Renaissance of Ferromagnetic Semiconductors and Spintronics Applications（強磁性半導体ルネサンスとスピントロニクスへの応用）

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Ferromagnetic semiconductors (FMSs) with high Curie temperature (T_C) are strongly required for spintronics device applications. So far, the mainstream study of FMSs is Mn-doped III-V FMSs; however they are only p-type and their T_C is much lower than 300 K. In this study, we present a new class of FMSs with high T_C, Fe-based narrow-gap III-V FMSs. Because Fe atoms are in the isoelectronic Fe^{3+} state in III-V, the carrier type can be controlled independently and thus both n-type and p-type FMSs are obtained. Using low-temperature molecular beam epitaxy, we have successfully grown both p-type FMS [(Ga,Fe)Sb [1], (Al,Fe)Sb [2]] and n-type FMSs [(In,Fe)As [3], (In,Fe)Sb [4]]. The most notable feature in these Fe-based FMSs is that the T_C value increases monotonically as the Fe content increases; and there is a tendency that T_C is higher as the bandgap is narrower, which contradicts the prediction of the mean-field Zener model. Intrinsic room-temperature ferromagnetism has been observed in $(Ga_{1-x},Fe_x)Sb$ with $x \geq 23\%$ [1] and $(In_{1-x},Fe_x)Sb$ with $x \geq 16\%$ [4], which are promising for practical spintronic devices operating at room temperature.

We also present our findings on new magnetotransport phenomena in heterostructures containing these Fe-doped FMSs. In an Esaki diode composed of a 50 nm-thick n-type FMS (In,Fe)As (6% Fe) / 250 nm-thick p^+ InAs:Be, we found that the magnetic-field-dependence of the current flowing through the pn junction (magnetoconductance, MC) can be largely controlled, both in sign and magnitude, with the bias voltages V [5,6]: The diode shows small positive MC (~0.5%) at $V < 450$ mV, but the MC changes its sign and magnitude at $V >$ 450 mV, reaching -7.4% (at 1T) at $V = 650$ mV. This bias-controlled MC originates from the change in the band components of (In,Fe)As that participate in the spin-dependent transport.

Furthermore, we found that the current flowing in a nonmagnetic n-type InAs quantum well (QW) that is interfaced to an insulating p-type (Ga,Fe)Sb layer (20% Fe, $T_C > 300$ K) exhibits a giant change of approximately 80% at high magnetic field and that its magnitude can be controlled by ten-fold using a gate. The mechanism for this large magnetoresistance is attributed to a strong magnetic proximity effect (MPE) via the *s-d* exchange coupling at the InAs/(Ga,Fe)Sb interface. It was found that a spin splitting in the InAs QW is induced by MPE, which can be varied between 0.17 meV and 3.8 meV by the gate voltage [7]. Other studies on ferromagnetic semiconductor heterostructures are underway and novel phenomena and properties are being investigated [7-9]; these new properties of the Fe-doped FMS-based materials and devices provide novel functionalities for future spin-based electronics.

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