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Magneto-transport properties of amorphous $Ge_{1-x}Mn_x$ thin films

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Abstract

Amorphous $Ge_{1-x}Mn_x$ thin films were grown in order to expand the solubility limit of Mn. The amorphous $Ge_{1-x}Mn_x$ thin films were grown on (1 0 0)Si substrate at 373 K by using a thermal evaporator. The solubility of Mn in amorphous $Ge_{1-x}Mn_x$ thin films reaches up to 17 at.%. The amorphous $Ge_{1-x}Mn_x$ thin films are ferromagnetic and the T_C is ~150 K. The largest saturation magnetization of amorphous $Ge_{1-x}Mn_x$ thin films is ~100 emu/cm^3 for $x = 0.118$ at 5 K. The variation of electrical resistivity with respect to temperature reveals that the amorphous $Ge_{1-x}Mn_x$ thin films have semiconductor characteristics. The in-field electrical resistivity of amorphous $Ge_{1-x}Mn_x$ thin films is lower than the zero-field electrical resistivity when $T < T_C$, but the reverse is true when $T > T_C$. However, the in-field electrical resistivity of amorphous $Ge_{1-x}Mn_x$ thin films is always higher than the zero-field electrical resistivity when $x > \sim 12$ at.%. Magneto-transport characteristics of amorphous $Ge_{1-x}Mn_x$ thin films show anomalous Hall phenomenon and negative magnetoresistance when $T < T_C$. The results suggest that the Mn atoms in amorphous $Ge_{1-x}Mn_x$ thin films be related to spin dependent scattering depending on magnetization.

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Keywords: Magnetic semiconductor; Spintronics materials; GeMn semiconductors; Amorphous semiconductor

1. Introduction

Recently magnetic element doped semiconductors, such as Mn-doped III–V, II–IV [1,2] and group IV semiconductors [3–12], have been studied extensively due to the application potentials in the spin-polarized injection. Among them Si- or Ge-based magnetic semiconductors are very attractive since the well-established current semiconductor technologies can be applied to them directly. But these materials have low solubility limit of Mn and thus low Curie temperature. Recently, theoretical and experimental works indicate that the Curie temperature of Si- or Ge-based magnetic semiconductor increases with Mn concentration [3,5]. In the case of $Ge_{1-x}Mn_x$, when Mn exceeds solubility limit of crystalline phase Ge, secondary phases, such as Ge_3Mn_5 and Ge_8Mn_{11} [7,9,13,14], are precipitated and they cause fatal disadvantages on electronic properties. However, amorphous $Ge_{1-x}Mn_x$ phase can contain Mn beyond the solubility limit of crystalline $Ge_{1-x}Mn_x$ without secondary phases. In this work, amorphous $Ge_{1-x}Mn_x$ thin films were grown in order to increase Curie temperature, and the magneto-transport properties of the a-$Ge_{1-x}Mn_x$ thin films were studied.

2. Experimental

Amorphous $Ge_{1-x}Mn_x$ (a-$Ge_{1-x}Mn_x$) thin films were grown on thermally oxidized (1 0 0)Si wafer by using an evaporator. Mn and Ge were co-evaporated at 373 K in the vacuum of 10^{-6} Torr. Film thickness was measured

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by using alpha step, and was ~500 nm. The composition of a-$Ge_{1-x}Mn_x$ thin films was determined by using an energy dispersive X-ray spectroscopy and X-ray photoelectron spectroscopy. The microstructure of a-$Ge_{1-x}Mn_x$ thin films was analyzed by using conventional X-ray diffractometer (XRD) and transmission electron microscopy (TEM). Magnetization and magneto-transport were analyzed by using a magnetic properties measurement system, a physical property measurement system and a superconducting quantum interference device in the temperature range of 2–300 K with magnetic field sweep between −9 T and 9 T. Hall effect was measured at room temperature using 0.5 T electromagnet. For Hall and resistivity measurements, Ohmic contacts using high purity In were made on the a-$Ge_{1-x}Mn_x$ thin films.

3. Results and discussion

XRD patterns given in Fig. 1 show $Ge_{1-x}Mn_x$ thin films are amorphous when $x < 0.173$, and diffraction peaks of Mn appear when $x > 0.310$. Mn precipitates were examined closely by taking cross-sectional TEM images and diffraction patterns.

The electrical resistivities of $Ge_{1-x}Mn_x$ thin films were measured at room temperature and are plotted in Fig. 2. The electrical resistivity of $Ge_{1-x}Mn_x$ thin films decreases with increasing Mn concentration and is 5×10^{-4}–10^{2} Ω cm.

