Ferromagnic Transitition Temperature of Diluted Magnetic III-V Based Semiconductor

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Abstract

Ferromagnetism in manganese compound semiconductors open prospects for tailoring magnetic and spin-related phenomena in semiconductors with a precision specific to III-V compounds. Also it addresses a question about the origin of the magnetic interactions that lead to a Curie temperature(T_C) as high as 110 K for a manganese concentration of just 5%. Zener's model of ferromagnetism, originally suggested for transition metals in 1950, can explain T_C of $Ga_{1-x}Mn_xAs$ and that of its II-VI counterpart $Zn_{1-x}Mn_xTe$ and is used to predict materials with T_C exceeding room temperature, an important step toward semiconductor electronics that use both charge and spin. In this article, we present not only the experimental result but calculated Curie temperature by RKKY interaction.

The problem in making III-V semiconductor has been the low solubility of magnetic elements, such as manganese, in the compound, since the magnetic effects are roughly proportional to the concentration of the magnetic ions. Low solubility of magnetic elements was overcome by low-temperature nonequilibrium MBE(molecular beam epitaxy) growth, and ferromagnetic (Ga,Mn)As was realized.

Magnetotransport measurements revealed that the magnetic transition temperature can be as high as 110 K for a small manganese concentration.

Key Words: Diluted Magnetic Semiconductor, ferromagnetism, (Ga,Mn)As, MBE, SQUID

1. Introduction[1]

The mass, spin and charge of electrons in the solid state lay the basic of the information technology. IC's and high frequency devices used for information processing with communications have had successes by the charge of electrons in semiconductor. In general, semiconductor devices take advantage of the charge of electrons, whereas magnetic materials are used for recording information involving electron spin. Mass storage of information is carried out by magnetic recording using spin of electrons in ferromagnetic materials. To make use of both charge and spin of electrons in semiconductors, we may then be able to use the capability mass storage and processing of information at the same time.

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Therefore, we may inject spin-polarized current into semiconductors to control the spin state of carriers, because the spin injection may allow us to carry out the quantum bit operations which required in quantum computing**(1)**. A high concentration of magnetic elements can be introduced in nonmagnetic III-V semiconductors currently in use for devices. Thus, in this article, we have grown (Ga,Mn)As by dilution of Mn into GaAs Films on semi-insulating (001) GaAs substrates by MBE and have analyzed its structural and magnetical properties. RHEED, SEM and XRD was carried out to investigate the structural properties, and SQUID was performed to analysis the magnetic behavior of (Ga,Mn)As.

2. Theoretical background

2.1 Ferromagnetic III-V's

An approach which compatible with the semiconductors used in present electronics is to make non-magnetic III-V semiconductors magnetic and ferromagnetic by introducing a high concentration of magnetic ions. III-V semiconductors are already in use in a wide variety of electronic equipment in the form of electronic and opto-electronic devices, such as cellular phones, CD's and in many other applications. Thus, the introducing of magnetic semiconductor opens up the possibility for magnetic phenomena, not shows in normal nonmagnetic III-V semiconductor in the opto-electronic devices.

2.2 Magnetic Semiconductors.

The usefulness of semiconductor resides in the ability to dope them with impurities with to change their properties. This approach can be followed to introduce magnetic elements into nonmagnetic semiconductors to make them magnetic. This category, called diluted magnetic semiconductor(DMS's) are alloys of nonmagnetic semiconductor and magnetic elements**(2)**. Research of DMS's and their heterostructures have centered mostly on II-VI semiconductors, such as CdTe and ZnSe, in which the valance of the cations matches that of the common magnetic ions such as Mn. Although this phenomenon makes DMS's relatively easy to prepare in bulk form as well as in thin films, II-VI based DMS's have been difficult to dope to create p-and n-type, which made the material less attractive for applications. The magnetic interaction in II-VI DMS's dominated by the antiferromagnetic exchange among the Mn spins, which dues to the paramagnetic, antiferromagnetic. or spin-glass behavior. It is impossible to until very recently to make a II-VI DMS's ferromagnetic at low temperature**(3)**.

