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The Resonant Tunneling Mode of a Single Electron Transistor

Kenji NATORI and Nobuyuki SANO
Institute of Applied Physics, University of Tsukuba
Tennoudai 1-1-1, Tsukuba, Ibaraki 305, Japan

ABSTRACT

The resonant tunneling mode of a single electron transistor is investigated. The Hamiltonian of the device system is arranged in a form of the Anderson's Hamiltonian of resonant tunneling. The current-voltage characteristics are derived for the low temperature and the low tunneling rate regime. The Coulomb staircase structure is pointed out. The current bistability and the related hysteresis are discussed. The Coulomb repulsion plays an important role in all these phenomena. A possible application to high density memories is suggested.

1. INTRODUCTION

Recently, the Coulomb blockade phenomena in a single electron transistor (SET) structure are extensively studied both from the nanostructure physics and from the device (circuit) application point of view. The key structure studied there consists of an electronic island coupled with two electron reservoirs through tunneling junctions. An electron tunnels from one of the reservoirs to the island and then from the island to the other reservoir. The island has large density of states and accommodates lots of electrons inside. Sequential independent tunneling events between the island and the reservoirs constitute the electronic transport, and the electrostatic energy of the dot charge plays an important role in controlling the tunneling probability.

In ultra-small SET's in future, however, the island which is usually made of semiconductor is down-sized to a very small quantum dot. Electrons in the dot occupy only a small number of discrete energy levels, and the relaxation process due to scattering inside the dot is not dominant. In these situations, the transport is controlled by the resonant tunneling process through the dot energy level, in place of the sequential independent tunnelings from the reservoir to the dot and then from the dot to the other reservoir. The net tunneling probability from one reservoir to the other directly depends on the electronic probability density on the dot, and the charging energy of the system also depends on the probability density. Thus the transport through the dot is controlled by the charging energy as is in the usual SET.

2. ANALYSIS AND RESULT

The device structure studied consists of an ultra-small semiconductor dot coupled with two electron reservoirs through tunneling junctions as is shown in Fig. 1. It also is capacitively coupled with the gate electrode as well as the substrate electrode so as to control the electric potential of the dot. The circuit diagram shown in Fig. 2 is identical with the usual SET. However, we assume only two spin-degenerate energy levels in the dot as is illustrated in Fig. 3, and the Coulomb repulsion is considered between the electrons in these two spin states. This corresponds to the case where the semiconductor has its conduction band minimum in the Γ valley with the small electron effective mass, as is the case with GaAs.

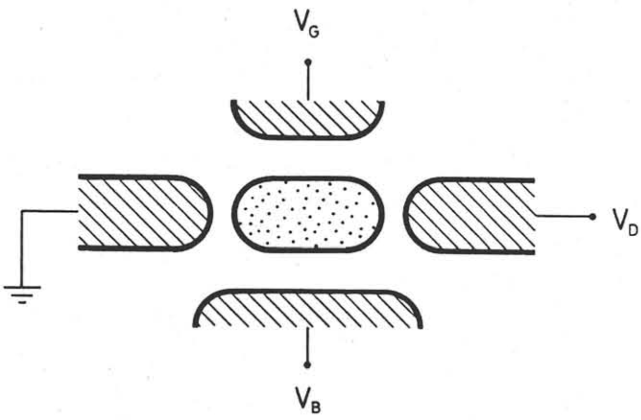

Fig. 1. A SET structure with the ultra-small semiconductor dot capacitively coupled to external electrodes.

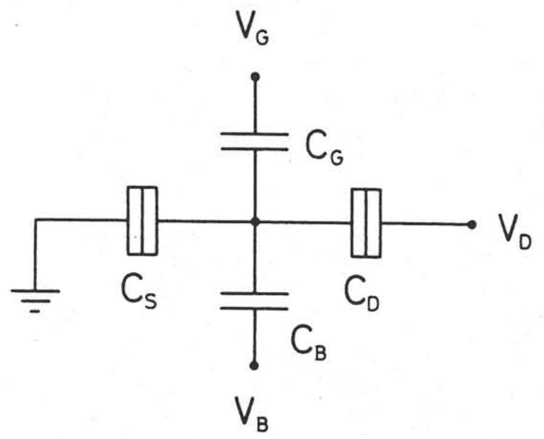

Fig. 2. The circuit expression of the device structure in Fig. 1.

