Scuola di Dottorato in Fisica Applicata “G. Galilei” - a.a. 2004/05

Topics in Nanotechnology – part 5

Version 1, May 2005

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Coulomb blockade and single electron devices

11/5/2005 – 16-18 – room S1

Outlook

• 0DEG (quantum dots) structures will be considered and *single electron* processes will be analyzed (transport inherently related to inter-dot tunneling)

•The simplest way to approach the single electron world: a nanosized capacitor

• *Continouos vs quantized* quantities: the “struggle” between adding a single electron to a nanosized capacitor and adjusting its potential

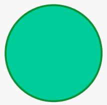
• Coulomb blockade effects, Culomb staircase and oscillations

• Three-terminal (active) devices: single electron transistor in conventional and alternative fashions

• Tunneling through a quantum dot (double barrier): resonant tunneling diodes

Nanosized conductors (an ideal case)

Capacitance of a nanosized conducor (e.g., a metal) sphere



$Q = C\,V$

$V = Q/4\pi\varepsilon_0 r$

$C = 4\pi\varepsilon_0 r$

$E = CV^2/2$

Es.: if r~10 nm, C ~ 1 aF
At V = 1V Q ~ 10^{-18} Coulomb
That is N ~ 6 e !!!

The discrete nature of electric charge dominates the behavor of nanosizd capacitors

In systems of very small conductors, the capacitances approach values sufficiently small that the charging energy given by (4.47) due to a single electron, $e^2/2C$, becomes comparable to the thermal energy, $k_B T_l$. The transfer of a single electron between conductors therefore results in a voltage change that is significant compared to the thermal voltage fluctuations and creates an energy barrier to the further transfer of electrons. This barrier remains until the charging energy is overcome by sufficient bias. How small must such a structure be? A simple example is the case of a conducting sphere above a grounded conducting plane. This example approximates a metal cluster imbedded in an insulator above a conducting substrate, which is a commonly realized structure that has been extensively studied experimentally. The exact solution may be found using the method of images, which gives the capacitance of the sphere as [33]

$$C = 4\pi\epsilon a\left(1 + \alpha + \frac{\alpha^2}{1-\alpha^2} + \cdots\right), \quad \alpha = \frac{a}{2l}, \tag{4.50}$$

where a is the radius of the sphere and l is the distance above the conducting substrate. As the radius of the sphere becomes small compared to l, the capacitance becomes independent of the distance of the cluster from the substrate. An alternate example is that of a flat circular disk located parallel to and a distance d above a ground plane. This example is more closely analogous to the semiconductor quantum dots fabricated by lateral confinement of a 2DEG as discussed in the previous sections. The solution is given in a problem in Jackson's textbook [34] (which we leave as an exercise for the reader!), with the capacitance given in the limit of $d \gg R$ as

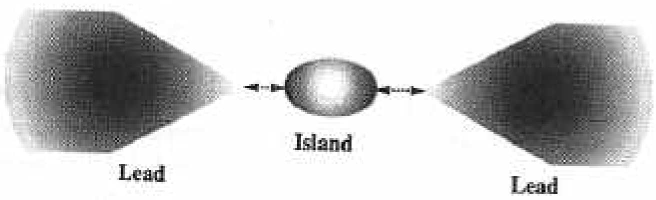
$$C = 8\epsilon R \tag{4.51}$$

where R is the radius of the disk. Equating the charging energy with the thermal energy, we see that at room temperature, $C \sim 3 \times 10^{-18}$ F. The corresponding radius for a sphere from (4.50) is on the order of $a \sim 28$ nm (assuming a relative dielectric constant of 1), and somewhat larger for the disk. The facts that $\epsilon > \epsilon_o$ in real structures and that the charging energy should be several times larger than the thermal energy imply that sub-10-nm structures need to be fabricated in order to see clear single-electron charging effects at room temperature. Although it is still somewhat challenging with today's lithographic techniques to nanoengineer such structures, it is not difficult to grow insulating films with random metallic clusters on this order in which Coulomb blockade effects are readily observed, even at room temperature. Further, if we perform measurements at cryogenic temperatures, then the size scale becomes comparably larger, allowing single-electron effects to be observed in nanofabricated quantum dot structures.

Accurate capacitance evaluation for realistic cases

After Ferry and Goodnick,
Transport in nanostructures,
Cambridge (1997)

Tunneling rules the behavior of the system



Tunneling inherently involved when "charging" the capacitor

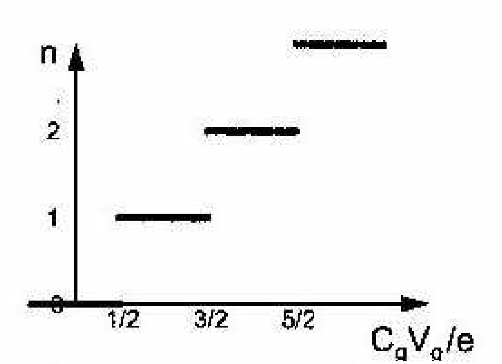


Figure 2: Electron number versus gate voltage characteristics of single-electron box. The number of electron in the quantum dot increases one by one as the gate voltage increases.

$$Q = CV \tag{4.46}$$

where C is the capacitance, Q is the charge on the conductor, and V the electrostatic potential relative to some chosen reference (e.g., ground). Since we are considering an ideal conductor, any charge added to the conductor rearranges itself such that the electric field inside vanishes, and the surface of the conductor becomes an equipotential surface. Therefore, the electrostatic potential associated with the conductor relative to its reference is uniquely defined. If we consider two conductors connected by a d.c. voltage source, a voltage $+Q$ builds up on one conductor and a charge $-Q$ on the other. The capacitance of the two conductor system is then defined as $C = Q/V_{12}$. The electrostatic energy stored in the two conductor system is the work done in building up the charge Q on the two conductors and is given by

$$E = \frac{Q^2}{2C}. \tag{4.47}$$

Electrostatic energy

For a system of N conductors, the charge on conductor i may be written

$$Q_i = \sum_{j=1}^{N} C_{ij} V_j, \tag{4.48}$$

where the diagonal values C_{ii} are the capacitance of conductor i if all other conductors are grounded. The diagonal elements are commonly referred to as the *coefficients of capacitance*; the off-diagonal elements are called the *coefficients of induction*. The total electrostatic energy stored in a multiconductor system is given by the generalization of Eq. (4.47) as

$$E = \frac{1}{2} \sum_i \sum_j (C^{-1})_{ij} Q_i Q_j, \tag{4.49}$$

It is important to note that the polarization charge on the capacitor, Q, does not have to be associated with a *discrete* number of electrons, N. This charge is essentially due to a rearrangement of the electron gas with respect to the positive background of ions, and as such it may take on a continuous range of values. It is only when we consider changes in this charge due to the tunneling of a single electron between the conductors that the discrete nature becomes apparent.

