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Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp1205-1206

Magnetic and transport properties of Group-IV based ferromagnetic semiconductor $Ge_{1-x}Fe_x$ with Boron doping

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1. Introduction

Over the past decade, a number of studies were carried out on group-IV ferromagnetic semiconductors. Especially, many investigations have been done for $Ge_{1-x}Mn_x$ [1]. It was pointed out that the origin of their ferromagnetism comes from intermetallic or Mn-rich metallic phases, such as nanocolumnar precipitation. Our group previously reported structural and magnetic properties of epitaxially grown $Ge_{1-x}Fe_x$, another group-IV magnetic semiconductor, and concluded that $Ge_{1-x}Fe_x$ is an intrinsic ferromagnetic semiconductor [2,3]. $Ge_{1-x}Fe_x$ grown by low-temperature molecular beam epitaxy (LT-MBE) was shown to have a diamond-type crystal structure without any other crystallographic phase of precipitates [3]. The ferromagnetism of $Ge_{1-x}Fe_x$ was investigated using magnetic circular dichroism (MCD) spectroscopy [2]. The MCD measurements revealed that band structure of $Ge_{1-x}Fe_x$ were identical with those of bulk Ge. However, the origin of ferromagnetism is still unknown, and optimization of the magnetic and transport properties has not been achieved. One of the methods for controlling the semiconductor properties is doping donors or acceptors. In this paper, we report magnetic and transport properties of the ferromagnetic semiconductor Boron doped $Ge_{1-x}Fe_x$, in which we try to control the density of holes.

2. MBE growth

Epitaxial growth of $Ge_{1-x}Fe_x$ by MBE

Fig. 1 shows typical layer structures of samples investigated in this study, consisting of Ge (2nm) / B-doped $Ge_{1-x}Fe_x$ (100nm) / Si (3-8nm) / SiO_2 (50nm) / undoped Si(001). $Ge_{1-x}Fe_x$ thin films were epitaxially grown on Si-on-insulator (SOI) substrates by MBE at low substrate temperature (T_S=200°C) with the Fe content x = 2.3%, 6.5%, 10.5%, 14.0%. Boron doped $Ge_{1-x}Fe_x$ films (B concentration = 3.2×10^{17}, 2.6×10^{18}, $4.4\times10^{19}/cm^3$) were grown using a high temperature effusion cell (HTEZ, MBE-Komponenten) in some of these samples. Reflection high-energy electron diffraction (RHEED) was used to monitor the surface of $Ge_{1-x}Fe_x$ films during the MBE growth. The RHEED patterns of the $Ge_{1-x}Fe_x$ films were bright 2×2 streaks (Fig. 2), and these indicate the diamond crystal structure for all the samples.

Processing $Ge_{1-x}Fe_x$ thin films

After the epitaxial growth, the $Ge_{1-x}Fe_x$ films were fabricated into Hall bar shaped devices (200μm × 50μm). Hall effect measurements on $Ge_{1-x}Fe_x$ were carried out in a superconducting magnet cryostat (Oxford Instruments, Spectromag 4000) to saturate the magnetization of $Ge_{1-x}Fe_x$. Thin Si-on-insulator substrates were used in order to prevent parallel conduction through the Si substrates.

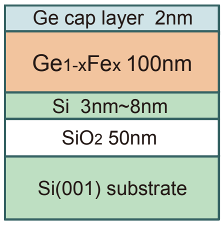

Fig. 1 Schematic of the layer structure used in this study.

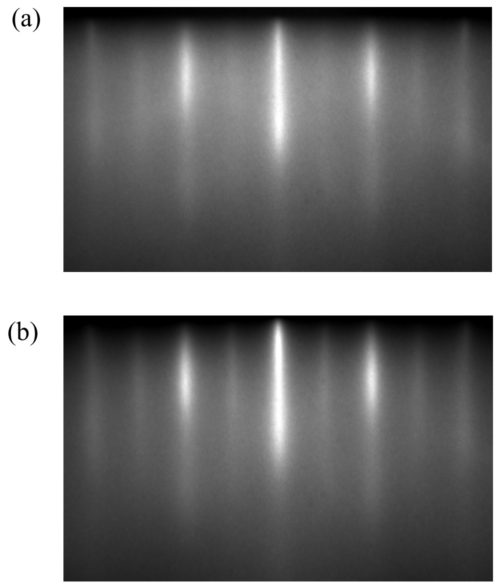

Fig. 2 RHEED pattern of the Boron doped $Ge_{1-x}Fe_x$ film (a) (x=10.5%, Boron doping concentration of $4.4\times10^{19}/cm^3$, 100nm) and Ge cap layer (b).