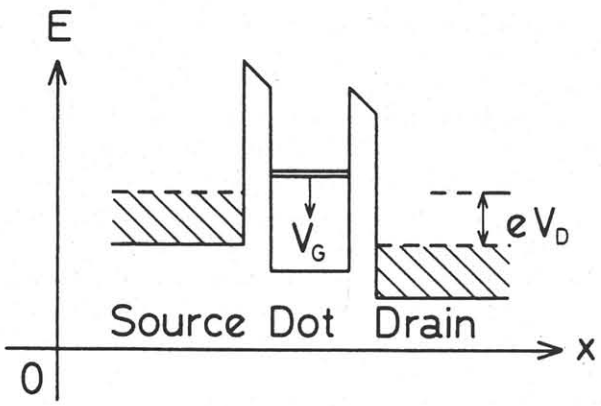

Fig. 3. Energy levels in the dot with spin degeneracy.

All the other electrodes are assumed to have degenerate carriers up to the Fermi levels related to their electrode potentials. The Coulomb repulsion is a very important factor in these ultra-small electron systems.The classical electrostatic energy of a capacitor consists of inter- and intra-electrode Coulomb interaction between charges. The Coulomb repulsion above considered constitutes a part of the intra-electrode Coulomb interaction, and we have substituted that part in the classical expression by a quantal counterpart.
Thus the Hamiltonian that describes the total system is reduced to the well-known Anderson's Hamiltonian of the resonant tunneling[1]).

$$H = H_S + H_{dot} + H_D + H_{S-dot} + H_{D-dot} \quad (1)$$

H_S and H_D are the Hamiltonians that describe the electronic states in the source and the drain electrode respectively, and H_{S-dot} and H_{D-dot} are those that describe the electronic tunneling between the source and the dot and between the drain and the dot, respectively. H_{dot} describes the electronic state in the dot and is expressed as

$$H_{dot} = (E_0 + \sum_{\ell} \alpha_\ell V_\ell) \sum_{\sigma=(\uparrow,\downarrow)} n_{0\sigma} + U n_{0\uparrow} n_{0\downarrow} \quad (2)$$

where, E_0 is the level energy of the dot, V_ℓ is the electrode potential of the ℓ-th electrode, α_ℓ is the constant, $n_{0\sigma}$ is the electron number in the (0σ) state in the dot, and U is the Coulomb energy between the $(0\uparrow)$ and the $(0\downarrow)$ state. ℓ runs over (Source, drain, gate and back-gate).
The mean field approximation is applied to Eq.(2) and we obtain

$$H_{dot} = \sum_{\sigma=(\uparrow,\downarrow)} (E_0 + \sum_{\ell} \alpha_\ell V_\ell + U\langle n_{0-\sigma}\rangle) n_{0\sigma} + const. \quad (3)$$

where $\langle\cdots\rangle$ denotes the thermal average of the quantity. We focus on the electric characteristics of the system at low temperatures for sufficiently small tunneling rate. The low temperature is necessary so that the thermal energy may not surpass the coulomb repulsive energy. The Anderson's Hamiltonian is known to lead to the resonant Kondo transparency of the dot at ultra-low temperature less than the Kondo temperature. However, we are interested in the characteristics of realistic devices and we exclude the ultra-low temperature effect. If the tunneling rate is not small, neither is the level width in the dot and the resonant nature of the tunneling is lost. If the width is larger than the Coulomb repulsive energy, the control of the transport by the Coulomb repulsion becomes meaningless. The transmission coefficient for resonant tunneling through the dot is evaluated and the electronic current is calculated with the Landauer's formula. The transmission coefficient through a single level is given by the Breit-Wigner,s formula, and the energy dependence expressed by the Lorentz resonance curve is illustrated in Fig.4.

