AIP | Journal of Applied Physics

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Citation: J. Appl. Phys. **89**, 7392 (2001); doi: 10.1063/1.1359475
View online: http://dx.doi.org/10.1063/1.1359475
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v89/i11
Published by the American Institute of Physics.

Magnetic and transport properties of III–V diluted magnetic semiconductor $Ga_{1-x}Cr_xAs$

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Magnetic and transport properties of Cr-based III–V diluted magnetic semiconductor $Ga_{1-x}Cr_xAs$ Cr concentrations up to $x=0.10$ have been investigated. For all the films, no long-range magnetic order was observed down to 2 K. A sign of paramagnetic Curie temperature is positive, indicating that the dominant magnetic interaction between Cr atoms is ferromagnetic. The effective number of Bohr magneton is estimated to be 5.1 ± 0.4, which is close to that of Cr^{2+} ion. The magnetization curve shows superparamagnetic behavior at low temperatures. The radius of the local spin order in $x=0.034$ is estimated to be 1.5–2.0 nm at $T=5$ K and it decreases with increasing temperature. From Hall effect measurements at room temperature, the magnitude of mobility is estimated to be less than 0.5 cm^2/V s. This low mobility strongly suggests that the hopping conductivity is dominant in $Ga_{1-x}Cr_xAs$ films. [DOI: 10.1063/1.1359475]

I. INTRODUCTION

Recent progress in crystal growth techniques allow one to synthesize new III–V diluted magnetic semiconductors (DMS) such as $(In_{1-x}Mn_x)As$ (Ref. 1) and $(Ga_{1-x}Mn_x)As$.[2] Their unique magnetic properties and excellent matching with III–V optoelectronics and electronics materials make them very important for the development of a new class of spin-electronic devices. Contrary to II–VI DMSs, up to now III–V DMSs have been limited only to the Mn-based DMSs. Therefore it is quite interesting to synthesize new III–V DMSs with other magnetic transition metals.

Recently, we have succeeded in synthesizing a Cr-based III–V DMS $Ga_{1-x}Cr_xAs$.[3] Since the physical properties of $Ga_{1-x}Cr_xAs$ have not been clarified, we report the magnetic and transport properties of a new Cr-based III–V DMS $Ga_{1-x}Cr_xAs$.

II. EXPERIMENT

$Ga_{1-x}Cr_xAs$ films were grown by a low-temperature molecular beam epitaxy (LTMBE) method. A GaAs buffer layer was first grown on (001) GaAs substrates at a substrate temperature $T_S\sim600\,°C$. Then a 400-nm-thick $Ga_{1-x}Cr_xAs$ layer was grown at $T_S\sim250\,°C$ under the As to Ga beam flux ratio of ~30. Cr concentration x was determined by an electron probe micro-analysis. A streaky reflection high energy electron diffraction (RHEED) patterns was observed for the films with $x<0.10$. With increasing x, the RHEED patterns became spotty, indicating a roughening of grown films. Also, x-ray diffraction showed that the films with low Cr concentration ($x<0.05$) are twins-free, but with increasing x the density of twins sharply increases. Magnetic circular dichroism (MCD) spectra were measured in a reflection mode under the magnetic field applied perpendicularly to the film.[4] Magnetization measurements were carried out using a superconducting quantum interface device magnetometer (SQUID). To derive the magnetization of $Ga_{1-x}Cr_xAs$ films, the magnetization of GaAs substrate was subtracted from the total magnetization.

III. RESULTS AND DISCUSSION

Figure 1 shows the MCD spectrum of $Ga_{1-x}Cr_xAs$ ($x=0.034$) in a magnetic field $H=10$ kOe at temperature $T=5$ K, together with that of $x=0.0$. The MCD signals for $Ga_{1-x}Cr_xAs$ are strongly enhanced near the energies corresponding to the $\Gamma(\sim1.5$ eV) and $\Lambda(\sim3.0$ eV) critical points (CP) of $x=0.0$. The MCD spectral shape of $Ga_{1-x}Cr_xAs$ film is very similar to that of $Ga_{1-x}Mn_xAs$.[4] For Cr concentration $x>0.10$, no enhancement MCD signals at the CP was observed. Therefore it can be concluded that $Ga_{1-x}Cr_xAs$ ($x<0.10$) is a DMS with a zinc-blende type band structure and the strong sp-d mixing occurs at each CP.

