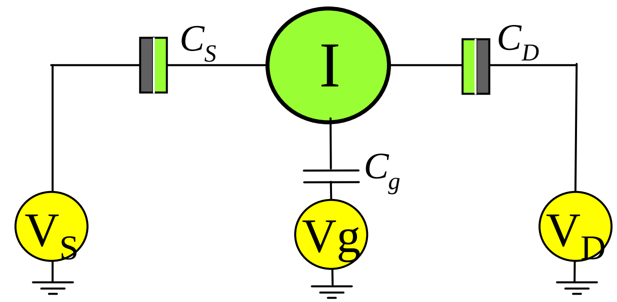
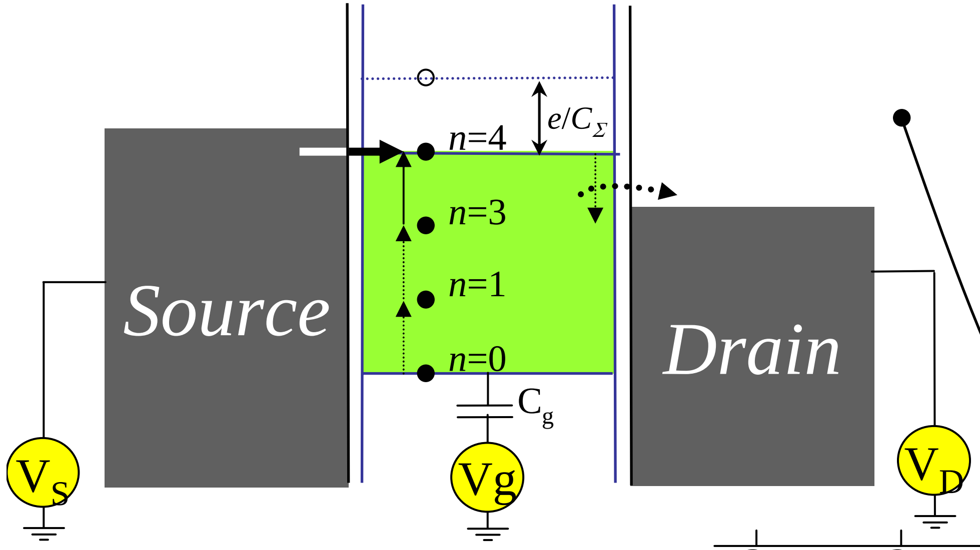
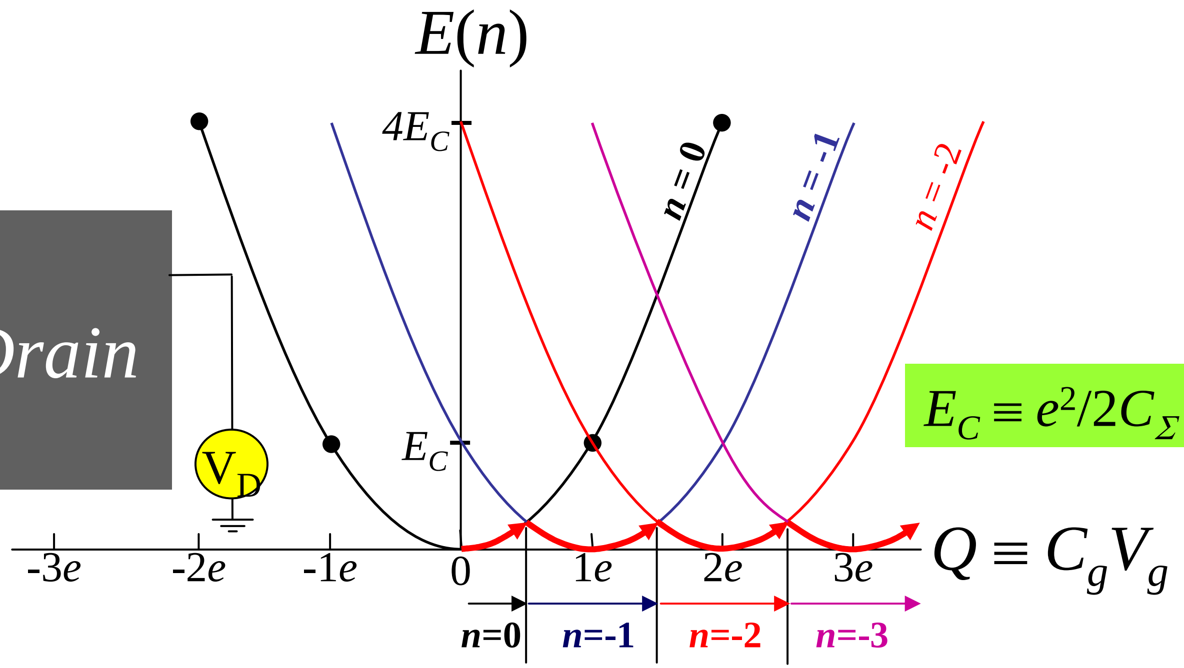
Single Electron Transistor



Electrostatic energy $E(n) = (ne + C_g V_g)^2 / 2C_\Sigma$

$C_\Sigma = C_S + C_D + C_g$

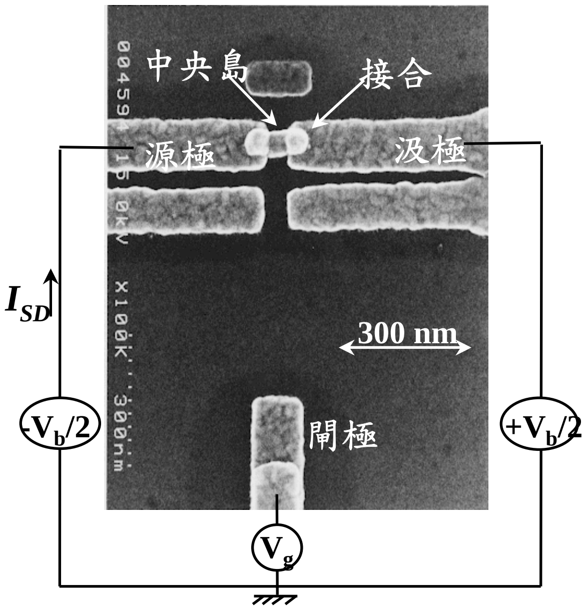




$E_C \equiv e^2 / 2C_\Sigma$

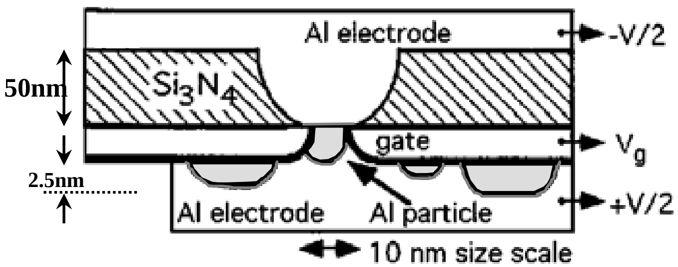
Various Single electron transistors:

(1) All metal transistors: *Al* island



our work (and many other groups)

(2) Sandwich structure: *Al* particle

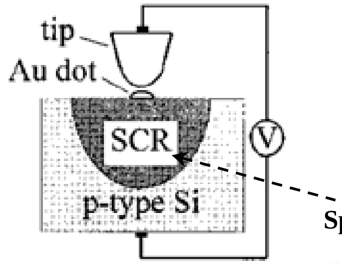


Al particles are isolated by thin Al_2O_3 layer

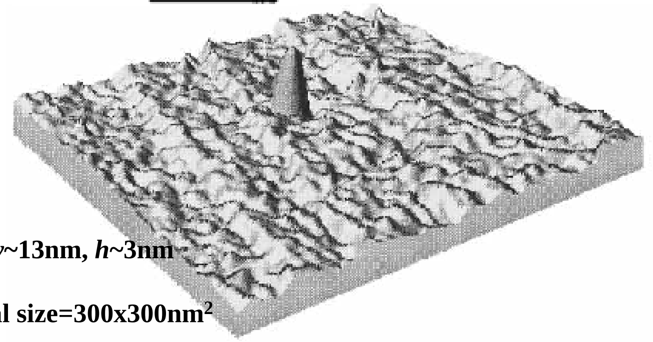
D.C.Ralph, C.T.Black and M. Tinkham
PRL, 78, 21 p. 4087 (1997) (Harvard Univ)

(3) STM: on *Au* particle

(STM=Scaning Tunneling Microscope)



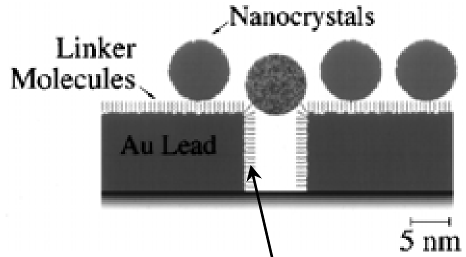
P. Radojkovic *et al*.
J. Vac. Sci. Technol. B 14(2), 1229 (1996)
(Technical Univ. of Munich)



dot: *w*~13nm, *h*~3nm

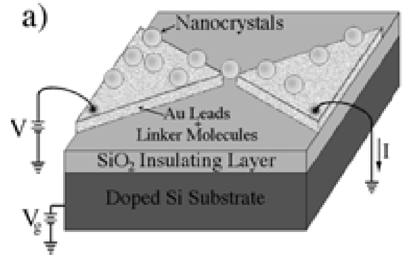
lateral size=300x300nm^2

(4) Colloidal: *Au* or *CdSe* particles

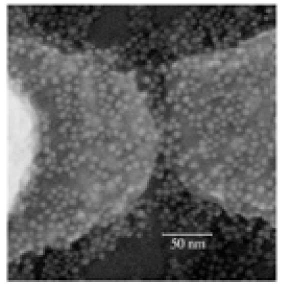


self-assmbled molecular
of dithiol molecules

a)



