Quantum electronics

中央研究院物理研究所　陳啟東

Outline:

Device fabrication

e-beam lithography, examples

Measurement electronics

Electron transport in

Ballistic systems

Highly disordered systems

Hopping conduction in diluted trap systems

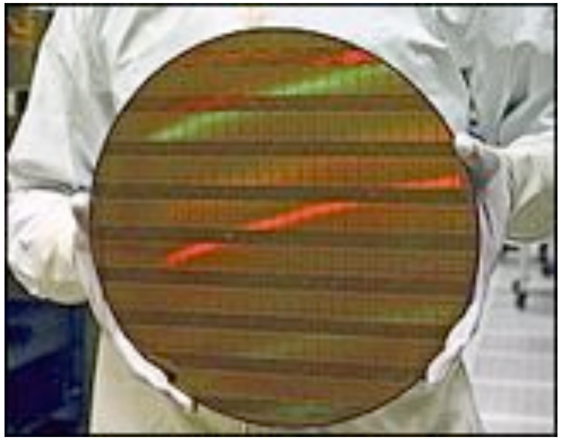
Tunneling through quantum dots

Quantum bits:

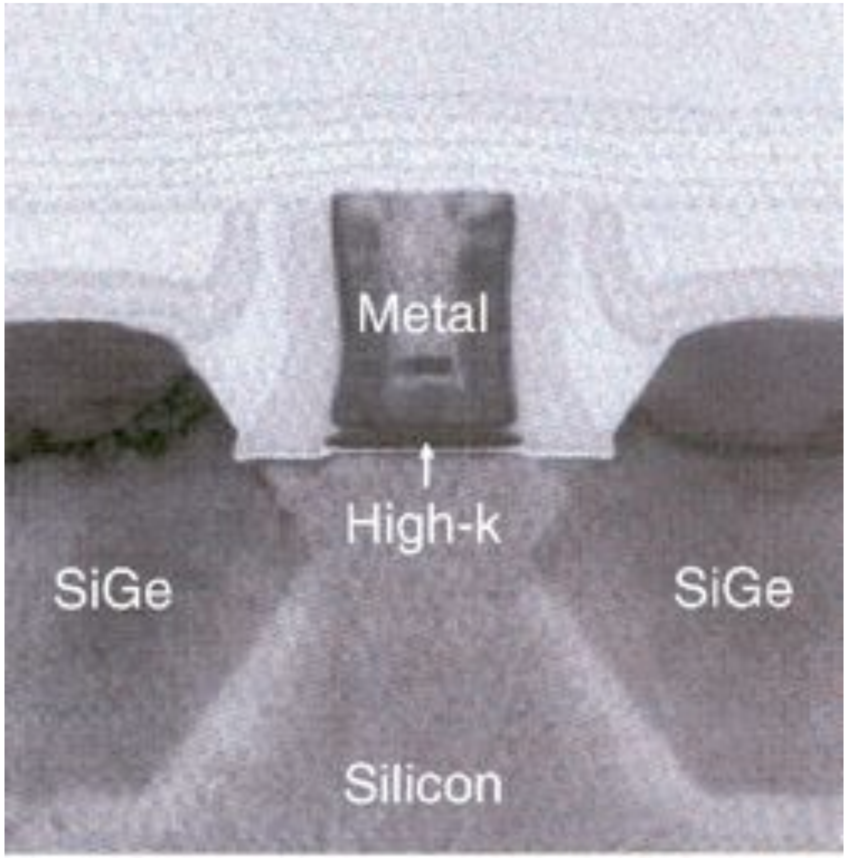
Resonant tunneling between coupled quantum-dots

from small Josephson junctions to charge qubits

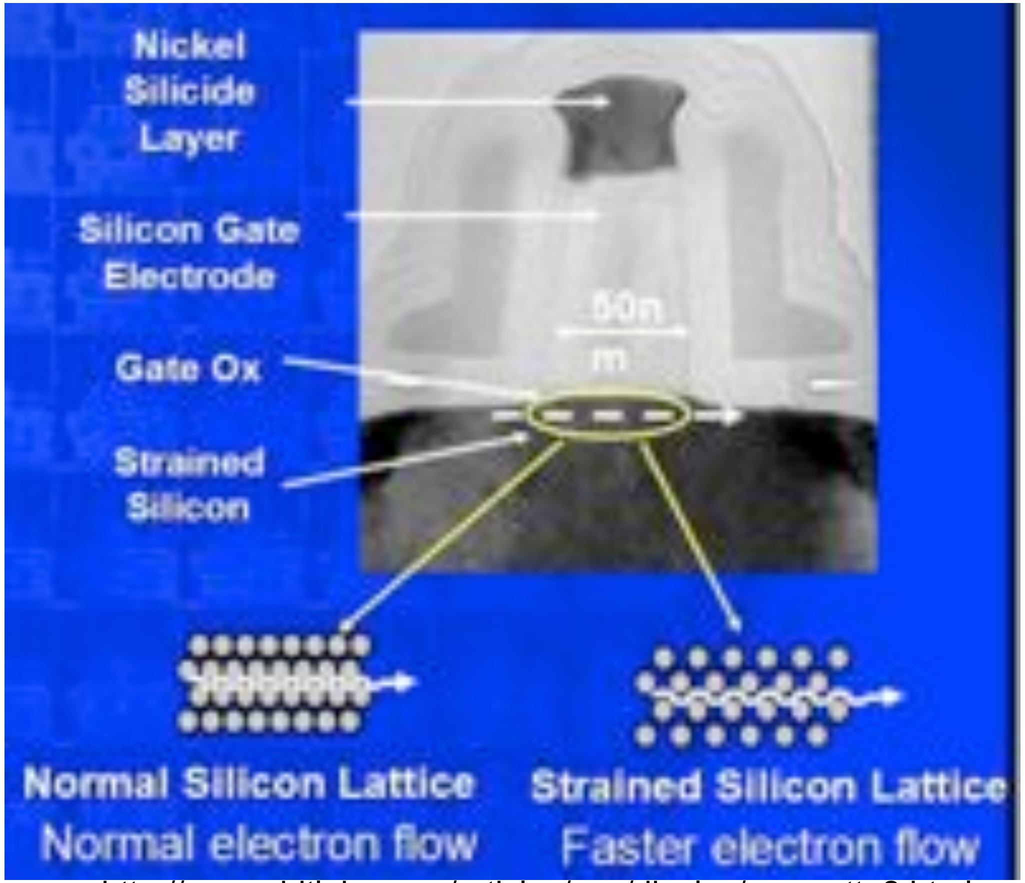
Present-day semiconductor industry



Scientific American, January 30, 2007



http://channel.hexus.net/content/item.php?item=12389

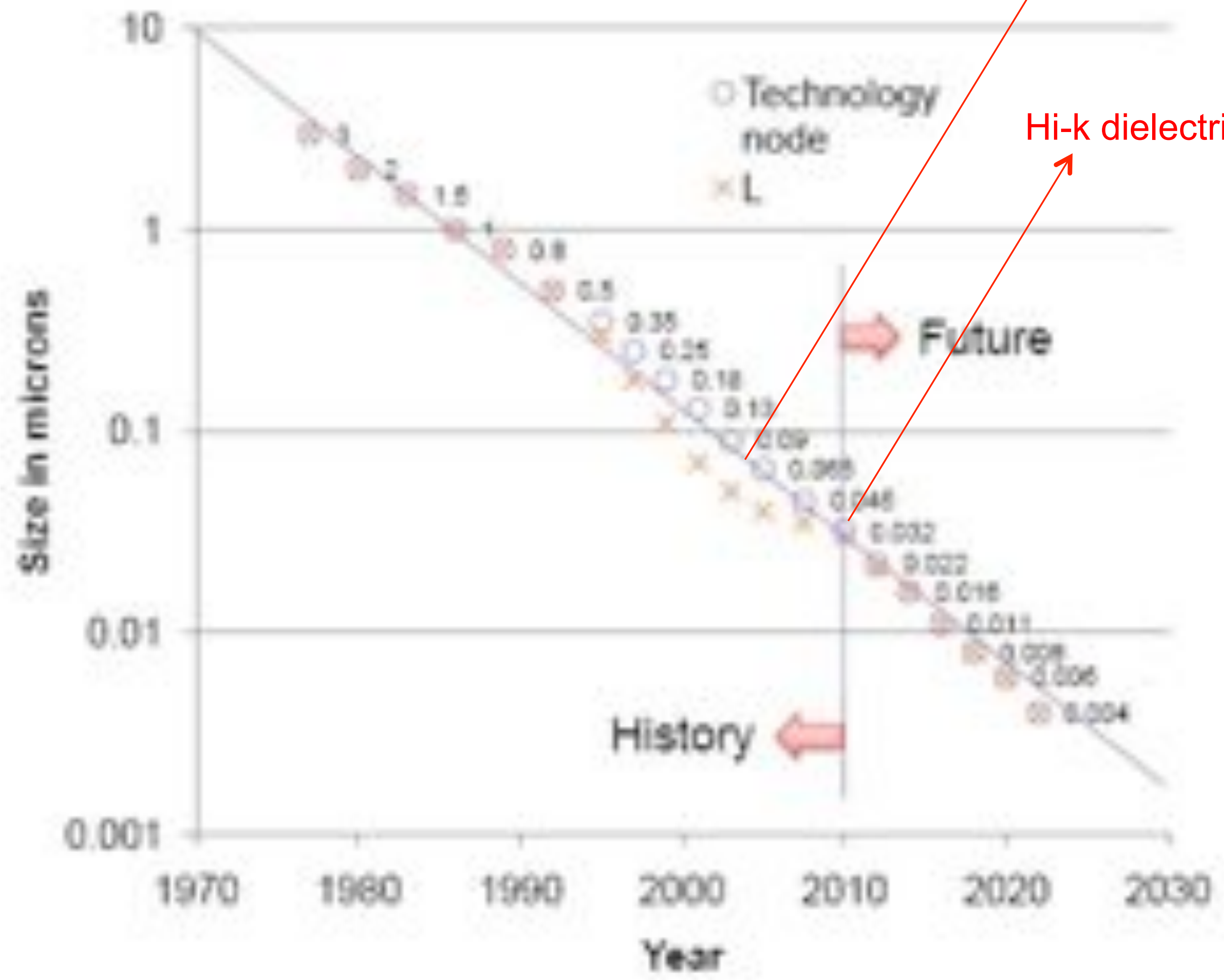


http://www.xbitlabs.com/articles/cpu/display/prescott_2.html

Gate length map

[Strained Silicon]

Hi-k dielectrics + metal gate

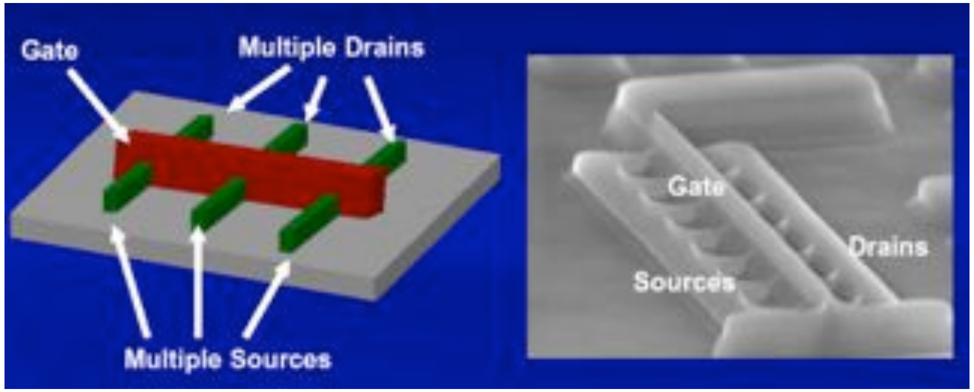


http://theasicguy.com/2010/06/

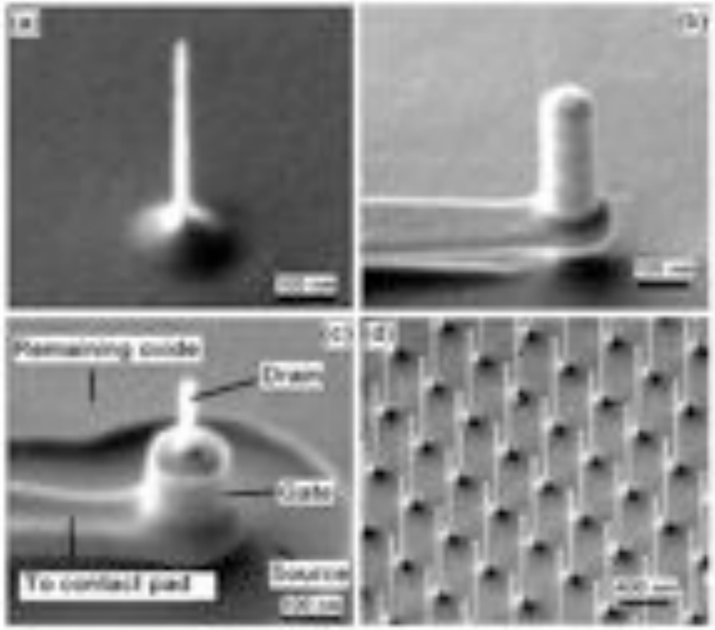
[Michael Keating, SNUG 2010]

