Electric-field control of ferromagnetism in (Ga,Mn)As

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The authors show modulation of Curie temperature T_C and coercivity $\mu_0 H_c$ by applying external electric fields E in a ferromagnetic semiconductor (Ga,Mn)As, where a field-effect transistor structure with an Al_2O_3 gate insulator is utilized. Application of $E=+5$ (−5) MV/cm decreases (increases) T_C of the channel layer. $\mu_0 H_c$ also decreases (increases) with increasing (decreasing) E below T_C. The mechanism of the modulation of $\mu_0 H_c$ by E is discussed. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2362971]

Control of magnetic phase transition and coercivity $\mu_0 H_c$ by the application of external electric fields E to modulate the carrier concentration p that mediates magnetic interaction in ferromagnetic semiconductors[1,2] has recently been reported in several systems.[3–8] This additional degree of freedom is expected to add a new dimension to the future magnetism usage, because before the properties of magnetic materials were unable to alter by outside means without changing temperature, unlike the conductivity in semiconductors. We reported the control of Curie temperature T_C of a III-V ferromagnetic semiconductor (In,Mn)As in a field-effect transistor (FET) structure using spin-coated SiO_2 (dielectric constant $\kappa=3-4$) as an insulator, where application of $E=\pm 1.5$ MV/cm resulted in a change of T_C by 2 K in a 5 nm thin (In,Mn)As channel layer.[3] Electrical control of ferromagnetism in GaAs-based structures, however, was so far demonstrated only in Mn δ-doped GaAs/AlGaAs heterostructures.[7] In our previous work on FETs with a (Ga,Mn)As channel layer, application of E resulted in a small change of $\mu_0 H_c$ but with no detectable change in T_C.[9] (Ga,Mn)As films show a tendency to become insulating at a thickness below 5 nm, which forced us to work on thicker films having high sheet carrier concentration $p_\square$ than the (In,Mn)As case. Because the maximum amount of modulation of $p_\square$ is determined by κ and the breakdown field of the insulator, thick channel layers result in a small modulation ratio. This is one of the possible reasons for not having been able to unambiguously observe the modulation of magnetism in (Ga,Mn)As thin films. In this study, by employing Al_2O_3 with a high κ and a high electric breakdown field, higher than the insulating films used previously for (In,Mn)As, we show that one can clearly observe an electrical control of T_C and $\mu_0 H_c$ in a (Ga,Mn)As film.

A 7-nm-thick $Ga_{0.953}Mn_{0.047}As$ channel layer was grown at 220 °C on a 7 nm GaAs/30 nm $Al_{0.80}Ga_{0.20}As$/500 nm $In_{0.13}Ga_{0.87}As$/100 nm GaAs buffer layer structure, which was grown on a semi-insulating GaAs (001) substrate by molecular beam epitaxy. The (In,Ga)As buffer layer introduces tensile strain in the (Ga,Mn)As layer, making the magnetic easy axis perpendicular to the plane. First, the sample was processed into a Hall bar geometry having a 30 μm channel along the $[\bar{1}10]$ direction by photolithography and wet etching. Then, it was introduced into an atomic layer deposition chamber and a 50-nm-thick Al_2O_3 layer was deposited at a substrate temperature of 100 °C, by using alternating pulses of $Al(CH_3)_3$ and H_2O with N_2 purges between each step.[10] Finally, 5 nm Cr/100 nm Au gate electrode was evaporated. The dielectric constant κ and the breakdown field of the Al_2O_3 film were determined to be 6.7 and above 8 MV/cm, respectively, from the capacitances of square-shaped 100 nm Au/50 nm Al_2O_3/100 nm Au capacitors having various areas ($2.5\times10^{-3}-4.0\times10^{-2}$ mm^2).[10] To probe the magnetic properties through the anomalous Hall effect, Hall effect measurements were performed using a constant dc current of 1 μA, a current level low enough to avoid Joule heating. We applied maximum $|E|=5$ MV/cm, where the leakage current was less than 70 nA/cm^2.

Figure 1 shows the magnetic field H dependence of the Hall resistance R_{Hall} at $E=0$ and temperatures T from 5 to 60 K. Clear hysteresis loops show that the (Ga,Mn)As layer is ferromagnetic below $T_C\sim 60$ K. They also indicate that R_{Hall} is dominated by the anomalous Hall effect proportional to the perpendicular-to-the-plane component of magnetization M of the channel layer.

R_{Hall} vs $\mu_0 H$ (μ_0: permeability of vacuum) at 35 and 50 K under three different E measured in the sequence of −5, 0, and +5 MV/cm are displayed in Figs. 2(a) and 2(b), respectively. Application of E has a pronounced effect on $\mu_0 H_c$; for example, at 35 K [Fig. 2(a)] $\mu_0 H_c$ is modified by a factor of 2, from 2 mT at $E=-5$ MV/cm (in the direction of enhancement of hole concentration) to 1 mT at $E=+5$ MV/cm.[6,8] At 50 K [Fig. 2(b)], clear hysteresis loops at

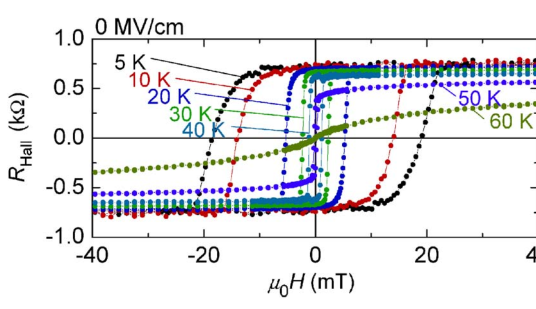

FIG. 1. (Color online) External magnetic field $\mu_0 H$ dependence of Hall resistance R_{Hall} at temperatures from 5 to 60 K.

