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Sudden Drop of Dissipation in Field-Coupled Quantum Dot Resistors

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We propose a novel device where energy loss accompanied by current flow through a resistor is recovered, and therefore Joule heat production is exclusively low. This "energy-recovery effect" is caused by dynamical transition due to electronic coherent interference, namely Coulomb interaction within specially designed coupled quantum dots. We study the characteristics of this device as a resistor. We find a sudden drop of energy dissipation due to current flow as a function of electrochemical potential of the reservoir which is coupled to the quantum dots. In addition, we show that resistance of the device depends on the strength of the Coulomb interaction.

KEYWORDS: dissipation, energy-recovery effect, resistor, quantum dot, FET

In the current technology of very large scale integration (VLSI), heat production from devices is a limiting factor for the miniaturization of integrated circuits. Considerable research efforts have been devoted to reduce power consumption, mainly by using MOSFET technology.[1] Recent advances in nanotechnology made it possible to construct devices which control the flow of individual electrons.[2,3] Examples are single-electron transistors of polysilicon[4] and quantum dots.[5-9] A quantum dot is a nanodevice with a small number of localized electrons. It is realized by split-gate techniques in the two-dimensional electron gas in a GaAs/AlGaAs heterostructure.[5,6] Most recent works on quantum dots are focused on the size of current I through the quantum dot as a function of applied bias voltage V and gate voltage.[2,3] If the quantum dot is small enough, the current increases in discrete steps as a function of the bias voltage. This is due to discrete energy levels in the dot or Coulomb blockade, or both.[2,3] Because of the discreteness of the I–V characteristics, the quantum dot may become an important tool for digital quantum electronics. However, Joule heat $H = IV$ is produced even in such sophisticated devices whenever current flows through the dot.

We propose a novel device using two coupled quantum dots in which the energy loss due to current can be *recovered*. This effect, which we call the "energy-recovery effect", is caused by dynamical transition between quantum mechanical states due to the Coulomb interaction within coupled quantum dots. This device provides two advantages: (i) the reduced heat production may allow higher packing density, and (ii) energy can be recycled.

The device consists of two layered circuits (labeled 1 and 2) of electric currents, as shown in Fig. 1(a). Each circuit consists of a quantum dot and electric leads attached to it on both sides. These leads are characterized in this study by electrochemical potentials μ_{1L}, μ_{1R}, μ_{2L}, and μ_{2R}. A quantum dot is of submicron size[10,11] so that energy levels are discrete inside and electronic polarization in the dot is negligible. Two quantum dots are set closely with an insulating layer between them so that electrons within the dots are coupled via the Coulomb interaction.

The energy level structure of the device is shown in Fig. 1(b). An essential point is that electrons cannot pass through the quantum dots without changing their energies. Such a structure could be realized under the bias voltage of meV order by using impurity levels in semiconducting leads or resonant levels in the resonant tunneling diodes inserted between the quantum dots and electric leads, instead of literal conduction bands.

Our device principally operates in the following way.

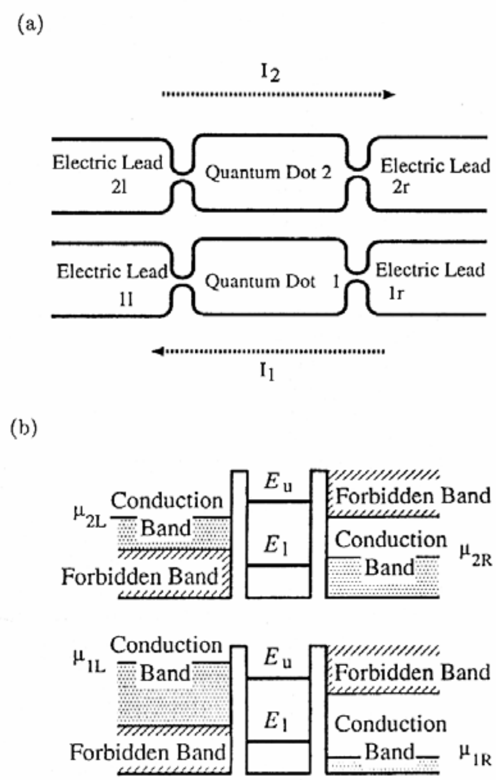

Fig. 1. (a) Schematic design of the device and (b) energy level structure in two quantum dots and four electric leads.

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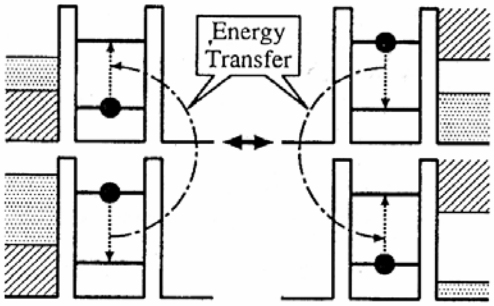

Fig. 2. Two degenerate states which contribute to the energy-recovery effect.