Latest development and future technologies

FinFET or Multi-gate FET (MuGFET)

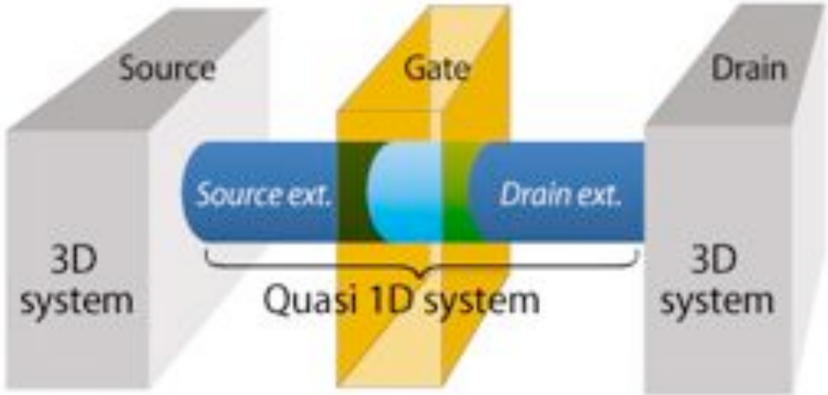


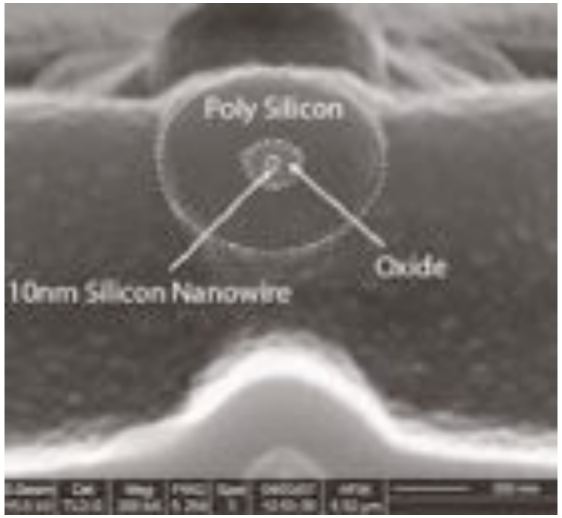
Vertical Silicon-Nanowire Formation



http://www.ime.a-star.edu.sg/html/newsrelease/2008/Shortcuts-May08Jun08.htm

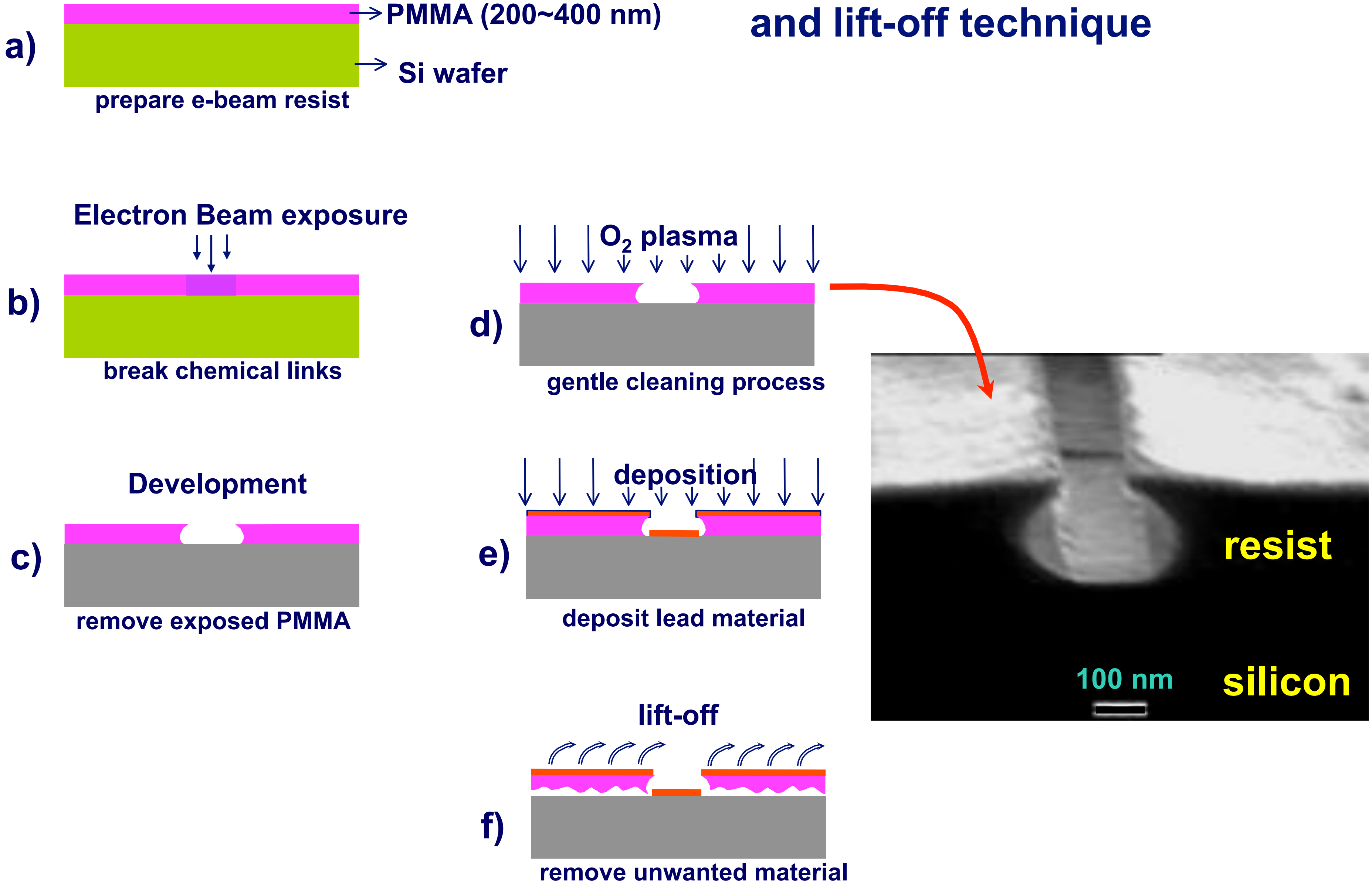
Gate-All-Around Field-Effect-Transistors



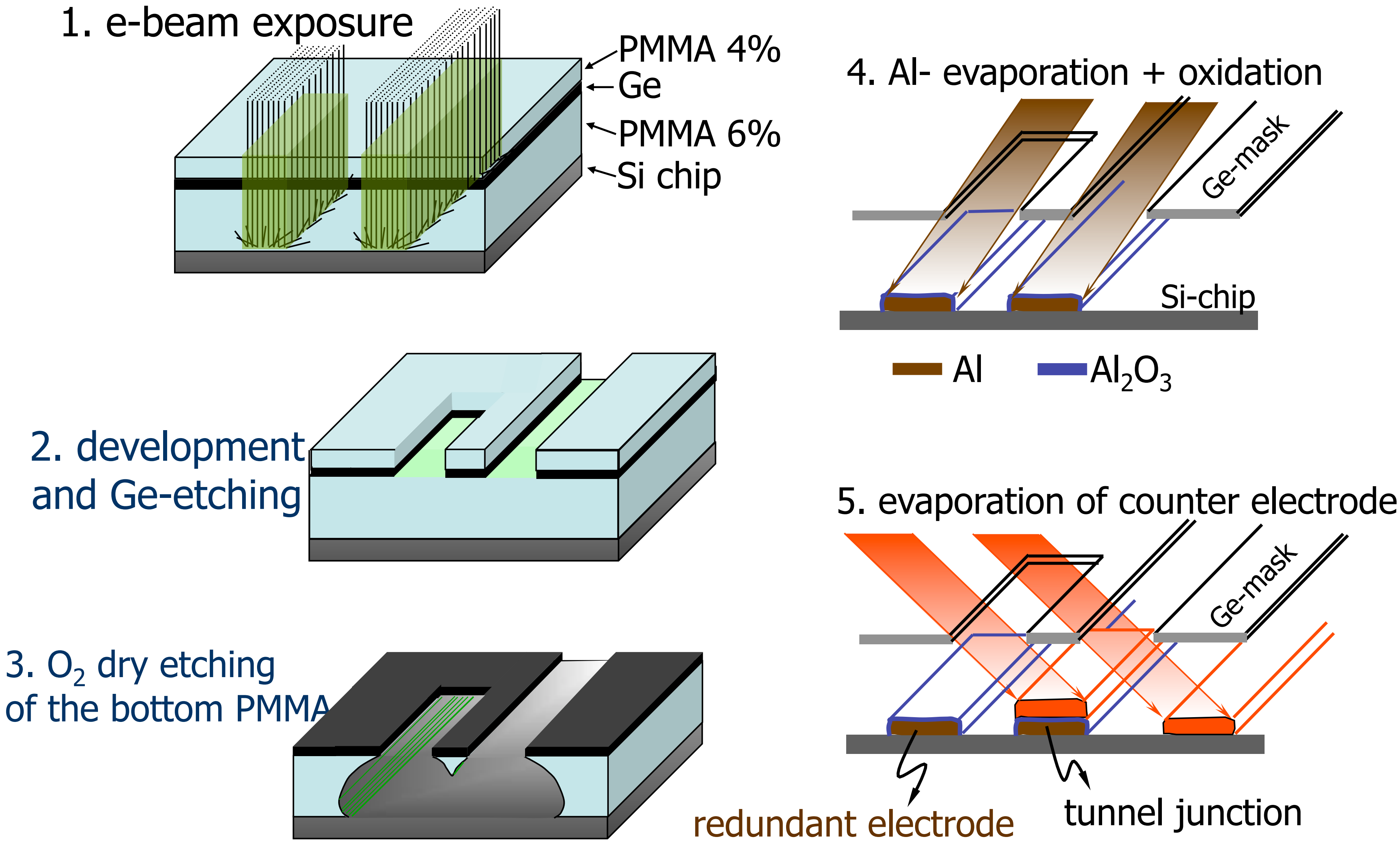


http://www.advancedsubstratenews.com/2010/12/
Advanced Substrate Corners
Posted by Professor Ru HUANG on December 8, 2010

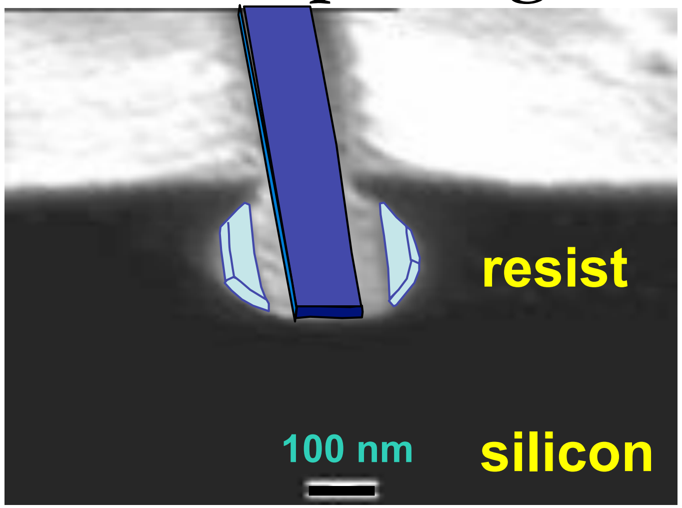
Electron beam lithography
and lift-off technique

