Journal of Ceramic Processing Research. Vol. 5, No. 3, pp. 238~240 (2004)

JOURNAL OF
Ceramic
Processing Research

Growth of ferromagnetic semiconducting Si:Mn film by a vacuum evaporation method

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We have fabricated $Si_{0.93}Mn_{0.07}$ film at very low temperature (673 K) by vacuum evaporation and the film is ferromagnetic with a well-defined Curie temperature of 210±5 K. The as-deposited film was amorphous, however, the film epitaxially crystallizes by annealing at 973 K. For this sample, the coercive field decreases monotonically with increasing temperature. The coercive fields, H_c, are 320, 150, and 70 Oe at 5, 100, and 200 K, respectively, and the saturation magnetizations, M_s, are 2.43, 1.78, and 0.67 emu/g at 5, 100, and 200 K, respectively. The resistivity decreases as the temperature increases in the $Si_{0.93}Mn_{0.07}$ film. The temperature dependence of resistivity shows a normal semiconductor behavior.

Key words: Ferromagnetic, Si:Mn, Vacuum Evaporation, Magnetic, Electrical, Semiconductor.

Introduction

Recently, dilute magnetic semiconductors (DMSs) have been widely studied, especially, the III-V and II-VI compound semiconductors.[1-3] We have an interest in group IV-based DMSs which are promising materials, especially, for microelectronics applications. Park *et al.* reported on the epitaxial growth of a Mn_xGe_{1-x}, by molecular beam epitaxy (MBE) in which the Curie temperature was found to increase linearly with manganese (Mn) concentration from 25 to 116 K.[4] Gajdzik *et al.* reported on ferromagnetism in Mn/C/Si triple layers above room temperature.[5] Recently, Yokota *et al.* reported the fabrication of single phase $Si_{0.997}Ce_{0.003}$ films and their magnetic and electrical transport properties, and also examined the annealing effects, which vary the crystallographic state of the host Si and the coordination of Ce.[6] Here, we demonstrate the growth of ferromagnetic semiconducting $Si_{1-x}Mn_x$ film by vacuum evaporation and report an investigation of the magnetic and electrical properties of $Si_{0.93}Mn_{0.07}$ film.

Experimental Procedures

The $Si_{1-x}Mn_x$ films were deposited by vacuum evaporation on (111) Si substrates. The deposition rates of Si and Mn were measured using a thickness monitor. These $Si_{1-x}Mn_x$ films were characterized by energy dispersive spectroscopy (EDS), X-ray diffraction (XRD), superconducting quantum interface device magnetometer (SQUID) and the temperature dependence of resistivity (ρ–T).

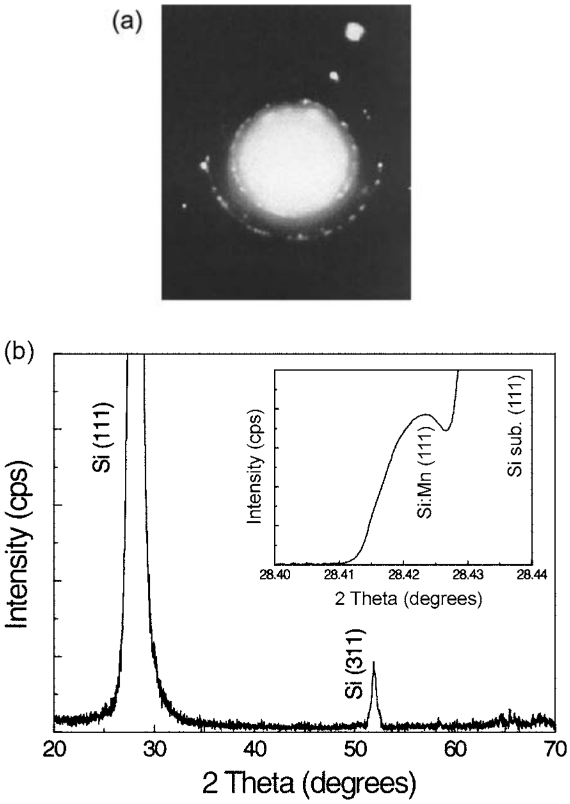

Fig. 1. Selective area electron diffraction (SAED) pattern of the as-deposited Si:Mn film and an x-ray diffraction pattern of the Si:Mn film after annealing. Inset shows the narrow scan around Si (111).

The XRD patterns of the as-deposited Si:Mn film show that the film was amorphous (not shown here).

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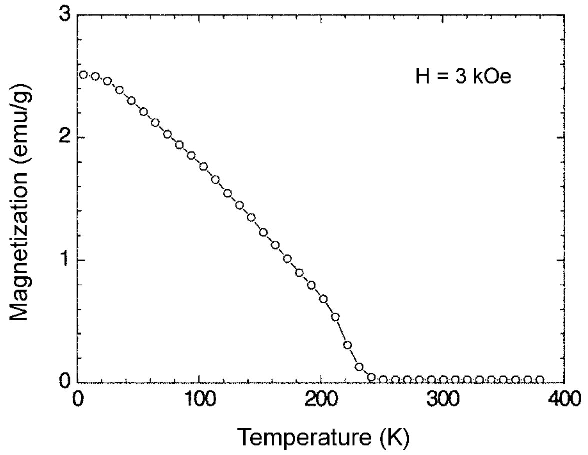

Fig. 2. Magnetization (*M*) vs temperature (*T*) for a $Si_{0.93}Mn_{0.07}$ film in an applied field H=3 kOe.

