Existence of localized spins in pair-delta doped GaAs structures

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Abstract

The correlation between the negative magnetoresistance and concentration of localized holes in Be/Si pair delta-doped GaAs structures grown by molecular-beam epitaxy was investigated. The negative magnetoresistance was observed in a high temperature range. The magnitude of negative magnetoresistance is nearly proportional to the concentration of localized holes. The transition temperatures from the negative magnetoresistance to the positive one decrease with increasing the concentration of localized holes. The temperature-dependence of the Hall mobility is similar to that of negative magnetoresistance for each sample. The Hall resistance was measured in order to investigate possible ferromagnetic ordering of localized spins at low temperatures.

Keywords: 75.47.-m, A1. Doping, Low dimensional structures, Magnetic field, A3. Molecular beam epitaxy, B1. Gallium compounds, B2. Semiconducting gallium arsenide.

1. Introduction

The technology of spintronics which adds the spin degree of freedom to conventional semiconductor charge-based electronics is now being widely investigated. The one main part of such researches is the incorporation of magnetic elements which possess localized spins into Ⅲ-Ⅴ semiconductors such as $Ga_{1-x}Mn_xAs$ and $In_{1-x}Mn_xAs$ [1,2]. Another main part is the use of spin-orbit coupling for generation of spin polarization which can be made without use of magnetic elements in semiconductor structures[3,4]

It has been known since the early time of researches on impurity-doped semiconductors that even non-magnetic shallow impurities such as P in Si possess localized spins by forming hydrogenic states. Existence of localized spins, however, occurs only at low temperatures because of thermal excitation of carriers from shallow impurity levels to either a conduction band or valence band.

In recent studies we found a transition from thermally activated conduction to metallic conduction at room temperature in Be delta-doped structures grown by molecular beam epitaxy(MBE)[5,6]. The structures is made of a combination of a Be delta-doped layer and an ultra-thin low temperature-grown GaAs(LT-GaAs) layer with 1 nm-thick spacer layer between them. A part of holes in the Be delta-doped layer are trapped by deep-donor antisite As(As_{Ga}) atoms in the LT-GaAs layer, resulting in localization of remaining holes at deep levels of the delta-doped layer. Thermally activated conduction occurs at room temperature via excitation of these localized holes to extended states. We observed similar transitions with a pair of Be and donor impurity delta-doped layers where Se or Si were used as donor impurities[7]. In the study of magnetotransport properties of Be and donor pair delta-doped structures, the negative magnetoresistance was observed with a magnetic field parallel to the delta-doped layers in the high temperature range[8]. The negative magnetoresistance results from localized spins which are associated with the localized holes in the Be delta-doped layer. In the present paper we report results which show direct correlation between the negative magnetoresistance and the concentration of localized holes. The negative magnetoresistance of the sample which has a higher concentration of localized holes is observed at lower temperatures. The temperature-dependence of the Hall mobility for each sample was found to be similar to that of the negative magnetoresistance.

2. Experiment

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 and As flux for the growth were 5.8×10^{-7} and 3.0×10^{-5} Torr, respectively, which gave rise to a growth rate of 0.9 ㎛/h. After desorption of an oxide layer of the substrate surface, the surface was annealed for 10 min at 600℃, followed by growth of a 150-nm-thick GaAs buffer layer at 580℃. After growth of the buffer layer, the substrate temperature was lowered to 400℃ for Be and Si delta-doping and growth of a GaAs spacer layer with a thickness of 1 nm. In order to avoid oxidation of the delta-doped layers a 15-nm-thick cap layer was grown. Beryllium and Si concentrations in delta-doped layers were estimated with their effusion cell temperatures and deposition times on GaAs surfaces. Flux intensities for given effusion cell temperatures were calibrated by growing uniformly doped layers at 400℃ and estimating their carrier concentrations with Hall effect measurements. Detailed explanations of the growth experiments were given in earlier papers[5,6].

