Study of metal-insulator transition of the quasi-two-dimensional hole system in the δ-doped GaAs structures

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1. Introduction

In recent years metal-insulator transitions have attracted a great deal of attention in the area of condensed matter physics. The main reason for this interest is that at a metal-insulator transition the electronic structure of a material changes drastically and, hence, novel electronic properties often emerge in the vicinity of the condition of the metal-insulator transition[1]. As famous examples of such phenomena, high temperature superconductivity occurs in cuprate oxides and colossal magneto-resistance was found in maganites. Metal-insulator transitions are known to occur in these materials.

The metal-insulator transitions in doped semiconductors, which are often called Mott transitions in spite of the main role of the Anderson localization in this case, have been extensively studied since 1950s both theoretically and experimentally. These metal-insulator transitions, however, can occur only at very low temperatures around the liquid He temperature and, therefore, have been studies only from a point of view of the theoretical interest. If one can grow a layered structure where a metal-insulator transition resulting from impurity doping occurs at room temperature, we may have an opportunity to explore novel electronic properties in the vicinity of the metal-insulator transition. Such novel electronic properties may have a great deal of chance for technological applications because of the room temperature occurrence and technological maturity of semiconductor materials.

The purpose of this research is to explore unique potential of MBE in order to obtain new electronic properties of semiconductor materials, in particular GaAs whose MBE growth condition is best established at present. By using MBE we first try to grow layered structures where a metal-insulator transition occurs at room temperature and investigate electrical properties resulting from the metal-insulator transition.

2. Experiment

Figure 1 schematically shows a sample structure and an energy diagram corresponding to this structure without transfer of carriers. The Be δ- doping and growth of a GaAs spacer layer were carried out at 450 ℃, and therefore, doped Be atoms are expected to act as acceptors and form a narrow triangular-like potential well for holes as shown in Fig. 1(b). In the ultrathin LT-GaAs layer antisite As atoms, As_{Ga}, form midgap donor states whose energy levels are known to be located at approximately $E_V + 0.7$ eV where E_V is the valence-band edge[2].

Samples were grown by utilizing a conventional MBE system. Semi-insulating epiready (100) GaAs wafers were used as substrates and mounted on a Mo holder with indium. A Ga flux used throughout growth

experiments was 5.8×10^{-7} Torr, which gave rise to a growth rate of 0.9 ㎛/h. After growth of the buffer layer, the sample temperature was lowered to 450 ℃ for Be δ doping and growth of a GaAs spacer layer with a thickness of 1 nm. The lower sample temperature was chosen for minimizing diffusion and surface segregation of Be[3].

Immediately after growth of the spacer layer, the sample temperature was lowered for growth of LT-GaAs layers. For setting the growth temperature, the sample temperature was first set at 200 ℃ by using a pyrometer and then further lowered by 50 ℃ which was confirmed by reading a thermocouple placed behind the substrate holder. An ultrathin LT-GaAs layer with a thickness of 1 nm was grown with an As flux of 3.0×10^{-5} Torr followed by growth of a LT-GaAs cap layer with a thickness of 5 nm. The condition used for the growth of the ultrathin LT-GaAs cap layer is known to give rise to a high concentration of antisite As atoms without forming the extended defects according to our earlier study[4]. An As flux for growth of the GaAs cap layer is 6.2×10^{-6}Torr, which is known to give rise to a nearly stoichiometric LT-GaAs layer with the aforementioned growth rate[5]. The cap layer was grown in order to prevent oxidation of the ultrathin LT-GaAs layer in air.

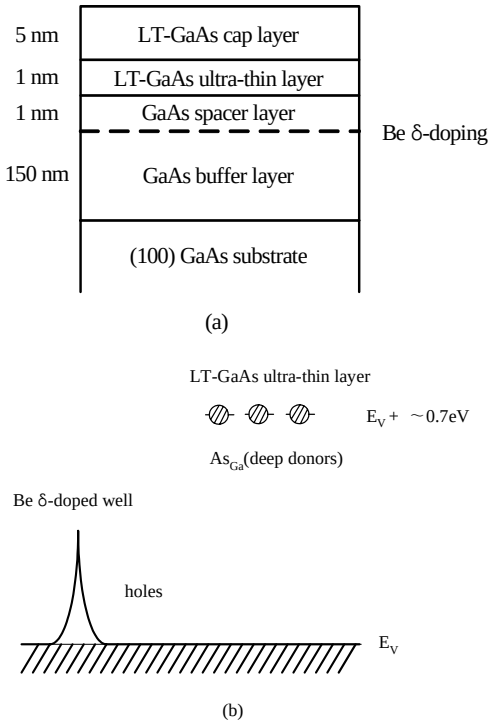

FIG. 1(a) Structure of the -doped GaAs samples. Layer thickness are shown on the left-hand side. (b) Energy diagram of a Be -doped well and antisite As atoms. Shaded regions represent the states occupied by electrons.

A square 5 × 5 mm sample was cut for the van der Pauw and Hall effect measurements, and an In contact was made at each corner of a sample. No annealing was made for making contacts, but good ohmic contacts were obtained in all samples.

