Observation of quantum size effect at the conduction band bottom of n-type ferromagnetic semiconductor (In,Fe)As thin films

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Ferromagnetic semiconductors (FMSs), which inherit the properties of both semiconductors and ferromagnets, are essential for spin-based electronic applications. Among various FMS materials, (In,Fe)As is the first n-type electron-induced III-V FMS [1-5] and particularly promising due to its unique properties such as the large *s-d* exchange interaction energy [2,3], large spontaneous spin splitting in the conduction band [5], and high coherency of electron carriers [3,4]. We found that, in (In,Fe)As ultrathin films, the band gap energies at the critical points E_1(L point) and E_2 (X point) are increased with decreasing the film thickness, which is caused by the quantum size effect (QSE) [3]. However, this previous work was performed by using magnetic circular dichroism (MCD) with visible – ultraviolet light (wavelength λ = 200 - 900 nm, photon energy E_{ph} = 1.4 – 6 eV), and thus unable to reveal the effect of QSE on the band structure at the conduction band (CB) bottom (Γ point, band gap 0.42 eV) of (In,Fe)As, which is most crucial for the transport properties.

In this work, we investigate the QSE at the Γ point in the band structure of (In,Fe)As quantum wells (QWs) by performing infra-red MCD spectroscopy (λ = 700 - 2000 nm, E_{ph} = 0.6 – 1.8 eV). The samples consist of Be-doped ($In_{0.92}$,$Fe_{0.08}$)As (t_{InFeAs} = 8 - 14 nm) / AlSb (400 nm) / AlAs (10 nm) / GaAs (100 nm), grown on semi-insulating GaAs (001) substrates by low-temperature molecular beam epitaxy (Fig.1). In this structure, electron carriers in the (In,Fe)As are confined by the vacuum potential at the surface and the CB offset (~1.3 eV) at the (In,Fe)As/AlSb interface. As shown in Fig. 2, the MCD spectra of these samples clearly exhibit oscillatory behavior in the energy range below 1.3 eV, which are not observed in a 100 nm-thick (In,Fe)As thin film. These MCD peaks systematically blue-shift with decreasing t_{InFeAs}. As shown in Fig. 3, these MCD peak energies can be fitted well by the theoretical values of the second, third and forth quantized levels in rectangular QW potentials with thickness t_{InFeAs}, infinite potential barriers and an electron effective mass m^* = 0.06m_0. These results show the evidence of the quantization of electron carrier energy in the CB bottom of (In,Fe)As. The detailed information of the quantized CB structure of (In,Fe)As revealed in this work is essential for quantum transport applications of this material.

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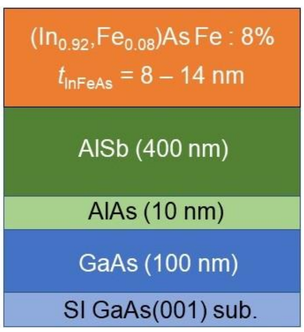

Fig. 1 Schematic sample structure of (In,Fe)As QW.

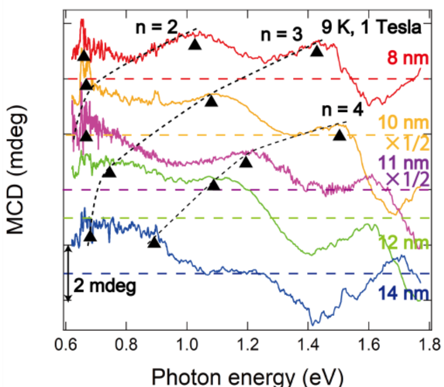

Fig. 2 MCD spectra of (In,Fe)As QW with t_{InFeAs} = 8, 10, 11, 12, and 14 nm, measured at 9 K and 1 T.

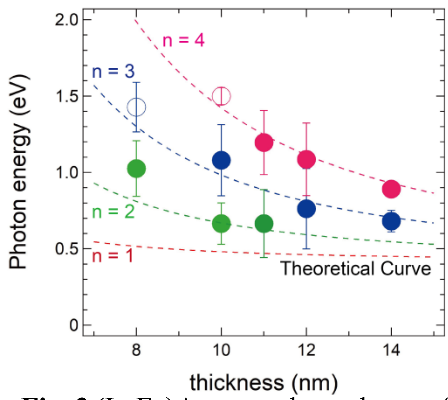

Fig. 3 (In,Fe)As t_{InFeAs} dependence of the MCD peaks and the calculated quantized level energies of the infinite rectangular well.

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