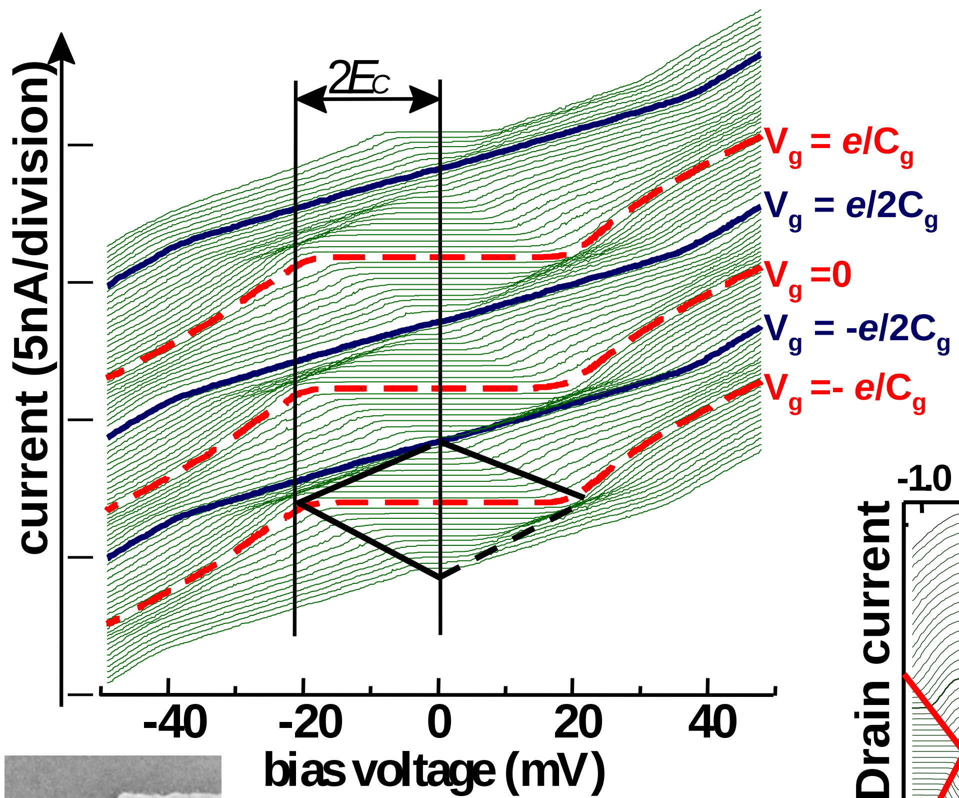
b)

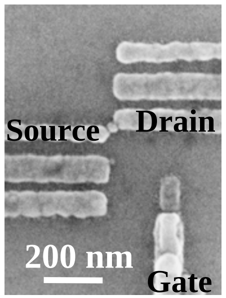


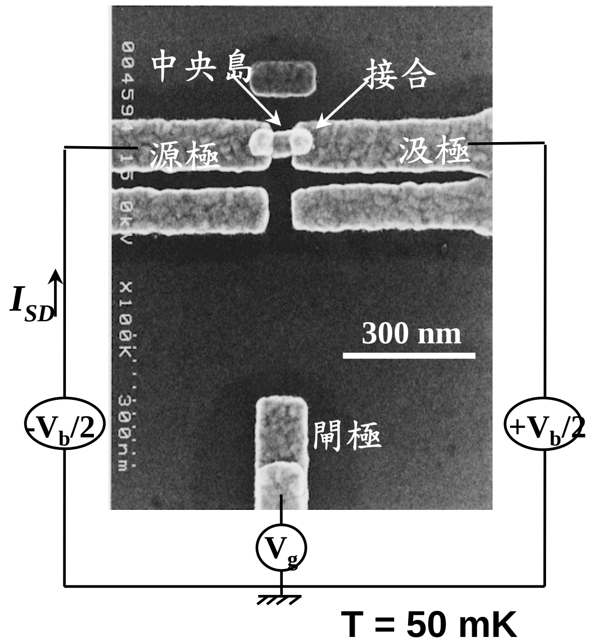
David L. Klein *et al*.
Nature, 389, p.699 (1997)
(Lawrence Berkeley National Lab.)

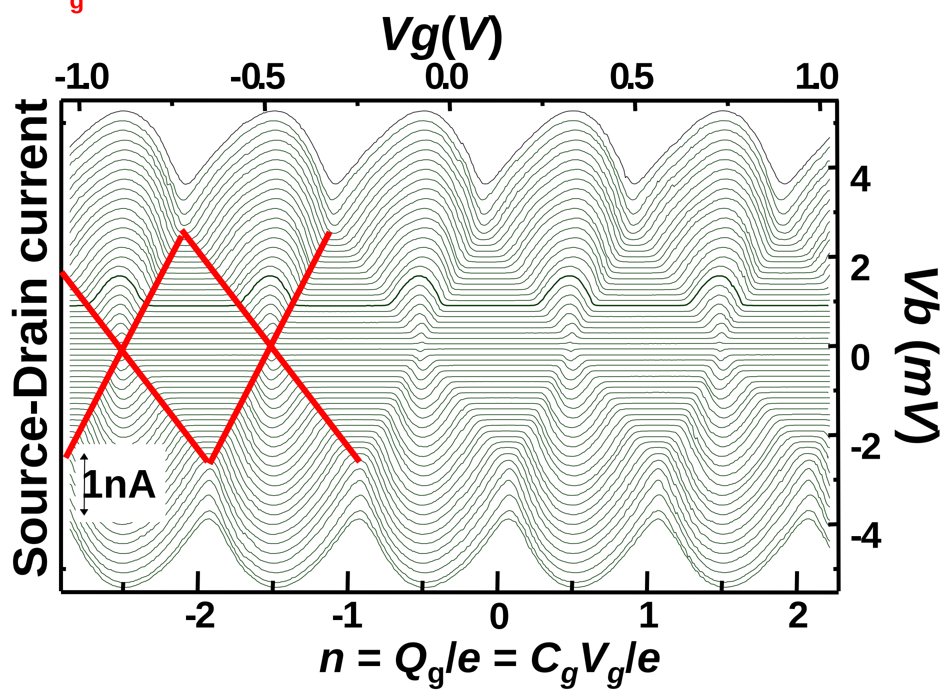
Ronald P. Andres *et al*. Science 722,1323 (1996)
(Purdue Univ.)

$I(V_b)$ vs. $I(V_g)$

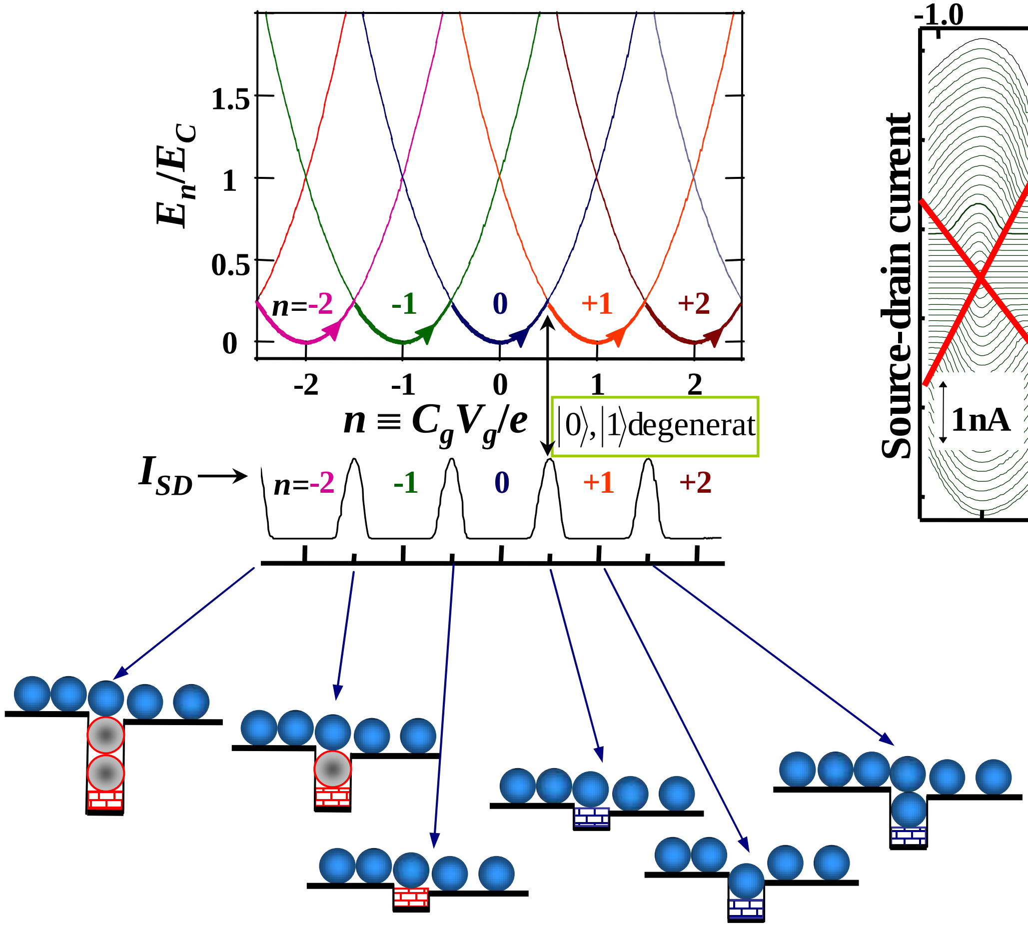

current (5nA/division)
2E_C
V_g = e/C_g
V_g = e/2C_g
V_g =0
V_g = -e/2C_g
V_g =- e/C_g
-40
-20
0
20
40
bias voltage (mV)