Discrete (charge) vs continuous (voltage)

Conditions to observe "quantized effects"

Basic Operation of Single-Electron Box

As the size of the quantum dot decreases, the charging energy W_c of a single exce charge on the dot increases. If the quantum-dot size is sufficiently small and the char ing energy W_c is much greater than thermal energy $k_B T$, no electron tunnels to and fro the quantum dot. Thus, the electron number in the dot takes a fixed value, say zer when both the electrodes are grounded. The charging effect, which blocks the inje tion/ejection of a single charge into/from a quantum dot, is called Coulomb blockac effect. Therefore, the condition for observing Coulomb blockade effects is expressed a

$$W_c = \frac{e^2}{2C} \gg k_B T \; , \qquad ($$

where C is the capacitance of the quantum dot and T is the temperature of the system.

Temperature-related energy fluctuations must be negligible (low T operation!!)

However, it should be noted that by applying a positive bias to the gate electrode w could attract an electron to the quantum dot. The increase of the gate voltage attracts a electron more strongly to the quantum dot. When the gate bias exceeds a certain value a electron finally enters the quantum dot and the electron number of the dot becomes on Further increase of the gate voltage makes it possible to make the electron number tw Thus, in the single-electron box, the electron number of the quantum dot is controlle one by one, by utilizing the gate electrode (Figure 2).

Specific conditions must be fulfilled to realize experimentally the quantum-driven phenomenon

Conditions for Observing Single-Electron Tunneling Phenomena

In order to observe single-electron tunneling phenomena, or Coulomb blockade effect there are two necessary conditions. One condition is, as described above, that the char ing energy of a single excess electron on a quantum dot is much greater than the therm energy (Eq. (1)). The other condition is that the tunneling resistance R_t of the tunnelir junction must be larger than resistance quantum h/e^2. This condition is required to su press the quantum fluctuations in the electron number, n, of the dot so that they are suffi ciently small for the charge to be well localized on the quantum dot. The condition obtained by keeping uncertainty principle $\Delta W \Delta t > h$ while letting ΔW be the chargin energy of the quantum dot, $\sim e^2/C$, and Δt be the lifetime of the charging, $R_t C$. Then, th uncertainty principle reduces to

$$\Delta W \cdot \Delta t \sim \frac{e^2}{C} \cdot R_t C = e^2 R_t > h \; . \qquad ($$

As a result, one obtains the condition for the tunneling resistance R_t in order to obser the Coulomb blockade effects

$$R_t \gg \frac{h}{e^2} = 25.8 \text{ k}\Omega . \qquad ($$

Tunneling resistance must be large enough *(weak coupling)*

Da R. Waser Ed., Nanoelectronics and information technology (Wiley-VCH, 2003)

Semiconductor quantum dots

4.2 Single electron tunneling and Coulomb blockade

4.2.1 Introduction to Coulomb blockade and experimental studies

In Section 4.1 we discussed the electronic states of essentially isolated quantum dot and quantum box structures. The addition of an electron to the many-particle system resulted in a renormalization of the states due to the electron-electron interaction. However, we did not consider the effect on the surrounding environment of adding this electron to the dot. When we discuss transport *through* quantum dots, we are implicitly considering the coupling to this external environment, which provides the sources and sinks for electrons into and out of the dot (see Fig. 4.10). The quantum dot (also referred to as an "island") is isolated from the surroundings except for tunneling between the leads and the island. In a split-gate semiconductor quantum dot such as Figs. 2.15 and 2.17, the tunneling junction between the dot and the leads consist of point contact structures biased below the pinch-off for 1D conduction (see Section 3.6). In metal tunnel junctions, the metallic island is surrounded by an insulator such as an oxide, through which electrons tunnel to and from the metal electrodes. The principal difference in the analysis of metal islands versus semiconductor islands is in the relative number of electrons and the effects of quantum confinement on the allowed energy states. As we saw in the previous section, quantum confinement effects in semiconductor quantum dots may be quite large, leading to structures that justifiably may be considered artificial atoms consisting of just a few particles. Metallic systems, on the other hand, have much larger electron densities, and mean free paths at the Fermi energy of only a few nanometers. Therefore, metallic islands behave more or less as small bulk-like systems. However, both systems share a common feature, that the discrete nature of the electron charge becomes strongly evident when particles tunnel into and out of the structure shown in Fig. 4.10.

The nanosized "capacitor" may be considered as a quantum dot

Conductive or semiconductive does not make large difference in terms of charge quantization effects

But with semiconductors energy quantization (quantum box) and artificial atom issues become important

Quantized energy level for a 0DEG structure (quantum box) must be taken into account

238 QUANTUM WELLS, WIRES, AND DOTS

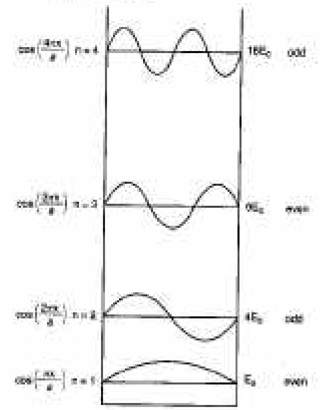


Figure 9.11. Sketch of wavefunctions for the four lowest energy levels ($n = 1$–4) of the one-dimensional infinite square well. For each level the form of the wavefunction is given on the left, and its parity (even or odd) is indicated on the right. (From C. P. Poole, Jr., Handbook of Physics, Wiley, New York, 1998, p. 280.)