3. Experiments.

We have grown (Ga,Mn)As Films on semi-insulating (001) GaAs substrates in an MBE chamber equipped with solid source of Ga, Mn, Al, and As. Reflection high energy electron diffraction(RHEED) patterns were used to monitor the surface reconstruction during the growth. For the GaAs buffer layer, after lowering the substrate temperature T_s to 260℃, a 200nm GaAs was grown before the growth of (Ga,Mn)As. Typical growth rate was 0.6㎛/hour, with Mn concentration x in $(Ga_{1-x}Mn_x)As$ films up to 0.07. The lattice constant *a* of the (Ga,Mn)As layer were determined by x-ray diffraction(XRD) as a function of x. In order to investigate the magnetic properties of (Ga,Mn)As films, we measured SQUID(superconducting quantum interface device) magnetometer. The surface properties was measured by SEM(Secondary Electron Microscopy).

4. Results and Discussions

4.1 RHEED, SEM and XRD

Fig.1 show RHEED results of GaMnAs thin films during the growth. When the GaAs buffer layer growth was initiated at 260℃, the (2X4) surface reconstruction pattern was changed a(1X1) pattern

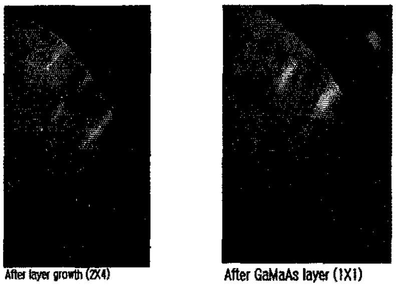
After layer growth (2X4)
After GaMaAs layer (1X1)

Fig. 1 RHEED result of initial growth of GaMnAs.

The (Ga,Mn)As growth was started by simply commencing the Mn beam during the low-temperature GaAs growth and keeping T_s constant at 260℃. XRD as a function of x is shown in Fig. 2. As can be seen from Fig. 2, a increases linearly with x following Vegard's law.

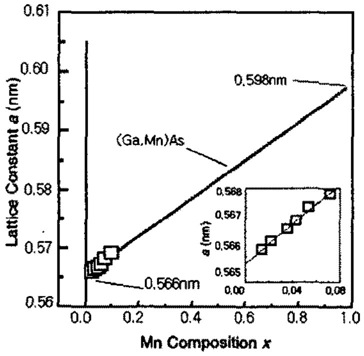

Fig. 2 The lattice constant a versus Mn composition x in (Ga,Mn)As.

The extrapolated lattice constants for zinc-blende MnAs(0.5987nm)are in good accord with the MnAs. SEM image shows the surface roughness of (Ga,Mn)As films.

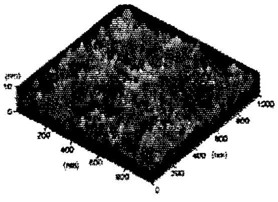

Fig. 3 SEM image of the MBE grown (Ga,Mn)AS surface

4.2 Magnetic properties : SQUID

The magnetic field dependance of magnetization M at 5K for of (Ga,Mn)As film with Mn content x=0.035 shows in Fig. 4.

The field was parallel to the sample surface. The SQUID data showed the presence of ferromagnetic order in the (Ga,Mn)As films at low temperature. Sharp, squire hysteresis loops, indicating a well-ordered ferromagnetic structure, appeared in the magnetization M versus magnetic field(B) curves when B was applied in the plane of the film. This sharp hysteresis was followed by a "paramagnetic" increase that appeared to follow a Brillouin function as B was further increased. In

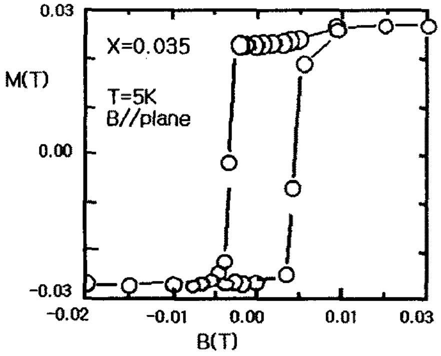

Fig. 4 Magnetic field dependance of magnetism M at 5K for a (Ga,Mn)As with Mn contents x=0.035.

general, most metallic sample showed a negligibly small paramagnetic contribution, whereas in insulating samples, the paramagnetic contribution reached almost about 50% of total saturation magnetization(4).

