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Realization of GaAs-Based Single Electron Devices Having Single and Multiple Dots by Schottky In-Plane-Gate Control of Two Dimensional Electron Gas

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Novel GaAs single and multiple dot single electron transistors (SETs) based on Schottky in-plane-gate (IPG) control of 2DEG have been successfully fabricated. Dot formation and transport in single-dot and multiple-dot SETs were investigated both theoretically and experimentally. All the fabricated devices showed clear Coulomb blockade (CB) oscillations which were roughly consistent with theory, indicating that the present approach is extremely useful for realization of complex functional devices.

1. Introduction

In spite of rapid progress towards high temperature operation of single electron transistors (SETs) recently made by Si-based SETs, GaAs-based SETs reported so far mostly operate in mK range. This is predominantly due to the split gate potential control which produces a rather weak and gradual confinement potential with soft-wall potential boundaries unlike the Si-SiO_2 interface. On the other hand, we have recently proposed and fabricated a novel GaAs SET based on Schottky in-plane-gate (IPG) control of two dimensional electron gas (2DEG) where electric fields perpendicular to the 2DEG edge realize stronger confinement. The device showed Coulomb blockade (CB) oscillation up to 20K.[1]

The present paper investigates, both theoretically and experimentally, dot formation and transport in single-dot, double-dot and multiple-dot SETs based on Schottky IPG control of 2DEG formed at AlGaAs/GaAs heterointerface in order further to explore the possibilities of our novel approach. It is shown that the present IPG-based SET structures are extremely promising for realization of multi-functional SET devices.

2. Basic Structure and Computer Simulation of IPG SET Devices

The basic structures and principles for single- and multiple-dot devices are schematically shown in **Fig.1(a)-(d)**. Schottky IPGs can control the electric field perpendicular to the edge of 2DEG plane and produce strong and efficient confinement of electrons within a quantum dot.[2-4] In these structures, dot sizes and tunneling barriers are voltage-tunable, allowing various conventional as well as "turnstile" operations. For example, the device in **Fig.1(c)** and **(d)**, having multi finger gates, may be operated for example as a "single electron shift register". Other more complex functional devices seem to be feasible by proper design of 2DEG bars and IPGs.

The cross sections of structures are shown in **Fig.2**. **Figure 2(a)** shows the original proposal of the IPG structure.[5] Its slight modification in **Fig.2(b)** is also obviously possible and may be more useful in some applications for SET devices.

For SET device simulation, potential distributions in the Schottky IPG structures were calculated in the classical regime by solving 3-dimensional Poisson's equation with the successive over relaxation (SOR) method. For transport calculation, WKB approximation and Beenakker's formula for conductance[6] were used.

Examples of calculated dot shape and tunneling barrier profiles are shown in **Fig.3** for a single-dot device structure given in **Fig.1(a)**. Formation of quasi-elliptic dot is clearly seen. Tunnel barriers and electron number in the dot are controlled by IPG voltage as shown in **Fig.3(b)**. **Figure 4** gives the calculated potential distribution of the multiple-dot device of **Fig.1(c)** with a cross-section of **Fig.2(b)**. An elliptic dot chain is formed with proper gate biasing and the dot size can also be controlled by gate bias.

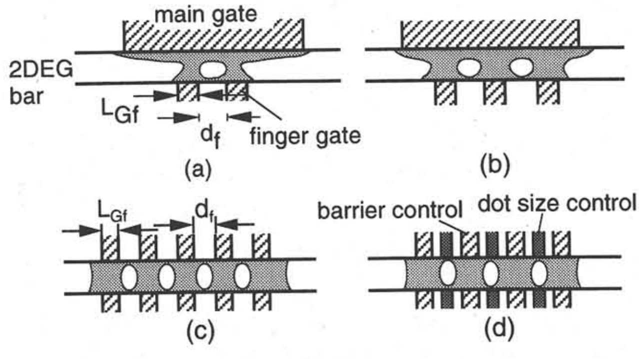


Fig.1. Basic structures and principles.

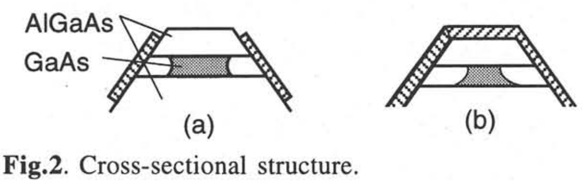


Fig.2. Cross-sectional structure.