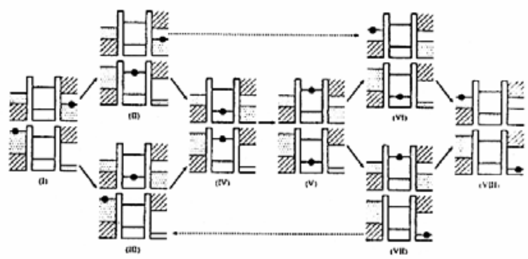

Fig. 3. Electron configurations in the quantum dots considered in the present study and patterns of currents of probability when the coupling between quantum dots is weak.

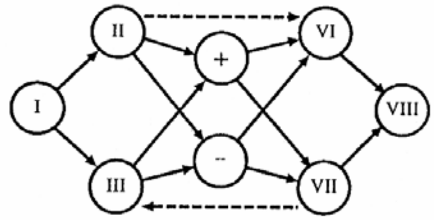

Fig. 4. Patterns of currents of probability when the coupling between quantum dots is strong. States ψ_+ and ψ_- are mixtures of states $\psi_{\rm IV}$ and $\psi_{\rm V}$ in Fig. 3.

From the time-dependent Schrödinger equation, the quantum mechanical state oscillates between two degenerate unperturbed states (in our model, two configurations are shown in Fig. 2) alternately with the frequency (strength of the coupling)/$\hbar$.[12] Accordingly, when, for instance, an electron occupies the upper level of dot 1 and another occupies the lower level of dot 2 at some time, the former falls and the latter rises simultaneously. Although the electric energy is emitted by the current in circuit 1, it is transformed not to Joule heat but to the electric energy of the charge carriers in circuit 2. This is the principle of the energy-recovery effect.

This system is described by the following Hamiltonian:

$$H = H_0 + H_{\rm U} + H_{\rm el-ph} + H_{\rm T}, \qquad (1)$$

$$H_0 = \sum_{\eta,k} \varepsilon_{\eta k} a^\dagger_{\eta k} a_{\eta k} + \sum_{\rm m} E_m c^\dagger_{\rm m} c_{\rm m},$$

$$H_{\rm U} = \sum_{\rm m_1 \sim m_4} ({\rm m_1 m_2}|U|{\rm m_3 m_4}) c^\dagger_{\rm m_1} c^\dagger_{\rm m_2} c_{\rm m_3} c_{\rm m_4},$$

$$H_{\rm T} = \sum_k V(a^\dagger_{1{\rm L}k} c_{1u} + a^\dagger_{1{\rm R}k} c_{1l} + a^\dagger_{2{\rm L}k} c_{2u} + a^\dagger_{2{\rm R}k} c_{2l}) + {\rm H.c.},$$

where the tunneling Hamiltonian $H_{\rm T}$ is treated as perturbation. Here $a_{\eta k}$ ($a^\dagger_{\eta k}$) ($\eta = (i, \eta)$) is an annihilation (creation) operator of an electron in the electrode η (= L or R) of the circuit i, with wave number k and energy $\varepsilon_{\eta k}$, while $c_{\rm m}$ ($c^\dagger_{\rm m}$) (${\rm m} = (i, m)$) is an annihilation (creation) operator of an electron in the quantum dot of circuit i (=1 or 2) belonging to the energy level m (=u or l).

It is assumed for simplicity that energy level structures are the same in both circuits. The energy level separation $\Delta E \equiv E_{\rm u} - E_{\rm l}$ in a quantum dot is so large that only two energy levels are considered in each dot. The Hamiltonian $H_{\rm el-ph}$ describes the electron-phonon interaction inside the quantum dots that leads to energy dissipation. In this situation, phonons having energy $\hbar\omega \sim \Delta E$ are emitted. It is required that the lifetime of an electron due to phonon emission be longer than the period of the above-mentioned oscillation. Otherwise an electron on the upper energy level in a dot falls to the lower one by emitting a phonon before the energy-recovery effect occurs. This requirement is fulfilled by the present device technology, since the typical energy-level separation ΔE is on the meV order,[10,11] which is much smaller than $\hbar\omega_{\rm optical}$ ($\sim 10^2$ meV) where $\omega_{\rm optical}$ is minimum frequency of the optical phonons, and consequently, acoustic phonons are exclusively emitted.