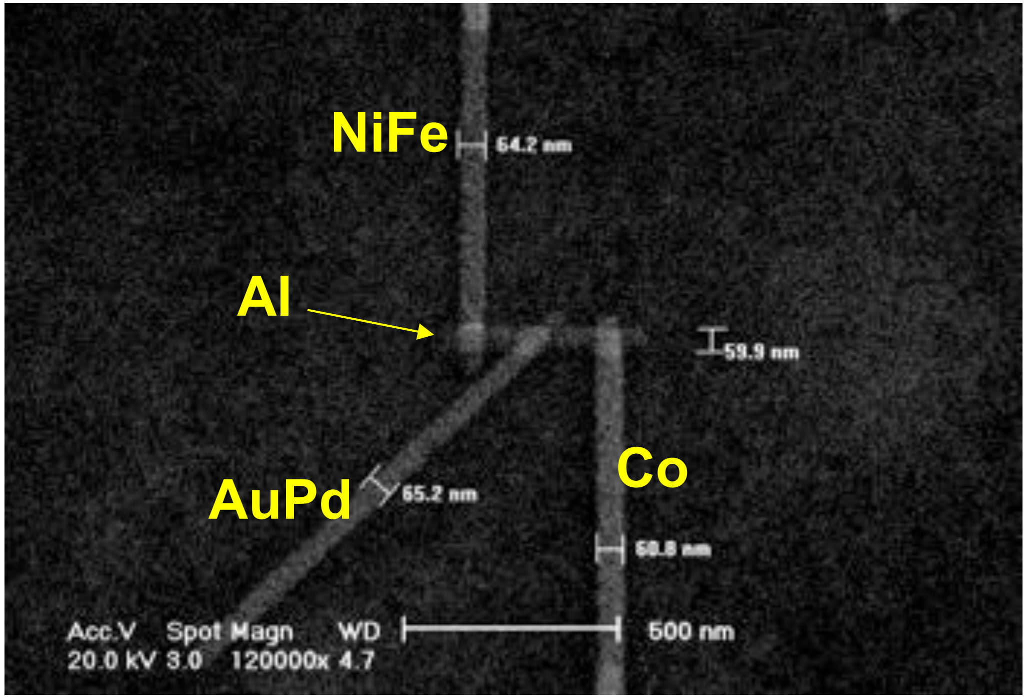


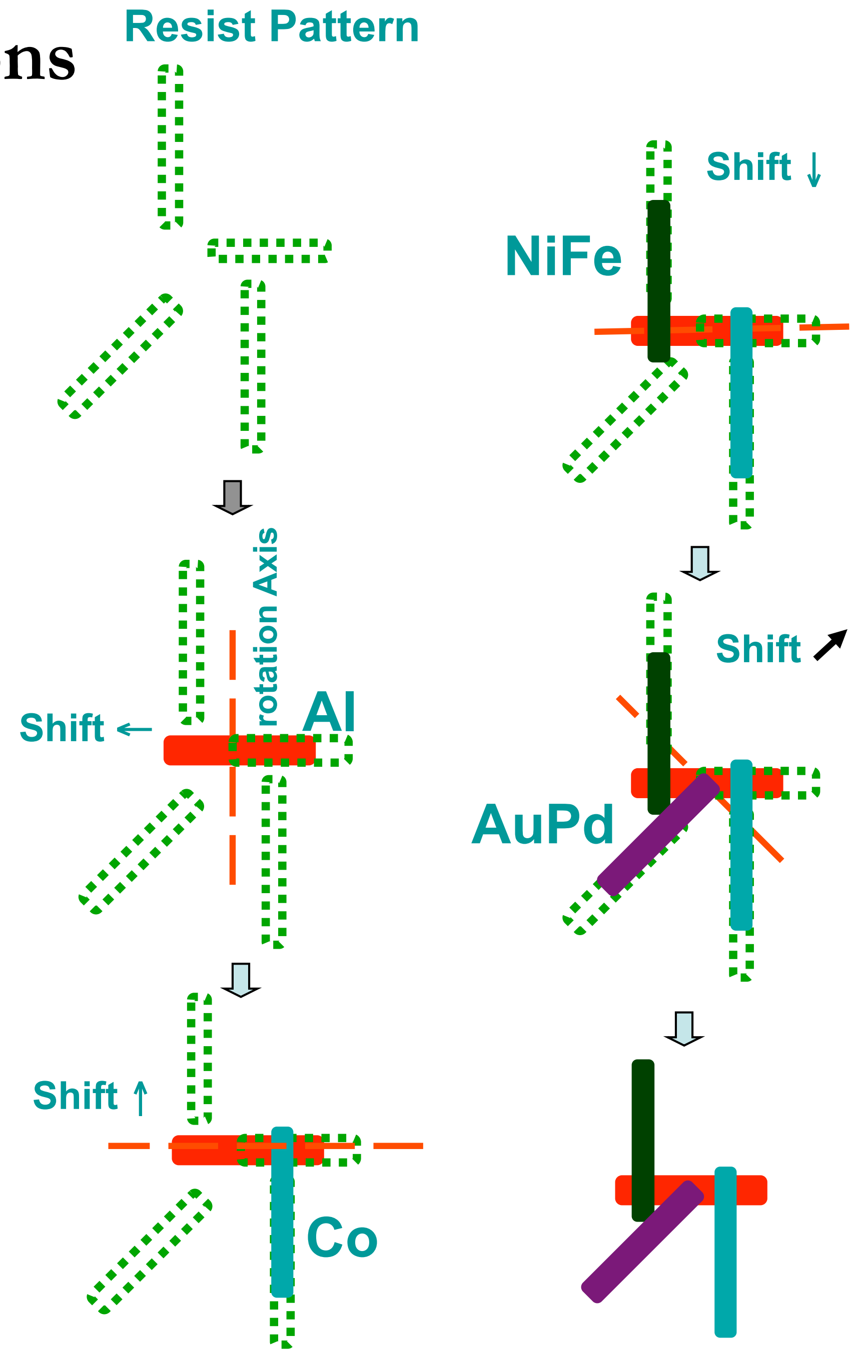
Resist profile engineering:
Fabrication of Aluminum tunnel junctions



Multiple angle evaporations

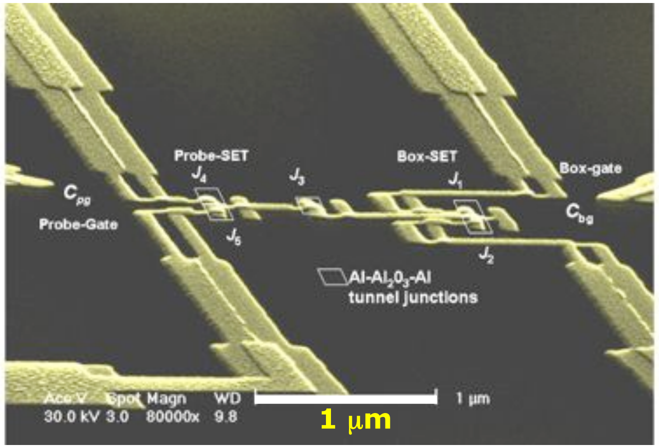




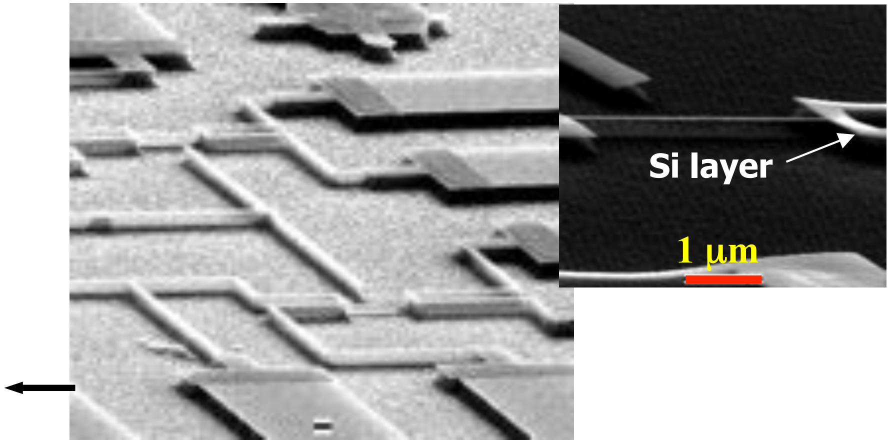


Metallic electronics

Single electron devices

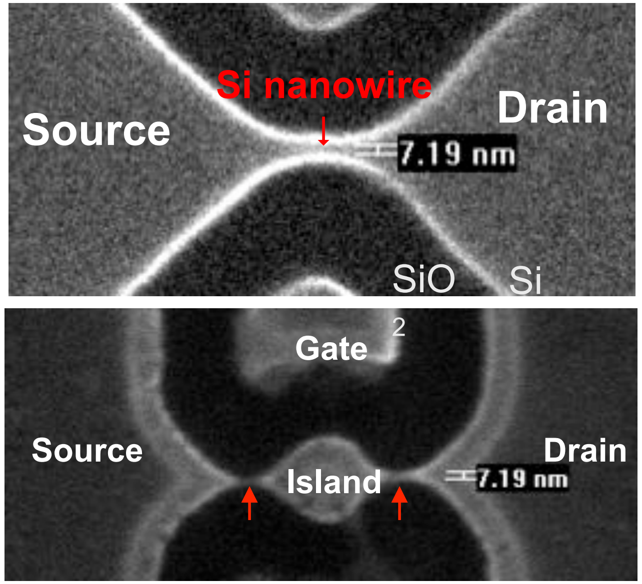


Suspending wire devices

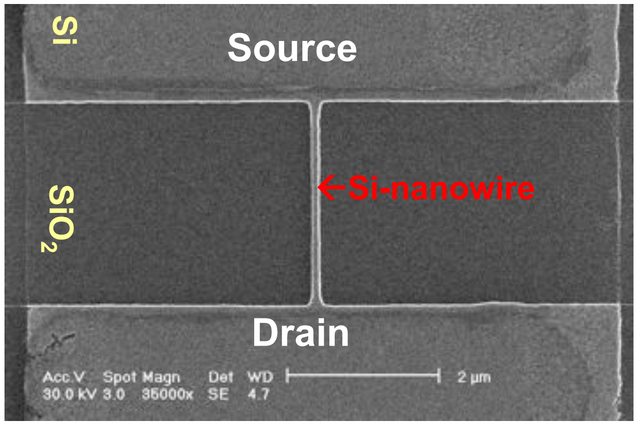


silicon nanoelectronics

7 nm Si-nanowire



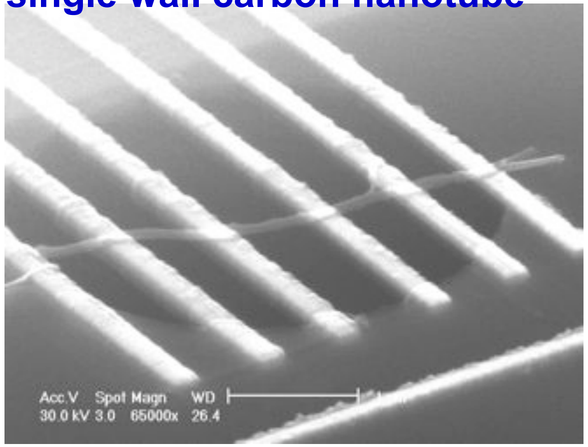
100nm Si-nanowire charge sensor



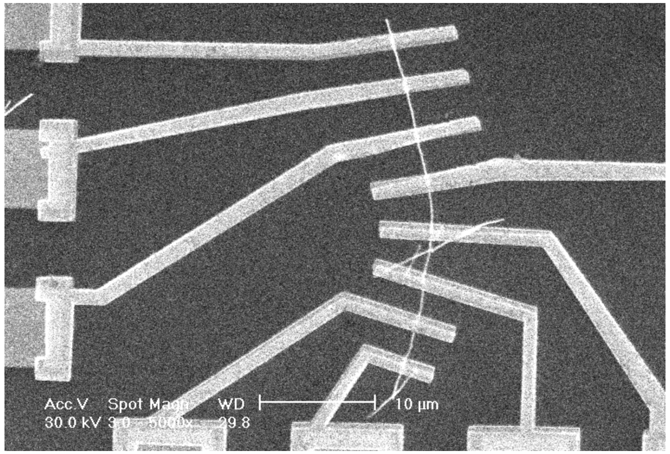
(Silicon On Insulator)

