

Observation of bias-induced resonant tunneling peak splitting in a quantum dot

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We have observed that, in zero magnetic field, a dc bias across a lateral confined quantum dot (QD) splits each resonant peak in the differential conductance versus the gate voltage measurement into two. The splitting is nearly linear with the applied bias V_D . Temperature-dependence study indicates that the corresponding energy separation between the two splitting peaks is close to eV_D . A model is proposed that explains this splitting in terms of the bias-induced shifting of energy levels in the QD and the splitting of the Fermi level. Using our model, the bias-induced energy level shift in the QD can be calculated.

Transport through a field-induced quantum dot (QD) or a Coulomb dot have been studied previously both experimentally¹⁻⁴ and theoretically.^{5,6} The oscillatory behavior in the source-drain current as a function of the gate voltage was observed and was attributed to electron resonant tunneling through quantum levels or Coulomb levels in the dots. In this paper, we describe the effects of source-drain bias on electron transport through a QD. We observed that, in zero magnetic field, a dc bias across the dot splits each resonant peak in the differential conductance versus the gate voltage curve into two. We explain the splitting in terms of the bias-induced energy level shifting in the QD and the splitting of the Fermi level.

The QD was created at an interface of AlGaAs/GaAs heterostructure using a new gate structure that we proposed and demonstrated recently.⁴ The gate structure consists of a nanoscale dot gate inside the gap of a split gate (Fig. 1). The dot gate, which has a dot in the middle of a wire, is positively biased to induce a QD and two one-dimensional (1D) wires. The wires connect the dot to the source and drain of the transistor. The split gate is negatively biased to change the electron population in the dot and wires. The transistor is operated at the region where the Fermi level is lower than the first 1D subband edge of the wires. Therefore the two wires act like barriers that separate the dot from the source and drain. For the device used in this study, the diameter of the dot is 80 nm, the wire width is 30 nm. The gate length and gap width of the split gate are 0.3 and 0.5 μm , respectively. The distance between the gate metal and the two-dimensional electron gas (2DEG) is 40 nm. The details of the AlGaAs/GaAs heterostructure are discussed in Ref. 4. At 4.2 K in the dark, the 2DEG has a mean-free path of 2 μm .

The differential conductance of the device was measured by applying a small ac voltage on top of a dc bias across the source and drain, and detecting the ac source-drain current using a lock-in amplifier. For linear response, the differential conductance is the same as the conductance. However, for nonlinear response, they could be very different. Figure 2 shows the differential conductance versus the dot-gate voltage at 0.5 K with zero dc bias. The dot-gate voltage controls the barrier height under the wire as well as the potential profile of the QD, and therefore controls the energy levels in the QD. The four well-separated oscillation peaks in the dif-

ferential conductance are due to electron resonant tunneling through the energy levels inside the dot.⁴ As discussed in Ref. 4, the energy level spacing in this QD are caused by both quantum size effect and Coulomb effect.

Surprisingly, we observed that, in zero magnetic field, as the dc drain bias increased, each oscillation peak in the differential conductance gradually split into two. Figure 3 details the splitting of the third peak in Fig. 2. A small dc drain bias V_D broadens the differential conductance peak first; when V_D is larger than 0.3 mV, the peak splitting becomes distinguishable. As V_D increases further, one peak shifts to the left and the other to the right, almost linearly with V_D . The two split peaks are not symmetric. The height of the right peak always increases with the drain bias while the height of the left peak shrinks. One might think that the right peak corresponds to resonant tunneling through a higher energy level in the QD and thus lower potential barriers, therefore it should have a larger tunneling probability. However, this cannot explain the observation that the height of the left peak from the third peak splitting can actually be less than that of the right peak from the second peak splitting.

To accentuate the peak splitting, we plot the evolution of the current peaks and their separation V_{split} , with applied V_D in Figs. 4(a) and 4(b), respectively. The V_{split} as a function of V_D can be fit rather well by a second-order polynomial [Fig. 4(b) solid line]: $V_{\text{split}} = -2 + 6.6V_D - 0.7V_D^2$, where both V_{split} and V_D are in units of mV. Clearly, for small drain bias, V_{split} is primarily a linear function of V_D . At $V_D = 3$ mV, the qua-

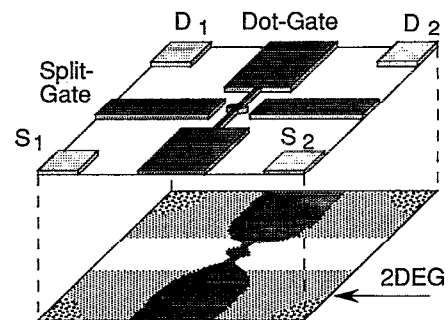


FIG. 1. Schematic diagram of a field-induced quantum dot transistor that has a dot gate inside the gap of a split gate.