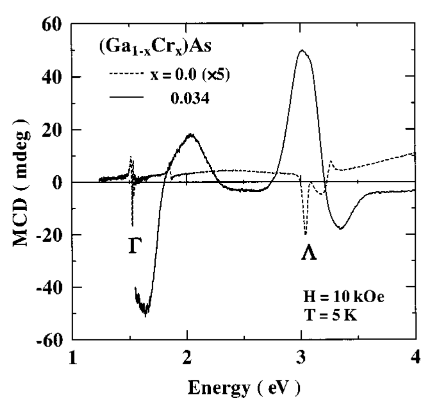

FIG. 1. MCD spectrum of $Ga_{1-x}Cr_xAs$ ($x=0.034$) in $H=10$ kOe at $T=5$ K (solid line) together with that of $x=0.0$ (broken line) for comparison.

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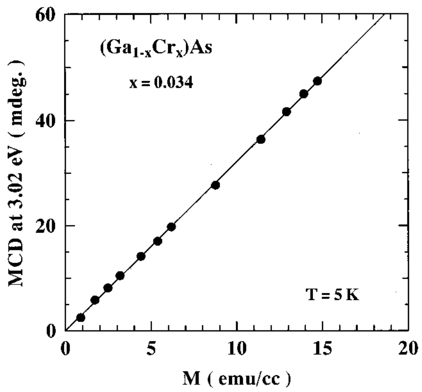

FIG. 2. MCD amplitude of $Ga_{1-x}Cr_xAs$ ($x=0.034$) at the Λ critical point (3.02 eV) as a function of the magnetization of the sample measured by SQUID.

Since the MCD signal at the Λ CP comes from $Ga_{1-x}Cr_xAs$, its amplitude should be proportional to the magnetization M of $Ga_{1-x}Cr_xAs$. To determine whether the magnetic impurities or precipitation exist in our samples, we compare the field dependence of MCD and M of the samples measured by SQUID. Figure 2 shows the MCD amplitude at 3.02 eV of $Ga_{1-x}Cr_xAs$ (x=0.034) at T=5 K as a function of M. The data are on a single straight line, indicating that the measured magnetization comes from $Ga_{1-x}Cr_xAs$ and is free from the possible magnetic precipitations.

The temperature dependence of susceptibility χ and inverse susceptibility χ^{-1} for $Ga_{1-x}Cr_xAs$ (x=0.034) in $H=10$ kOe are given in Fig. 3. The shape of the curve for χ shows a Curie–Weiss type paramagnetism and no long-range magnetic order down to 2 K. Fitting χ^{-1} versus T curve using a Curie–Weiss law, the effective number of Bohr magneton P_{eff} and paramagnetic Curie temperature θ_p are obtained to be 5.1±0.4 and 15 K ±5 K, respectively. The value of P_{eff} is close to that of a Cr^{2+} ion (4.9), suggesting that Cr ions act as acceptors in $Ga_{1-x}Cr_xAs$. It should be remarked that a sign of θ_p is positive, indicating that the dominant magnetic interaction between Cr ions is ferromagnetic. Moreover, the χ^{-1} versus T curve deviates from a Curie–Weiss law below about $T=30$ K, implying that the effect of the ferromagnetic interaction becomes pronounced at low T.

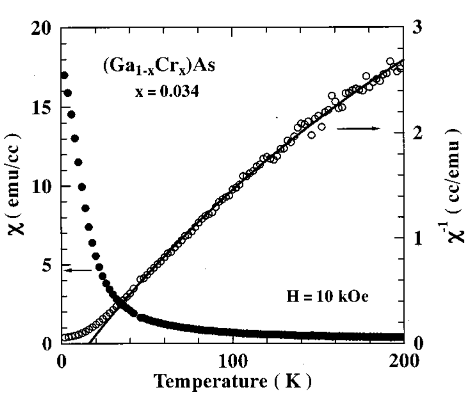

FIG. 3. Temperature dependence of susceptibility χ (●) and inverse susceptibility χ^{-1} (○) for $Ga_{1-x}Cr_xAs$ ($x=0.034$) in $H=10$ kOe. The solid line shows a fitting result by a Curie–Weiss law.

