Carrier type switching in quaternary alloy ferromagnetic semiconductor (In,Ga,Fe)Sb by controlling the composition of In and Ga

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Ferromagnetic semiconductors (FMSs) are promising materials for low-power spin-based devices because they show both the properties of ferromagnets and semiconductors. Recently, we have successfully grown both p-type and n-type Fe-doped III-V FMSs with high Curie temperature (T_C); p-type (Ga,Fe)Sb with T_C = 400 K [1] and n-type (In,Fe)Sb with T_C = 385 K [2] by low-temperature molecular-beam epitaxy (LT-MBE). With alloying p-type (Ga,Fe)Sb and n-type (In,Fe)Sb, we may be able to switch the carrier type with only a slight change of the lattice constant and band structure while maintaining high T_C, which will be useful for understanding the origin of the carrier type and ferromagnetism in the Fe-doped FMSs.

In this work, we have grown both p-type and n-type $(In_{1-x-y},Ga_x,Fe_y)Sb$ thin films with room-temperature ferromagnetism. We grew heterostructures consisting of (from top to bottom) InSb (2 nm) / $(In_{1-x-y},Ga_x,Fe_y)Sb$ (15 nm, x = 2, 4, 6, 8, 10 %, y = 16 %) / AlSb (100 nm) / AlAs (6 nm) / GaAs (100 nm) on a semi-insulating GaAs(001) substrate by LT-MBE. Figure 1(a) shows X-ray diffraction (XRD) spectra of our samples and the estimated lattice constants of $(In_{1-x-y},Ga_x,Fe_y)Sb$ as a function of the In content. The XRD spectra suggest that the $(In_{1-x-y},Ga_x,Fe_y)Sb$ layers grown by LT-MBE maintain the zinc-blende crystal structure with no other second phases. The lattice constants of $(In_{1-x-y},Ga_x,Fe_y)Sb$ follow the Vegard's law, suggesting that In, Ga, and Fe atoms reside in the group-III (cation) sites. Figure 1(b) shows Hall resistance R_{Hall} of (In_{1-x-y},Ga_x,Fe_y) (x = 6, 10 %, y = 16 %) measured at 300 K with a magnetic field applied H perpendicular to the film plane. From the linear slope of the $R_{Hall} - H$ at high H (> 10000 Oe), the carrier type of $(In_{1-x-y},Ga_x,Fe_y)Sb$ is found to be switched from p-type to n-type by decreasing x from 10 % to 6 %. This trend is consistent with the previous result; (In,Fe)Sb is n-type and (Ga,Fe)Sb is p-type. Table I shows the summary of the carrier type, carrier concentration, and T_C of $(In_{1-x-y},Ga_x,Fe_y)Sb$ (x = 2, 6, 10 %, y = 16 %). The carrier type of $(In_{1-x-y},Ga_x,Fe_y)Sb$ can be changed between p-type and n-type with a slight change of the lattice constant and band structure.

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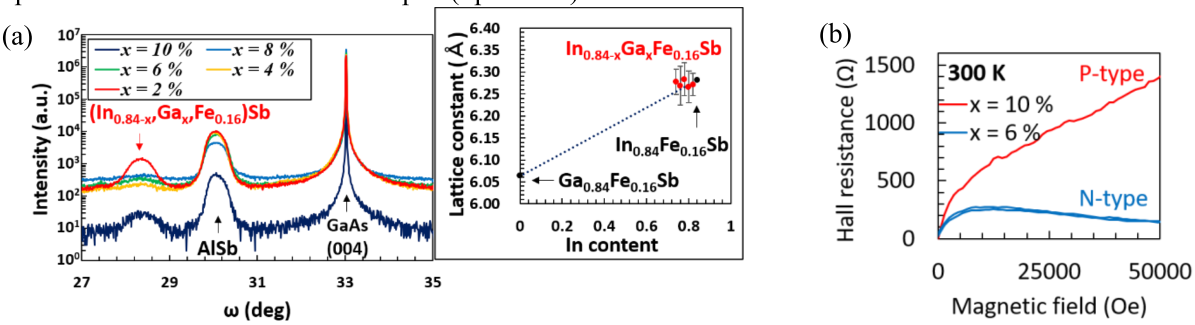

Figure 1 (a) XRD spectra of our samples and the lattice constants of $(In_{0.84-x-y},Ga_x,Fe_{0.16})Sb$ (x = 2, 4, 6, 8, 10 %) as a function of In content. (b) Hall resistances of (In_{1-x-y},Ga_x,Fe_y) (x = 6, 10%, y = 16 %) measured at 300 K with a magnetic field applied perpendicular to the film plane.

Ga content x (%)	Carrier concentration (cm^{-3})	T_C (K)
10	P-type, 2.2×10^{18}	340
6	N-type, 1.2×10^{19}	340
2	N-type, 2.0×10^{18}	300

Table I Carrier type, carrier concentration, and T_C of $(In_{1-x-y},Ga_x,Fe_y)Sb$ (x = 2, 6, 10 %, y = 16 %). T_C is estimated from the Arrott plot.

References: [1] S. Goel *et al*, Phys. Lett. B **99**, 014431 (2019). [2] N. T. Tu *et al*, Appl. Phys. Express **12**, 103004 (2019)