See R. Compaño et al.
MEL-ARI EC Project
Technol. Rodmap 1999

Coulomb blockade (Cb) and SE tunneling

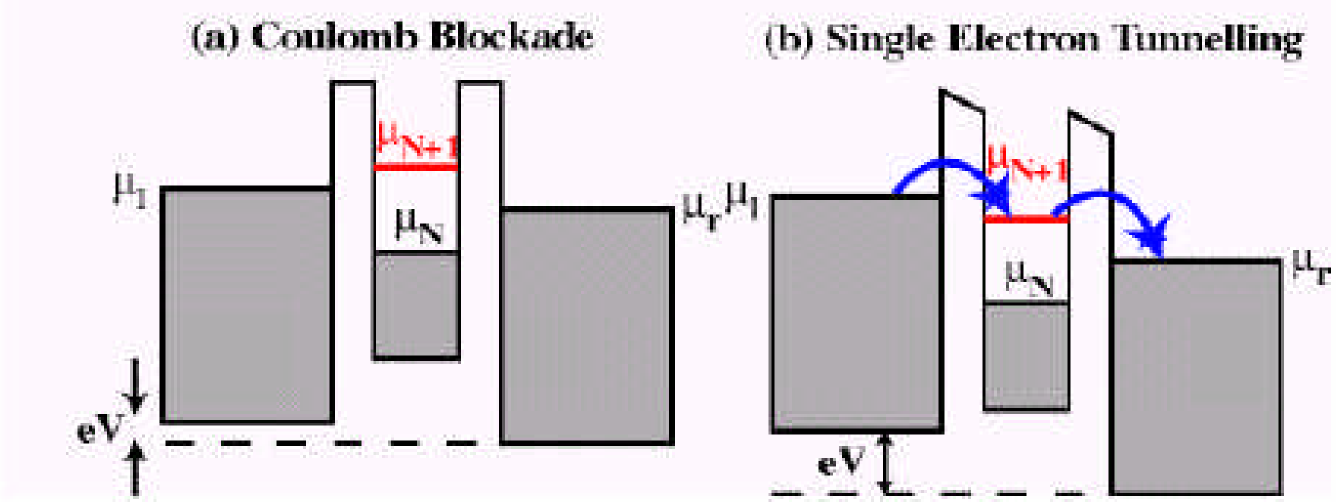


Figure 2.2:- For an island of total capactiance C with N electrons,being μ_N the chemical potential of the highest filled electron state, μ_{N+1} the chemical potential of the first available empty state for an electron and μ_l and μ_r the chemical potentials of the left and right electrodes respectively, it may be shown that the energy to add an electron to the island is μ_{N+1}-μ = e^2/C. Therefore provided $e^2/C \gg k_BT$ (the thermal energy - i.e. C is small) and the tunnelling resistance, $R_T \gg R_K$ =25.8kΩ (i.e. the electron wavefunction may be localised on the island) for a voltage V applied across the electrodes, no electrons may flow if $\mu_{N+1} > \mu_l$ and μ_r - the state known as Coulomb blockade (a). If a larger bias is applied across the electrodes such that $\mu_l > \mu_{N+1} > \mu_r$ then empty states may be populated in the island and single electrons may tunnel through the island (b). A gate may be used to change the Fermi level of the island and therefore switch the single electron current on or off.

In quantum mech. terms:

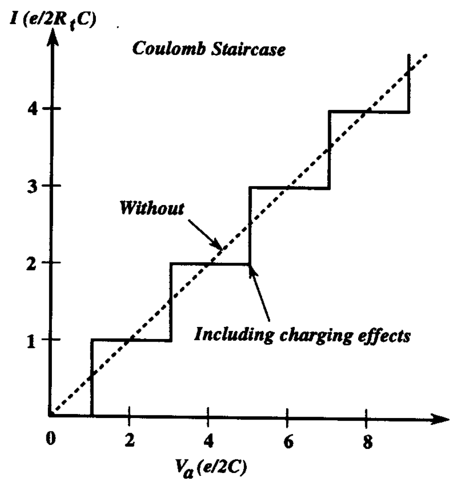
double barrier resonant tunneling

Coulomb blockade: an additional electron is accepted by the dot only if the voltage is raised above some limit

Coulomb oscillations and staircase

Da G. Timp, Nanotechnology (Springer-Verlag, 1999)

After Ferry and Goodnick, Transport in nanostructures, Cambridge (1997)



g. 4.15. Ideal current-voltage characteristics for an asymmetric double junction system with and thout consideration of Coulomb charging effects. For this system, $C_1 = C_2 = C$ and $R_t = R_{t1} \gg$ 2

(Discrete) charge effects inhibit continuous charging of the capacitor, i.e., tunneling transport of electrons through the dot

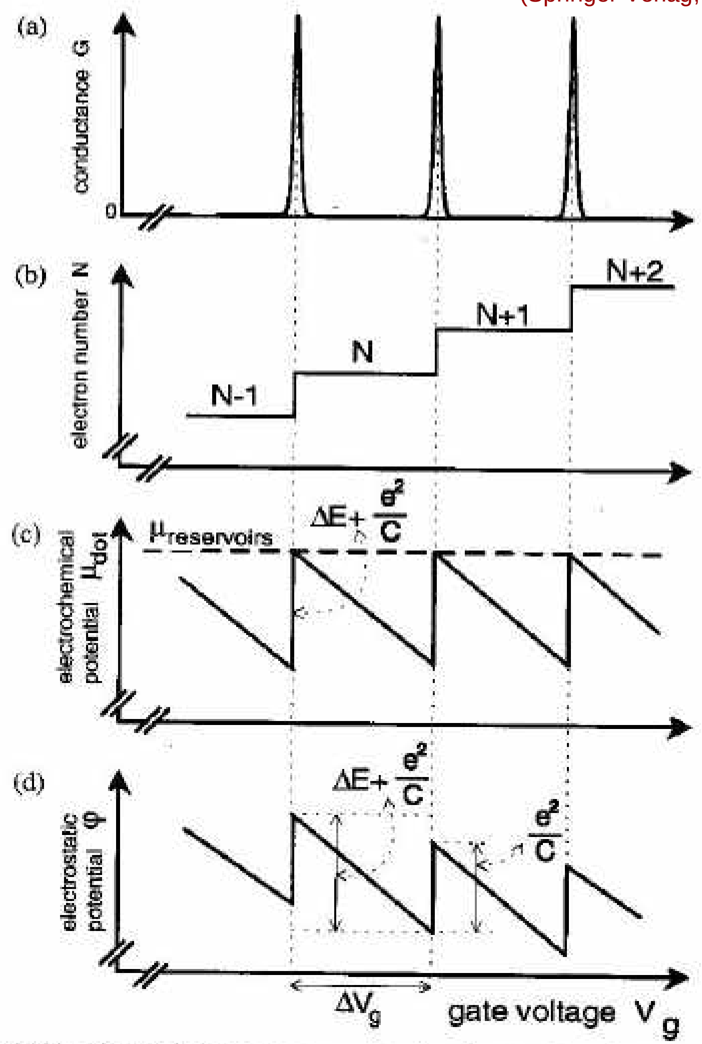


FIGURE 6. Schematic comparison, as a function of gate voltage, between (a) the Coulomb oscillations in the conductance G, (b) the number of electrons in the dot $(N+i)$, (c) the electrochemical potential in the dot, $\mu_{dot}(N+i)$, and (d) the electrostatic potential ϕ.

