Quantum dots fabricated by selective area MOVPE and their application to single electron devices

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Abstract. A novel method of formation of uniform GaAs quantum dot (QD) structures, using selective area metalorganic vapour phase epitaxy (SA-MOVPE), and their application to single electron transistors (SETs) are demonstrated. The SiN_x -coated substrates having a wire-like opening with three prominences are used. The wire-like opening is aligned in the [110] direction, which corresponds to channel region of SET. AlGaAs/GaAs modulation-doped heterostructures are grown on these substrates. Due to three prominences on the wire, the quasi-one-dimensional electron gas (Q-1DEG) channel, having a periodic variation in its width, are naturally formed. This leads to the formation of a quantum dot near the central prominence and two tunneling barriers beside the dot, which are connected to quantum wires. I_D - V_G characteristics under constant source-drain bias condition show clear conductance oscillations near the pinch-off, and oscillations are observed up to 65 K. I_D - V_{DS} characteristics measured at 2.1 K show clear Coulomb blockade. The results indicate the formation of SET by SA-MOVPE. Using similar method, resistance-load single electron inverter circuit is also fabricated.

Keywords. Quantum dots; MOVPE; single electron devices.

1. Introduction

Semiconductor quantum wires (QWRs) and quantum dots (QDs) have attracted much attention for new optical device applications, such as quantum dot lasers. Many researchers have reported GaAs and In(Ga)As QD structures fabricated using selective area metalorganic vapour phase epitaxy (SA-MOVPE) (Fukui *et al* 1991; Nagamune *et al* 1993; Lebens *et al* 1990; Kumakura *et al* 1997), and self-organized growth (Leonard *et al* 1993; Temmyo *et al* 1995; Bimberg *et al* 1996). High density In(Ga)As QDs were automatically formed on GaAs substrate by the strain effects, and QD lasers were reported using this self-organized growth mode (Temmyo *et al* 1995; Bimberg *et al* 1996).

At the same time, new quantum functional devices, which consist of such QWRs and QDs, have attracted equal attention, in particular, for fabrication of single electron transistors (SETs), and electron wave interference devices (EWIDs). It is important to connect these QWRs and QDs with tunneling barriers, so as to form the periodically-modulated potential energy.

SA-MOVPE is one of the useful techniques for fabrication of these quantum nanostructures (Fukui *et al* 1991), and has been applied to fabricate optical integrated circuit (Aoki *et al* 1991). Using this selective growth, uniform QD structures can be formed by adjusting the growth conditions as well as substrate orientation and mask pattern, for example GaAs (001) (Nagamune *et al*

1993; Lebens *et al* 1990; Kumakura *et al* 1995), and GaAs (111)B (Fukui *et al* 1991) substrates. QD-network, which is composed of QDs connected with QWRs, was also reported in our previous study (Kumakura *et al* 1997). Thus, SA-MOVPE method holds a promise for its future use in optical devices and optoelectronic integrated circuits (OEIC). The application of QDs to electron transport devices, especially single electron devices, is also a very important research field for future electron devices. For fabrication of these devices, these well-arranged QDs have to be connected to each other. To realize the SET structure, we attempted to fabricate quantum dot-tunnel barrier systems by molecular beam epitaxy on patterned substrates (Dilger *et al* 1996).

In this paper we have presented fabrication process of GaAs SETs using GaAs/AlGaAs modulation-doped structures grown on the masked substrates by SA-MOVPE, and clarify the transport properties. SETs showed Coulomb blockade type conductance oscillation near the pinch-off voltage up to 65 K. Coulomb gap and total capacitance C_Σ was estimated to be 12 mV and 13 aF, respectively.

2. Fabrication process and device structure

Selective area (SA-) MOVPE growth was carried out using a low-pressure horizontal, RF-heated, quartz reactor system. The working pressure of 76 Torr was automatically controlled. Purified hydrogen (H_2) was used as a carrier gas. The source materials were trimethylgallium

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(TMGa), trimethylaluminum (TMAI) and 20% arsine (AsH_3) in H_2 . The partial pressures of TMGa and TMAI were kept constant at 3.8×10^{-6} and 6.3×10^{-7} atm, respectively. The partial pressure of AsH_3 was 1.3×10^{-4} atm for GaAs buffer layer, and 6.7×10^{-4} atm for $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer to achieve better quality, respectively. Growth rates of GaAs and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ were 0.93 and $1.5 \mu\text{m/h}$ for planar substrates, respectively.

