April 18 2007
前沿物理演講
Department of Physics / NTHU

Nano-devices at the scaling limit

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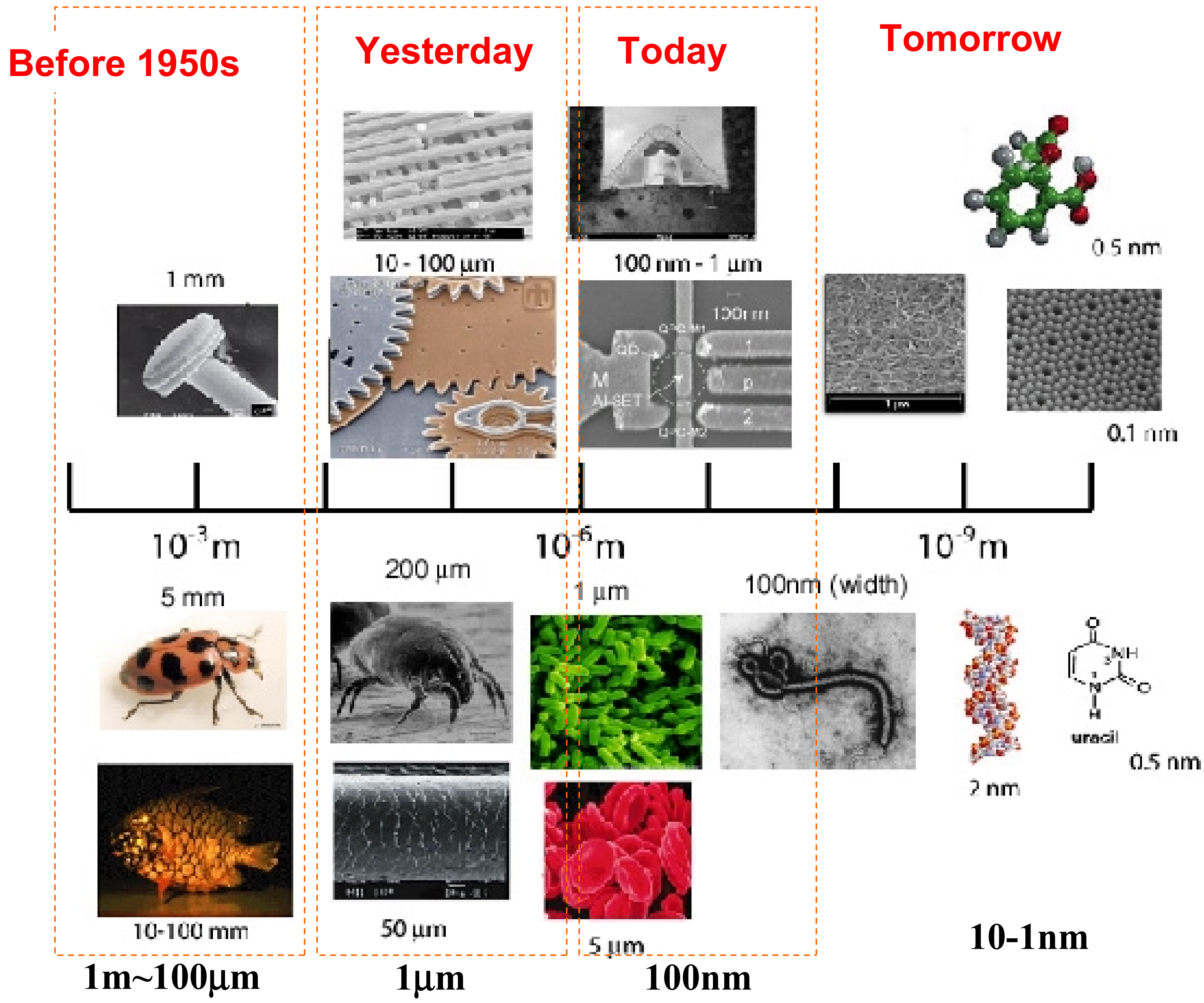
Outline

- ✱ Technology Roadmap – Introduction
- ✱ Fundamental limits to scaling
- ✱ Future nano-devices
    - Single electron transistor
- ✱ Summary

Introduction: Technological and biological length scales



Why scale down?

Driven for..

speed

dense memory

high frequency

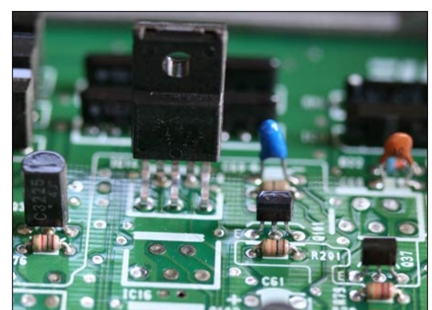
Scaling Down

complexity

space

Electromechanical relay

Vacuum tube



Solid state transistor

IC

?

Why Physicist?

Nobel Prize in Physics

"for their researches on semiconductors and their discovery of the transistor effect"

1956

William Bradford Shockley

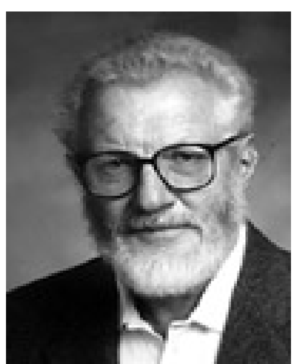
John Bardeen

Walter Houser Brattain

Solid state transistor

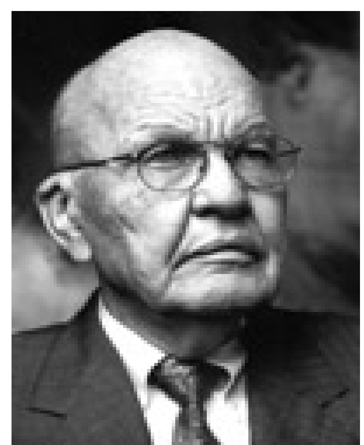
2000 "for developing semiconductor heterostructures used in high-speed and optoelectronics"

Zhores I Alferov



Herbert Kroemer

"for his part in the invention of the integrated circuit"

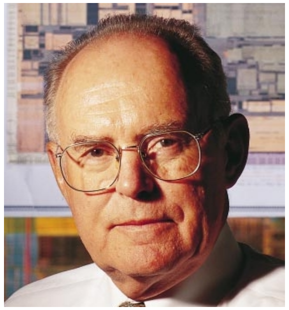


IC

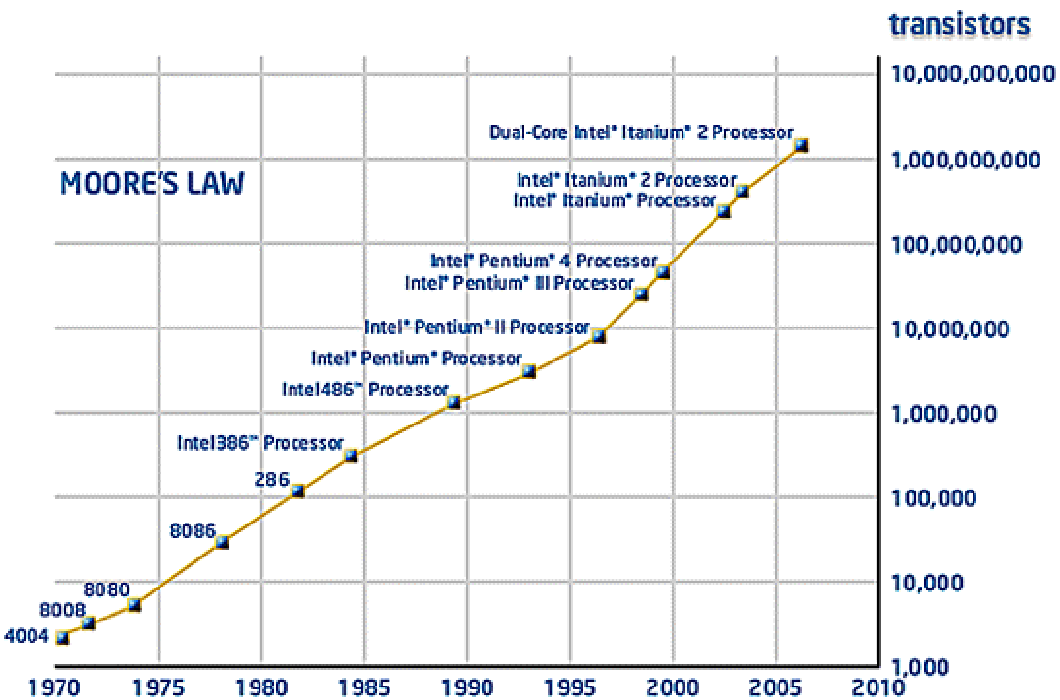
Jack S Kilby

20XX ?

