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N-type ferromagnetic semiconductor (In,Fe)Sb with high Curie temperature: Electrical control of ferromagnetism

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Abstract

We demonstrate electrical control ferromagnetism at high temperature (210 K) in an electric double layer transistor with an *n*-type high-T_C ferromagnetic semiconductor $(In_{0.89},Fe_{0.11})Sb$ thin film channel. A liquid electrolyte gate is used instead of a conventional solid gate to obtain a large change (40%) of the electron density in the $(In_{0.89},Fe_{0.11})Sb$ channel. By applying a small gate voltage (0 → +5 V), T_C of the (In,Fe)Sb thin film can be changed by 7 K, indicating that the magnetization as well as ferromagnetic phase transition in (In,Fe)Sb can be controlled at high temperature by the gate electric field despite a small change of electron concentration Δn = 2.2 ×10^{17} cm^{-3}. Our result paves a way for realizing semiconductor spintronic devices operating at room temperature with low power consumption.

1. Introduction

Electrical control of ferromagnetism in magnetic materials has attracted much attention, since it offers not only an opportunity to investigate many fundamental aspects of ferromagnetism but also a promising method for ultra-low-power magnetization switching, which is a key technology for low-power magnetic memory devices. Pioneering studies on electrical control of ferromagnetism have been performed on ferromagnetic semiconductors (FMSs), since they possess both semiconducting and ferromagnetic properties and their carrier concentrations are low enough to allow electrical manipulation of ferromagnetism. There have been many reports on the electrical control ferromagnetism in III-V [1-5], II-VI [6,7], and group IV [8] based ferromagnetic semiconductor FMSs. However, most of these studies were performed at temperatures lower than 110 K due to the limitation of their Curie temperatures (T_C). Recently, we have successfully grown a new *n*-type FMS (In,Fe)Sb with high T_C by low-temperature molecular-beam epitaxy (LT-MBE) [9]. T_C of *n*-type FMS (In,Fe)Sb can reach 335 K at a Fe concentration of 16% [9], indicating that (In,Fe)Sb is very promising for semiconductor spintronics devices operating at room temperature.

In this study, to realize the electrical control ferromagnetism at high temperature and to confirm the carrier-induced ferromagnetism in the *n*-type FMS (In,Fe)Sb with high T_C, we investigate the electric field effect in an *n*-type FMS $(In_{0.89},Fe_{0.11})Sb$ thin film channel by using an electric double layer transistor (EDLT) structure. Our results show that the magnetization of (In,Fe)Sb can be enhanced or suppressed, and T_C can be changed by 7 K despite a small change of electron concentration [10]. This result indicates that the ferromagnetism of (In,Fe)Sb can be modulated by an electric field at high temperature, and (In,Fe)Sb is an intrinsic electron-induced FMS.

2. Experiments and results

The studied (In,Fe)Sb thin film was grown on a semi-insulating GaAs(001) substrate by low-temperature molecular beam epitaxy (LT-MBE) as shown in Fig. 1(a). The MBE grown sample was patterned into a 50 × 200 μm^2 Hall bar with a side-gate electrode. Then the side-gate electrode (G) and the (In,Fe)Sb channel were covered by electrolyte (DEME–TFSI) to form a field effect transistor (FET) structure. Figures 1(a) illustrates the operating principle of our device. When a positive gate-source voltage V_{GS} is applied, ions in the electrolyte accumulate near the surface of the semiconductor channel and form an electric-double-layer capacitor, which changes the electron carrier density in the (In,Fe)Sb channel. Figure 1(b) shows the $I_{DS} - V_{GS}$ curve measured at 220 K. The current I_{DS} is increased at positive V_{GS} and decreased at negative V_{GS}, confirming the *n*-type character of the (In,Fe)Sb channel and the FET operation.

Figures 1(c) and (d) show the evolution of Hall resistance *vs.* magnetic field ($R_{Hall} - H$) characteristics at 205 and 210 K, respectively, when V_{GS} is changed as 0 V → +5 V → –5 V→ 0 V. As shown in Fig 1(c), the $R_{Hall} - H$ curve at 205 K under V_{GS} = 0 V still show small open hysteresis, indicating that the sample temperature is close to but below T_C. When V_{GS} = +5 V, the hysteresis becomes much larger, indicating an increase of magnetization (*M*). In contrast, the hysteresis becomes smaller when V_{GS} = –5 V, indicating a decrease of *M*. After that, the hysteresis loop returns to the initial state when V_{GS} is returned to 0 V. Clear magnetization modulation can also be seen at 210 K, as shown in Fig. 1(d). The hysteresis loop of the $R_{Hall} - H$ curves under V_{GS}

= 0 V and – 5 V is almost closed, but clearly open when V_{GS} = +5 V, indicating switching from the paramagnetic state to the ferromagnetic state. Our result indicates that the ferromagnetic properties of (In,Fe)Sb can be controlled by the gate electric field at high temperature (~210 K).