Nanowire electronic devices

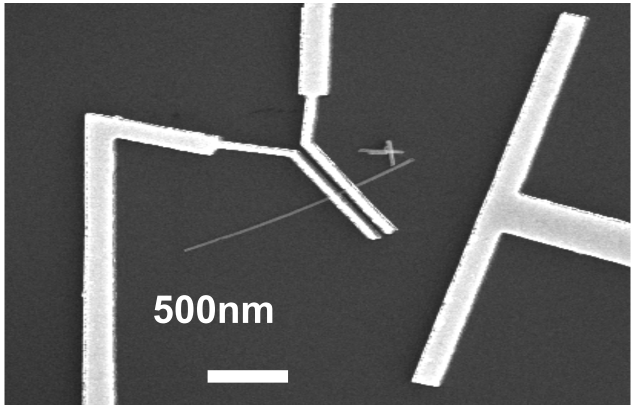
Suspended
single wall carbon nanotube



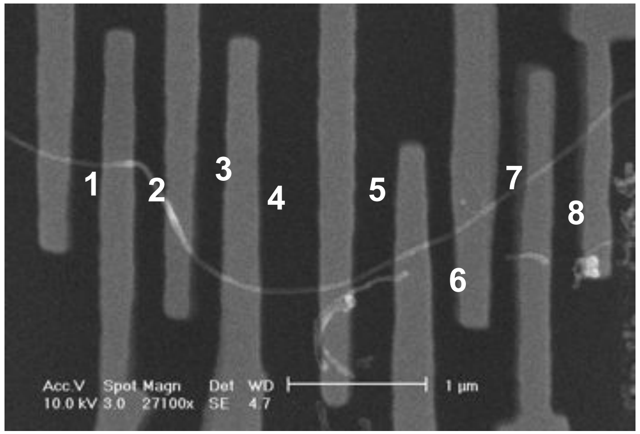
Bi_2Te_3 wire, 中研院物理所 陳洋元教授



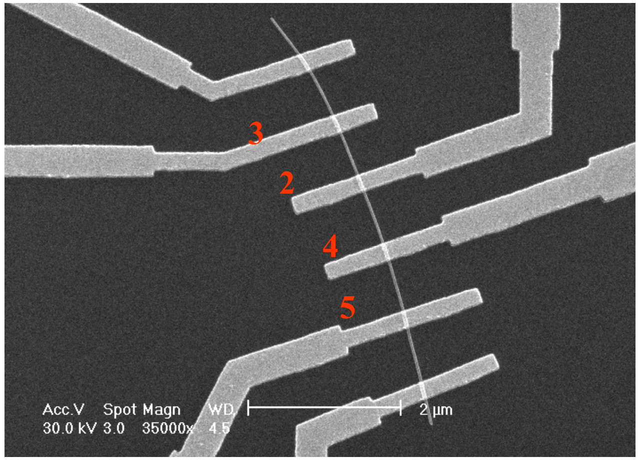
InN wire台大凝態中心林麗瓊教授



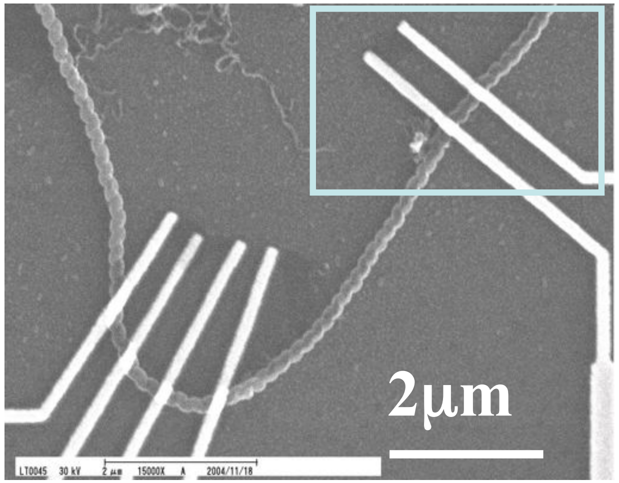
Multiwall carbon nanotube



Ni_3Si_2 wire, 清大材料 陳力俊教授

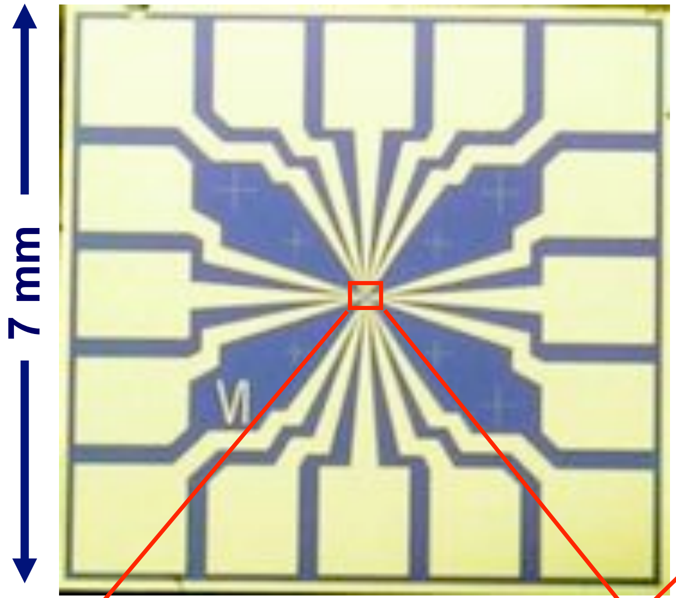


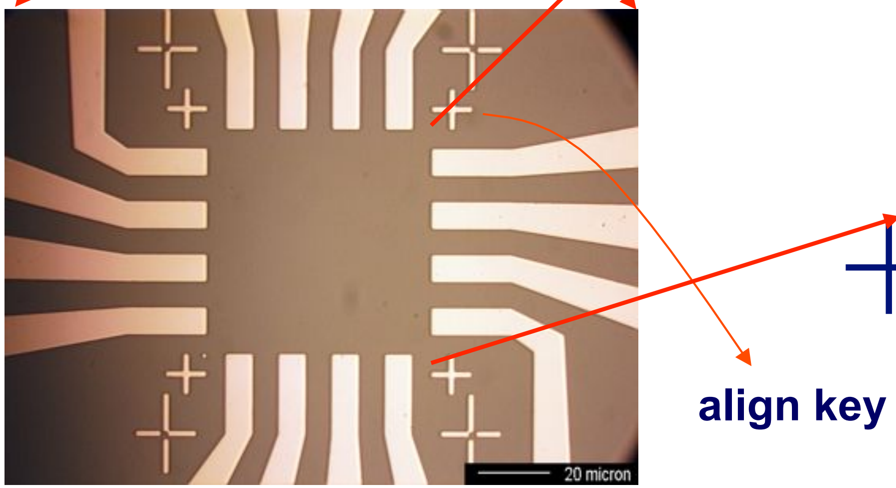
Carbon Helix 原分所陳益聰教授



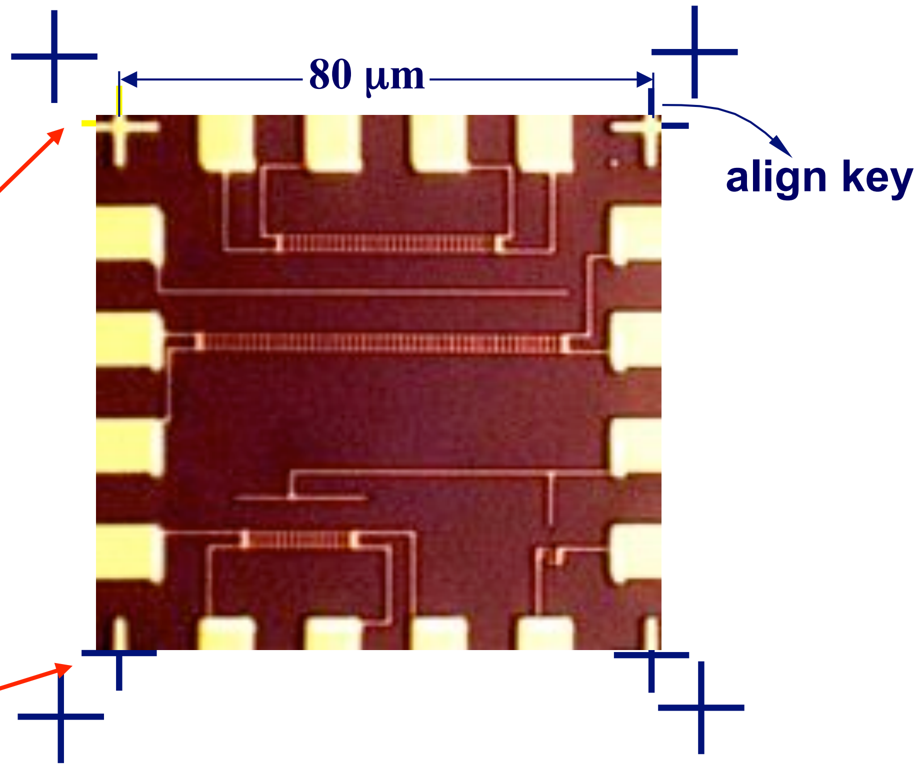
Mix and Match technology

Photolithography



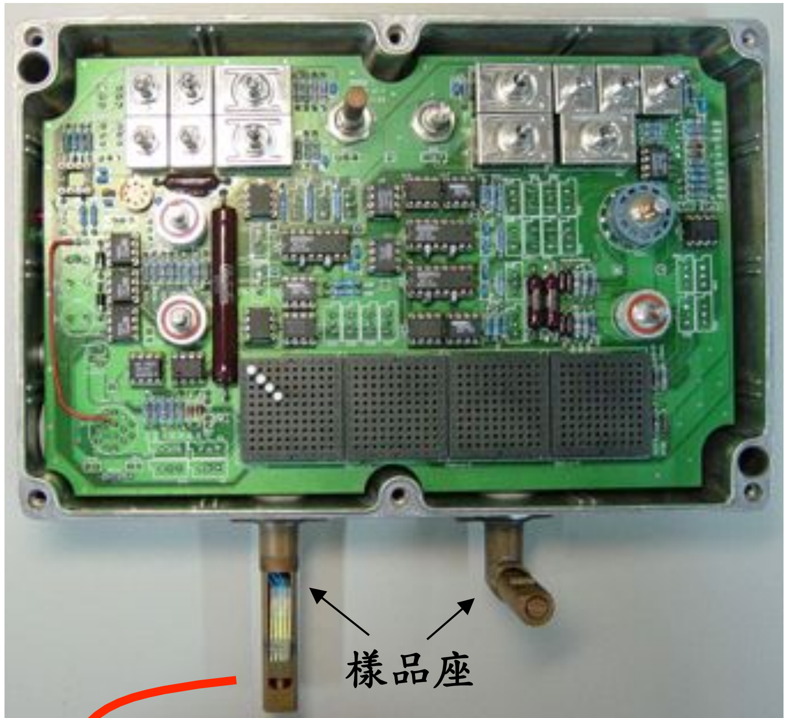


E-beam lithography

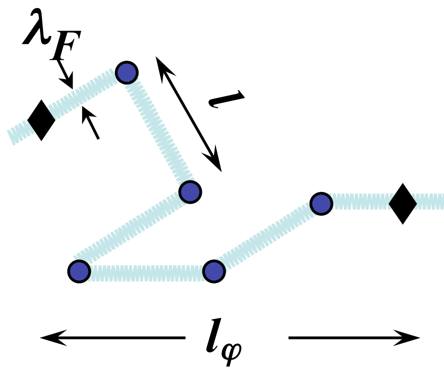


measurement setup

Available: 40mK, 5T

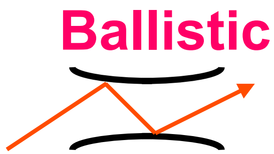


Characteristic length scales

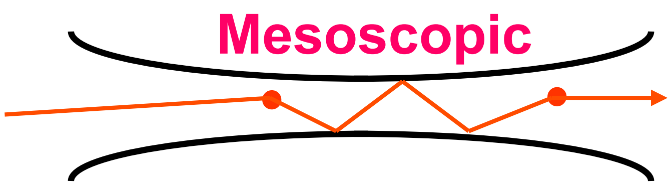


l : elastic mean free path

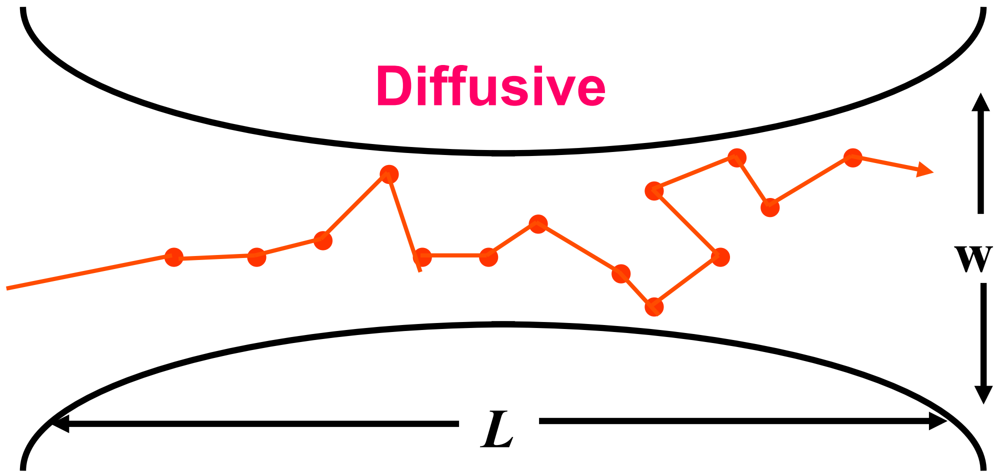
L_φ : phase-breaking length



$(w, L) < l$

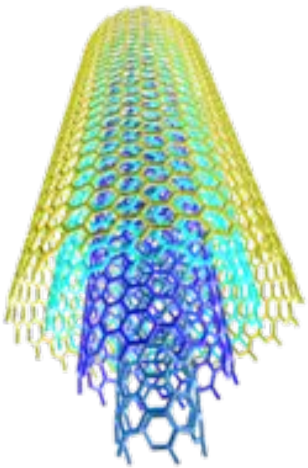


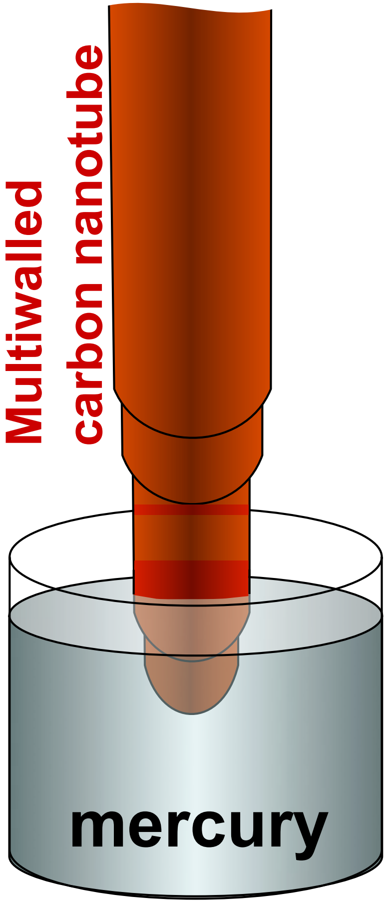
$l < (w, L) < L_\varphi$



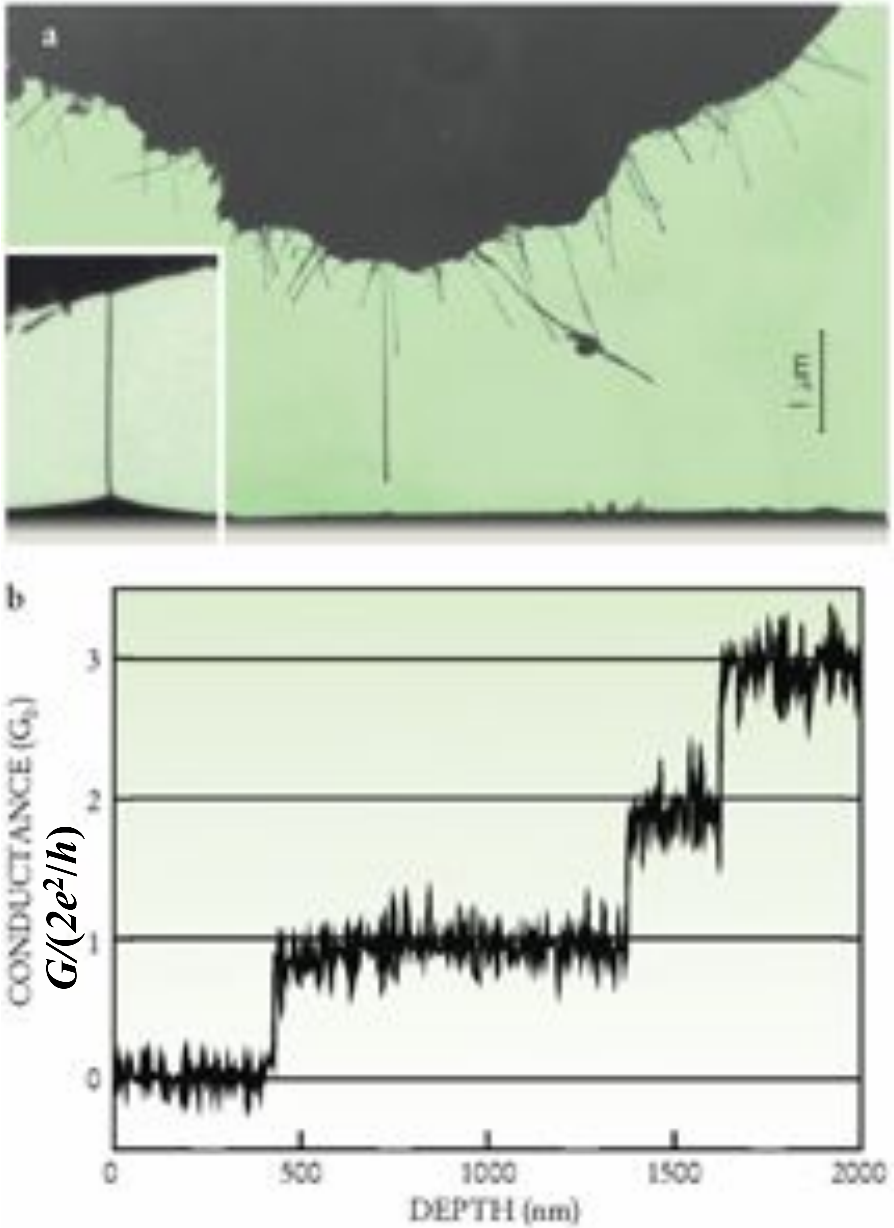