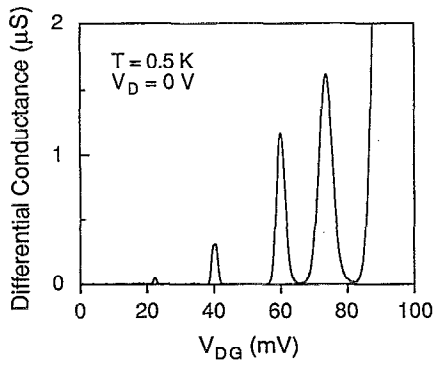


FIG. 2. Source-drain differential conductance vs the dot-gate voltage at 0.5 K with zero dc drain bias. The rms value of the ac drain bias is 0.1 mV. The split-gate voltage is fixed at -0.5 V.

dratic deviation term is about one third of the linear term.

Since the dot-gate voltage controls the energy levels in the QD, the energy separation between the two peaks E_{split} can be determined using $E_{\text{split}} = \alpha e V_{\text{split}}$, where α is the dot-gate modulation coefficient and a linear modulation is assumed. By studying the thermal broadening of the resonant peak width at zero dc drain bias, we obtained α to be 0.24.⁴ Thus, we can plot the energy splitting of the two peaks versus the drain bias as shown in Fig. 4(b). Notice that the splitting in energy is quite close to eV_D . This suggests that the two conductance peaks may be related to the Fermi levels at the source and the drain.

Before interpreting our data, we should point out that recently Johnson *et al.*¹ have reported the observation of double and triple splitting of resonant peaks in current-voltage characteristics at finite drain biases with a 4 T magnetic field. The multiple peaks were explained to be caused by the zero-dimensional excited states inside the quantum dot. However, we found this explanation cannot account for our observations. This is not only because of the absence of the triple splitting and magnetic field in our experiment, but also the facts that the splitting is a linear function of drain biases and the energy splitting is close to eV_D . In the fol-

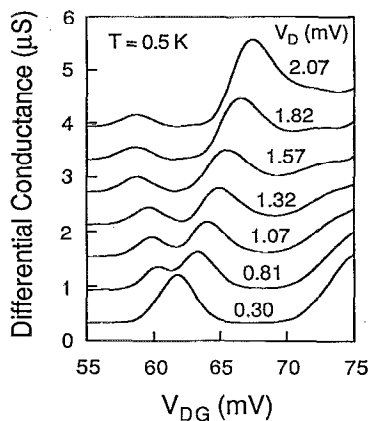


FIG. 3. As the dc drain bias increases, the third peak in Fig. 2 splits into two, one shifts to the left while the other shifts to the right. All the curves are displaced for clarity.

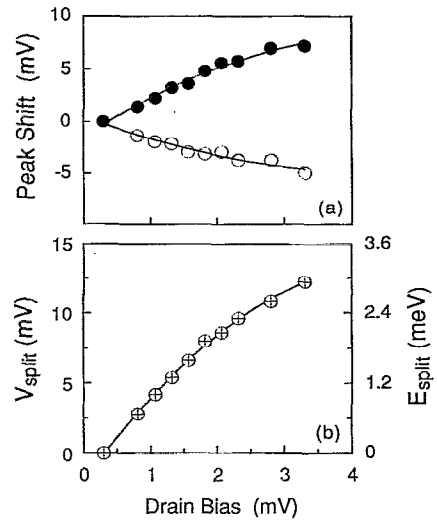


FIG. 4. (a) Relative positions of the split peaks in Fig. 3 vs the dc drain bias. (b) Separation between two peaks vs the dc drain bias. Vertical scale at the right-hand side is the energy splitting calculated using $E_{\text{split}} = \alpha e V_{\text{split}}$ with $\alpha = 0.24$.

lowing, we propose a different explanation based on bias-induced shifting of energy levels inside the QD, and the splitting of the Fermi level.

