ELSEVIER

Microelectronic Engineering 47 (1999) 101–105

MICROELECTRONIC ENGINEERING

Elastic and Inelastic Single Electron Tunneling in Coupled Two Dot System

Seigo Tarucha[ab], T. Fujisawa[b], K. Ono[a], D.G. Austing[b], T.H. Oosterkamp[c], W.G. van der Wiel[c] and L.P. Kouwenhoven[c]

[a] Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

[b]NTT Basic Research Laboratories, Atsugi-shi, Kanagawa 243-0124, Japan

[c]Department of Applied Physics, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands

Elastic and inelastic tunneling between zero-dimensional states are studied for a laterally coupled two dot device and for a vertically coupled two dot device. The resonance current observed in both devices consists of a symmetric peak of elastic tunneling and an asymmetric broad peak of inelastic tunneling. The elastic peak width compares to the energy of tunnel coupling. The inelastic current is related to acoustic phonon emission from detailed study on the temperature dependence.

1. INTRODUCTION

Singleelectron transistors (SET's) containing coupled two quantum dots are relevant devices for investigating the properties of tunneling between discrete zero-dimensional (0D) states. These devices enables to tune parameters that significantly influence the tunneling process. We use two different SET's to study the elastic and inelastic tunneling properties: the first contains laterally coupled dots and the second contains vertically coupled dots. Elastic tunneling is only allowed when the two 0D states are energetically aligned, and the energy spectrum is constant with temperature when the thermal energy is smaller than the tunnel coupling between the two dots. On the other hand, inelastic tunneling occurs when the energy conservation is maintained by emission or absorption of an energy quantum such as phonons and photons. The emission and absorption rates depend on the temperature of environment. With the lateral dot device we use various gate operations to tune the tunnel couplings between the dots and between the dot and the leads. We observe a resonance current as a function of energy difference between the 0D states by tuning two gate voltages [1]. The tunneling current is decomposed into a symmetric elastic and an asymmetric inelastic component. From measurements of the temperature dependence we find that the tunneling rates are well described by the Einstein coefficients, relating absorption with stimulated and spontaneous emission for acoustic phonons [2, 3]. The vertical dot device has a drawback in the freedom of gate operation. However, we are able to study the tunneling properties of 0D states whose quantum numbers are well identified [4].

0167-9317/99/$ – see front matter
PII: S0167-9317(99)00162-8

We observe a resonance current peak as a function of drain voltage. This peak arises from elastic tunneling between two 1s states. An inelastic current is superimposed on the high energy of the elastic current. This current spectrum is similar to that observed in the lateral dot device.

2. PHONON AND PHOTON EMISSION RATES FOR A DISK DOT

Figure 1 shows the calculated acoustic phonon and photon emission rates from 0D states in a GaAs disk, using the Fermi golden rule [5]. The emission rate is much greater for phonons than for photons in most of the energy range. The increase in the phonon emission rate at small energy reflects the effect of deformation potential. For large energy the phonon wavelength becomes larger than the smallest dimension (height) of the disk, and the emission rate decreases significantly, and finally becomes smaller that that for photons. Typical energies for various semiconductor dots, are respectively shown by the arrows. The electronic transition is dominated by phonon emission in the lateral and vertical dots, however, it is dominated by the photon emission in the InAs dot. The present argument on Fig. 1 can be applied for the electronic transition in coupled two dot system.

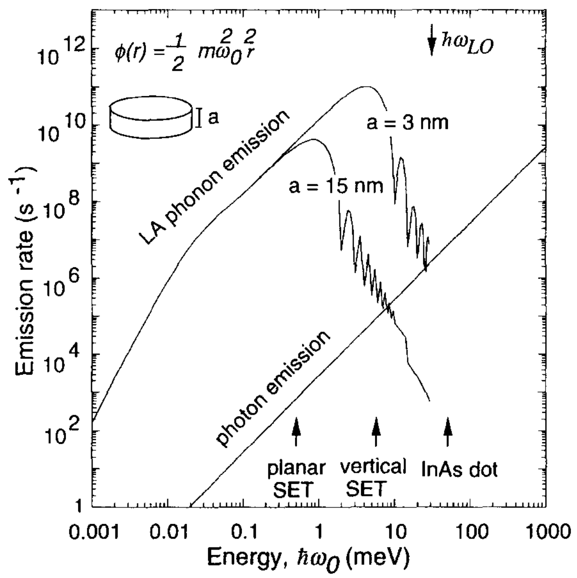


Figure 1. Emission rates of longitudinal-acoustic (LA) phonons and photons from 0D electron system. The 3 and 15 nm high disks are laterally confined by a parabolic potential. The calculation is performed for a transition between the lowest two lateral states spaced by the characteristic confinement energy $\hbar\omega_0$.