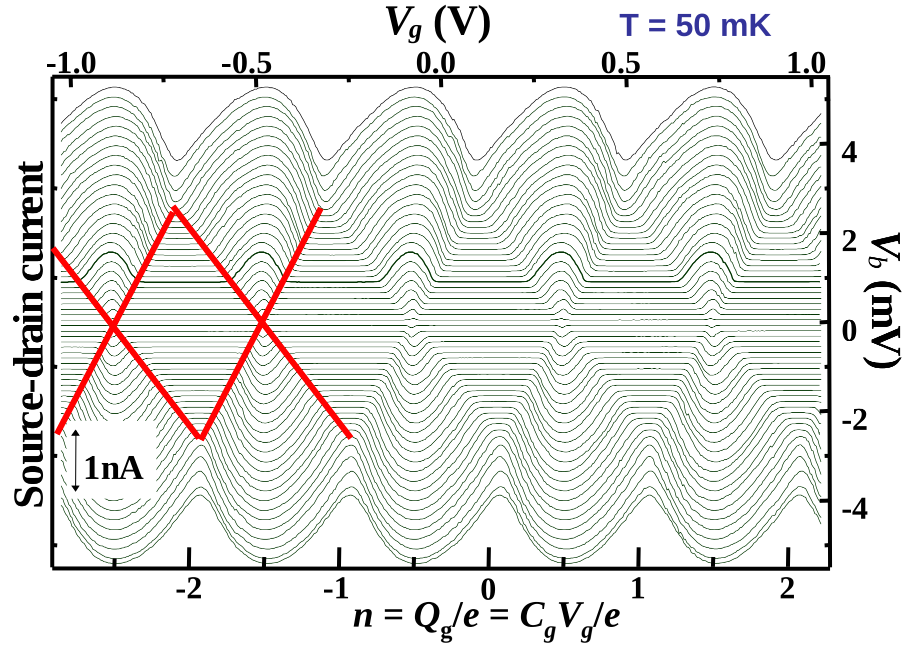

Source
Drain
200 nm
Gate


中央島
接合
源極
汲極
閘極
300 nm
I_SD
-V_b/2
+V_b/2
V_g
T = 50 mK

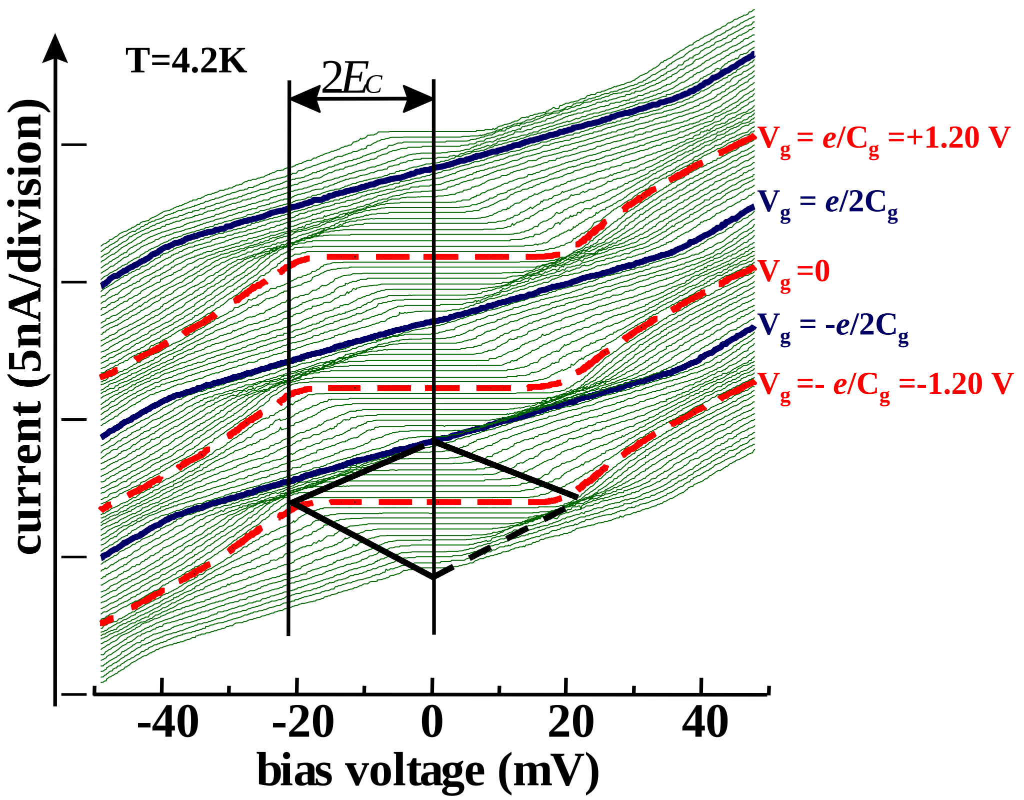

Vg(V)
-1.0
-0.5
0.0
0.5
1.0
Source-Drain current
1nA
Vb (mV)
4
2
0
-2
-4
-2
-1
0
1
2
n = Q_g/e = C_gV_g/e

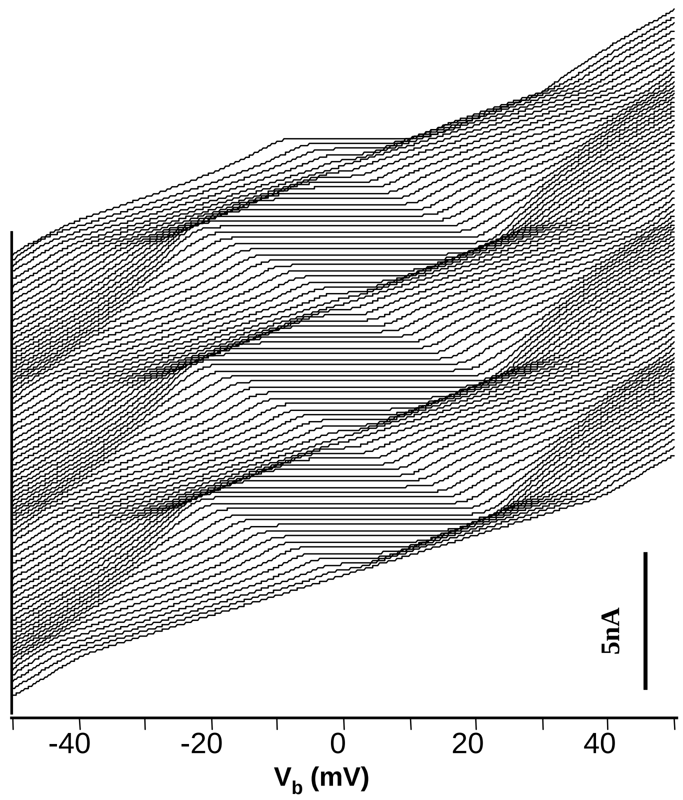
Coulomb Oscillation





Measurement vs. Simulation





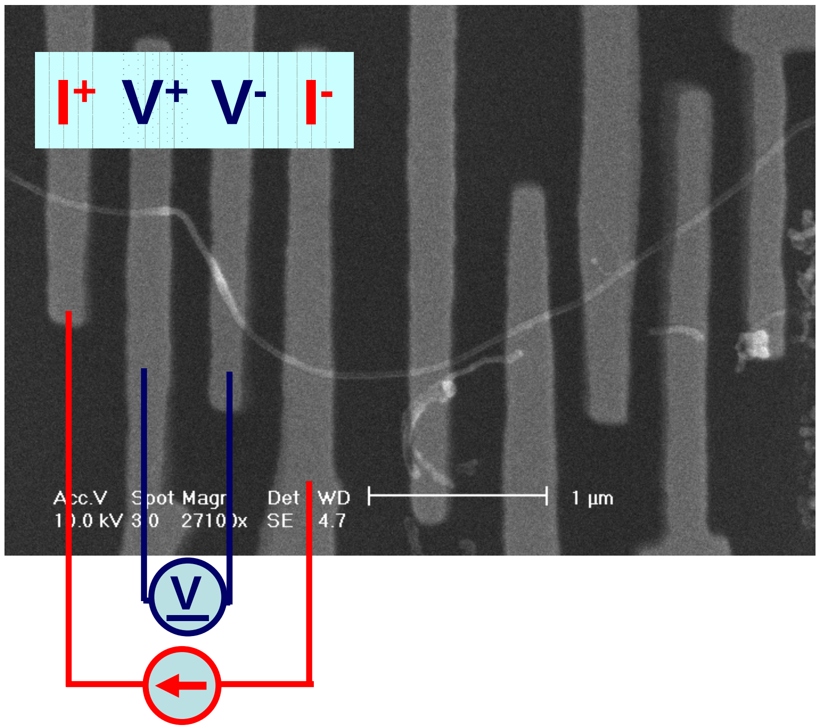
Tunneling rate in orthodox theory

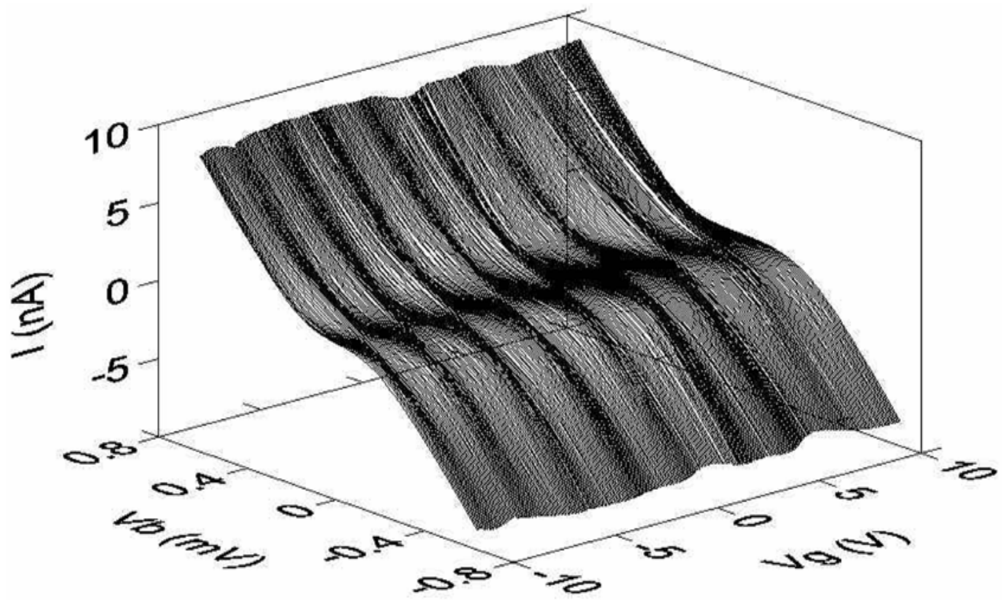
$$\Gamma(\Delta W) = \frac{1}{e^2 R}\frac{\Delta W}{1-\exp\left(-\Delta W/k_B T\right)}$$

Coulomb blockade oscillation
in Multiwalled Carbon nanotubes
observed by 4-probe techniques

4-probe = measuring the intrinsic properties of wires
contacts are irrelevant

→ tunneling related phenomena such as SET should not appear



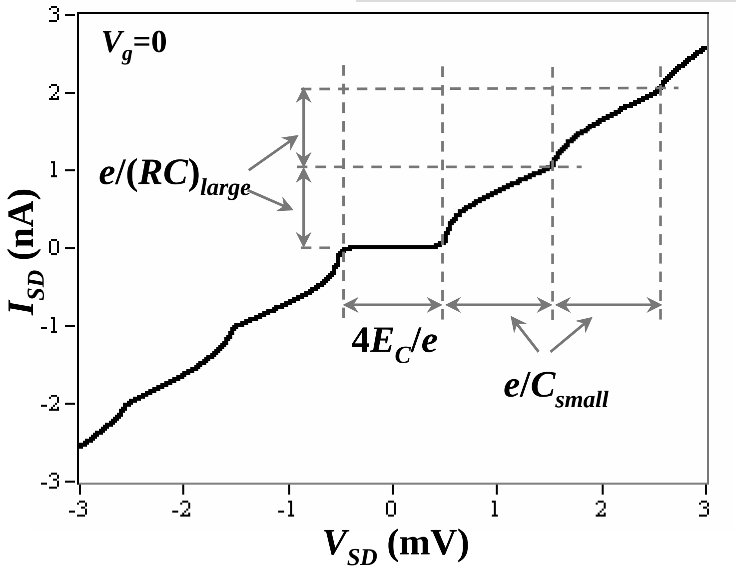


Asymmetric SET (simulations)