3. Results and discussion

Figure 2 shows the temperature dependence of the resistivity of 17 samples in the temperature range from 5 to 350 K. The Be doping concentration decreases monotonically from sample 1 to 17. The resistivity of the samples increases with a decrease in the Be concentration. The resistivity of nine samples with lower Be concentrations, from samples 9 to 17, which are denoted by open symbols, monotonically increases with lowering the temperature in the whole measurement temperature range. The resistivity of eight samples with higher Be concentrations from the sample 1 – 8, which are denoted by solid symbols, initially decreases with lowering the temperature, exhibiting metallic behavior, but starts to increase in the temperature range approximately between 255 and 200 K. With further lowering the temperature towards 0 K, the resistivity of these samples continues to increase. The resistivity of sample 9, whose Be concentration is the middle of

those of 17 samples, remains nearly constant in the temperature range from 350 to 275 K, and shows insulating behavior in the lower temperature range.

Figure 3 shows the relationship between the Be concentrations and the activation energies ε_1 which were derived from nearly linear changes of the Arrhenius plots of the samples from 9 to 17. In the figure, [Be] is the Be concentration of a sample, and $[Be]_c$ is the critical Be concentration 6.40×10^{13}cm^{-2} whose value was determined by extrapolating a linear change of activation energies ε_1 of the sample from 13 to 9 towards zero. The density of states D(E) in a quasi-two-dimensional electron system is given by

$$D(E) = j\frac{4\pi m^*}{h^2}$$

where j is the number of occupied subbands and m^* is an effective mass. For heavy holes($m^* = 0.62m$), the value of $4\pi m^*/h^2$ is 2.58×10^{11} meV^{-1}cm^{-2}[6]. The slopes of linear changes in Fig. 3 were found to be in the order of this value. Hence, by assuming that the slopes correspond to D(E) of heavy holes, the numbers j were derived for two parts of the linear change of ε_1 by using the least square method; they are 2.08 ± 0.23 and 1.03 ± 0.07 for the low and high activation energy parts, respectively. The close agreement between the slopes of linear changes in Fig. 3 and the density of states in the quasi-two-dimensional hole system implies that holes in the Be δ-doped layers behave as a quasi-two-dimensional system even at room temperature, where the activation energy corresponds to the energy difference between the Fermi level and the energy of the critical extended state. The value of j further suggests that the Fermi level is located in the lowest subband of heavy holes in the high activation energy part and the critical extended state is located in the second lowest subband.

A model of percolation via quantum point contacts is used for the analysis of the temperature-dependence of the resistivity. The thermally activated conduction in metallic side at low temperature is explained by assuming the existence of more than one percolation threshold which result from the

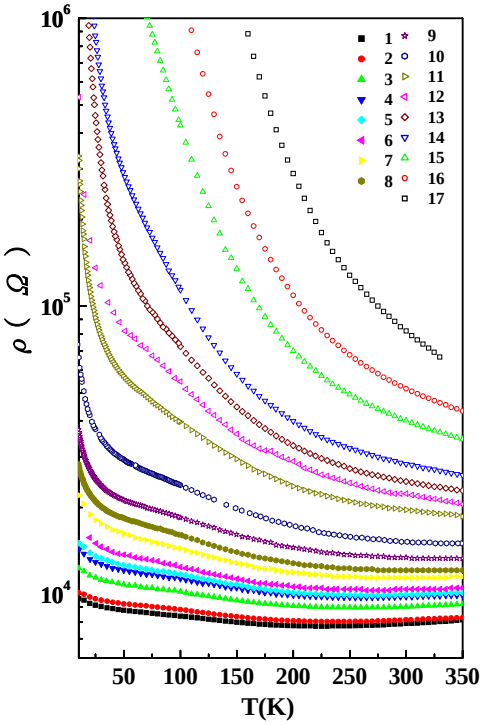

FIG. 2. Temperature dependence of the resistivity of 17 samples with different Be doping concentrations.

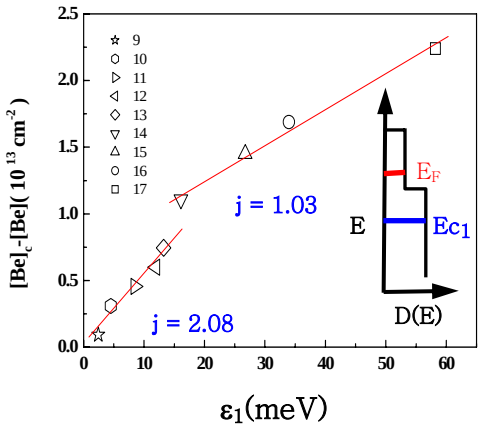

FIG. 3. Relationship between the Be concentrations and the activation energy. The inset schematically shows the energy band of the Be -doped layer where and are the Fermi level and the first percolation threshold, respectively

nature of quantum point contacts.

The temperature dependence of the resistivity in both insulating and metallic side at high temperature exhibits a scaling behavior similar to that observed in Si-MOSFET and other two-dimensional electron systems[7]. These results suggest that the transition found in this structure is closely related to a continuous phase transition, namely quantum phase transition.

4. References

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