Study on the transport mechanism by the localized carriers in GaAs layers grown by molecular beam epitaxy

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Background

In recent years metal-insulator transitions have attracted a great deal of interest and have been extensively studied in condensed matter physics. The reason for this is that at the transition electronic properties drastically changes due to enhanced electron-electron interactions and, hence, novel electronic properties such as colossal magneto-resistance and superconductivity often emerge under the close to the transitions[1]. For example, for a Cu-oxide being a high T_C superconductor, it exhibits superconducting behavior at the vicinity of critical point of Mott transition.

In impurities doped semiconductor, conduction occurs via hopping among impurity ions at low temperatures and at low concentrations. With increasing impurity concentrations in a semiconductor, an impurity band forms due to the overlap of wave functions of electrons at impurity atoms. Anderson has proposed that localization occurs due to the disorder (random potentials) in this band[2], while Mott suggested that there may be the contribution of the electron-electron interaction to such carrier localization[3]. In general Anderson localization is thought as the origin of localization of carriers in the impurity band since impurity atoms are randomly distributed in a semiconductor. With a further increase in the impurity concentration beyond a certain critical value, however, carriers start to move freely without activation energy. The metal-insulator transition occurs in this way. In past metal-insulator transitions in impurity doped semiconductors have been studied mainly from a view point of theoretical interest because these transitions can occur only at very low temperatures around liquid He temperature due to thermal excitation of carrier from shallow impurity levels to either conduction or valence bands. If one can grow a crystal layer in which a metal-insulator transition occurs at room temperature, it will stimulate theoretical interests but also lead to a new possibility for the application to electronic devices.

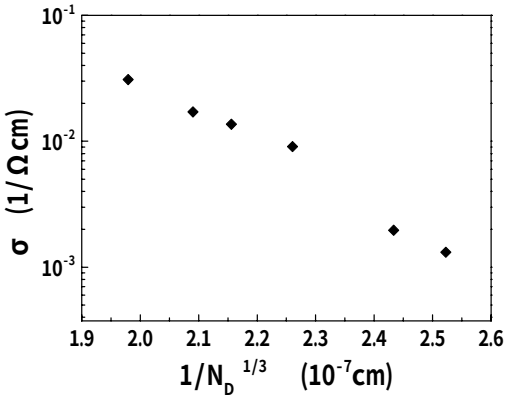
Objectives

In this thesis research by fully utilizing the capability of MBE, we have tried to grow GaAs layers where a metal-insulator transition occurs at room temperature and investigate electrical properties and conduction mechanism of such layers.

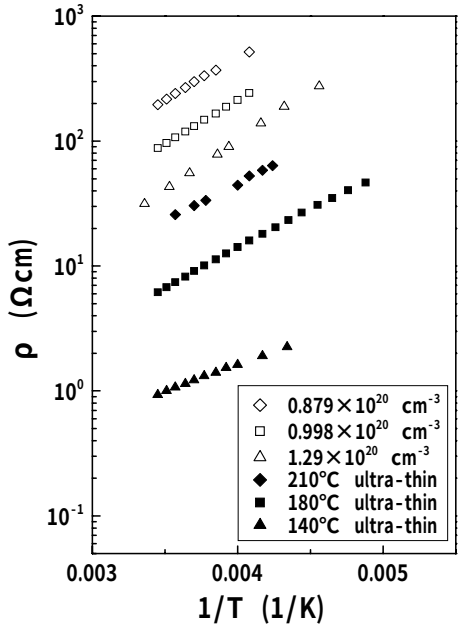
Hopping conduction in GaAs layers grown by MBE at low temperatures

A GaAs layer grown by molecular-beam epitaxy at a low temperature (LT-GaAs) contains a high concentration of excess As as a form of point defects. The majority of excess As point defects are antisite As atoms. In the case of LT-GaAs layers grown by MBE, a metal-insulator transition might occur at room temperature since antisite As atoms contained in LT-GaAs layer become donor impurities and their levels are located around 0.75 eV far below the conduction band edge[4]. In Chapter 3 we reported the study on the possibility of metal-insulator transition with increase of antisite As concentration in GaAs layers.

