Field effect transistors
  - high performance
  - optimised geometries (not shown)

NB: Nanotube quality and contact transparency are important

Outline

- Electronic structure (1D, 0D)
  - density of states
- Electron transport in 1D systems (general)
  - quantization, barriers, temperature
- Transport in nanotubes (1D)
  - contacts, field-effect,...
- Low temperature transport, quantum dots (0D)
  - Coulomb blockade, shells, Kondo, ...
- Nanotube electronics, circuits, examples
- Problem session
- Wellcome party

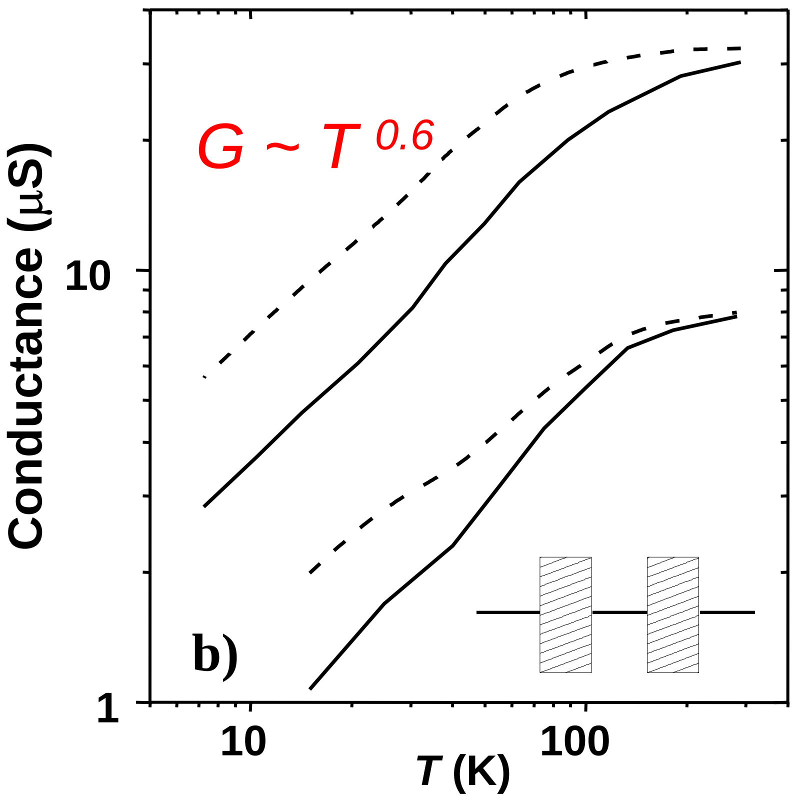
Transport in metallic tube – oscillations at low *T*



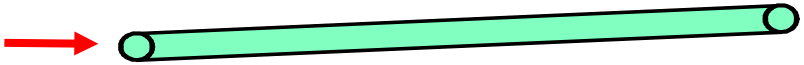
Seen first in data by Bockrath et al and Tans et al (1997)

Power laws in tunneling

Typical T dependences



tunneling into end of Luttinger liquid



$\alpha = (g^{-1}-1)/4$ g = Luttinger parameter

$\alpha = 0.6 \rightarrow g \sim 0.29$

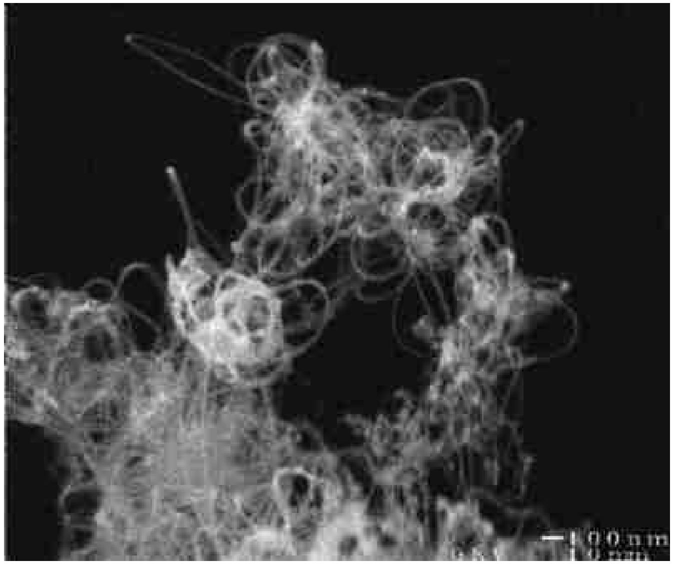
Bockrath *et al*, Nature (1999)

Evidence for Luttinger liquids

Predicted: Egger & Gogolin (1997), Kane, Balents & Fischer (1997)

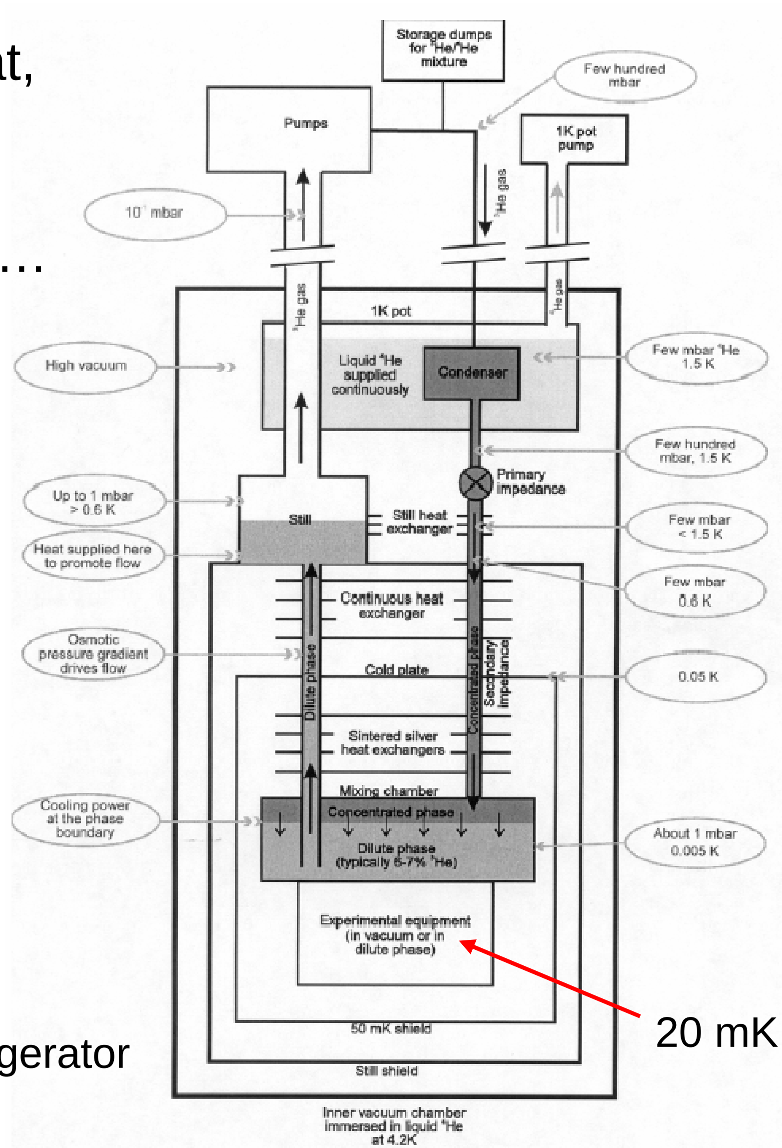
Initiator for breakthroughs 1997+

Availability of high quality single walled nanotube material (Smalley group, Rice University, 1995-96)



Low temperature transport

It is cryostat,
it exists,
OK,
let's get on…

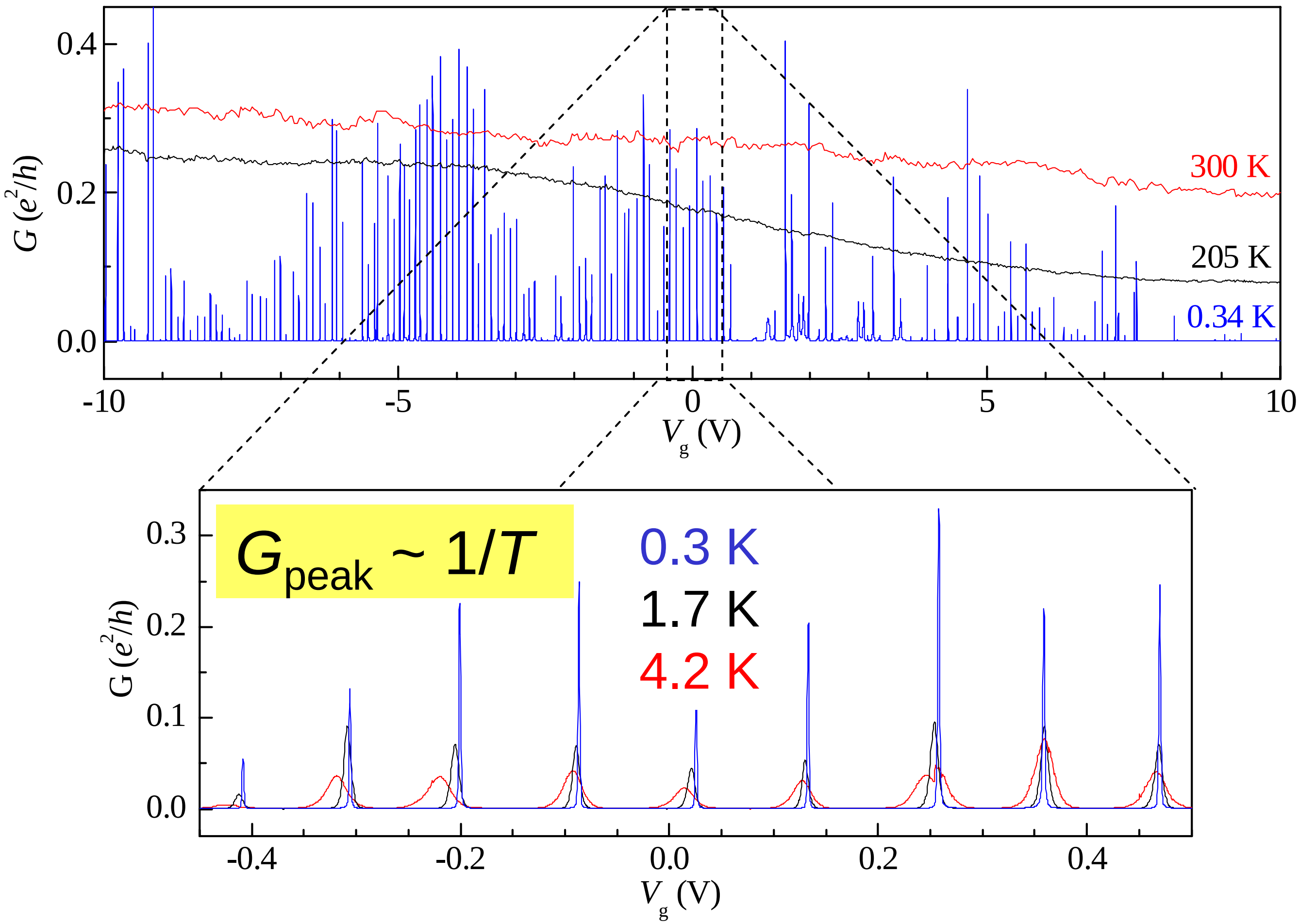


20 mK

Dilution refrigerator

sample

Low temperature data



Coulomb blockade in the quantum regime below ~4 K

- *“Nanotube quantum dot”*

First by Tans *et al*. (1997), Bockrath *et al*. (1997)

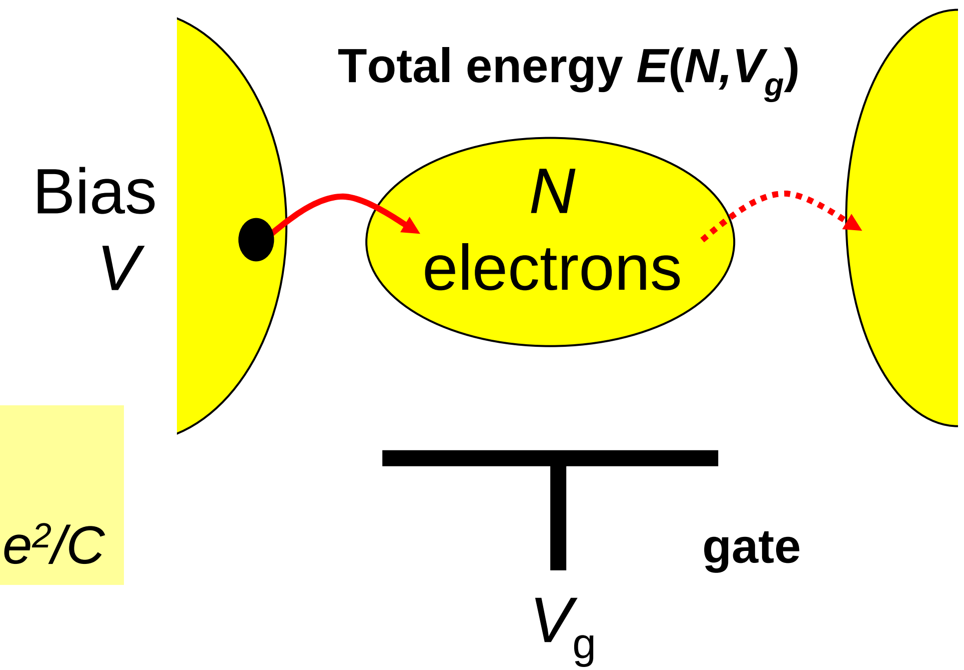
Coulomb blockade

Electrons can tunnel only
at V_g for which

$E(N+1, V_g) = E(N, V_g) \pm kT$

Cost for adding one electron:

charging energy: $E_C \sim Q^2/C \sim e^2/C$

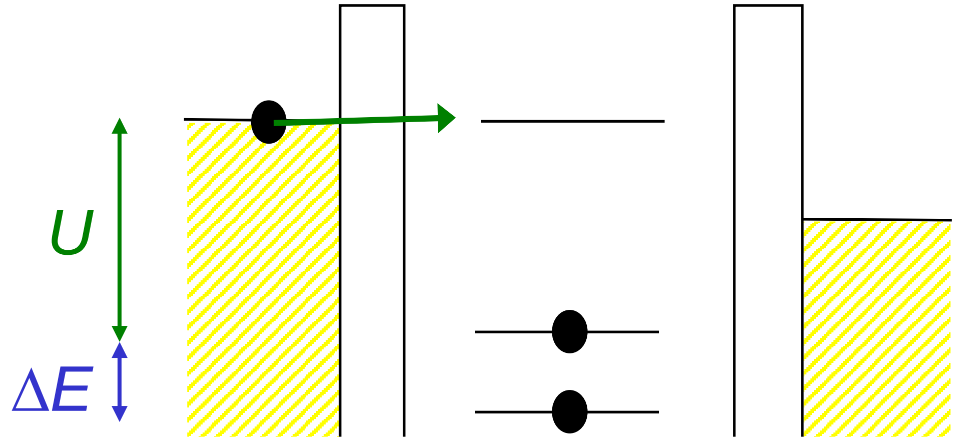


Quantum dots
(artificial atoms)

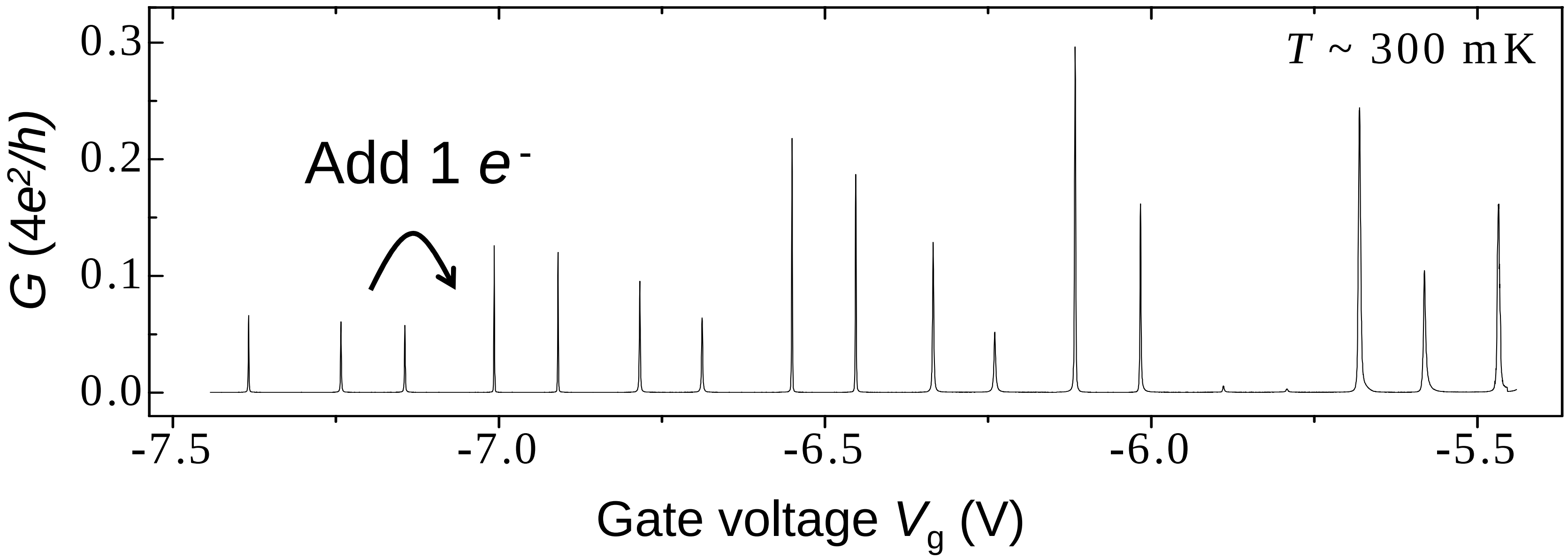
Two energy parameters:

