Planar field-induced quantum dot transistor

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We propose and demonstrate a new field-induced quantum dot transistor that has a nanoscale dot-gate inside the gap of a split gate. Because of the novel structure and small dot size, strong oscillations in the drain current as a function of the gate bias were observed at a temperature up to 4.2 K or with a drain bias up to 5 mV. Temperature dependent study showed that the energy gaps in the dot are as large as 4.5 meV. Simulation indicates that, in the device, quantum size effect and Coulomb effect are comparable; both contribute significantly to the energy gaps in the quantum dot.

Semiconductor quantum-dot transistors are of great importance to fundamental understanding of electron transport in nanostructures and to future development of microelectronics.[1,2] Previously, transistors based on the transport through a three-dimensionally confined potential box (so-called dot) induced by the field effect of gate electrodes were studied.[3–6] Although these transistors are commonly called quantum-dot transistors (QDTs), it is the classical Coulomb energy levels, not quantum energy levels, in the box that are responsible for the observed drain current oscillations. This is because the typical dot size of these transistors is much larger than 0.1 μm, making quantization energy much smaller than Coulomb energy. In this letter, we propose and demonstrate a field-induced QDT with a new gate structure, and show that both quantum effect and Coulomb effect are important to the energy levels in this QDT.

The new QDT has a nanoscale dot-gate placed inside the gap of a split gate. Both gates are on top of a heterostructure [Fig. 1(a)]. The dot gate, which consists of a dot at the middle of a wire, is positively biased to induce a QD and two one-dimensional (1D) wires at the heterostructure interface. The wires connect the dot to the two-dimensional electron gas (2DEG) at the source and the drain. The split gate is negatively biased to change the number of electrons inside the dot and to make the confinement potential stronger. For a given positive dot-gate bias, the electric field beneath the dot is larger than that beneath the wires, therefore the conduction band edge under the dot is lower than that under the wires, creating a quantum dot attached to two wires.

The edge of the first 1D subband in the wire can be controlled by the gate voltage to be above or below the Fermi level of the 2DEG. In the first case, the two wires act like potential barriers that separate the QD from the source and drain. Scanning the dot gate or the split gate will move the energy levels in the dot up or down with respect to the Fermi level. When an energy level inside the dot lines up with the Fermi level, resonant tunneling of electrons from the source to the drain occurs. In the second case, the QD is connected to the source and drain by two 1D channels, new phenomena due to quantum interference will manifest. In this letter, we only discuss the first case. The second case will be reported elsewhere.[7]

Figure 1(b) shows scanning electron micrograph of a typical gate structure: a dot gate has a dot of 80 nm diam in the middle of a 30 nm wide metal wire, and the split gate has a gap of 0.5 μm and a gate length of 0.3 μm. The gates were fabricated on top of a δ-doped AlGaAs/GaAs heterostructure using *e*-beam lithography followed by a liftoff of Ti/Au.[8] The heterostructure was grown by molecular beam epitaxy and has a 40 nm distance between the gate metal and the 2DEG. At 77 K in the dark, the 2DEG has an electron concentration of 3.5×10^{11} cm^{-2} and a Hall mobility of 90 000 cm^2/V s.

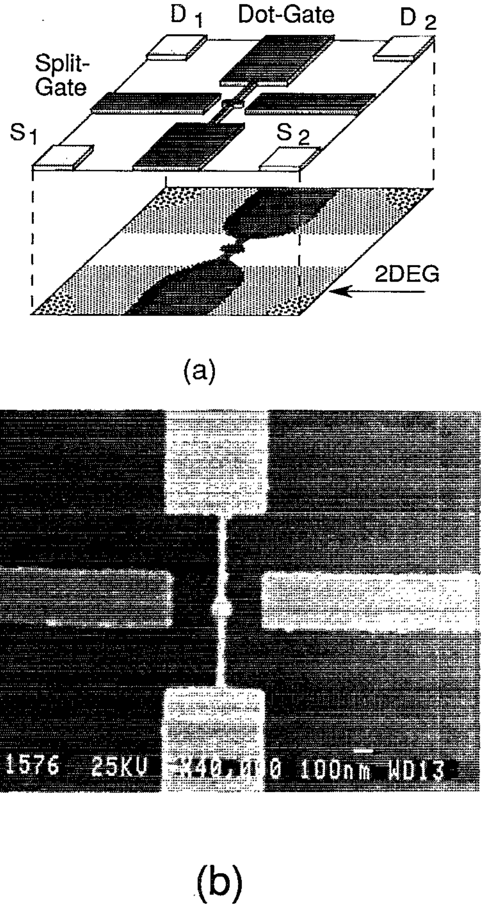

FIG. 1. (a) Schematics, (b) scanning electron micrograph of a field-induced quantum dot transistor that has a dot gate inside the gap of a split gate. The dot gate has an 80 nm diam metal dot in the middle of a 30-nm-wide metal wire.