SA-MOVPE was carried out on the masked substrates at the growth temperature of 700°C . The layer sequences are as follows; a 400 nm GaAs buffer layer, a 50 nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer, a 15 nm GaAs well layer, a 10 nm undoped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer, a 50 nm n -doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer, and a 10 nm n -doped GaAs capping layer. The mobility and sheet electron concentration of two-dimensional electron gas (2DEG) grown on a planar substrate were $62,000 \text{ cm}^2/\text{V}\cdot\text{s}$ and $1.2 \times 10^{12} \text{ cm}^{-2}$ at 77 K, respectively.

Schematic illustration of the mask pattern for SET structure is shown in figure 1a. The pattern is formed on semi-insulating (001) GaAs coated with 40 nm-thick SiN_x layer by electron beam lithography and wet chemical etching. The wire-like opening with three prominences aligned in the [110] direction corresponds to channel region of SET.

Figure 1b shows SEM image after the selective growth, and figure 1c the schematic illustration of the device structure. The wire region consists of {111}B facet sidewalls, and {110} facet sidewalls are formed near the prominences. A (001) plane appeared on the top portion of the whole structure. Due to three prominences on the wire, the quasi-one-dimensional electron gas (Q-1DEG) channel has periodic variation in its width and thickness. This leads to the formation of a quantum dot near the central prominence and two tunneling barriers beside a dot, which are connected to quantum wires. For reference, quantum wire was also grown on masked substrate without prominences. The channel width of the present Q-1DEG is 400 nm by SEM observation.

After the growth of these structures, source and drain Ge/Au/Ni ohmic electrodes were formed on the wide 2DEG regions (figure 1b) by a lift-off process followed by alloying at 350°C for 5 min in N_2 atmosphere. Next, Schottky gate of Al electrode was formed by a lift-off process on the three prominences region. Since no growth occurs on {111}B facets, both edges of the Q-1DEG channel are exposed to air. Therefore, Schottky gate has direct contact at the edges of the Q-1DEG, and controls the electric field perpendicular to the edges. The gate length is $5 \mu\text{m}$.

3. Transport properties of GaAs single electron transistor structure

Figure 2 shows I_D - V_G characteristics of quantum dot structure connected with quantum wires with constant source-drain bias condition ($V_{\text{DS}} = 200 \mu\text{V}$) for various

temperatures. Clear conductance oscillations were observed near the pinch-off, and oscillations were observed up to 65 K. We have already fabricated several devices with the same structure. Although the pinch-off gate voltages were slightly different in each device due to run-to-run fluctuation of the doping carrier density for the MOVPE growth, clear conductance oscillations were observed for these devices. These results suggest that three prominences in the channel region play an important role for the conductance oscillations.

Figure 3 shows typical I_D - V_{DS} characteristics measured at 2.1 K, which shows clear Coulomb blockade effect. Coulomb gaps and their modulation by the gate voltage were seen near the pinch-off voltage. The maximum

Figure 1. (a) Schematic illustration of SiN_x masked substrate for selective area MOVPE, (b) SEM image after the selective growth on the masked substrate, and (c) schematic illustration of the device structure.

Coulomb gap Δ is about 12 mV, which corresponds to a thermal energy kT of 140 K. Following a simple model of Coulomb blockade, the total capacitance C_Σ of the dot can be estimated to be about 13 aF from $\Delta = e/C_\Sigma$. The radius R of the dot is estimated to be about 14 nm, using the relation of $C_\Sigma = 8\epsilon\epsilon_0 R$.

The possible mechanism for the formation of small dot and tunneling barriers was as follows: When the depletion layer from the surface and both edges of Q-1DEG is expanded by applying the negative gate voltage, potential energy modulation was formed due to variation of effective channel width. The conductance oscillation far from the pinch-off voltage was thought to be the result of electron wave interference, similar to Si quantum dot (Leobandung *et al* 1995). Near the pinch-off voltage, the difference of the width of depletion layer from the edges of Q-1DEG and/or the thickness variation of GaAs channel due to three prominences may lead to formation of small dot and wires with tunneling barriers. Therefore, Coulomb blockade type conductance oscillation was observed near the pinch-off gate voltage.

4. Resistance-load SET inverter circuit

Next, we fabricated resistance-loaded SET inverter, which corresponds to that proposed by Likharev (1987). Figures 4a and b show a scanning electron microscope

Figure 2. Temperature dependence of I_D - V_G characteristics.

Figure 3. Typical I_D - V_G characteristic at 2.1 K.

Figure 4. (a) SEM image of the device structure grown on this masked substrate, and (b) the equivalent circuit of the device, which corresponds to resistance-loaded SET inverter circuit proposed by Likharev (1987).