U – 'charging energy' e^2/C
(e-e interaction strength)

ΔE – single-particle
level spacing



Single-electron charging at low T

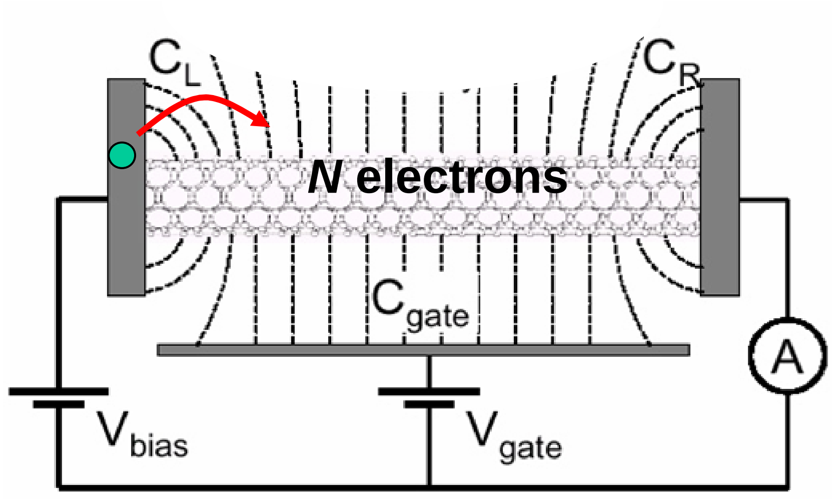


1) large electrostatic charging energy

$U = e^2/C_{\text{total}} \sim 10 \text{ meV} > k_B T$

2) tunnel contacts

well-defined number N of electrons



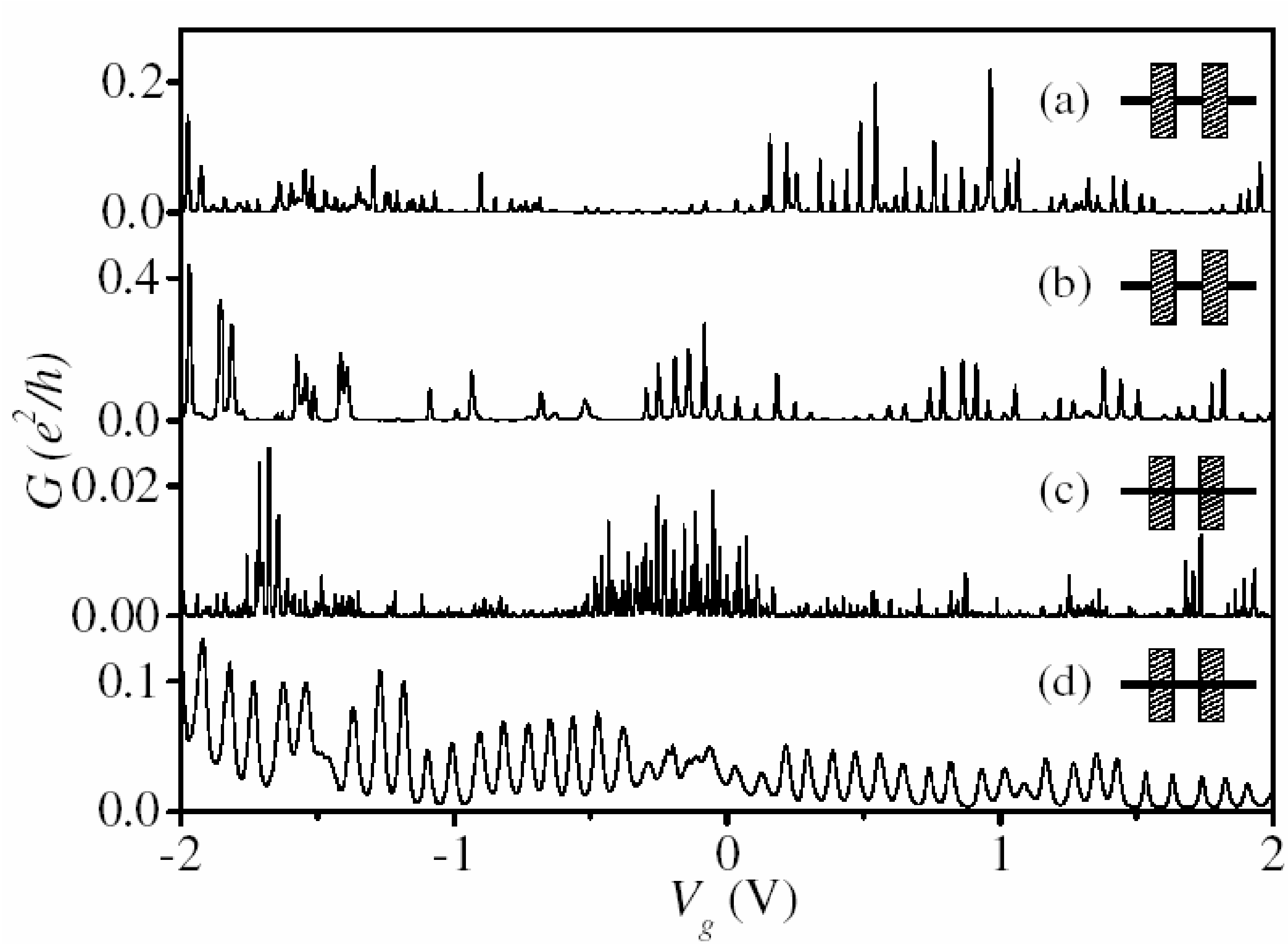
fixed number N of electrons

i.e. zero current - **Coulomb blockade**

except when $E(N)=E(N+1)$...

Published data not always typical...

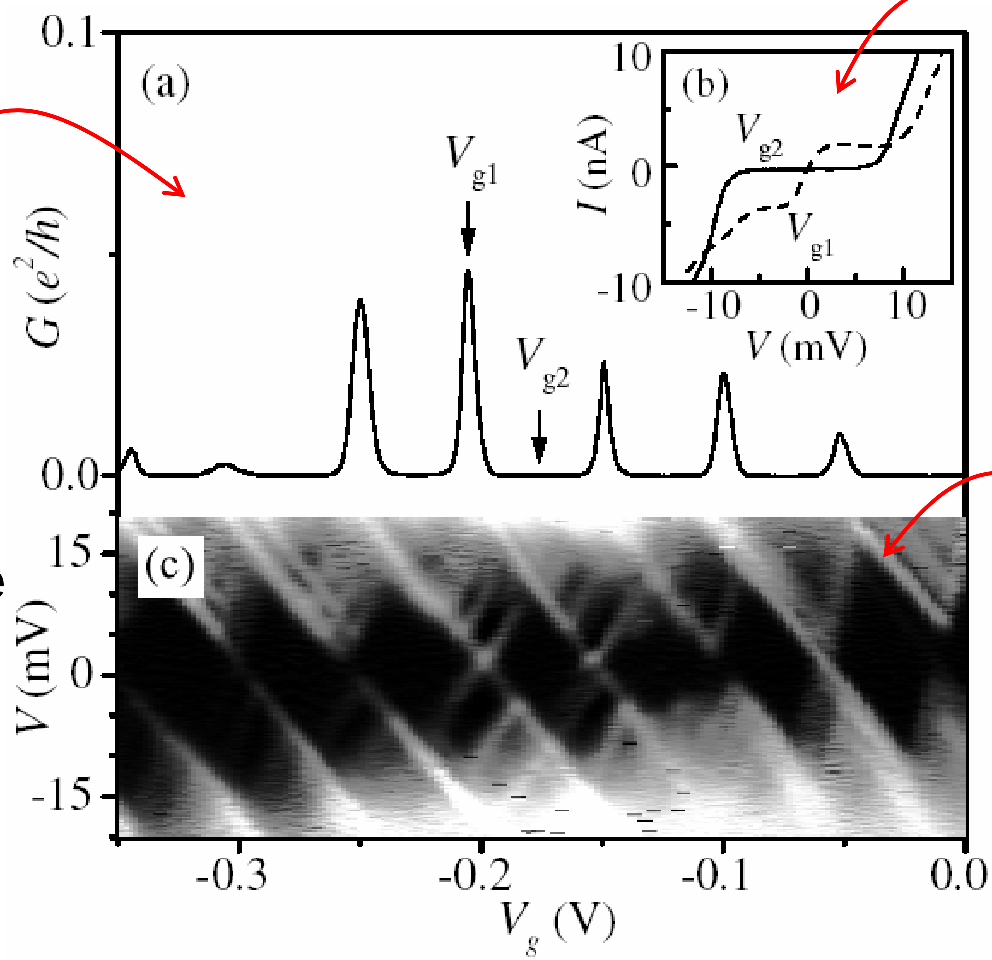
T = 4K



Non-linear characteristics

T = 4.2 K

Coulomb blockade peaks (zero bias)

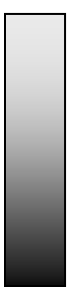


Nonlinear I-V curve (fixed gate volt.)

Differential conductance

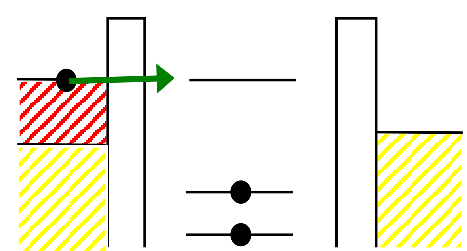
high

d*I* / d*V*



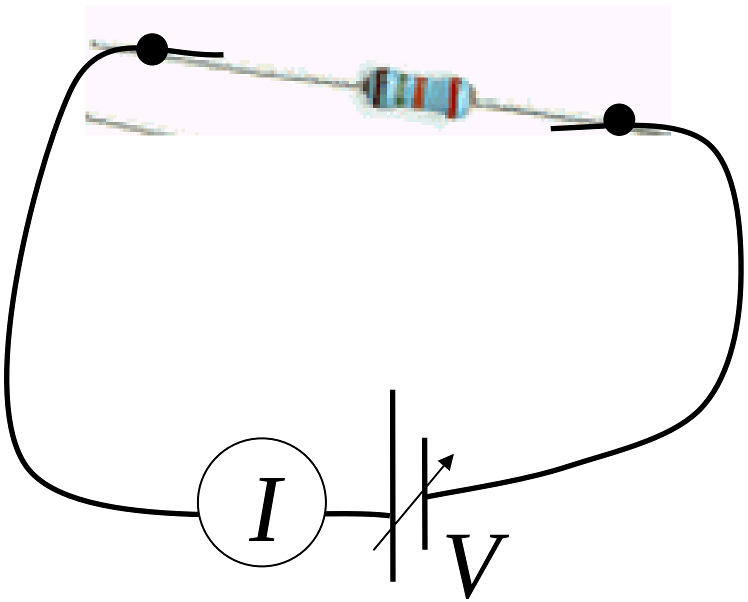
0

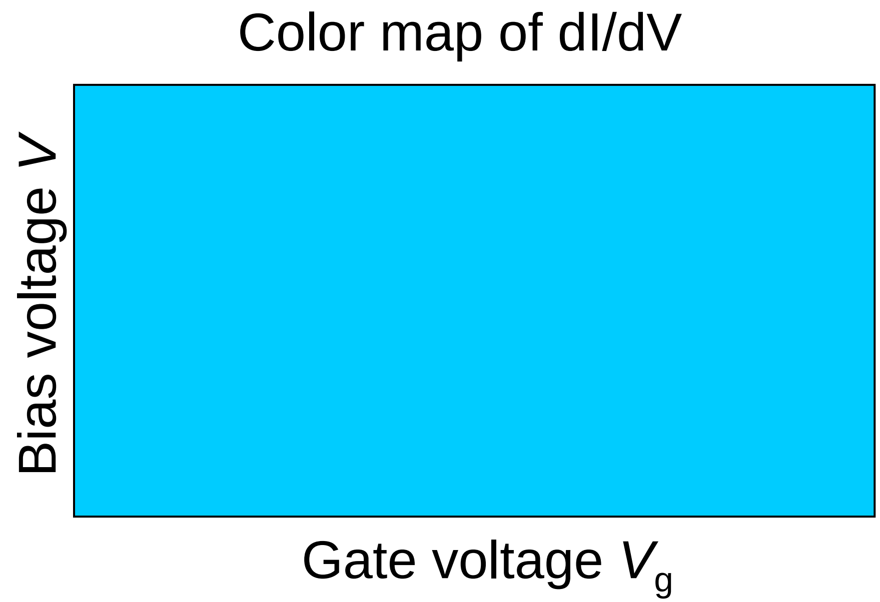
”Bias spectroscopy”, ”Coulomb diamonds”, …



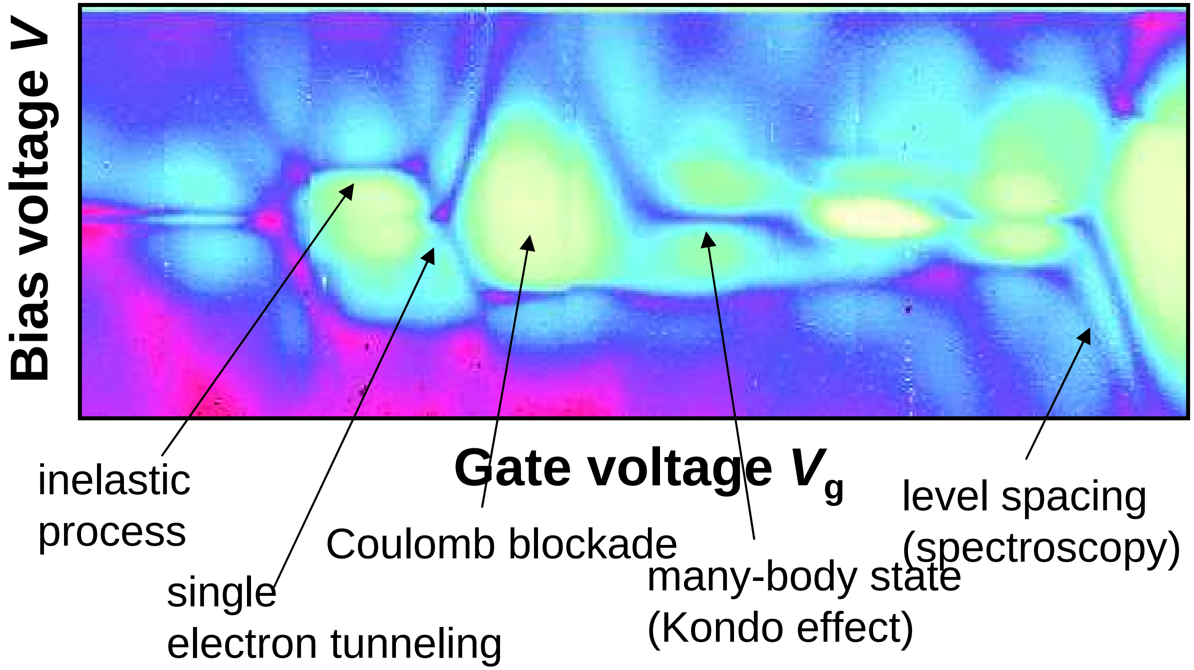
Appl. Phys. A 69, 297 (1999).