3. LATERALLY COUPLED DOTS

The laterally coupled dot (Fig.2(a)) is fabricated in a two-dimensional electron gas (2DEG) of an AlGaAs/GaAs heterostructure[1]. The two dots, L and R, are formed by applying negative voltages to the three gates. The energy states in each dot are discrete due to the effects of single electron charging and quantum mechanical confinement. The lowest energy state for one additional electron in the left dot is labeled in Fig.2 (b) to (d) as E_L and similarly E_R for the right dot. Figure 2(c) illustrates the resonance condition, $E_L = E_R$, for elastic tunneling. When the two states are not aligned, only inelastic tunneling is allowed for which some energy needs to be exchanged with the environment. Figure 3(a) shows a typical current spectrum vs $\varepsilon = E_L - E_R$. The gate voltages V_{GR} and V_{GL} are swept simultaneously such that the respective energies are like in Figs.2 (b) to (d); that is $\varepsilon = 0$ occurs in the middle between the Fermi energies of source and drain, μ_S and μ_D, and $\varepsilon = eV_{SD}$ (its maximum) corresponds to having E_L and E_R aligned to one of the Fermi energies. To analyze the large asymmetry, we decompose the total current $I_{tot}(\varepsilon) = I_{el}(\varepsilon) + I_{inel}(\varepsilon > 0)$ into a symmetric part $I_{el}(\varepsilon) = I_{el}(-\varepsilon)$ (dashed curve) and the remaining asymmetric part $I_{inel}(\varepsilon > 0)$ (dot-dashed curve). At T=0, $I_{el}(\varepsilon)$ is due to elastic tunneling and has a Lorenzian line shape $I_{el}(\varepsilon) = I_{el,max}w^2/(w^2 + \varepsilon^2)$. The full-width at half-maximum (FWHM), $2w$, can be tuned by the central gate voltage V_{GC} roughly from 4 to 20 μeV (T = 23 mK). From measurements of $I_{el}(\varepsilon)$ vs V_{SD}, it is possible to extract values for the tunnel couplings Γ_L, Γ_R and T_c[2]. The remaining current, $I_{inel}(\varepsilon > 0)$ is due to inelastic tunneling. I_{inel} is non-zero over an energy range of ~100 μeV, despite the thermal energy kT=2 μeV being much smaller. In general, we find that I_{inel} vanishes when one of the levels, E_L or E_R, crosses one of the Fermi energies, implying that I_{inel} is cut off at $|\varepsilon| = eV_{SD}$. Below this cut off I_{inel} is not influenced by the value of V_{SD}. For T=0, we can write the condition for a non-zero I_{inel} as $\mu_S > E_L > E_R > \mu_D = \mu_S - eV_{SD}$. The amount of I_{inel} is given by $I_{inel}(\varepsilon) = e(\Gamma_L^{-1} + \Gamma_i^{-1}(\varepsilon) + \Gamma_R^{-1})^{-1}$. When the inelastic rate $\Gamma_i(\varepsilon)$ from E_L to E_R is much smaller than the rates through the outer barriers, then $I_{inel}(\varepsilon) = e\,\Gamma_i(\varepsilon)$.

We use the Einstein relations to analyze I_{inel}. The rates for absorption, W_a, and emission, W_e, can be described by $W_a = B\rho$ and $W_e = A + B\rho$, where the Einstein coefficients stand for spontaneous emission (A) and stimulated emission/absorption (B), and ρ is the energy density. $B = A\langle n\rangle/\rho$, where $\langle n\rangle$ is the average occupation number of phonons given by the Bose-Einstein distribution function. Γ_i is then given by

$$\Gamma_i(\varepsilon < 0) = W_a(\varepsilon) = \langle n\rangle A(-\varepsilon) \tag{1}$$

$$\Gamma_i(\varepsilon > 0) = W_e(\varepsilon) = (\langle n\rangle + 1)A(\varepsilon) \tag{2}$$

$A(\varepsilon) = I_{inel}(\varepsilon > 0)$ at the lowest temperature since $\langle n\rangle \ll 1$. The emission current at higher