$L_\varphi << (w, L)$

Ballistic transport:
Length independent conductance

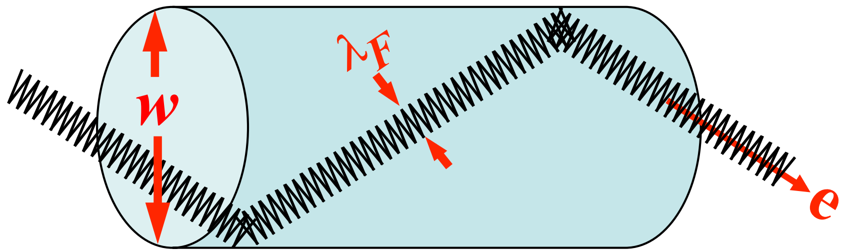




Walt de Heer,
Georgia Institute of Technology



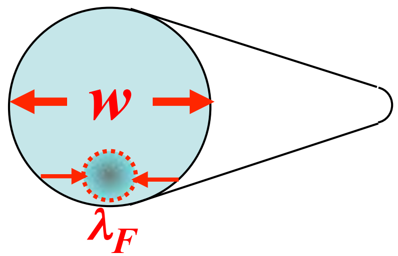
Ballistic system:



Devices with

1. Small diameter → only a few conduction channels

$$N \approx \pi w^2/\pi\lambda_F^2$$



2. Small electron density → no *e-e* scattering
3. No impurity, no defect → no impurity scattering

$$G_0 = N\,2e^2/h$$

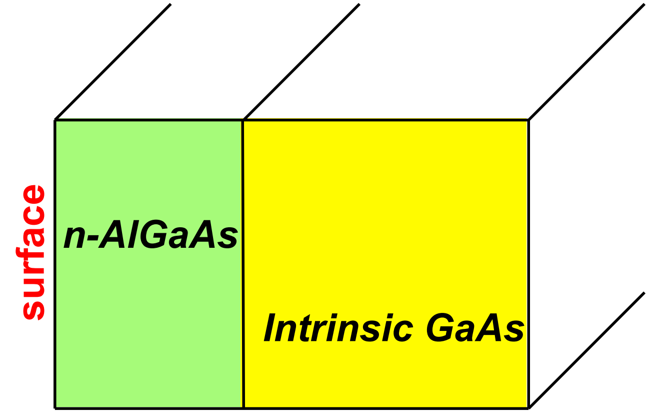
$$R_0 = \frac{1}{N}\frac{h}{2e^2} = \frac{R_Q}{N} \approx \frac{6.5k\Omega}{N}$$

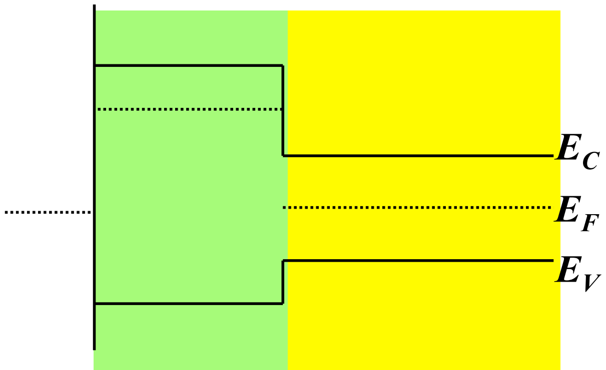
R_Q: quantum resistance

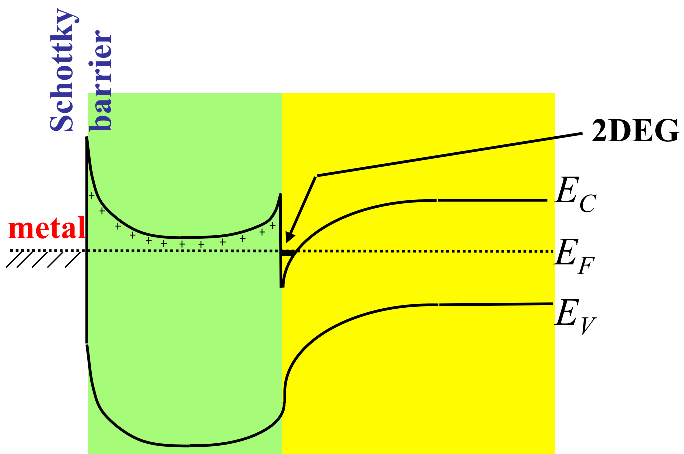
Resistance independent of the length,
only determined by number of channels *N*

Resistance takes place at the macroscopic contacts

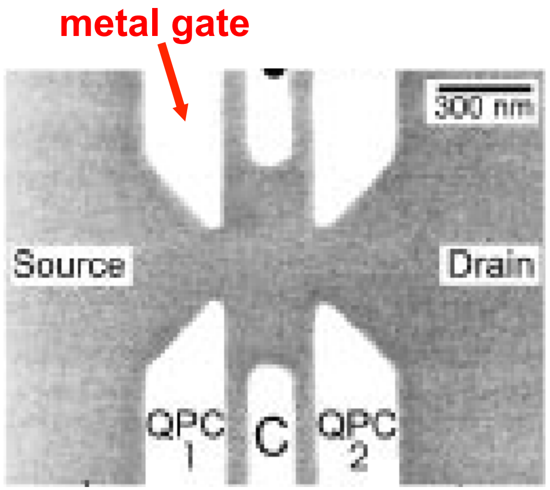
Two Dimensional Electron Gas (2DEG)

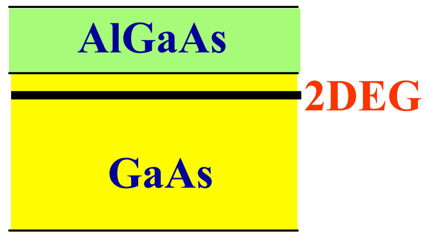


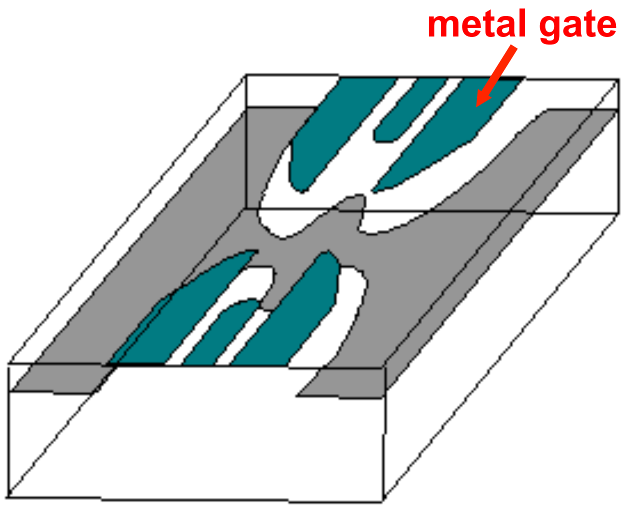




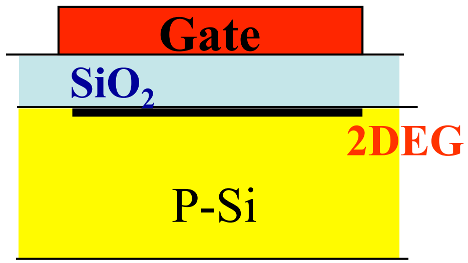
Formation:







MOS type of 2DEG

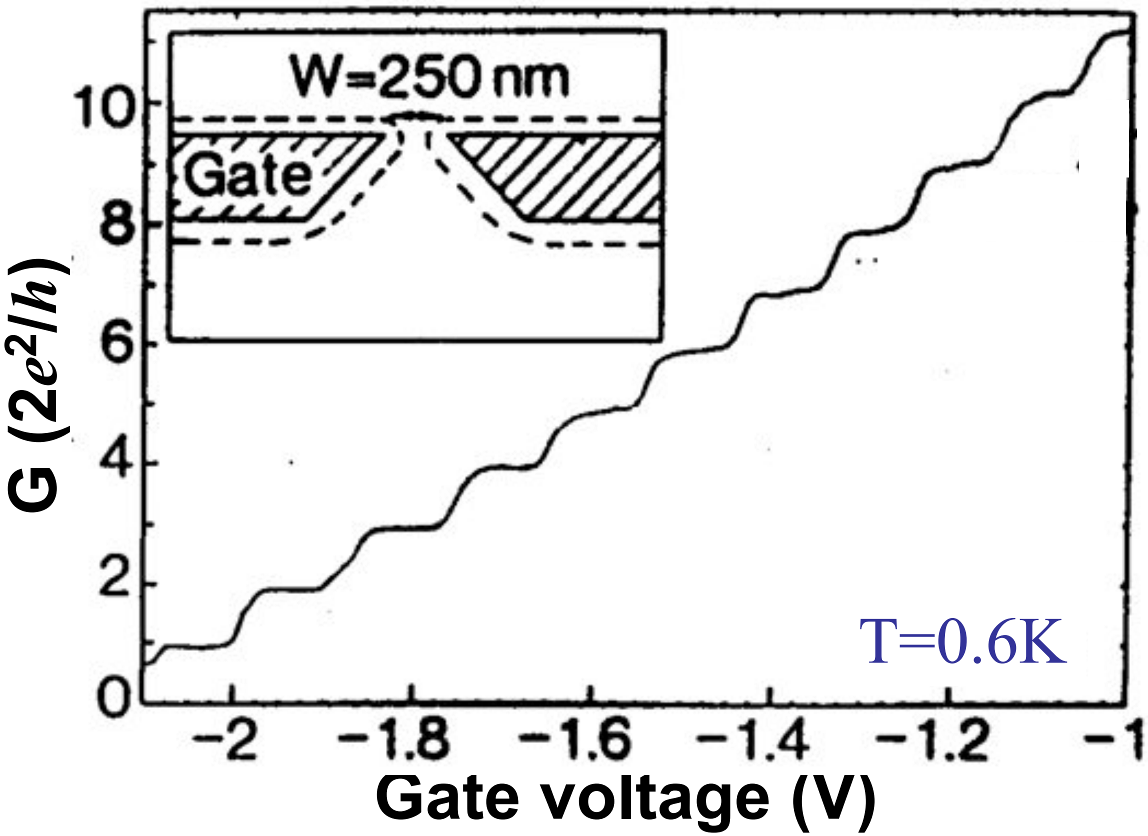


Conductance Quantization

Experiments on Quantum Point Contacts

B.J.van Wees et al. PRL 60, 848 (1988)

GaAs-AlGaAs heterostructure : 2DEG



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

$$T_n(E_F) = \sum_{n=1}^N |t_{m\to n}|^2$$

For adiabatic constriction

$$t_{m\to n} = \delta_{nm}$$

For abrupt constriction

$$t_{m\to n} \neq 1$$

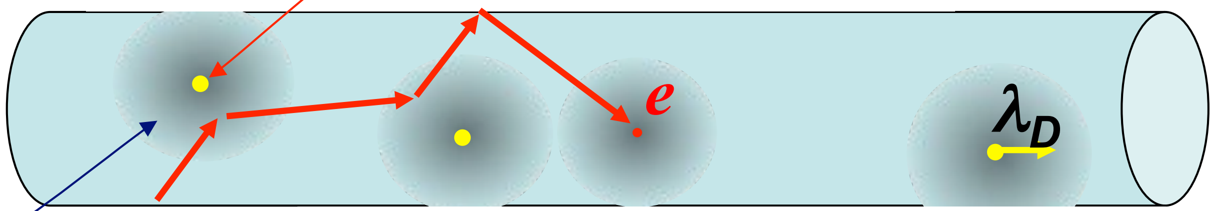
Optimized gate length

$$L_{opt} \approx 0.4\sqrt{\omega\lambda_F}$$

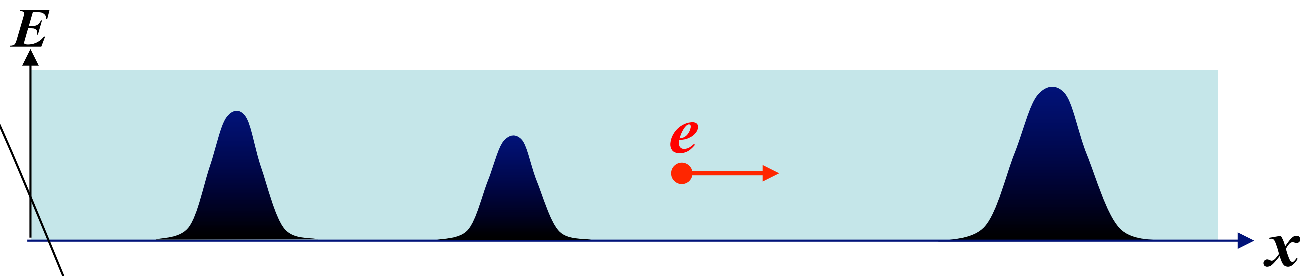
Origin of resistance

electron transport in disorder systems

impurities / defects / dislocation /other carriers



impurity potential

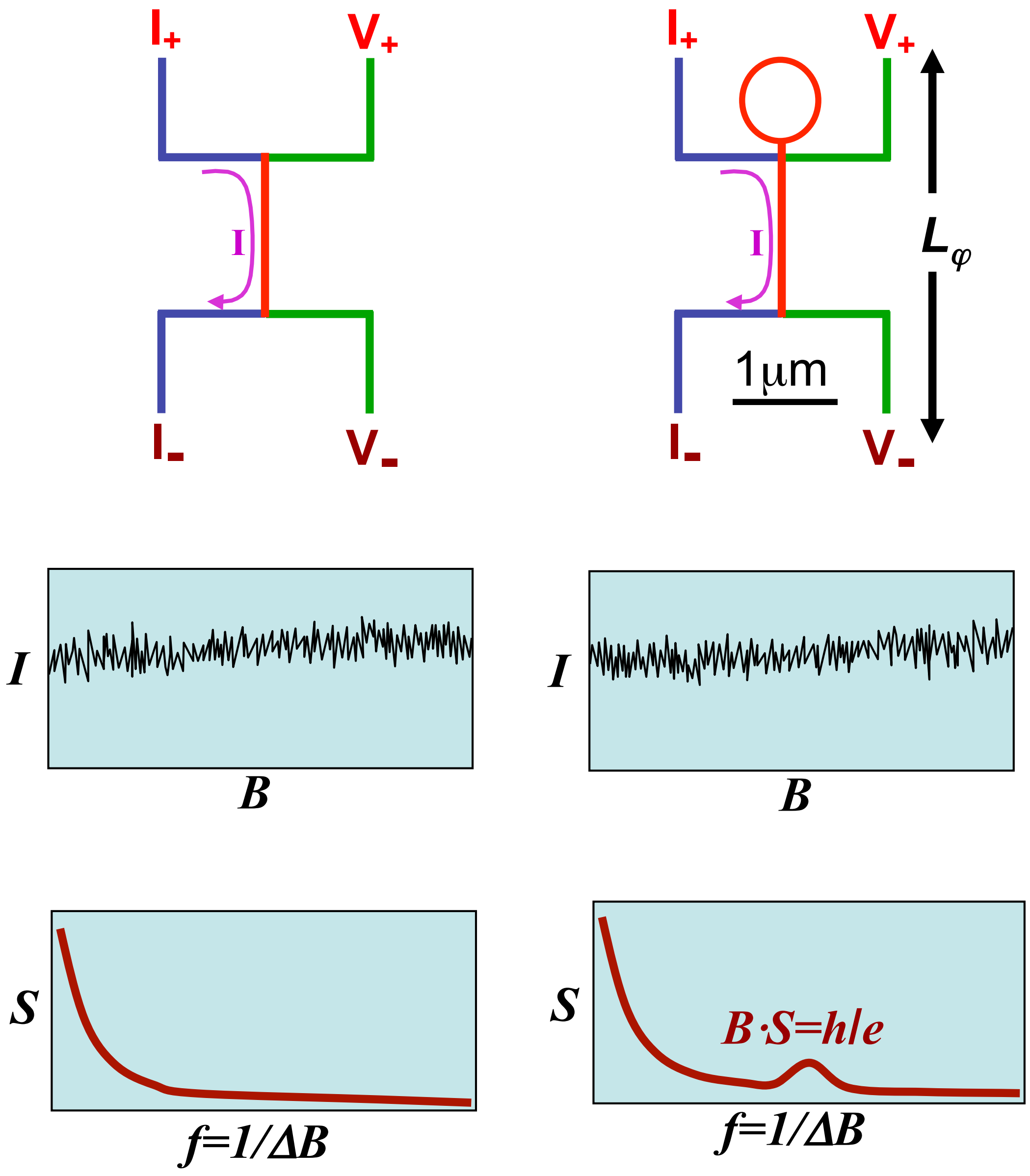


$$i\hbar \frac{\partial \Psi}{\partial t} = \left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + V \right) \Psi$$

Debye length $\lambda_D = \sqrt{\varepsilon k_B T / e^2 N_i}$

ε = dielectric permittivity,
k_B = Bolzmann constant,
T = absolute temperature,
e = electron charge

Quantum correction to the conduction



The quantum correction to the conductance can be strongly influenced by phase coherent regions extending beyond the probes and outside the classical current paths

Observation of h/e Aharonov-Bohm Oscillations in Normal-Metal Rings

R. A. Webb, S. Washburn, C. P. Umbach, and R. B. Laibowitz
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 27 March 1985)

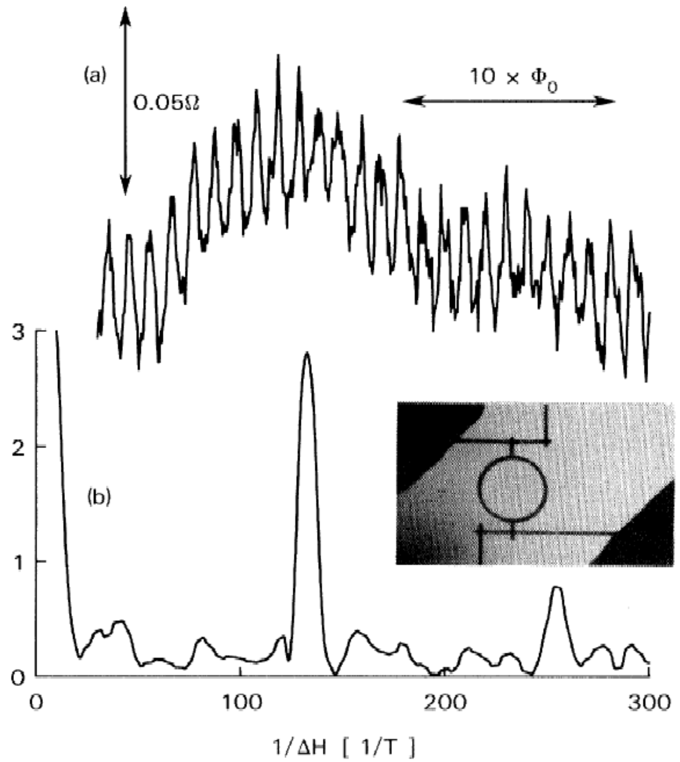


FIG. 1. (a) Magnetoresistance of the ring measured at $T=0.01$ K. (b) Fourier power spectrum in arbitrary units containing peaks at h/e and $h/2e$. The inset is a photograph of the larger ring. The inside diameter of the loop is 784 nm, and the width of the wires is 41 nm.

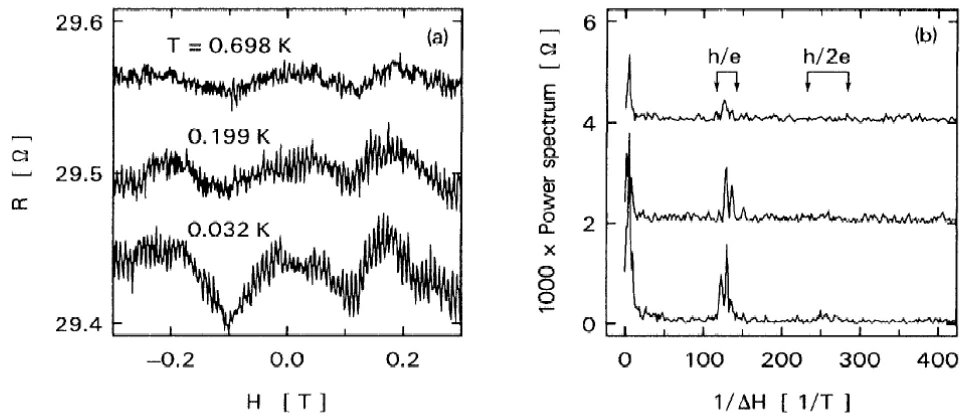
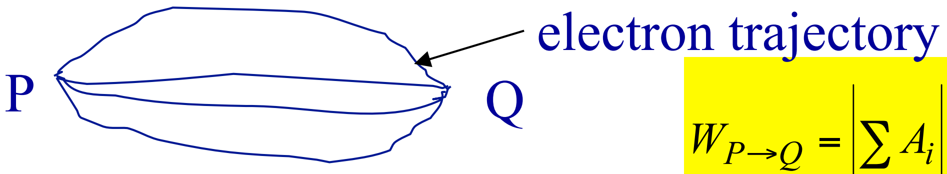


FIG. 2. (a) Magnetoresistance data from the ring in Fig. 1 at several temperatures. (b) The Fourier transform of the data in (a). The data at 0.199 and 0.698 K have been offset for clarity of display. The markers at the top of the figure indicate the bounds for the flux periods h/e and $h/2e$ based on the measured inside and outside diameters of the loop.