We restrict electron configurations in the coupled dots to those presented in Fig. 3. This restriction is verified from the following conditions. (1) The largest terms of the Coulomb interaction, $(iuil|U|iuil)$, between electrons within the same quantum dots are very large compared with the energy-level separation ΔE. Thus one quantum dot cannot be occupied by two electrons. (2) The second largest terms of the Coulomb interaction are (1u2u$|U|$2u1u) and (1l2l$|U|$2l1l) between quantum states with the same symmetry. Even if these terms are not larger than ΔE, the configuration in which both the upper levels in both the dots are occupied at the same time is excluded for simplicity as well as the simultaneous occupation of both the lower levels, because these configurations make no contribution to the energy-recovery effect. (3) The remaining configurations of the two-electron states are $\psi_{\rm IV}$ and $\psi_{\rm V}$ shown in Fig. 3. The matrix elements which combine these states are (1u2l$|U|$2l1u) = (1l2u$|U|$2u1l) $\equiv U_1$ and (1u2l$|U|$2u1l) = (1l2u$|U|$2l1u) $\equiv U_2$. The former U_1 causes the energy shift of two-electron state which can be taken into $E_{\rm u}$ or $E_{\rm l}$. On the other hand, U_2 leads to the energy-recovery effect, which provides charge flows in both circuits without energy dissipation. The matrix elements U_1 and U_2 are assumed to be smaller than ΔE so that the configurations $\psi_{\rm IV}$ and $\psi_{\rm V}$ in Fig. 3 are realized.

We consider two different networks of paths of probabilities as shown in Fig. 3 when U_2/V is small and in

Fig. 4 when U_2/V is large. The probabilities $\rho_\alpha(t)$ that the quantum states ψ_α are realized, change with time according to the master equations

$$\frac{\partial \rho_\alpha}{\partial t} = \sum_\beta [I_{\beta\alpha}(t) - I_{\alpha\beta}(t)], \qquad (2)$$

where $I_{\beta\alpha}$ represent probability currents from the quantum states β to α per unit time. In both figures, an arrow line which starts from a state labeled by α to a state labeled by β represents net probability current which appears on the right-hand side of eq. (2). The solid arrows represent processes without any change of electron energies. Simultaneously, a single electron may fall from an upper level to a lower one in a dot emitting a phonon, and the quantum state within a dot changes as represented by the dashed arrows in Figs. 3 and 4. (This process does not change the quantum states in the electrodes.)

All probability currents are estimated using Fermi's "Golden Rule" and can be written by the Fermi-distribution function and the density of states of the conduction electrons, transition probability Γ through the barriers between the quantum dots and electrodes, and the phonon-emitting rate $\Gamma_{\rm phonon}$ for transition from $\psi_{\rm II}$ to $\psi_{\rm IV}$. In our study, the probability per unit time of the transition from configuration VI to II is ignored for simplicity. This is allowed if the Debye temperature of the material is much higher than the operating temperature. It is assumed, when the phonon emission processes are considered, that electrons on the upper level in configurations IV and V do not emit phonons, since the final state of this process in which two electrons simultaneously occupy the lower levels is prevented by the strong Coulomb correlation. When U_2 is small and the flow pattern in Fig. 3 is appropriate, the master equations also include the interdot transition rate $\Gamma_{\rm dot}$ between configurations IV and V.

The probabilities $\rho_i(t)$ satisfy the following normalization condition

$$\rho_{\rm I}(t)+\rho_{\rm II}(t)+\rho_{\rm III}(t)+\rho_{\rm IV}(t)+\rho_{\rm V}(t)+\rho_{\rm VI}(t)+\rho_{\rm VII}(t) = 1. \qquad (3)$$

Here, $\rho_{\rm VIII}$ is omitted since the electronic state in the coupled quantum dots in $\psi_{\rm VIII}$ is identical to that in $\psi_{\rm I}$.

The electric currents I_1 and I_2 in circuits 1 and 2, respectively, can be derived by solving coupled equations (2) and summing probability currents as:

$$I_1 = I_{\rm I,II} + I_{\rm III,IV}, \quad I_2 = I_{\rm VIII,VII} + I_{\rm VI,V} \qquad (4)$$

when interdot coupling is weak and

$$I_1 = I_{\rm I,II} + I_{\rm III,+} + I_{\rm III,-}, \;\; I_2 = I_{\rm VIII,VII} + I_{\rm VI,+} + I_{\rm VI,-} \qquad (5)$$

for strong interdot coupling. (Note that I_2, current through circuit 2, is defined in the opposite direction of I_1.)

