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Formation mechanism of ferromagnetism in $Si_{1-x}Mn_x$ diluted magnetic semiconductors

Y.H. Kwon[a], T.W. Kang[a], H.Y. Cho[a], T.W. Kim[b,*]

[a]Quantum Functional Semiconductor Research Center, Dongguk University, 3-26 Chungku Pildong, Seoul 100-715, South Korea
[b]Department of Electronics and Computer Engineering, Advanced Semiconductor Research Center, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul 133-791, South Korea

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Abstract

$Si_{1-x}Mn_x$ diluted magnetic semiconductor (DMS) bulks were formed by using an implantation and annealing method. Energy dispersive X-ray fluorescence, transmission electron microscopy (TEM), and double-crystal rocking X-ray diffraction (DCRXD) measurements showed that the grown materials were $Si_{1-x}Mn_x$ crystalline bulks. Hall effect measurements showed that annealed $Si_{1-x}Mn_x$ bulks were p-type semiconductors. The magnetization curve as a function of the magnetic field clearly showed that the ferromagnetism in the annealed $Si_{1-x}Mn_x$ bulks originated from the interaction between interstitial and substitutional Mn^+ ions, which was confirmed by the DCRXD measurements. The magnetization curve as a function of the temperature showed that the ferromagnetic transition temperature was approximately 75 K. The present results can help to improve understanding of the formation mechanism of ferromagnetism in $Si_{1-x}Mn_x$ DMS bulks.

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Diluted magnetic semiconductor (DMS) materials, which combine semiconductors with additional magnetic transition metals, have become particularly attractive for investigations of basic physical properties and for potential applications in spintronic devices [1–5]. Among the various DMSs, $(Ga_{1-x}Mn_x)As$ and $(In_{1-x}Mn_x)As$ DMSs grown on GaAs substrates were not only the first fabricated but also have been the most extensively studied [1–8]. There has been increasing interest in group IV DMS materials because their promising applications in spintronic devices [9–11]. Among the candidates for group IV DMS systems, $Si_{1-x}Mn_x$ DMS materials are attractive because of dramatic potential applications in spintronic devices utilizing the advantages of both their ferromagnetic properties and the mature device technologies for Si materials [12–16]. Recently, some theoretical studies concerning the source of the holes and the localized moment in $Si_{1-x}Mn_x$ and $Ge_{1-x}Mn_x$ DMS materials were reported [17,18]. The epitaxially grown $Si_{0.95}Mn_{0.05}$ thin films showed an anomalous Hall effect due to internal magnetization around 70 K [16], which was supported by the theoretical calculations on ferromagnetic ordering in group-IV semiconductors [19]. Even though some studies concerning the formation and the physical properties of $Si_{1-x}Mn_x$ materials have been performed [20–22], the origin of the ferromagnetism in $Si_{1-x}Mn_x$ materials with DMS properties has not been clarified yet.

This communication reports data for the structural and magnetic properties of $Si_{1-x}Mn_x$ DMS materials formed by

* Corresponding author. Tel.: +82 2 2220 0354; fax: +82 2 2292 4135.
E-mail address: twk@hanyang.ac.kr (T.W. Kim).

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using an implantation and annealing method. Energy dispersive X-ray fluorescence (EDX), transmission electron microscopy (TEM), and double-crystal rocking X-ray diffraction (DCRXD) measurements were performed to characterize the composition and the structure of the as-implanted and the annealed $Si_{1-x}Mn_x$ materials. Hall effect measurements were carried out in order to investigate the electrical properties of the annealed $Si_{1-x}Mn_x$ materials, and superconducting quantum interference device measurements were performed to characterize their magnetic properties. The DCRXD measurements were also used to investigate the origin of ferromagnetism in the $Si_{1-x}Mn_x$ DMS materials.

The host materials used in this study were p-type Si (100) wafers, and 200-keV Mn^+ ions were implanted into those Si wafers. The doses for the implantation of Mn^+ ions into the Si bulk were 5×10^{15}, 1×10^{16}, and $5\times10^{16}\ cm^{-2}$. The projected range for the depth distribution of the Mn^+ ions, determined from the TRIM code, was 150 nm, with a standard deviation of ±50 nm. The Mn^+-implanted Si wafers were annealed to recrystallize the $Si_{1-x}Mn_x$ materials and to activate the Mn^+ ions. Thermal treatment was performed at 600, 700, 800, and 900 °C in a nitrogen atmosphere for approximately 5 min.