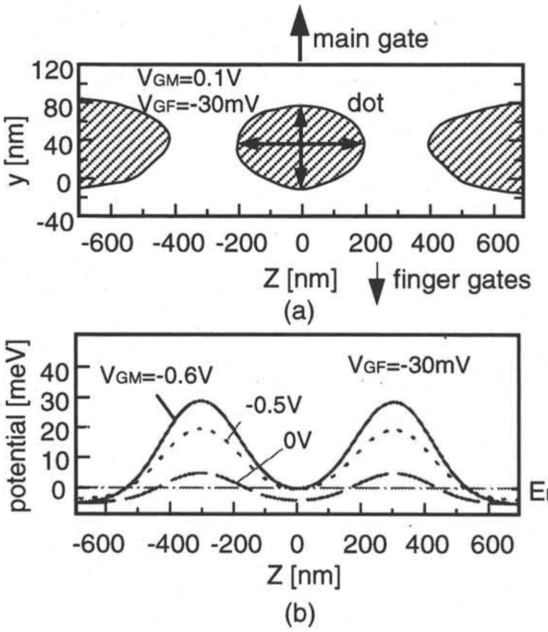


Fig.3. (a) Dot shape, (b) tunneling barrier profiles for single-dot device.

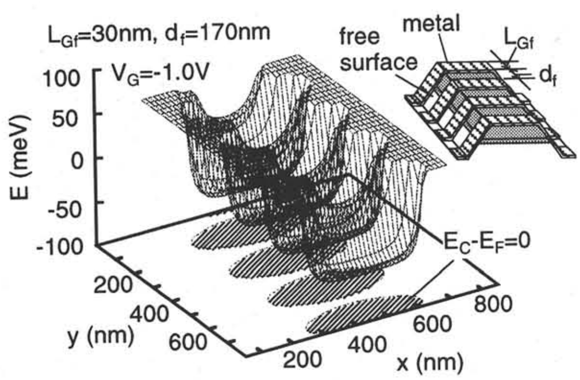
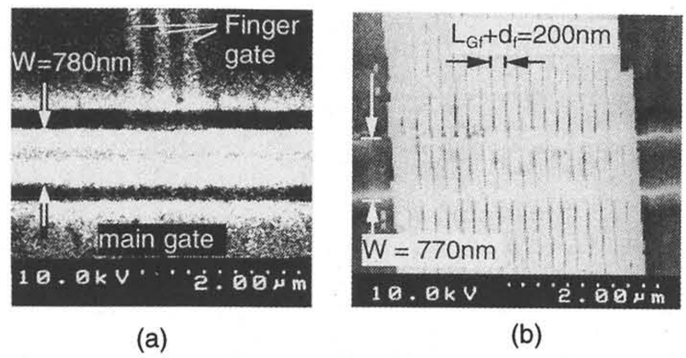


Fig.4. Potential distribution of the multiple-dot device.

3. Device Fabrication

In this study, single dot and double dot devices with the cross section of **Fig.2(a)** and 18-dot multiple dot device with the cross section of **Fig.2(b)** were fabricated. First, $Al_{0.3}Ga_{0.7}As/GaAs$ double-hetero QW structures were grown by standard MBE growth at substrate temperature of 600°C. Submicron 2DEG bars were formed by EB lithography and wet chemical etching. Schottky IPG electrodes with a few hundred nm intervals were defined by EB lithography, and formed either by Pt plating using an in-situ electro-chemical process[7] or by conventional Cr/Au lift-off process for the structures. SEM micrographs of fabricated double-dot and multi-dot (18 dot) SETs are shown in **Fig.4**. For double-dot device, L_{Gf}=200nm and d_f=200nm were realized. For multiple-dot device, L_{Gf}=30nm and d_f=170nm were realized.



(a) (b)

Fig.5. SEM images of (a) double-dot device and (b) multi-dot device.

Table 1. Device dimension and observed CB characteristics of single-dot devices.

device	d_f (nm)	L_{Gf} (nm)	W (nm)	*1 ΔV_G (mV)	*2 ΔV_Σ (mV)	*3 T_{max} (K)
A	600	400	600	5~10	–	3.4
B	600	200	800	10~20	–	10
C	400	200	550	10~15	6	20
D	200	200	600	70~100	10	30

*1 ΔV_G (mV): CB oscillation period
*2 ΔV_Σ (mV): observed Coulomb gap
*3 T_{max} : maximum temperature of CB oscillation observation

4. Experimental Results and Discussion

Examples of the observed CB oscillation and CB characteristics from the fabricated single-dot device are shown in **Fig.6(a)** and **(b)**. The observed correlation between device dimension and CB characteristics is summarized in **Table 1**. CB oscillation was visible in Sample D up to T_{max}=30K which was much higher than that of the split-gate SETs. The Coulomb gap is estimated to be 10mV, also corresponding to the observed maximum temperature of the Coulomb oscillation of 30K. As shown in **Table 1**, the reduction of device dimension enhanced the maximum temperatures of CB oscillation observation. Further reduction of finger gate spacing into 50 nm should realize 77-300 K operations.

