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2004 J. Phys.: Condens. Matter 16 S5693

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J. Phys.: Condens. Matter **16** (2004) S5693–S5696 PII: S0953-8984(04)79407-2

Control of magnetization reversal in ferromagnetic semiconductors by electrical means

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Received 15 April 2004
Published 19 November 2004
Online at stacks.iop.org/JPhysCM/16/S5693
doi:10.1088/0953-8984/16/48/029

Abstract

A new scheme of magnetization reversal, an electrically assisted magnetization reversal, is realized in a carrier-induced ferromagnetic semiconductor (In, Mn)As structure. The demonstration has been done with field-effect transistors (FETs) having a thin (In, Mn)As channel by the application of a gate electric field to control the hole concentration p.

Magnetization reversal is a fundamental process for writing bits onto magnetic materials and is generally done by applying magnetic fields locally to them. In order to realize higher data density per unit area, manipulation of magnetization reversal by other means has become an important challenge for magnetic information storage [1–5], because the required magnetic fields become too high to generate for nanometre-scale magnetic bits. Here, we show that electrical manipulation of the magnetization processes is possible in a ferromagnetic semiconductor (In, Mn)As [6] and demonstrate electrically assisted magnetization reversal.

(In, Mn)As exhibits carrier-induced ferromagnetism and is used as a channel layer of a metal–insulator–semiconductor field-effect transistor (FET) structure for the field-effect experiments. In such a magnetic FET device, application of an external electric field E to a thin p-type (In, Mn)As channel has been shown to modify the ferromagnetic transition temperature T_C of the channel layer through the change of hole concentration p [7]; since holes mediate ferromagnetic interaction among Mn localized spins, the negative (positive) bias increases p and results in an increase (decrease) of T_C. The magnetization M of the magnetic channel layer has been probed by the use of the anomalous Hall effect.

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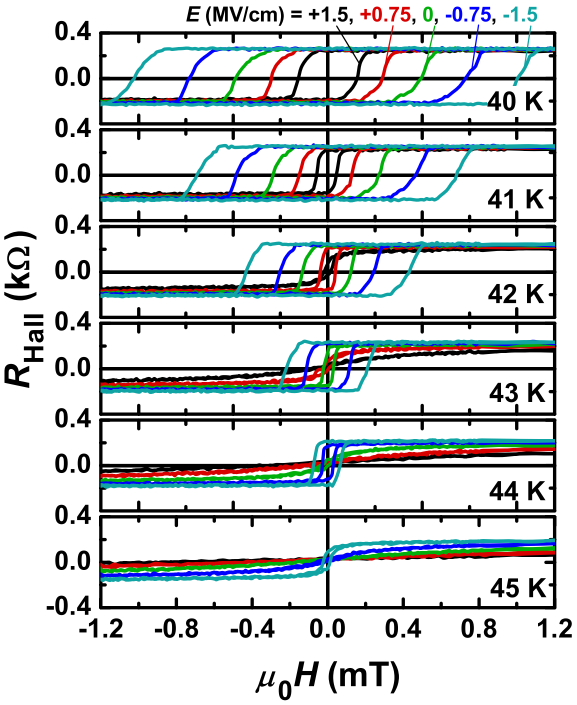

Figure 1. Electric field dependence of the magnetic hysteresis curves measured by R_{Hall} of sample A in the temperature range 40–45 K. Application of E results in a change of coercive force $\mu_0 H_C$. The magnetic field sweep rate is 0.36 mT min^{-1}.

(This figure is in colour only in the electronic version)

In the present study, the (In, Mn)As channel layer thickness of two FETs is set to 5 and 4 nm for sample A and sample B, respectively. The layers were grown by molecular beam epitaxy at 240 °C on 5 nm InAs grown at 450 °C, 200 or 300 nm $(Al_{0.8}Ga_{0.2})Sb$, and 50 nm AlSb, both grown at 550 °C on a semi-insulating GaAs (001) substrate. The Mn concentration of samples A and B is $x = 0.063$ and 0.033, respectively. The channel layer of the Hall-bar geometry FETs is covered with a 0.9 μm thick spun-on SiO_2 gate insulator and then by a Cr/Au metal gate electrode.

The magnetic easy axis direction in (In, Mn)As is perpendicular to the sample plane due to the strain in the channel layer [8–10]. T_C at zero gate electric field determined from the Arrott plots using the anomalous Hall effect is 52 K for sample A and 38.5 K for sample B. Application of electric fields E of ±1.5 MV cm^{-1} results in a ∓1.5 K change of T_C for sample A and ∓2.0 K for sample B. The corresponding change in hole concentration is $\mp 2.7 \times 10^{12}$ cm^{-2}, which is obtained from the gate capacitance.

Application of electric fields has a significant effect on H_C, as shown in figure 1 for sample A in the temperature range 40–45 K. For instance, H_C can be modified by a factor of 5 at 40 K, from 1 mT at -1.5 MV cm^{-1} to 0.2 mT at +1.5 MV cm^{-1}, while virtually keeping the square shape of the hysteresis loops unchanged. Since the magnitude of H_C is a function of an external electric field, the magnetization reversal process can now be electrically assisted.