Ohmic resistor





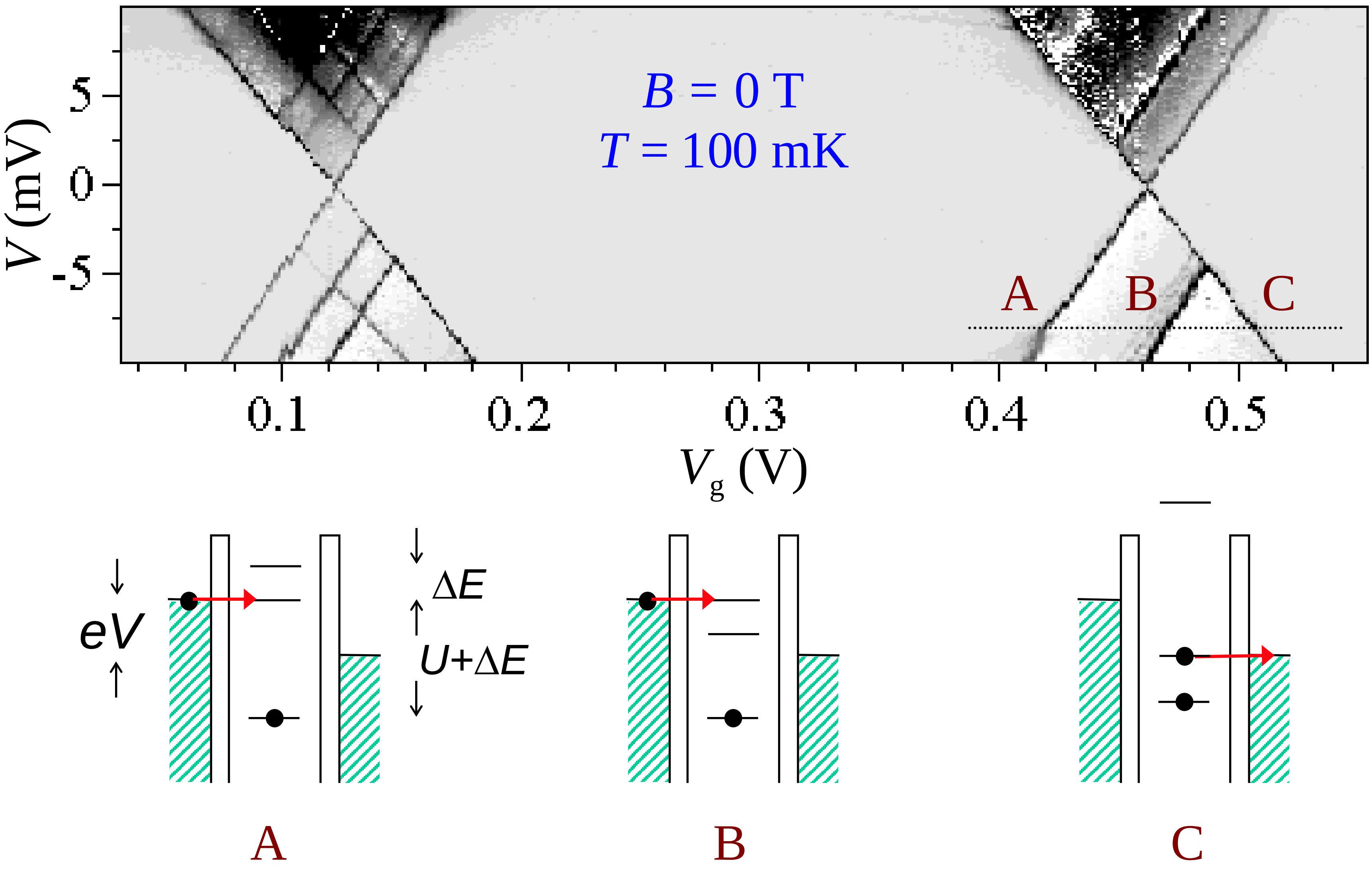
Color map of dI/dV (white: high *R*, blue: low *R*)



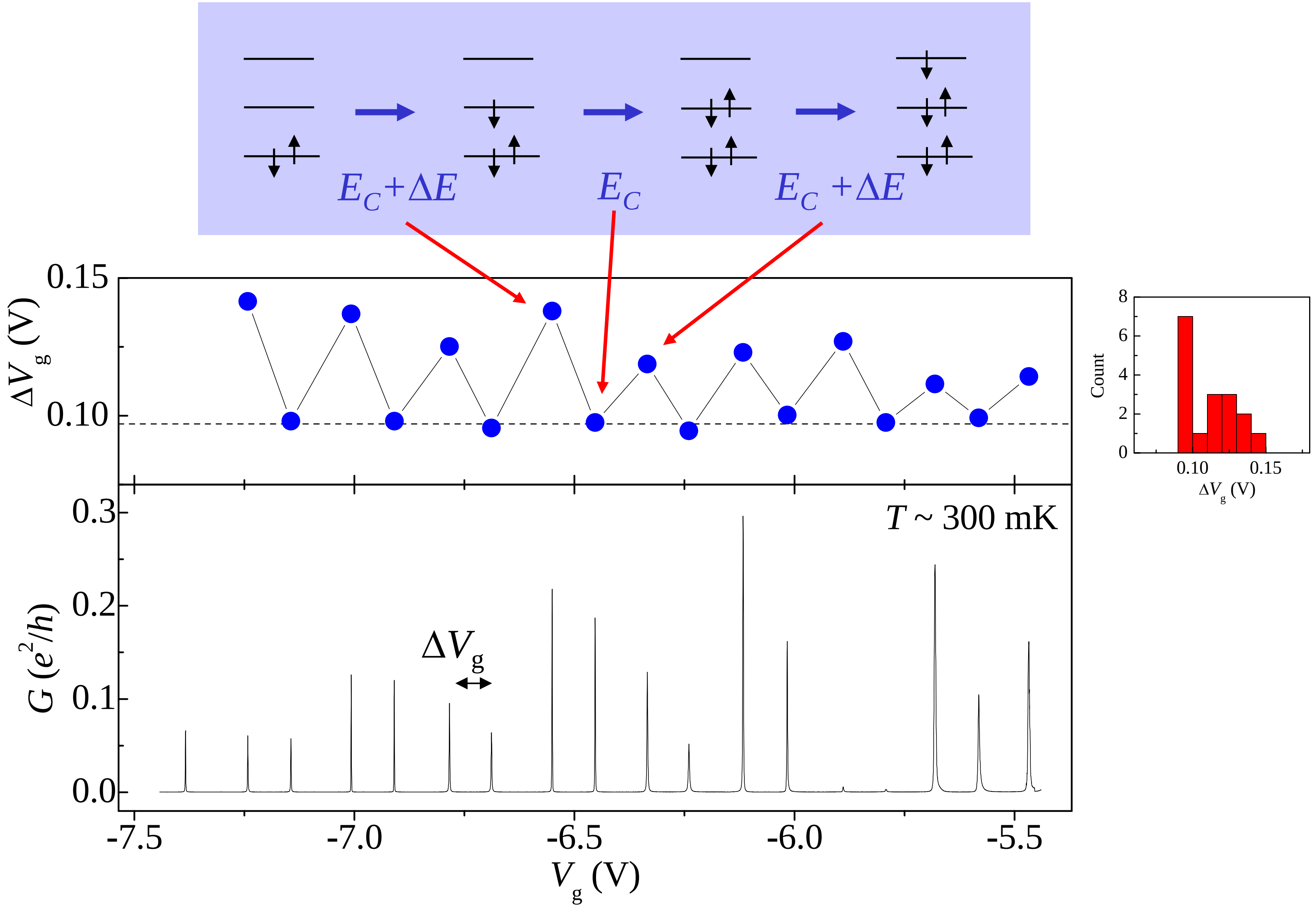
Measurement at T = 100 mK

Electron transport governed by:
- tunneling processes
- discrete electron charge
- orbitals of the molecule
- electron-electron interactions and many-body effects

Transport spectroscopy of a tube quantum dot



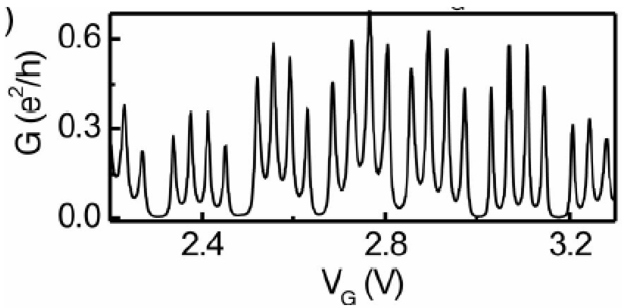
Shell filling in closed dot



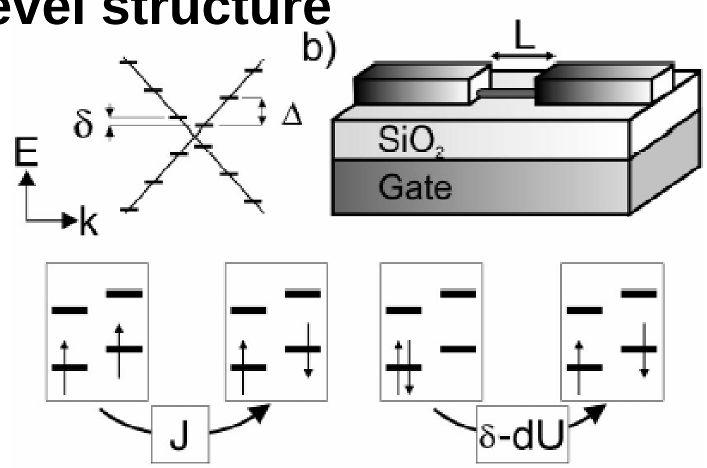
Molecular spectroscopy by electrical measurements

PRL 89, 46803 (2002)

4-electron shells and excited states



Level structure



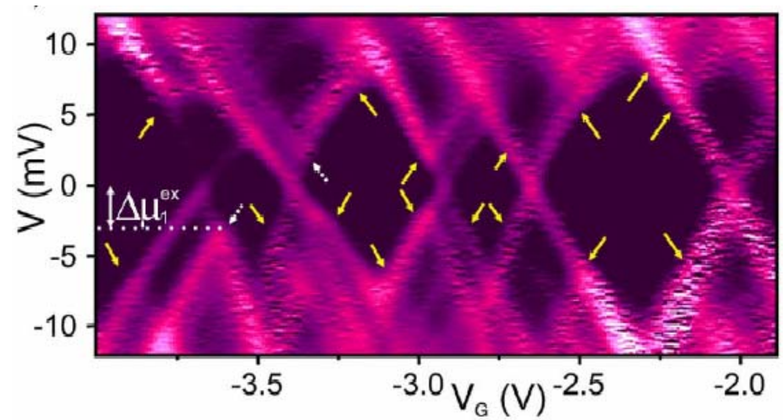
5 parameters:

- charging energy U
- level spacing Δ
- subband mismatch $\delta < \Delta$

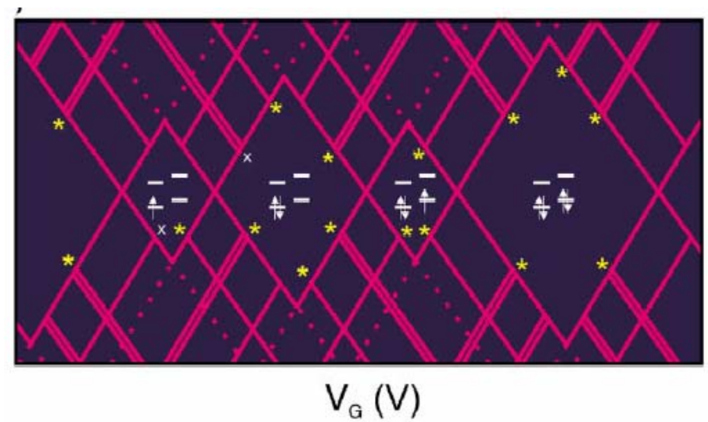
(small) - exchange energy J

(small) - residual Coulomb energy dU

Experiment



Model



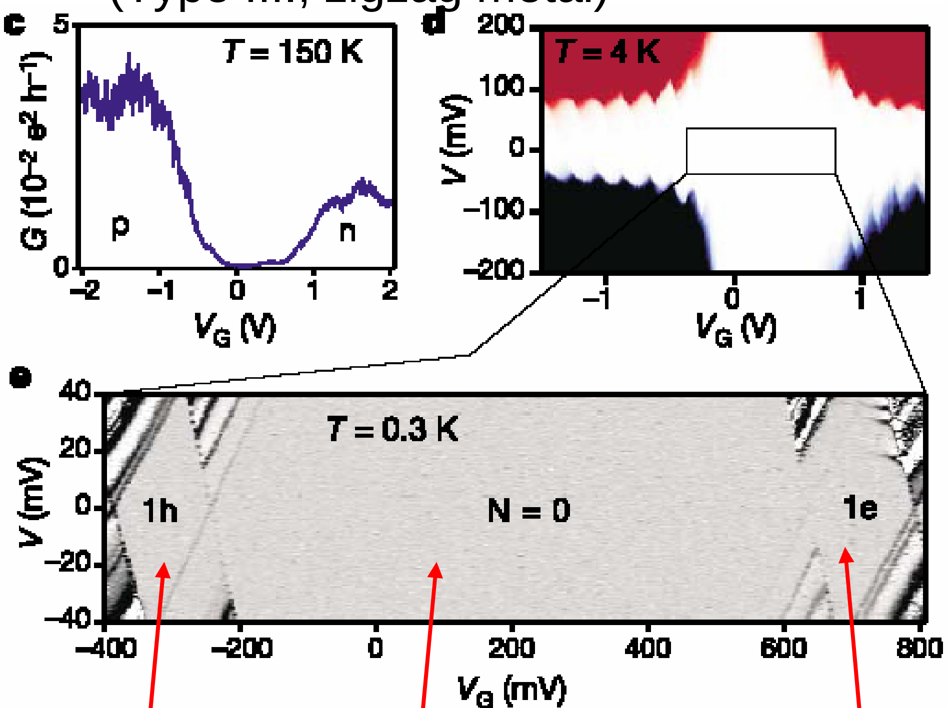
(Liang et al, PRL 88, 126801 (2002))

Sapmaz et al, PRB 71, 153402 (2005)

Semiconducting quantum dot
with electron-hole symmetry

Small-gap semiconducting tube

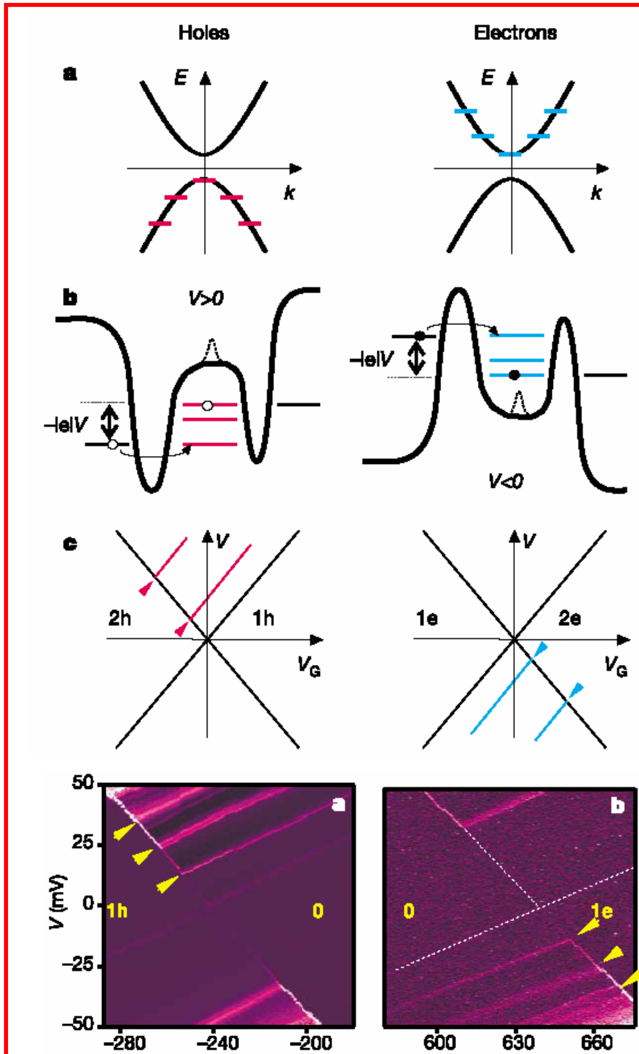
(Type III., zigzag metal)



First hole enters

Empty dot

First electron enters



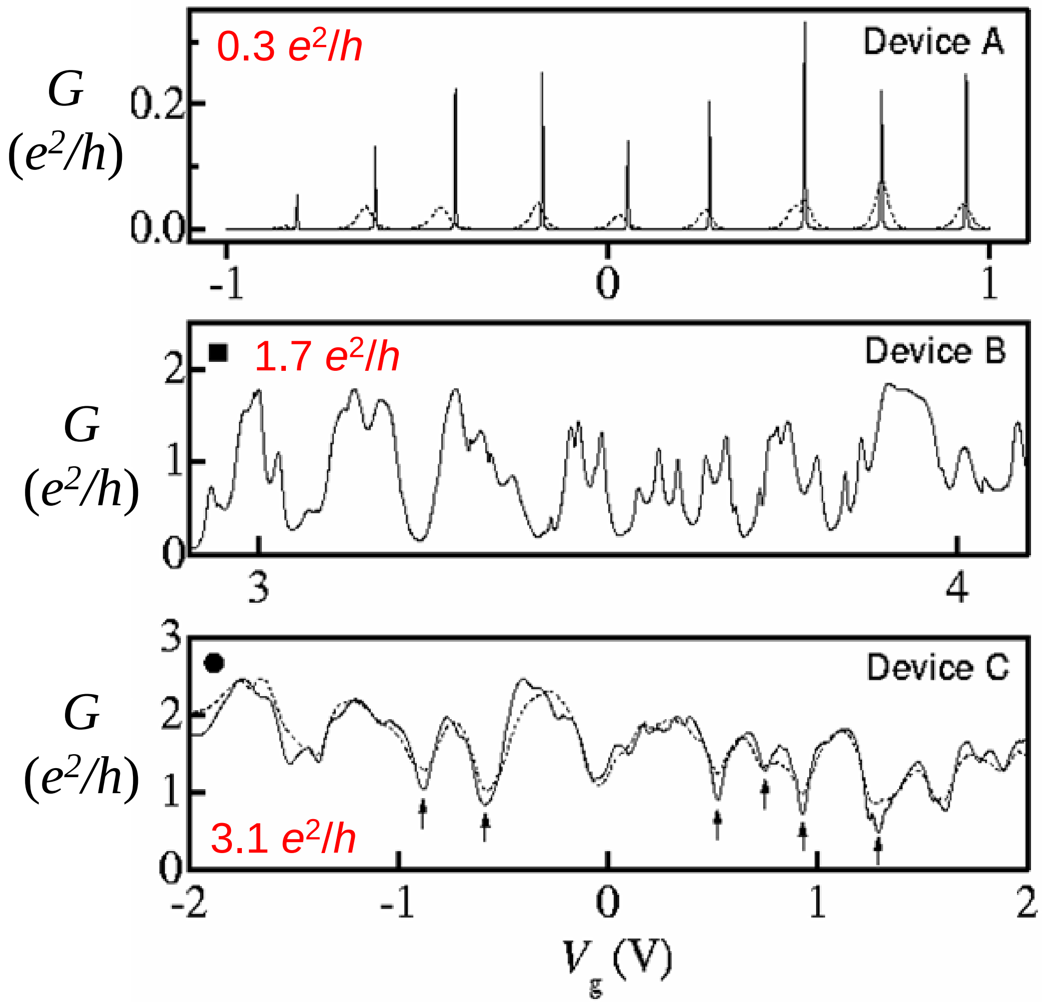
Few-electrons dots can be made

Jarillo-Herrero et al, Nature 429, 389 (2005).