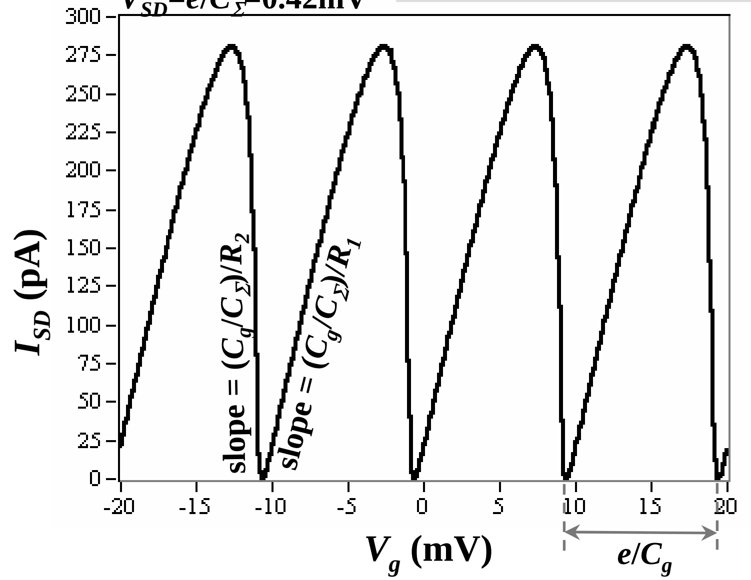
Coulomb Staircase

R_1= 50 kΩ, R_2= 1 MΩ, C_1=0.2fF, C_2=0.15fF, C_g=16aF, E_C=2.54K, T=20mK

appears when $R_1C_1 \neq R_2C_2$



appears when $R_1 \neq R_2$



Charging effect probed by STM

Capacitance of a dielectric disk : $C = 8\varepsilon_0\varepsilon_r r$
Capacitance of a dielectric sphere : $C = 4\varepsilon_0\varepsilon_r r$

For a GaAs sphere, $C = 1.47 \times 10^{-18}$ r farad for radius r in nm

VOLUME 63, NUMBER 7 p. 801 PHYSICAL REVIEW LETTERS 14 AUGUST 1989

Scanning-Tunneling-Microscope Observations of Coulomb Blockade and Oxide Polarization in Small Metal Droplets

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[3]*Scientific Laboratory, Ford Motor Company, Dearborn, Michigan 48121*
(Received 20 March 1989)

C≈7aF for ε_r=10

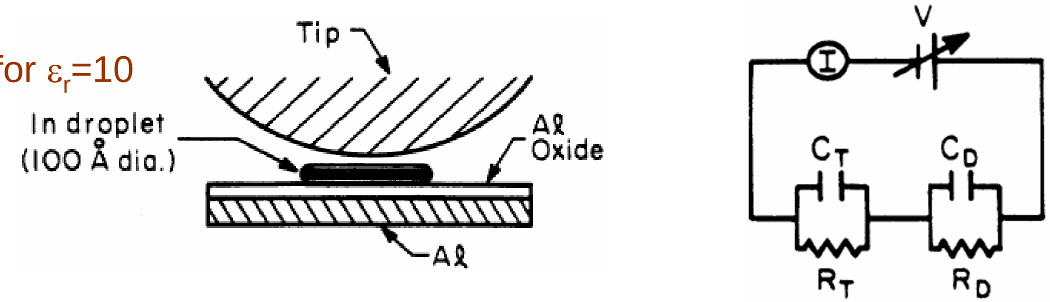
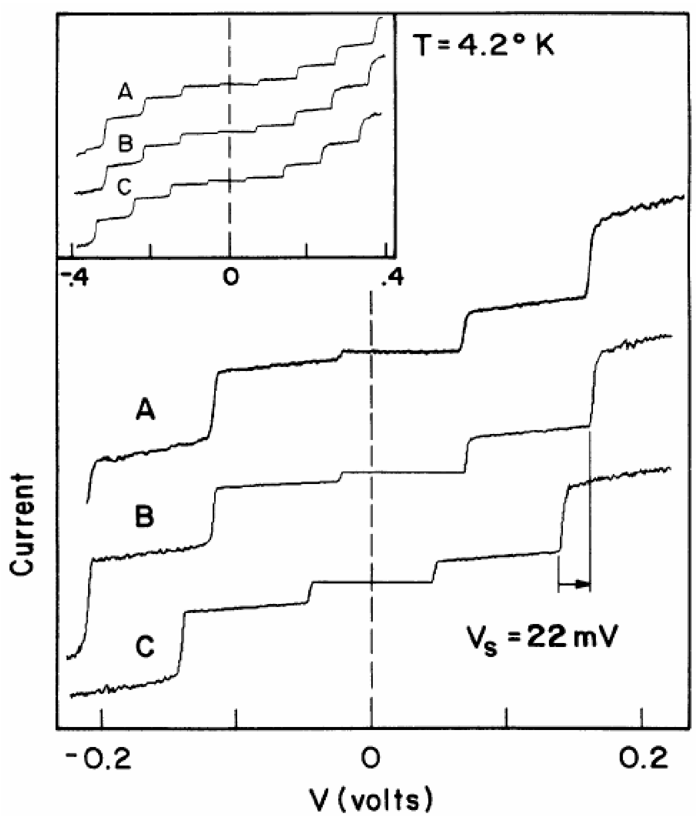
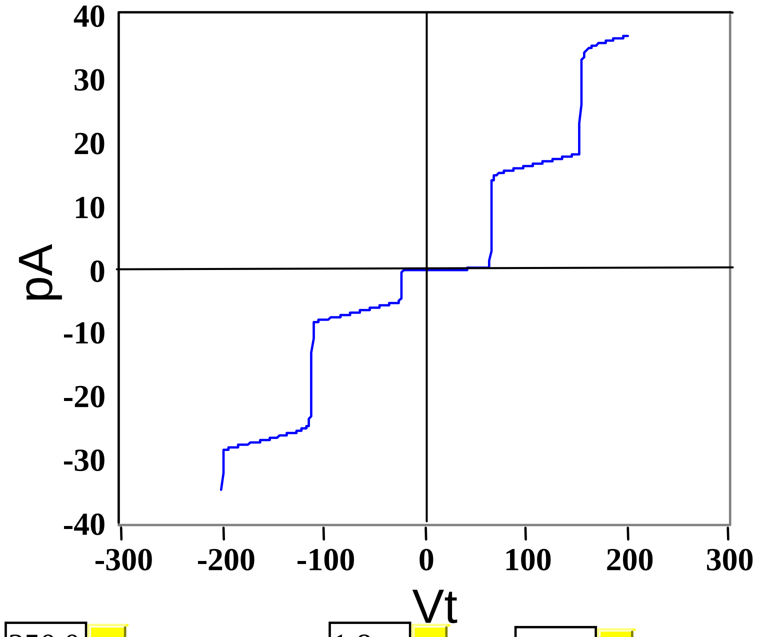


FIG. 1. Schematic showing an In droplet separated from an Al ground plane by a tunneling oxide layer (≃10 Å thickness) with an Au STM tip positioned about 10 Å above it. The equivalent circuit is shown with a voltage source and capacitor C_T for tip to droplet and C_D for droplet to ground plane. The resistors characterize the tunneling probability for each junction and are strictly shot-noise devices.





Ct 350.0 zF Cd 1.8 aF Cg 0.01 aF $\frac{Vp}{Vg} = \frac{C_g}{C_t + C_d}$

Rt 4.40 GOhm Rd 7.20 MOhm Vg 3.87 V

$$V_D = \frac{VC_T}{C_D + C_T} + \frac{Ne}{C_D + C_T} + V_p$$

FIG. 2. Curve *A* is an experimental *I-V* characteristic from an In droplet in a sample with average droplet size of 300 Å. The peak-peak current is 1.8 nA. Curve *B* is a theoretical fit to the data for $C_D = 3.5 \times 10^{-19}$ F, $C_T = 1.8 \times 10^{-18}$ F, $R_D = 7.2 \times 10^6$ Ω, and $R_T = 4.4 \times 10^9$ Ω. The obvious asymmetric features in curve *A* require a voltage shift $V_s = 22$ mV ($V_p = 18$ mV). Curve *C*, calculated for $V_s = 0$, shows the (seldom observed) symmetric case. As explained in the text, a small quadratic term was added to the computed tunneling rate for each junction. Inset: A wider voltage scan for this same droplet; again, the topmost curve is experimental data.

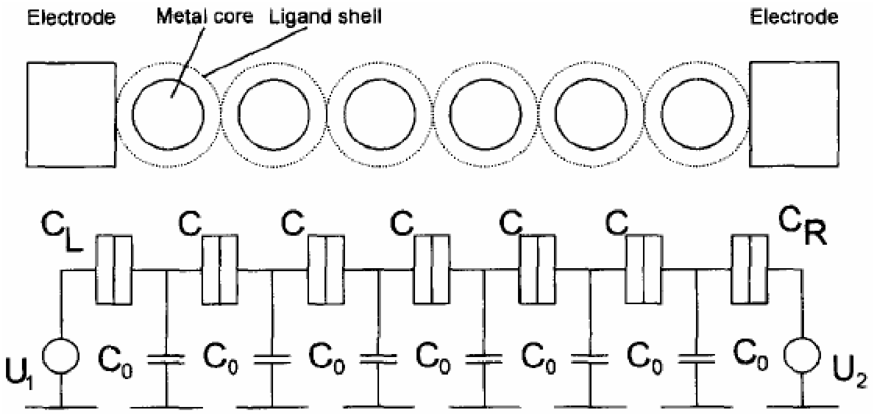
by scanning the substrate.[14] However, we do not understand at this time why C_T is greater than C_D. At $T = 4$

Potential distribution in a finite 1-D array of arbitrary mesoscopic tunnel junctions

V. Gasparian[1], U. Simon*

Institut für Anorganische Chemie, Festkörperchemie, Universität GH Essen, Schützenbahn 70, Essen 45127, Germany

