Hole density of ferromagnetic semiconductor (Ga, Mn)As studied via pulsed high magnetic field

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Abstract. Transport measurements of as-grown and annealed (Ga,Mn)As samples were conducted under pulsed high magnetic field up to 40T. Assuming that the magnetization follows modified Brillouin function, we obtained the hole densities of the (Ga,Mn)As samples at various temperatures, which generally increase with temperature and become two times larger after annealing process. The hole density determined by electrical transport measurement at low magnetic field up to 1.5T is found to be underestimated.

1. Introduction
Ferromagnetic semiconductors have enormous potential for spintronics device application [1]. Ferromagnetism in (Ga,Mn)As, the most widely studied III-V ferromagnetic semiconductor material, is widely believed to arise from the p-d exchange interaction between magnetic ions and holes [2]. In the Zener model, the ferromagnetic transition temperature in (Ga,Mn)As is directly related to the Mn concentration and the hole density [2]. Therefore, it is important to better estimate the hole density, which may help understand this material, especially the mechanism that determines the Curie temperature( $T_C$ ). Conventionally, in order to determine the hole density of (Ga,Mn)As, Hall measurement experiment is carried out at extremely low temperature and super-high magnetic fields where the magnetization can be saturated, allowing the extraction of the ordinary Hall coefficient [3]. Furthermore, the hole density at a certain temperature can be obtained as long as the applied magnetic field is large enough to saturate the magnetization. Here we present the hole densities of as-grown and annealed (Ga,Mn)As samples studied via pulsed high magnetic field up to 40T.

2. Samples and experimental technique
The 200nm thick (Ga,Mn)As sample was grown on a 100nm thick GaAs(001) wafer by low-temperature molecular-beam epitaxy (LT-MBE) technique [4]. Reflection high-energy electron-diffraction (RHEED) patterns were used to monitor the surface reconstruction throughout the growth process, and substrate temperature was controlled by a W-Re thermal couple. After growth, some parts were cut from the (Ga,Mn)As sample and annealed successively in air atmosphere via a hot plate furnace with a temperature precision of ±1°C. To avoid forming the second phase during annealing process, the annealing temperature was carefully chosen and not over 290°C, and annealing time was 1h.

In order to perform electrical transport measurement, Hall bar structures with width 300µm and length 900µm were fabricated by standard lithography and wet chemical etching techniques, and
Au/Ti contacts were deposited to form good ohmic contacts with the (Ga,Mn)As layers. Magnetoresistance and Hall resistance measurements were conducted simultaneously at up to 40T pulsed high magnetic fields with pulse width of 20ms and various temperatures across Curie temperatures in the Wuhan National High Magnetic Field Center of China (WHMFC).

3. Experimental results and discussion
The temperature dependence of longitudinal resistance in zero external magnetic field for as-grown and annealed (Ga,Mn)As samples is shown in figure 1. As is common in magnetic metals and semiconductors, the longitudinal resistances have local maximum at the transition temperature between the paramagnetic and ferromagnetic phase [5], indicating that the Curie temperatures for as-grown and annealed (Ga,Mn)As samples are $T_c = 48K$ and $T_c = 112K$, respectively. Obviously, post-growth low temperature annealing can lead to a large increase of $T_c$ since the ferromagnetic disordering, induced by defects such as Mn interstitials and As antisites that act as compensating donors, is reduced upon annealing. Compared with the as-grown (Ga,Mn)As layer, the longitudinal resistance of the annealed one becomes flatter above $T_c$ and drops more dramatically below $T_c$.

Figure 1. Temperature dependence of longitudinal resistance for as-grown and annealed (Ga,Mn)As samples with $T_c = 48K$ and $T_c = 112K$, respectively.