Examples of measurements

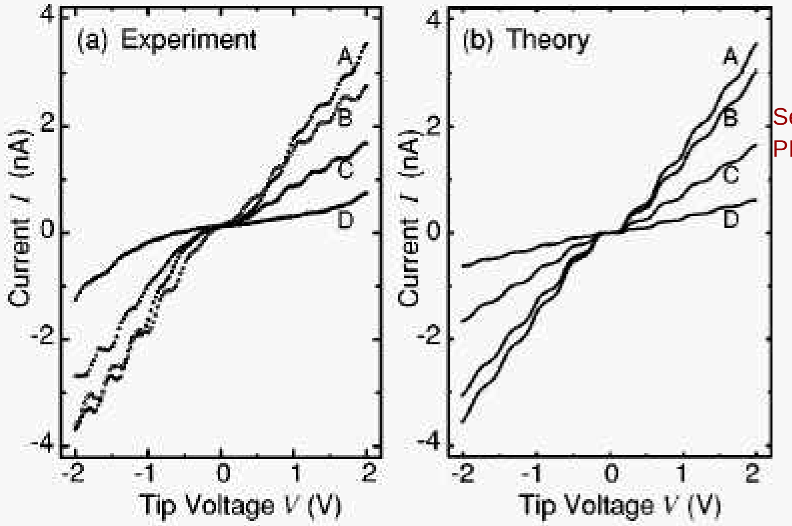
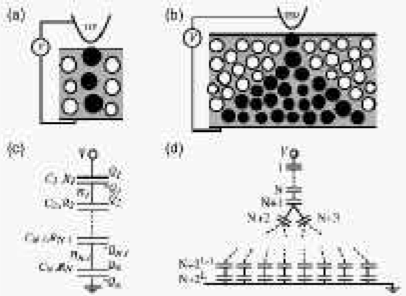


FIG. 3. (a) Experimental I-V curves for a 10-nm-thick $Co_{36}Al_{22}O_{42}$ at room temperature. A, B, C, and D refer to different distances between the STM tip from the surface of the sample. The lateral position for A and B is different from that for C and D. (b) Corresponding theoretical curves in a triple tunnel junction system at $T=300$ K. The tunnel resistance at the bottleneck is taken to be $R_1=600$, 700, 1300, and 3500 MΩ for lines A, B, C, and D, respectively. The other tunnel resistances are $R_2=R_3=1$ MΩ and the capacitances are $C_1=4.48\times10^{-19}$ F, $C_2=2.13\times10^{-19}$ F, and $C_3=3.62\times10^{-19}$ F for all curves.

See Imamura et al. PRB 61 46 (2000)



STM measurements
room-temperature
granular metal films
(ø 1-10 nm)

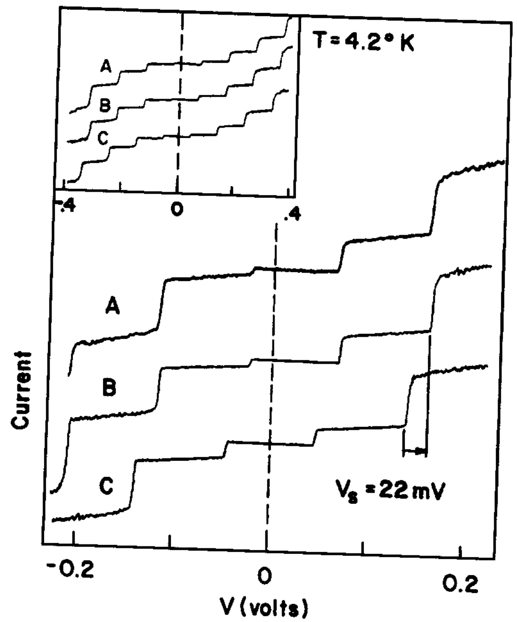
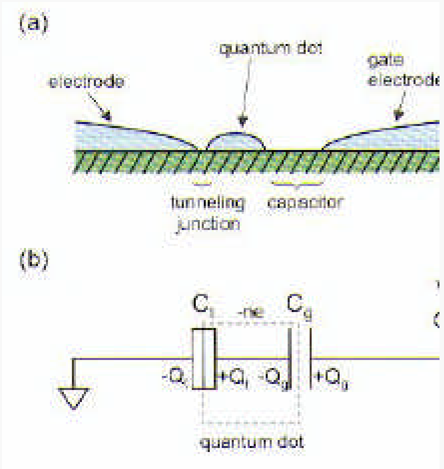


Fig. 4.12. Experimental (A) and theoretical (B and C) I-V characteristics from an STM-contacted 10 nm diameter In droplet illustrating the Coulomb staircase in a double junction system. The peak-to-peak current is 1.8 nA. The curves are offset from one another along the current axis, with the intercept corresponding to zero current. [After Wilkins *et al.*, Phys. Rev. Lett. **63**, 801 (1989), by permission.]

STM used to make a point-like tunneling with nanosized dots

Single Electron Transistor (SET)



Bias Conditions for Coulomb Blockade Effects

The voltage range, which keeps the electron number at n in the dot, is extracted by co sidering the free energy of the system. The free energy of the system having n electro in the island $F(n)$ is expressed as

$$F(n) = W_c(n) - A(n) \ , \qquad (\text{}$$

where $W_c(n)$ is the charging energy and $A(n)$ is the work done by the voltage source co nected to the gate electrode in order to make the electron number be from zero to n.

It is important to note that when tunneling phenomena do not occur the tunneli junction behaves as a normal capacitor and that the polarization charge on the capacit does not have to be associated with a discrete number of electrons, n. This polarizati charge is essentially due to a rearrangement of the electron gas with respect to the positive background of ions. Therefore, the polarization charge takes a continuous range of value, although the number of electrons in the quantum dot takes a discrete number of electrons, n. The polarization charges on the tunneling junction and gate capacitor are obtained from the following relationship.

$$Q_t - Q_g = -ne \ , \qquad \frac{Q_t}{C_t} + \frac{Q_g}{C_g} = V_g \ , \qquad (5)$$

where Q_t and Q_g are the polarization charge on the tunneling junction and the gate capacitor, respectively. By using Q_t and Q_g, the charging energy $W_c(n)$ of the quantum dot is expressed as,

$$W_c(n) = \frac{Q_t^2}{2C_t} + \frac{Q_g^2}{2C_g} \ , \qquad (6)$$

which reduces to

$$W_c(n) = \frac{e^2 n^2}{2C_\Sigma} + \frac{1}{2}\frac{C_t C_g V_g^2}{C_\Sigma} \ , \qquad (7)$$

where $C_\Sigma = C_t + C_g$. In addition, the work, $A(n)$, done by the gate voltage source in order to make electron number of the quantum dot be from zero to n is expressed as,

$$A(n) = \int I(t) \cdot V_g dt = Q_g V_g = en\frac{C_g}{C_\Sigma}V_g + \frac{C_t C_g V_g^2}{C_\Sigma} \ . \qquad (8)$$

In order to maintain the electron number in the quantum dot, the following conditions are required.

$$F(n) < F(n \pm 1) \qquad (9)$$

From Eqs.(7) to (9), the voltage range, within which Coulomb blockade effects are in effect and the electron number of the dot takes a fixed value of n, can be obtained as follows.