A square 5mm × 5mm sample was cut for the van der Pauw measurements of resistivity and Hall effect measurements, and an In contact was made at each corner of a sample. For magnetoresistance and Hall resistance measurements, a Physical Property Measurement System(PPMS) was used. A rectangular 3mm×8mm sample was cut, and four In contacts were made with an equal spacing in the longitudinal direction. For the Hall resistance measurements, six In contacts were made; four contacts were set in the longitudinal direction in a similar manner to the above samples, and the remaining two contacts were set in the transverse direction.

3. Results and Discussion

The three samples described in the present paper exhibit *p*-type conduction and the metallic temperature dependence in the high temperature range. The resistivity decreases with lowering the temperature from room temperature to approximately 200K, while it exhibits the opposite temperature-dependence below 200K. Figure 1 shows the magnetic-field-dependence of resistance of three samples at three different temperatures. The applied fields are parallel to the delta-doped layer. In the high temperature range the magnetoresistance is negative and changes into positive values with lowering the temperature. The transition temperatures from the negative to positive magnetoresistance for samples Be/Si-1, Be/Si-2, and Be/Si-3 are 65K, 90K, and 150K, respectively. The change of magnetoresistance from negative to positive values is explained by increased contribution of hopping conduction at lower temperatures.

The concentration of localized holes in these samples were estimated by using the equation, n_{loc} = [Be]-[Si]-p where [Be] is the Be doping concentration correspond to the concentration of holes, [Si] correspond to the concentration of holes trapped by Si atoms, and p the concentration of free holes. Beryllium and Si delta-doping concentrations of these samples are listed in Table Ⅰ. The doping concentrations [Be] and [Si] are estimated by using their calibrated concentrations and shutter open times[5]. The free hole concentration p was estimated at 300K by the Hall effect measurement. The calculated concentrations of localized holes of samples Be/Si-1, Be/Si-2, and Be/Si-3 are 1.20×10^{13} cm^{-2}, 1.13×10^{13} cm^{-2}, and 0.49×10^{13} cm^{-2}, respectively. As seen in Fig. 1 the transition temperature from negative to positive magnetoresistance becomes lower for a higher concentration of localized holes.

Figure 2(a) shows temperature-dependence of magnetoresistance $\Delta R / R_0$ of three samples, where R_0 is the zero-field resistance and $\Delta R = R(B) - R_0$ with B = 9T. Three samples exhibit negative magnetoresistance in the high temperature side. The magnitude of $\Delta R / R_0$, in particular the largest value of negative magnetoresistance, is nearly proportional to the concentration of localized holes.

The results presented above can be explained by assuming that a localized hole in the delta-doped layer forms a hydrogenic impurity state which possesses a localized spin. According to the spin-disorder scattering model[9], the negative magnetoresistance occurs as a result of the alignment of localized spins by the applied magnetic field which reduces spin-disorder scattering of carriers. If negative magnetoresistance results from scattering of carriers by localized spins, there should be direct correlation of the magnitude of negative magnetoresistance with the concentration of localized holes. The observed results, therefore, can be reasonably explained by the spin-disorder scattering model.

Fig. 2(b) shows temperature-dependence of the Hall mobility of three samples. As shown in the figure, the temperature-dependence of the Hall mobility is very similar to that of negative magnetoreisistance for each sample. The sample of Be/Si-1 which contains the highest concentration of localized holes shows the largest value of the Hall mobility. Their seems to be close correlation between the Hall mobility and concentration of localized holes, which suggests a interesting possibility regarding the interaction between carriers and localized spins and will be investigated further.

The Hall effect of a magnetic material is normally divided into two parts. One is the normal Hall effect, and the other is the anomalous Hall effect. The former results from the coupling of an applied magnetic field and an orbital motion of a carrier, while the latter is caused by the coupling of localized spins and an orbital motion of a carrier. The origin of the negative magnetoresistance, therefore, is closely related to that of anomalous Hall effect and the origin of the positive magnetoresistance is similar to that of the normal Hall effect. The net magnetoresistance is determined by the relative magnitudes of these two types of magnetoresistance. If the magnitude of the positive value is larger than that of the negative one, the net magnetoresistance is positive. In the

Fig. 2(b), the part ocorresponding to the normal Hall effect is considered to be approximately 25cm^2/sV because all samples exhibit this value at the temperatures below 70K where their magnetoresistance becomes positive in Fig. 2(a).

