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Single Electron Transistor Using GaN Coupled Quantum Dots Formed on SiO_2/Si Substrate

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1. Introduction

Quantum coherent states produced by coupled quantum dots (QDs) will produce new solid-state devices such as quantum logic gates. [1] So, formation of coupled QDs is important for new device fabrication. However, no one knows which material is best for realization of the devices. Material research is also required from the viewpoints of dephasing time of the coherent state, device operation temperature, industrial easiness and so on. Quantum dot structure of wide band gap GaN and related nitride materials are of great interest since large conduction band offset of 2.3 eV at GaN/AlN interface [2] provides strong electron confinement in their quantized levels and the small dimensions make energy scale in their system large. Dephasing time of an electron in the GaN quantum dots is also expected to be long because large electric field due to spontaneous polarization confines the electron at surface regions apart from the substrate. [2] In this study we have proposed new technique to fabricate coupled QDs using self-assembling technique, in which Ga droplets are formed on the substrate surface and they are crystallized by nitrogen supply and enlarged by crystal growth in order to make the coupled QDs with small size. The electrical transport properties of the coupled QDs were investigated by making single electron transistors for future device applications.

2. Experimental

Fabrication process of a single electron transistor is shown in Fig.1. GaN QDs were formed on SiO_2/Si (001) substrates by gas-source molecular beam epitaxy (GSMBE) in which solid Ga and ammonia were used as group III and V sources. The substrate was introduced into the GSMBE chamber and thermally cleaned in ultrahigh vacuum at 700°C. After cooling the substrate temperature down to 300°C, Ga molecules were supplied to form Ga droplets (Fig. 1 (a)) and they were annealed with an ammonia gas supply for 10 min at 800°C for crystallization. (Fig. 1 (b)) **Then the GaN QDs were enlarged to form the coupled QDs by MBE technique** (Fig. 1 (c)) and the surface was covered with a thin AlN layer as a tunneling barrier. (Fig. 1 (d)) The QD structure was observed by scanning electron microscopy (SEM). Single electron transistors (SETs) were fabricated by electron beam lithography and lift-off process of evaporated Au/Al film on the substrate. (Fig. 1 (e)) Electron transport properties through the coupled QDs were investigated by connecting the dots with source and drain electrodes. (Fig. 1 (d))

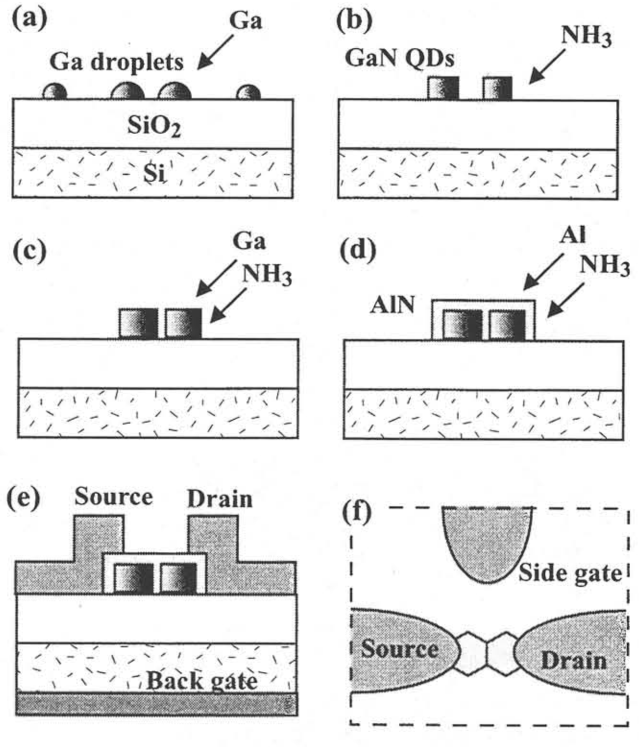

Figure 1 Fabrication process on SET using GaN QDs. (a) Ga droplet formation (b) GaN QD nucleus formation by crystallization process. Small droplets are vanished by evaporation and coalscence processes. (c) Coupled QDs formation by enlargement process (d) Coupled QDs were covered with AlN barrier layer. (e) Electrodes were formed by lift-off process of Au/Al films. (f) Top view of SET.

3. Results and Discussion

A SEM image of GaN coupled QDs obtained by self-assembling technique is shown in Fig.2. A couple of QDs is found to be contacted each other to form coupled QDs. The diameter of GaN is approximately 30 nm and typical distance between source and drain electrodes was 30 nm, so that multi-tunneling junctions are fabricated between the electrodes. Figure 3 shows typical transport properties of SET measured at 6 K using the electrode alignment shown in Fig 1(f). Side gate voltages were changed from -0.5 V to -1.1 V with increases of -20 mV. Each curve has an offset of 100 pA. It is found that Coulomb blockade regions in Vsd are not closed but are slightly modulated by the gate voltage changes. So-called stochastic Coulomb blockade is observed.

