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Study of localized electron states in pair delta doped GaAs structures

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[Introduction]

Recently our group found the transition from thermally activated conduction to metallic conduction at room temperature in Be delta-doped GaAs structures[1,2]. The samples with lower Be concentrations show the thermal activated conduction at all measurement temperatures. The samples with higher Be concentrations, on the other hand, show the metallic conduction near room temperature. The latter samples also show thermal activated conduction at low temperatures. In the strict sense, therefore, this transition is not a metal-insulator transition. This transition has two remarkable characteristics. First, the critical resistivity and high temperature limits of resistivity of samples near the transition are close to the quantum unit of resistivity, $h/2e^2$ namely 12.9kΩ. The other is that the change in the activation energy for thermally activated conduction in insulating samples with the Be doping concentration was found to correspond closely to the density-of-states for the quasi-two-dimensional heavy hole system in GaAs, which indicates that carries in the delta-doped layer form a quasi-two-dimensional system at room temperature. This transition phenomenon occurs only in p-type samples but not in n-type samples. We speculated the origin of this transition as follow. At first GaAs with only a Be delta-doped layer was reported to show metallic conduction at room temperature regardless of the doped concentration. The transition from thermal activated conduction to metallic conduction in our samples suggests that holes are strongly localized in a delta-doped layer. Strong localization of carries is considered to result from trapping of holes by anti-site As which is known to form a deep donor level. It is speculated that holes occupy deep levels of the delta-doped well and are subject to server potential variation due to a high concentration of Be^-ions and As_{Ga}^+ ions. Thermal activated conduction occurs via excitation of these localized holes to the extended states in the delta-doped layer. As the Be concentrations increases, the Fermi level passes the mobility edge resulting in the transition from thermal activated conduction to metallic conduction. There are, however, other defects, that is, Ga vacancies. Properties of LT-GaAs have not been well understood yet. Therefore it is difficult to investigate the details of transition.

[Objectives]

This thesis study has two objectives: one is to verify the above explanation of the origin of transition. For this purpose, we carried out two studies. One is preparation of samples with new structures which do not have LT-GaAs ultra-thin layers. We studied the transition with the samples in which Se or Si delta-doped layers are placed as donor delta-doped layers. The second study is the calculation of electron states in the delta-doped layer with the self-consistent method. In this calculation, we consider two cases, p- and n-type pair delta-doped structures.

During the course of the study on the above-mentioned delta-doped pair structures, a possibility of magnetic transition was found. The second objective of the research is, therefore, set to investigate this possibility. The results imply the existence of localized spins in these samples. By carrying out electron spin resonance (ESR) measurements and magnetoresistance measurements, we try to confirm the existence of localized spins. In the case of magnetoresistance measurements, negative magnetoresistance may be observed if spins exist. We measured magnetoresistance with the magnetic field parallel or perpendicular to delta-doped layer.

It has known since early times that non-magnetic univalent impurities such as P in Si form hydrogen states and have localized spins and which was confirmed with ESR measurements of carriers[3]. Recently, active studies are carried out in DMS, in which ferromagnetism is achieved by doping transition metal or rare earth metal elements, such as Mn and Cr, into semiconductors[4]. In this study, however, we have found that holes are localized at Be impurity atoms and give rise to localized spins at high temperature in delta-doped pair structures.

[Results and discussion]

We made the Be/Se delta-doped pair structures as shown Fig.1. From these samples, a similar transition to that of Be/LT-GaAs pair structure was observed. From Be/Si delta-doped pair structures, we observed similar transition phenomena. Fig2 shows the temperature dependence of resistivity for Be/Si pair structures. We concluded, therefore, that the transition phenomena occurs due to the existence of the donor and acceptor impurity layers and is not related to the particular characteristics of LT-GaAs layers.

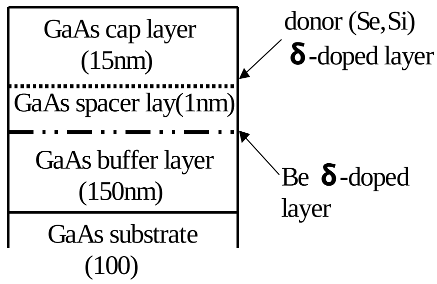

Fig.1 The configuration of Be/donor delta-doped layer pair structures

We calculated electron states in delta-doped layers in the p-type and n-type cases. In the p-type case, a width of a well width is 1.3nm at the Fermi level, so that it can be considered as a quasi-two dimensional system at room temperature. In the n-type case, on the other hand, the width is about 9nm.

