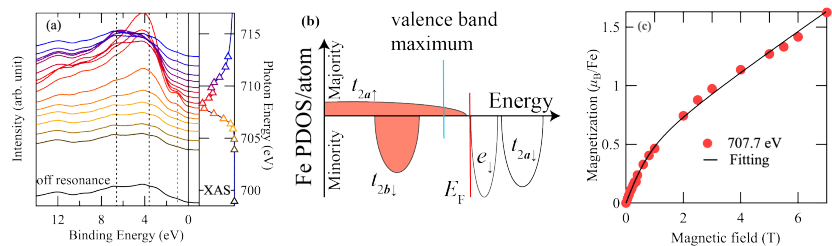


Onset of ferromagnetism in Fe-doped magnetic semiconductors depending on the electron occupation of the impurity band

Takahito Takeda¹, Shoya Sakamoto², Le Duc Anh^{1,3,4}, Yukiharu Takeda⁵, Shin-ichi Fujimori⁵, Miho Kitamura⁶, Koji Horiba⁶, Hiroshi Kumigashira^{6,7}, Atsushi Fujimori^{8,9}, Masaaki Tanaka^{1,10}, and Masaki Kobayashi^{1,10}
 Grad. Sch. Eng., Univ. of Tokyo¹, ISSP, Univ. of Tokyo², IEI, Univ. of Tokyo³, PRESTO, JST⁴, MSRC, JAEA⁵, IMSS, KEK⁶, IMRAM, Tohoku Univ.⁷, Dep. Phys., Univ. of Tokyo⁸, Dep. Appl. Phys., Waseda Univ.⁹, CSRN, Univ. of Tokyo¹⁰
 E-mail: takeda@cryst.t.u-tokyo.ac.jp

Ferromagnetic semiconductors (FMSs) are realized by introducing magnetic ions in semiconductor hosts. The magnetic interaction between the doped magnetic ions is mediated by the spin of the carriers, and such ferromagnetism is called carrier-induced ferromagnetism. For this decade, Fe-doped III-V FMSs such as n-type (In,Fe)As [1], n-type (In,Fe)Sb [2], p-type (Ga,Fe)Sb [3], and insulating (Al,Fe)Sb [4] have been grown by molecular beam epitaxy (MBE). In contrast to these Fe-doped III-V FMSs, (Ga,Fe)As shows paramagnetism [5]. Recently, to unveil the origin of the ferromagnetism, the electronic structures and magnetic properties of the Fe-doped III-V FMSs have been studied by soft x-ray spectroscopy [6,7,8].

In this study, we have focused on the paramagnetic Fe-doped III-V semiconductor (Ga,Fe)As. The comparison of the experimental results between paramagnetic (Ga,Fe)As and other Fe-doped III-V FMSs is helpful for unveiling the mechanism of the ferromagnetism. We have conducted resonant photoemission spectroscopy (RPES) and x-ray magnetic circular dichroism (XMCD) measurements at the Fe $L_{2,3}$ absorption edge on the (Ga_{0.95}Fe_{0.05})As thin film to reveal the electronic structure and magnetic properties. Figure 1(a) shows the photon energy dependence of the RPES spectra at the Fe L_3 edge. The RPES spectra in the vicinity of the Fermi level (E_F) suggest that the e_d state of (Ga_{0.95}Fe_{0.05})As is vacant [see Fig. 1(b)]. In contrast, the e_d state is partially occupied by electrons in (Ga,Fe)Sb and (Al,Fe)Sb. Analyzing the magnetization curve by XMCD shown in Fig. 1(c), a part of the Fe ions makes nm-scale Fe-rich domains in (Ga_{0.95}Fe_{0.05})As. The domain size in (Ga_{0.95}Fe_{0.05})As is an order of magnitude smaller than that in the Fe-doped III-V FMSs [6,7]. The result indicates that the short-range magnetic interaction among the Fe ions is dominant in (Ga_{0.95}Fe_{0.05})As. Based on the observations, we have found that the occupancy of the e_d states contributes to the appearance of the ferromagnetism in the Fe-doped III-V semiconductors, for p-type as well as n-type.



References [1] P. Nam Hai, *et al.*, Appl. Phys. Lett. **101**, 182403 (2012). (2014). [2] A. V Kudrin, *et al.*, J. Appl. Phys. **122**, 183901 (2017). [3] N. T. Tu, *et al.*, Appl. Phys. Lett. **105**, 132402 (2014). [4] L. D. Anh, *et al.*, Appl. Phys. Lett. **107**, 232405 (2015). [5] S. Haneda *et al.*, Jpn. J. Appl. Phys. **39**, L9 (2000). [6] S. Sakamoto, *et al.*, Phys. Rev. B **100**, 035204 (2019). [7] S. Sakamoto, *et al.*, Phys. Rev. B **101**, 075204 (2020). [8] T. Takeda, *et al.*, Phys. Rev. B **101**, 155142 (2020).

Fig. 1 : Results of soft x-ray spectroscopy. (a) Photon energy dependence of RPES spectra. (b) Image of Fe 3d partial density of states (PDOS). (c) Magnetization curve by XMCD (red dots) and fitting (solid curve). The fitting function is the combination of a Langevin function and a linear function.