Bias-dependent magneto-conductance in n-type ferromagnetic semiconductor (In,Fe)As-based Esaki diodes

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Ferromagnetic semiconductors (FMSs) have been attracting a lot of attentions because they provide opportunities to integrate spin-dependent phenomena into semiconductor electronic devices. Among various FMSs, (In,Fe)As is a promising one, because it is the only n-type electron-induced III-V-based FMSs that has been realized so far [1]. Quantum size effects were also observed in (In,Fe)As thin films [2], and electrical control of the ferromagnetism of (In,Fe)As quantum wells by wavefunction engineering has been demonstrated [3].

Here we study spin-dependent transport in an Esaki diode composed of a 50 nm-thick n-type (In,Fe)As (6% Fe)/5 nm-thick InAs/250 nm-thick p^+ InAs:Be (Be concentration 5×10^{18} cm^{-3})/p^+ type InAs (001) substrate. Figure 1(a) shows the magneto-conductance (MC) of the Esaki diode measured at 3.5 K at various bias voltages V. At V smaller than 460 mV, the diode shows small positive MC (~0.5%), which is typical of FMSs. However, when V > 460 mV, the MC changes its sign and its magnitude increases with V, reaching -7.4% (at 1T) at V = 650 mV (Fig. 1(c)). The band profiles of the pn junction of the diode at small V and large V (V > 460mV) are illustrated in Fig. 1(b). The conduction band (CB) of (In,Fe)As is spin-split and there is an Fe-related impurity band (IB) right below the CB bottom [4]. At small V, electrons tunnel from the CB of (In,Fe)As to the valence band (VB) top of p-InAs, while the tunneling of electrons from IB (*d* orbitals) is prohibited by the orbital symmetry. However, at V > 460 mV where the energy of CB and IB of (In,Fe)As is aligned with the energy of empty CB of p-InAs, the current is diffusive and the prohibition by the orbital symmetry is relaxed. Therefore, electrons in the IB start to flow into the p-InAs CB and experience strong *s-d* scattering at the interface. We show that it is possible to explain the change in sign and magnitude of the MC by the onset of *s-d* scattering, which is caused by the contribution of the IB electrons in (In,Fe)As to the diffusive current at large positive bias voltages.

Reference: [1] P. N. Hai, et al., APL **101**, 182403 (2012). [2] L. D. Anh, et al., APL **104**, 042404 (2014). [3] L. D. Anh, et al., PRB **92**, 161201(R) (2015). [4] L. D. Anh et al., 2016 JSAP Spring Meeting 19p-W241－2.

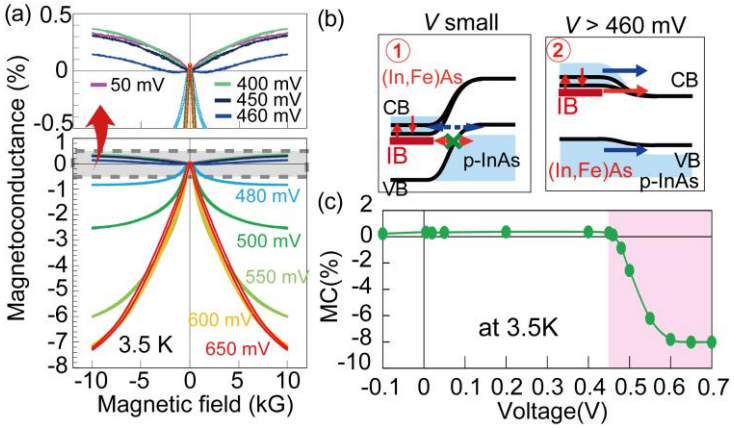

Fig 1. (a) Magneto-conductance (MC) at various bias voltages V of the Esaki diode. The upper panel is the magnified plot of the gray area in the bottom panel. (b) Band profiles of the Esaki diode at small V (left) and V > 460 mV (right). (c) MC as a function of bias voltage V.