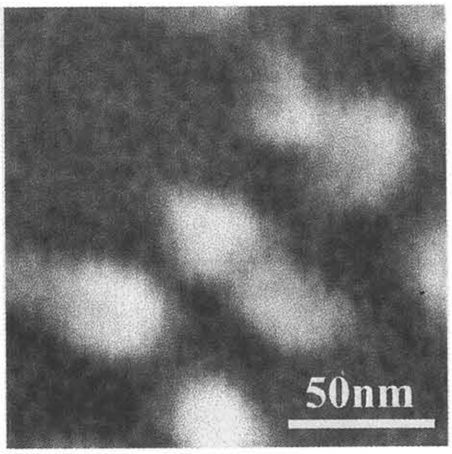

Figure 2 SEM image of GaN coupled QD obtained by self-assembling technique.

Figure 4 shows transport property for another device measured at 2.7 K. In this device, large Coulomb gap more than 0.5 V is observed. In addition, reproducible negative differential conductance is observed in this device. This origin of the phenomenon is considered to be resonant tunneling between zero dimensional states in coupled QDs. This is a first evident that GaN coupled QDs were obtained.

4. Conclusions

GaN coupled QDs were formed on SiO_2/Si substrate by GSMBE using new self-assembling coupled QDs formation technique. SETs using GaN coupled QDs showed Coulomb blockade phenomena with negative conductance due to resonant tunneling effects in coherent states produced in GaN coupled QDs. This technique opens a new way toward fabrication of devices using coupled coherent states like quantum logic gates.

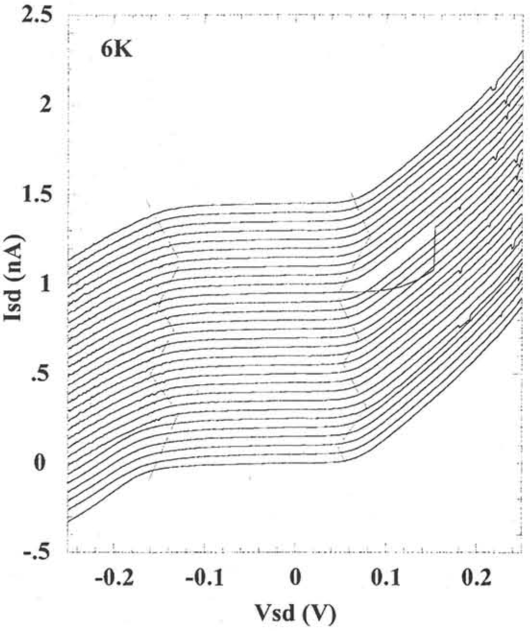

Figure 3 I-V characteristic of a SET at 6 K. Side-gate voltages were changed from -0.5 V to -1.1 V with increases of -20 mV. Each current has an offset of 100 pA. The regions between dashed lines correspond to blockade regions.

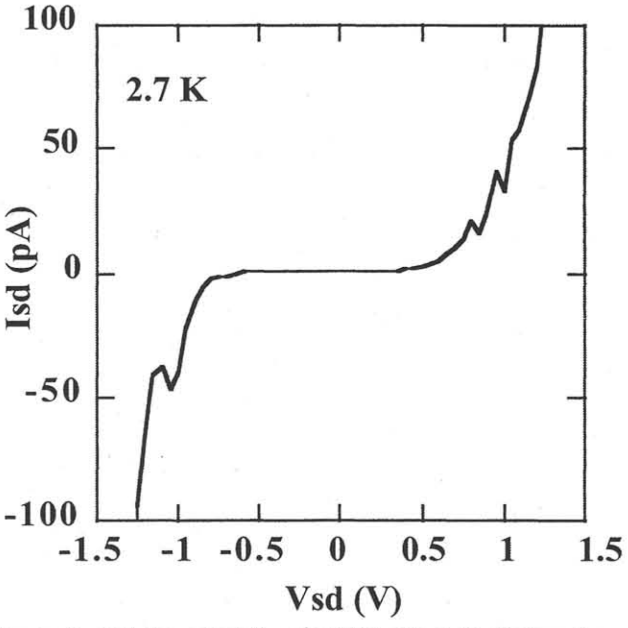

Figure 4 I-V characteristic of a SET at 2.7 K. Gate voltages was 0 V.

References

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