Elastic and Inelastic Single Electron Tunneling in Coupled Two Dot System

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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

Single-electron 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 enable 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 the 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].
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 than 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.

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 effect 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, $\mu_S$ and $\mu_D$, 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 Lorentzian line shape \( I_{el}(\epsilon) = I_{el,\text{max}}\frac{\epsilon^2}{(\epsilon^2 + \delta^2)} \). The full-width at half-maximum (FWHM), \( 2\delta \), can be tuned by the central gate voltage \( V_{SG} \) roughly from 4 to 20 \( \mu \text{eV} \) (\( T = 23 \text{ mK} \)). From measurements of \( I_{el}(\epsilon) \) vs \( V_{SD} \), it is possible to extract values for the tunnel couplings \( \Gamma_L, \Gamma_R \) and \( \Gamma_{T_2}[2] \). The remaining current, \( I_{inel}(\epsilon > 0) \), is due to inelastic tunneling. \( I_{inel} \) is non-zero over an energy range of \( \sim 100 \mu \text{eV} \), despite the thermal energy \( kT = 2 \mu \text{eV} \) 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 \( |\epsilon| - eV_{SD} \). 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 \( I_{inel}(\epsilon) = \epsilon(\Gamma_L^{-1} + \Gamma_R^{-1}(\epsilon) + \Gamma_{T_2}^{-1})^{-1} \). When the inelastic rate \( \Gamma_{i}(\epsilon) \) from \( E_L \) to \( E_R \) is much smaller than the rates through the outer barriers, then \( I_{inel}(\epsilon) = e \Gamma_{i}(\epsilon) \).

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 \( \rho \) 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. \( \Gamma_{i} \) is then given by

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\begin{align*}
\Gamma_{i}(\epsilon < 0) &= W_a(\epsilon) = \langle n \rangle A(-\epsilon) \\
\Gamma_{i}(\epsilon > 0) &= W_e(\epsilon) = (\langle n \rangle + 1)A(\epsilon)
\end{align*}
\]

\( A(\epsilon) = I_{inel}(\epsilon > 0) \) at the lowest temperature since \( \langle n \rangle \ll 1 \). The emission current at higher...
temperatures follows from $I_{\text{inel}}(\varepsilon > 0, T) = e(\langle n \rangle + 1)A(\varepsilon)$, whereas the absorption current follows from $I_{\text{inel}}(\varepsilon < 0, T) = e\langle n \rangle A(-\varepsilon)$. We thus evaluate $W_a/A$ and $W_e/A$ vs $kT/|\varepsilon|$ for various $\varepsilon$ 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 ($\hbar^2 \alpha^2 \sim 5$ 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, $\ell$: 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).

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.

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