Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 1085–1086

Coherent Resonant Transport and Coulomb Blockade Oscillations through Quantum Dot Structures with a Novel Gate Configuration Realized from a Pseudomorphic AlGaAs/InGaAs/GaAs Heterostructure

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Most of single electron transistors have been fabricated from modulation doped GaAs/AlGaAs heterostructures by using a split-gate technique to make a dot tunneling structure. A dot profile, however, is not well defined due to the large depletion and also due to the complicated configuration of the Schottky gates. The large depletion arises from a low carrier density in the GaAs/AlGaAs heterostructures. In this work we have used a pseudomorphic AlGaAs/InGaAs/GaAs heterostructure to fabricate a dot whose profile is well defined by trenches and line Schottky gates. A pair of trenches form a narrow wire and the line Schottky gates placed on the wire form tunnel junctions. The pseudomorphic heterostructure has a sufficiently high carrier density to reduce the depletion length. Thus fabricated single electron transistor has a dot smaller and better defined as compared to that of conventional GaAs/AlGaAs single electron transistors and allow us to study interesting properties of quantum transport.

Our heterostructure is grown by MBE on a (001) GaAs substrate, consisting of a 20nm GaAs cap layer, a 30nm Si-doped AlGaAs layer, a 10nm AlGaAs spacer layer, a 12nm InGaAs well layer, a 300nm GaAs barrier, and an AlGaAs/GaAs superlattice buffer layer. The mobility and electron density of 2DEG are respectively $6.5\times 10^4 cm^2/Vs$ and $9\times10^{11} cm^{-2}$ at 1.6K. A narrow wire is first defined by two trenches using a shallow-etch technique The lateral depletion length is about 0.06um. On top of the wire line Schottky gates are deposited as shown in Fig. 1(a). The position of the gates are precisely aligned to the etched trenches by using the electron beam lithography technique. The gates are isolated by mesa etched wire, which reduces their mutual influence.

Fig. 2. shows coherent resonant tunneling observed in one of the devices. The parameters of the gate structures are given in Fig.1(a) and the geometrical channel width W=0.3um. Application of negative voltage to the gates g3 and g4 depletes the regions beneath the gates and forms potential barriers. So a dot can be formed between g3 and g4. The gate g2 is used to change the number of the electrons in the dot. The gate g1 is not used and Vg1=0V. The small short-period oscillations are Coulomb blockade (CB) oscillations due to the charging effect in the dot. The large amplitude modulation arises from coherent resonant tunneling due to the formation of standing waves (bound states) created from interference effects. The interference effect is probably pronounced because the electrons move in a waveguide defined by the two trenches and tunnel through a dot being like an optical Fabry-Perot cavity. We used an independent-electron Landauer formula to calculate the conductance oscillations due to the coherent resonant tunneling as a function of Vg2. The calculation well reproduces the modulated period. A fraction of the electrons may lose their phase coherence due to inelastic scattering in the dot, and reduces the amplitude modulation. The fact that the mean value of the modulation increases as the tunneling probability is raised by increasing either the drain voltage or temperature confirms that the difference in amplitude between our calculation and our measurement arises from the effect of incoherent tunneling.

Figures 3 and 4 show the CB oscillations observed in the device, whose gate parameters are given in Fig.1(a). The geometry channel width is 0.45um. Dot-1 is defined by the gates g3 and g1, dot-2 by g3 and g4, and dot-3 by g4 and g1, as seen in Fig. 1(b). Fig.3 shows the CB oscillations arising from dot-1, -2 and -3, respectively when only the respective dot is formed by application of relevant gate voltages. The CB oscillation period is about 7 mV for dot-1, 10mV for dot-2, and 40mV for dot-3, respectively, and the values of the periods are in agreement with our calculated values. Fig.4 shows CB oscillations for the two dots in a coupled case. We have observed small short-period oscillations superimposed on the large and long-period oscillations. The short period is the same as that for dot-1, and the long period is the same as that for dot-3. The results can not be explained by stochastic CB. We explain them as the effects of the coupling between the two dots. On the other hand, the results from the two decoupled dots by decreasing Vg4 can be well described by the stochastic CB. We argue that the direct coupling of the wave functions between the two dots is strong, and suppose a model based on coherent resonant tunneling. The fact that the conductance for the small periodic oscillations in the coupled case does not go down to zero also suggests that coherent resonant transport should be considered to explain our experimental results.