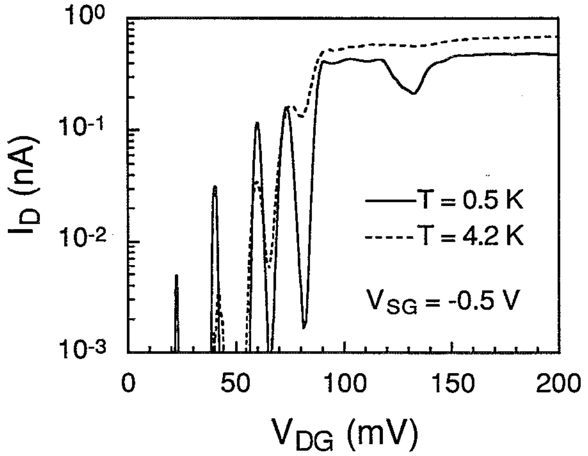

FIG. 2. The drain current vs the dot-gate voltage at 0.5 K (solid line) and 4.2 K (dashed line). The split gate voltage is fixed at −0.5 V. The ac drain bias is 0.1 mV.

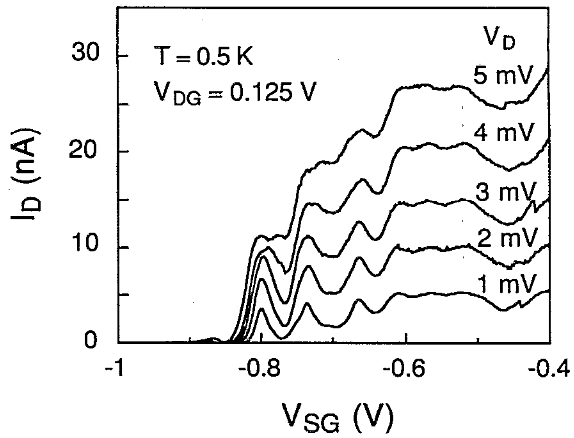

FIG. 4. The drain current vs split-gate voltage with different drain biases at 0.5 K.

The device was measured using a lock-in technique. Figure 2 shows the semi-log plot of the drain current versus the dot-gate voltage at a fixed split-gate voltage of −0.5 V. At T=0.5 K, four well-defined oscillation peaks were observed (solid line in Fig. 2). The peak heights increase exponentially with the dot-gate voltage, indicating the tunneling nature of the current. The peak separations in Fig. 2 have an average value of 17.2 mV, but they are not perfectly periodic. This is expected, since scanning the dot-gate changes both the dot size and the charge in it. Notice the "on" and "off" drain currents differ by a few orders of magnitude at 0.5 K. Strikingly, the difference is still large at 4.2 K (Fig. 2 dashed line), indicating a quite strong confinement in the dot.

Alternately, we can fix the dot-gate voltage and measure the drain current as a function of the split-gate bias, as shown in Fig. 3. Similar oscillations as those in Fig. 2 appear. However, the peak separation is about 68 mV, much larger than that in Fig. 2. This is because the split gate is far away from the quantum dot and hence it modulates the dot much less effectively than the dot gate.

We also studied the effect of drain bias. Figure 4 shows drain current versus split-gate voltage for five different drain biases from 1 to 5 mV. The measurement were directly taken from HP4145 semiconductor parameter analyzer, which essentially performs a simple dc measurement. As the drain bias increases, the peak widths are widened and the peak-to-valley ratio decreases. At a drain bias of 5 mV, the oscillation peaks smear out into steps. The drain bias behavior indicates that the gaps between energy levels should be around 5 meV.

Th energy gaps in the QD can be determined experimentally in two ways. One is from the temperature dependent study of valley current. Assuming that the current valley occurs when the Fermi level is at the middle of an energy gap, we can write $I_v = A/T \mathrm{sech}^2(\Delta/4k_BT)$, where Δ is an energy gap and A is a proportionality constant.[9] Figure 5 shows the valley current between the third and the fourth peaks in Fig. 2 at different temperatures. The data can be well fitted by the above equation (the solid line in Fig. 5). From the fitting, we found that the energy gap

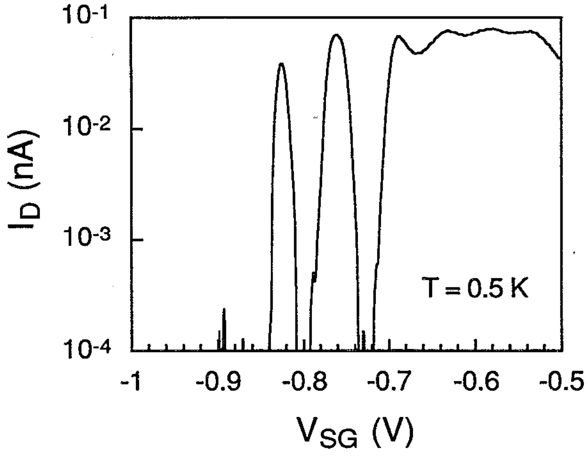

FIG. 3. The drain current vs the split-gate voltage at 0.5 K with the dot-gate voltage fixed at 0.125 V. The ac drain bias is 18 μV.