The selective area electron diffraction (SAED) pattern (Fig. 1(a)) also suggests that the film was amorphous without any precipitation of silicides and other crystalline components. In order to crystallize the film, samples were annealed at 773-1173 K for 1 minute in a vacuum (~0.13 Pa or ~10^{-3} Torr) by a rapid thermal annealing (RTA) system. Figure 1(b) shows the XRD pattern of the sample annealed at 973 K. The $Si_{1-x}Mn_x$ related peak shows a shoulder at the lower angle side of the (111) Si substrate diffraction maxima (inset in Fig. 1(b)). The diffraction intensity on the shoulder, which was identified as that from the film, is hundreds of times larger that that expected diffraction intensity from a polycrystalline film, leading us to conclude that, the film consists of epitaxially grown Si and a very small amount of poly-Si. A detailed cross-sectional TEM analysis has revealed that polycrystalline Si exists near the surface of the film (not shown here). Since the poly-crystalline region could be removed by chemical etching, all the experiments subsequently discussed were performed using the sample etched with this layer removed. No silicide precipitation has been recognized in the annealed sample, even by SAED observations.

Figure 2 shows the temperature dependent magnetization (*M*-*T*) measured in an applied field of 3 kOe for the sample annealed at 973 K. The onset of ferromagnetism is seen at $T_c = 210 \pm 5$ K with an error arising from the uncertainty of substracting the Curie-Weiss tail above T_c. Figure 3 shows three magnetization curves taken at 5, 100, and 200 K after substraction of the diamagnetic contribution of the Si substrate. The coercive field decreases monotonically with increasing temperature. For our samples, the coercive fields, H_c, are 320, 150, and 70 Oe at 5, 100, and 200 K, respectively. Magnetization was measured up to 3 kOe without evidence of an increase of magnetization beyond the value acquired in 3 kOe. In this study, the saturation magnetizations, M_s, are 2.43, 1.78, and 0.67 emu/g at 5, 100, and 200 K, respectively.

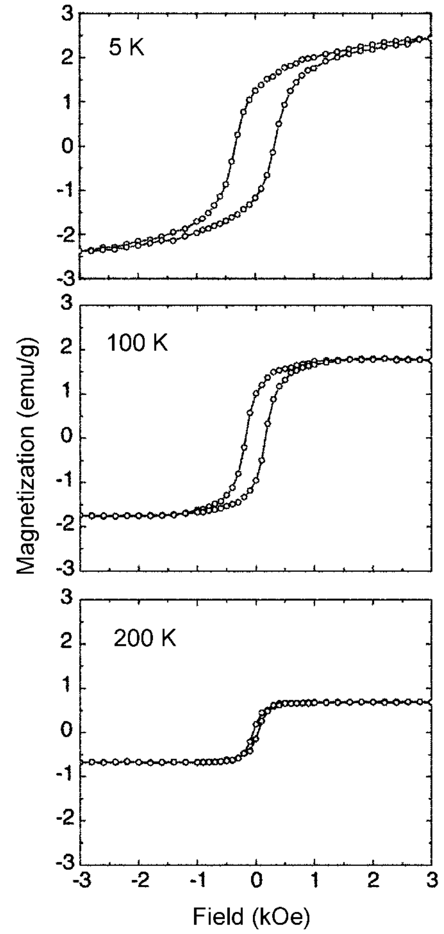

Fig. 3. Magnetization vs magnetic field curves (*M*–*T*) of a $Si_{0.93}Mn_{0.07}$ film for different measuring temperatures (*T*).

Figure 4 shows the resistivity change versus the inverse temperature of the sample annealed at 973 K. The temperature dependence of resistivity was measured in the temperature range from 5 to 350 K. The resistivity increases with decreasing temperature according

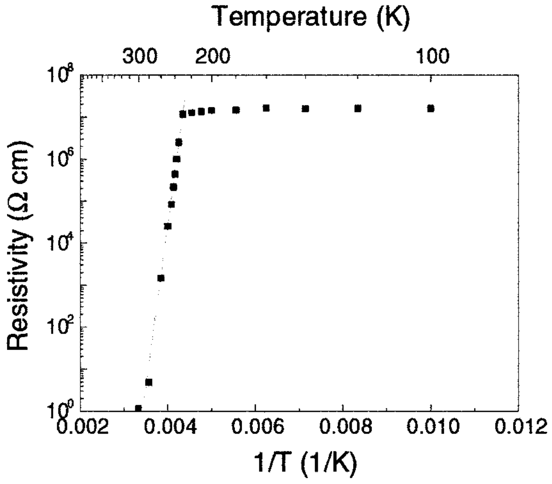

Fig. 4. Temperature dependence of resistivity (*ρ*–*T*) for annealed $Si_{0.93}Mn_{0.07}$ film annealed at 973 K.

to $\rho = \rho_0 \exp(E_a/kT)$, as is usually found for thermally-activated conduction processes having an activation energy of E_a.[6] The resistivity exponentially decreases from 210 ± 5 K with an increase in temperature.

Conclusions

In conclusion, we have fabricated $Si_{0.93}Mn_{0.07}$ film at very low temperature (673 K) by a vacuum evaporation method and the film is ferromagnetic with a well-defined Curie temperature of 210 ± 5 K. The as-deposited film was amorphous, however, the film epitaxially crystallizes by annealing at 973 K. For this sample, the coercive field decreases monotonically with increasing temperature. The coercive fields, H_c, are 320, 150, and 70 Oe at 5, 100, and 200 K, respectively, and the saturation magnetizations, M_s, are 2.43, 1.78, and 0.67 emu/g at 5, 100, and 200 K, respectively. The resistivity decreases as the temperature increases in the $Si_{0.93}Mn_{0.07}$ film. The temperature dependence of resistivity shows a normal semiconductor behavior.

Acknowledgment

This work was supported by KOSEF through the QSRC at Dongguk Univ.

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