From closed to open quantum dots

G (T = 300 K)

Coulomb blockade peaks



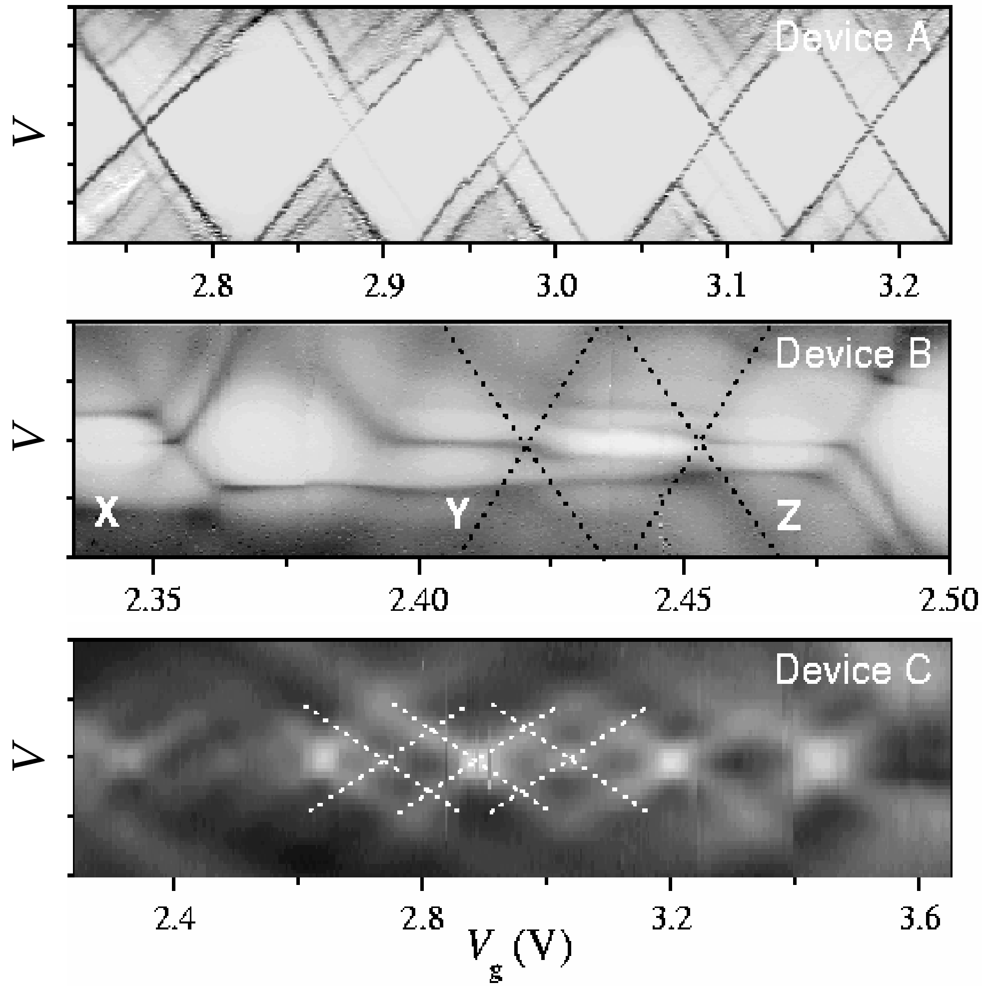
Dips* rather than *peaks

Tunnel contacts
weak coupling limit

Metallic contacts -
strong coupling limit

Gray scale plots of the diffential conductance dI/dV vs. V_g and V

1D quantum dot

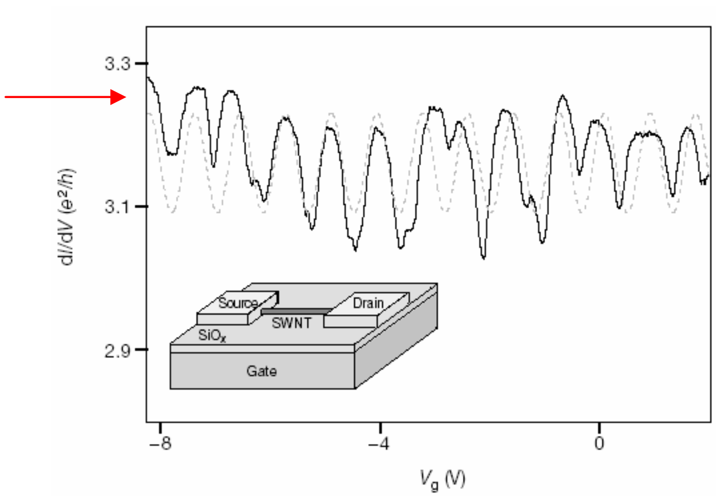


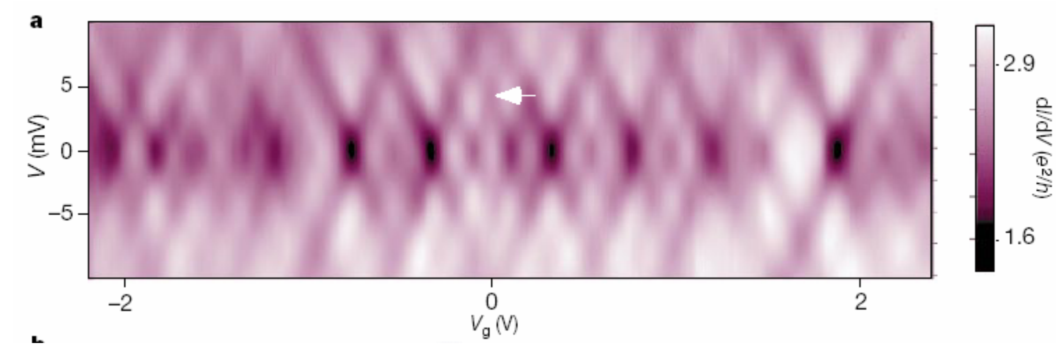
Tunnel contacts
weak coupling limit

Metallic contacts -
strong coupling limit

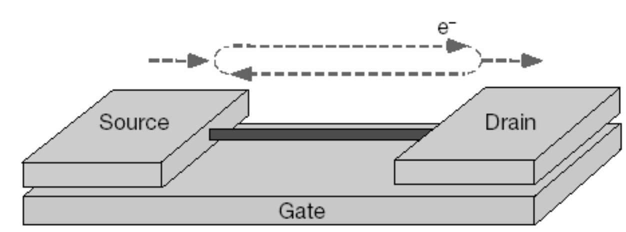
1D 'molecular Fabry-Perot etalon'
Liang *et al*, Nature (2001).

Fabry-Perot resonances in nanotube waveguide



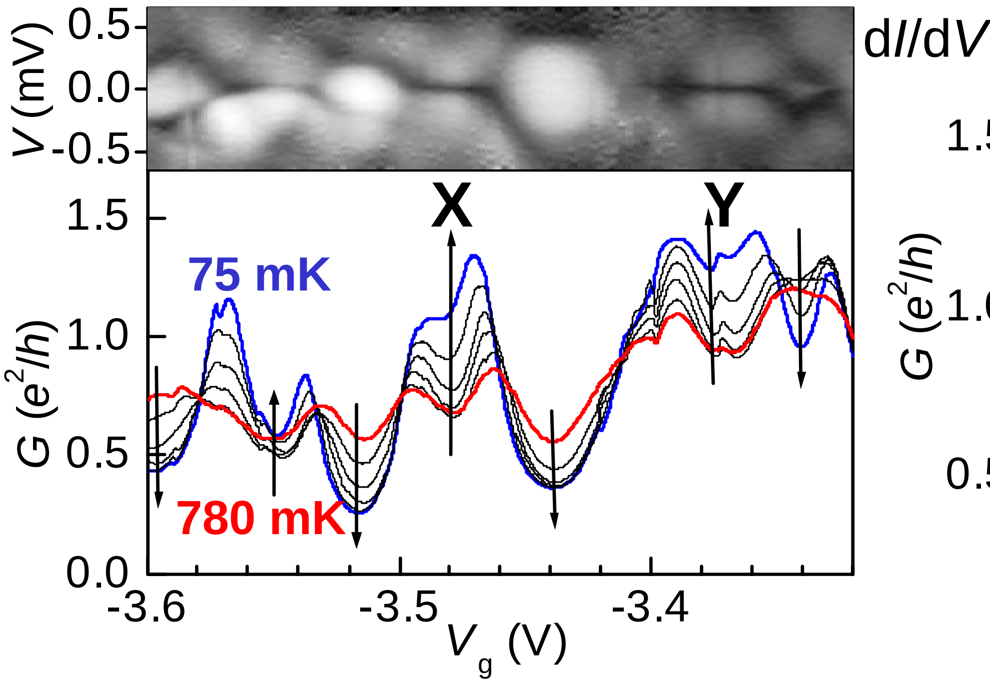


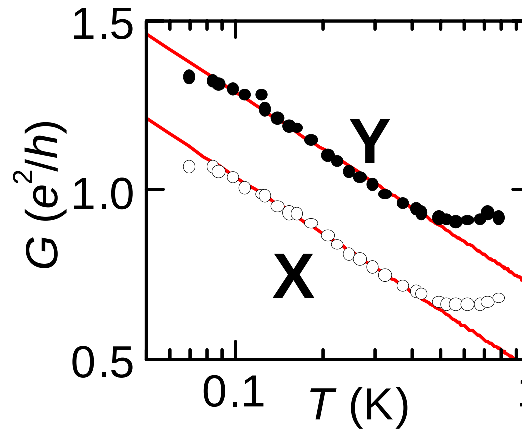
- Generally high conductance – a coherent electron waveguide
- Dips in conductance due to interference in the resonant cavity

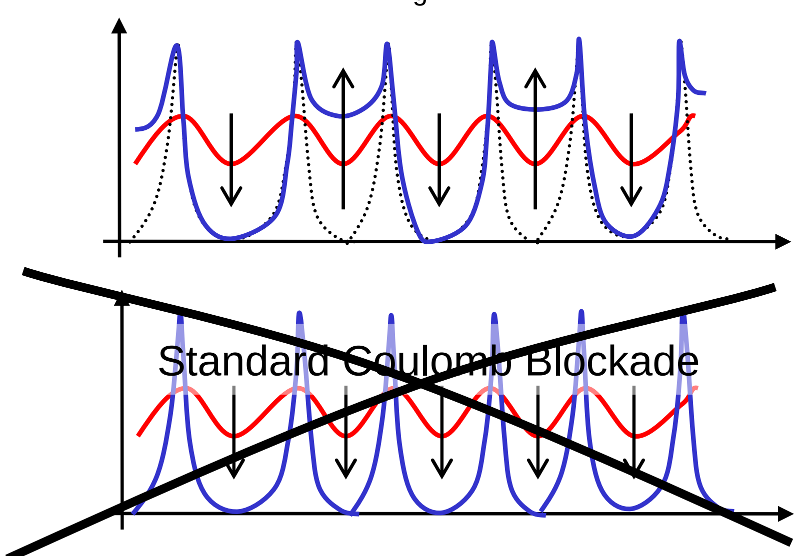


Liang et al, Nature 411, 665 (2001)

With medium-transparency contacts







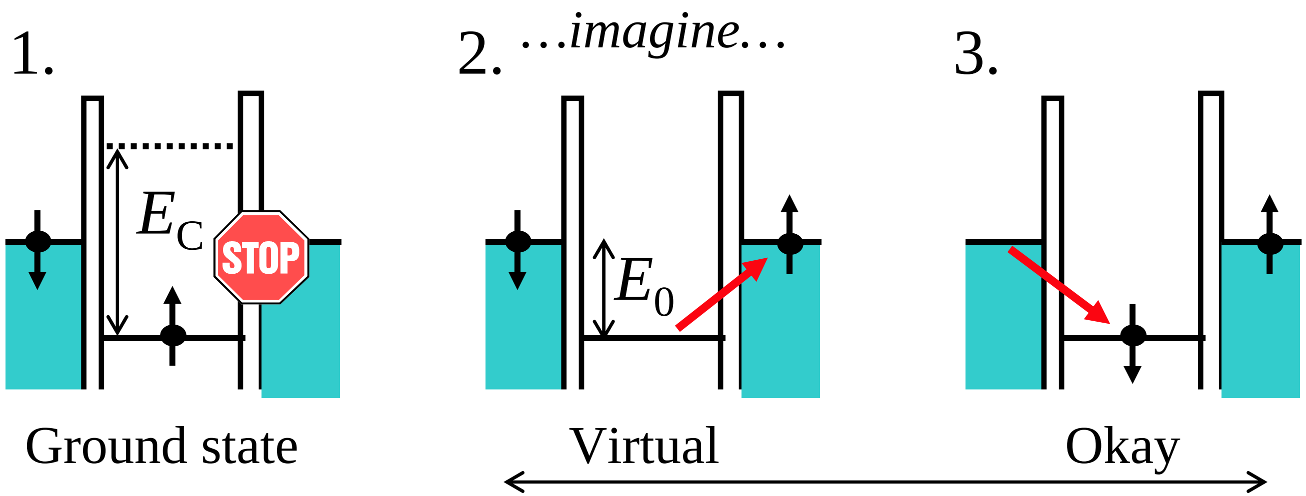
1) Alternations
2) Peaks in d*I*/d*V*
3) *G* ~ -log*T*

*- Key signatures of the **Kondo effect***

Nature **408**, 342 (2000)

M

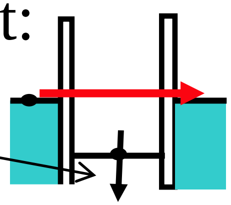
Cotunneling and Kondo



Heisenberg: $\Delta t \sim h/E_0$

Net result:

- transport→
- spin flip

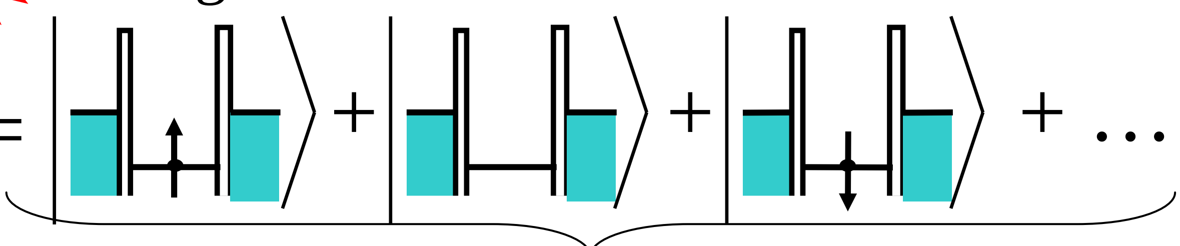


"*Co-tunneling*" due to more open contacts (higher order process)

NEW!

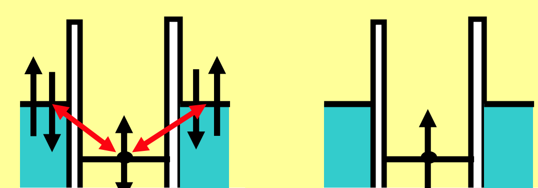
New ground state - "Kondo state":

$|\Psi\rangle =$



Coherent superposition

$T < T_K$ | $T > T_K$

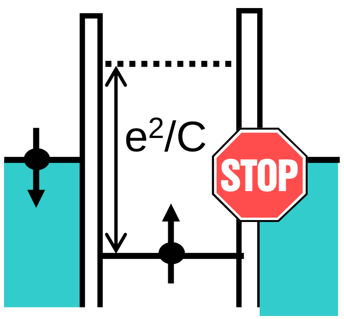


resonance | blockade

The Kondo effect, correlations

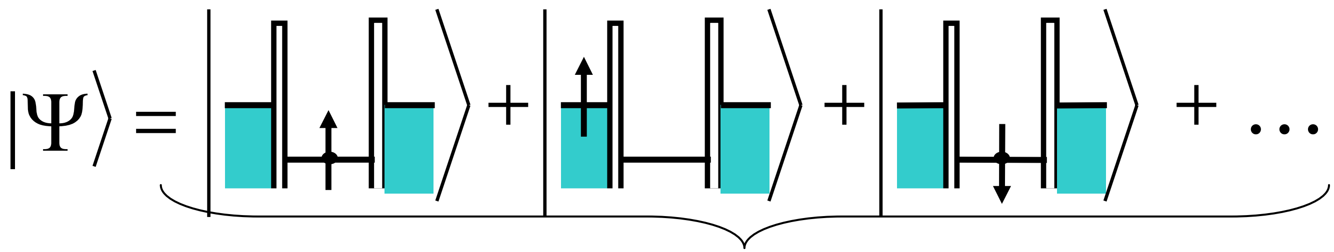
Anderson model: $$H = \underbrace{\sum_{k\sigma} E_k c^\dagger_{k\sigma} c_{k\sigma}}_{\textbf{contact}} + \underbrace{\sum_{\sigma} E_0 f^\dagger_\sigma f_\sigma}_{\textbf{localised state on nanotube}} + \underbrace{\sum_{k\sigma} V_k (c^\dagger_{k\sigma} f_\sigma + f^\dagger_\sigma c_{k\sigma})}_{\textbf{coupling}}$$

Normal ground state:



Coulomb blockade

For strong coupling (large *V*), new ground state:

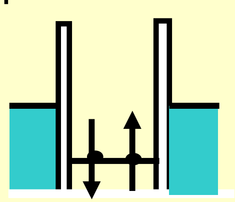


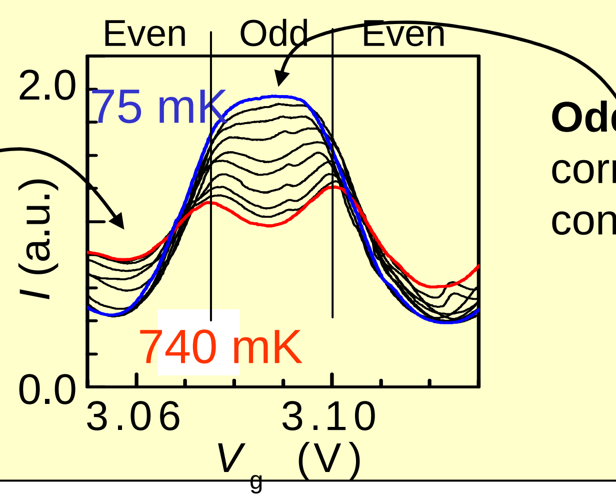
coherent superposition (when *T* low enough)

$\longrightarrow$ predicts resonance for transport (for S=1/2)

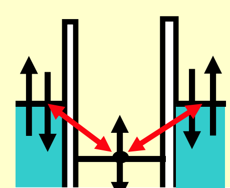
EXPERIMENT

Even *N*, *S=0*:
no correlated state,
suppression of conductance

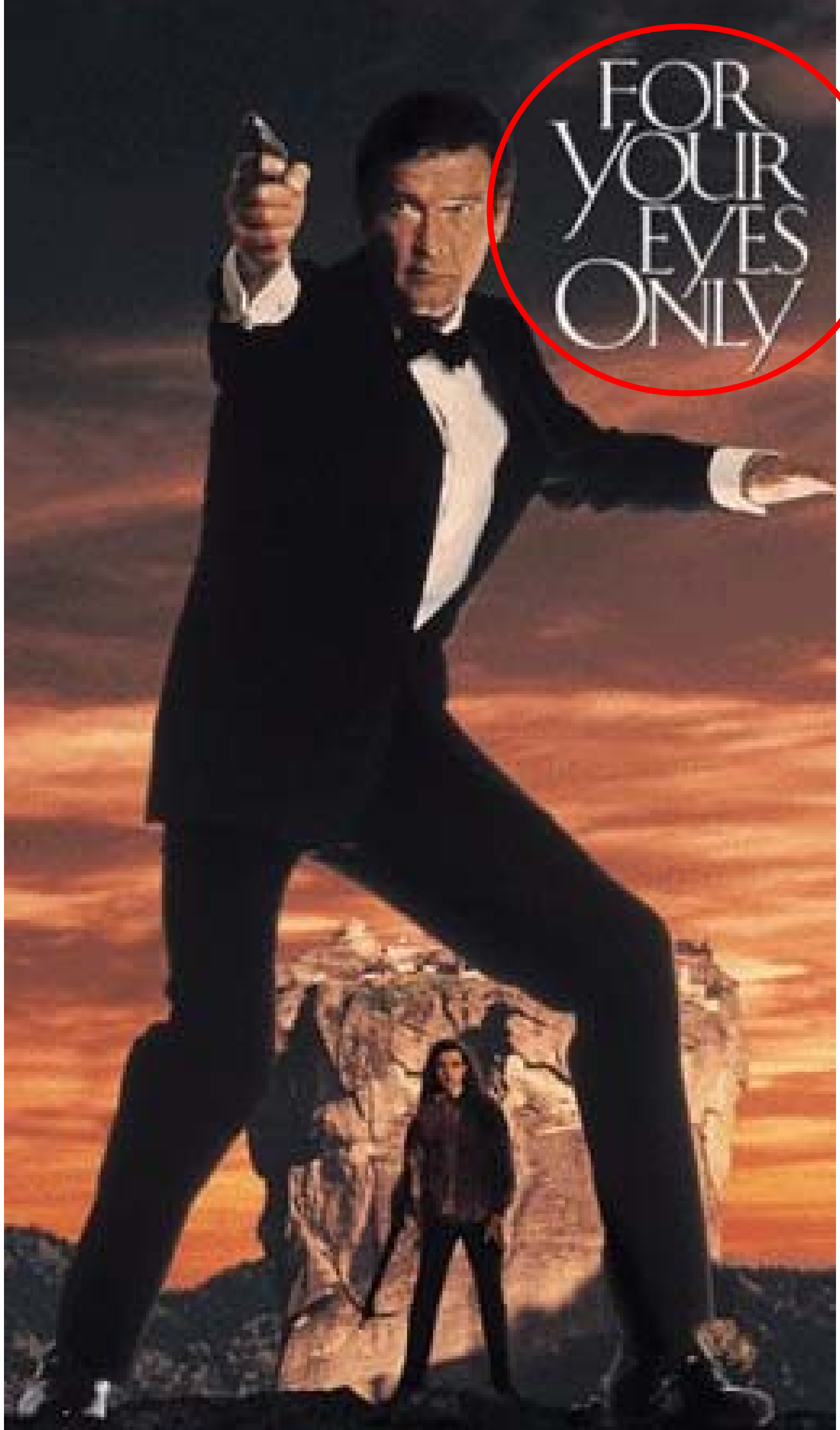




Odd *N*, *S=1/2*:
correlated state at really low *T*,
conductance restored!

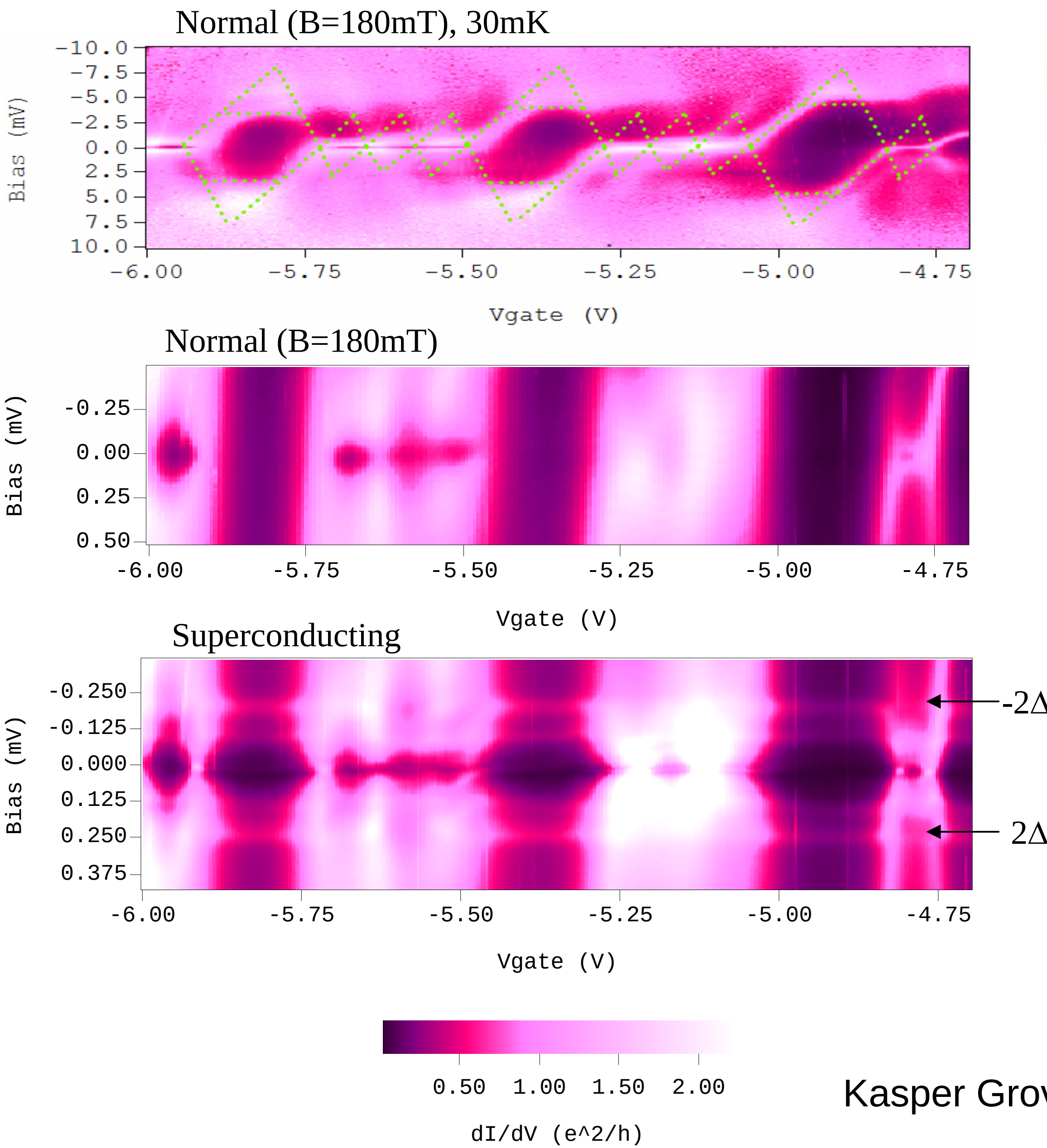


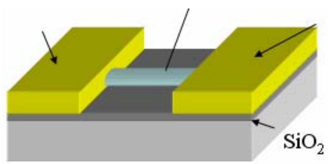
Highly tuneable system



...recent data...

Superconductor-SWCNT-Superconductor junction





Four-period shell filling.
Ec~ ΔE ~ 3-4meV

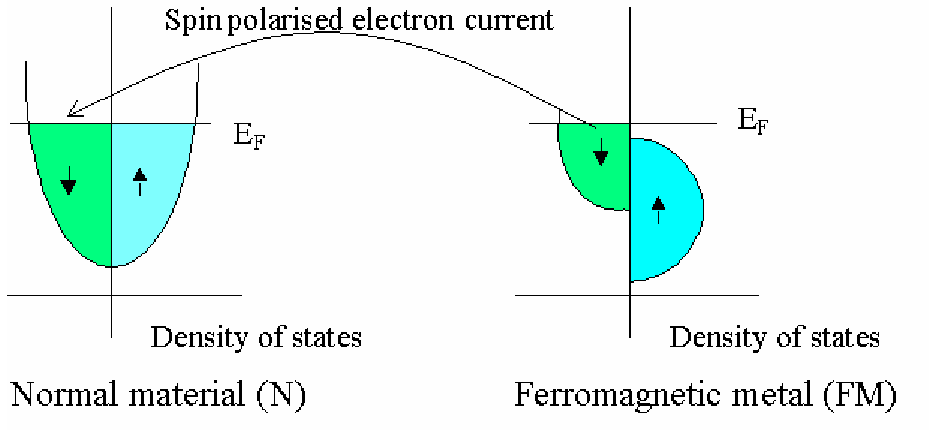
SWCNT contacted to
Ti/Al/Ti 5/40/5 nm leads
(T_c = 760mK)

Clear sign of Multiple Andreev Reflections, i.e., structure in dI/dV vs bias at $V_n=2\Delta/en$, n=1,2,3,...

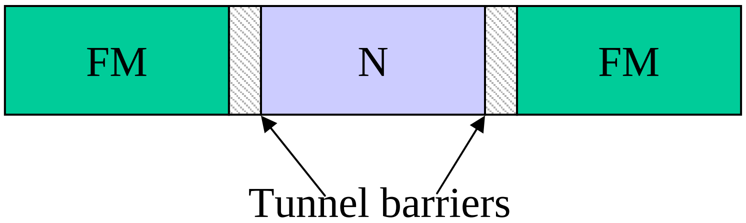
Kasper Grove-Rasmussen et al

Poster

Ferromagnetic contacts



FM-N-FM system



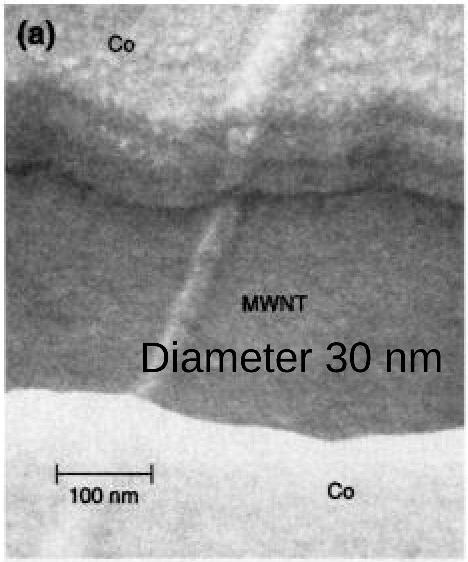
Difference between tunnel resistance for parallel (R_p) and anti-parallel (R_{ap}) magnetised contacts (Julliere, 1975):

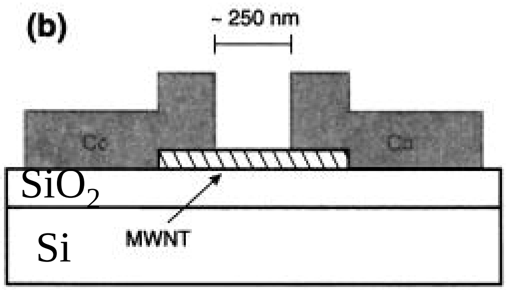
$$\frac{\Delta R}{R_{ap}} = \frac{R_{ap} - R_p}{R_{ap}} = \frac{2P^2}{1+P^2}$$

P: fraction of polarised conduction electrons in the FM.

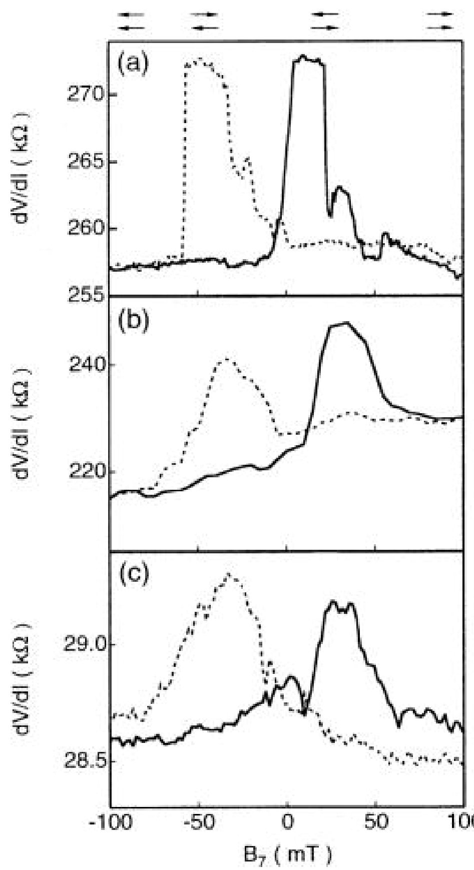
Multiwall tubes with magnetic leads

K. Tsukagoshi, B.W. Alphenaar, H. Ago, Nature **401**, 572 (1999)



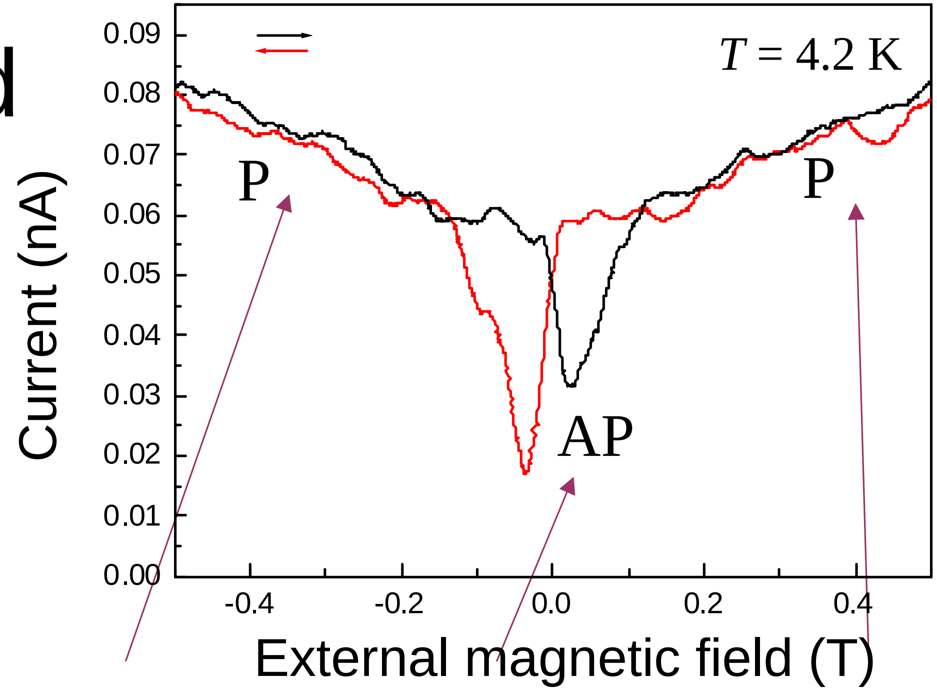


Two-terminal <u>resistance</u> vs. B-field
for three different devices at 4.2 K

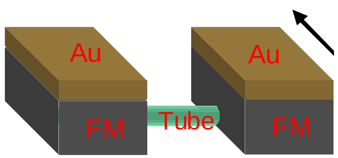


In the best case:
$\Delta R/R_a \sim 9\ \%$
Multiwall tubes:
diffusive conductors
intrinsic magnetoresistance

Spin-polarized transport ?