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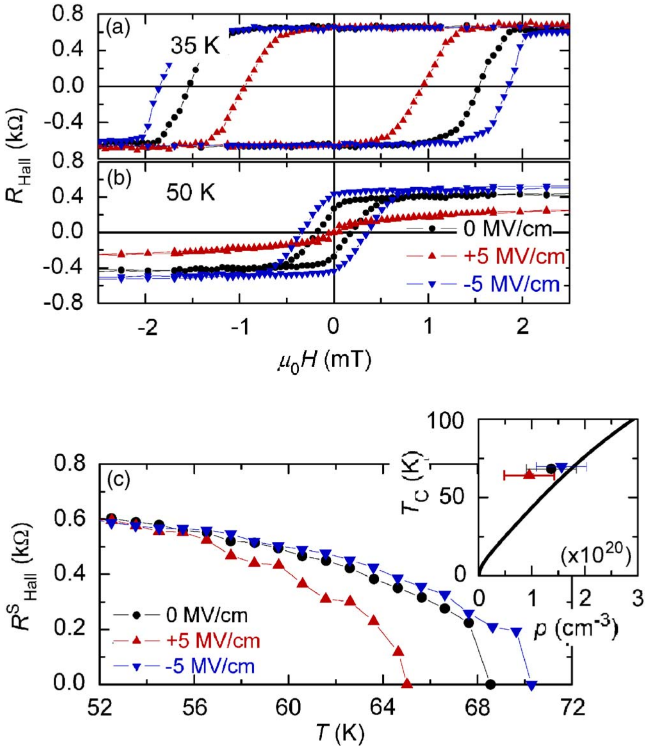

FIG. 2. (Color online) External magnetic field μ_0H dependence of Hall resistance R_{Hall} under external electric fields of $E=+5$, 0, and -5 MV/cm (a) at 35 K and (b) 50 K. (c) Temperature T dependence of R^S_{Hall} proportional to the spontaneous magnetization determined by the Arrott plots (R^2_{Hall} vs μ_0H/R_{Hall} plot). The inset shows the hole concentration p dependence of Curie temperature T_C with theoretical calculation by the p-d Zener model (solid line).

$E\leqslant 0$ are transformed to a trace that shows $\mu_0H_c=0$ by application of $E=+5$ MV/cm. These results show that magnetism of the (Ga,Mn)As channel layer can be modified isothermally by the external E, as observed in (In,Mn)As.[3,6,8]

To determine T_C at each electric field, we adopt the Arrott plot (R^2_{Hall} vs μ_0H/R_{Hall} plot) using R_{Hall} in place of M to determine spontaneous R_{Hall}, R^S_{Hall}, which is proportional to the spontaneous M of the channel, as a function of temperature. Figure 2(c) shows the T dependence of R^S_{Hall} at $E=-5$, 0, and +5 MV/cm. Thus determined T_C at $E=0$ MV/cm is 68.5 K. We can see that T_C at $E=+5$ (-5) MV/cm is 65 (70) K, which is 3.5 (1.5) K lower (higher) than that at $E=0$. The application of $E=+5$ (-5) MV/ modulates 43.5% (-12.3%) of R_{sheet} at 70 K (near T_C). From the gate capacitance, we estimate that $|E|=5$ MV/cm produces a sheet hole concentration change $\Delta p_{\square}$ of 1.8×10^{13} cm^{-2}; hence, assuming a constant mobility and using 7 nm as the channel thickness, p at $E=0$ is determined to be $(1.3\pm 0.5)\times 10^{20}$ cm^{-3}. The p dependence of T_C is displayed in the inset of Fig. 2(c). Solid line shows the theoretical calculation by the p-d Zener model with a mean-field approximation.[11,12] As can be seen from the figure, the calculated curve is in agreement with the observed magnitude and modulation of T_C.

