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E-2-1 (Invited)

Electric Field Control of Ferromagnetism in Semiconductors

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1. Introduction

Owing to the nonmagnetic nature of III-V compounds magnetism was not a part of the rich soil of new physics and applications offered by the III-V heterostructures. The synthesis of magnetic III-V semiconductors [1, 2] and subsequent discovery of carrier-induced ferromagnetism in them [3, 4] now allows us to combine phenomena associated with ferromagnetism with the established properties of III-V heterostructure. Here, in the first half, we first review a mean-field model for the carrier-induced ferromagnetism in III-V semiconductors that can explain a number of experimental properties including the ferromagnetic transition temperature T_C. In the second half, we describe isothermal and reversible electric field control of carrier-induced ferromagnetism in a ferromagnetic semiconductor (In,Mn)As using a field-effect transistor structure.

2. Preparation and Properties of III-V Ferromagnetic Semiconductors

Low temperature molecular beam epitaxy

A high concentration of Mn beyond its solubility limit has been introduced into the host III-V compound (in the present case GaAs and InAs) by low-temperature molecular beam epitaxy (LT-MBE) at substrate temperatures around 250 °C in order to suppress the formation of the second phases. Mn introduces magnetic moments as well as holes due to its acceptor nature. Thus introduced holes mediate ferromagnetic interaction and make the resulting alloys ((Ga,Mn)As and (In,Mn)As) ferromagnetic.

Magnetic and transport properties

Magnetization measurements revealed the presence of ferromagnetic order at reduced temperatures and that the transition temperature T_C of (Ga,Mn)As follows $T_C = 2000x$ (K) when $x \leq 0.05$, above which T_C decreases with the increase of x. The highest T_C so far obtained in magnetic III-V's is 110 K for (Ga,Mn)As with $x = 0.053$ [5]. The Hall effect of the ferromagnetic III-V's is expressed as a sum of the ordinary Hall effect and the anomalous Hall effect. The Hall resistivity R_{Hall} is expressed as,

$$R_{Hall} + \frac{R_0}{d}B + \frac{R_M}{d}M \quad ,$$

where R_0 is the ordinary Hall coefficient, B the magnetic field, R_M the anomalous Hall coefficient, M the magnetization perpendicular to the film, and d the thickness of the semiconductor layer. Very often the anomalous Hall term dominates and R_{Hall} is a good measure of M.

3 Hole induced ferromagnetism

A mean field model based on exchange interactions mediated by delocalized holes in the ensemble of localized spins has been developed [6, 7]. The model uses the parameterized hole-spin exchange interaction, an exchange integral $N_0\beta$. T_C is obtained by minimizing the free-energy functional with respect to M at a given hole concentration p. The carrier contribution part is calculated by solving a 6 x 6 Luttinger-Kohn Hamiltonian with the presence of exchange. T_C for (Ga,Mn)As calculated using $N_0\beta =$ 1.2   0.2 eV taken from photoemission experiments [8], and Mn composition of $x = 0.053$, hole concentration of $p = 3.5 \times 10^{20}$ cm^{-3}, and a carrier-carrier interaction enhancement of 1.2 [9], is 130 K, which compares very favorably with the experimental value of 110 K. The model also explains (1) the strain dependence of the magnetic easy axis, (2) the anomalous magnetic circular dichroism observed in (Ga,Mn)As [10], and (3) the T_C's of hole-induced ferromagnetism observed in II-VI DMS (Zn,Mn)Te [11].

4. Electric field control of ferromagnetism

Since the ferromagnetism in Mn-doped III-V's is hole-induced, change in hole concentration is expected to result in modification of ferromagnetic interaction among Mn spins and lead to change in transition temperature. This has been demonstrated in an insulating-gate field-effect transistor structure having an (In,Mn)As channel [12]. The 5 nm thick channel layer ($x = 0.03$) was grown on a buffer layer structure designed in such a way to relax almost all the lattice mismatch between the epitaxial structure and the GaAs substrate. Figure 1 shows the magnetization curves at three different gate voltages V_G (+125, 0, -125 V) applied to the gate of the magnetic FET, having a 0.8 m gate insulator. Here, magnetization is measured by the Hall resistance, which is proportional to M. At zero gate bias, the channel is weakly ferromagnetic at 22.5 K as can be seen from the presence of small hysteresis. Application of positive gate voltage partially depletes the holes and reduces the ferromagnetic interaction mediated by them resulting in a paramagnetic magnetization curve without hysteresis. When holes are accumulated by applying negative gate voltage, a clear hysteresis appears. The magnetization curve resumes its original curve as the gate voltage returns to 0 V. The 125 V swing gives rise to ± 6% change in hole concentration and results in the transition temperature change of ± 4%. This agrees well with that expected from the mean-field model [7]. It is worth noting that photogenerated carriers can also be used to modify the properties of (In,Mn)As, as has been reported in literatures [13].

4. Conclusions

The electric-field control of ferromagnetism together with the new possibilities such as electrical spin injection enabled by the magnetic III-V's [14] unlock a number of ways to manipulate the spin degree of freedom in semiconductors, which is often neglected in modern semiconductor electronics. Thus the present study is believed to lead us to a new form of electronics, semiconductor spintronics, where both charge and spin of electrons play critical role.

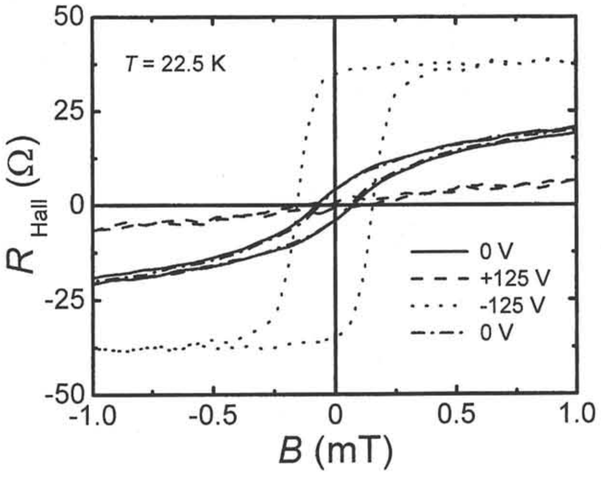

Figure 1 Hall resistance, R_{Hall}, of an insulated gate (In,Mn)As field-effect transistor as a function of magnetic field under three different gate voltages. R_{Hall} is proportional to the magnetization of the (In,Mn)As channel. Positive gate voltage of 125 V partially depletes holes and results in weaker ferromagnetic interaction and a paramagnetic response, whereas negative gate voltage produces square hysteresis. Zero gate voltage curves, before and after application of positive and negative gate voltage, are virtually identical.

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