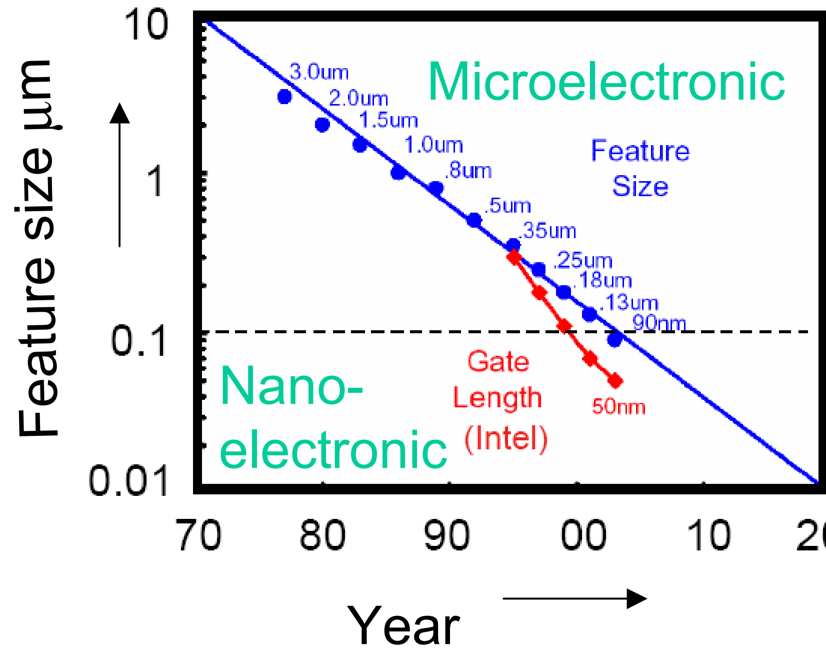
What's the problem? Current status.

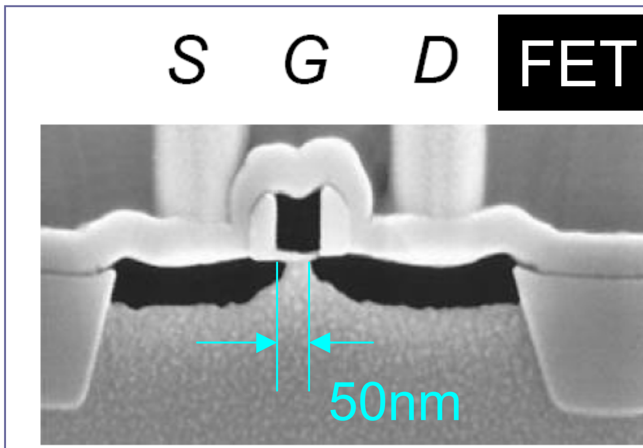


Gordon Moore
"*every 1.5 years complexity doubles*"



Ref: http://www.intel.com/technology/mooreslaw/





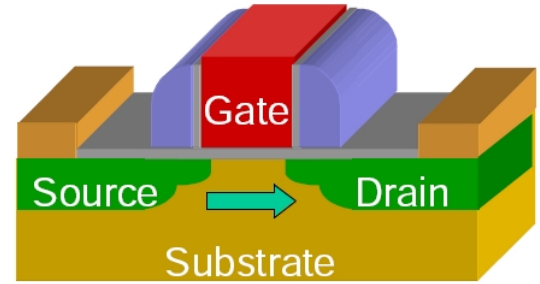
90nm technology node

What's the problem in CMOS?

❶ Gate leakage
SD leakage
Device-device variability

❷ Power dissipation limits device density

❸ CMOS will operate near ultimate limits



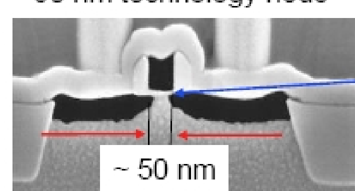
Silicon MOSFET

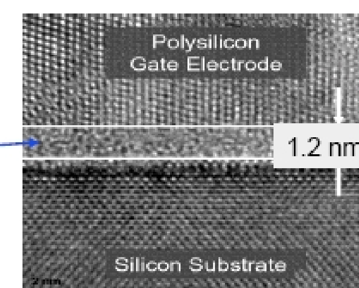
$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

Keep C but A $\downarrow$

$\Rightarrow \varepsilon_r \uparrow$ or d $\downarrow$

90 nm technology node

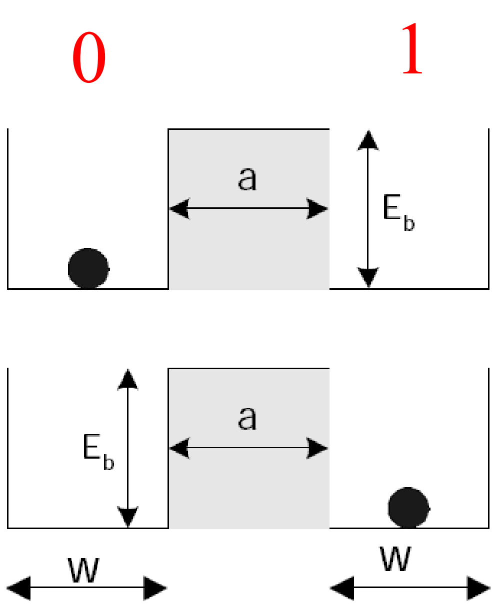




A physical system as a computing medium:

1. Distinguish ability
2. Conditional change of the state

A two-well bit



D: Distinguishability

P: probability of spontaneous transition

e.g. D=Max, P=0

D=0, P=0.5

$$P_{Classical} = \exp\left(-\frac{E_b}{k_B T}\right)$$

Suppose the minimum distinguishable barrier:

$$\frac{1}{2} = \exp\left(-\frac{E_b}{k_B T}\right)$$

$$\Rightarrow \quad E_b = k_B T \ln 2$$

Minimum energy dissipation per logic transition

See Zhirnov, Cavin, Hutchby, and Bourlanoff. Prof. IEEE, special issue on nanoelectronics and nanoscale processing. Nov. 2003

Least energy computer

$$\begin{pmatrix} E_b = k_B T \ln 2 \\ \Delta x \Delta p \geq \hbar \\ \Delta E \Delta t \geq \hbar \end{pmatrix}$$

Heisenberg – uncertainty principle

Min switch time

$$t_{\min} = \frac{\hbar}{E_b} = \frac{\hbar}{2k_B T \ln 2} = 1.2 \times 10^{-13} s$$

