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Electric field control of thermal stability and magnetization switching in (Ga,Mn)As

D. Chiba, T. Ono, F. Matsukura, and H. Ohno

Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto 611-001, Japan
PRESTO, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan
Department of Applied Physics, Faculty of Engineering, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 133-8565, Japan
WPI Advanced Institute for Materials Research (WPI-AIMR), Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan
Center for Spintronics Intergraded Systems, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan
Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

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Magnetization switching induced by electric fields in the absence of external magnetic field has been demonstrated in a field effect structure with a (Ga,Mn)As layer having an in-plane magnetic anisotropy. The switching is related to the modulation of the in-plane magnetic anisotropy by electric fields. Reducing magnetic anisotropy energy height by electric fields, we observe stochastic magnetization switching. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4821778]

The switching of magnetization direction between two stable states separated by an energy barrier is a fundamental technology for writing information in magnetic memories and storages. Application of an external magnetic field or spin polarized currents is a conventional way to switch magnetization direction. For realization of higher-capacity spin polarized currents is a conventional way to switch magnetic recording device, one has to reduce the size or volume of magnetic bits, while maintaining sufficient thermal stability (KV), where K is the magnetic anisotropy energy density. Larger magnetic anisotropy results in higher magnetic field or higher current density for switching, and hence larger power consumption. The electric field-control of magnetic anisotropy and magnetization switching is now being investigated extensively. This method can potentially reduce the power consumption for switching, because it requires only charge/discharge current for writing information. In this letter, we show an electric field-induced in-plane magnetization switching in a ferromagnetic semiconductor (Ga,Mn)As in the absence of an external magnetic field. The switching takes place through the electric field-induced reduction of the energy barrier height. We determine the energy barrier as a function of electric field as well as of the temperature.

A 4-nm-thick Ga0.93Mn0.07As layer is grown on a semi-insulating GaAs (001) vicinal substrate (4° off from (001) toward [100]) at 200 °C by molecular beam epitaxy. The buffer layer underneath consists of 4-nm GaAs/30-nm Al0.3Ga0.7As/30-nm GaAs. The sample is first annealed at 180 °C for 5 min, then, processed into a Hall bar geometry along [110] with 40-μm width and 144-μm length as shown in Fig. 1(a). 5-nm Cr/100-nm Au electrode pads are evaporated and lifted off to form voltage probes and source (S) and drain (D) contacts. Subsequently, a 43 nm-thick ZrO2 (dielectric constant is 23) gate insulator is deposited at 120 °C by atomic layer deposition. Finally, a 5-nm Cr/100-nm Au gate (G) electrode is evaporated and lifted off. A photograph of the completed device and the measurement configuration are shown in Fig. 1(b). The Curie temperature of the sample at gate electric field E = 0 is 135 ± 5 K, which is determined from the temperature T dependence of the resistivity. By applying constant voltage between source and drain, dc current ID is applied to the channel. The transverse resistance (planar Hall resistance) Rxy is measured to detect the magnetization direction φ, the magnetization angle from the [100] direction (Fig. 1(c)).

Figure 2(a) shows the time t dependence of Rxy at 97 K when the magnitudes of E and the in-plane external magnetic field H are swept in the sequences shown in Figs. 2(b) and 2(c). At t = 0, E = −2 MV/cm and H = 30 mT along θ = 46° (the definition of θ is given in Fig. 1(c)) are applied to initialize φ. Then the magnitude of H is decreased gradually to zero (t = 0−137 s) at a constant E = −2 MV/cm. Next, E is

FIG. 1. (a) Photograph of the Hall bar shaped (Ga,Mn)As mesa structure taken under an optical microscope. (b) Photograph of the device and measurement configuration. (c) Vector diagram of the magnetization direction and the external magnetic field H. The angles φ and θ are the angles of M and H measured from [100] direction, respectively.
changed linearly in the positive direction to +2 MV/cm, and
is returned linearly to its initial value of −2 MV/cm ($t = 137 − 912$ s). During the sweep of $E$, the values of $I_D$ changes (Fig. 2(d)), reflecting the modulation of the hole concentration. The notable feature is an abrupt jump in $R_{yx}$ pointed with an arrow in Fig. 2(a), indicating a magnetization switching in the absence of a magnetic field.

It is known that (Ga,Mn)As has an in-plane magnetic anisotropy which is the sum of biaxial easy axes along [100] and [010] and uniaxial easy axis along [110] or [110]. The magnetic free energy $F$ is given by

$$ F = \frac{M H_B}{2} \left[ \sin^2 2\varphi + h_{U1} \sin^2 \left( \frac{\varphi - \pi}{4} \right) - 2 h \cos (\theta - \varphi) \right] $$

$$ = -\frac{M H_B}{2} f, $$

where $M$ is the magnitude of magnetization, $H_B$ is the biaxial anisotropy field, $h_{U1}$ and $h$ are the ratios of the uniaxial anisotropy field $H_{U1}$ along [110] and the external field $H$ to $H_B$, respectively. In our definition, [110] is the easy axis when $H_{U1} > 0.$ We fit $R_{yx} \propto \sin^2(2(\varphi - 45^\circ))$ to the $R_{yx} - \theta$ curve measured at $\mu_0 H = 0.15$ T and 90 K by using coherent magnetization rotation model, where $H_B$ and $H_{U1}$ are adopted as fitting parameters.\textsuperscript{19-23} The relationship between $\varphi$ and $\theta$ is determined by imposing the conditions, $\partial f/\partial \varphi = 0$ and $\partial^2 f/\partial \varphi^2 > 0.$ The fit determines $\mu_0 H_B$ and $\mu_0 H_{U1}$ as 25 and −22 mT, respectively, and thus $h_{U1}$ is 0.88. Figure 3(a) shows the $f - \varphi$ energy diagram at $h_{U1} = 0.85$ and $h = 0$. There are two energetically stable states in the vicinity of $\varphi = 135^\circ$ at $H = 0$ (Fig. 3(b)). It is natural to consider that these two states correspond to the states before (A in Fig. 3(a)) and after (B) the switching in Fig. 2(a). The application of $E$ is expected to reduce the barrier height $\Delta F$ which separates states A and B.

