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AlGaAs/InGaAs/GaAs Single Electron Transistors Fabricated by Ga Focused Ion Beam Implantation

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Single electron transistors are formed in an AlGaAs/InGaAs/GaAs modulation-doped heterostructure by Ga focused ion beam implantation. The AlGaAs/InGaAs/GaAs system has a smaller depletion length than the conventional AlGaAs/GaAs system, and the 2D electron gas density is enhanced by the presence of a confining double barrier structure. A sub-μm diameter dot can be easily fabricated from a material with a small depletion length by the maskless process of focused ion beam implantation. Coulomb oscillations and a Coulomb staircase have been clearly observed by controlling three in-plane-gates.

Focused ion beam (FIB) implantation is now available for fabricating semiconductor mesoscopic structures. Ga-FIB implantation, which converts n-type semiconductor to π-type, has been successfully used to study ballistic transport, charging effects in a small dot, etc.[1-4] An extremely small dot structure fabricated by Ga-FIB shows a Coulomb staircase which has a very large voltage step.[3] However, this small dot results from a random distribution of implantation induced damages. A controllable dot structure can be easily formed in a material which has a smaller depletion length. Recently, we have observed ballistic electron transport at room temperature in a Ga-FIB constricted AlGaAs/InGaAs/GaAs modulation-doped heterostructure (MDH).[4] This originates from the small depletion length, and a long electron mean free path at room temperature. The depletion length is reduced to about 0.1 μm, which is also desirable for fabricating a single electron transistor. In this paper, we describe the fabrication of a single electron AlGaAs/InGaAs/GaAs MDH transistor by Ga-FIB and give details of the Coulomb oscillation and staircase characteristics as a function of voltage on the three in-plane-gates.

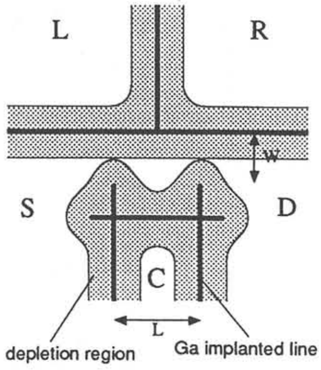

Fig. 1. Schematic diagram of the sample structure. The single electron transistor is controled by three in-plane-gates, L, R, and C.

From the surface the wafer consists of a 200 Å GaAs cap layer, a 300 Å Si doped $Al_{0.3}Ga_{0.7}As$ barrier layer, a 100 Å $Al_{0.3}Ga_{0.7}As$ spacer layer, a 120 Å $In_{0.18}Ga_{0.82}As$ well layer, a 3000 Å GaAs barrier layer, and a $Al_{0.3}Ga_{0.7}As$/GaAs superlattice buffer layer. These layers were pseudomorphicly grown by molecular beam epitaxy on a GaAs substrate. The electron density and mobility of the two-dimensional electron gas (2DEG) at 1.5K are $9x10^{11}cm^{-2}$ and $6.5x10^{4}cm^{2}/Vs$, respectively. Ga ions are implanted at an acceleration energy of 100 keV, and activated by annealing at 760 °C for 15 seconds. The fabrication process is described in more detail in Ref. 4. The small dot and surrounding three in-plane-gates were defined by Ga-FIB as shown in Fig. 1. The Ga ion dose is somewhat larger than that in used previously to prevent leakage in the in-plane-gate operation. The in-plane-gate structure written by Ga-FIB process enables confinement and gate control to be achieved simultaneously. The width, W, and the separation length, L, of the two tunnel barriers ranges from 0.2 to 0.5 μm for W and 0.3 to 0.5 μm for L. A back gate electrode was also fabricated at the bottom of the substrate.