Aharonov-Bohm effect



Probability for P → Q

$$W_{P\to Q} = \left|\sum_i A_i\right|^2 = \underbrace{\sum_i |A_i|^2}_{\text{Clasical diffusion}} + \underbrace{\sum_{i\neq j} A_i A_j^*}_{\text{Quantum interference}}$$

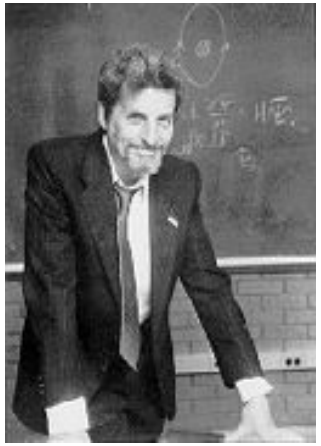
electrons pick a phase φ when traveling along a path P

$$\varphi = \frac{e}{\hbar}\int_P A\cdot dx$$

phase difference between two paths with the same ends

$$\phi = \frac{1}{\hbar}\int_P^Q A\cdot dl_1 - \frac{1}{\hbar}\int_P^Q A\cdot dl_2 = \frac{1}{\hbar}\int_P^Q A\cdot dl_1 + \frac{1}{\hbar}\int_Q^P A\cdot dl_2 = \frac{1}{\hbar}\oint A\cdot dl$$

$$= \frac{2e}{\hbar}\int(\nabla\times A)\cdot dS = \frac{2e}{\hbar}\int BdS = 2\pi\frac{B\cdot S}{h/2e}$$

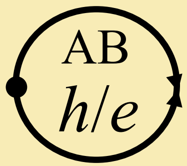


Yakir Aharonov

Probability for back-scattering

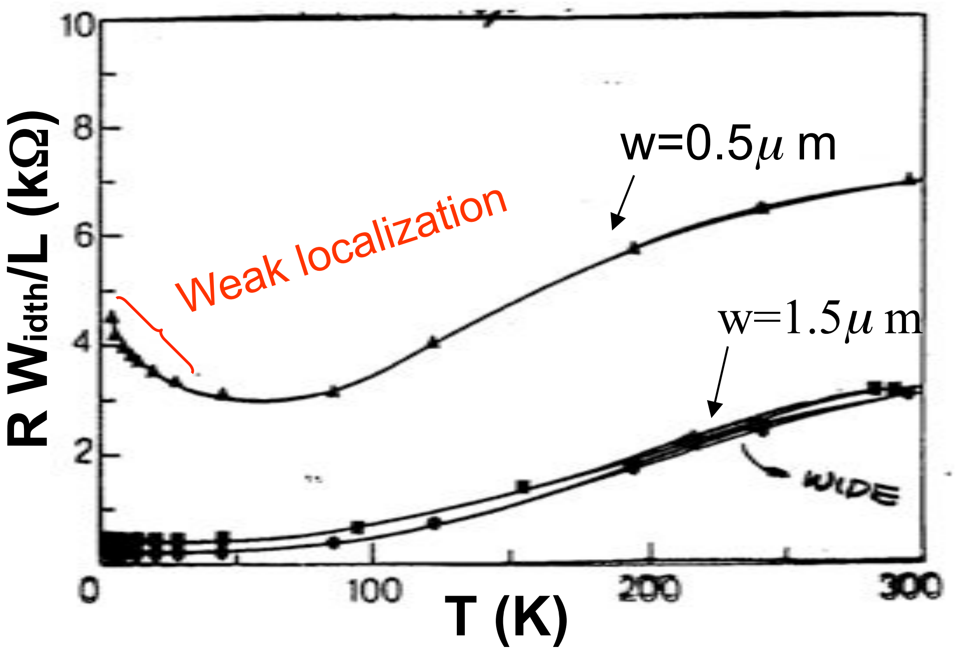
$$W_{P\leftrightarrow P} = 2|A|^2 + 2|A|^2\cos\left(2\pi\frac{B\cdot A}{h/2e}\right) \rightarrow \text{period} = h/2e$$

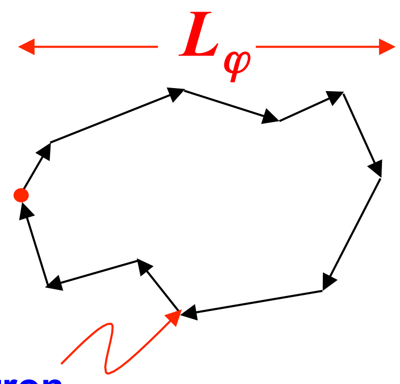
Aharonov-Casher effect



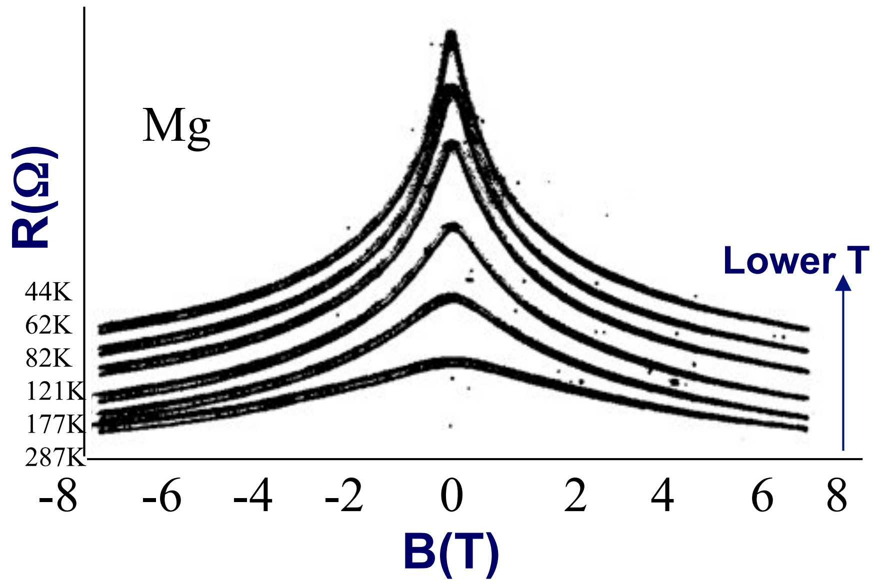
Aharonov-Bohm effect

Weak localization takes place for length scale < L_ϕ



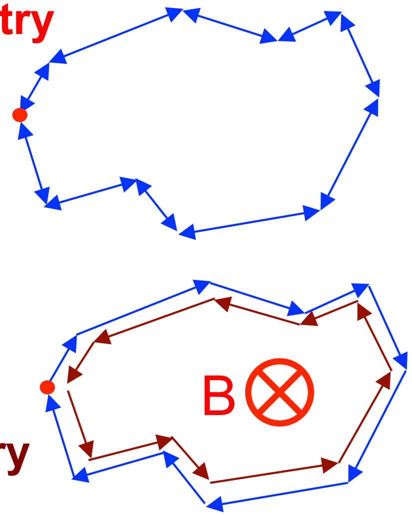


Other possible explanations:
- electron-electron interaction
- Kondo-effect

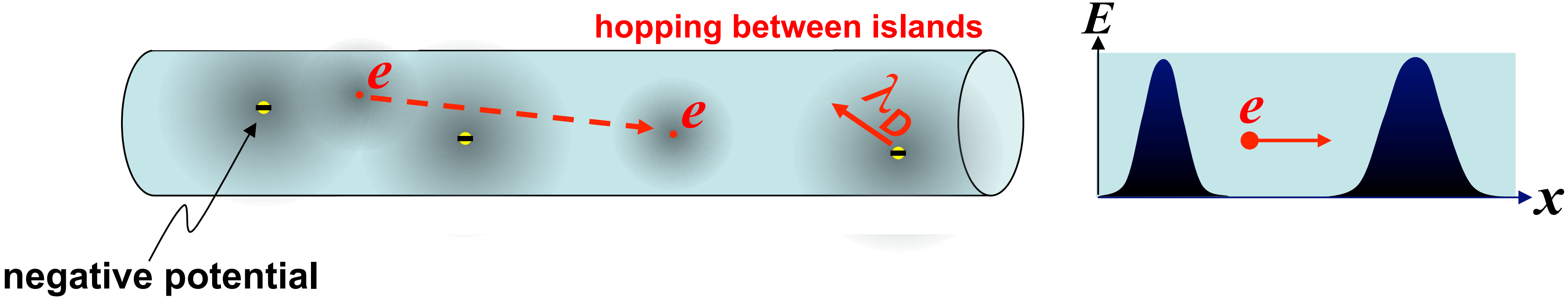


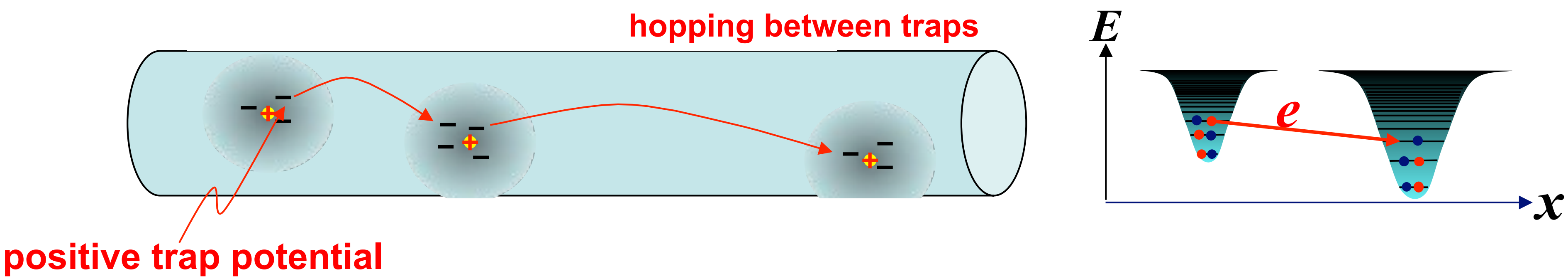
time reversal symmetry

Magnetic field: break the time reversal symmetry

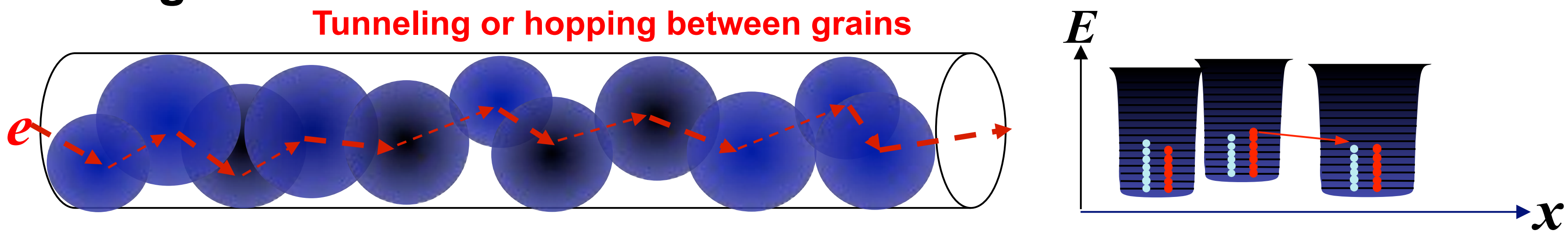


Hopping conduction in disordered systems





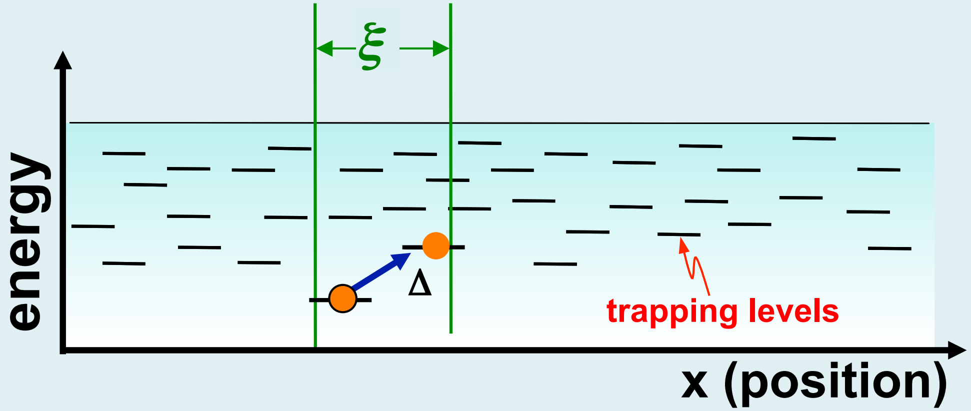
Metallic grains



Hopping transport

R_o increases with decreasing temperature

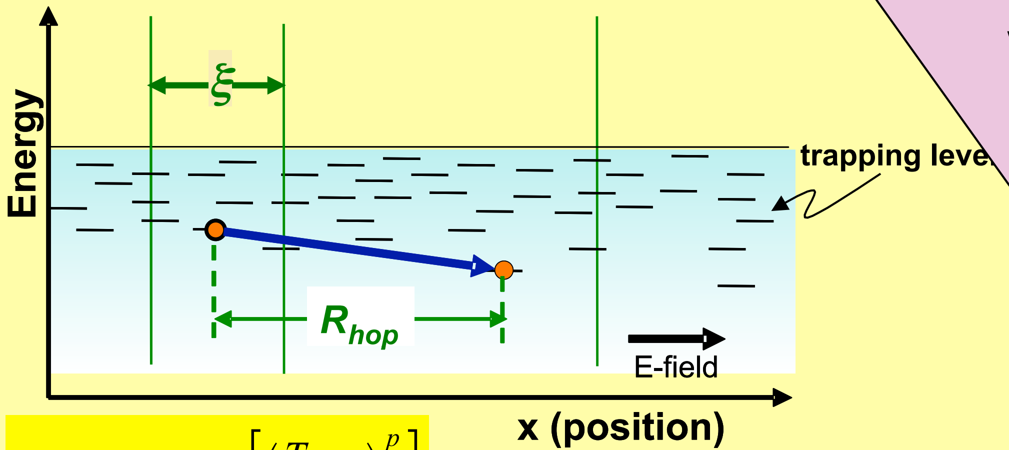
Nearest neighbor hopping (Arrhenius form)