As shown in Fig. 5, a dc drain bias V_D will split the Fermi level at the drain from that at the source by eV_D . As the dot-gate voltage shifts the energy levels in the QD downward, the tunneling current through an energy level starts when the energy level aligns with the Fermi level at the source, but stops when the level drops below the Fermi level at the drain. Now we impose a small ac voltage v_d on a dc drain bias and detect the ac drain current as the dot-gate voltage is scanned. If the energy level in the QD is independent of the drain bias, an ac current would flow only when the energy level is within $e v_d$ around the Fermi level at the drain (note the source is grounded but the Fermi level at the drain oscillates with an amplitude of $e v_d$), this gives only one differential conductance peak. In reality, however, the QD energy level *does* shift with the drain bias, an ac bias modulates not only the Fermi level at the drain but also the energy level in the QD. Thus, there should be another differential conductance peak when the energy level is near the Fermi level at the source.

The above discussion can be described quantitatively as follows. The current through a quantum dot is given by⁷

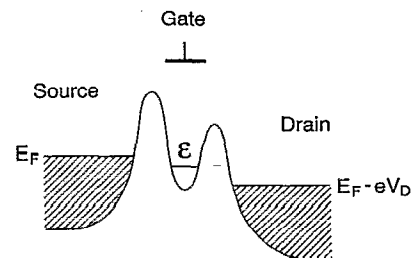


FIG. 5. Band diagram for a quantum dot under a drain bias.

$$I_D = \frac{e}{\hbar} \int (f_S - f_D) \Gamma(E) D(E) dE, \quad (1)$$

where f_S and f_D are the Fermi-Dirac distribution functions at the source and drain, respectively; $\Gamma(E)/\hbar$ is the tunneling rate through the double barriers; and $D(E)$ is the density of states inside the QD. For simplicity, we consider only one discrete energy level ϵ inside the dot, and assume $D(E) = \delta(E - \epsilon)$. At zero temperature, it is straightforward to show that the differential conductance σ , defined as $(\partial I_D / \partial V_D)_{V_G}$, is given by

$$\sigma = \frac{e^2}{\hbar} [\gamma \delta(E_F^S - \epsilon) + (1 - \gamma) \delta(E_F^S - \epsilon - eV_D)] \Gamma(\epsilon), \quad (2)$$

where E_F^S is the Fermi level at the source, $\gamma = -[\partial \epsilon / \partial (eV_D)]_{V_G}$ describes the dependence of ϵ on V_D , and we have neglected the variation of Γ with respect to V_D . Equation (2) clearly indicates that, as long as γ is nonzero (namely, the energy level in the dot shifts with V_D), the differential conductance must have two peaks.

Using Eq. (2), many of our observations can be well explained. First, under a sizable V_D , the differential conductance peak from each energy level should split into two. The left (or right) peak occurs when a discrete energy level inside the QD aligns with the Fermi level at the source (or drain). Therefore the energy separation between the two peaks is eV_D . Second, as V_D increases, one peak will shift to the left and the other to the right, almost linearly with V_D . This is because a dc drain bias will shift the energy level downward by γV_D , therefore to align the energy level with the Fermi level at the source, the dot-gate voltage must minus (negative shift) $\gamma V_D / \alpha$ from that at zero dc bias; to align the energy level with the Fermi level at the drain, the dot-gate voltage must add (positive shift) $(1 - \gamma) V_D / \alpha$. This also implies that the coefficient γ can be calculated from the ratio of the positive and negative shifts. From the linear fitting of Fig. 4(a), we found γ for our device to be 0.36. The quadratic devia-

tion suggests that γ is not strictly a constant but decreases slightly at large V_D . Thirdly, the amplitudes of the left and right peaks are proportional to $\gamma \Gamma_l$ and $(1 - \gamma) \Gamma_r$, respectively. This implies that the left peak will diminish while the right peak will be enhanced as V_D increases, because the shift in the dot-gate voltage makes the tunneling barrier higher for the left peak but lower for the right peak, leading to a smaller Γ_l but larger Γ_r . Finally, since γ is smaller than $1 - \gamma$, the amplitude of the left peak is less than that of the right peak by an extra factor $\gamma / (1 - \gamma)$. This explains why the height of the left peak from the third peak splitting could be lower than that of the right peak from the second peak splitting.

In summary, we have observed, in zero magnetic field, a dc bias across a lateral confined QD splits each resonant peak in the differential conductance versus gate-voltage measurement into two. The splitting is nearly linear with the drain bias. Temperature-dependence measurement indicates the splitting in energy is very close to eV_D . A model is proposed that explains the splitting in terms of bias-induced energy level shifting inside the QD and the splitting of the Fermi level. The model agrees well with the experiment, and allows us to obtain the dc bias induced shift of energy level in the QD.

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