In the Hall effect measurement, the magnetic field is applied in the direction perpendicular to the delta-doped layer. According to our previously reported paper[8], the magnetoresistance of delta-doped samples under the perpendicular field is positive at all measured temperatures. As seen in the Fig. 6(a) in ref. 8, the magnitude of the positive magnetoreistance is small in high temperature range above 100K, while the positive magnetoresistance becomes large values at temperatures below 100K. The small positive magnetoresistance in the high temperature range, therefore, is considered to be contributed partly by the negative magnetoresistance, corresponding to the anomalous Hall effect.

Even if the anomalous Hall effect is larger than the normal Hall effect as in the case of samples Be/Si-1 and Be/Si-2 in the high temperature range of Fig. 2(b), the negative magnetoresistance may not necessarily be observed because of the mean free path effect[10] on the spin disorder scattering. The negative magnetoresistance is caused by the correlated scattering of a carrier by neighboring localized spins. If the means free path is shorter than the average spacing of localized spins, the correlated scattering by localized spins and hence the negative magnetoresistance are suppressed for a given concentration of localized spins. One may not, therefore, observe the negative magnetoresistance under the perpendicular magnetic field, even if a concentration of localized spins is high enough to give rise to the anomalous Hall effect larger than the normal Hall effect.

Because of the existence of localized spins, one may consider the possibility of their ordered alignments at low temperatures. In order to investigate such a possibility the Hall resistance of Be/Si-1 sample was measured at T = 5K and 30K. Figure 3 shows magnetic-field-dependence of the Hall resistance. No hysteresis of Hall resistance curves nor anomalous Hall effect were observed, which indicates the absence of ferromagnetic ordering in these samples.

In summary, the present paper reports the observation of the direct correlation between the negative magnetoresistance and concentration of localized holes in Be/Si pair delta-doped GaAs structure. The transition temperature from negative magnetoresistance to positive one and the magnitude of negative magnetoresistance are directly correlated to the concentration of localized holes. The temperature-dependence of the Hall mobility exhibits close similarity to that of negative magnetoresistance for each sample. The ferromagnetic ordering of localized spins at low temperatures was not observed in these samples.

References

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Figure captions

Fig. 1 Magnetic field dependence of resistance of samples at three different temperatures.

Fig. 2(a) Temperature dependence of magnetoresistance $\Delta R / R_0$, where R_0 is the zero-field resistance and $\Delta R = R(B) - R_0$ with B=9T. (b) Temperature dependence of the Hall mobility of three samples.

Fig. 3 Magnetic field dependence of Hall resistance of Be/Si-1 sample at 5K and 30K.

Table caption

Table Ⅰ. Beryllium and Si delta-doping concentrations of three samples.

Table Ⅰ.

sample	[Be] (cm^{-2})	[Si] (cm^{-2})
Be/Si-1	**3.32×10^{13}**	**0.67×10^{13}**
Be/Si-2	**2.90×10^{13}**	**0.67×10^{13}**
Be/Si-3	**4.15×10^{13}**	**1.23×10^{13}**