Received 2 September 1997 Physica B 240 (1997) 289–297



$$-\varphi_i = \frac{e}{C_{eff}} \Pi^{|i-k|}$$

$$\Pi \equiv x - \sqrt{x^2 - 1} \qquad C_{eff} = \sqrt{C_0^2 + 4CC_0}$$

$$x = 1 + C_0 / 2C$$

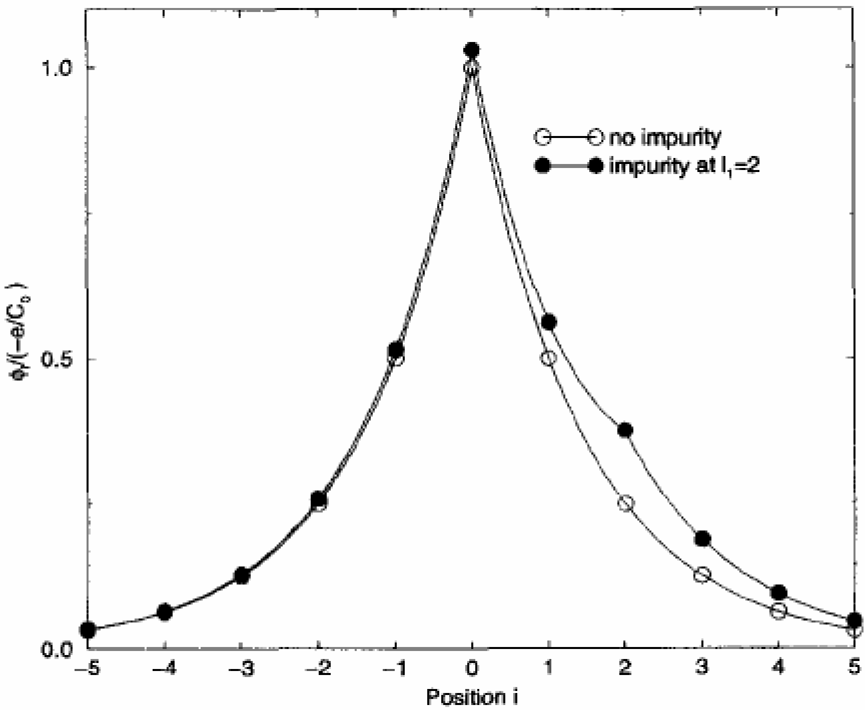
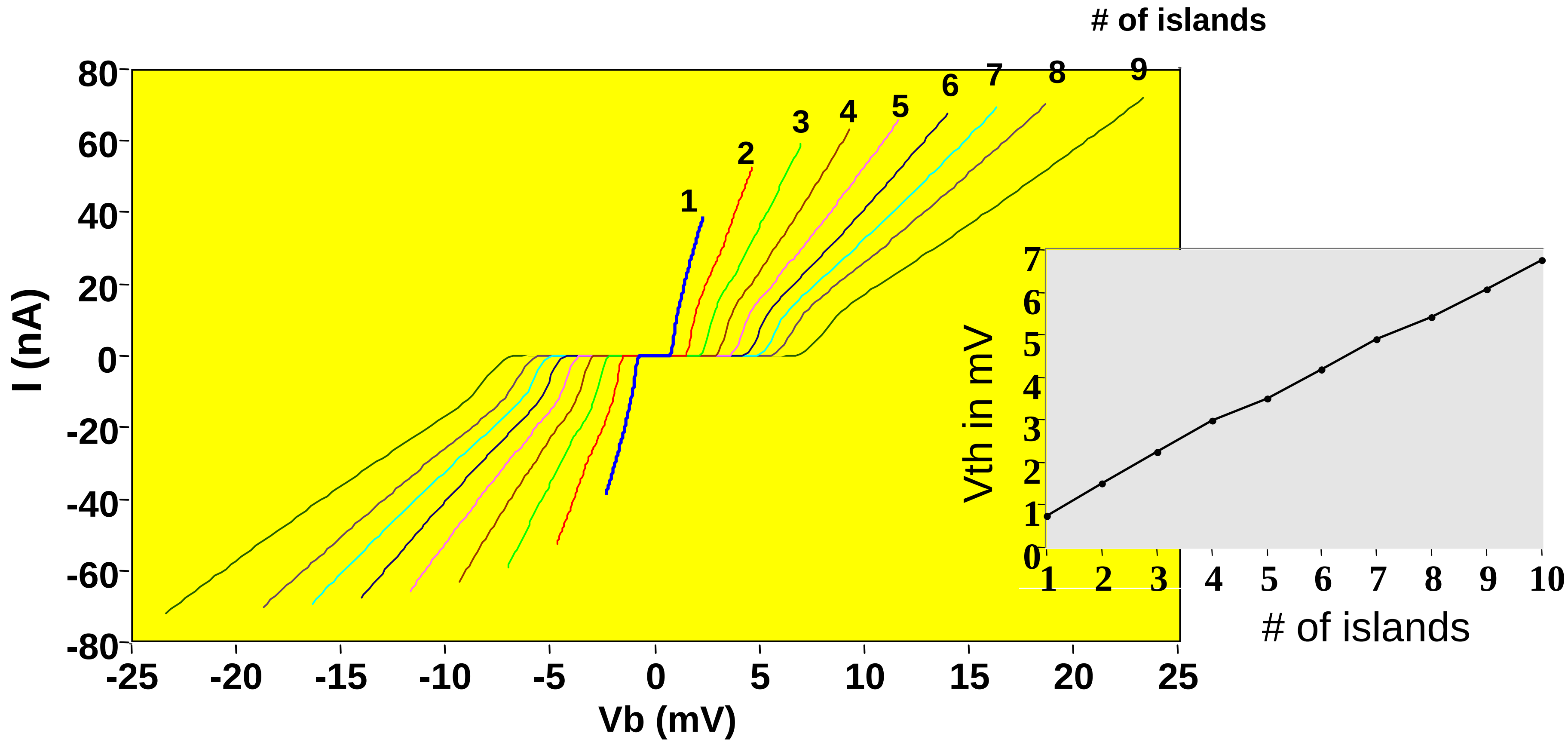


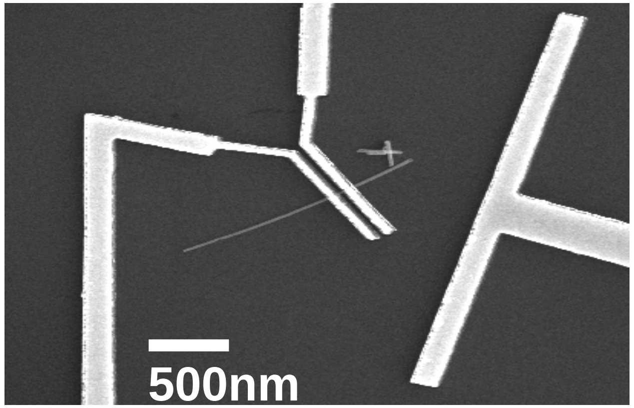
Fig. 2. Potential distribution of the infinite array in the units of $-e/C_0$ and for one impurity at $l_1 = 2$ with $C_1/C_0 = -0.999$.