In order to analyze the variation of the electrical resistivity Hall measurement has been done at room temperature. The $Ge_{1-x}Mn_x$ thin films are turned out to have p-type carriers, and carrier concentration is 7×10^{17}–2×10^{22} cm^{-3}. As seen in Fig. 3, Hall analysis reveals that, as increasing Mn concentration, the hole concentration increases predominantly over the hole mobility which decreases, so

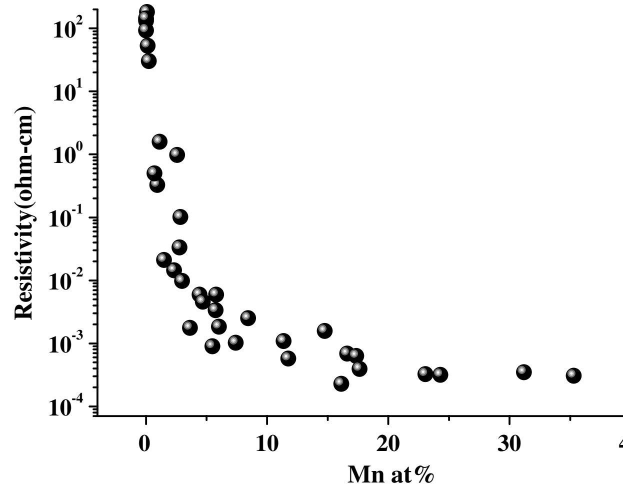

Fig. 2. Sheet resistivities of $Ge_{1-x}Mn_x$ semiconductor thin films measured at room temperature using four-point probe.

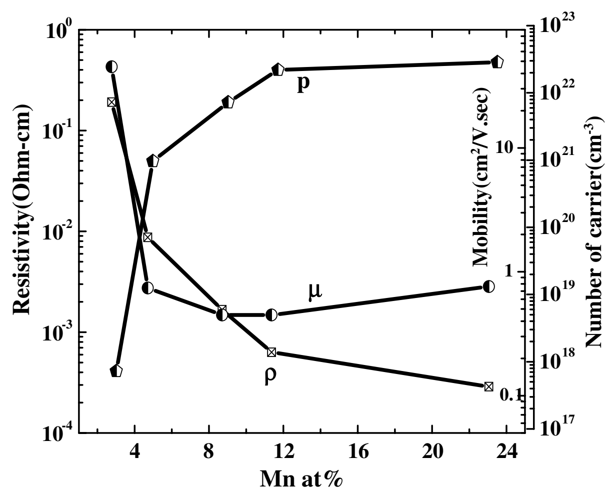

Fig. 3. Hall data of $Ge_{1-x}Mn_x$ thin films measured at room temperature.

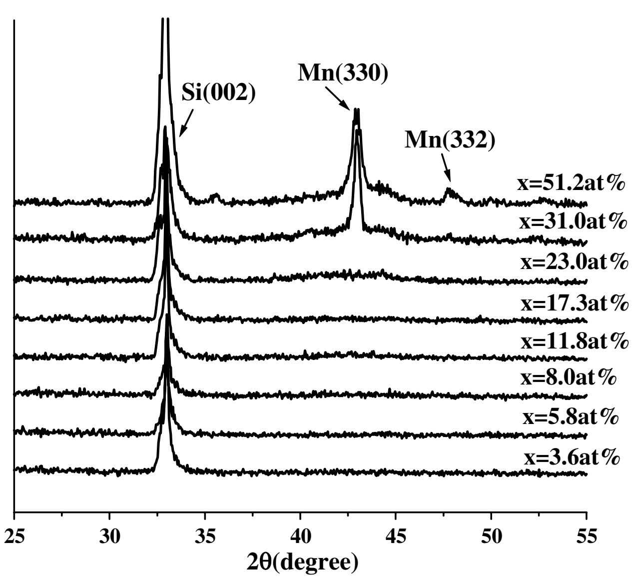

Fig. 1. X-ray diffraction patterns of $Ge_{1-x}Mn_x$ films.

that electrical resistivity decreases with increasing Mn concentration.

Fig. 4 is the magnetizations of $Ge_{1-x}Mn_x$ thin films measured using a SQUID. $Ge_{1-x}Mn_x$ thin films are ferromagnetic at low temperature and gradually change into paramagnetic as temperature increases. The Curie temperature of $Ge_{1-x}Mn_x$ thin films varies with Mn concentration and is approximately 150 K. The saturation magnetization also varies with Mn concentration. The largest saturation magnetization is ~100 emu/cm^3 at 5 K for $x = 0.118$.

Fig. 5 is the magnetic field effect of electrical resistivities of a-$Ge_{1-x}Mn_x$ thin films as a function of temperature. Fig. 5 reveals typical semiconductor characteristics of electrical resistivity. The in-field electrical resistivity of a-$Ge_{1-x}Mn_x$ thin films is lower than the zero-field electrical resistivity when $T < T_C$, but the reverse is true when $T > T_C$. However, the electrical resistivity of a-$Ge_{1-x}Mn_x$ thin films is higher than the zero-field electrical resistivity in all range of temperature when Mn concentration is lar-