An electrical conductivity of LT-GaAs layers with a thickness of 0.6μm and ultrathin LT-GaAs layers with a thickness of 1nm including more excess As atoms were examined by using the van der Pauw method. The hopping conduction among antisite As atoms was observed. The conductivity of thick GaAs layers changes with the concentration of antisite As atoms following the nearest-neighbor hopping model. Fig.1 shows a nearly linear relation of logarithm of the conductivity with the average spacing of antisite As atoms. From the slope of the linear change of the logarithm of the conductivity, the Bohr radius of the donor was estimated to be between 2.8 and 4.0Å. Critical concentrations derived from these radii of the donor wave function with Mott's criterion with these radii are between 2.5×10^{20} and 6.5×10^{20} cm^{-3}. Temperature dependence of the resistivity of LT-GaAs layers is shown in Fig.2, in which the upper three lines were obtained from thick LT-GaAs layers. The lower three lines are the resistivity of ultrathin LT-GaAs layers. Activation energies derived from the temperature dependence of the resistivity of the thick LT-GaAs layers increase from 0.13 to 0.15eV with increase of antisite As concentrations. The resistivity of ultrathin GaAs layers at room temperatures has become small compared to thick GaAs layers. The lower the growth temperatures, the smaller the resistivity. The concentration of antisite As atoms contained in ultrathin GaAs layers grown at 210, 180, 140 ℃ are $2.3\times10^{20}cm^{-3}$, $2.7\times10^{20}cm^{-3}$, $3.6\times10^{20}cm^{-3}$ and the activation energy of these samples are 0.113, 0.123, 0.085eV, respectively. Although these concentrations of antisite As atoms approached the expected critical value, metal-insulator transition was not realized.



▲Fig.1 Conductivity of thick LT-GaAs layers at room temperature as a function of the average spacing of antisite As atoms



►Fig.2 Temperature dependence of the resistivity of thick and ultrathin LT-GaAs layers

<u>Metal-insulator transition in Be δ-doped layers in GaAs strustures</u>

In Chapter 4, we presented the study on the possible metal-insulator transition found at room temperatures in Be δ-doped GaAs structures. These sample consists of a Be δ-doped layer, a 1nm-thick GaAs spacer layer and a ultrathin LT-GaAs layer containing excess As atoms.

Fig.3 shows the temperature dependence of the resistivity of 17 samples in the temperature range from 5 to 350K. All these samples showed p-type conduction which is caused by holes that remain in δ

-doped wells. Since the Hall mobility are larger than that for the hopping conduction at higher Be doping concentration, p -type conduction is considered to be caused by thermal excitation of holes from localized states to extended states. By further increasing the Be concentration, the activation energy decreases and eventually leads to the metal-like temperature dependence of the conduction at room temperature, suggesting a possible metal-insulator transition.

Activation energies from localized states to extended states in impurity bands are typically a few meV[5] in ordinary impurity doped semiconductors. In our case activation energies of these samples for the conduction are, however, larger than that of ordinary impurity-doped semiconductors. The strong localization of holes in the δ-doped well is attributed to a large variation of a random potential caused by negatively charged Be ions and positively charged antisite As atoms. High temperature limits of the resistivity of insulating samples near the transition were found to be close to the value of the quantum unit of resistance, $h/2e^2$. Fig.4 shows the relationship between the Be concentrations and the activation energies E_1 and E_2. Activation energies of these samples changes linearly with the Be concentration, and the slope of the linear change corresponds to the density of states in quasi two-dimensional heavy-hole system of GaAs.

