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Recent progress and topics in semiconductor spintronics and ferromagnetic semiconductors

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Ferromagnetic semiconductors (FMSs) have been intensively studied for decades as they have novel functionalities that cannot be achieved with conventional metallic materials, such as the ability to control magnetism by electrical gating or light irradiation [1-3]. Prototype FMSs such as (Ga,Mn)As, however, are always p-type, making it difficult to be used in real spin devices. Here, we demonstrate that by introducing Fe into InAs, it is possible to fabricate a new n-type electron-induced FMS with the ability to control ferromagnetism by both Fe and independent carrier doping. The studied $(In_{1-x},Fe_x)As$ layers were grown by low-temperature molecular beam epitaxy on semi-insulating GaAs substrates. Electron carriers in these layers are generated by independent chemical doping of donors. The ferromagnetism was investigated by magnetic circular dichroism (MCD), superconducting quantum interference device (SQUID), and anomalous Hall effect (AHE) measurements. With increasing the electron concentration (n = 1.8×10^{18} cm^{-3} to 2.7×10^{19} cm^{-3}) and Fe concentration (x = 5 - 8%), the MCD intensity shows strong enhancement at optical critical-point energies of InAs, indicating that the band structure of (In,Fe)As is spin-split due to *sp-d* exchange interaction between the localized *d* states of Fe and the electron sea. SQUID and AHE measurements are also consistent with the MCD results. The Hall and Seebeck effects confirm the n-type conductivity of our (In,Fe)As samples. The electron effective mass is estimated to be as small as 0.03-0.175m_0, depending on the electron concentration. These results reveal that the electrons are in the InAs conduction band rather than in the impurity band, allowing us to use the conventional mean-field Zener model of carrier-induced ferromagnetism [4]. This band picture is different from that of (Ga,Mn)As [5][6]. Our results open the way to implement novel spin-devices such as spin light-emitting diodes or spin field-effect transistors, as well as help understand the mechanism of carrier-mediated ferromagnetism in FMSs [7-14].

Furthermore, we have found new phenomena in (In,Fe)As and its quantum heterostructures: novel crystalline anisotropic magnetoresistance with two fold and eight fold symmetry [7], and control of ferromagnetism by strain, quantum confinement, gate electric field and wave-function engineering in quantum heterostructures with a (In,Fe)As quantum well [10-12]. Very recently, we have found very intriguing phenomena; sudden restoration of the band ordering associated with the ferromagnetic phase transition in the prototypical ferromagnetic semiconductor (Ga,Mn)As [15], and control of the bias-voltage dependence of tunneling anisotropic magneto-resistance using quantization in (Ga,Mn)As quantum wells [16]. Also, we have successfully grown narrow-gap III-V-based FMSs; p-type (Ga,Fe)Sb and n-type (In,Fe)Sb with high

Curie temperature (T_C > 300K) [17][18]. Combining different n-type and p-type FMSs with high T_C will lead to new spin-related functionalities and devices.

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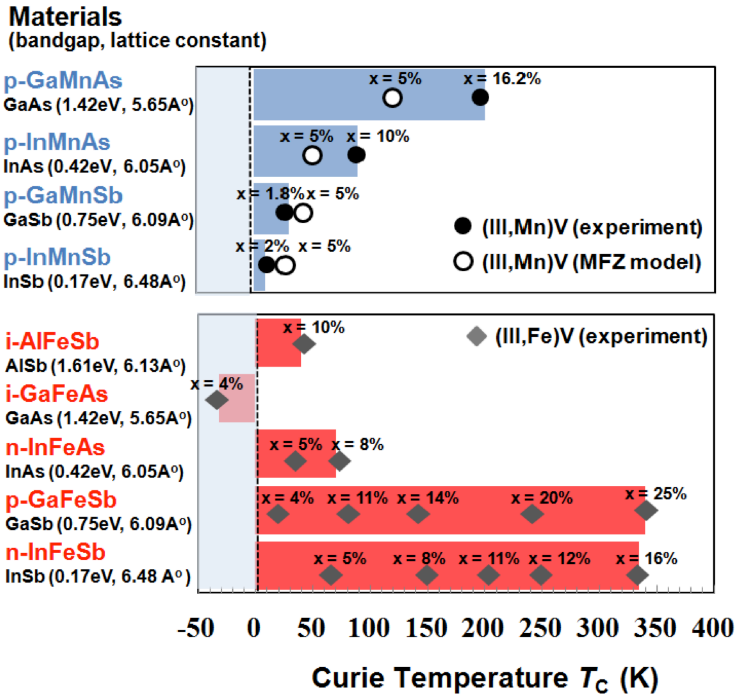

Fig.1: Highest Curie temperature (T_C) values of Mn-doped (blue bars) and Fe-doped (red bars) III-V ferromagnetic semiconductors (FMSs) observed so far. Black circles and black diamonds show experimental T_C values. White circles show the T_C values of Mn-doped III-V FMSs calculated by the mean-field Zener (MFZ) model with Mn concentration of 5% and hole concentration of 3.5×10^{20} cm^{-3}.

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