IV characteristics for 1D array with C=100aF, R=20kΩ



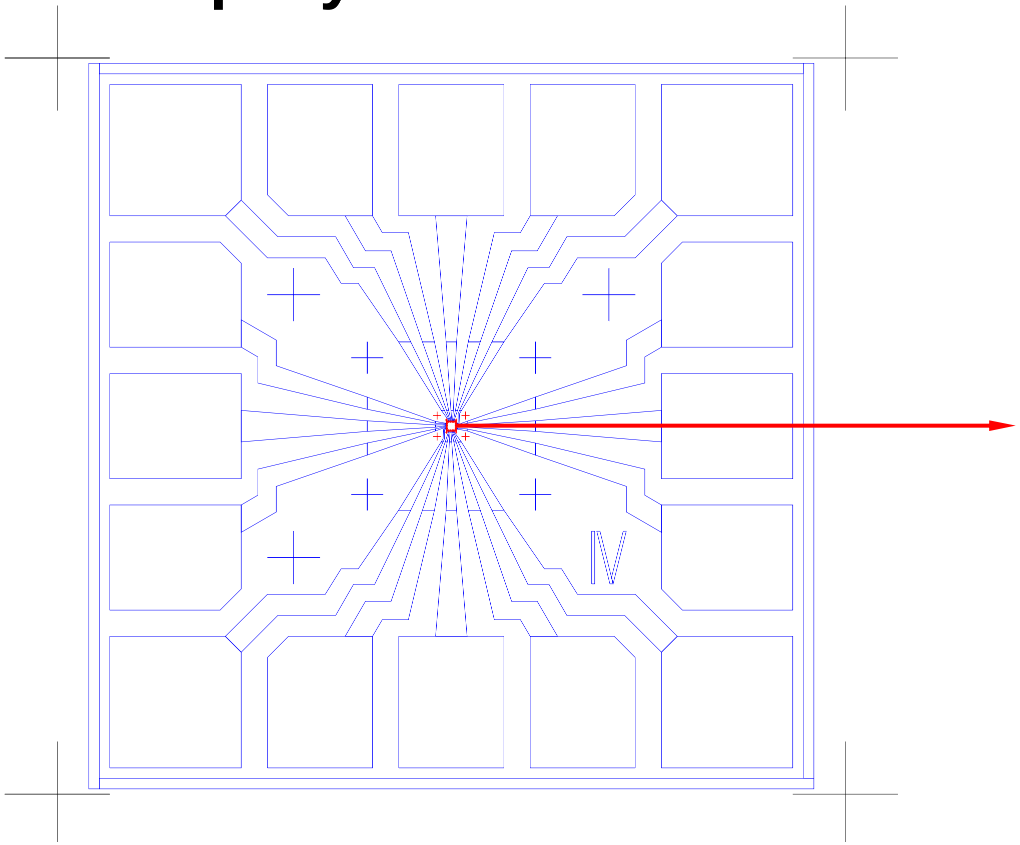
e/C=0.8mV

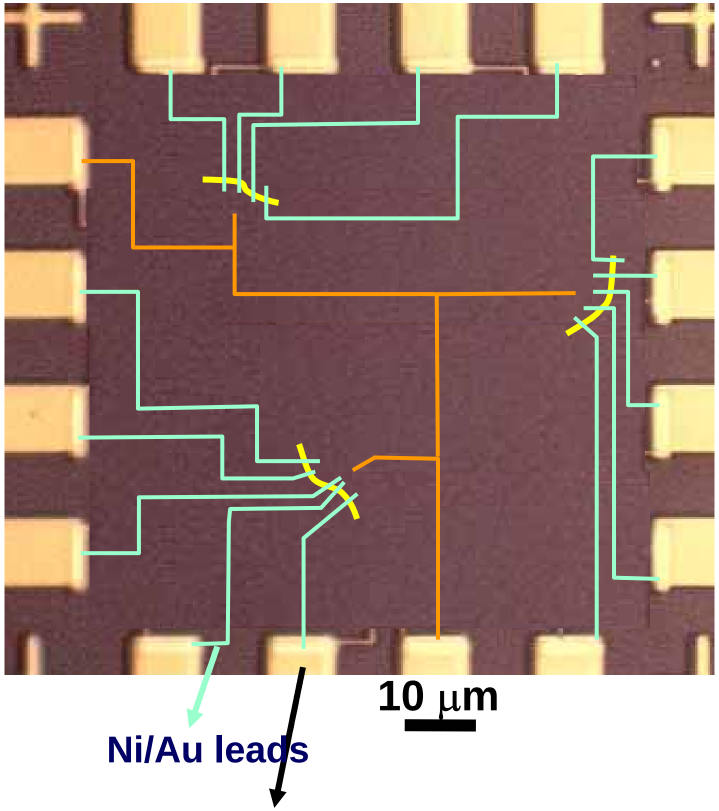
Device fabrication



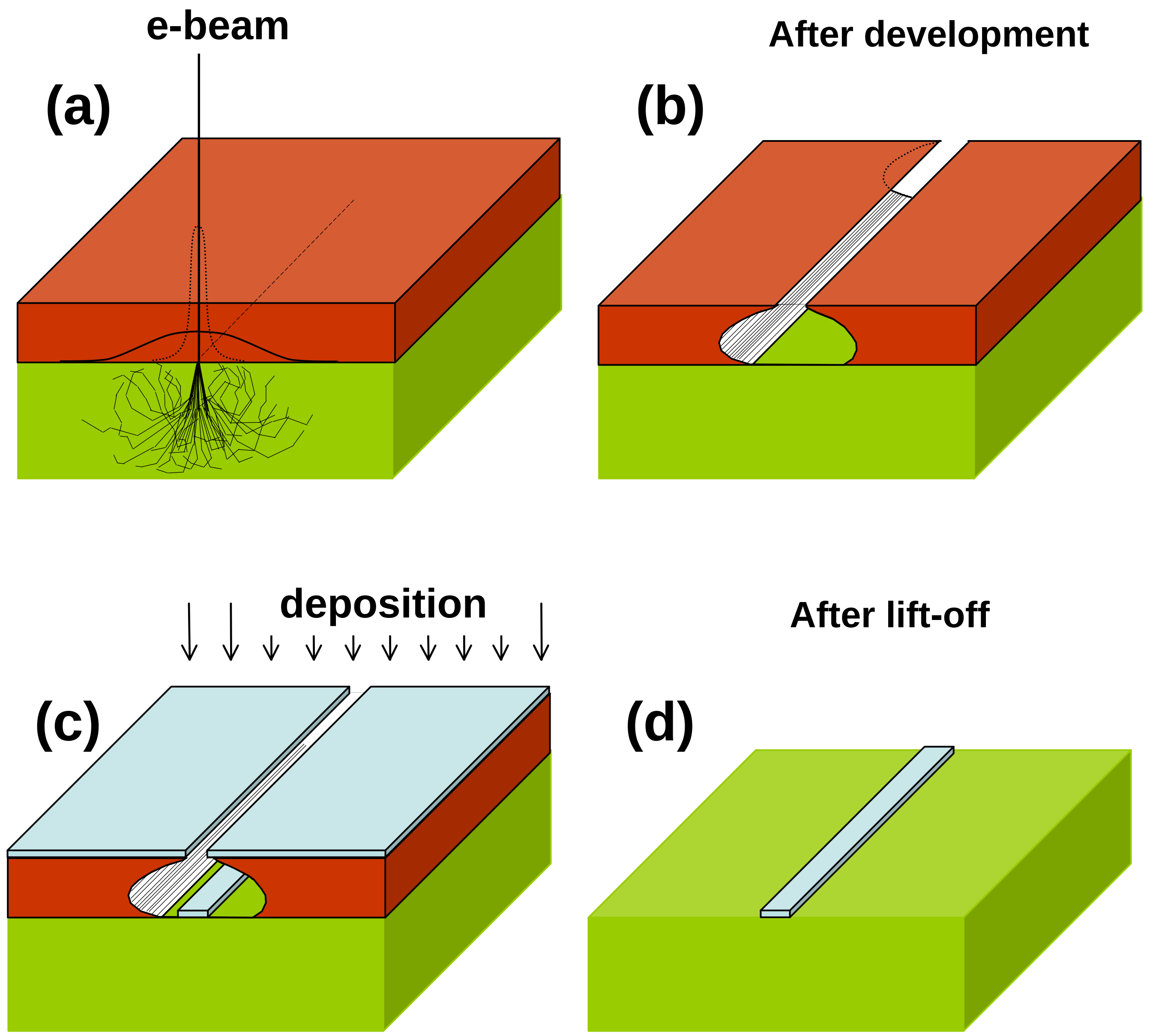
Wires from
台大凝態中心林麗瓊教授
中研院原分所陳貴賢教授

Chip layout



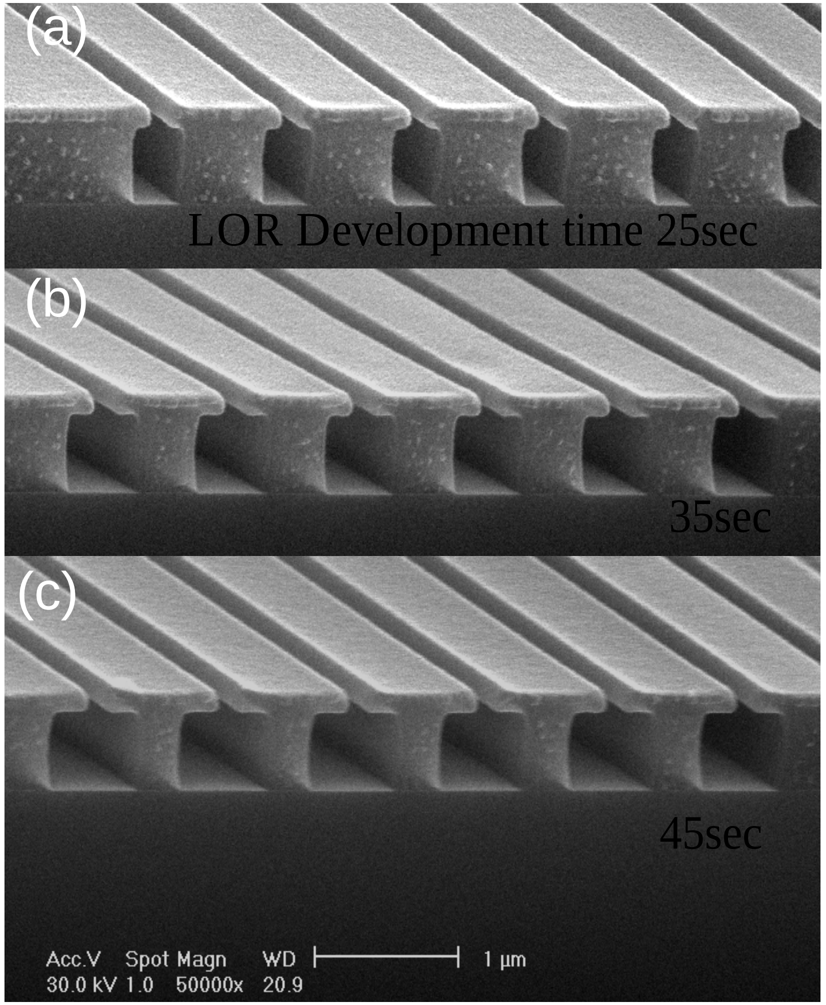


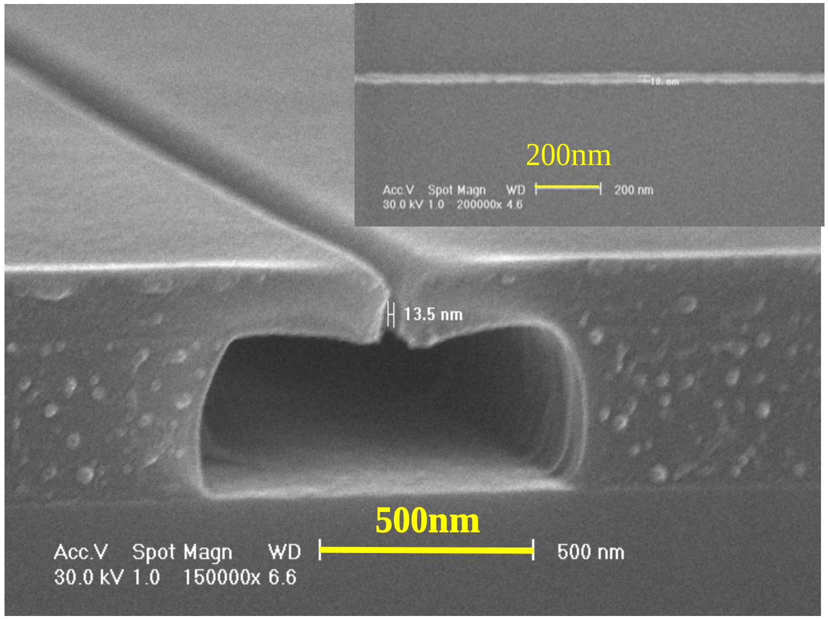
E-beam lithography for nano-scaled electrodes

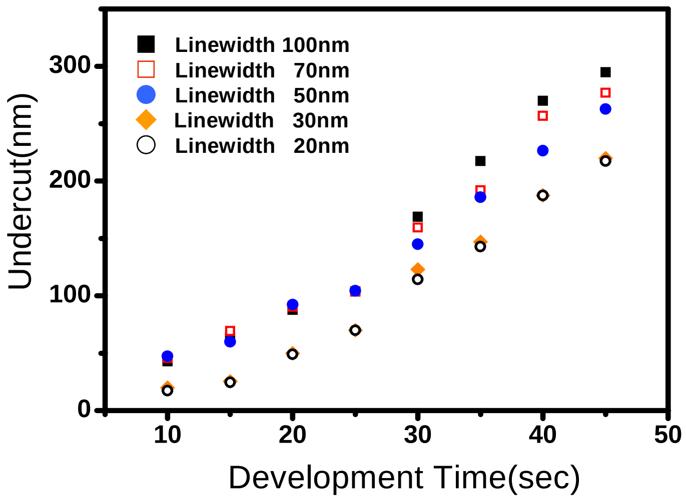


Bi-layer polymer system (PMMA/LOR)

We chose to use a PMMA/LOR bi-layer polymer system because LOR is a polydimethylglutarimide (PMGI)-based polymer and has a much higher charge-sensitivity than that of top PMMA layer.