Min device size

$$x_{\min} = \frac{\hbar}{\sqrt{2mE_b}} = 1.5 nm$$

T=300K

Max gate density

$$\mathrm{n} = \frac{1}{x_{\min}^2} = 4.6 \times 10^{13} \frac{gate}{cm^2}$$

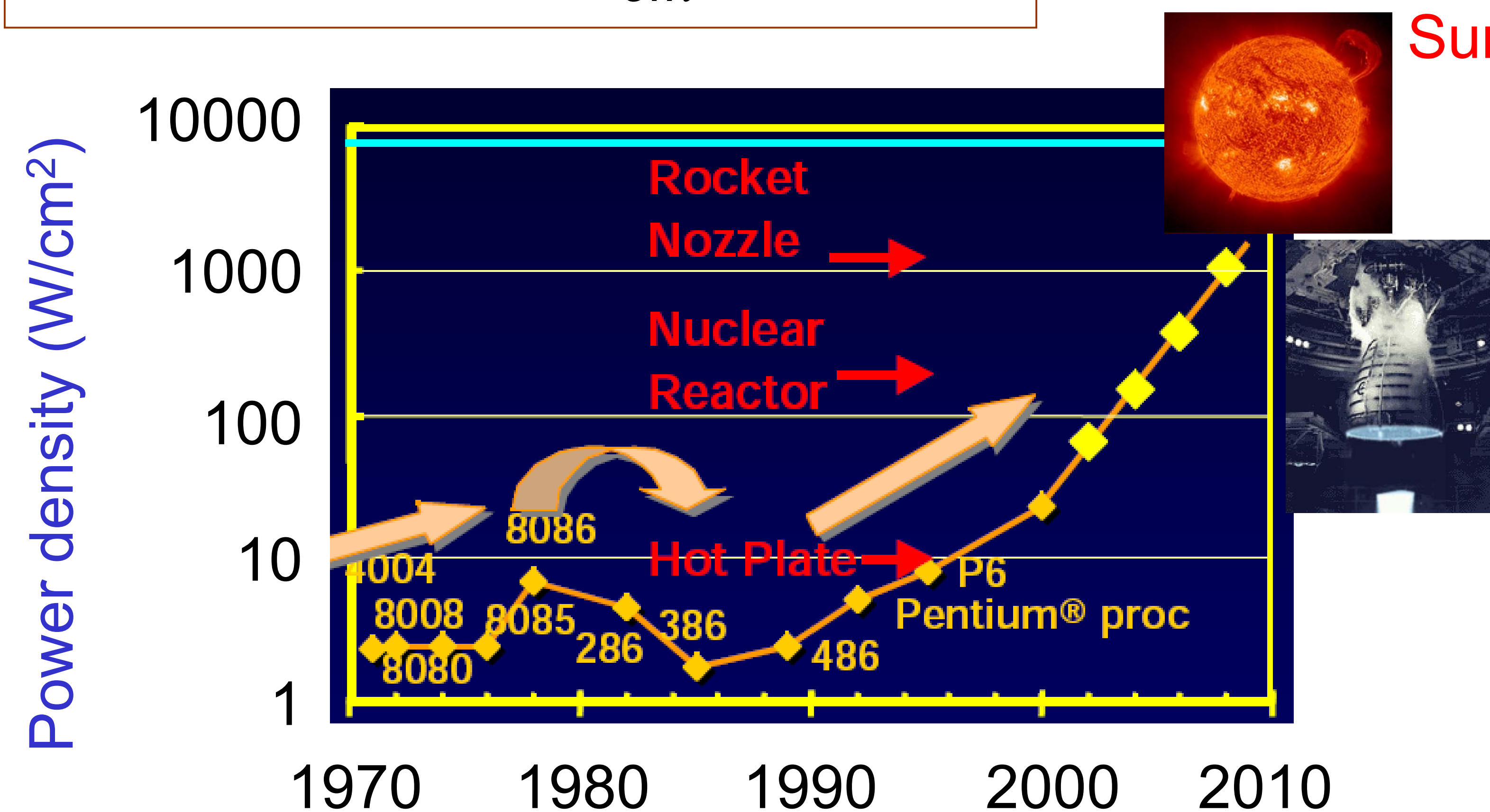
Total power consumption

$$P_{bit} = \frac{E_b}{t_{sc}} = \frac{(k_B T \ln 2)^2}{\hbar}$$

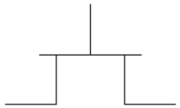
$$P_{Chip} = nP_{bit} = 4.8\times10^6 \frac{W}{cm^2} \quad \mathrm{T=300K}$$

The circuit is Vaporized when it is turned on!

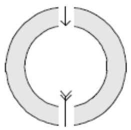
Sun surface



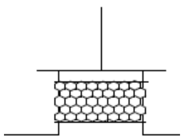
The solution????? Emerging Technology



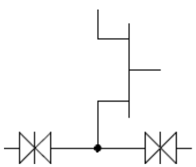
FET (Field Effect Transistor) $\Rightarrow$ Materials



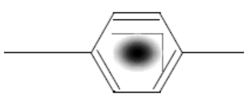
RSFQ (Rapid single flux quantum device)



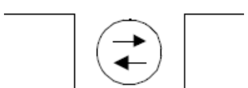
1D structure (Carbon nanotube, ZnO_2 wire)



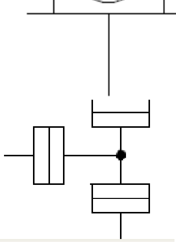
RTD (Resonance tunneling diode)



Molecular



Spin transistor



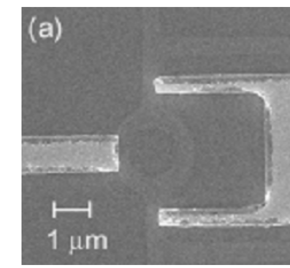
SET (Single electron transistor)

Quantum coherent devices

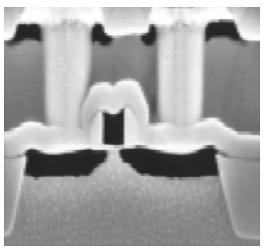
…….etc.