$$\left(n - \frac{1}{2}\right)\frac{e}{C_g} < V_g < \left(n + \frac{1}{2}\right)\frac{e}{C_g} \qquad (10)$$

This condition is also expressed with critical charge Q_c as follows.

$$|Q| < Q_c \ , \qquad (11)$$

where Q_c is expressed as,

$$Q_c = \frac{e}{2}\left(1 + \frac{C_g}{C_t}\right)^{-1} \ . \qquad (12)$$

Free energy change $\Delta F(n, n+1)$ that accompanies a transition of the electron number from n to $n + 1$ is also simply expressed with critical charges Q_c as,

$$\Delta F(n, n+1) = F(n+1) - F(n) = \frac{e}{C_t}(Q_t - Q_c) \ . \qquad (13)$$

SET operation (in electronic terms)

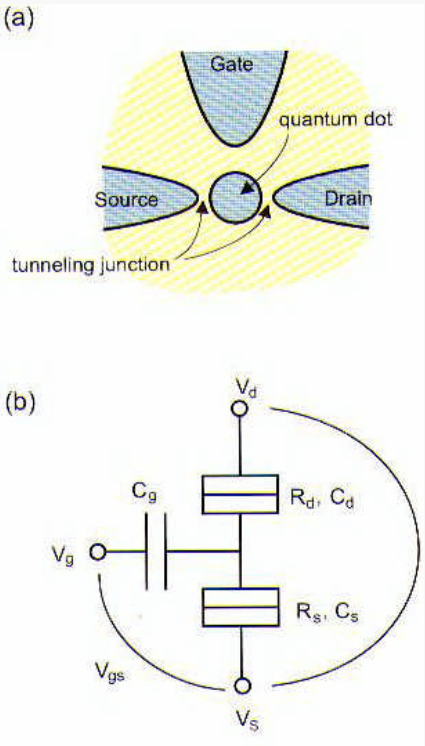


Figure 3:
(a) Schematic structure of single-electron transistor.
(b) Equivalent circuit of single-electron transistor.

Operation of Single-Electron Transistors

The operation of single-electron transistors can be described by using Thévenin's theorem and applying derived Eqs. (10) - (12) for a single-electron box.

By using the Thévenin's theorem, the circuit connected to the tunneling junction of the source is transformed to the circuit shown in Figure 4a. From this equivalent circuit and Eq. (10), the condition to maintain the electron number at n in the dot is expressed as

$$\left(n-\frac{1}{2}\right)\frac{e}{C_g+C_d}<\frac{C_gV_g+C_dV_d}{C_g+C_d}<\left(n+\frac{1}{2}\right)\frac{e}{C_g+C_d}, \tag{14}$$

which reduces to

$$\frac{1}{C_d}\left(ne-\frac{e}{2}-C_gV_g\right)<V_d<\frac{1}{C_d}\left(ne+\frac{e}{2}-C_gV_g\right). \tag{15}$$

In the same manner, the circuit connected to the tunneling junction of the drain is transformed to the circuit shown in Figure 4b and the condition to maintain the electron number at n in the dot is expressed as

$$\frac{1}{C_s+C_g}\left(-ne+\frac{e}{2}+C_gV_g\right)>V_d>\frac{1}{C_s+C_g}\left(-ne-\frac{e}{2}+C_gV_g\right) \tag{16}$$

Figure 5a shows the relationship between the drain voltage V_d and the gate voltage V_g, which satisfies the conditions expressed by Eqs. (15) and (16). The gray areas shown in Figure 5a are Coulomb blockade regions, where the Coulomb blockade is effective and the electron number in the dot takes a fixed value indicated in the areas.

On the other hand, in other regions, the quantum dot can take at least two electron numbers. In the green regions shown in Figure 5a the quantum dot can take two electron numbers. For example, in the green region indicated by A, the electron number in the dot is zero or one. More precisely, the electron number of one is preferable for the tunneling junction of the source and the electron number of zero is preferable for the tunneling junction of the drain. Therefore, when a finite positive source-to-drain voltage V_{ds}, indicated by dashed line in Figure 5a, is applied between the source and drain electrodes and the gate voltage is $e/2C_g$, an electron transport process described below is observable. The initial electron number of the dot is assumed to be zero. For the tunneling junction of the source, the electron number of one is preferable so that an electron tunnels from the source to the dot and the electron number in the dot becomes one. However, for the tunneling junction of the drain, the electron number of zero is preferable so that an electron tunnels from the dot to the drain and the electron number in the dot becomes zero. As a result, an electron tunnels from the source to the drain, and source-to-drain current is observable at these bias conditions.

In the same manner, at the gate voltage of $ne/C_g + e/2C_g$, the source-to-drain current I_{ds} is observed, and thus oscillating I_{ds} versus V_g characteristics shown in Figure 5b is observed in single-electron transistors. The oscillating I_{ds} - V_g characteristics are called Coulomb oscillations.

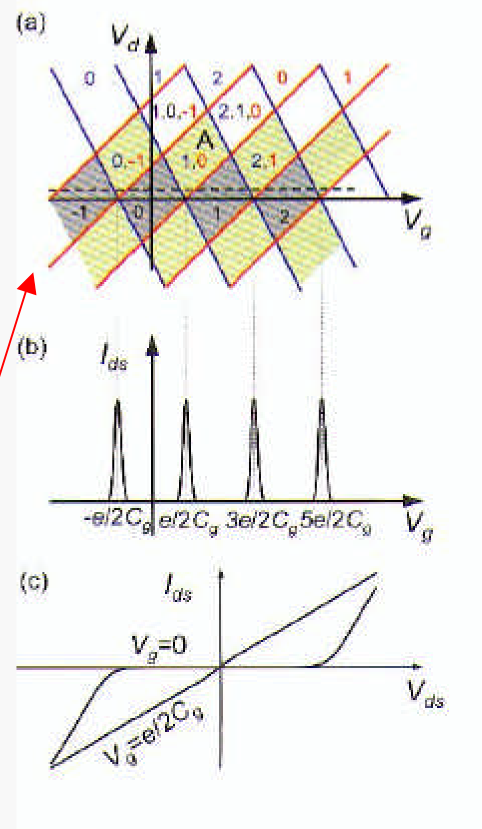
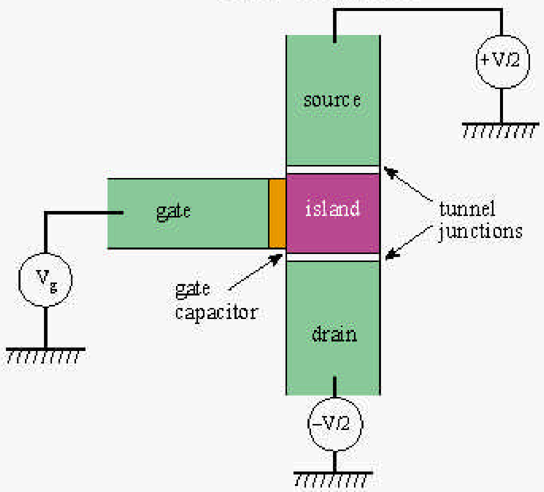
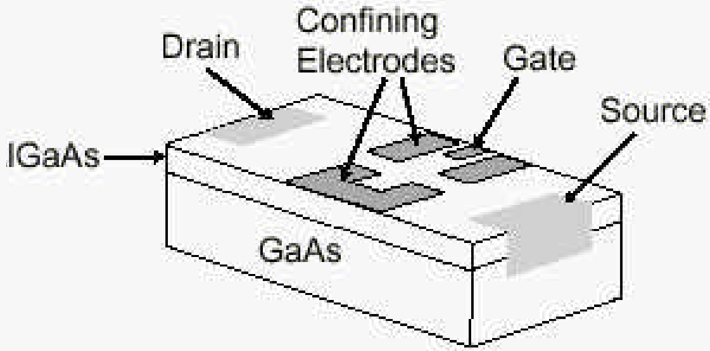