4.3 Curie temperature : Tc(K).

The dependance on temperature T(5K to 300K) and magnetic field B of sheet resistance R_{sheet} and Hall resistance R_{Hall} of 150 to 200nm of (Ga,Mn)As layer were measured with a standard DC transport measurement setup. The temperature dependance of R_{sheet} in samples with intermediate Mn composition ($0.035<x<0.053$) showed they were on the metal side of the matal-insulator side. We concentrate on the metallic samples, especially the one with 0.053; results for other metallic sample were basically the same.

R_H can be expressed as,

$$R_{Hall} = \frac{R_0}{d} + \frac{R_s}{d} M \qquad (1)$$

where R_0 is the Hall coefficient, R_s is the anomalous Hall coefficient, d is the sample thickness, and M is the magnetization of the sample. R_s is proportional to R_{sheet} in the present sample and therefore, $R_s/d = cR_{sheet}$, where c is a constant. M of the sample can be determined from R_{Hall}, since the anomalous Hall term is the dominant term up to 300K. Fig. 5 shows ferromagnetic transition temperature Tc, which determined from magneto-transport measurement as a function of Mn composition x. The closed circle means metallic sample, whereas open circle show insulating sample. This sample shows high Tc(110K), which is comparable with other research group.

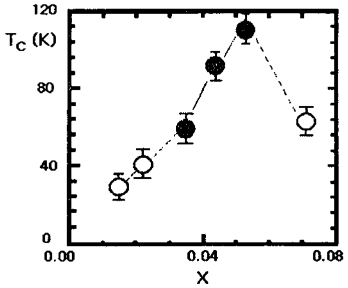

Fig. 5 Ferromagnetic transition tempera-ture Tc determined from magneto-transport measurement as a function of Mn composition x.

In the result of Fig.6, T and B dependance of R_{Hall} reflects that of M, confirming the dominating contribution of the anomalous Hall effect. The paramagnetic Currie temperature θ was obtained from the T dependance of the inverse of the zero field slope of R_{Hall}/R_{sheet} In the absence of holes, the magnetic interaction among Mn has been shown to be antiferromagnetic in n-type (In,Mn)As(5) and in fully carrier compensated (Ga,Mn)As.

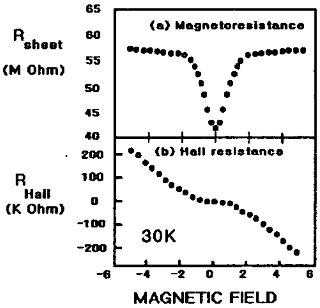

Fig. 6 The magnetic field dependance of (a) magneto-resistance and (b) Hall resistance for (Ga,Mn)As films measured at 30K.

These results shows that the ferromagnetic interaction is hole induced. Currie temperature can be calculated from the exchange constant in RKKY(Rudermann Kittel Kasuya Yosida) interaction, which was shown to be responsible for the carrier induced ferromagnetism in a II-VI's. Although the result depends slightly on the cut-off length of the RKKY interaction, the calculated Tc was in good accord with the experimentally determined. This result suggest that the RKKY interaction is most likely responsible for the appearance of ferromagnetism in (Ga,Mn)As. As shown in Fig.5, ferromagnetism observed in insulating samples can probably be understood in the carrier-mediated RKKY-like interaction. The insulating sample close to the metal-insulator transition. The localization length is not extended over the millimeter of sample size, but is still quite long compare with the nanometer length scale of magnetic interaction. So the RKKY-like interaction can be effective in the insulating sample. The understanding of the ferromagnetism of (Ga,Mn)As is not enough, only by RKKY, though.

5. Conclusions

The magnetic element Mn introduced into III-V GaAs semiconductor to make the semiconductor magnetic in order for expectation of possibility to make the diluted magnetic semiconductor, which is a candidate for exploring a new field in semiconductor physics and technology. RHEED results with SEM image indicates of two-dimensional layer-by-layer growth by low temperature MBE growth at 260℃ could show distinct condition for possibility to open thin film growt of DMS's. From SQUID data we could obtain and calculated the Currie temperature as high as 110K, it is good agree with experimental result.

The magnetic field dependance of magnetization M at 5K for (Ga,Mn)As film with Mn content x=0.035 shows ferromagnetic characteristics. RKKY approximation can be effective to analysis and be understood in the carrier-mediated interaction such as (Ga,Mn) As.

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