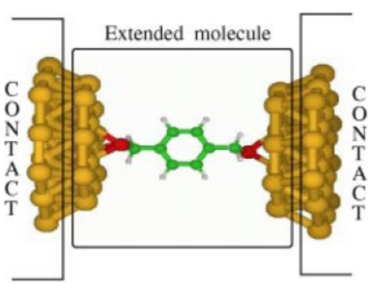
Wave function of the electrons

RSFQ
Quantum coherent device



$$\Psi = \overbrace{\Phi(\vec{r})\,\chi}^{\text{Phase}}$$





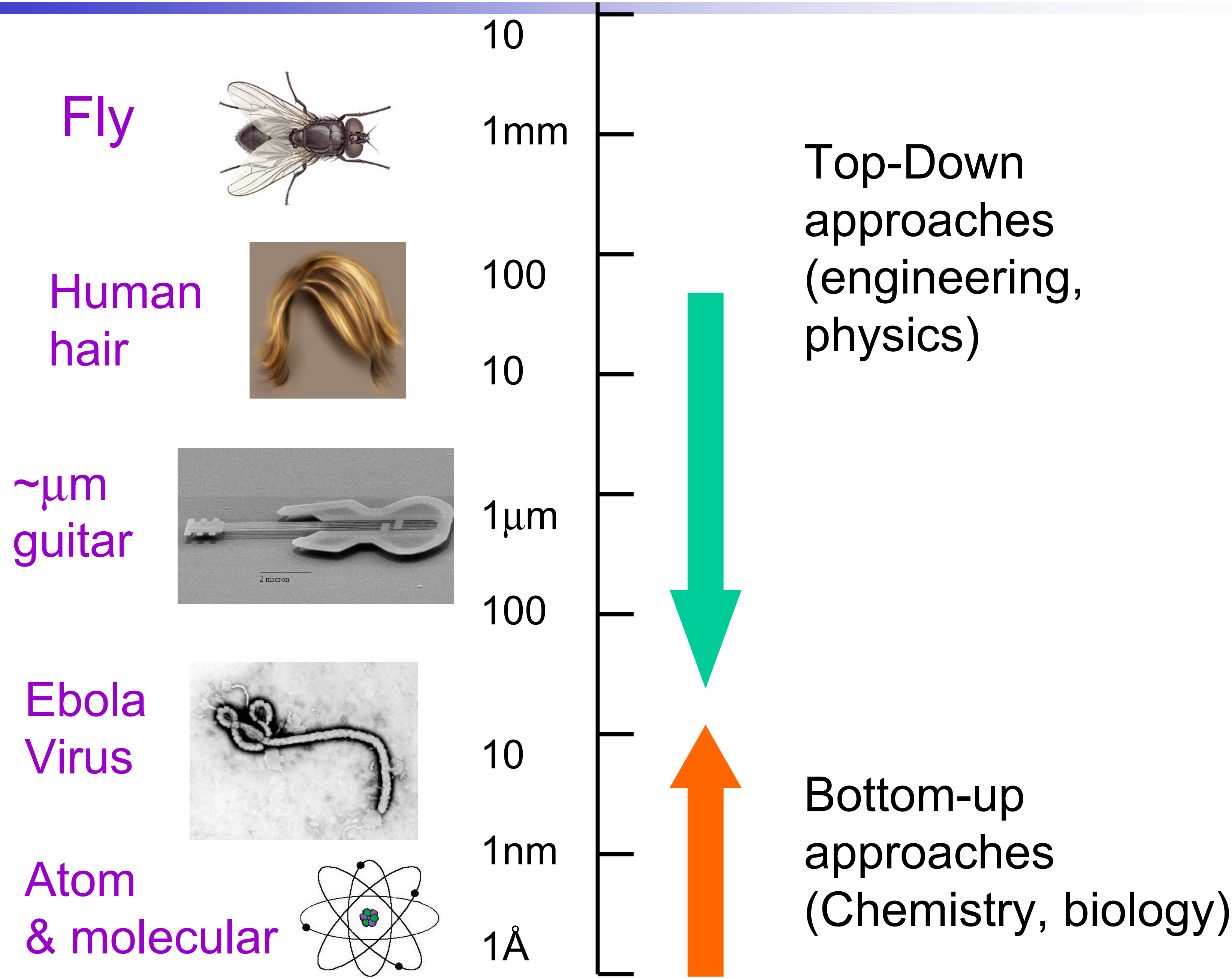
Charge

FET
RTD
Single electron transistor
1D Nano-structure
Molecular device

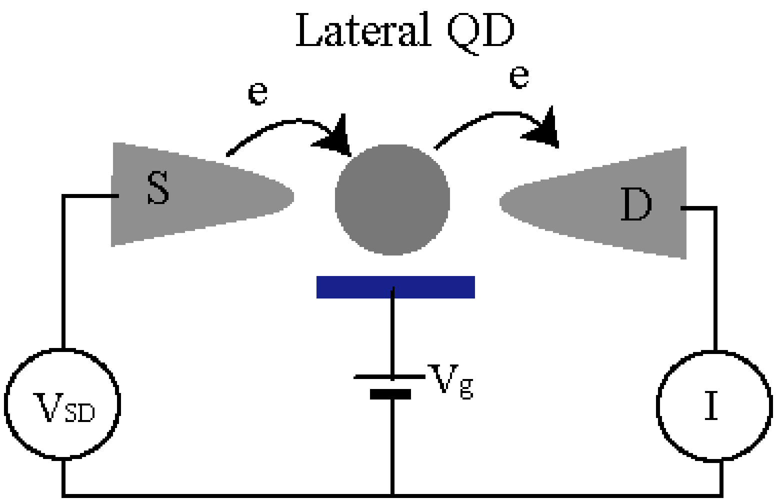
Spin

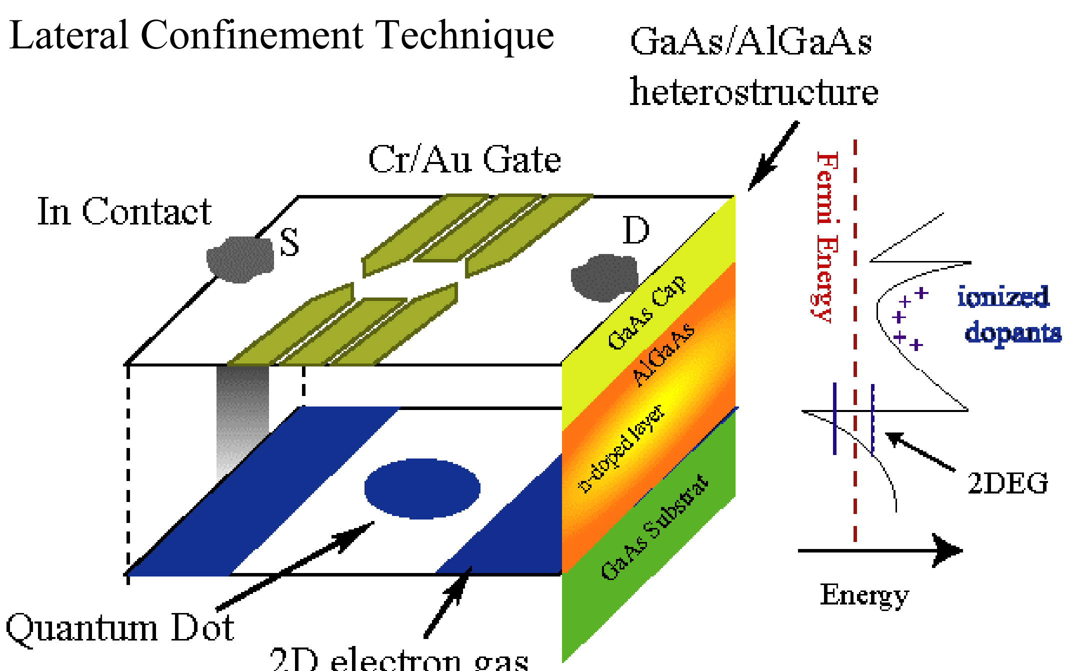
Spin transistor

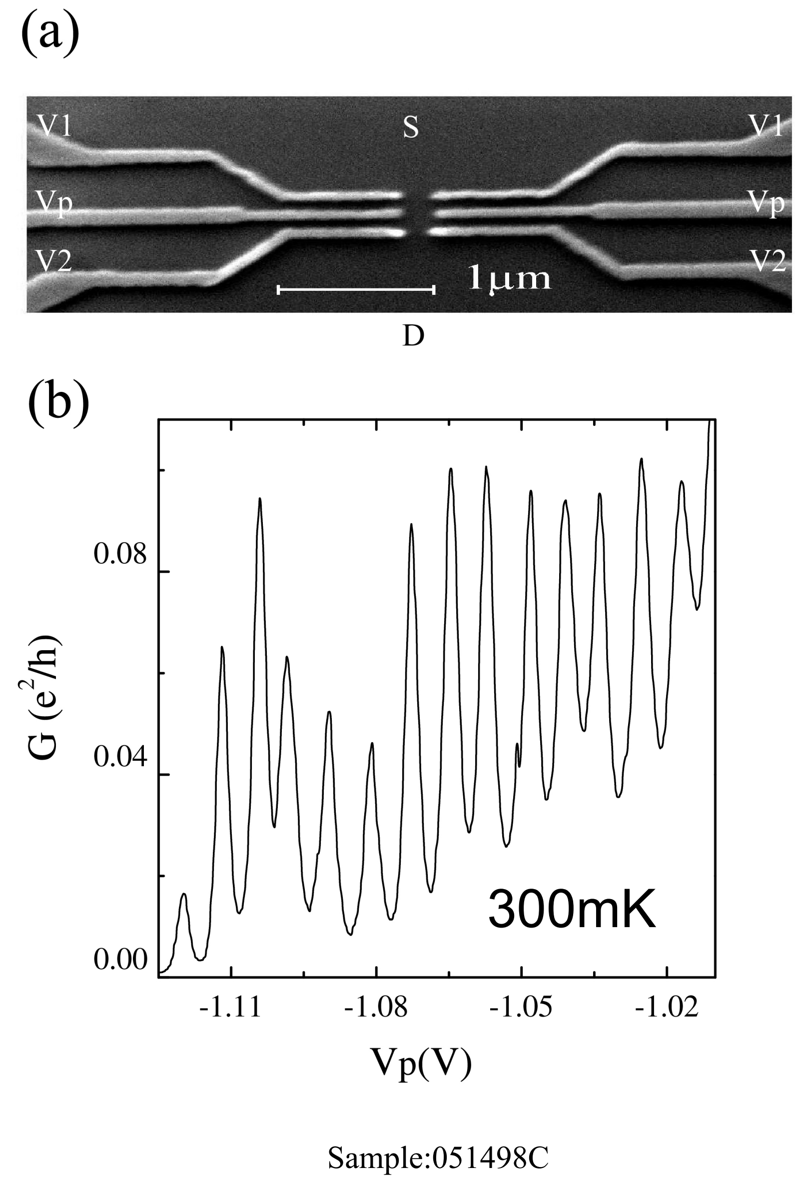
Top-down / Bottom-up approach



Single Electron Transistor – single quantum dot –artificial atom