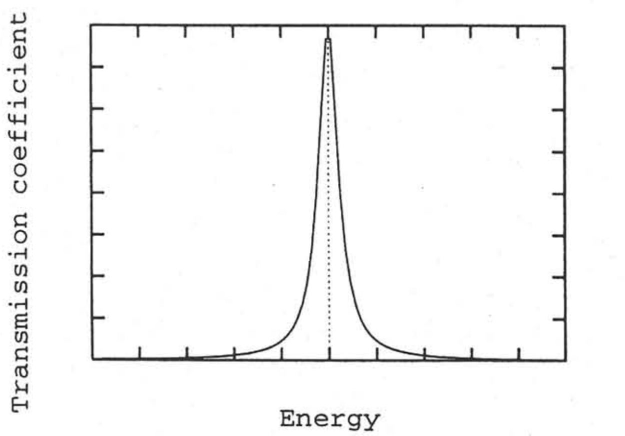

Fig. 4. The transmission coefficient with the Lorentz resonance curve.

The V_G-I characteristics is evaluated as in Fig. 5 and they are strongly varied as V_D is varied. This is because the resonant transmission strongly depends on the relative magnitude of U to the energies corresponding to V_G and V_D. The scale of the current axis is in

$$I_0 = \frac{4\pi e}{h} \frac{\Gamma_L \Gamma_R}{\Gamma_L + \Gamma_R} \quad (4)$$

where e is the unit charge, h is the Planck constant, and $2\Gamma_L$ and $2\Gamma_R$ are the half widths of the resonance curve with respect to the left and the right tunneling barrier, respectively. The width of the current transition region in the figure is around the magnitude of the sum of kT and $(\Gamma_L + \Gamma_R)$, where k is the Boltzmann constant and T is the temperature, and we have assumed it is sufficiently small. As V_G is increased the dot level in Fig. 3 is lowered, first reaching to the Fermi level of the source electrode, and then to that of the drain electrode. More precisely, the $(0\uparrow)$ level, for example, intersects the source Fermi level and $n_{0\uparrow}$ increases from 0, then Eq.(3) shows the $n_{0\downarrow}$ level is pushed up above the Fermi level thus removing the degeneracy. Further increase of V_G will pull down also the $(0\downarrow)$ level under the Fermi level and $n_{0\downarrow}$ increases to a positive value. The non-zero value of $n_{0\sigma}$ means the non-zero transmission coefficient through the (0σ) level and the contribution to the current. The stepwise increase of $(n_{0\uparrow} + n_{0\downarrow})$ means the stepwise increase of the current as in Fig. 5. The removal of the level degeneracy is due to the presence of Coulomb repulsion U and the stepwise behavior in Fig. 5 is nothing but the Coulomb staircase. The current reduction to zero level at larger V_G in Fig. 5 is due to the fact that the dot resonance level is pulled down to less than the drain Fermi level.

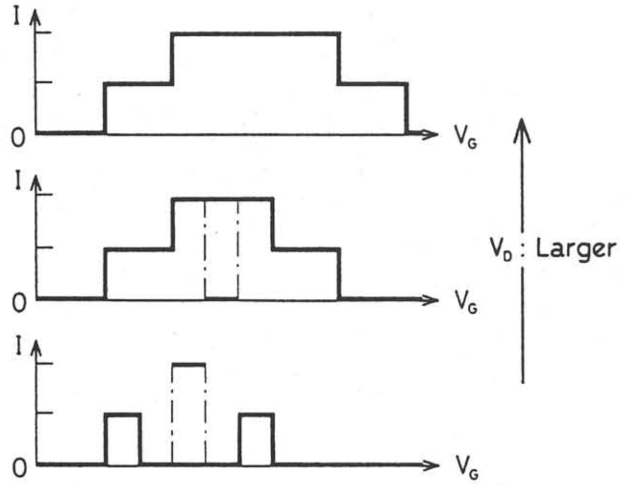

Fig. 5. Examples of the I-V_G characteristics for three different V_D values. The horizontal axis scale is arbitrary. The current bistability is observed in restricted bias regions.

