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MAGNETOTRANSPORT IN AN N-TYPE DILUTED MAGNETIC SEMICONDUCTOR: (Ga,Mn)N

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In recent years, semiconductor spintronics has been rapidly developing due to potential device applications, in which the spin of charge carriers (electrons or holes) provides novel functionalities to carry signals and process information. Diluted magnetic semiconductors (DMSs) are well known to exhibit intriguing properties such as carrier-mediated ferromagnetism and spin-dependent transport resulting from the coupling between the charge transport states and the magnetic moments (spin) [1-3]. In this work, we report on the magnetotransport in the ferromagnetic epitaxial (Ga,Mn)N films grown by plasma-enhanced molecular beam epitaxy (PEMBE).

The (Ga,Mn)N films were grown by a PEMBE system under ultrahigh vacuum conditions (UHV) with a base pressure of ~ 2 x 10^{-10} Torr. High-purity Ga and Mn metals (6N and 5N5, respectively) were used as source materials. As a nitrogen source, high-purity (6N) nitrogen gas was supplied through an RF plasma source. For the epitaxial growth, MOCVD-grown 2 μm thick GaN templates on sapphire (0001) were prepared as substrates prior to the growth of the Mn-doped GaN layers. All the films were grown at 700 °C. The van der Pauw Hall and magnetoresistance (MR) measurements were performed by applying a magnetic field up to 9 T in the temperature range 4 – 300 K.

Ferromagnetic ordering for the $(Ga_{1-x}Mn_x)N$ films with Mn concentration (x = 0.06 – 0.5 %) was observed in the temperature range 4 – 300 K. The $M - T$ curves were fitted with theoretical equations based on mean field theory in order to estimate curie temperature (T_c), providing $T_c \approx 550$ K and $T_c \approx 700$ K, respectively, for the (Ga,Mn)N films with x = 0.16 % and x = 0.50 %. All the films were found to show n-type characteristics ($n \approx 10^{16} - 10^{17}/cm^3$, $\mu_H \approx 10^3$ cm^2/Vs, $\rho \approx 0.2$ Ω•cm). Although the electron concentration in the (Ga,Mn)N films is as low as in the range $10^{16} - 10^{17}/cm^3$, the ferromagnetic ordering in the (Ga,Mn)N is believed due to the Ruderman-Kittel-Kasuya-Yoshida (RKKY) indirect exchange coupling of electron spins and localized Mn moments, as theoretically predicted in the low carrier density regime. The negative MR for the (Ga,Mn)N films with Mn =

0.73 % is visible at temperatures below 50 K, and found to gradually increase with decreasing temperature, reaching ~ 8 % at 4 K (see Fig. 1). Also, the positive MR, *i. e.*, ordinary MR due to the classical Lorentz force on the charge carriers, is observed in the temperature range 150 – 300 K. Such negative MR has been previously found in (Ga,Mn)As [2]. The origin of the negative MR in (Ga,Mn)As is not clear yet, but is believed to result from either the formation of magnetic polaron consisting of a hole carrier and a cloud of Mn spins polarized by the *p-d* exchange coupling of the Zeeman shift of the Fermi energy, related to metal-insulator boundary depending on Mn concentration. The negative MR in the (Ga,Mn)N films is attribute to spin-disorder scattering in association with the weakly localized electrons depending upon applied magnetic fields. The temperature dependence of R_{sheet} is shown in the inset of Fig. 1. Regardless of an applied magnetic field, no hump indicating T_c was found in the range 4 – 300 K. A crossover from negative MR is found to occur at ~ 60 K. The negative and positive MR behaviors were found to be hardly dependent upon magnetic anisotropy from longitudinal, transverse, perpendicular MR measurements. Magnetoresistance in magnetic semiconductors is shown to become predominant near the ordering temperature due to the fluctuations in the magnetic moments scattering the charge carriers. The negative MR in the (Ga,Mn)N films is not the case, since T_c was found to exceed room temperature. We discuss the origin of the MR for the ferromagnetic (Ga,Mn)N films in further detail.

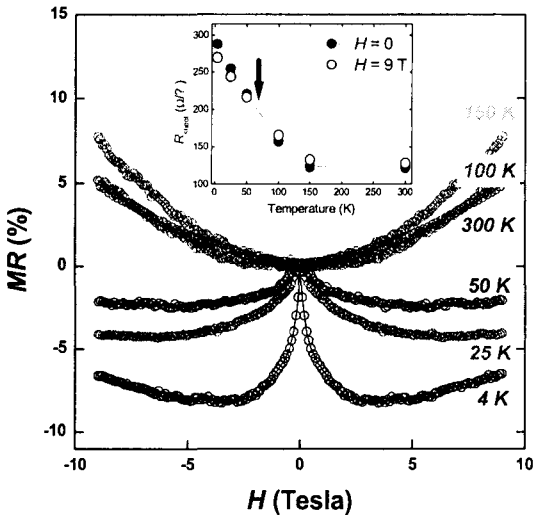

Fig. 1. The variation of magnetoresistance ($\Delta R/R$) with magnetic fields applied perpendicular to the sample plane for (Ga,Mn)N films with Mn = 0.73 %. The inset shows the temperature dependence of R_{sheet} measured at zero field and 9 *T*. The arrow indicates a crossover from negative MR to positive MR at 60 K.

References

[1] H. Ohno, SCIENCE 281, 951 (1998)

[2] Y. Iye, *et al.*, Mater. Sci. Eng. B63, 88 (1999)