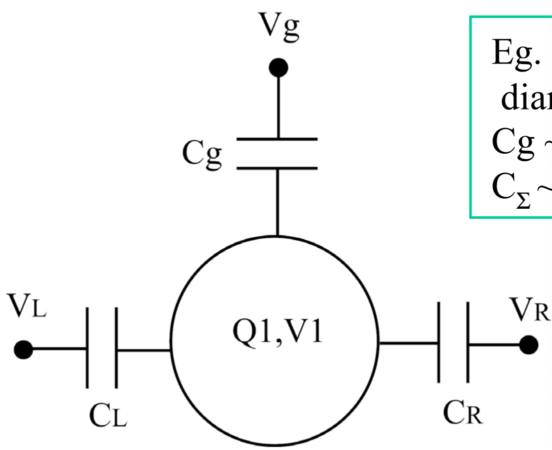




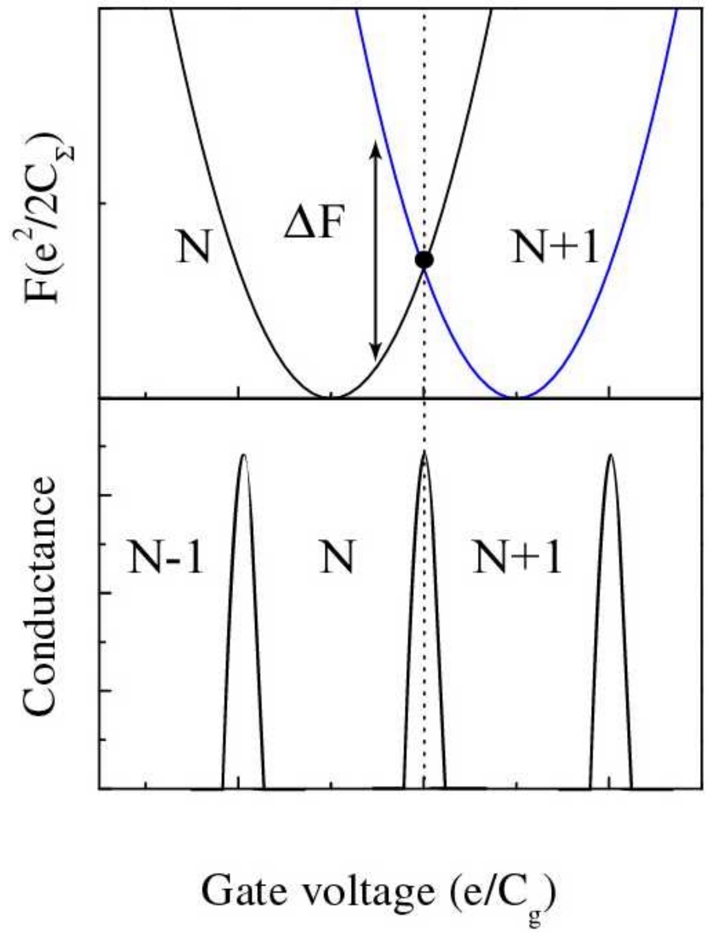


Single Electron Transistor – Charging effect

- Capacitive Charging Model



Eg.
diameter ~ 0.5-0.2μm
Cg ~100-10 aF
C_Σ ~2-0.9 fF



$$C_\Sigma = C_L + C_g + C_R \qquad Q_1 = -N|e|$$

$$\Rightarrow F(N_1) = \frac{[-N|e| + C_g V_g + C_L V_L + C_R V_R]^2}{2C_\Sigma}$$

$$For\ \ linear\ \ regime\ \ \mu_L - \mu_R = -|e|V \approx 0$$

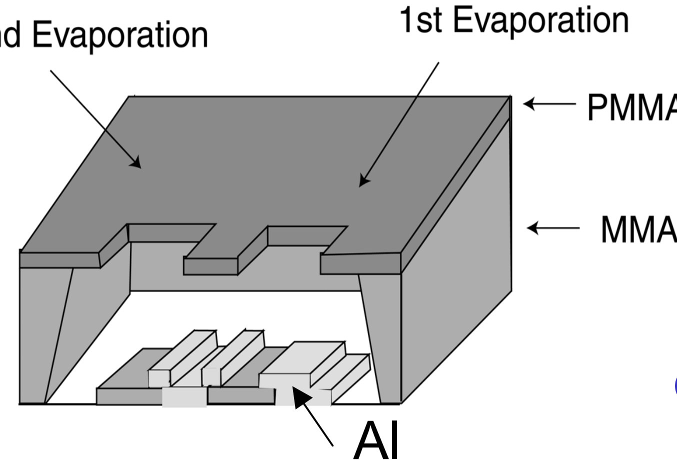
$$Given\ \ gate\ \ voltage,\ Energy\ \ barrier$$