Figure 2 shows the longitudinal and Hall resistance as a function of pulsed high magnetic field up to 40T for the annealed (Ga,Mn)As sample at different temperatures. As shown in figure 2 a, the overall longitudinal resistance decreases with increasing magnetic field. The negative magnetoresistance effect can be understood as a reduction of random spin-flip scattering due to the alignment of spins by the magnetic field [5]. However, at very low temperatures below $T_c$, a positive magnetoresistance and abnormal negative magnetoresistance appear at low pulsed magnetic fields, as shown in figure 2 c. The easy axis of magnetization is in the plane of the (Ga,Mn)As thin film. The positive magnetoresistance is due to an increased spin-disorder induced by the turning of the magnetization direction from the spontaneous in-plane direction to the perpendicular direction by the magnetic field [1]. The abnormal negative magnetoresistance results from weak localization, i.e., quantum interference on time-reversed paths [6]. The disordered valence-band holes of (Ga,Mn)As can be coupled to localized Mn moments through a p-d kinetic exchange interaction and the perpendicular magnetic field can wash out the quantum interference of the holes by effectively reducing their phase coherence length leading to a negative (in case of weak localization) or
positive (in case of weak antilocalization) magnetoresistance. The Hall resistance, dominated by the 
anomalous Hall effect, increases abruptly at low temperatures but much more slowly at high 
temperatures, and it almost reaches saturation at pulsed high magnetic fields up to 40T, which may 
make the division of the anomalous Hall term from the Hall resistance easier.

![Graph](image)

**Figure 2.** a-longitudinal resistance $R_{xx}$ as a function of perpendicular pulsed magnetic 
fields up to 40T for the annealed (Ga,Mn)As sample at various temperatures; b-the 
corresponding pulsed magnetic field dependence (up to 40T) of Hall resistance $R_{Hall}$; 
c-longitudinal resistance $R_{xx}$ as a function of perpendicular pulsed magnetic fields up 
to 1.5T for the same sample at 4K; d-the corresponding pulsed magnetic field 
dependence (up to 1.5T) of Hall resistance $R_{Hall}$.

The Hall resistance $R_{Hall}$ can be written as

$$R_{Hall} = \frac{R_{o}}{d} B + \frac{R_{s}}{d} M$$

$R_{o}$ is the ordinary Hall coefficient and it depends on the carrier density. $R_{s}$ is the anomalous Hall 
coefficient where skew scattering and side-jump scattering contributions are $R_{s} \propto R_{ss}$ and $R_{s} \propto R_{ss}^2$, 
respectively [7]. $M$ is the magnetization of the sample and $d$ is the thickness of the (Ga, Mn)As film. 
The conventional way to obtain the carrier density is to perform Hall measurement in the limit where 
the magnetization is fully saturated, i.e., at low temperatures and high magnetic fields, and the carrier 
density is proportional to the slope of the $R_{Hall}$–$B$ curve since the slope contribution from the 
anomalous Hall term is much smaller and can be neglected. However, with the help of pulsed high 
magnetic fields up to 40T, it is found that the magnetization of the (Ga, Mn)As sample can be 
saturated even at temperatures above $T_c$, making it possible to obtain the carrier density at various 
temperatures. Assuming that the magnetization $M$ follows modified Brillouin function and $R_{s} \propto R_{ss}^n$ 
($n$ is sample dependent, but for all samples $0 < n < 1$), we fit the anomalous Hall resistance of the 
(Ga,Mn)As sample. Subtracting the anomalous Hall term from the Hall resistance $R_{Hall}$, we can obtain 
the ordinary Hall term, and hence the carrier density, as shown in figure 3. The carriers are holes at all 
measured temperatures. The hole densities for as-grown and annealed (Ga,Mn)As samples generally 
increase with temperatures, and it becomes two times larger after annealing, for example, at 4K, the
holes density increase from $1.64 \times 10^{20} \text{cm}^{-3}$ for as-grown sample to $2.6 \times 10^{20} \text{cm}^{-3}$ after annealing. However, the hole density at 4K determined from pulsed magnetic fields up to 1.5T is only $1.3 \times 10^{20} \text{cm}^{-3}$ for the annealed (Ga,Mn)As sample, indicating that the hole density is underestimated by electrical transport measurement at low magnetic fields.

![Figure 3](image)

Figure 3. Hole densities for as-grown and annealed (Ga, Mn)As samples determined from pulsed high magnetic fields up to 40T.

4. Conclusions

Transport measurements of as-grown and annealed (Ga,Mn)As samples were conducted under pulsed high magnetic field up to 40T. Assuming the magnetization follows modified Brillouin function, we obtained the hole densities of the (Ga,Mn)As samples at various temperatures, which generally increases with temperature and may become two times larger via annealing process. The hole density determined by electrical transport measurement at low magnetic field up to 1.5T is found to be underestimated.

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