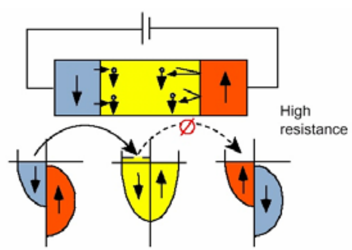


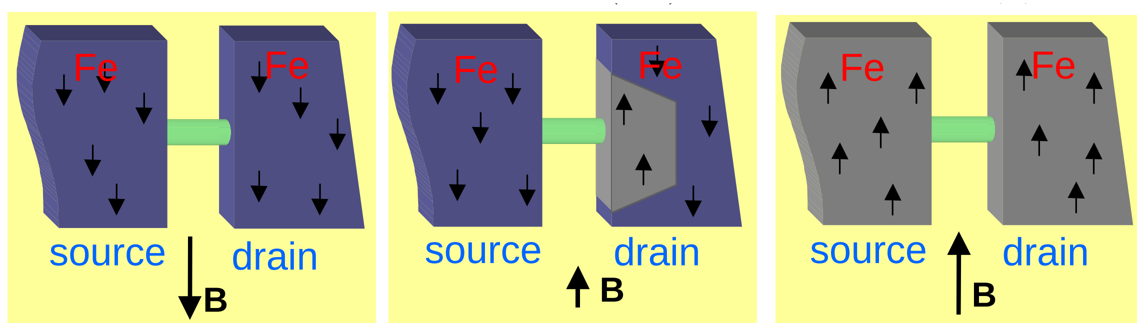
Sweep directions:



Micromagnet electrodes, single-walled

The simplified picture





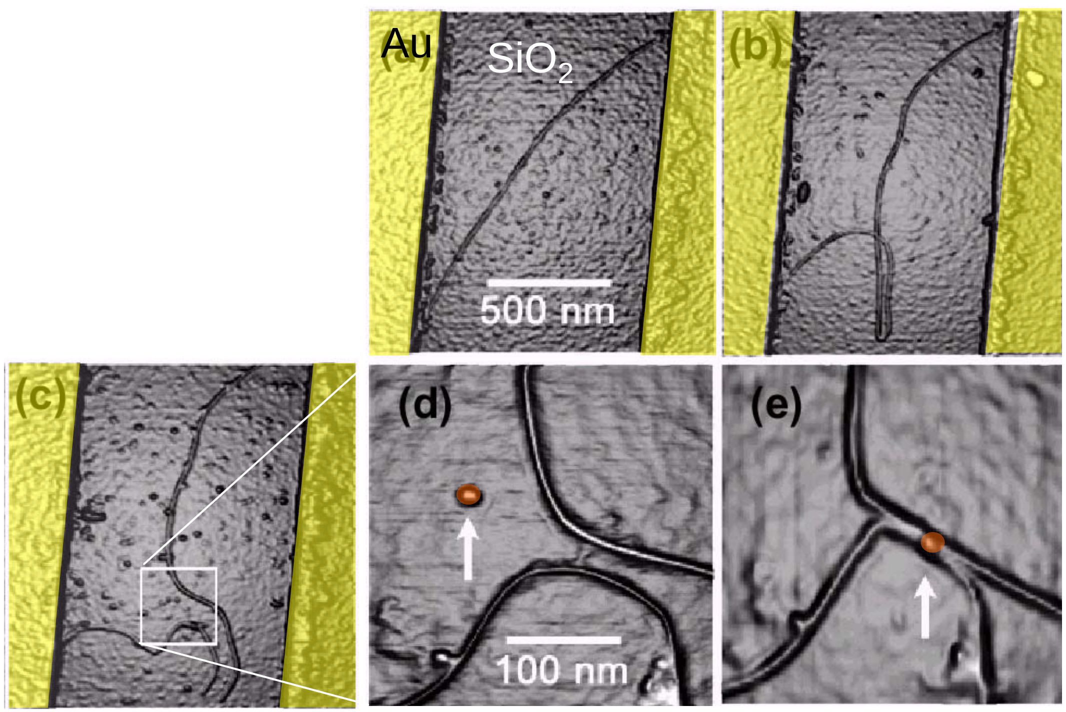
Jensen et al, PRB (June 2005)

"Spin-tronics"

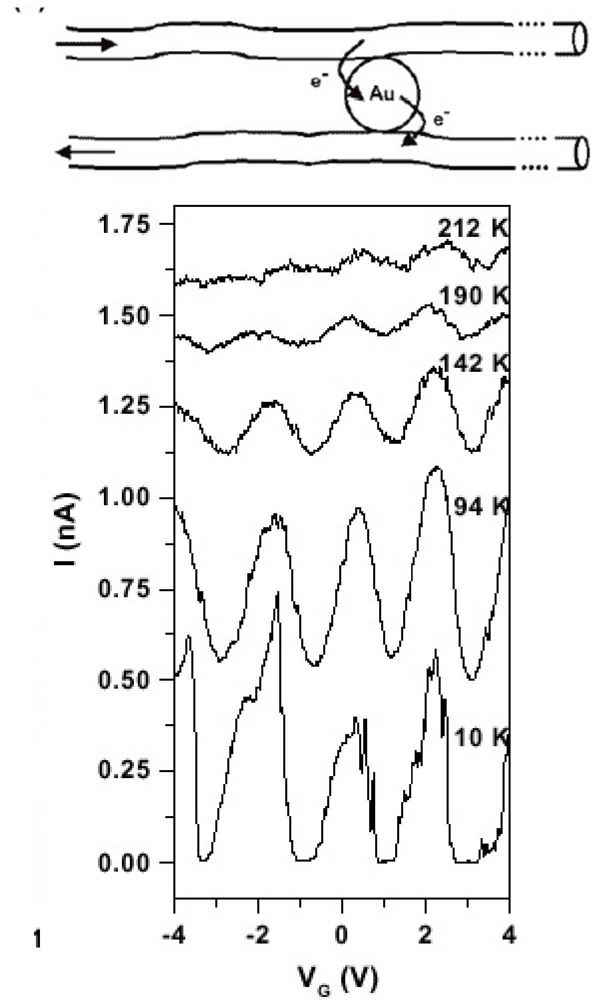
Use the electronic spin rather than charge as carrier of information

Gold nanoparticle single-electron transistor with carbon nanotube leads

AFM manipulation

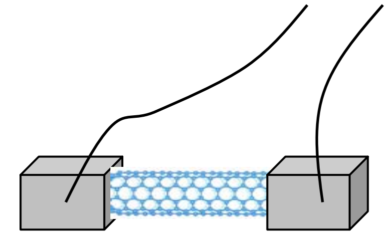


- 7 nm gold particle ($e^2/C \sim 60$ meV)



C. Thelander *et al*, APL **79**, 2106 (2001).

Electrons in nanotubes



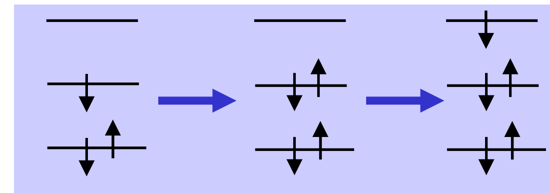
Attach leads to 1D electron system

Low T measurements

Normal metal

Single-electron effects

- spectroscopy, shells (2, 4)
- Fabry-Perot resonances



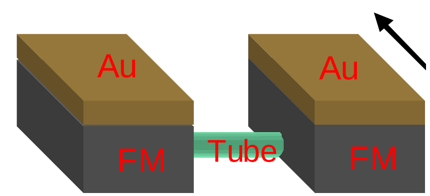
Correlated states

-Kondo effect, long-range interactions,
Luttinger liquid

Ferromagnet

Magnetic contacts

- Spin transport, spin transistors?



Superconductor

Superconducting contacts

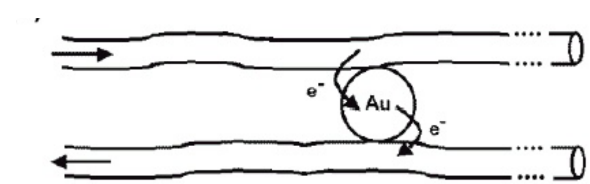
- supercurrents?

Spin

Nanoparticle

AFM manipulation of nanoscale objects

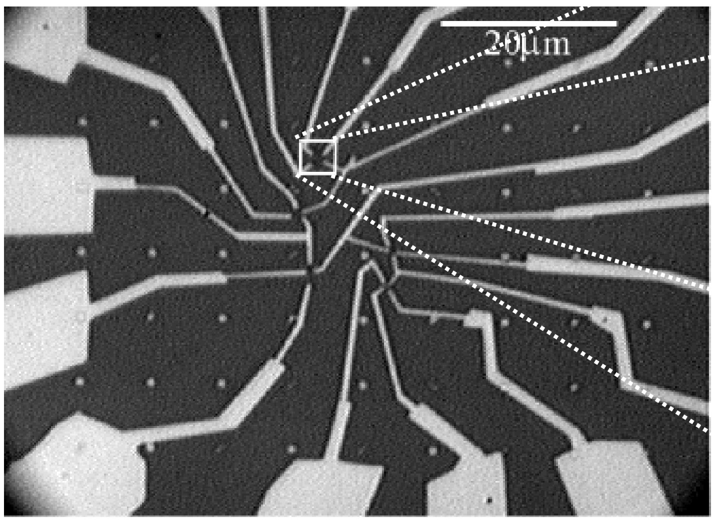
- Gold particle transistor, 1D-0D-1D



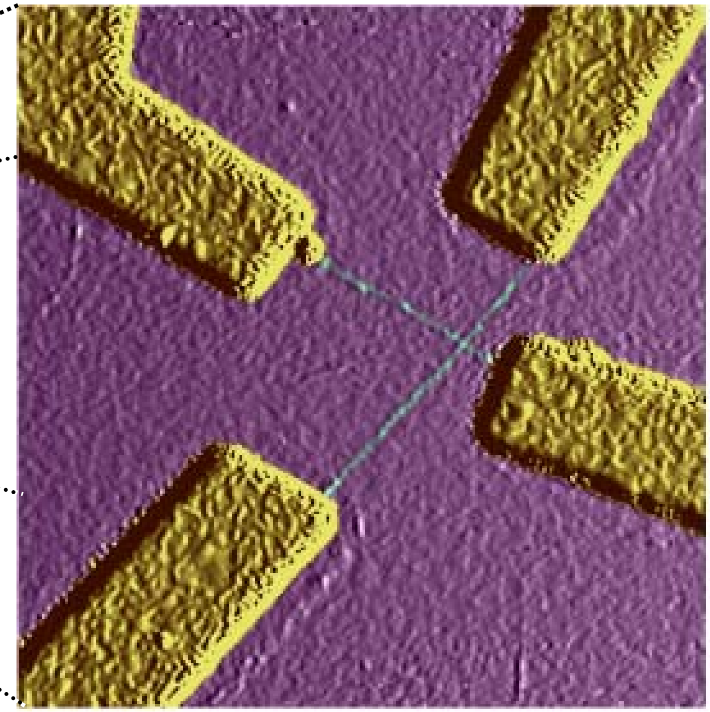
Outline

- Electronic structure (1D, 0D)
  - density of states
- Electron transport in 1D systems (general)
  - quantization, barriers, temperature
- Transport in nanotubes (1D)
  - contacts, field-effect,...
- Low temperature transport, quantum dots (0D)
  - Coulomb blockade, shells, Kondo, ...
- Nanotube electronics, circuits, examples
- Problem session
- Wellcome party

Crossed Nanotube Devices

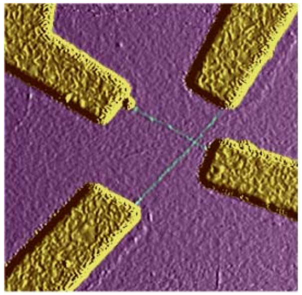


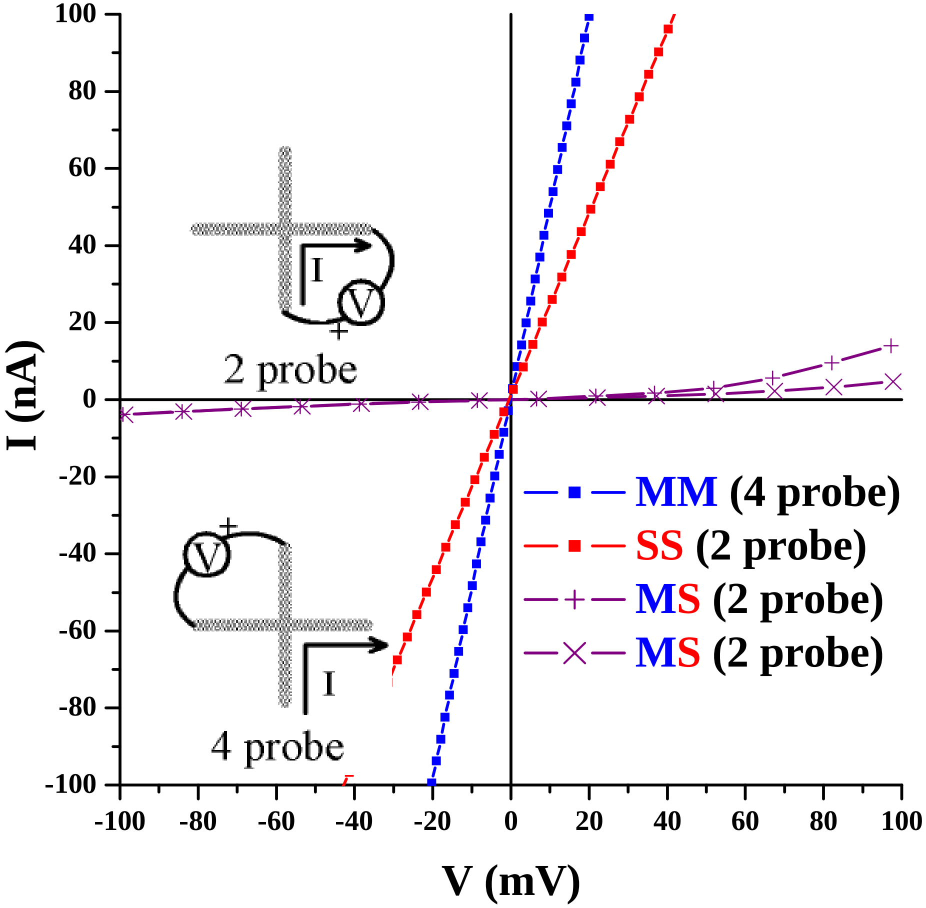
Optical micrograph showing five sets of leads to crossed nanotube devices



AFM image of one pair of crossed nanotubes (green) with leads (yellow)

Crossed Nanotube Junctions





MM junctions:

R = 100-300kΩ

T = 0.02-0.06

SS junctions:

R = 400-2400kΩ

T = 0.003-0.02

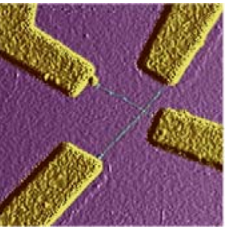
MS junctions:

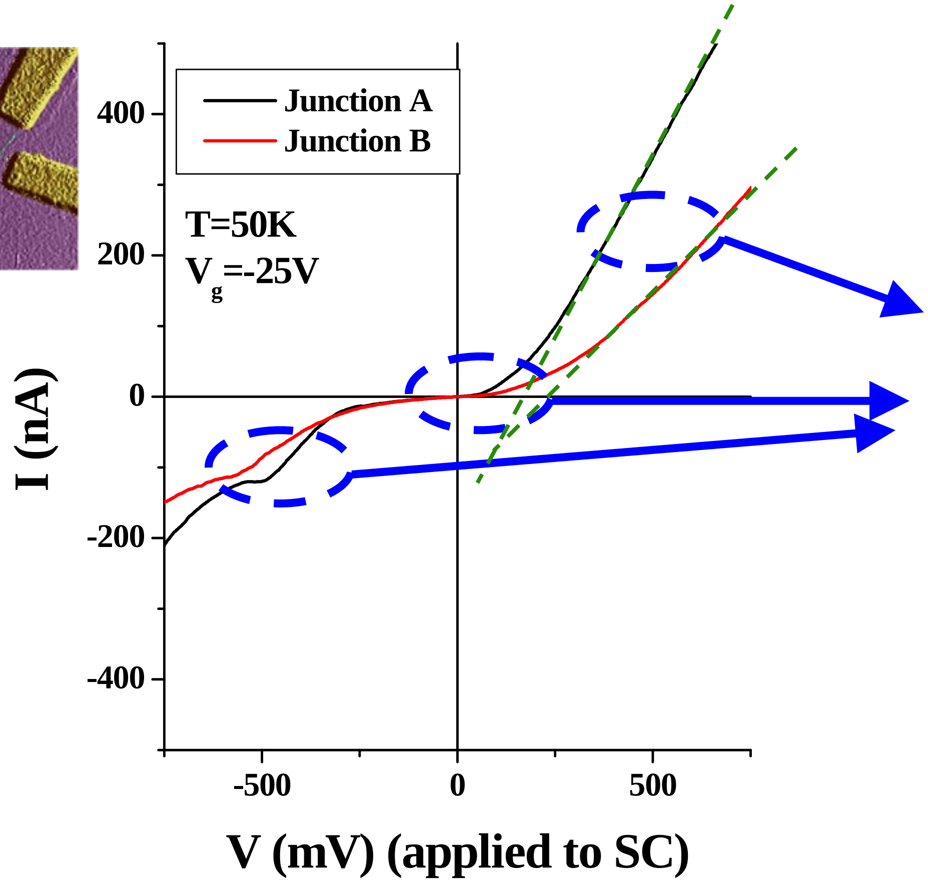
R = 30-50MΩ

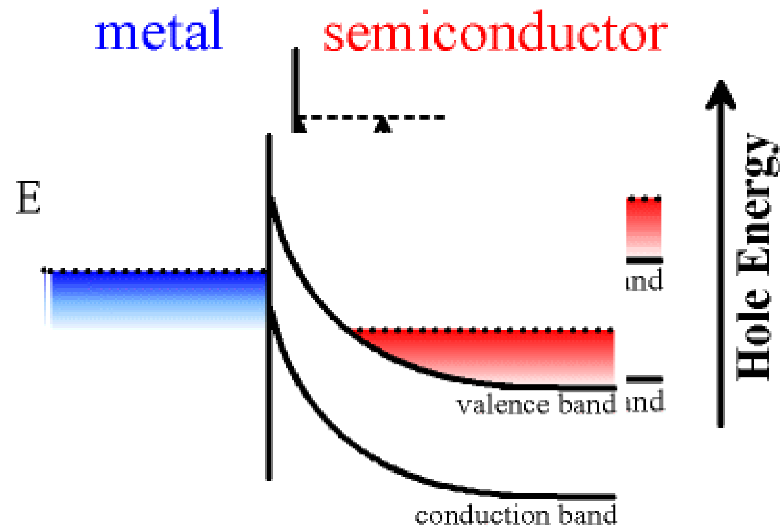
T = 2 x 10^{-4}

Fuhrer et al., Science (2000)