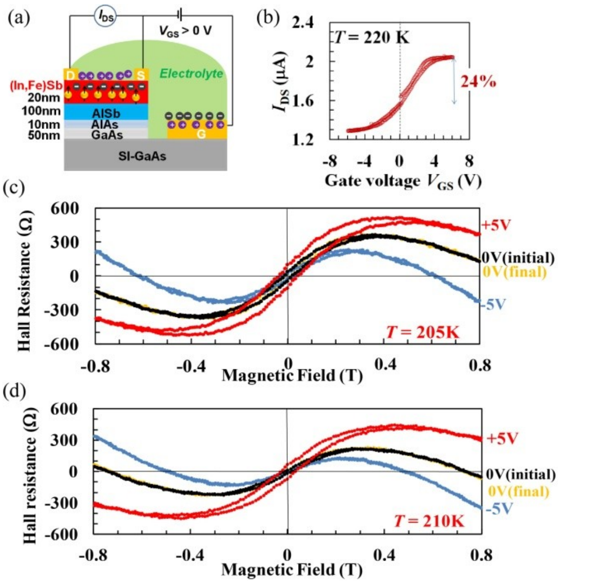

Figure 1. (a) Schematic structure of the FET device with electrolyte (DEME–TFSI) between the gate (G) and the (In,Fe)Sb channel under a positive gate voltage V_{GS} > 0 V. (b) Drain (D) – source (S) current (I_{DS}) – gate voltage (V_{GS}) characteristics measured at 220 K for a FET device. (c) and (d) Hall resistances (R_{Hall}) – magnetic field (H) curves under V_{GS} = +5, 0, and –5 V measured at temperatures T = 205 and 210 K, respectively.

To estimate the change of T_C under electrical gating, we measured the R_{Hall} – H curves in the temperature range of 203 K – 230 K under V_{GS} = +5 V, 0 V and –5 V. The remanent R_{Hall} (Hall resistance at H = 0) at each temperature is shown in the Fig. 2(a). Because the remanent M (and hence remanent R_{Hall}) is zero at T_C, we can estimate T_C by measuring the remanent R_{Hall} *vs*. temperature. The T_C values are 216 K (at V_{GS} = +5 V), 209 K (at V_{GS} = 0 V), and 207 K (at V_{GS} = –5 V). This result indicates that T_C of (In,Fe)Sb can be changed by 7 K by applying a gate voltage as small as +5 V. Figure 2(b) shows V_{GS} dependences of Curie temperature T_C and electron concentration n. Here n was measured at 205 K. One can see that T_C and n show similar V_{GS}-dependences, and T_C is increased as n is increased. This result shows a strong correlation between the ferromagnetism and electron density, indicating that the ferromagnetism in (In,Fe)Sb is induced by electron carriers.

It should be addressed here that there are two significant advances in our result when compared with previous electrical-gating experiments in FMSs [1-8]. First, the electrical control of ferromagnetism is demonstrated at much higher temperature (210 K) in carrier(electron)-induced FMSs. Previous experiments on the electrical control of ferromagnetism in FMSs were performed at low temperature (< 110 K) due to the limitation of their Curie temperatures (T_C) [1-8]. Second, effective modulation of T_C is realized, despite the small change of carrier concentration. The change of T_C, $\Delta T_C = T_C (V_{GS}) - T_C (0)$, is up to 7 K, whereas the change of n, $\Delta n = n (V_{GS}) - n (0)$, is only 2.2 $\times 10^{17}$ cm^{-3}. This Δn is much smaller than the change of the hole concentration Δp (~10^{19} cm^{-3}) reported in almost all the previous gating experiments in FMSs [1-8].

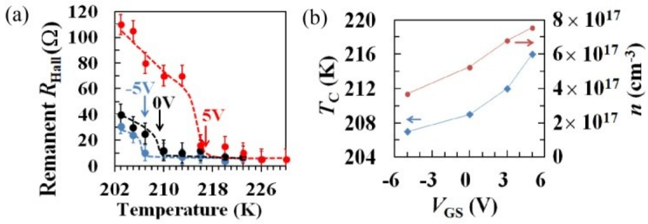

Figure 2. (a) Temperature dependence of the remanent R_{Hall} under V_{GS} = +5 V, 0 V and -5 V. The color arrows indicate T_C (where remanent R_{Hall} is zero). (b) V_{GS} dependence of T_C and n. Here, n was measured at 205 K.

3. Conclusions

We have demonstrated electrical control of ferromagnetism at high temperature (~210 K) in the high-T_C FMS (In,Fe)Sb. By applying a gate voltage (V_{GS} = 0 V → 5 V), T_C of the (In,Fe)Sb thin film can be changed by 7 K, despite the small change of electron concentration Δn = 2.2 $\times 10^{17}$ cm^{-3}. This result indicates that high-T_C (In,Fe)Sb is an intrinsic electron-induced FMS. Our demonstration of electrical control of ferromagnetism in high-T_C (In,Fe)Sb paves a way for realizing semiconductor spintronic devices operating at room temperature with low power consumption.

Acknowledgements

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