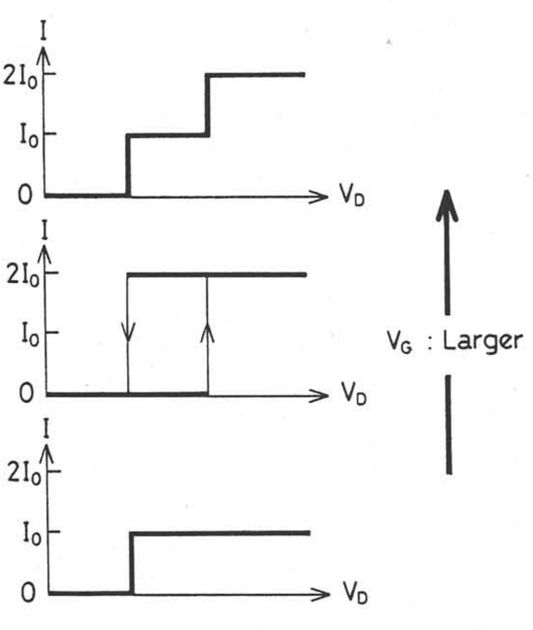

Fig. 6. Examples of I-V_D characteristics for three values of V_G. The probable hysteresis is also suggested.

A remarkable feature in Fig. 5 is that there are regions where two current values correspond to the same bias condition. This bistability is caused by the fact that Eq.(3) gives two kinds of self-consistent solutions in this bias range. In one of them, $(n_{0\sigma} = 0)$ and $(n_{0-\sigma} = 1)$ with the (0σ) level above the source Fermi level and the $(0-\sigma)$ level below the drain Fermi level. The current is zero for this solution. In the other, $(0 < n_{0\sigma} = n_{0-\sigma} < 1)$ and these two degenerate levels reside between the source and the drain Fermi level. The transmission through these two levels fully contribute to the current in this solution. Thus we can say that the bistability is the direct result of the Coulomb repulsion effect. The transition between these two solutions requires the simultaneous change of both $n_{0\sigma}$ and $n_{0-\sigma}$. If such a probability is sufficiently small, the state in one solution will be maintained until the transition is forced.

The V_D-I characteristics are also evaluated and are illustrated in Fig. 6, where the probable hysteresis related to the bistability is shown. The continuous variation of of the external bias demands continuous change of the present state. If the continuous extension of the present solution is not possible, the bias change forces the transition to the other solution and thus the hysteresis in the V_D-I curve will be brought about.

The presence of bistability and hysteresis suggests the application of this device to a simple memory device. The bistability between the zero current and the maximum current is advantageous for easy data sensing. The low current level allows low power consumption and suggests the possibility of ultra-high density memories. One of the key characteristics is the transition probability between the two bistable states. It gives the decay rate of the stored data and needs be sufficiently small. The other is the magnitude of U, and U must be sufficiently large so that the operating voltage range surpasses the environment noise level. U is the Coulomb repulsive energy and is enhanced by reducing the dot size.

3. SUMMARY

The resonant tunneling mode of a SET device is investigated. The Hamiltonian of the device system is arranged in a form of the Anderson's Hamiltonian of the resonant tunneling. The current-voltage characteristics are derived for the low temperature and the low tunneling rate case. The Coulomb staircase structure of the current-voltage characteristics is pointed out. The current bistability and the related hysteresis are derived and discussed. The Coulomb repulsive energy plays a dominant role in all these phenomena. A possible application of the bistability to high density memories is suggested.

Acknowledgement

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References

1) T. K. Ng and P. A. Lee: Phys. Rev. Lett., **61**(1988)1768.