Metal-Semiconductor Nanotube Junction







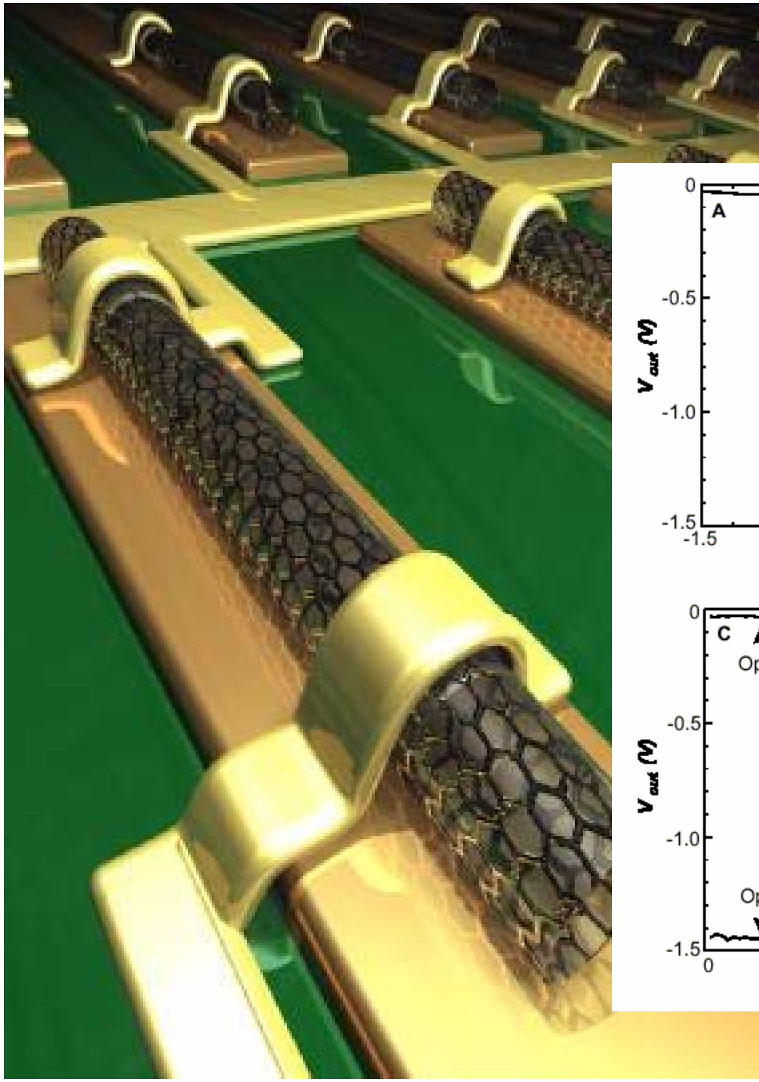
Reverse Bias

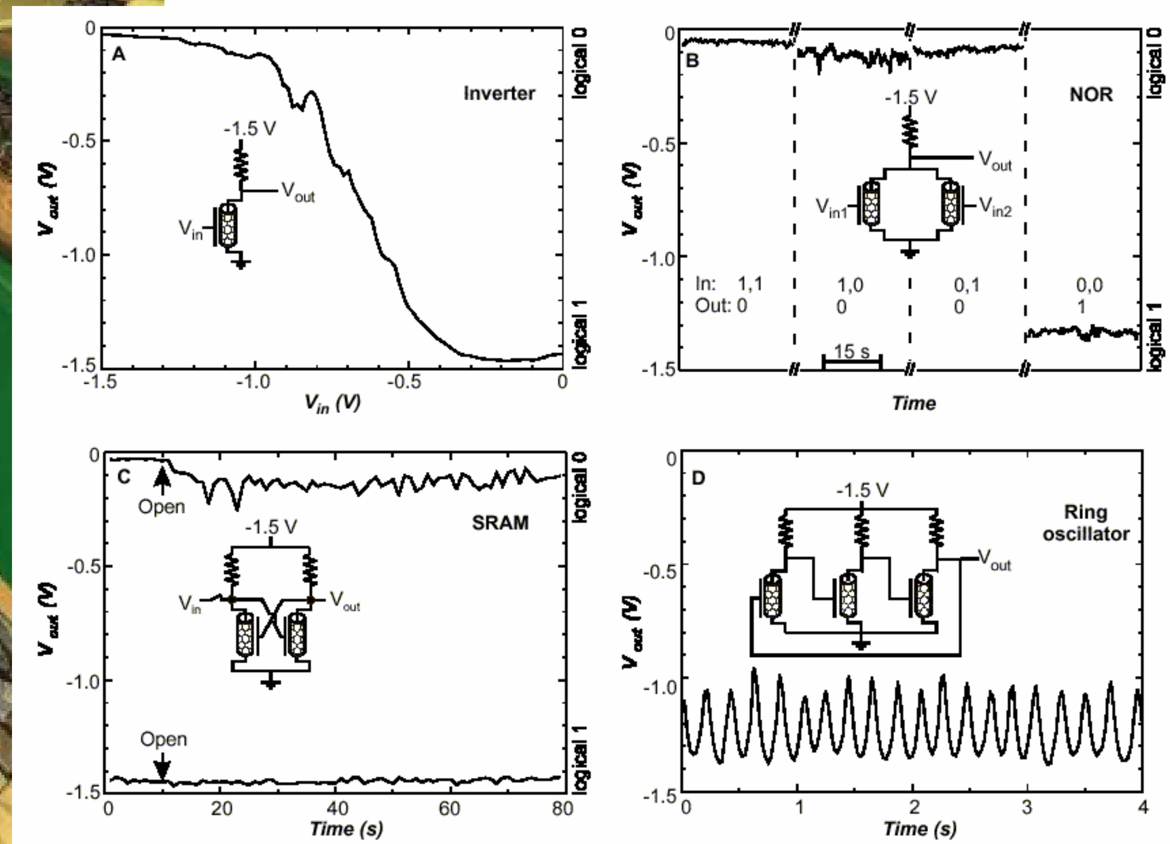
A (leaky) Schottky diode

⇨ $E_g/2$ = 190-290meV
(expect: 250meV)

Fuhrer et al., Science (2000)

Nanotube logic

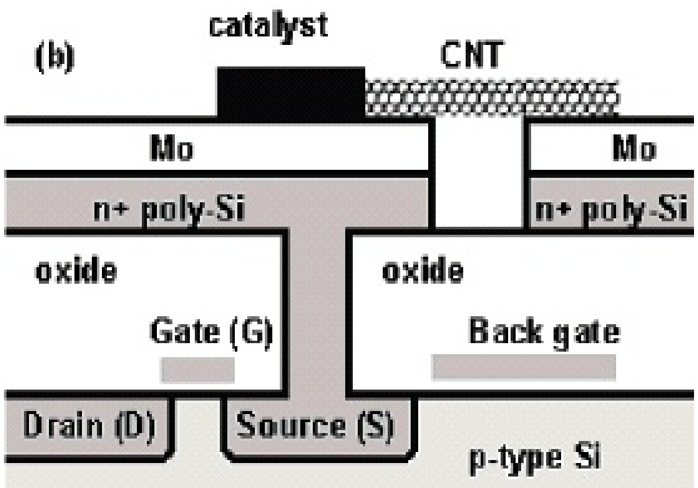




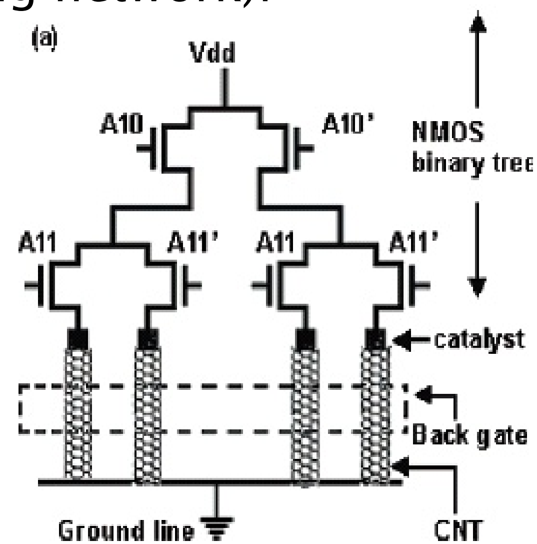
Bachtold et al, Science 2001

Integration of CNT with Si MOS

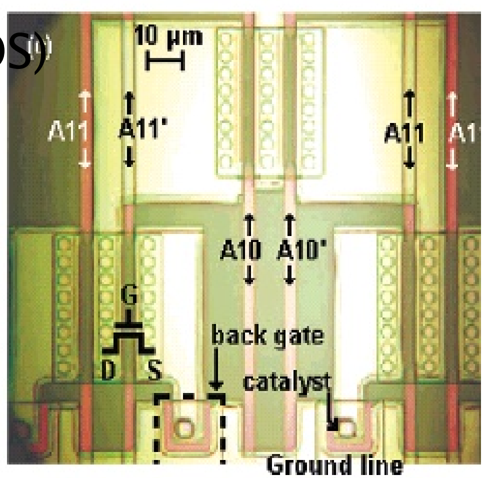
UC Berkeley and Stanford, Tseng et al., Nano Lett. 4, 123 (2004).



Random access nanotube test chip (switching network):



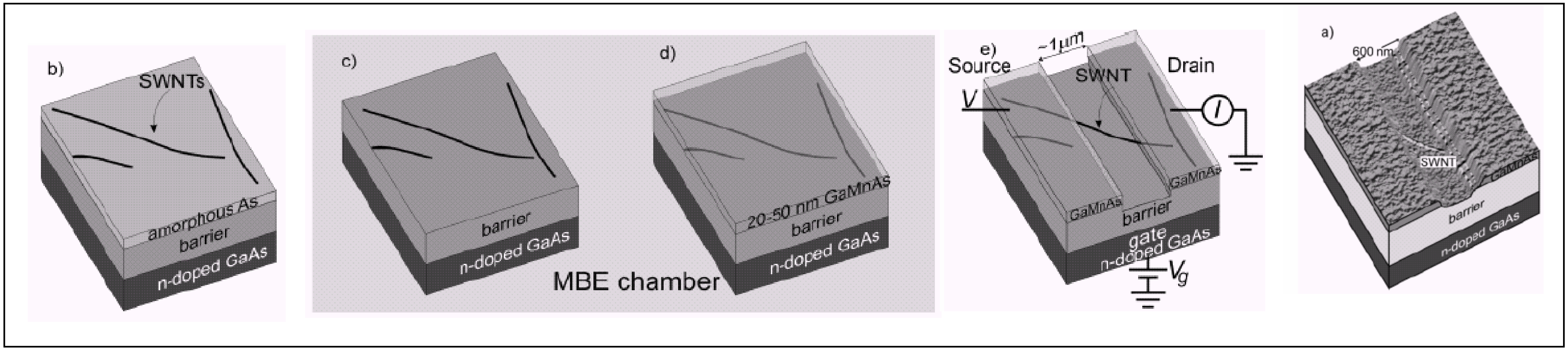
- N-channel MOS-FET circuit (standard Si IC processing)
- Nanotubes grown by Chemical Vapor Deposition
- Growth from CH_4+H_2 at 900 C (compatible with MOS)
- Contacted by Mo electrodes

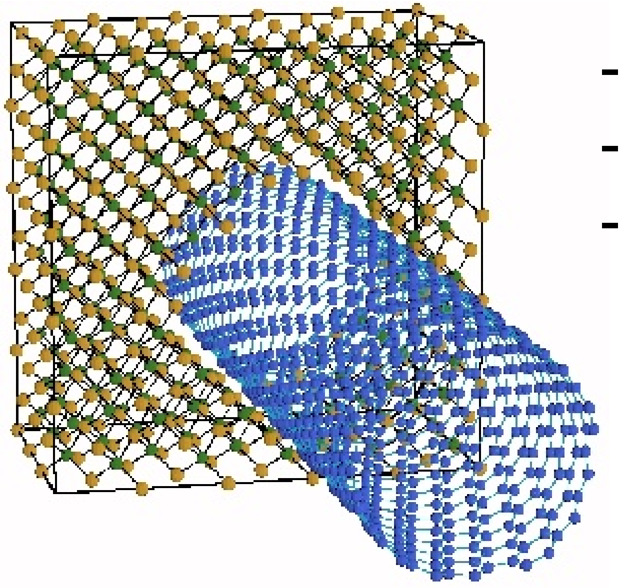


22 binary inputs to probe $2^{11}=2048$ nanotube devices on single chip

Proof of concept
(only 1% showed significant gate dependence)

Nanotube grown expitaxially into a semiconductor crystal



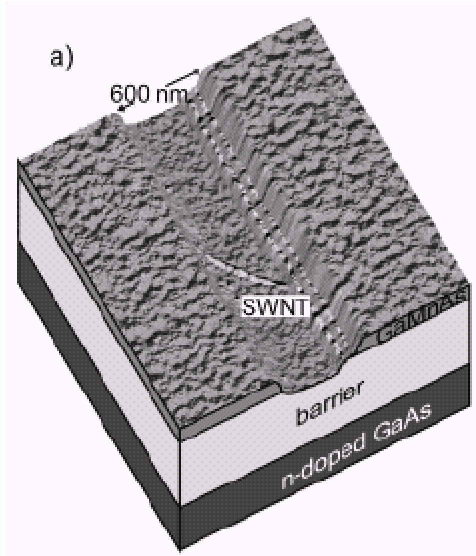


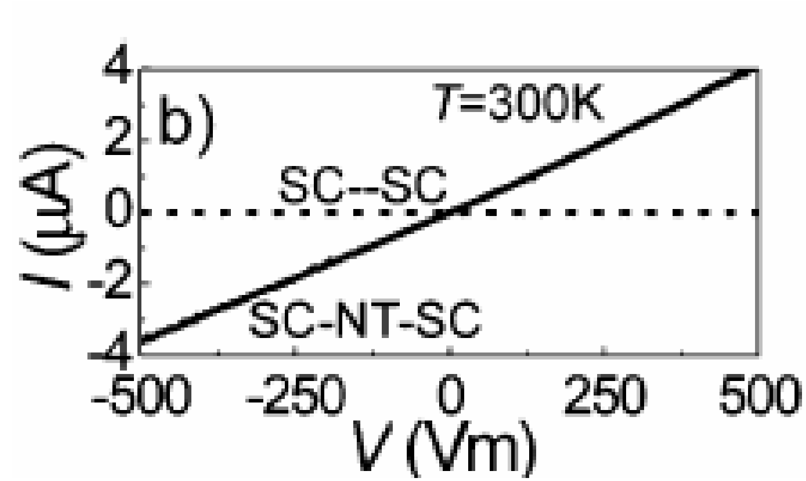
- Epitaxial overgrowth by MBE (single crystal)
- Nanotubes survive being buried
- Hybrid electronics from molecular and solid state elements

J.R. Hauptmann et al

Poster

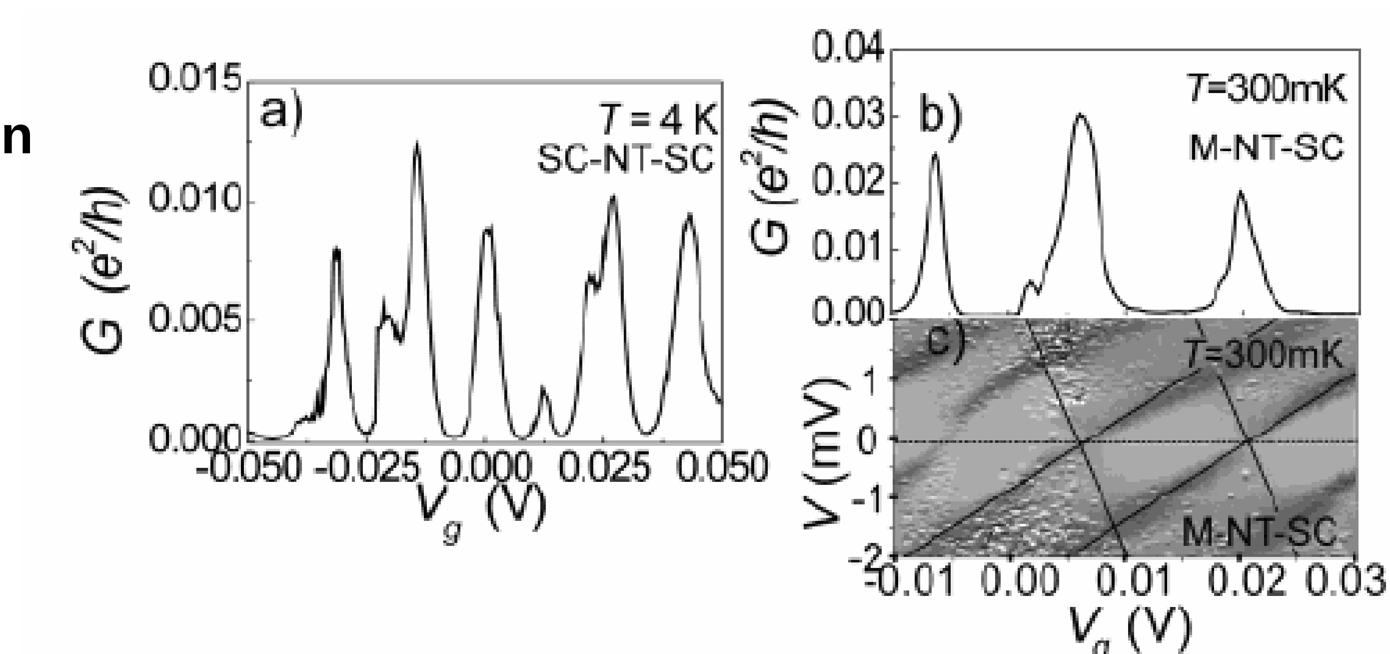
NanoLetters 4, 349 (2004)