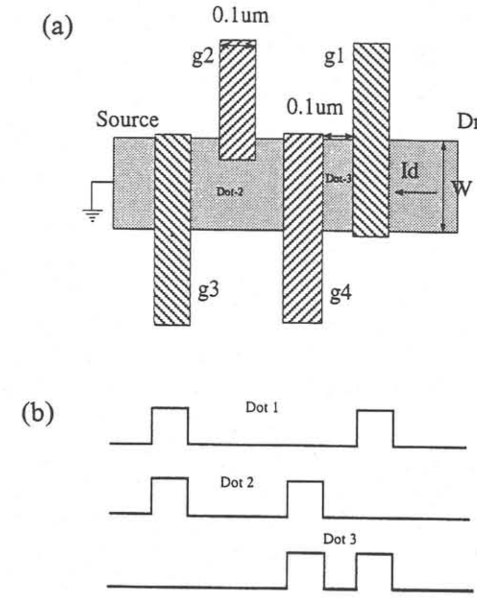

Fig. 1 (a) schematic diagram of the single electron transistors. The parameters of the gate structures for the two devices are the same. The geometry channel widths are different. (b) Energy diagram showing three quantum dots.

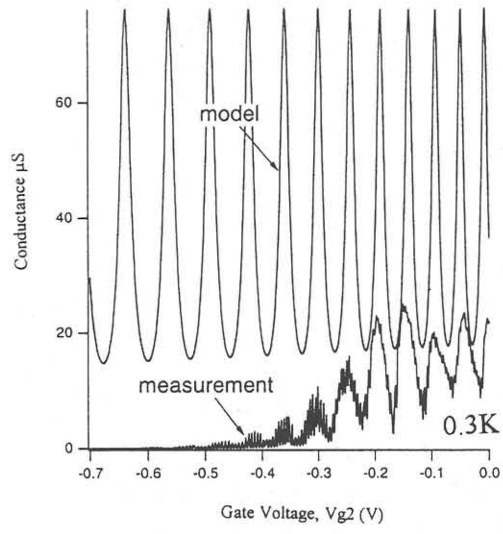

Fig. 2 The CB oscillations as a function of Vg2. the measurement is compared with the modulation of the peak conductance as obtained from our calculation. Vg1=0V, Vg3=−440mV, and Vg4=−440mV.

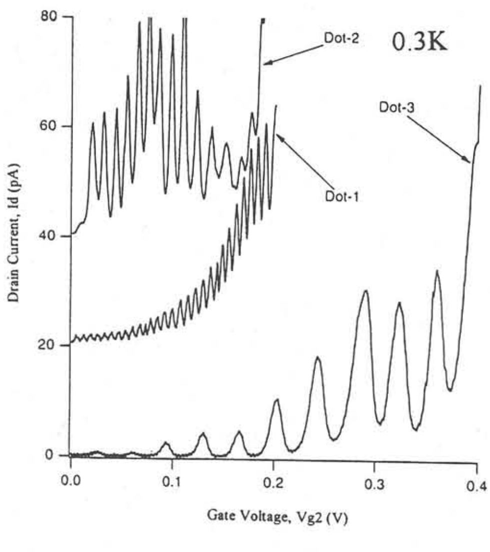

Fig. 3 The CB oscillations as a function of Vg2 for the three respective dots.
Dot-1 : Vg1=−115mV, Vg3=−100mV, Vg4=0
Dot-2 : Vg1=0, Vg3=−100mV, Vg4=−120mV
Dot-2 : Vg1=−115mV, Vg3=0, Vg4=−120mV

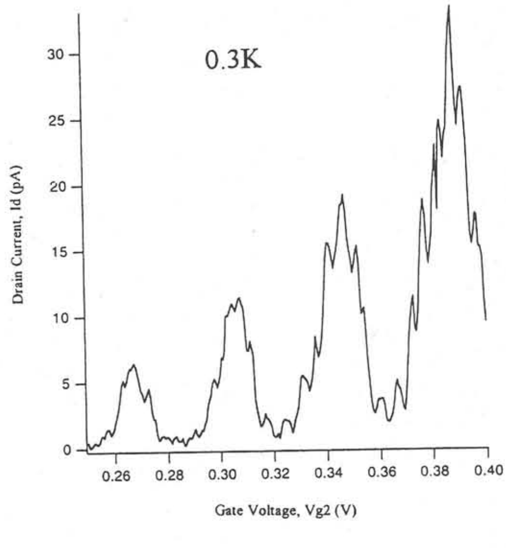

Fig. 4 The CB oscillations as a function of Vg2 for the two coupled dots.
Vg1=−115mV, Vg3=−100mV, Vg4=−120mV