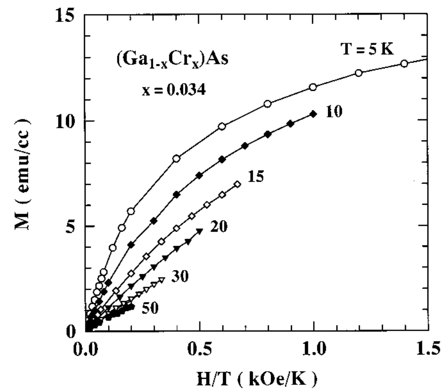

FIG. 4. Magnetization vs H/T curves for $Ga_{1-x}Cr_xAs$ ($x=0.034$).

To clarify the magnetic ground state of $Ga_{1-x}Cr_xAs$, we measured magnetization curves as a function of T. Figure 4 shows M versus H/T curves of $Ga_{1-x}Cr_xAs$ (x=0.034). Fitting the curve by the Brillouin function at $T=5$ K, the value of effective spin S_{eff} is obtained to be 20–50, showing superparamagnetism in $Ga_{1-x}Cr_xAs$. Using a spin of Cr^{2+} ion $S_{Cr}=2$ and the lattice constant $a=0.565$ nm, the radius of the local spin order is estimated to be 1.5–2.0 nm at $T=5$ K for $x=0.034$. If S_{eff} does not change with T and H, the dependence of M versus H/T should follow a single Brillouin function irrespective of T. However, from Fig. 4, M versus H/T curves clearly change with T. Also, M decreases with increasing T. This indicates that the size of the local spin ordering in $Ga_{1-x}Cr_xAs$ decreases with increasing T.

Hall voltages for $Ga_{1-x}Cr_xAs$ at room temperature is too small to determine the conduction type. The magnitude of mobility is roughly estimated to be less than 0.5 cm^2/V s. Such a low mobility strongly suggests that the hopping conductivity is dominant. On the other hand, the p-type conduction was clearly observed in $Ga_{1-x}Mn_xAs$, even the valence of most of the Mn ions is the same as Cr ions, that is, Mn^{2+}.[5] This difference in type of conductivity is qualitatively explained by the difference of the isolated acceptor level of the magnetic ion, that is, an acceptor level of Cr in GaAs [0.89 eV (Ref. 6)] is several times as deep as that of Mn [0.11 eV (Ref. 7)].

There are two possible origins for the observed ferromagnetic interaction between Cr in $Ga_{1-x}Cr_xAs$. One is the carrier-induced interaction.[8] A band calculation[9] predicts the carrier-induced ferromagnetic interaction between localized spins in $Ga_{1-x}Cr_xAs$ as the same as $In_{1-x}Mn_xAs$ and $Ga_{1-x}Mn_xAs$. The other one is the superexchange interaction.[8] At present, it is not clear which mechanism is responsible in $Ga_{1-x}Cr_xAs$. More detailed studies are needed to elucidate the origin of magnetic interaction in $Ga_{1-x}Cr_xAs$.

IV. CONCLUSIONS

In summary, we have investigated magnetic and transport properties of Cr-based III–V DMS $Ga_{1-x}Cr_xAs$ having Cr concentrations up to $x=0.10$. No magnetic order was observed down to 2 K in all the films. A positive sign of the paramagnetic Curie temperature indicates that the dominant interaction between Cr ions is ferromagnetic. The effective number of a Bohr magnetron is close to that of a Cr^{2+} ion, suggesting that Cr ions act as acceptors. The magnetization curve shows the superparamagnetic behavior with a large effective spin at low temperature T. The radius of the local spin order in $x=0.034$ at $T=5$ K is calculated to be 1.5–2.0 nm and it decreases with increasing T. Low mobility at room temperature estimated from Hall measurement suggests the hopping conductivity is dominant in $Ga_{1-x}Cr_xAs$.

ACKNOWLEDGMENT

The authors are grateful to Dr. A. K. Bhattacharjee for his valuable discussions.

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