Observation of impurity band related transitions in high Curie temperature *p*-type ferromagnetic semiconductor (Ga,Fe)Sb

°Karumuri Sriharsha[1], Le Duc Anh[1,2], Nguyen Thanh Tu[1] and Masaaki Tanaka[1,3]
[1]*Department of Electrical Engineering and Information Systems, The University of Tokyo*
[2]*Institute of Engineering Innovation, The University of Tokyo*
[3]*Center for Spintronics Research Network (CSRN), The University of Tokyo*

Recently, new Fe doped narrow-gap ferromagnetic semiconductors (FMSs) such as p-type (Ga,Fe)Sb [1] and n-type (In,Fe)Sb [2] have shown high-Curie temperature (T_C) ferromagnetism, which is essential for the realization of semiconductor spintronic devices operating at room temperature. Understanding the band structure, especially the position of the Fermi level (E_F), of these materials is strongly required to elucidate the origin of high-T_C ferromagnetism as well as their device applications. In this study, using magnetic circular dichroism (MCD) spectroscopy in an infrared region (photon energy E_{ph} = 0.6 – 1.7 eV), we study the band structure of a series of $(Ga_{1-x},Fe_x)Sb$ samples with various Fe densities x = 2, 6, 10 and 20%. We report evidence for the presence of an impurity band (IB) in the band gap of (Ga,Fe)Sb with the E_F lying inside IB.

The samples examined in this work consist of, from the surface, $(Ga_{1-x},Fe_x)Sb$ (15 nm)/AlSb (300 nm)/AlAs (10nm)/GaAs (50nm), grown on semi-insulating GaAs (001) substrates by molecular beam epitaxy. The transport and magnetic properties of these samples were characterized by Hall measurements and MCD with visible – ultraviolet light (E_{ph} = 1.4 – 6 eV). Samples with x = 6, 10 and 20% show ferromagnetism with T_C = 15, 75 and >320 K, respectively. The MCD spectra in infrared region (E_{ph} = 0.6 - 1.5 eV) of these (Ga,Fe)Sb samples and a reference sample of GaSb thin film, measured at 9 K and 1 T, are shown in Fig. 1. The MCD spectra of the (Ga,Fe)Sb samples show two large peaks, a positive peak E_a lying close to the E_0 transition of GaSb (~0.8 eV) and a new negative peak E_b (~1.4 eV). When x is increased from 2 to 20%, the positions of these two peaks linearly move in opposite directions; E_a shifts to lower energy (from 0.84 eV to 0.54 eV) while E_b shifts to higher energy (from 1.41 eV to 1.58 eV) as shown in Fig 2. The values at x > 6% are smaller than the intrinsic band gap of GaSb (~0.8 eV) indicateing the presence of IB in the band gap of $(Ga_{1-x},Fe_x)Sb$ with the E_F lying inside it. As illustrated in Fig 3, E_a likely corresponds to the transition at the Γ point from E_F (in the IB) to the conduction band bottom (Γ_6), while E_b corresponds to the transition at the L point from the valence band (VB) (L_6) to E_F. With increasing x, the IB, which is located close to the VB top at small x, broadens and extends towards the band gap, thereby raising the E_F above the VB top, resulting in the red shift in E_a and the blue shift in E_b. The information of the IB and the position of E_F in (Ga,Fe)Sb revealed in this work is crucial for understanding the magnetic properties and spin device applications of this promising high-T_C FMS.

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References: [1] N. T. Tu, *et al.*, PRB **92**, 144403 (2015). [2] N. T. Tu, *et al.*, APEX **11** 063005 (2018).

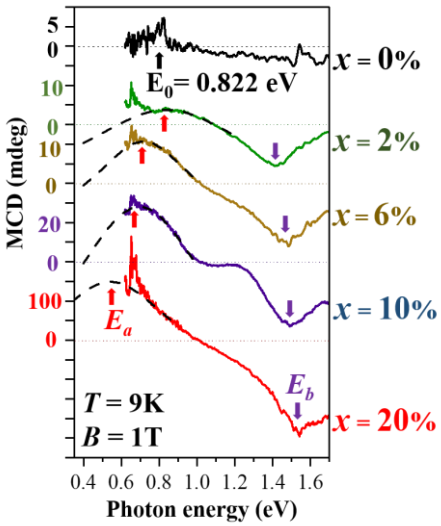

Fig 1. Infrared MCD spectra for the $(Ga_{1-x},Fe_x)Sb$ samples with different Fe densities x (= 0 – 20%).

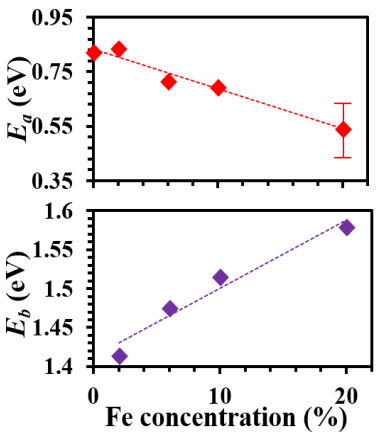

Fig 2. Positions of the E_a and E_b peaks with different Fe density x (= 0 – 20%). For the x = 20% sample, the peak is outside the detectable range, causing the uncertainty.

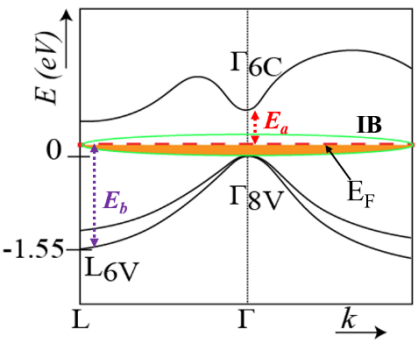

Fig 3. Band structure of (Ga,Fe)Sb showing an impurity band in the band gap and the transitions corresponding to E_a and E_b.