$$R_0 = R_A \exp\left(\frac{\Delta}{k_B T}\right)$$

Presence of a **hopping barrier**;
thermally activated hopping

Mott Variable range hopping



$$R_0 = R_A T^S \exp\left[\left(\frac{T_{Mott}}{T}\right)^p\right]$$

T_{Mott} = Mott characteristic temperature

$$p = \frac{1}{1+d}$$ d = system dimensionality

Efors-Shklovskii Variable range hopping

when Coulomb interaction is considered

$$R_0 = R_A T^S \exp\left[\left(\frac{T_{ES}}{T}\right)^{1/2}\right]$$

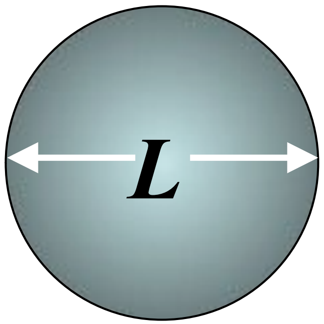
power-law dependence in DOS near E_F

$$N(E) = N_0 |E - E_F|^\gamma$$

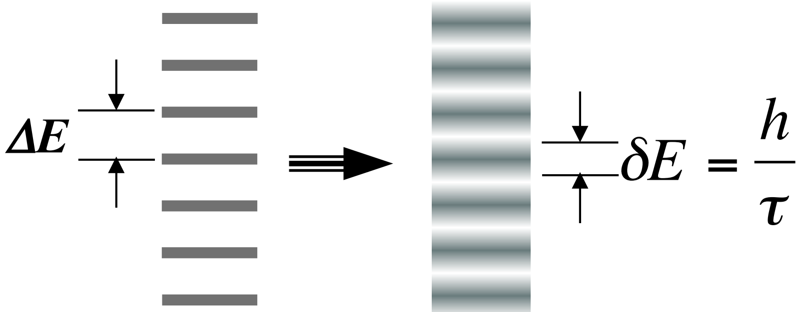
For 3D, γ=2

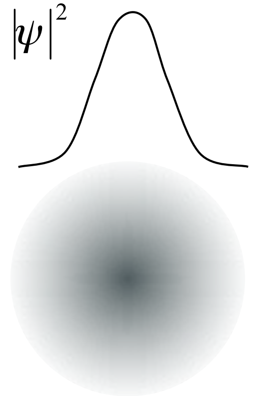
Nonlinear IV_b characteristics

Quantum origin of energy level broadening



broadening of quantized levels





τ = time for electron to travel through the grain

in ballistic regime: $\tau = L/v_F$

---

in diffusive regime: $\tau = L^2/D$ *for D:* **Einstein relation:** $\sigma = e^2 D N_0(E_F)$

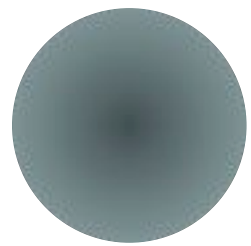
$$\Rightarrow \quad \delta E = \frac{h}{\tau} = \frac{hD}{L^2} = \frac{h}{e^2}\frac{\sigma}{L^2 N_0(E_F)}$$

Level spacing : $\Delta E = [L^d N_0(E_F)]^{-1}$

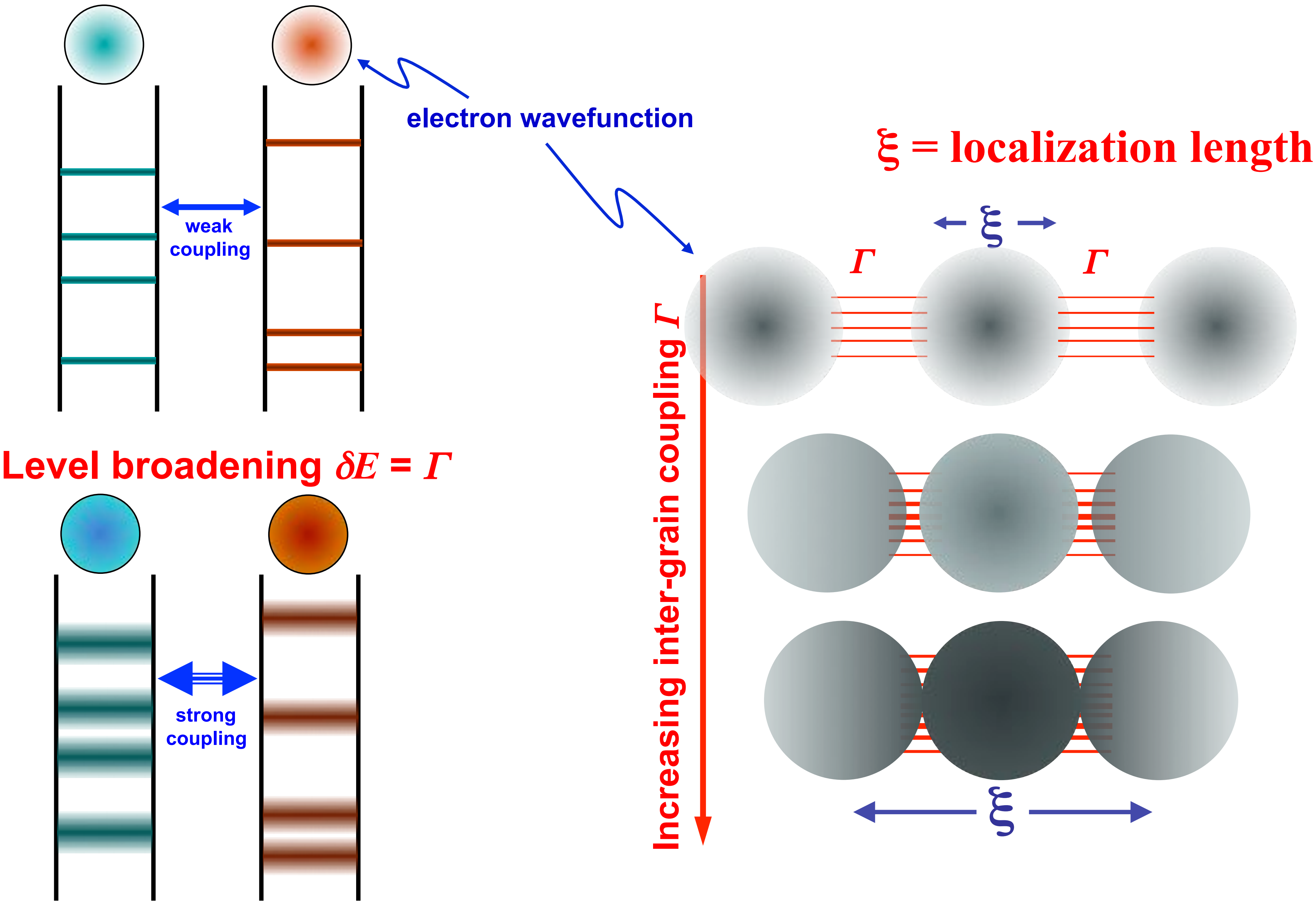
Thouless ratio $g \equiv \dfrac{\delta E}{\Delta E} \approx \dfrac{h}{e^2}\sigma L^{d-2} = \dfrac{G}{e^2/h}$

$g < 1$ (R>26kΩ) ⇒ localized state

$g > 1$ (R<26kΩ) ⇒ extended state



Inter-grain coupling induced level broadening



Resonate tunneling between coupled quantum dots

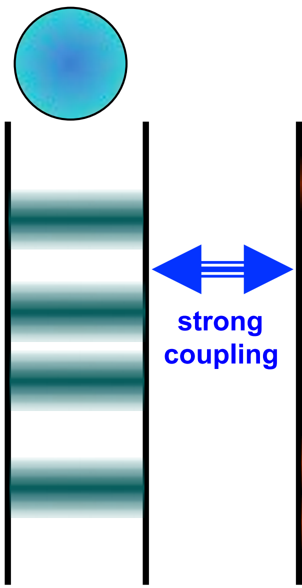
For very weak inter-coupling, two possible states exist : $|R\rangle$ and $|L\rangle$

With finite coupling Γ, $|R\rangle$ and $|L\rangle$ mix and form two eigenstates $|A\rangle$ and $|S\rangle$

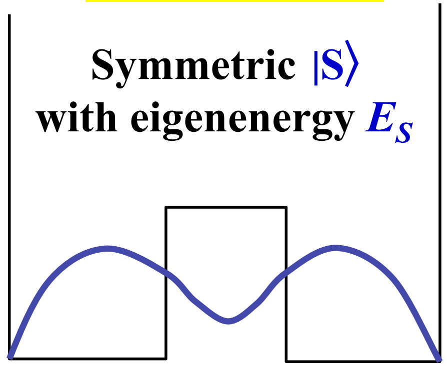
Coupling strength = Γ

tunneling rate $\gamma = \Gamma / \hbar$

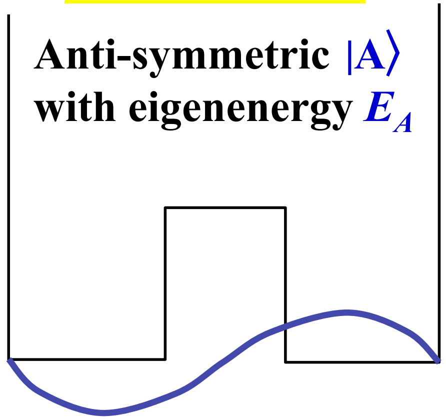
level broadening $\delta E = \Gamma$

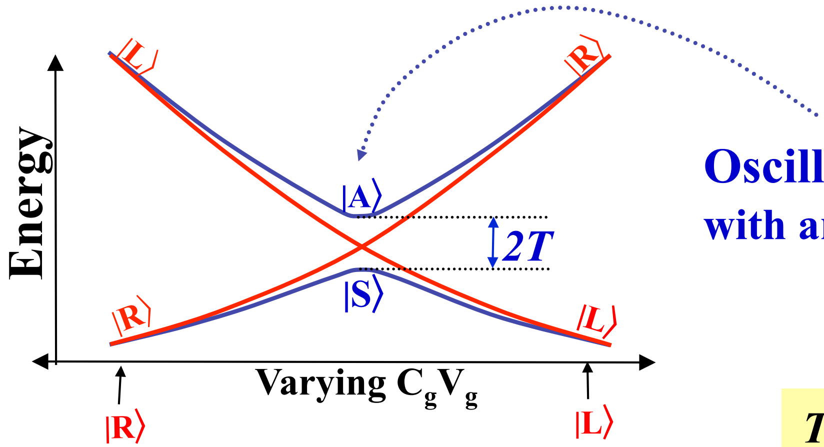


$$|S\rangle = \frac{1}{\sqrt{2}}\left(|R\rangle + |L\rangle\right)$$



$$|A\rangle = \frac{1}{\sqrt{2}}\left(|R\rangle - |L\rangle\right)$$





Oscillation between $|R\rangle$ and $|L\rangle$ with angular frequency

$$\omega = \frac{E_A - E_S}{\hbar} = \frac{2T}{\hbar}$$

T = coupling constant