Fig. 1

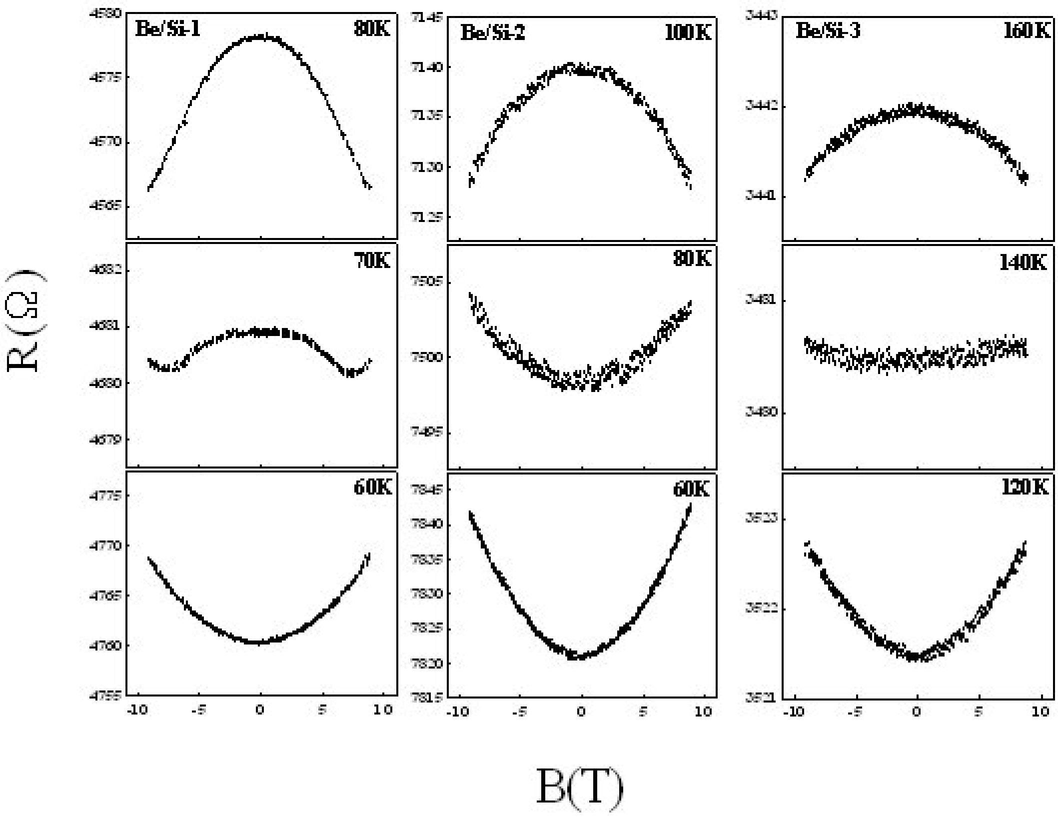
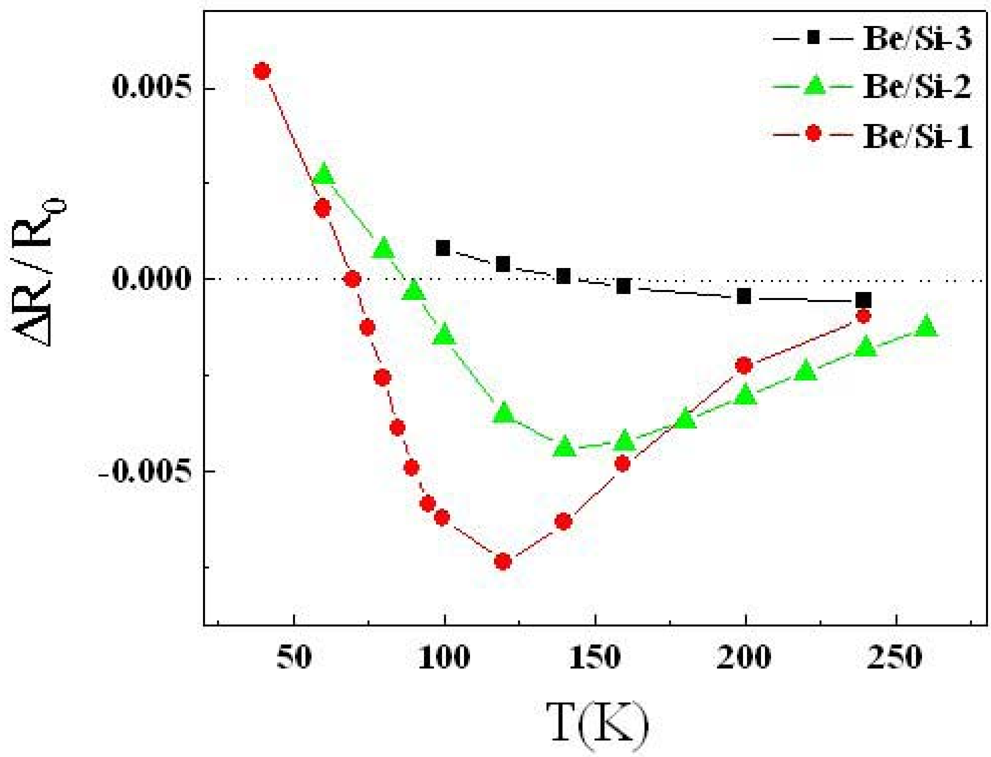