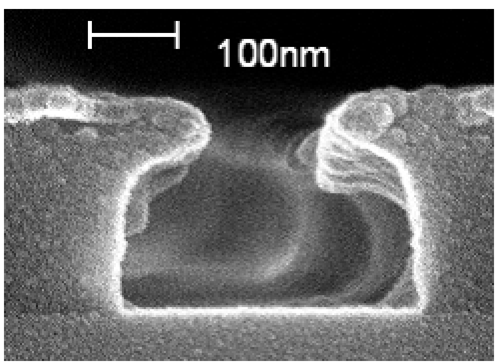
$$\Delta F = F_1(N+1) - F_1(N) = \frac{e^2}{C_\Sigma}\left(N + \frac{1}{2} - \frac{C_g V_g}{e}\right)$$

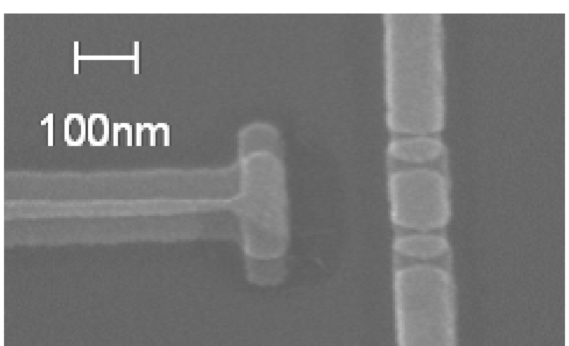
$$\Rightarrow Coulomb\ \ blockade$$

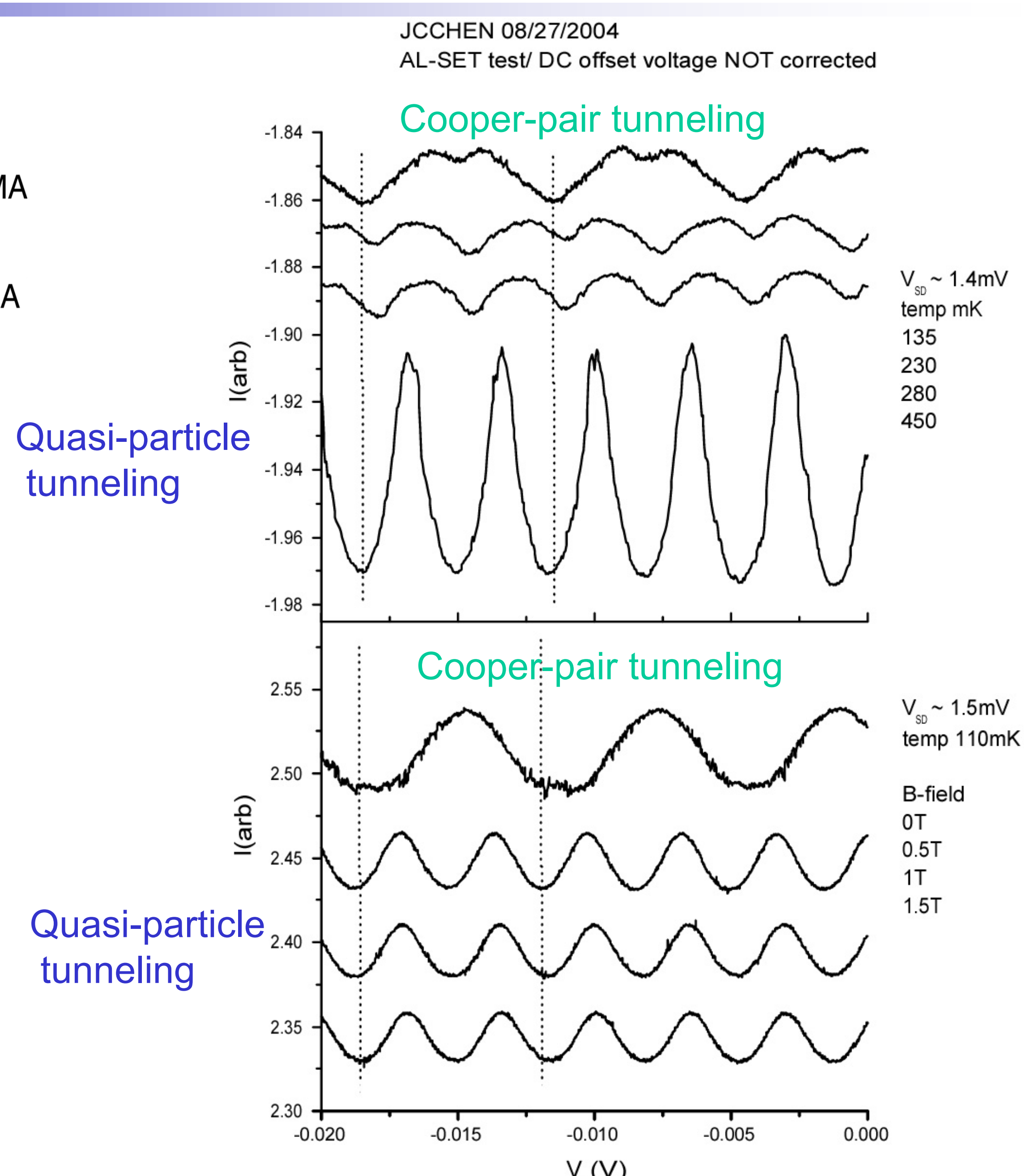
Al - Single Electron Transistor

Shadow Evaporation Technique

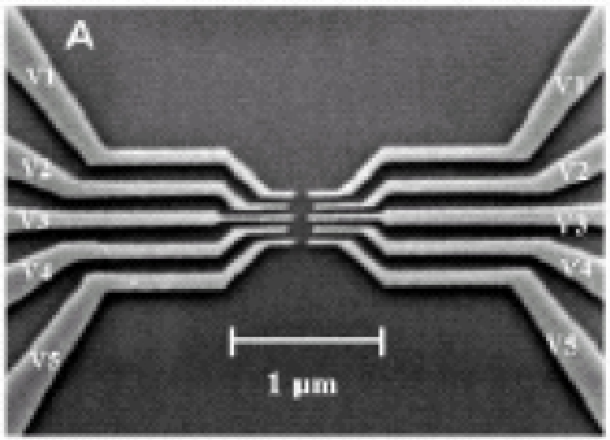


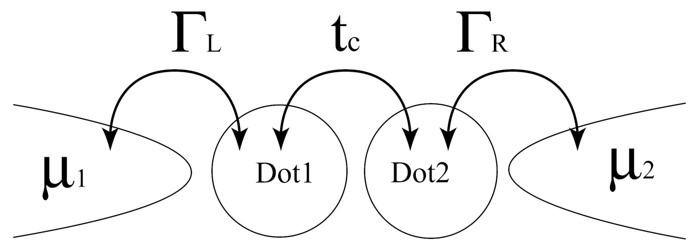






Double quantum dot – artificial molecular

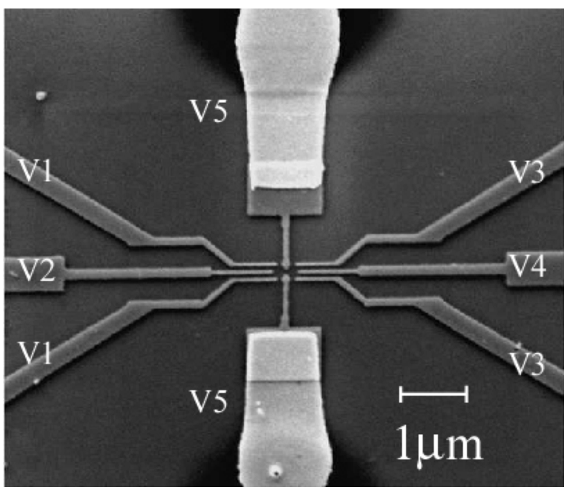


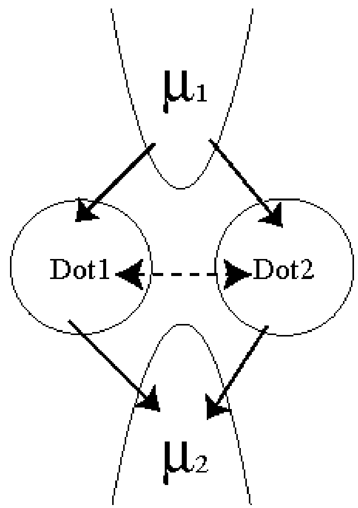


Coupling strength $J=4t_c^2/U_i$

U_i: intradot charging energy

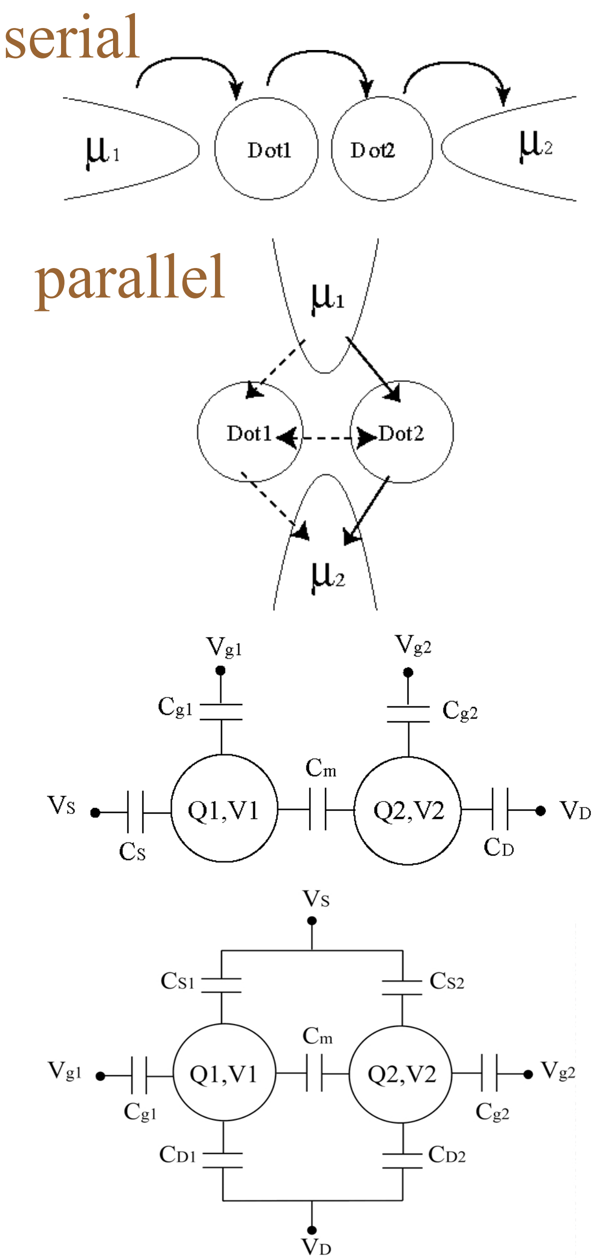
Γ: Lead-dot coupling



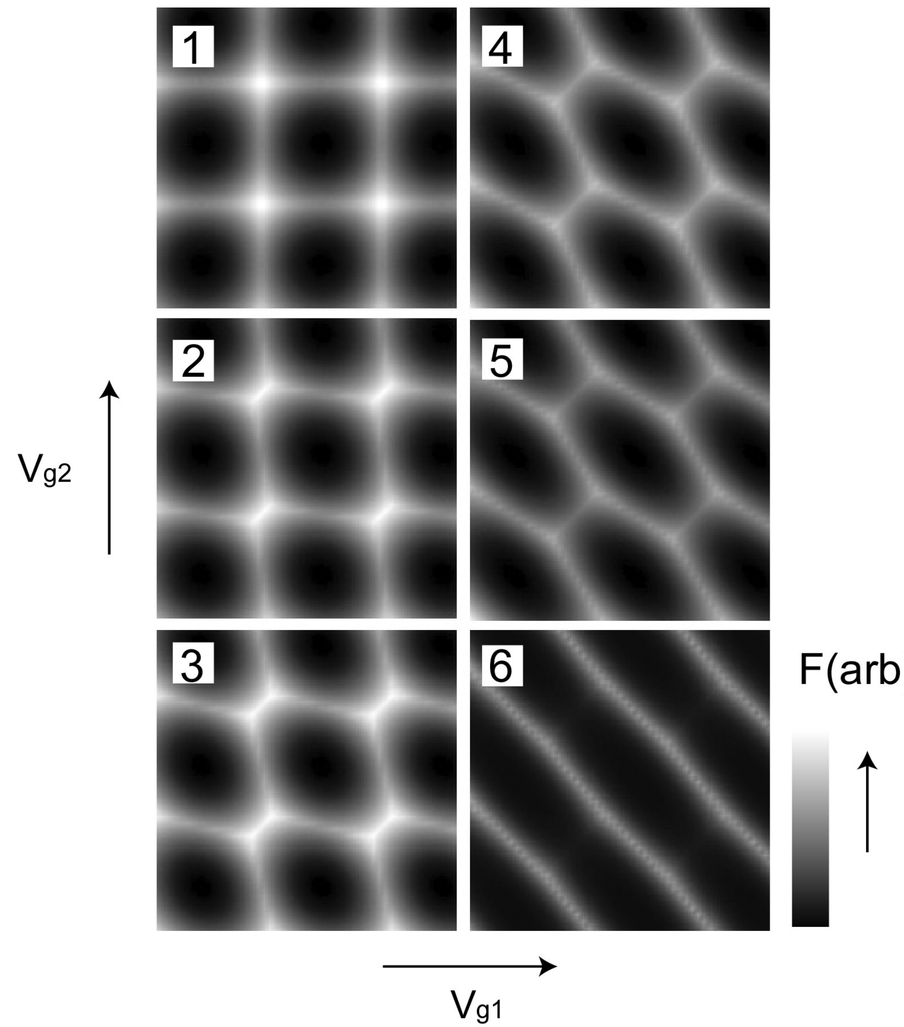


Advantage:
J and Γ can be tuned by the external gate voltages.
On-site Coulomb interaction can be externally adjustable

Coupled Double Quantum Dots

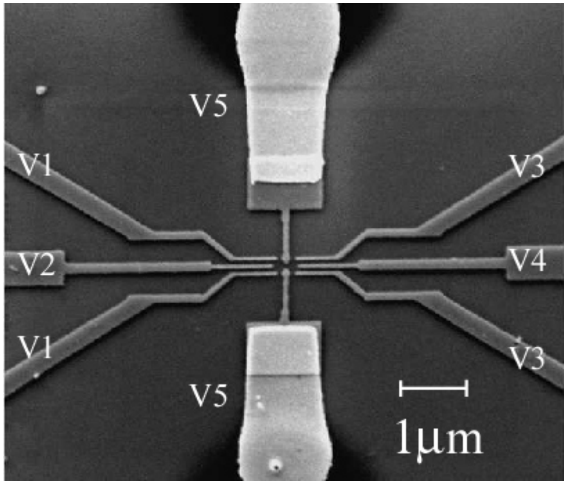


1. $C_m/C_\Sigma \sim 0$
   week coupling
2. $C_m/C_\Sigma \sim 0.13$
3. $C_m/C_\Sigma \sim 0.26$
4. $C_m/C_\Sigma \sim 0.5$
5. $C_m/C_\Sigma \sim 0.61$
6. $C_m/C_\Sigma \sim 0.88$
   strong coupling