Fig. 1 shows the EDX spectra of the $Si_{1-x}Mn_x$ materials for Mn^+ ions implanted at doses of (a) 5×10^{15}, (b) 1×10^{16}, and (c) $5\times10^{16}\ cm^{-2}$. The K shell peak corresponding to the Si host material and the L and the K shell peaks related to the Mn^+ ions are observed. The peak intensities of the L and the K shell peaks related to the Mn^+ ions increase with increasing Mn^+ concentration, which indicates an increase in the Mn mole fraction contained in the $Si_{1-x}Mn_x$ material. When the doses of the implanted Mn^+ atoms were 5×10^{15}, 1×10^{16}, and $5\times10^{16}\ cm^{-2}$, the Mn mole fractions in the $Si_{1-x}Mn_x$ materials were 2, 2.5, and 5%, respectively. The EDX spectra demonstrate that the stoichiometries of the grown materials implanted with Mn^+ ions at doses of 5×10^{15}, 1×10^{16}, and $5\times10^{16}\ cm^{-2}$ were $Si_{0.98}Mn_{0.02}$, $Si_{0.975}Mn_{0.025}$, and $Si_{0.95}Mn_{0.05}$, respectively.

A high-resolution TEM (HRTEM) image and the corresponding selected area electron diffraction pattern (SADP) for the $Si_{0.95}Mn_{0.05}$ bulks annealed at 700 °C are shown in Fig. 2(a) and (b), respectively. The HRTEM image shows that the annealed $Si_{0.95}Mn_{0.05}$ bulks are single crystals with dislocations, as shown in Fig. 2(a). The appearance of dislocations in the $Si_{0.95}Mn_{0.05}$ bulks originates from Mn^+ ions occupying preferential interstitial sites, together with substitutional sites [23,16]. A

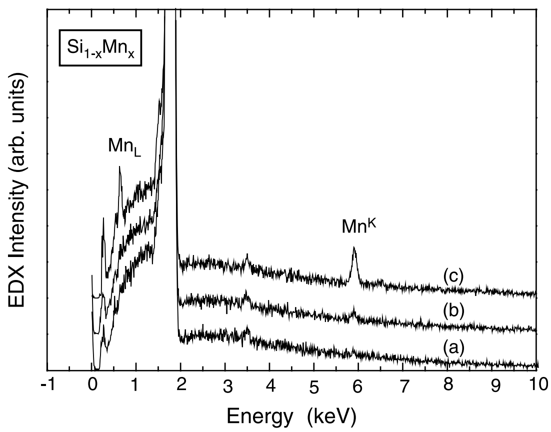

Fig. 1. Energy dispersive X-ray fluorescence spectra of the $Si_{1-x}Mn_x$ materials implanted with Mn^+ atoms at doses of (a) 5×10^{15}, (b) 1×10^{16}, and (c) $5\times10^{16}\ cm^{-2}$.

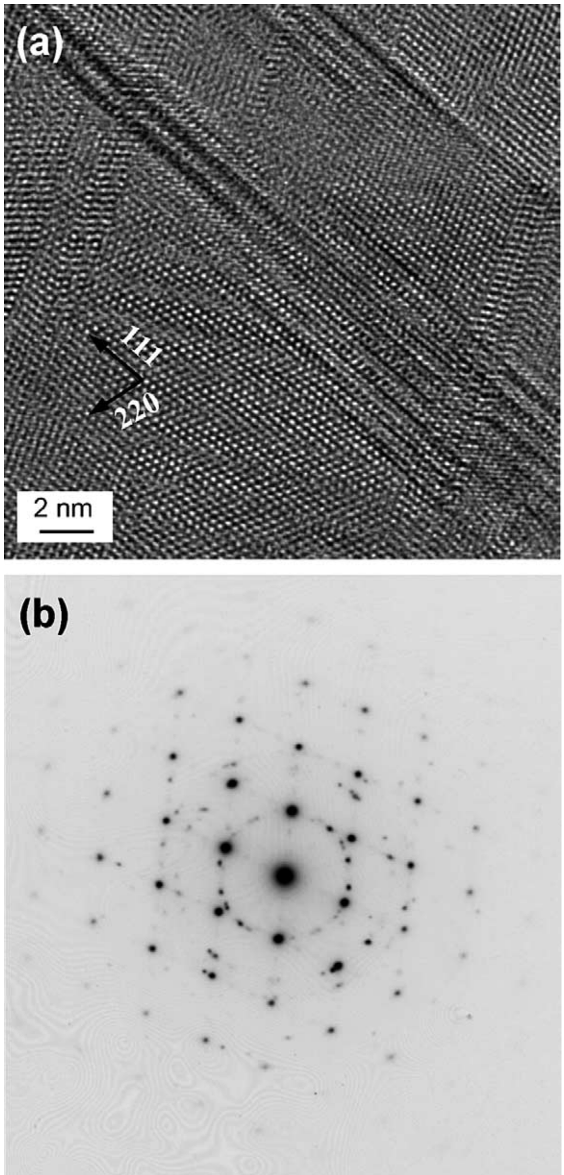

Fig. 2. (a) High-resolution transmission electron microscopy image and (b) selected area electron diffraction pattern for the $Si_{0.95}Mn_{0.05}$ bulks annealed at 700 °C.