In order to investigate the effect of electric field on $\Delta F$, we have carried out experiments to observe the thermal fluctuations of $M$ at 97 K. First, we set the electric field to $E_{\text{initial}} = -2$ MV/cm and $\varphi$ is initialized by applying $\mu_0 H$ of 20 mT along $\theta = 46^\circ$. Then $t$ dependence of $R_{yx}$ is recorded at every 47 ms for 500 s under a constant external field $H'$. The electric field is switched from $E_{\text{initial}}$ to $E'$ ($E'$ is negative and its magnitude is smaller than $E_{\text{initial}}$) at $t = 5$ s. Figure 4(a) shows the results obtained at $E' = -1$ MV/cm under various $H'$, and Fig. 4(b) summarizes the number of data points at a given $R_{yx}$ as a function of $H'$, which is created from the data in $t = 200−500$ s. The three sharp peaks labeled as A, B, and C in Fig. 4(b) indicate that there are three stable or meta-stable states. The initialized state at $t = 0$ corresponds to state A. At $H' = 0$ (we have carefully checked that the magnitude of the residual magnetic field is the order of a geomagnetic field when $H$ is set to zero), the switching of $R_{yx}$ is observed at $t = 5$ s, indicating the switching from states A to B is induced by the electric field, and no further switching is observed. This means that state B is more stable, i.e., $\Delta F$ for switching at the two states is not energetically equivalent. This may be attributed to the presence of an additional small uniaxial anisotropy field $H_{U2}$ along [100] as shown in Fig. 3(c).\textsuperscript{24} Although the origin of $H_{U2}$ is not understood yet, in the present case the use of vicinal substrate may be related to it. At higher $H$ ($>\sim 1.8$ mT), state A is stable, thus no switching is observed, while switching from states A to B always takes place at $t = 5$ s at lower $H$ ($<\sim 0.7$ mT). In between these two regimes, thermally activated stochastic switching through intermediate state C can be observed (see Fig. 4(a)). This state is presumably a multi-domain state.\textsuperscript{19} From the observed stochastic behavior, $\Delta F$ for states A and B can be obtained by assuming that the Arrhenius law gives the magnetization relaxation time $\tau$ as $\tau = \tau_0 \exp(\Delta F/k_B T)$, where $\tau_0 = 10^{-9}$ s is the inverse of attempt frequency, $k_B$ the Boltzmann constant, and $T = 97$ K. Here, each $\tau$ between two states is determined experimentally as the averaged dwell time, which is total dwell time at each state divided by the number of stochastic switching events to one of the two other states. The total dwell time at each state and the number of switching events are evaluated from the results at $t = 200−500$ s in Figs. 4(a) and 4(b). As shown in Fig. 4(c), the obtained $\Delta F$
for state A (B) increases (decreases) with the increase of *H*. At 1.23 mT, where *F* for states A and B is almost balanced by the Zeeman energy, we determine Δ*F* for the states to be ~150 meV. By assuming that Δ*F* describes the energy barrier for domain nucleation, we estimate roughly the domain wall width δ*w* to be submicrometer from the nucleation volume *V* ~ δ*w*²*τ*GaMnAs, where *τ*GaMnAs is the thickness of (Ga,Mn)As. The estimated δ*w* is comparable to that observed experimentally.

Figure 4(d) shows the time chart of *R*ₓᵧ obtained at μ₀*H* = 1.08 mT and various *E*. The number of data points taken at *t* = 200-500 s is shown in Fig. 4(e). The stochastic switching can be seen but its frequency depends on the magnitude of *E*. Figure 4(f) shows Δ*F* as a function of *E*, Δ*F* for the both states decreases with the increase of *E*, but their difference is almost constant. Thus, the electric field-induced switching demonstrated here is attributed to the reduction of Δ*F* by applying *E* under the condition that the free energies at states A and B are different.

We also demonstrate the memory operation at 97 K (Fig. 5). First, μ₀*H* of ~20 mT along θ = 46° is applied to initialize ϕ at *E* = −2 MV/cm, and then *H* is returned to 0. The value of *R*ₓᵧ is recorded at every 1.4 s. At times indicated by thick arrows, electric field is changed to −1 MV/cm for 15 ms, which results in a magnetization switching as noticed by a jump of *R*ₓᵧ. The *R*ₓᵧ can be returned to the initial value by using the same temporal change of electric field along with the assistance of pulsed μ₀*H* of 1.3 mT for 15 ms along θ = 46° at times indicated by thin arrows. The successive alternating operations bring about magnetization switching between states A and B with good reproducibly.

In summary, we have demonstrated electric field induced-magnetization switching in the absence of external magnetic fields. We have also shown that the stochastic magnetization switching among three states in a static magnetic fields. The results are explained in terms of electric field-dependent magnetic anisotropy and thermal stability.

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