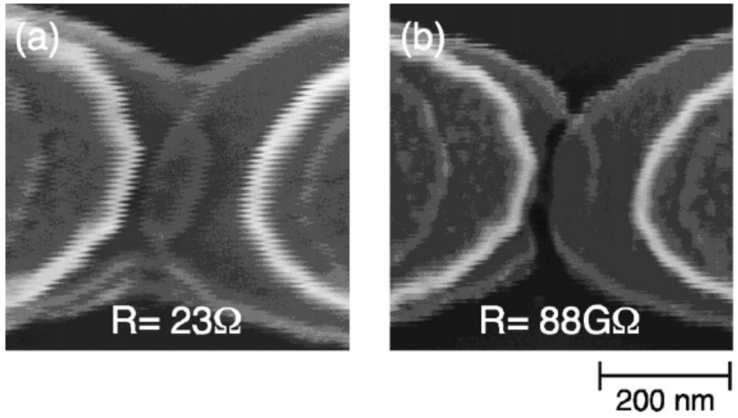




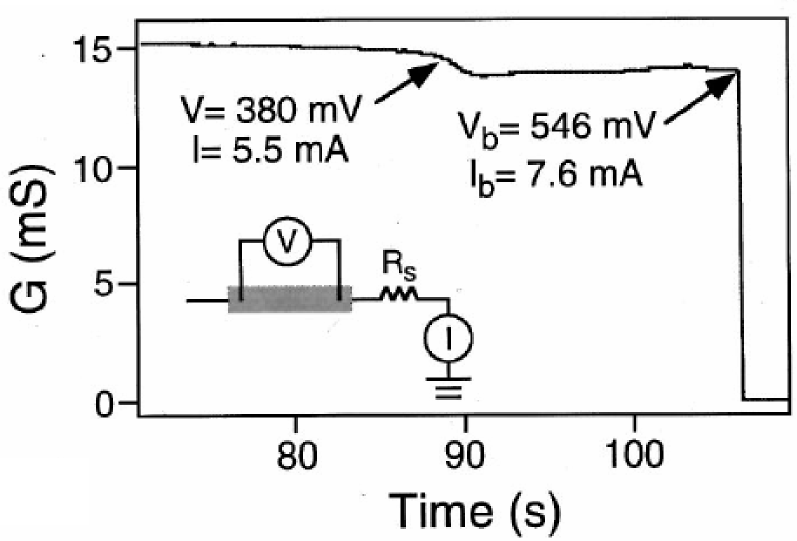
Sample fabrication facilities

Measurement equipment

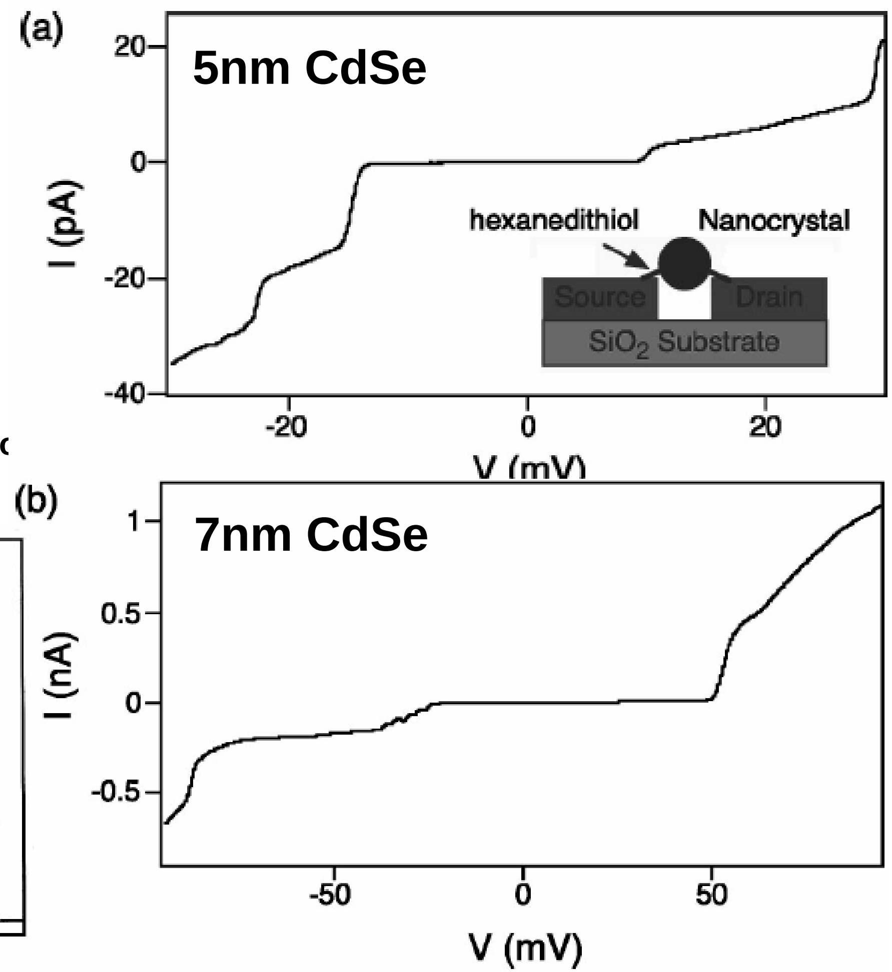
Break junction approach for electrical measurement of a single nano-particle



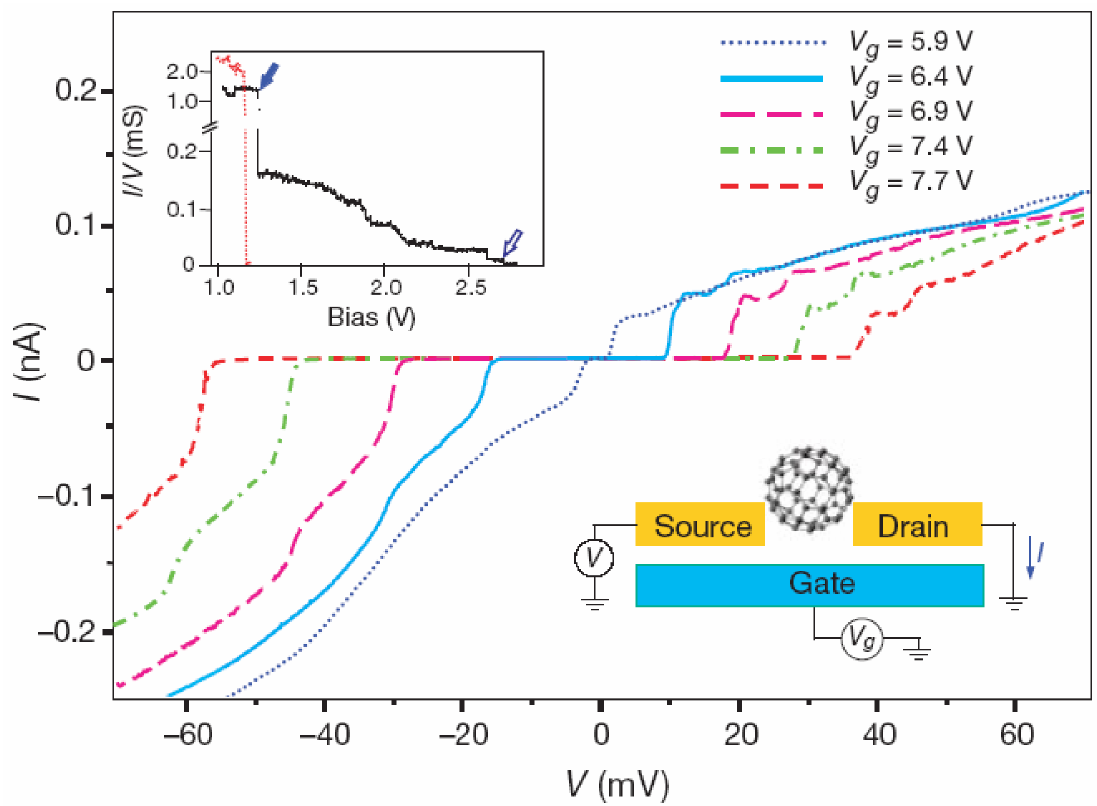
Fabrication of metallic electrodes with nanometer separatic
by electromigration [APL, 75, 301 (1999)]



IV at 1.5K



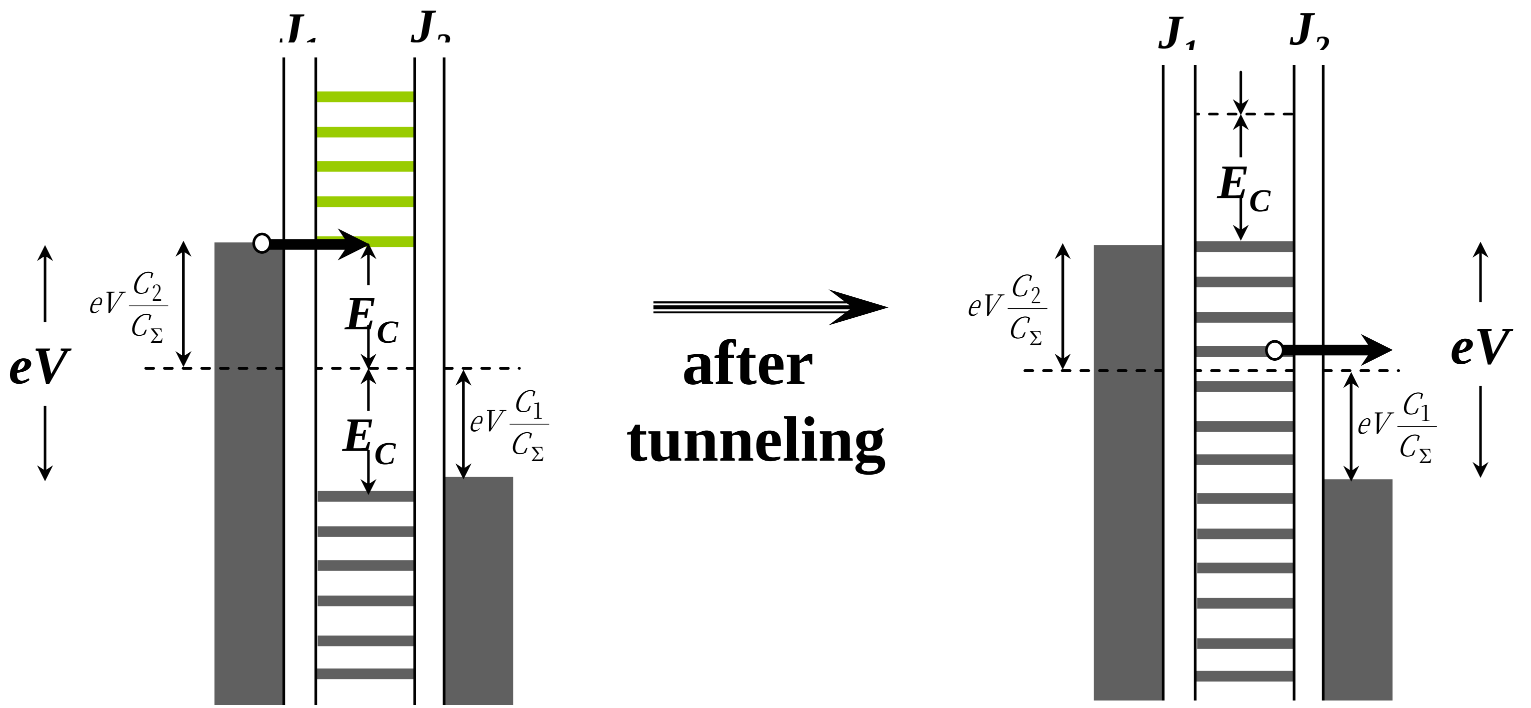
IV characteristics of a single C_{60} transistor at 1.5K



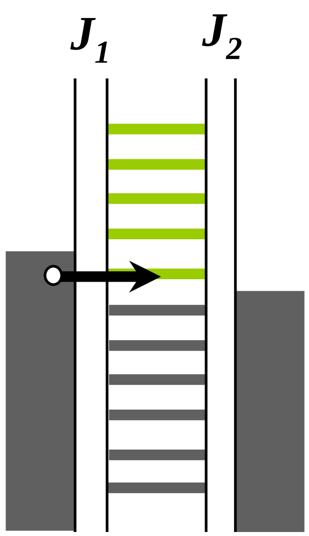
Nature 407, 58 (2000)

Figure 1 Current–voltage (I–V) curves obtained from a single-C_{60} transistor at T= 1.5 K. Five I–V curves taken at different gate voltages (Vg) are shown. Single-C_{60} transistors were prepared by first depositing a dilute toluene solution of C60 onto a pair of connected gold electrodes. A gap of,1 nm was then created using electromigration-induced breaking of the electrodes. Upper inset, a large bias was applied between the electrodes while the current through the connected electrode was monitored (black solid curve). After the initial rapid decrease (solid arrow), the conductance stayed above ,0.05 mS up to ,2.0 V . This behaviour was observed in most single-C_{60} transistors, but it was not observed when no C_{60} solution was deposited (red dotted curve). The bias voltage was increased until the conductance fell low enough to ensure that the current through the junction was in the tunnelling regime (open arrow). The low bias measurements shown in the main panel were taken after the breaking procedure. Lower inset, an idealized diagram of a single C60-transistor formed by this method.