The observed CB oscillation from the fabricated double-dot and multiple-dot (18-dot) devices are shown in **Fig.7(a)** and **(b)**, respectively. In the double-dot device shown in **Fig.5(a)**, peaks in hatched region clearly split into two peaks with decrease of the inter-dot barrier height through the control of the middle finger gate voltage V_{GF2}. This seems to be due to the inter-dot coupling effects, although the behavior of the peaks is far more complicated than what is expected from the classical capacitive coupling. One of the possible reason for this is capacitance mismatch between the two dots.[8] The multiple-dot devices also showed clear CB oscillations, as shown in **Fig.7(b)**. Asymmetric peak shapes were obtained, probably indicating that each peak

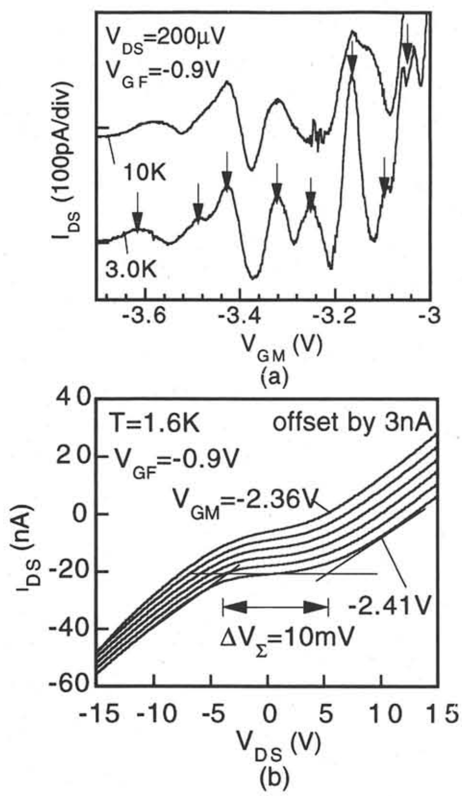


Fig.6. Observed (a) Coulomb oscillation and (b) Coulomb blockage of single-dot device.

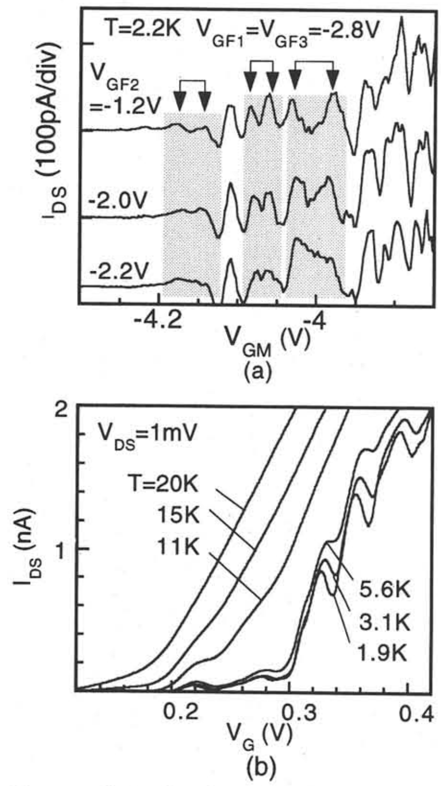


Fig.7. Observed Coulomb oscillations of (a) double-dot and (b) multiple-dot devices.

consists of some fine peaks due to multiple inter-dot coupling. The CB oscillation was observed up to 15K even when V_{DS}=1mV.

Conductance peak separations in CB oscillations for the single-dot and multiple-dot devices were simulated

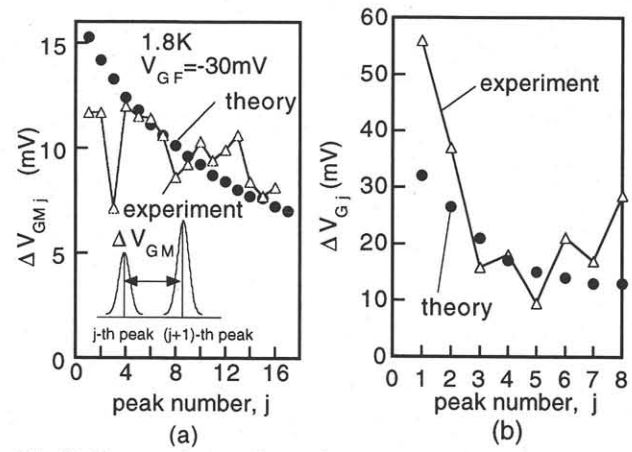


Fig.8. Comparison of conductance peak separation of (a) the single dot and (b) multi dot device between theory and experiment.

by using a 3-D potential calculation. Reasonably good semi-quantitative agreements were obtained between theory and experiment as shown in **Fig.8(a)** for single-dot device and **(b)** for multiple-dot device, respectively. However, a design theory in quantum mechanical regime including the dot-dot interaction is required for full understanding and description of behavior of single- and multiple-dot devices.

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