Room T *I-V*: R = 125 kOhm

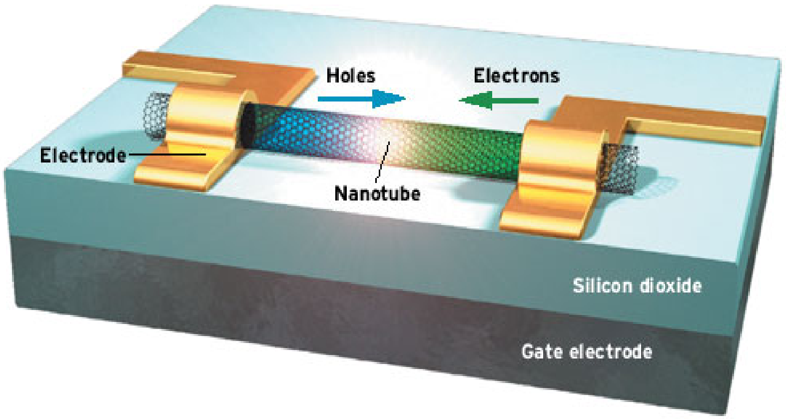
Single-electron transistors at low T



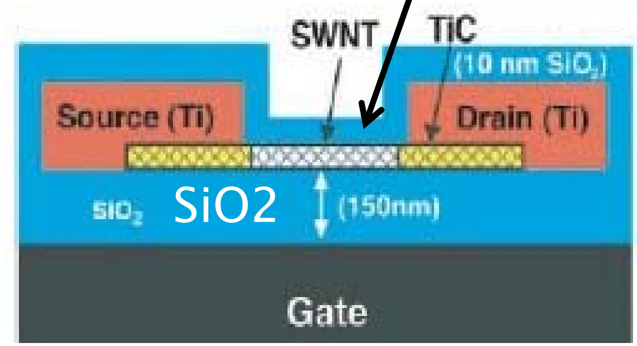
V. New aspects of tube electronics

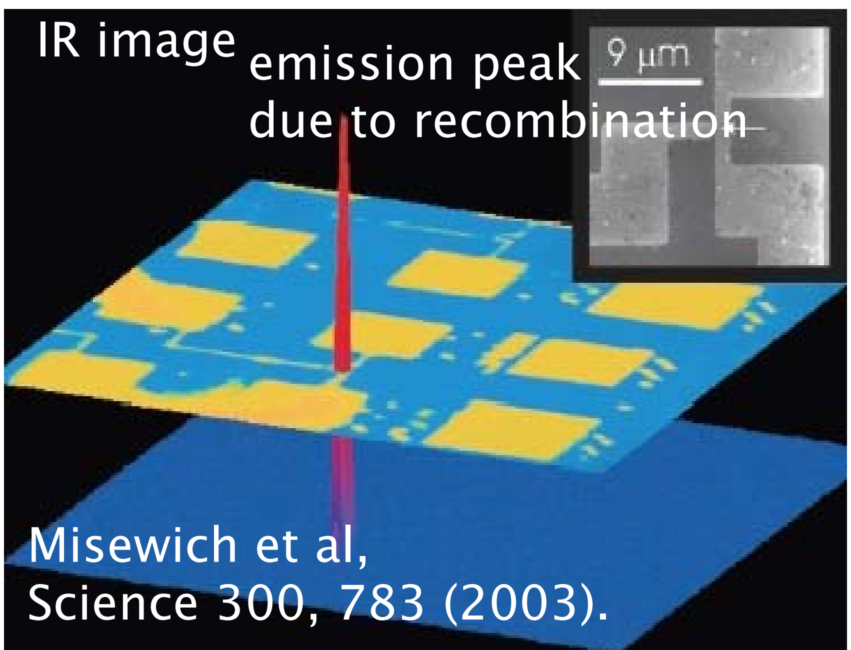
- Optoelectronics
- Nanoelectromechanical systems (NEMS)

Optical emission from NT-FET



Effective p-n junction in semiconducting CNT
(Schottky barriers + appropriate bias)

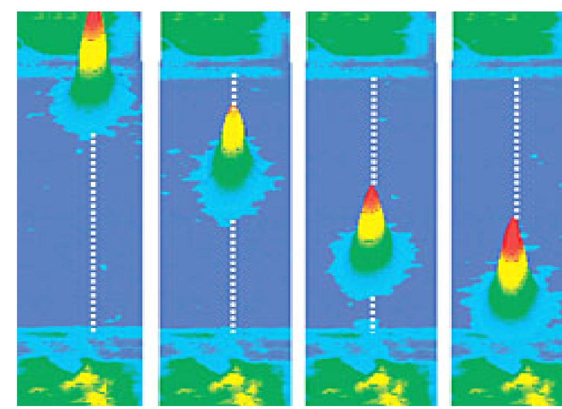




Misewich et al,
Science 300, 783 (2003).

ambipolar
nanotube
FET

moving
"LET"

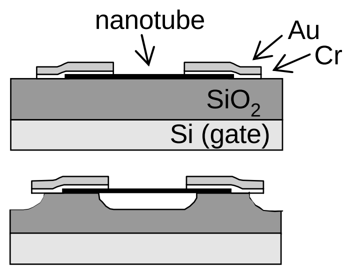


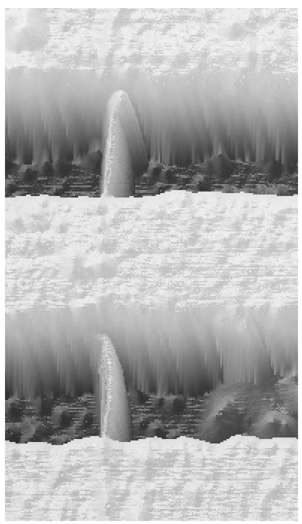
GATE

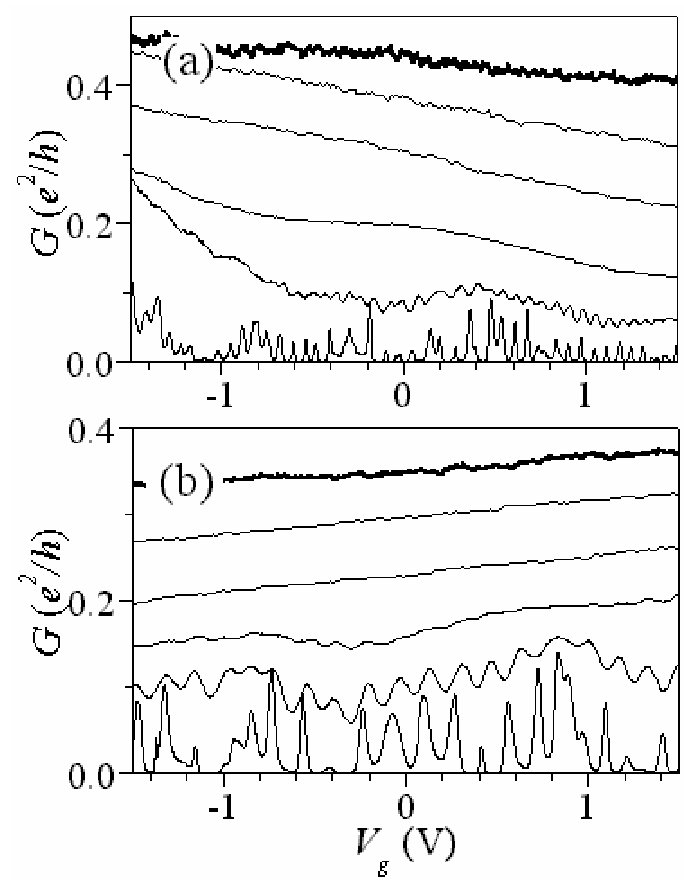
Avouris group (IBM), PRL 2004

M

Transport in suspended tubes







Before

ΔV_g~70mV

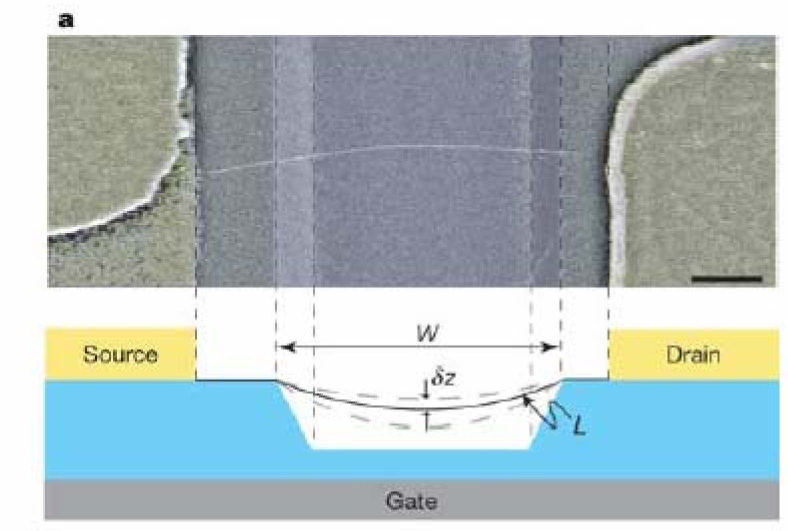
and after

ΔV_g~160mV

$\Delta V_g \sim e/C_g$, gate capacitance decreases

Appl. Phys. Lett. 79, 4216 (2001)

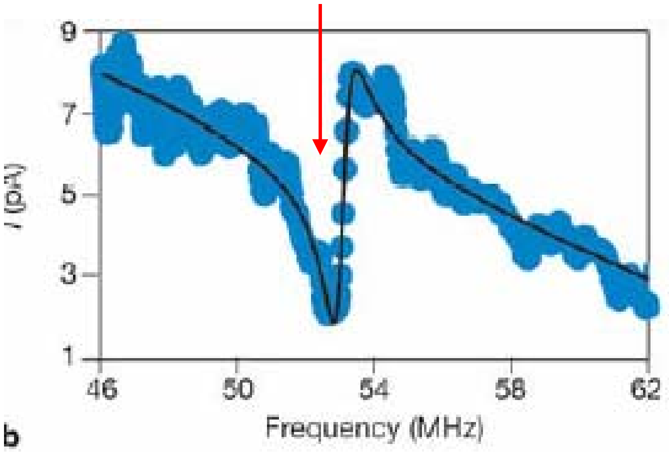
Nanotube Electromechanical Oscillator



Electrostatic interaction with underlying gate electrode pulls tube towards gate

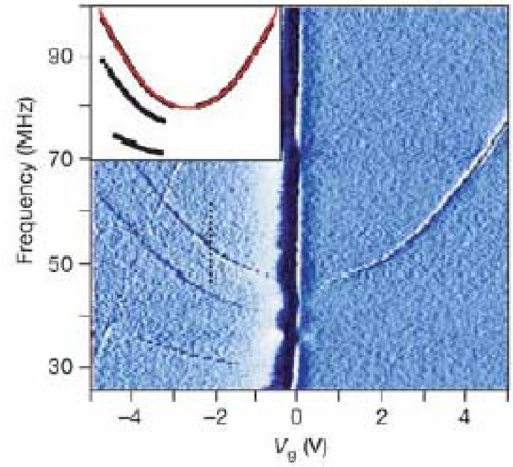
Put AC signal on source and gate

Resonance



Actuation and detection of vibrational modes

- Employing sensitive semiconducting tube
- Resonance (tension) tuned by DC gate voltage:

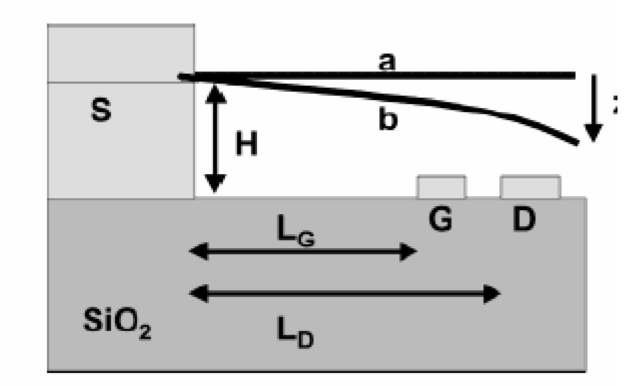


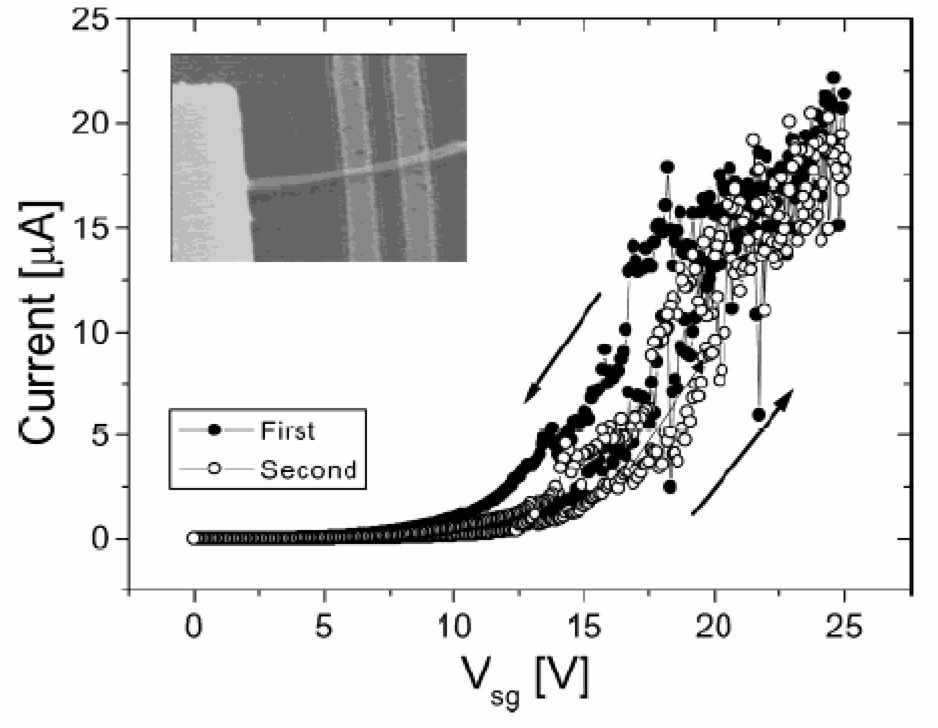
Sazonova et al, Nature 431, 284 (2004)

Nanorelay

Switch based on nanotube beam suspended above gate and source electrodes:

Electrostatic attraction to gate





Reversible operation of switch

S.W. Lee et al,
Nano Letters 4, 2027 (2004)

Outline

- Electronic structure (1D, 0D)
  - density of states
- Electron transport in 1D systems (general)
  - quantization, barriers, temperature
- Transport in nanotubes (1D)
  - contacts, field-effect,...
- Low temperature transport, quantum dots (0D)
  - Coulomb blockade, shells, Kondo, ...
- Nanotube electronics, circuits, examples
- Problem session
- Wellcome party

Anti-conclusion

- what we have not covered…

- High-performance FET transistors
- Behavior in magnetic field
- Luttinger liquid behavior, correlated electrons in 1D
- Small-gap tubes
- Sensors (chemical, bio, mechanical)
- Problems in separation and positioning
- Bottom-up fabrication of devices, self-assembly
- Many other recent developments (see NT05)
- ...

Focused on the basic understanding of transport and electrons in NT

Recommended reading

- Electronic transport (general)
  - S. Datta, *Electronic Transport in Mesoscopic Systems* (Cambridge Uni. Press, 1995)
  - C. Kittel, *Introduction to Solid State Physics* (Wiley, 2005)
    Chapter 18 by P.L. McEuen in 8th edition only!

- Nanotubes and transport
  - R. Saito et al, *Physical Properties of Carbon Nanotubes* (Imperial College, 1998)
  - M.S. Dresselhaus et al, *Carbon Nanotubes* (Springer, 2001)
  - S. Reich et al, *Carbon Nanotubes* (Wiley-VCH, 2004)

  - P.L. McEuen et al, "Single-Walled Carbon Nanotube Electronics," *IEEE Transactions on Nanotechnology*, **1**, 78 (2002)
  - Ph. Avouris et al, ”Carbon Nanotube Electronics”, *Proceedings of the IEEE*, 91, 1772 (2003)

“Carbon gives biology, but silicon gives geology and semiconductor technology.”

In: C. Kittel,
Introduction to Solid State Physics

Acknowledgements

- CNT (Copenhagen Nanotube Team,
  Niels Bohr Institute 1998-)
- David Cobden, Uni. Washington, Seattle

Enjoy the conference!

$$\frac{2e^2}{h}$$