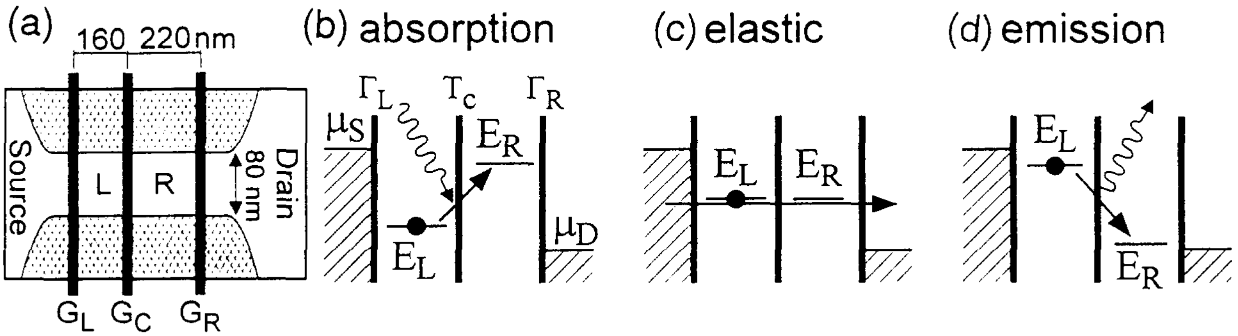
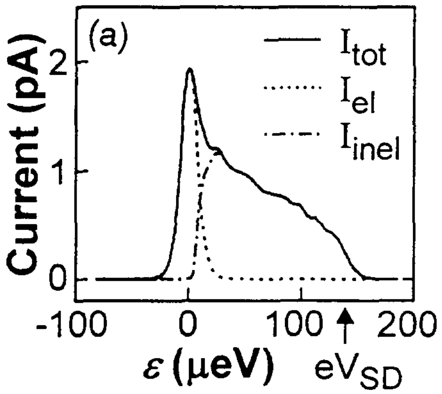


Figure 2. (a) Laterally coupled quantum dot device defined in a GaAs/AlGaAs heterostructre by focused ion beam implantation. The narrow channel connects the large2D source and drain leads. The two dots, L and R, are formed by applying negative voltages to the three gates, and respectively, contain ~15 and ~25 electrons; charging energies are ~4 and ~1 meV; the measured average spacing between single-particle states are ~0.5 and ~0.25 meV. (b to d) Energy diagrams along the spatial axis through the dots for the tunnel situations: Absorption, elastic and emission. An elastic current can flow when $\varepsilon = 0$, otherwise a non-zero current requires absorption ($\varepsilon < 0$) or emission ($\varepsilon > 0$). T_c is the tunnel coupling and Γ_i is the inelastic tunnel rate between the two dots. Γ_L and Γ_R are the tunnel rates across the left and the right barriers.



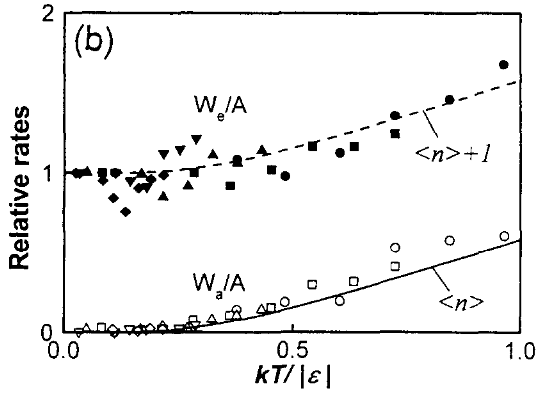


Figure 3. (a) Typical data of the current (solid) vs ε at 23 mK. The measured current is decomposed in an elastic (dashed) and an inelastic (dot-dashed) part. (b) The absorption rate W_a (open symbols) and emission rate W_e (closed symbols) normalized by the spontaneous emission rate A vs $kT/|\varepsilon|$. Circles, squares, upper- and lower-triangles, and diamonds are taken at $|\varepsilon| = 18$, 24, 24, 40, 60, and 80 μeV, respectively for I_{tot} in Fig. 3(a). The solid line indicates the Bose-Einstein distribution, <n>, whereas the dashed line shows <n> + 1.

temperatures follows from $I_{inel}(\varepsilon > 0, T) = e(<n> + 1)A(\varepsilon)$, whereas the absorption current follows from $I_{inel}(\varepsilon < 0, T) = e<n>A(-\varepsilon)$. We thus evaluate W_a/A and W_e/A vs $kT/|\varepsilon|$ for various ε and T, and plot the result in Fig. 3(b). The measured data closely follows the prediction that $[W_e - W_a]/A = 1$ according to Eqs.(1) and (2); that is, the two normalized rates differ by one over the temperature range T < 200 mK.