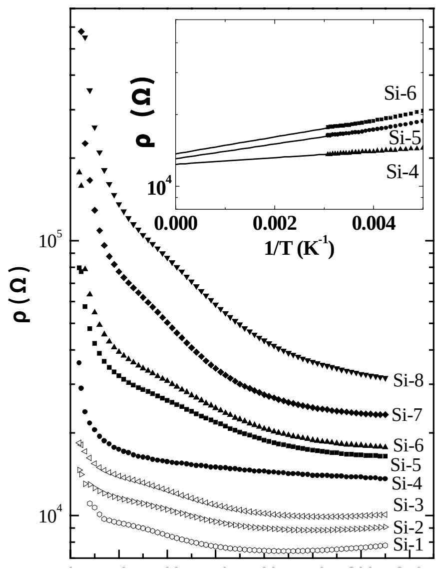

Fig.2 Temperature dependence of resistivity for Be/Si pair structures

Although we observed similar transitions in all samples with different donors, there is a difference among their electrical transport properties. There is difference in the Hall mobility at room temperature. Be/Se or Be/Si pair structures have Hall mobility with values of $70 cm^2/Vs$ or $20 cm^2/Vs$, respectively. The Be/LT-GaAs pair structure has intermediate values between those of Be/Se and Be/Si structures. In association with the difference of the Hall mobility, there are characteristic behaviors in the temperature dependence of resistivity. It was reported that the temperature dependence of Mn delta-doped GaAs samples in which a ferromagnetic transition occurred exhibited a similar maximum[4]. It has been known that non-magnetic impurity-doped semiconductors possess localized spins[3,5]. They suggest a possibility of existence of localized spins and magneto transition occurs in our samples.

We made ESR measurements to investigate the localized spins in our samples. In this measurement, we concluded that there were an enough number of Be atoms in delta-doped layers but not an enough number of spins which contributed to the signal intensity. Therefore we measured the temperature dependence and magnetic field dependence of magnetoresistance of delta-doped pair structures. When the magnetic field was applied perpendicular to the sample surface, positive magnetoresistance was observed at all measurement temperatures. Under the condition of the magnetic field parallel to the sample surface, on the other hand, negative magnetoresistance was observed for all donor species, that is, LT-GaAs, Se and Si. These results, in particular the anisotropic magnetoresistance, indicate the existence of localized spins in Be delta-doped layers. Negative magnetoresistance was observed in the temperature range from 300K to 80K, and in the lower temperature range, positive magnetoresistance was observed. The positive magnetoresistance observed below 80K implies that the hopping conduction is dominant in the lower temperature range. In addition, a bump was observed at low temperatures, where a maximum was observed in the temperature dependence of resistvity with zero magnetic field. This feature was observed only under the parallel magnetic field condition. We, therefore, consider that this bump may be related to ordered alignments of localized spin.

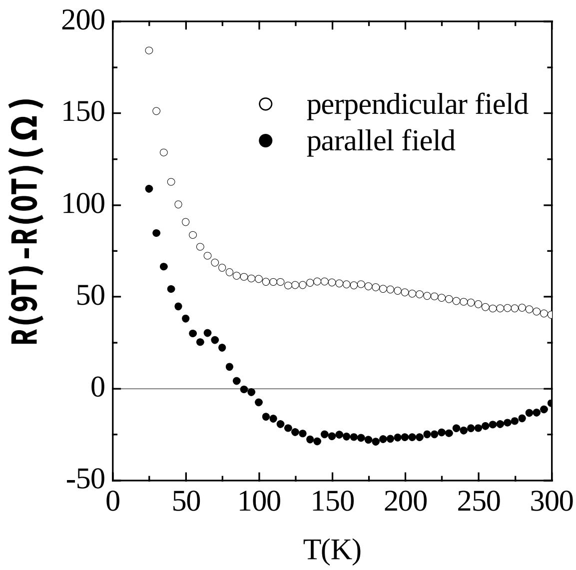

Fig.3 Temperature dependence of magnetoresistance for Be/Se pair structure

We measured the Hall resistance in order to find out whether a ferromagnetic transition occurs. The hystesisis, however, was not observed in the low temperature range. We, therefore, expect that an antiferromagnetic transition occurs instead of a ferromagnetic transition.

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[Tables of contents]

[Original articles]

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