Constrictions whose W is less than 0.4 μm can be set to work in the tunneling regime by changing the respective voltages on the in-plane-gates L or R. The quality of the constriction has been confirmed by observing clear quantized conductance steps at 4.2 K. Figure 2 shows the center gate voltage, V_C, dependence of the two-terminal conductance between the source (S) and the drain (D) in the sample for W = 0.35 μm and L = 0.40 μm. Measurement was performed at 0.3 K and the source-drain voltage, V_{SD}, was 0.3 mV. Clear Coulomb oscillations, which originate from the single electron charging effect,[5,6] were observed. The period of the oscillation is 15 mV indicating that the center gate capacitance is $1x10^{-17}$ F. The amplitude of the conductance oscillation, which is much smaller than $2e^2/h$, varies as a function of gate voltage. This is probably because the center gate voltage also affects the tunneling probability of the constrictions. Similar Coulomb oscillations are observed by changing the left- or right- gate voltage. Almost the same gate capacitance, $C_L = 1.5\times10^{-17}$ F and $C_R = 1.6\times10^{-17}$ F were measured, indicating that the dot is actually formed in the center of the structure as designed. The back gate, whose capacitance is 9×10^{-20} F, can also be used to observe the Coulomb oscillations. By changing the back gate the envelope of the oscillations was found to be identical to that obtained with the center gate. These Coulomb oscillations can be observed even at 1.4 K, but they disappear at 4.2 K.

Figure 3 shows the source-drain I-V and dI/dV-V characteristics measured at 0.3 K. When the gate voltages are set to appropriate values, small steps in the I-V curves and peaks in the derivative plots can be seen around $V_{SD} = 0$ V. The position of the step can be shifted by changing the center gate voltage, V_{CG}. This Coulomb staircase is known to be observed when the tunneling probability of the two constrictions differs significantly. The staircase has a period of about 0.5 mV, which is nearly equivalent to the charging energy of the dot. The condition for the Coulomb blockade, that $e^2/2C > kT$, implies that Coulomb blockade can be observed at temperatures below 3 K. This is consistent with the temperature dependence of the Coulomb oscillations.

In summary, we have fabricated a single electron AlGaAs/InGaAs/GaAs MDH transistor by Ga-FIB. Both the Coulomb oscillations and the staircase characteristics suggest that a small dot can be simply formed by Ga-FIB in a controlled manner. This is largely due to the small depletion length in the AlGaAs/InGaAs/GaAs MDH.

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6) L. P. Kouwenhoven, A. T. Johnson, N. C. van der Vaart, C. J. P. M. Harmans. and C. T. Foxon, Phys. Rev. Lett. 67 (1991) 1626.

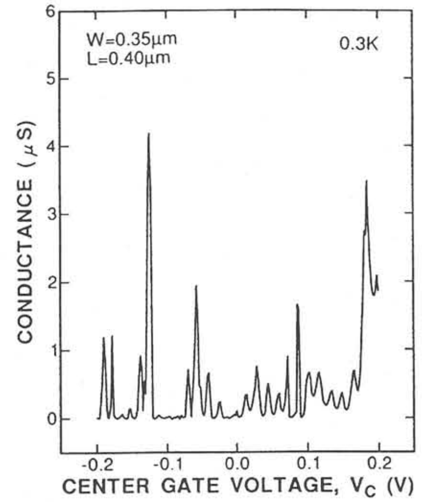

Fig. 2. The center gate voltage, V_C, dependence of two-terminal conductance between the source (S) and the drain (D) in a sample with W = 0.35 µm and L = 0.40 µm. Coulomb blockade oscillations were observed at 0.3 K.

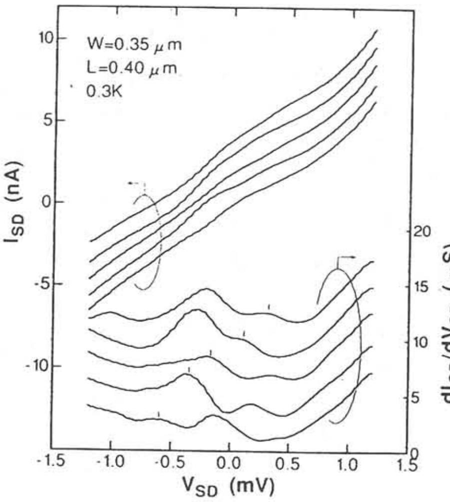

Fig. 3. The source-drain I-V and dI/dV-V characteristics measured at 0.3 K. Small steps forming the Coulomb staircase in the I-V curves are more easily identified in the derivative characteristics. The curves are offset for clarity. From the lowest curves the center gate voltages are from 285 mV to 325 mV.