4. VERTICALLY COUPLED DOTS

Figure 4 shows the device configuration containing vertically coupled dots[6]. A triple barrier tunneling structure consisting of two InGaAs wells (12 nm) and three AlGaAs barriers (6.6 and 8.4 nm for the outer and 7.6 nm for the central) is processed to a mesa of a 0.5 μm-diam. pillar. A gate metal is wrapping the pillar and works to squeeze the two dots inwards equivalently as the bias voltage, V_g, is made more negative. Each dot is so strongly confined by the heterojunctions in the vertical direction that only the lowest state contributes to the transport. In the lateral direction it is parabolically confined by the depletion potential ($\hbar\omega_0 \sim 5$ meV), and a number of lateral states are involved in the transport. The electronic states are well represented by two good orbital quantum numbers: radial quantum number, n, and angular momentum, ℓ: for example, 1s-like with $(n, \ell) = (0,0)$ and 2p-like with $(0, \pm 1)$ for the first and second lowest levels, respectively. We adjust V_g and V_{SD} to observe a resonance current flowing through the two dots. A typical current data for tunneling between 1s states in the two dots is shown in Fig. 4. This current spectrum is similar to that of Fig. 3(a). Elastic tunneling gives rise to a symmetric peak, whereas inelastic tunneling gives rise to a current on the right. This current is sitting on a plateau of cotunneling current (short dashed line). When we assume that one third of V_{SD} is actually applied between the two dots, FWHM of the elastic tunneling peak is 150 μeV and comparable to the calculated tunnel coupling (~100 μeV). The inelastic current spreads out over an energy range of 1 meV (3 mV in V_{SD}) on the high V_{SD} of the elastic peak. This is in the regime of strong phonon emission (Fig. 1).

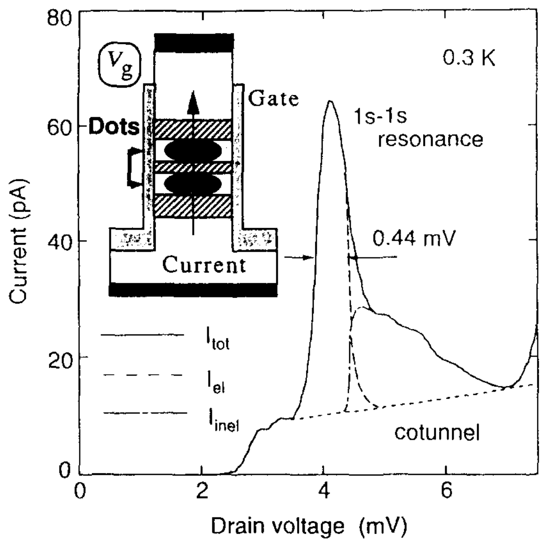


Figure 4. Typical data of the current vs V_{SD} for tunneling between 1s-like states in the vertically coupled two dots. The current is decomposed in an elastic (long dashed line) and an inelastic (dot-dashed) part. The short dashed line indicates a cotunneling current. Inset: Schematic of the vertical device having a 0.5 μm-diameter pillar of an AlGaAs/InGaAs/AlGaAs/InGaAs/AlGaAs triple barrier structure. The two dots are separated by a central barrier and wrapped by a common gate metal, which works to vary the number of electrons one-by-one, starting from zero.

5. CONCLUSIONS

We have studied elastic and inelastic tunneling between 0D states in laterally coupled two dots and in vertically coupled two dots. The observed tunneling current observed in both devices arises from a symmetric peak of elastic tunneling and an asymmetric broad peak of inelastic tunneling. The elastic peak width compares to the tunnel coupling, while the inelastic current is related to acoustic phonon emission. This is because the quantum confinement is relatively weak for these devices. However, photon emission can be dominant in more strongly confined dot system such as coupled InAs selfassembled dots.

ACKNOWLEDGEMENTS

A part of this work is supported by NEDO joint research program (NTDP-98).

REFERENCES

1. T. Fujisawa and S. Tarucha, Superlattices and Microstructures, 21 (1997) 247; Jpn. J. Appl. Phys. 36 (1997) 4000.
2. T. Fujisawa, T.H.oosterkamp, W.G. van der Wiel, B.W. Broer, R. Aguado, S. Tarucha and L.P Kouwenhoven, Science,282 (1998) 932.
3. P.W. Milonni, The Quantum Vacuum, an Introduction to quantum electrodynamics (Academic Press, San Diego, 1994).
4. S. Tarucha, D.G. Austing, T. Honda, R.J. van der Hage and L.P. Kouwenhoven, Phys. Rev. Lett. 77 (1996) 3613.
5. U. Bockelman and G. Bastard, Phys. Rev. B 15, 42 (1990) 8947.
6. D.G. Austing, T. Honda and S. Tarucha, Semicond. Sci. and Technol. 11 (1996) 388.