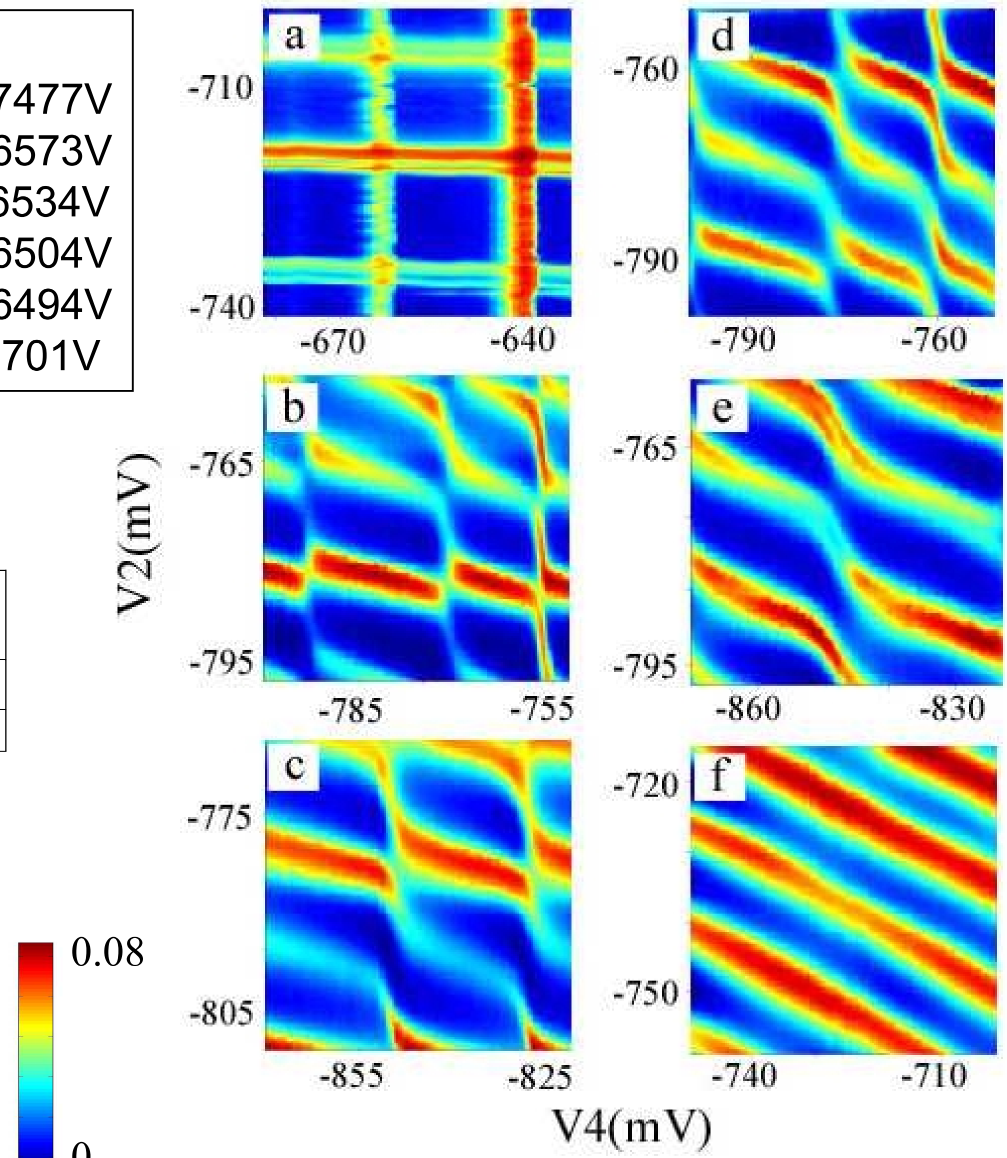


Ref. W.G. van der Wiel Rev. Modern Physics Vol 75, p.1 (2003)

Double quantum dot –Coulomb Blockade Spectrum



V5
a. -0.7477V
b. -0.6573V
c. -0.6534V
d. -0.6504V
e. -0.6494V
f. -0.5701V



Sample Characterization:

	C_Σ (af)	U (meV)	ΔE (μeV)	r_e (nm)	N (e#)
L-dot	63.6	2.517	219	70	58
R-dot	54.3	2.95	308	60	43

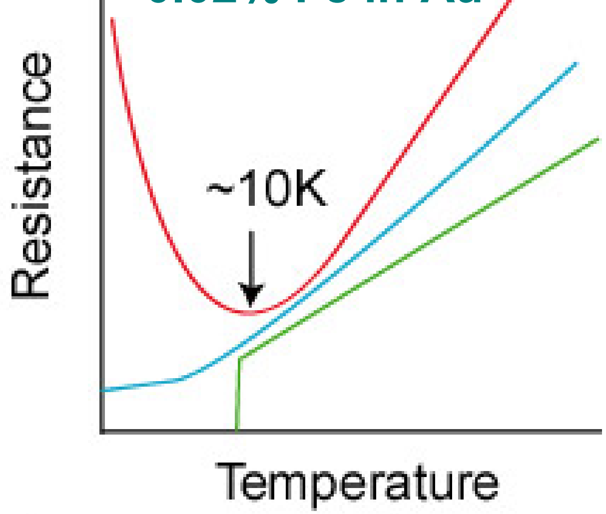
$$\alpha = \frac{U}{\Delta V_p e} = \frac{C_g}{C_\Sigma} = \frac{\Delta \mu_d}{\Delta V_g} \quad , C_g = \frac{e}{\Delta V_p}$$

$$C_\Sigma = 8\varepsilon_0 \varepsilon_r r_e \quad , N = n \times \pi r_e^2 \quad , \Delta E = \Delta V_S \alpha e$$

Quantum dot – Kondo effect

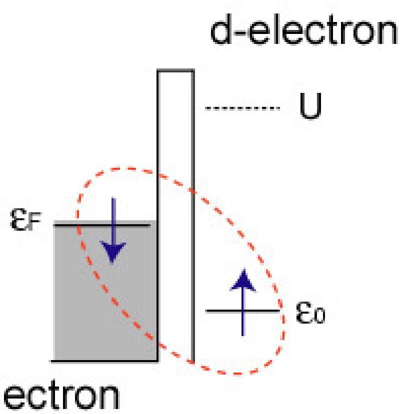
Kondo Physics:

0.02% Fe in Au



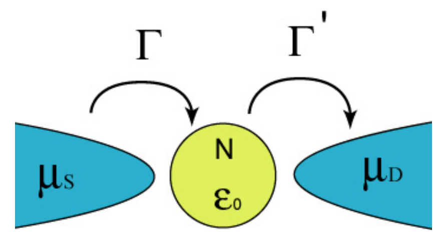
Green: superconductor
Blue: normal metal
Red: metal+ magnetic impurity

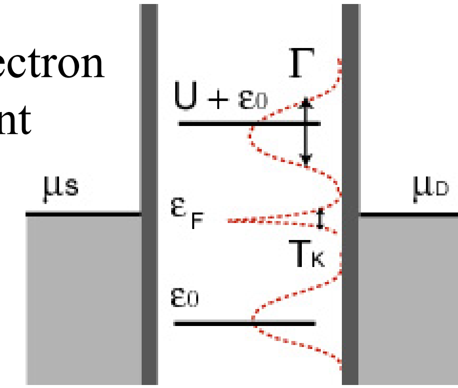
Jun Kondo 1964

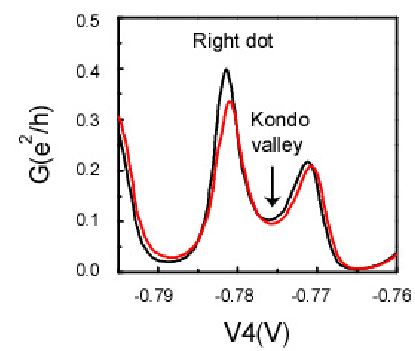


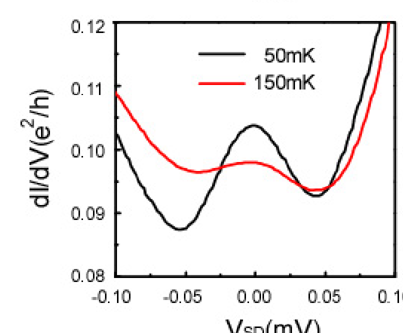
Quantum dot used to simulate Kondo effect

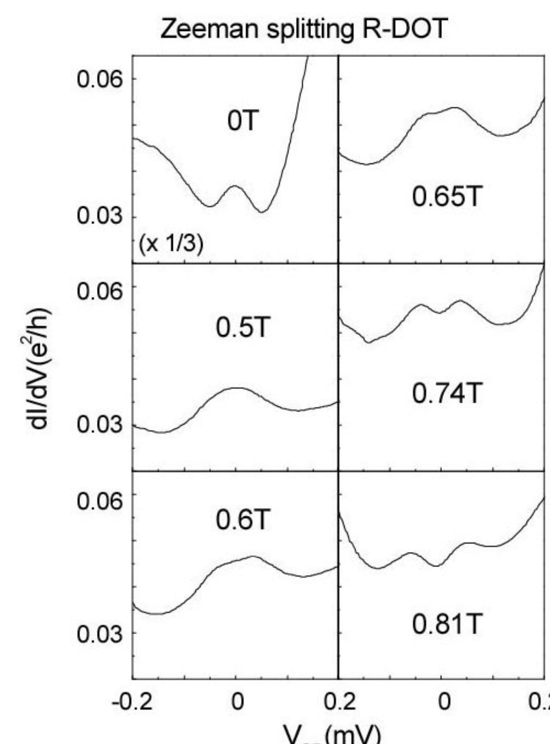
N=odd ⇒ unpaired electron
Local magnetic moment