Figure 2 shows that this is indeed possible. Here, we first saturated the magnetization of the (In, Mn)As channel layer under $E = -1.5$ MV cm^{-1} by applying a large enough

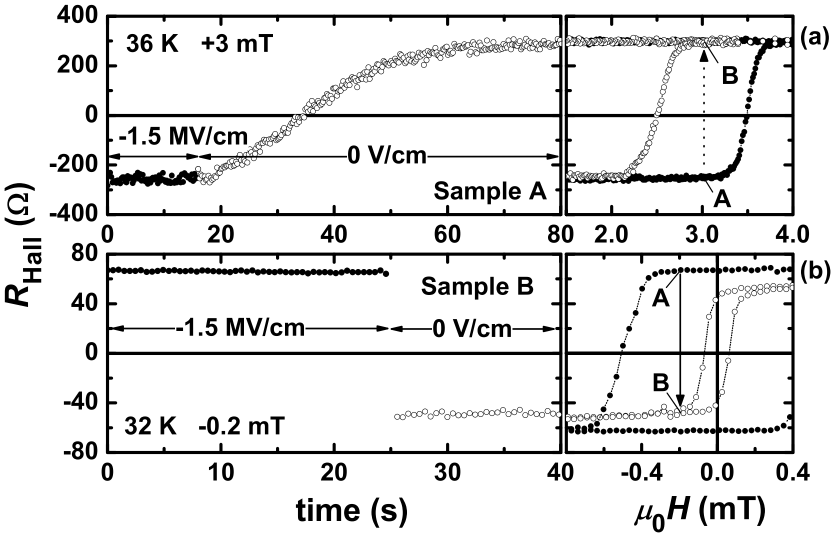

Figure 2. Time evolution of R_{Hall} resulting from a sequence of applied electric fields in sample A (a) and B (b) at 36 and 32 K, respectively, showing an electrically assisted magnetization reversal (left panels). The initial R_{Hall} at $t = 0$ is prepared under $E = -1.5$ MV cm^{-1} by first applying a large enough positive (sample B) or negative (sample A) magnetic field to saturate the channel magnetization and then reducing the field to $\mu_0 H_0$ (=3 and -0.2 mT for sample A and B, respectively). This state corresponds to state A on the hysteresis curve under $E = -1.5$ MV cm^{-1} (closed symbols) shown in the right panels. The sign change of R_{Hall}, i.e. magnetization reversal, occurs in response to switch-off of the electric field ($E = 0$) at $t = 25$ s (sample A) or 18 s (sample B), which makes the magnitude of H_{C} smaller than H_0. The state is then at state B on the hysteresis curve under $E = 0$ (open symbols in the right panels).

magnetic field, and then reduced the field through 0 mT to an opposite small bias magnetic field $\mu_0 H_0$ (=3 and -0.2 mT for sample A and B, respectively). This is the initial state indicated by point A in the right panels of figure 2 for each sample, where two R_{Hall}–B curves under $E = 0$ and -1.5 MV cm^{-1} are shown. Change of R_{Hall} as a function of time, t, is displayed in the left panels of figure 2. Since the magnitude of $\mu_0 H_0$ is smaller than the coercive force $\mu_0 H_{\mathrm{C}}$ under $E = -1.5$ MV cm^{-1}, the state remains at point A until E is switched off ($E = 0$ MV cm^{-1}). In response to this switching, the sign of R_{Hall} changes, showing that electrical switching triggers magnetization reversal. Because $|H_{\mathrm{C}}| < |H_0|$ at $E = 0$ V cm^{-1}, the electrical switching brings the state to point B (final state) of the right panel. The remarkable difference of the switching speed between the two samples may be related to T/T_{C} and/or H_0/H_{C} of the final state. Increased T/T_{C} and/or H_0/H_{C} are expected to result in faster switching. In figure 2, T/T_{C} of sample A and B is 0.69 and 0.83, and H_0/H_{C} is 1.3 and 2.0, respectively. Further investigation of the relationship between switching speed and experimental condition, including the design of the device, is necessary. This electrically assisted magnetization reversal (‘assisted’ because a small negative magnetic field is needed) without changing applied magnetic fields or temperature demonstrates the possibility of a new scheme for Curie point writing, where magnetization reversal is assisted by making the system closer to or beyond its Curie temperature[4].

The results presented here offer functionalities which have not been accessible. Furthermore, by the use of a ferromagnetic semiconductor (Ga, Mn)As, we have demonstrated

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[4] Curie point writing is being used in magneto-optical memory disks and is currently being investigated for ultra high density magnetic recording. In both cases, it is done by heating the region of interest using laser light irradiation.

current-driven magnetization reversal of a magnetic electrode in magnetic tunnel junctions [11] and current-driven magnetic domain wall propagation [12], both achieved at low current densities ($<10^5$ A cm^{-2}) without magnetic field. Therefore magnetic semiconductors may become a key material [13, 14], once their T_C reaches well beyond room temperature.

Acknowledgments

The authors thank K Takanashi, S Mitani, T Dietl, K Ohtani, and Y Ohno for useful discussions. This work was partly supported by the IT-Program of Research Revolution 2002 (RR2002) from MEXT, a Grant-in-Aid from MEXT, and the 21st Century COE Program 'System Construction of Global-Network Oriented Information Electronics' at Tohoku University.

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