High-temperature ferromagnetism in a new *n*-type Fe-doped ferromagnetic semiconductor (In,Fe)Sb

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Ferromagnetic semiconductors (FMSs), which have the properties and functionalities of both semiconductors and ferromagnets, provide fascinating opportunities for basic research in condensed matter physics and device applications. To realize practical semiconductor spintronics devices, both *n*-type and *p*-type FMSs with high Curie temperatures (T_C) are strongly required. However, the T_C values of III-V FMSs reported so far are 200 K in *p*-type (Ga,Mn)As, 100 K in *p*-type (In,Mn)As, and 80 K in *n*-type (In,Fe)As, which are still much lower than room temperature.[1)-3)] Recently, we have successfully grown a new *p*-type FMS (Ga,Fe)Sb by low-temperature molecular beam epitaxy (LT-MBE). (Ga,Fe)Sb is an intrinsic FMS and has T_C = 340 K at Fe content 25%, which is the highest in III-V-based FMSs reported so far.[4)] In this paper, we present the magnetic properties of a new *n*-type Fe-doped $(In_{1-x},Fe_x)Sb$ with x = 5 - 16% grown by LT-MBE. The high-resolution STEM image and TED pattern of a representative sample with x = 16% indicate that the crystal structure of (In,Fe)Sb layer is of zinc-blende type without any visible second phase (see Fig. 1(a)). Figure 1(b) shows the magnetic circular dichroism (MCD) spectra of our $(In_{1-x},Fe_x)Sb$ (x = 5 - 16%) samples at 5 K with a magnetic field of 1 T applied perpendicular to the film plane. The MCD spectra show strongly enhanced peaks at E_1 (~2.0 eV) and $E_1 + \Delta_1$ (2.49 eV), corresponding to the optical critical point energy of the InSb band structure.[5)] This result indicates that $(In_{1-x},Fe_x)Sb$ x = 5 - 16% preserves the zinc-blende crystal and band structure with large spin-splitting. Figure 1(c) shows the MCD-*H* characteristics of the sample with x = 16% at various temperatures. Clear hysteresis curves are observed, demonstrating the presence of ferromagnetic order even at 300 K. T_C of $(In_{1-x},Fe_x)Sb$ increases with increasing x and reaches 350 K at x = 16%, which is similar to that of (Ga,Fe)Sb (T_C=340 K at Fe content 25%) despite its lower Fe content. Our results show that the combination of new *n*-type (In,Fe)Sb and *p*-type (Ga,Fe)Sb is promising for semiconductor spintronics devices operating at room-temperature.

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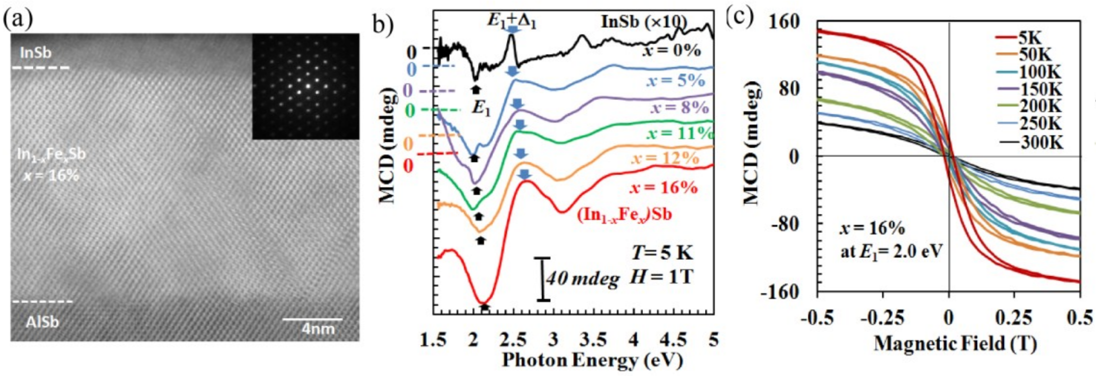

Fig. 1. (a) Cross-sectional STEM image and TED pattern of the 15 nm-thick $(In_{1-x},Fe_x)Sb$ layer (x = 16%). (b) Reflection MCD spectra measured at 5 K under a magnetic field of 1 T applied perpendicular to the film plane for 15-20nm thick $(In_{1-x},Fe_x)Sb$ films with x = 5 - 16%. MCD spectrum of a reference undoped InSb sample is also shown. (c) MCD-*H* characteristics of the $(In_{1-x},Fe_x)Sb$ sample with x = 16% at various temperatures.

References

[1)] L. Chen, X. Yang, F. Yang, J. Zhao, J. Misuraca, P. Xiong, and S. von Molnar, Nano Lett. **11,** 2584 (2011).
[2)]T. Schallenberg and H. Munekata, Appl. Phys. Lett. **89,** 042507 (2006).
[3)] P. N. Hai, L. D. Anh, and M. Tanaka, Appl. Phys. Lett. **101,** 252410 (2012).
[4)] N. T. Tu, P. N. Hai, L. D. Anh and M. Tanaka, Appl. Phys. Lett. **105**, 132402 (2014); Phys. Rev. B **92**, 144403 (2015); Appl. Phys. Lett. **108**, 192401 (2016).
[5)] S. Logothetidis, L. Vina, and M. Cardona, Phys. Rev. B **31**, 947 (1985).