(SEM) image of the device structure grown on the masked substrate and equivalent circuit of the device. In this device, Al Schottky contact was additionally formed on load resistance part. The length between source and drain electrodes was $10\text{ }\mu\text{m}$, and the widths of Al Schottky contact for the SET- and R_L -control gates were $2\text{ }\mu\text{m}$ and $1\text{ }\mu\text{m}$, respectively. It can be possible to set the optimized value of the R_L in the inverter circuit by only applying gate voltage, V_R . Initial resistance value of R_L without applying the V_R was roughly estimated to be several $\text{k}\Omega$, then, this value can be controlled, e.g. about $60\text{ k}\Omega$ by applying the V_R of -3.6 V in this experiment.

The drain current, I_D versus SET-control gate voltage, V_G characteristics of this device were measured at 1.9 K with V_R of 0 V and -3.6 V for the constant source-drain voltage, V_{DS} of $200\text{ }\mu\text{V}$. Figures 5a and b show I_D - V_G characteristics. Clear and similar conductance oscillations near the pinch off gate voltage were observed for both V_R of 0 V and -3.6 V . In particular, the periods of oscillation peaks were the same for both measurements, thus, V_R did not affect the conductance oscillations at all. Figures 6a and b show I_D - V_{DS} characteristics of this device with V_R of 0 V and -3.6 V , and with different V_G values indicated in figures 5a and b by arrows, respectively. Clear Coulomb gaps and their modulations

Figure 5. Drain current, I_D vs SET-control gate voltage, V_G characteristics of the device with V_R of (a) 0 V , and (b) -3.6 V for the constant source-drain voltage, V_{DS} of $200\text{ }\mu\text{V}$ measured at 1.9 K .

Figure 6. I_D - V_{DS} characteristics of the device with V_R of (a) 0 V , and (b) -3.6 V , and with different V_G values indicated in figures 5(a) and (b) by arrows.

Figure 7. $V_{out}-V_{in}$ and I_D-V_{in} characteristics of this inverter circuit.

were observed for both cases. The maximum Coulomb gap in this sample is about 6 mV, and total capacitance, C_Σ of the dot can be estimated to be about 27 aF, which corresponds to the dot radius of 28 nm. These results indicate that V_G and V_R do not interfere with each other, and can be controlled independently.

Next, I_D-V_{in} (input voltage) and V_{out} (output voltage)- V_{in} characteristics were measured at 1.9 K under the constant V_{DS} (V_{dd}) condition. Figure 7 shows I_D-V_{in} and $V_{out}-V_{in}$ characteristics of this inverter circuit. V_{DS} was 500 μ V. V_{in} corresponds to the gate voltage, V_G for the SET. Open and solid circles correspond to I_D versus V_{in} and V_{out} versus V_{in} in the Coulomb blockade region near the pinch off gate voltage. V_{peak} in the x-axis means one of the conductance peaks in the Coulomb oscillations. As V_{in} was swept from V_{peak} (i.e. $V_{in} - V_{peak}$ of zero) to the negative gate voltage, V_{out} was smoothly increased, clearly showing the inverter operation. From I_D-V_G and I_D-V_{DS} measurements with applying the gate voltage, V_R to the R_L , conductance oscillation was originated from Coulomb blockade effects. Although the value of the load resistance was set at 60 k Ω by applying the gate voltage, V_R , R_L value was estimated to be about 7 k Ω from I_D and V_{out} characteristics. For $I_D=0$, V_{out} should be 0.5 mV, but actual value of V_{out} was 0.37 mV. These discrepancies are not well understood yet. At present, the logic swing, ΔV_{out} relative to the ΔV_{in} ($\Delta V_{out}/\Delta V_{in}$) is small. We can fabricate higher gain inverter circuit for further optimi-

zation of device parameters, such as, the value of load resistance, tunneling resistance, dot size and so on.

5. Summary

We have demonstrated GaAs quantum dot connected with GaAs quantum wires by SA-MOVPE, and applied these structures to GaAs SETs and resistance-load single electron inverter circuit. Their transport properties were investigated at low temperature. In SETs, near the pinch-off voltage, Coulomb blockade type conductance oscillations were observed up to 65 K. Coulomb gap and total capacitance C_Σ were estimated to be 12 mV and 13 aF, respectively. Next, the inverter operation using this SET with load resistance was confirmed. Therefore, it is possible to form the SET integrated circuits by further optimization of the mask shape, growth conditions and device parameters.

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