Epitaxial strain dependence of the magnetic anisotropy of *n*-type ferromagnetic semiconductor (In,Fe)Sb studied by ferromagnetic resonance measurements

Akhil Pillai[1], Shobhit Goel[1], Le Duc Anh[1,2,3], and Masaaki Tanaka[1,4]
[1]*Dept. of EEIS, Univ. of Tokyo,* [2]*IEI, Univ. of Tokyo,* [3]*PRESTO, JST,* [4]*CSRN, Univ. of Tokyo*
Email: akhil@cryst.t.u-tokyo.ac.jp

Ferromagnetic semiconductors (FMSs) with high Curie temperature (T_C) are promising material candidates for non-volatile memory and logic devices. Thus far, (In,Fe)Sb is the first and only *n*-type III-V FMS that shows intrinsic ferromagnetism at room temperature ($T_C \simeq 335$ K) [1]. Towards practical device applications, it is imperative to understand the magnetic anisotropy (MA) of (In,Fe)Sb, which is crucial for controlling the magnetization direction. Here, we investigate the MA of (In,Fe)Sb thin films grown on different buffer types, which exert different epitaxial strains on the FMS layer ranging from tensile to compressive strain, using ferromagnetic resonance (FMR) measurements. Our study also presents the first observation of FMR in the *n*-type FMS (In,Fe)Sb at room temperature.

Two different samples A and B, with structures consisting of (In,Fe)Sb (15 nm, 15% Fe) on 100 nm-thick AlSb or InSb buffer, respectively, were grown on GaAs (001) substrates by low-temperature molecular beam epitaxy (Fig. 1a). Both samples show T_C higher than room temperature. Using X-ray diffraction measurements, we estimated the epitaxial strain applied to the (In,Fe)Sb layer, which is compressive strain of +2% in sample A (AlSb buffer) and tensile strain of -1.5% in sample B (InSb buffer). In both samples, we observe clear FMR spectra at room temperature. The FMR spectra measured with a perpendicular magnetic field ($\theta_H = 0°$) show a larger resonant field $\mu_o H_R$ than that with an in-plane magnetic field ($\theta_H = 90°$), where θ_H is the angle between the magnetic field $\boldsymbol{H}$ and the [001] axis. (Figs. 1b,c). We measure FMR spectra in various directions of $\boldsymbol{H}$ from $\theta_H = 90°$ to $\theta_H = 0°$, and monitor the dependence of $\mu_o H_R$ on the $\boldsymbol{H}$ direction, as shown in Fig. 1d. By fitting our model to the $\boldsymbol{H}$ angle-dependence of $\mu_o H_R$, we estimated MA parameters such as shape anisotropy constant (K_{sh}), magnetocrystalline anisotropy constant (K_i), and effective MA constant ($K_{eff} = K_{sh} + K_i$) of the (In,Fe)Sb thin films. In both samples, K_{eff} is negative with dominant contribution from the negative K_{sh} (sample A: -12.8 kJm^{-3}, sample B: -361.7 Jm^{-3}), indicating an in-plane magnetization easy axis induced by shape anisotropy. However, on changing the epitaxial strain from tensile (sample B) to compressive (sample A), the estimated value of K_i changes from -142.3 Jm^{-3} to +11.8 kJm^{-3}. These values indicate that in (In,Fe)Sb samples, the K_i component favors in-plane magnetization in the case of tensile strain (InSb buffer, -1.5%) while it favors perpendicular magnetization in the case of compressive strain (AlSb buffer, +2%). This feature is similar to that of (Ga,Fe)Sb [2]. These results suggest a way to control the MA of (In,Fe)Sb using strain, which is helpful for device applications.

This work was partly supported by Grants-in-Aid for Scientific Research, CREST (JPMJCR1777) and PRESTO (JPMJPR19LB) Programs of JST, and the Spin-RNJ.

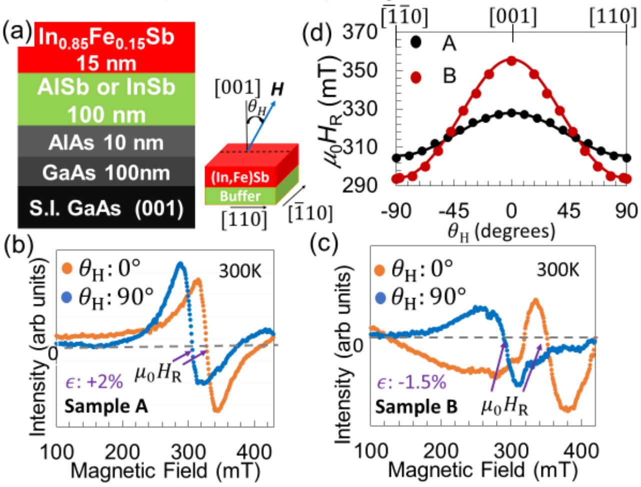

FIG. 1 (a) Sample structure. Inset shows the definition of θ_H and magnetic field $\boldsymbol{H}$ used in measurements. (b) FMR signals for (In,Fe)Sb/AlSb (Sample A) (c) FMR signals for (In,Fe)Sb/InSb (Sample B). ϵ is the epitaxial strain due to the buffer layers. (d) FMR resonant field $\mu_o H_R$ *vs.* $\boldsymbol{H}$ direction θ_H in both samples. Dots and curves denote experimental data and fitting results, respectively.

References: [1] N. T. Tu *et. al.*, Appl. Phys. Express **11**, 063005 (2018). [2] S. Goel *et. al.*, PRB **99**, 014431 (2019).