Figure 5:
(a) Relationship between the drain voltage V_d and the gate voltage V_g, satisfying the conditions expressed by Eqs. (15) and (16). The diamond-shaped structure along the x-axis is called Coulomb diamond.
(b) source-to-drain current I_{ds} versus gate voltage V_g characteristics of single-electron transistors.
(c) I_{ds} versus V_{ds} characteristics of single-electron transistors.

A gate is added to change the voltage, i.e., to control the tunneling through the dot

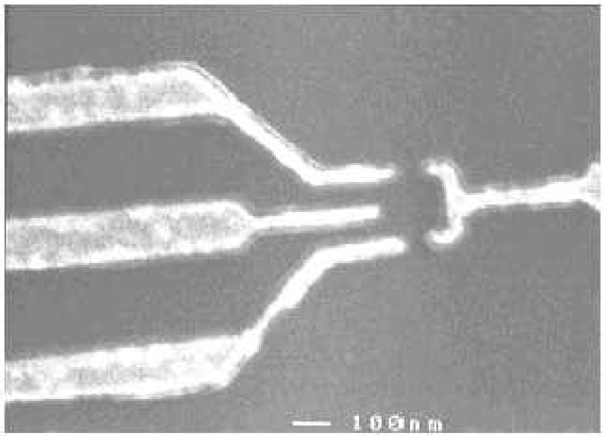
A SET made with conventional nanotechnology





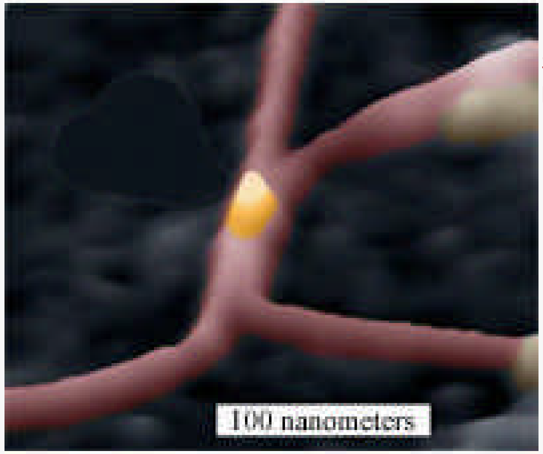
See Kastner
Ann.Phys 9 885 (2000)

Fig. 1 Schematic drawing of a SET. Wires are connected to source and drain contacts to pass current through the 2DEG at the GaAs/AlGaAs interface. Wires are also connected to the confining electrodes to bias them negatively and to the gate electrode that controls the electrostatic energy of the confined electrons.



SET: three-terminal device similar to MOSFET but: single electron capabilities, high speed (ps range), no consumption *(but requires low T!!)*

Alternative practical implementations

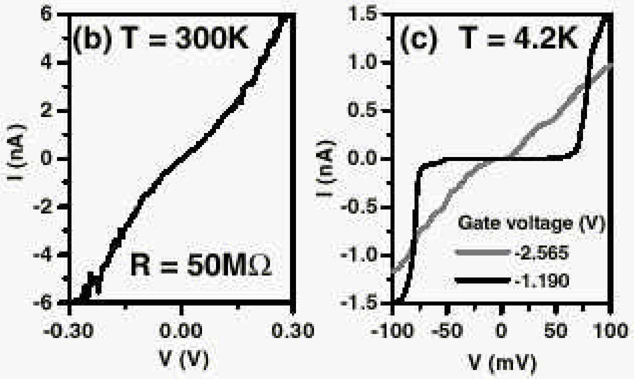


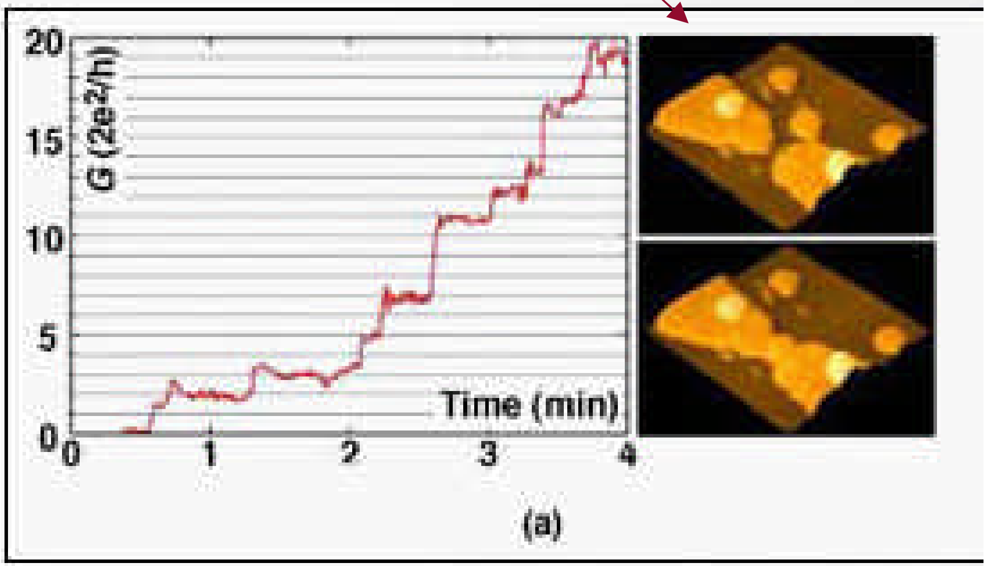
See Thelander and Samuelson
Nanotechnology 13 108 (2002)

Produced by **scanning probe manipulation**
of small metal dots

A tiny speck of gold positioned between two parallel carbon nanotubes forms a transistor that forwards one electron at a time. These single electron transistors could be used to make extremely small, low-power logic circuits.