Next, we focus on the modulation of μ_0H_c by E. We first investigated the magnetic anisotropy of the (Ga,Mn)As layer by rotating H to probe the magnetization reversal process: for this, we used a magnet that rotates around the sample. Figures 3(a)–3(c) show the θ_H dependence of R_{Hall} at 30, 50, and 70 K, respectively, where θ_H is the angle of H from the [001] direction (the plane perpendicular to the current). The

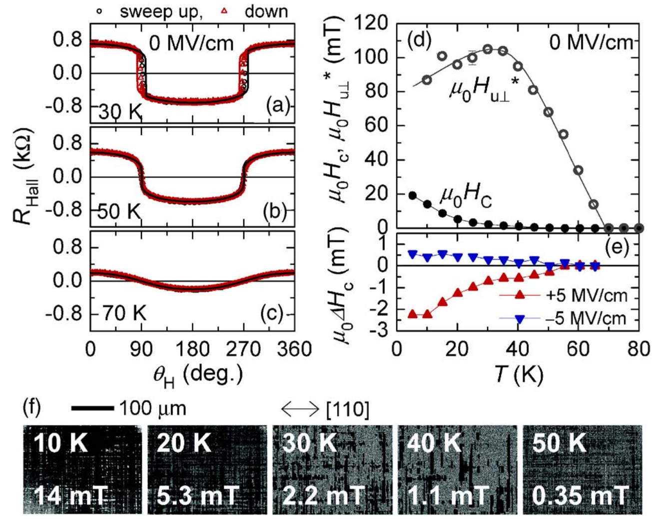

FIG. 3. (Color online) Angle θ_H dependence of Hall resistance at (a) 30, (b) 50, and (c) 70 K. The applied μ_0H and E are 68 mT and 0 MV/cm, respectively. θ_H is the angle of μ_0H from the [001] direction in the plane perpendicular to the current. Solid lines are fitted curves by the Stoner-Wohlfarth model. Sweep up (down) is shown by the open circles (triangles). (d) T dependence of μ_0H_c and $\mu_0H_{u\perp}$. (e) T dependence of coercivity modulation $\mu_0\Delta H_c$ [$=\mu_0H_c(E)-\mu_0H_c(0)$] under the applications of $E=+5$ (triangles) and -5 MV/cm (inverse triangles). (f) Magneto-optical Kerr effect images at T from 10 to 50 K. The images were taken 5 s after application of μ_0H (close to μ_0H_c) indicated in each image. The dark region indicates the region where M is reversed.

applied μ_0H and E are 68 mT and 0 MV/cm, respectively. Here, we calculate the magnetic energy assuming the Stoner-Wohlfarth model and a uniaxial anisotropy with the easy axis along the [001] direction,

$$E = K_{u\perp}\sin^2\theta_M - \frac{M^2}{2\mu_0}\sin^2\theta_M - MH\cos(\theta_M-\theta_H),$$

where $K_{u\perp}$ is the perpendicular uniaxial anisotropy energy constant and θ_M is the angle of M from the [001] direction. The first term is uniaxial anisotropy energy, the second term demagnetizing energy, and the third term the Zeeman energy. Note that the equation is appropriate only for the region with coherent magnetization rotation, and therefore for analysis we selected data points in the range of θ_H, where the coherent magnetization rotation is expected to be taking place (the region far from $\theta_H=90°$ and 270°). By imposing the conditions of $\partial E/\partial\theta_M=0$ and $\partial^2E/\partial\theta_M^2>0$ and using the relation of $R_{\mathrm{Hall}}\propto\cos\theta_M$, we calculate the R_{Hall}-θ_H curves to reproduce the data, where the sum of uniaxial anisotropy and demagnetization fields $2\mu_0K_{u\perp}/M-M=\mu_0H^*_{u\perp}$ is used as a fitting parameter. The solid lines in Figs. 3(a)–3(c) show the results of fit, which reproduce the data. The determined T dependence of $\mu_0H^*_{u\perp}$ is summarized in Fig. 3(d) by open circles. μ_0H_c and its modulation $\mu_0\Delta H_c[=\mu_0H_c(E)-\mu_0H_c(0)]$ by the application of E are shown in Figs. 3(d) and 3(e), respectively.[13] $\mu_0H^*_{u\perp}$ is much greater than μ_0H_c shown by the closed circles at all temperatures below T_C. This shows that the magnetization reversal process does not occur coherently, but through magnetic domain nucleation. Figure 3(f) shows the magneto-optical Kerr effect (MOKE) images at T from 10 to 50 K. These images were taken 5 s after the application of perpendicular positive $\mu_0H\sim\mu_0H_c$ to the initial magnetization state saturated in the negative direction at each T. The distribution of the dark region, where M

is reversed and positive, indicates that the nucleation field $\mu_0 H_n$ of domains determines $\mu_0 H_c$. This reveals that the modulation of $\mu_0 H_c$ by E is a result of the modulation of $\mu_0 H_n$. Although further studies are clearly necessary to address the mechanism of this modulation, we note that the domains along the $\langle 110 \rangle$ crystal axes are tracing the cross-hatch lines caused by the lattice mismatch between (In,Ga)As and GaAs.

In summary, we have described the observation of modulation of both T_C and $\mu_0 H_c$ by the external electric fields in a FET structure with a (Ga,Mn)As channel layer and an Al_2O_3 insulator. Calculation based on the *p-d* Zener model is shown to reproduce the magnitude of T_C modulation. Both the analysis of the transport data and the MOKE images indicate that $\mu_0 H_c$ is determined by the nucleation field $\mu_0 H_n$ and, thus, the change in carrier concentration is found to affect the magnitude of $\mu_0 H_n$.

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