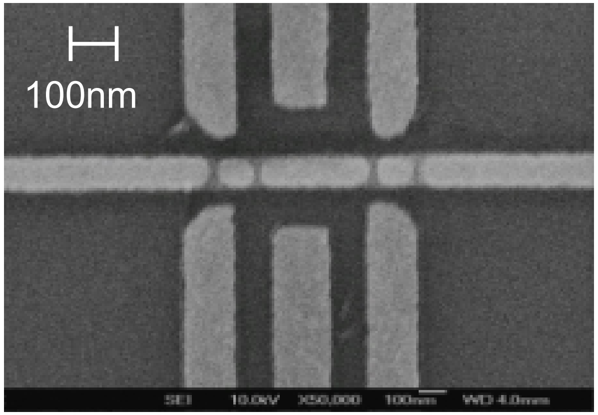


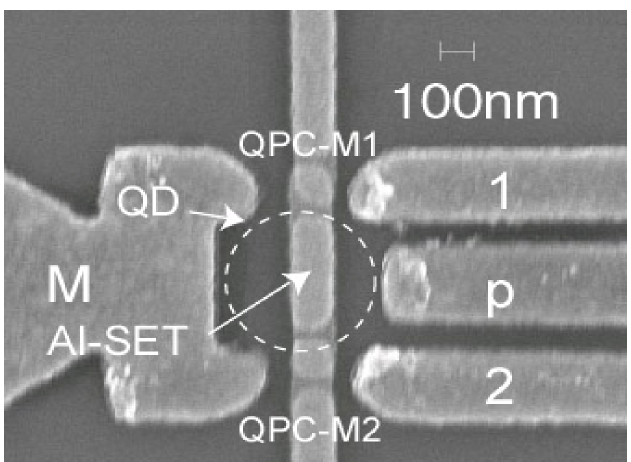






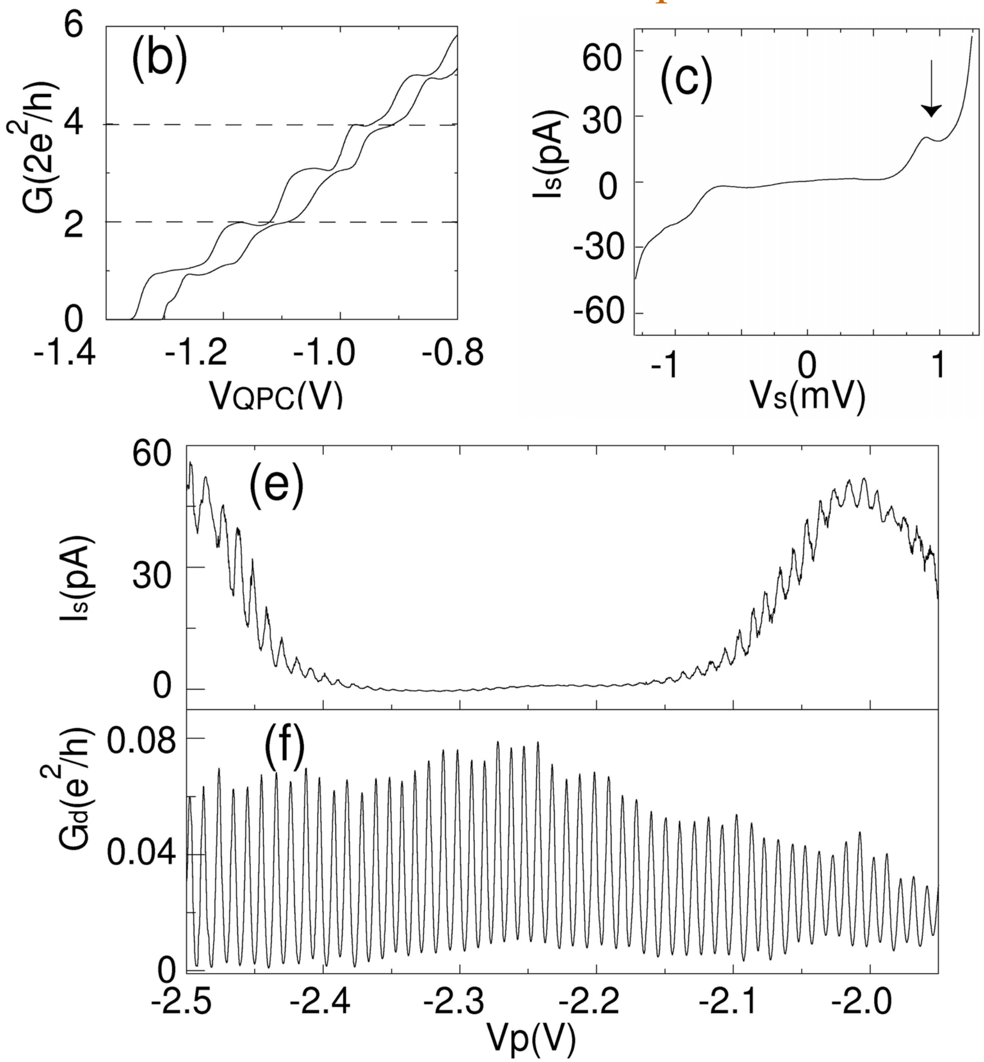
Hybrid QD+Al-SET



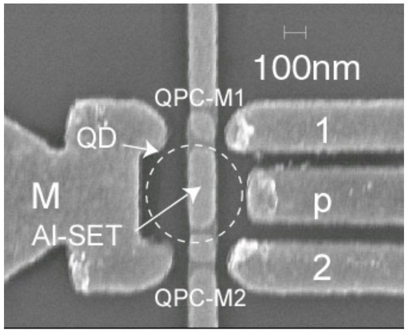


Al-SET is a very sensitive probe to detect the electronic environment nearby.

Temperature: 70-100mK



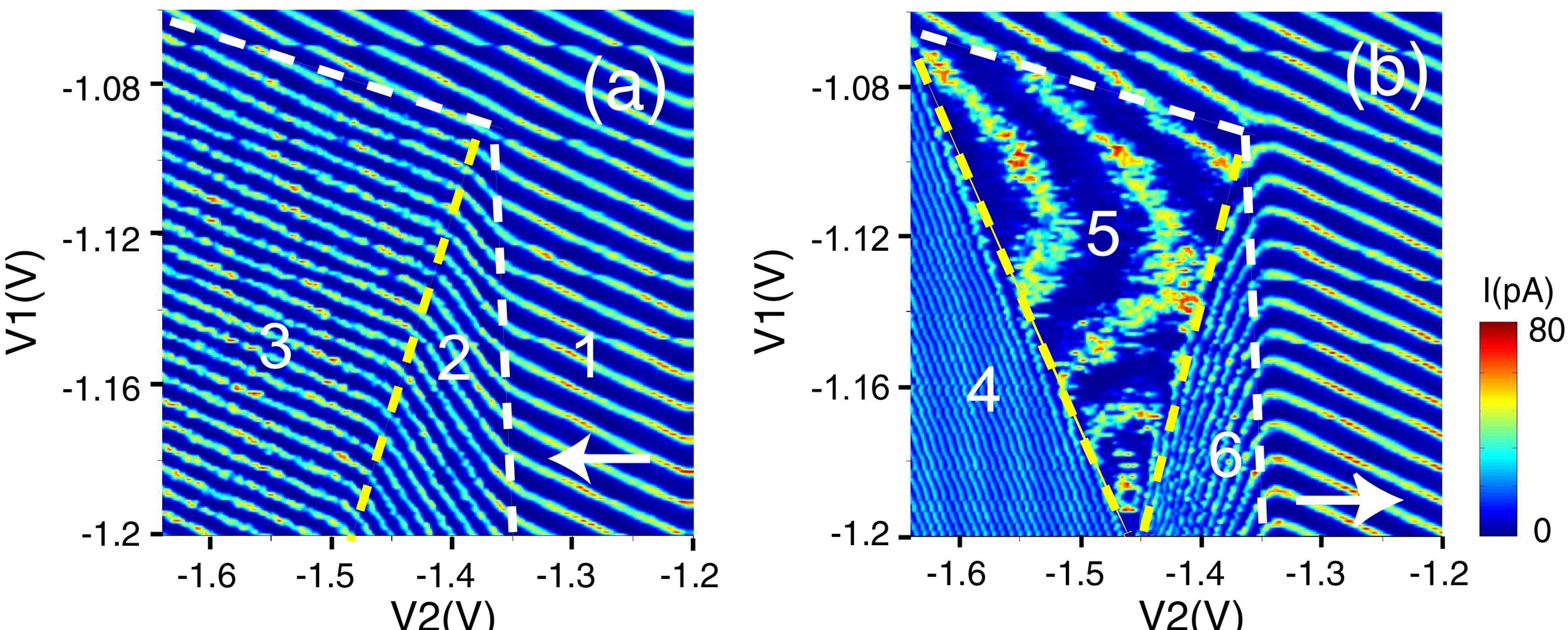
Meta-stable states of QD observed by Al-SET



Al-SET is a very sensitive probe to detect the electronic environment nearby.

$QD:$ source/drain grounded

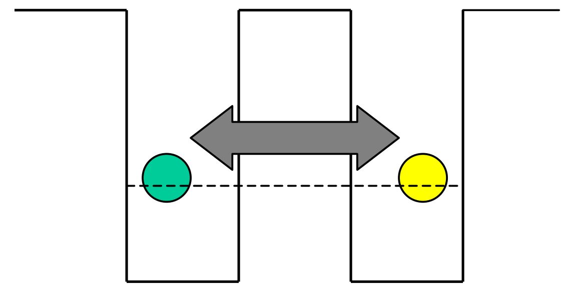
$$V^{SET}{}_{SD} = 800\mu V(DC) + 20\mu V(AC)$$



Classic to quantum transition

Classical memory bits become indistinguishable, which limits our ability to use them for computation.

However



The superposition of indistinguishable states is a key concept of quantum computation.

A quantum bit or qubit is a physical system with two quantum states.

Construct computation schemes and systems resembling operation of human brains

- Properties of human brain:
- Mass: ~1.5kg
- Volume:1.5l
- Energy consumption:~10W
- Information stored: 10^{14} bits
- 10^{13} bits/s

Summary

Message:

The goal of nano-electronic research

1. Short term: the inventions of new-type device and materials that extend CMOS technology.

2. Long term: the inventions of completely new information technology.