Source: Lund University





See Junno et al.,
APL 72 548 (1998); APL 80 (2002)

More on tunneling through quantum dots

Da R. Waser Ed., Nanoelectronics and information technology (Wiley-VCH, 2003)

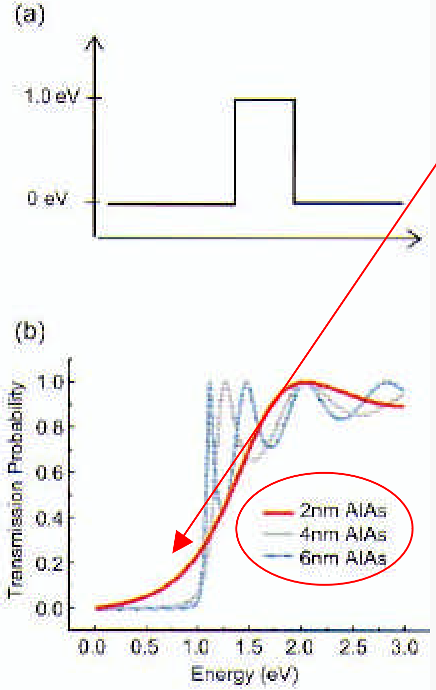


Figure 2: Schematic band diagram of a single AlAs barrier (a) and the corresponding tunneling transmission probability for different barrier thicknesses (b).

2.1.1 Tunneling Through a Single Barrier

We consider the tunneling probability through a single potential barrier Figure 2. The experimental equivalent is an AlAs barrier embedded in GaAs. The electron transmission probability as a function of the electron energy was calculated according to Eq. (15) for three different thicknesses of the barriers. First we observe a finite transmission probability for electrons far below the potential height of 1.0 eV. This effect is known as the tunneling effect. The electron wave function in front of the barrier leaks out through the barrier and leads to a finite transmission. The smaller the barrier thickness, the higher is the tunneling probability of the electrons with energies below the potential energy of the barrier. In a classical picture the electrons could not penetrate the barrier. In addition we see a modulation of the transmission probability for electrons at energies above the 1.0 eV barrier height. In this region interference effects of transmitted and reflected electron waves appears, which demonstrate the wave character of the electrons.

2.1.2 Tunneling Through a Double Barrier Structure

To see the difference between the tunneling effect through a single barrier and the resonant tunneling effect, we discuss the case of a double barrier structure (see Figure 3). We consider two 4 nm thick AlAs barriers separated by a 5 nm GaAs well. In contrast to the transmission through a single barrier now electrons with very low energies can cross the double barrier structure with a transmission probability of 1. Three additional very sharp maxima appear below 1 eV in Figure 3b: they could be interpreted as quasi-bound states with a very narrow energetic bandwidth, through which electrons can tunnel like through open channels in the barrier. This is at first astonishing and not compatible with a sequential tunneling picture. In a sequential transport picture we would expect that the transmission probability through two barriers is very much smaller than through one barrier because the transmission through the first barrier is already much below 1. A completely new quantum mechanical system has been developed which can not be described by the behaviour of each single system. This may also be a drawback for quantum devices in general. Quantum mechanical devices can therefore not be placed extremely close to each other without changing the characteristics of the single device.

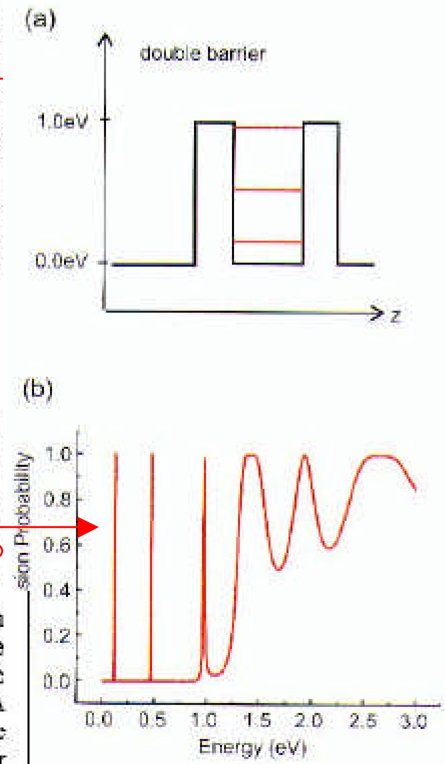


Figure 3: Schematic band diagram of a double barrier structure of AlAs embedded in GaAs (a) and the corresponding tunneling transmission probability (b).

Single barrier

"Resonances" may appear corresponding to the positions of the quantum dot energy levels

Double barrier

Resonant Tunneling Diode (RTD)

subband

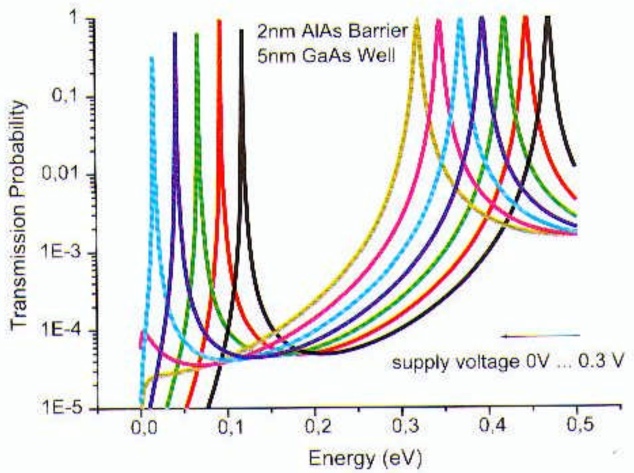


Figure 5: Transmission probability of a double barrier structure at different supply voltages.