We find that current through circuit 1 can be controlled by the bias voltage across the quantum dot in circuit 2 by interdot coupling. In particular, we obtain I_1 as a function of the chemical potential $\Delta\mu_{\rm 2L} \equiv E_{\rm u} - \mu_{\rm 2L}$ in the electrode (2L) measured from the upper energy level $E_{\rm u}$ in the quantum dot. In Fig. 5(a), the solid lines and the dashed lines represent currents I_1 and I_2, respectively. Both currents change markedly when the sign of $\Delta\mu_{\rm 2L}$ is changed. When $\Delta\mu_{\rm 2L}$ is negative, the bias voltage enforces I_2 in the same direction as I_1. In this case, even if an electron on the lower energy level in the quantum dot of circuit 2 is lifted to the upper energy level by interdot coupling, the electron cannot escape to the left electrode, because the chemical potential of the electrode is higher than the upper energy level in the dot. Accordingly, current flow is only due to the process associated emission of phonons where electrons fall from the upper level to the lower level in quantum dot 1. When $\Delta\mu_{\rm 2L}$ is positive, current flows due to the energy-recovery processes and this exceeds the current due to the phonon-emitting processes. Consequently, energy dissipation drops abruptly when $\Delta\mu_{\rm 2L}$ changes its sign, as shown in Fig. 5(b). In the present study, the energy dissipation per unit time is defined by

$$D = [(\mu_{\rm 1L} - \mu_{\rm 1R})I_1 + (\mu_{\rm 2L} - \mu_{\rm 2R})I_2]/I_1. \qquad (6)$$

In addition, we study the effect of the strength of coupling between the two quantum dots. From Fig. 5(a), we also see the current through the device is presented as a function of the strength of the coupling represented by ratio $\Gamma_{\rm dot}/\Gamma$. For a certain positive value of $\Delta\mu_{\rm 2R}$,

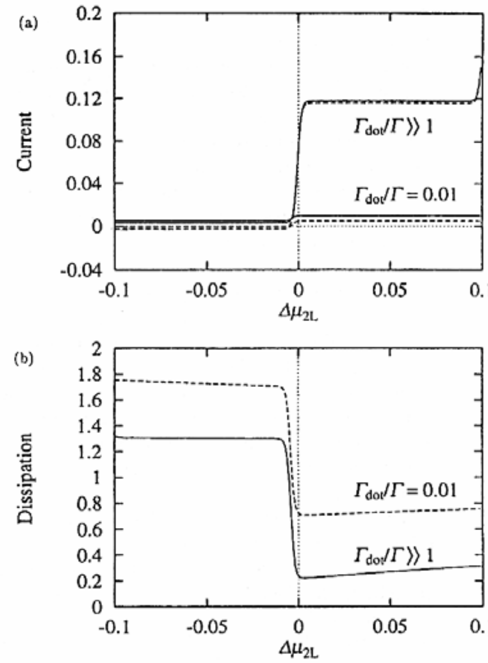

Fig. 5. (a) Currents in circuits 1 (solid line) and 2 (dashed line) and (b) energy dissipation per electric carrier as functions of the electrochemical potential $\Delta\mu_{2L}$ relative to $E_{\rm u}$ for fixed values of $\mu_{1L} = E_{\rm u} + 0.1(E_{\rm u} - E_{\rm l})$, $\mu_{1R} = E_{\rm l} - 0.1(E_{\rm u} - E_{\rm l})$, $\mu_{2R} = E_{\rm l} + 0.1(E_{\rm u} - E_{\rm l})$, and the temperature $kT = 0.001(E_{\rm u} - E_{\rm l})$. All energies are scaled by $(E_{\rm u} - E_{\rm l})$ and the current is scaled by $e\Gamma$.

we obtain a large current in the strong coupling limit ($\Gamma_{\rm dot}/\Gamma >> 1$), whereas very little current flows when the coupling is weak ($\Gamma_{\rm dot}/\Gamma = 0.01$).

In summary, in our device, one quantum dot acts as a regular adjustable resistor and the other complementary quantum dot acts as a battery where the energy which is lost in the resistor is recovered. The conductance of each dot depends on the strength of the Coulomb interaction between the coupled quantum dots. This strength may be changed by inserting another layer between the coupled layered circuits and varying carrier density on it. The additional carriers would screen the Coulomb interaction between the two quantum dots. For both cases of strong and weak coupling limits, we have shown the characteristics of the device by solving the master equations and using Fermi's "Golden Rule". For the intermediate region of interdot coupling, a similar calculation can be performed with the Green function technique.[13-16] It should also be possible to extend this approach to coupled three-level systems using the theory of nonlinear quantum resonance.[17] Energy dissipation in a tunneling device is often discussed in the light of dissipation which is lost in an environment and which affects the tunneling rate.[18] In contrast, we have focused our attention on the reduction of energy dissipation inside the quantum dots due to phonon emission, based on the assumption that the tunneling rate is not changed by the outside environment. To further understand the actual situation, we must take into account the additional energy dissipation outside, although this cannot be reduced by any mechanical process.

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