Be/Si-1
80K
70K
60K
Be/Si-2
100K
80K
60K
Be/Si-3
160K
140K
120K
R(Ω)
B(T)

Fig. 2(a)



Be/Si-3
Be/Si-2
Be/Si-1
0.005
0.000
-0.005
$\Delta R/R_0$
50
100
150
200
250
T(K)

Fig. 2(b)

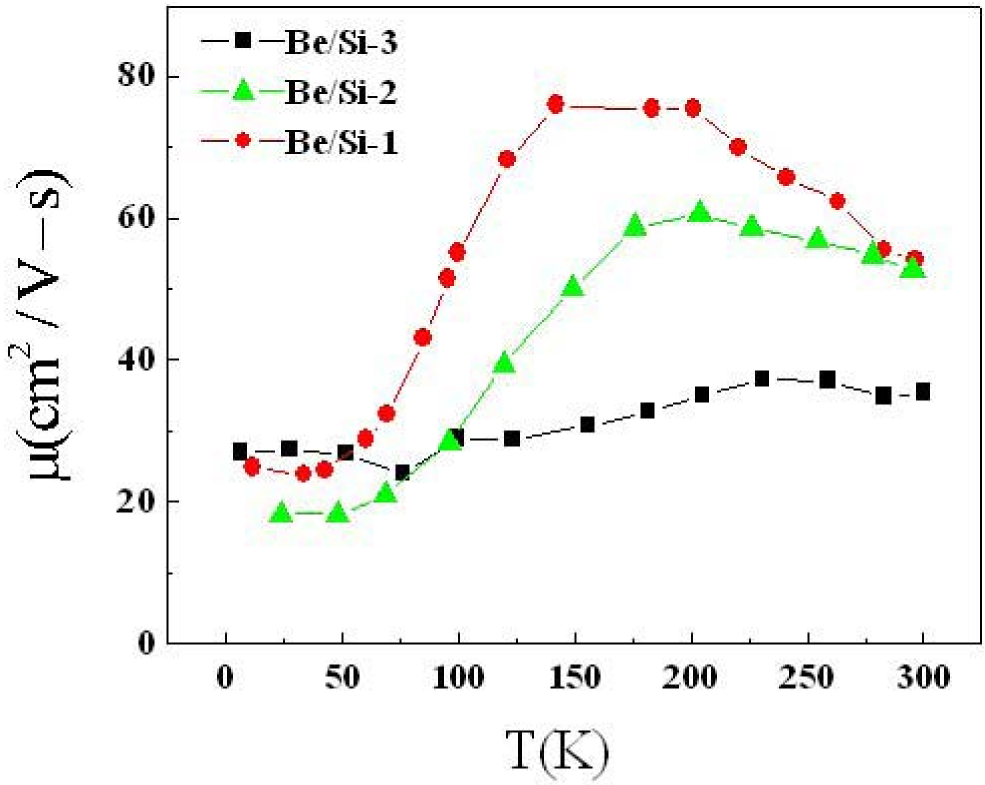

Be/Si-3
Be/Si-2
Be/Si-1
80
60
40
20
0
0
50
100
150
200
250
300
μ(cm² / V−s)
T(K)

Fig. 3