Electron transfer through a quantum dot with charging energy E_C



What makes electrons flow?



biasing: $\mu_1 - \mu_2 = qV_D$

Fermi function:

$$f_1(E) \equiv \frac{1}{1+\exp[(E-\mu_1)/k_BT]} = f_0(E-\mu_1)$$

$$f_2(E) \equiv \frac{1}{1+\exp[(E-\mu_2)/k_BT]} = f_0(E-\mu_2)$$

Coupling strength for J_1 and J_2 = γ_1 and γ_2

$$I_1 = e\left(\frac{\gamma_1}{\hbar}\right)\left(f_1(\varepsilon_1) - p\right) \qquad I_2 = e\left(\frac{\gamma_2}{\hbar}\right)\left(f_2(\varepsilon_2) - p\right)$$

p = average number of electron in the QD $\quad 0 \le p \le 1$

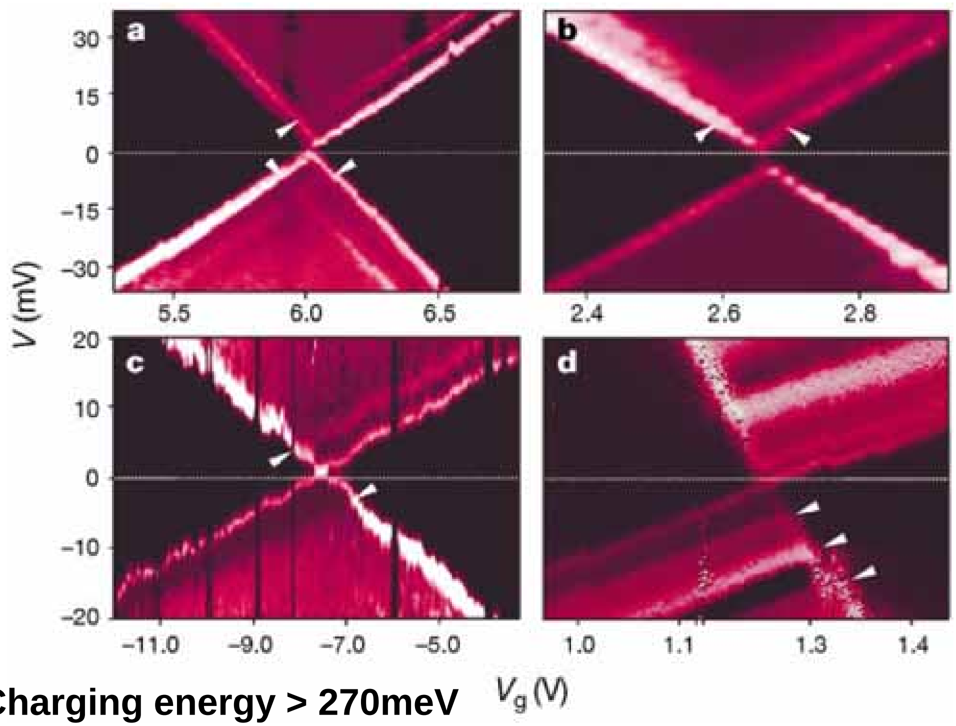
At steady state, $I_1 = I_2$ $\quad p = \dfrac{\gamma_1 f_1 + \gamma_2 f_2}{\gamma_1 + \gamma_2}$

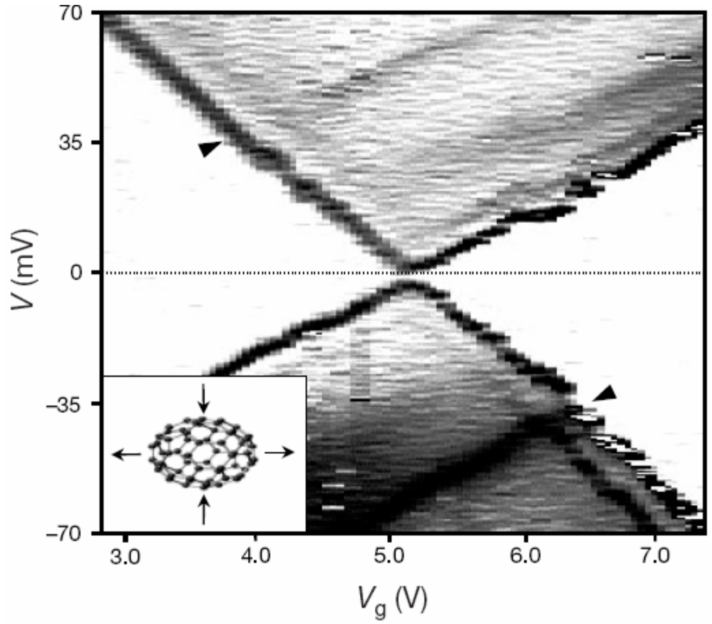
$$\Rightarrow I = I_1 = -I_2 = \frac{e}{\hbar}\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}[f_1(\varepsilon) - f_2(\varepsilon)]$$

Handbook of Nanoscience, Engineering, and Technology
Section: 12.2.2 Current flow as a balancing act
By Magnus Paulsson, Ferdows Zahid and Supriyo Datta,
Edited by William A. Goddard,III et al. CRC Press, 2003

Quantum transport: atom to transistor
Sec. 1.2 What makes electrons flow

In large bias range



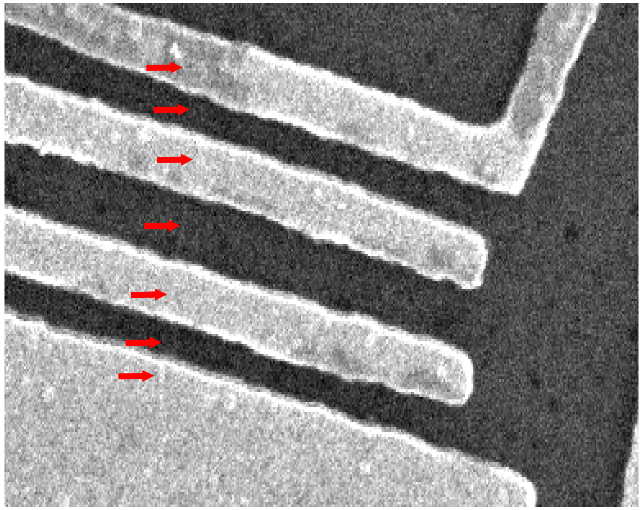


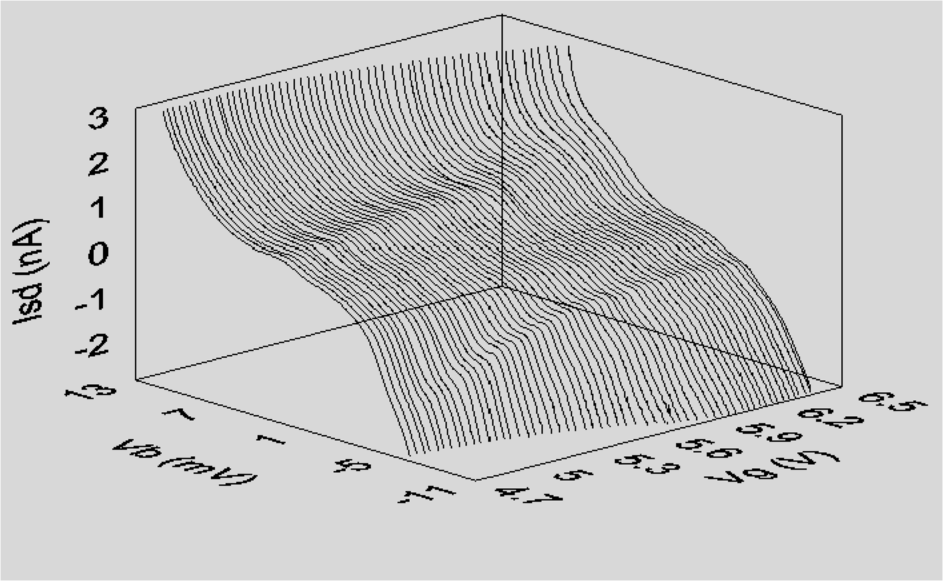
Charging energy > 270meV

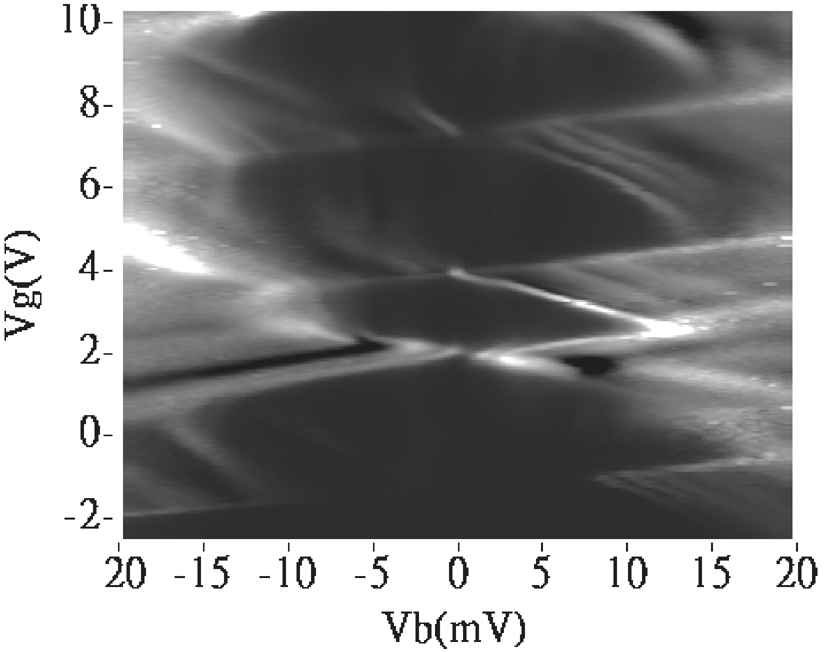
Two-dimensional differential conductance (∂I/∂V) plots as a function of the bias voltage (V) and the gate voltage (V_g). Data were obtained from four different devices prepared from separate fabrication runs. The dark triangular regions correspond to the conductance gap, and the bright lines represent peaks in the differential conductance. a–d, The differential conductance values are represented by the colour scale, which changes from black (0 nS) through pink to white (white representing 30 nS in a, b and c and 5 nS in d). The white arrows mark the point where ∂ I/∂ V lines intercept the conductance gap. During the acquisition of data in d, one ‘switch’ where the entire ∂ I/∂ V characteristics shift along the V_g axis occurred at V_g = 1.15 V. The right portion of the plot d is shifted along the V_g axis to preserve the continuity of the lines.

Single-walled carbon nanotube
with quantum dot behavior

SEM image







ΔE=2.5~3.0 meV

E_C=6~9 meV (70~100K)

Where is the Fermi Energy?