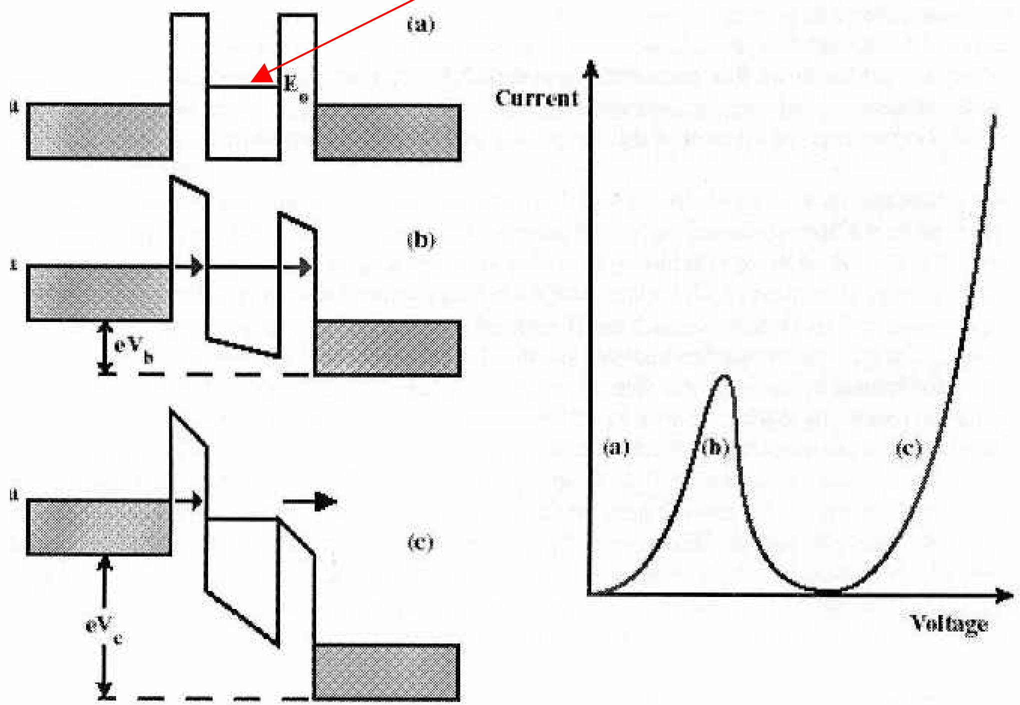
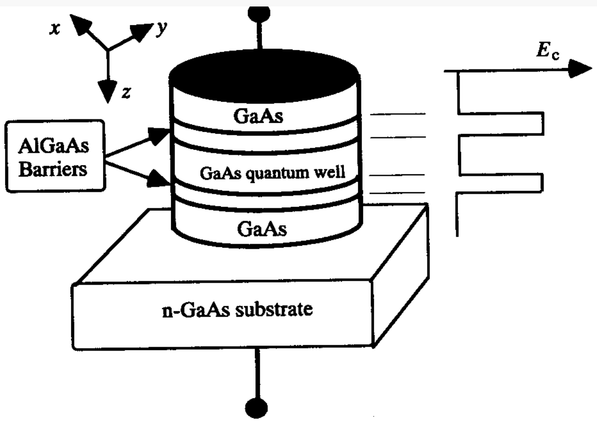


Figure 2.3:- Basic concept of the RTD. The subband energy Eo is approximately inversely proportional to the square of the well thickness. The peak in the I-V curve occurs when the incident electrons match the energy of the subband and the electrons resonantly tunnel from the source to the drain.

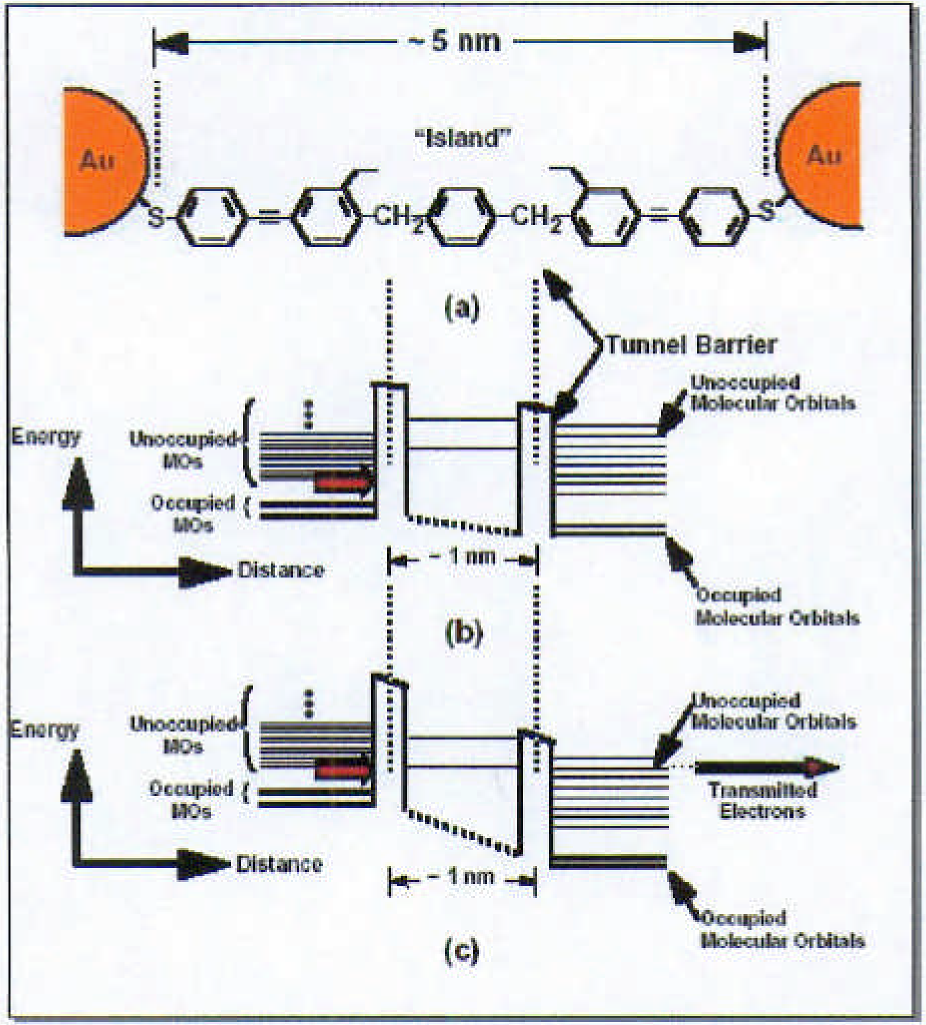
Artificial atom levels

RTD proposed as a system woth extremely high speed and low consumption

Conventional and (very) alternative RTDs



'ig. 6.1.1. Resonant tunneling device. A GaAs layer a few nanometers thick is andwiched between two AlGaAs barrier layers of similar thickness. Adapted with permission from Fig. 2 of F. Capasso and S. Datta (1990), *Physics Today*, **43**, 74.



Intramolecular electronics is inherently able to work with single electrons

Conclusions

✓ The abiity to control single electrons has a huge appeal, because of potential advantages in terms of operation speed, power consumption, miniaturization and efficiency

✓ Single electrons are “felt” by nanosized structures: a metal nanosized capacitor can be tunneled only when a proper potential is established (Coulomb staircase)

✓ Coulomb staircase is a manifestation of a quantum effect related to the small dimensions of the structure and to the discrete nature of the electric charge

✓ Coulomb blockade can be exploited also to produce three terminal devices (SET)

✓ Double barrier tunneling through a quantum dot is also a single electron process exploitable to produce a class of novel diodes (RTDs)