Heavily Fe-doped *n*-type ferromagnetic semiconductor (In,Fe)Sb with high Curie temperature and large magnetic anisotropy

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Carrier-induced ferromagnetic semiconductors (FMSs) are promising for non-volatile and reconfigurable spintronics devices with low-power consumption, since they are unique materials having both ferromagnetic and semiconducting properties. To be used for realistic devices, however, FMSs must satisfy several fundamental requirements. *First,* their Curie temperature (T_C) must be much higher than room temperature (300 K). *Second*, both *p*-type and *n*-type FMSs are needed to make *p-n* junctions. *Third,* the magnetic anisotropy of FMSs must be large enough. Over the past years, however, many efforts on various FMS materials have failed in realizing an FMS that can satisfy these three requirements.[1,2] Recently, we have successfully grown both *p*-type FMS (Ga,Fe)Sb and *n*-type FMS (In,Fe)Sb with high T_C (335 - 340 K), which are the highest values so far reported in III-V based FMSs.[3,4] However, these T_C values are not high enough for stable operation of spin devices at room temperature (300 K). Furthermore, Fe-doped FMSs lack large magnetic anisotropy, thus they have small remanent magnetization and small coercive force, which are inappropriate for device applications.

In this study, to increase T_C and the magnetic anisotropy of the *n*-type FMS (In,Fe)Sb, we studied 12 – 30 nm-thick (In_{1-x},Fe_x)Sb films with high Fe concentrations (x = 20 - 35%) grown by low-temperature molecular beam epitaxy (LT-MBE). Magnetic properties investigated by magnetic circular dichroism (MCD) spectroscopy indicate that the (In_{1-x},Fe_x)Sb thin films with x = 20 – 35% maintain the zinc-blende (ZB) crystal and ZB band structure with single-phase ferromagnetism. T_C of (In_{1-x},Fe_x)Sb reaches 390 K at x = 35%, which is significantly higher than room temperature and much higher than the highest T_C values of other III-V FMSs as shown in Fig. 1(a). Figure 1(b) shows the in-plane and perpendicular magnetization *vs.* magnetic field (M – H) curves of the (In_{1-x},Fe_x)Sb sample x = 35% measured at 10 K by superconducting quantum interference device (SQUID) magnetometry; and Fig. 1(c) shows the enlarged in-plane M – H curves of the (In_{1-x},Fe_x)Sb samples (x = 20 – 35%) near zero field at 10 K. We found that the magnetic anisotropy of (In,Fe)Sb is significantly enhanced by increasing x. A large coercive force (H_C = 160 Oe) and large remanent magnetization (M_r/M_S = 71%) have been observed for the (In_{1-x},Fe_x)Sb thin film with x = 35%. This result overcomes the big problem of small magnetic anisotropy in Fe-doped FMSs and is an important step towards practical spintronics devices. Our result indicates that the *n*-type FMS (In_{1-x},Fe_x)Sb is very promising for spintronics devices operating at room temperature. This work is supported by Grants-in-Aid for Scientific Research (Grant No. 16H02095, 15H03988, 17H04922, 18H05345), CREST of JST (No. JPMJCR1777), the Yazaki Foundation, and the Spintronics Research Network of Japan.

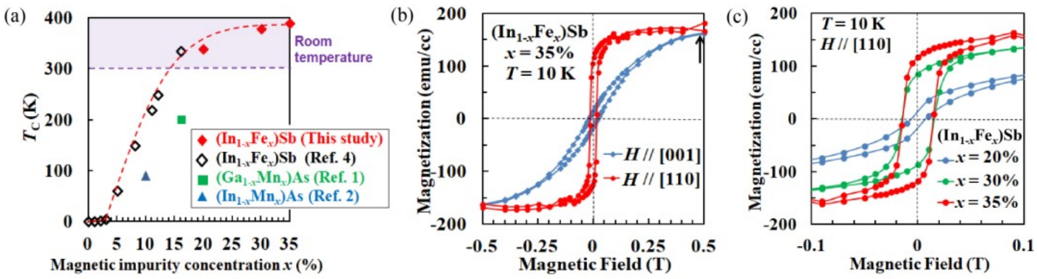

Figure 1. (a) T_C of (In_{1-x},Fe_x)Sb thin films as a function of the magnetic impurity concentration x observed in this study (red closed diamonds) and our previous study (open diamonds, Ref. 6). For comparison, the highest T_C values of the well-studied FMSs (In_{1-x},Mn_x)As (triangle, Ref. 2) and (Ga_{1-x},Mn_x)As (rectangle, Ref. 1) are also shown. (b) In-plane and perpendicular magnetization *vs.* magnetic field (M – H) curves of the (In_{1-x},Fe_x)Sb thin film with x = 35% at 10 K. (c) In-plane M – H curves of the (In_{1-x},Fe_x)Sb thin films with x = 20 – 35%, at 10 K.

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