3. Measurement results

Magnetic circular dichroism (MCD)

Fig. 3 shows the magnetic field dependence of the MCD signals at various photon energies for the B doped $Ge_{1-x}Fe_x$ film (x=10.5%). Normalized intensities of these MCD signals are shown in this graph, in which the data were normalized at 1T. The MCD signals exhibited clear ferromagnetic hysteresis curves, and the normalized signals are completely identical to each other at these photon energies. Furthermore, when MCD spectra measured at different magnetic fields (0.2, 0.5 and 1.0T) are normalized, all of them are almost completely overlapped on one spectrum. These results indicate that the ferromagnetism of the B-doped $Ge_{1-x}Fe_x$ comes from a single phase, which is an intrinsic ferromagnetic semiconductor..

Anomalous Hall effect

Fig. 4 shows the result of Hall effect measurements of $Ge_{1-x}Fe_x$ (x=10.5%) with a Boron doping concentration of $4.4\times10^{19}/cm^3$. The slope of the Hall resistance (at ~5T) indicates p-type doping at 10 ~ 300 K. The anomalous Hall effect (proportional to magnetization) was clearly observed at low temperatures, where ferromagnetic hysteresis was also observed. In ferromagnetic materials, the Hall resistivity R_{xy} is the sum of the ordinary and anomalous components. In this work, the anomalous component was deduced by subtracting the ordinary components (proportional to the magnetic field) which is the linear slope of R_{xy} at a high magnetic field (at ~5T). Using the anomalous component of R_{xy}, we performed the analyses of the anomalous Hall conductivity σ_{AHE} and conductivity σ_{xx} of $Ge_{1-x}Fe_x$. The relation between σ_{AHE} and σ_{xx} (where $\sigma_{AHE} = \sigma_{xx}^{\gamma}$) was plotted, and the exponent γ was estimated to be 1.0 ~ 1.2. This result indicates that the origin of the anomalous Hall effect in $Ge_{1-x}Fe_x$ is skew scattering.

3. Conclusion

Boron doped $Ge_{1-x}Fe_x$ was confirmed to be an intrinsic ferromagnetic semiconductor with no ferromagnetic precipitates through magnetic circular dichroism (MCD) measurements. The anomalous Hall effect (AHE) was clearly observed and the relation between σ_{AHE} and σ_{xx} indicates that the origin of AHE in $Ge_{1-x}Fe_x$ is skew scattering.

Acknowledgements

This work was partly supported by Grant-in-Aids for Scientific Research including Specially Promoted Research, the Special Coordination Programs for Promoting Science and Technology, and FIRST Program of JSPS. The authors acknowledge the support of Global COE Program "Secure-life Electronics" sponsored by JSPS and MEXT.

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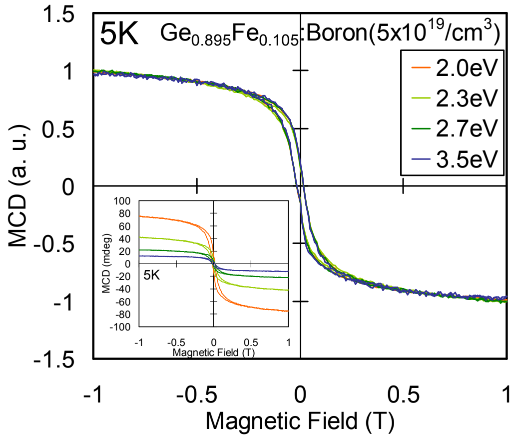

Fig. 3 Magnetic field dependence of MCD (magnetic circular dichroism) at various photon energies of the $Ge_{1-x}Fe_x$:Boron film (x=10.5%, Boron doping concentration of $4.4\times10^{19}/cm^3$).

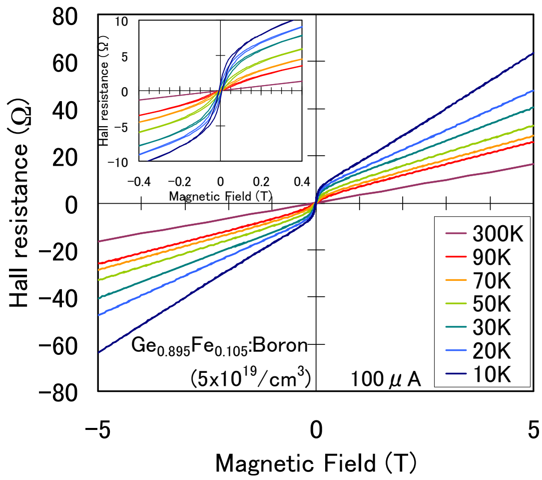

Fig. 4 Magnetic field dependence of Hall resistivity of the $Ge_{1-x}Fe_x$ film (x=10.5%, Boron doping concentration of $4.4\times10^{19}/cm^3$) at various temperatures.