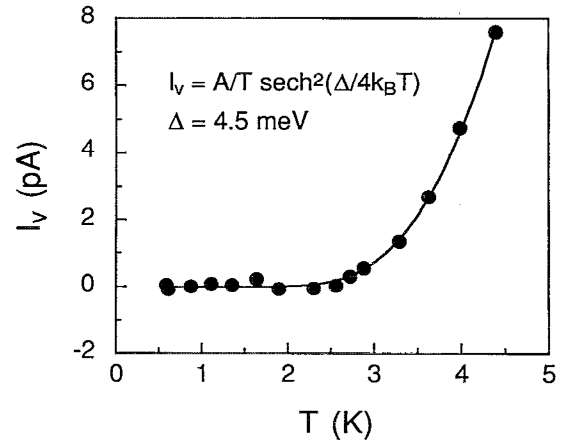

FIG. 5. Thermal activation of valley current. The solid line is the curve fitting which gives an energy gap of 4.5 mV.

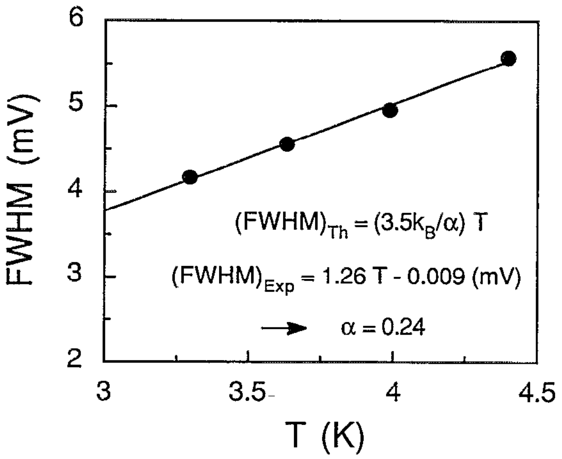

FIG. 6. FWHM of the third peak vs temperature.

is about 4.5 meV, which is consistent with that from the drain bias study. This gap is impressively large for a lateral confined system. The large gap is achieved by using a small dot size and the novel gate structure.

Another way to determine the energy gap is to first obtain the dot-gate modulation coefficient α and then estimate the gap using $\Delta=\alpha\delta V_{DG}$, where δV_{DG} is the spacing of the dot-gate voltage between two adjacent peaks in the I-V characteristics. At high temperature, the width of the drain current peak is dominated by the thermal broadening, and the full width half maximum (FWHM) of a current peak equals to $3.5k_BT/\alpha$ in terms of the dot-gate voltage. By measuring FWHM of the third peak in Fig. 2 as a function of temperature, we obtain $\alpha=0.24$ (Fig. 6). Since the average peak separation is about 17 mV, we obtain $\Delta=4.1$ meV. This agrees with the value obtained previously.

We now discuss whether the energy gaps are caused by quantum-size effect or Coulomb effect or both. Qualitatively, for a disk of a radius R, the quantization energy scales as $1/R^2$ while the Coulomb energy scale as $1/R$. The former dominates if R is small while the latter dominates if R is large. At some intermediate R, both quantum and Coulomb effects are important. For GaAs, this intermediate R is about 50 nm, which is comparable with our dot size. To be quantitative, we first obtain the confinement potential of the QD by solving Poisson's equation. The energy gap is then calculated from the energy difference between two- and one-electron ground states. The calculations include one-particle energy, Coulomb energy and exchange energy. For a dot-gate voltage of 60 mV, we obtain an energy gap of 5.4 mV. This agrees with the experiment. Among this 5.4 mV energy gap, one-particle quantization energy contributes 2.2 mV while Coulomb and exchange energy contribute 3.2 mV. This means that both quantum effect and Coulomb effect are important in determining the energy levels in the QDT. From this point of view, perhaps, the transistor should be called "single electron and quantum effects transistor."

In conclusion, we have proposed and demonstrated a new quantum dot transistor. Strong drain current oscillations have been observed, and they are still distinct at temperature up to 4.2 K or a drain bias up to 5 mV. Temperature dependent study of the electron transport shows the energy gap is as large as 4.5 meV. The large energy gap is due to the small dot size and the novel device structure. Our calculations indicate that both quantum and Coulomb effects are important to the energy levels and transport in the device.

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