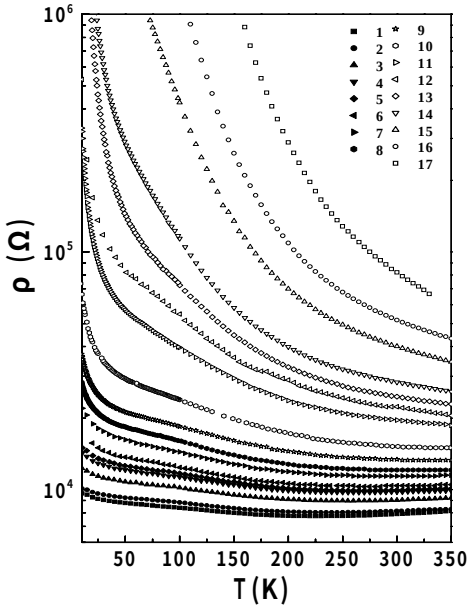


Fig.3 Temperature dependence of the resistivity of 17 samples with different Be doping concentrations

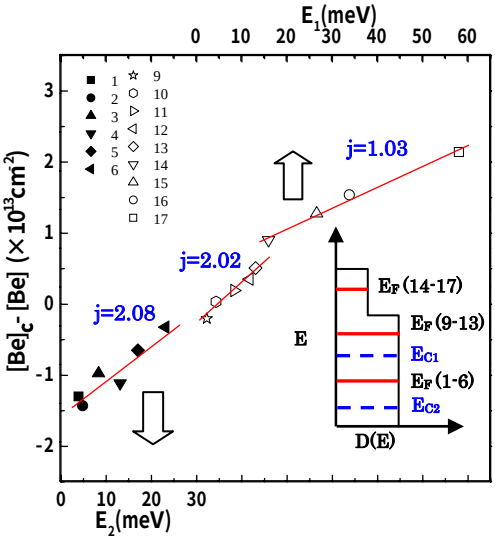


Fig.4 Relationship between the Be concentrations and the activation energies E_1, E_2. The inset schematically shows the energy band of the Be δ-doped layer where E_F, E_{C1}, and E_{C2} are the Fermi level, the first percolation threshold and the second percolation threshold, respectively.

Study on the origin of quantum conductance in δ-doped layers

We investigate the microscopic physical process underlying the electrical transport properties of Be delta-doped structures, in particular the origin of the emergence of the quantum unit of resistance, $h/2e^2$. Meir proposed a simple noninteracting electron model, combining local quantum tunneling and global classical percolation in order to describe observed meta-insulator transitions in two dimensions[6]. In the model the conductance through each QPC is given by the Landauer formula,

$$G(\mu,T)=\frac{2e^2}{h}\frac{1}{1+\exp[(\varepsilon_C-\mu)/k_BT]}\times M$$

where M is number of subbands. In our case the mobility edge is considered to be located in the second subband, i.e., $M=2$. The resistance of 20×20 square lattice has been calculated as a function of the Fermi level μ and temperature T. In the calculation, ε_C of QPCs are assumed to range uniformly from 0 meV to 30 meV, and the Fermi energy μ is change from 0 meV to 30 meV with a 1 meV step. For a given μ, the resistivity of 100 different distributions of QPCs is calculated and averaged.

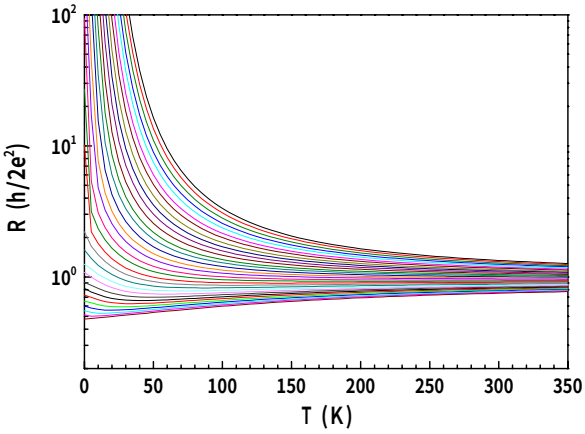


Fig.5 Temperature dependence of the resistance for two-dimensional square lattice

Fig.5 shows the results of the calculation. These plots are basically similar to those reported by Meir, but the temperature scales are different due to different energy scales. As expected, the resistivity of the samples in both insulating and metallic side approaches $h/2e^2$ at high temperatures.

References

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Contents

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