Magnetization manipulation in (Ga,Mn)As by subpicosecond optical excitation

G. V. Astakhov
Physikalisches Institut der Universität Würzburg, 97074 Würzburg, Germany
and Ioffe Physical Technical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia

A. V. Kimel
IMM, Radboud University Nijmegen, 6525 ED Nijmegen, The Netherlands

G. M. Schott
Physikalisches Institut der Universität Würzburg, 97074 Würzburg, Germany

A. A. Tsvetkov and A. Kirilyuk
IMM Radboud University Nijmegen, 6525 ED Nijmegen, The Netherlands

D. R. Yakovlev
Experimentelle Physik 2, Universität Dortmund, 44221 Dortmund, Germany,
and Ioffe Physical Technical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia

G. Karczewski
Institute of Physics, Polish Academy of Sciences, 02-668 Warsaw, Poland,
and Physikalisches Institut der Universität Würzburg, 97074 Würzburg, Germany

W. Ossau, G. Schmidt, and L. W. Molenkamp
Physikalisches Institut der Universität Würzburg, 97074 Würzburg, Germany

Th. Rasing
IMM Radboud University Nijmegen, 6525 ED Nijmegen, The Netherlands

(Received 18 October 2004; accepted 19 February 2005; published online 5 April 2005)

We demonstrate complete reversal of a full magnetic hysteresis loop of the magnetic semiconductor (Ga,Mn)As by ultrashort optical excitation with a single subpicosecond light pulse, with obvious implications for ultrafast magneto-optical recording. Our approach utilizes the fourfold magnetic anisotropy of (Ga,Mn)As, in combination with the magnetic linear dichroism of the material.

© 2005 American Institute of Physics.
[DOI: 10.1063/1.1899231]

During the last decade (III,Mn)V ferromagnetic semiconductors (FS) such as (Ga,Mn)As have been the subject of intense research. This huge interest is caused by the very promising multifunctional circuits that can be envisioned when FSs are integrated with standard semiconductor devices for example, spin injection, electrical control of ferromagnetism, very large magnetoresistance, tunneling anisotropic magnetoresistance, and current-induced switching have been demonstrated in (III,Mn)V-based devices. In the following we show how the specific magnetic properties of (Ga,Mn)As can be applied to ultrafast magneto-optical recording.

The ferromagnetic materials that are commonly used in magneto-optical memory devices possess uniaxial magnetic anisotropy, i.e., there is an easy axis, along which the magnetization can be either parallel or antiparallel. As a result, the magnetization as a function of external magnetic field exhibits a hysteresis loop resulting from the switching between two metastable magnetization states. In contrast, the ferromagnetic semiconductor (Ga,Mn)As has a biaxial magnetic anisotropy and as a result possesses two equivalent easy axes. This property modifies the hysteresis loop such that a switching of the magnetization between two different pairs of states can be observed. In this letter we demonstrate that this switching may be induced by applying a single laser pulse that can be as short as $10^{-13}$ s. Moreover, these four possible orientations of the magnetization can serve for recording of two bits of information at one spot, thus leading to a doubling of the recording density.

We present here results for a 350-nm-thick Ga$_{0.98}$Mn$_{0.02}$As epilayer. It was deposited on a (001) GaAs substrate followed by a 3 μm Al$_{0.5}$Ga$_{0.5}$As buffer by low-temperature molecular beam epitaxy. The high structural quality of the sample was confirmed by x-ray diffraction. Magnetic characterization of the sample was done with a superconducting quantum interference device magnetometer. The Curie temperature is about 50 K. For temperature below 20 K the magnetic anisotropy shows two in-plane easy axes along the [100] and [010] crystallographic directions, respectively.

For the ultrafast laser excitation of the sample we used amplified 100 fs pulses from a Ti:sapphire laser at a repetition rate of 1 kHz and a wavelength of 805 nm. A mechanical shutter was used to select one single pulse. This pulse was focused on the sample to a spot size of 100 μm. Pump fluence was up to 175 mJ/cm$^2$. A magnetic field was applied in the plane of the sample at an angle of 41° with the [100] axis. During all experiments the sample was kept at a bath temperature of 10 K.

As a local probe of the magnetization ($M$), we used a linearly polarized continuous-wave laser at the wavelength of 815 nm, which was focused at the sample onto a spot with...
a diameter of 50 μm. The angle of incidence was about 20° and the plane of incoming linear polarization was set at 45° with respect to the [100] axis. In order to read out the magnetization orientation with respect to the crystallographic axes, the magnetic linear dichroism (MLD) was used. This effect, frequently referred to as the Voigt effect, results from the perpendicular-biaxial anisotropy, where [100] and [010] are the easy axes. The biaxial anisotropy leads to an M-shaped major hysteresis loop in the magnetic birefringence, as shown in Fig. 1(c). Two jumps, at fields $H_{12} = 6$ mT and $H_{23} = 88$ mT, are clearly seen when the magnetic field is swept from minus to plus. Similar jumps occur at $H_{34} = -H_{12}$ and $H_{41} = -H_{23}$ when the field is swept in the opposite direction.

These magnetization jumps, appearing at magnetic fields $H_{ij}$, are related to the sudden appearance of a single macroscopic domain with magnetization in the final state ($J$) oriented under 90° with respect to that of the initial state ($I$). Such a behavior is confirmed by the sharp magnetization loops which were mapped using the MLD [Figs. 1(c) and 1(d)] and found to be independent of the spot size. The fields $H_{ij}$ can be estimated through a characteristic pinning energy of such domains $E$ using the following simple equation:

$$\frac{H_{ij} \cdot M_{ij} - H_{ij} \cdot M_i}{2} = E. \tag{1}$$

Based on this equation, we were able to measure precisely the sample orientation with respect to the magnetic field direction:

$$H_{23} = \tan(\varphi + 45°),$$

and obtain in our case $\varphi = 41°$.

When the field sweep is limited to $H_0 < H < H_{23}$, two mutually reversed hysteresis loops appear instead of the major loop [see Fig. 1(d)]. These are referred to as minor hysteresis loops and characterize the magnetization switching between the states 1 and 2 (lower minor loop), as well as between states 3 and 4 (upper minor loop) as shown in Fig. 1(b).

Let us now turn to the single pulse switching behavior that is the main point of the present letter [Fig. 1(e)]. When a small field $H_0 < H_{23}$ is applied, the magnetization is brought in state 2. Any reduction of the coercivity at this stage will result in a decrease of $H_{23}$. As soon as $H_0 > H_{23}$, switching from state 2 to state 3 occurs. This is the switching process we now focus on. The reduction of the coercivity may be induced by heating of the sample, using either a current or laser pulse. The latter has been exploited in this work.

The essential figure demonstrating single pulse magnetization switching is Fig. 2. We measured the minor birefringence hysteresis loop of Fig. 1(d) before and after optical excitation of our Ga$_{0.98}$Mn$_{0.02}$As layer with a single ultrashort (100 fs) laser pulse. Before the photobleach, the lower minor hysteresis loop (open symbols) is measured. After a single pulse excitation in a magnetic field of 75 mT, the magneto-optical hysteresis has been turned to the upper minor loop and the experimental lower minor loop (open symbols) is measured. Again, solid and open symbols correspond to up-sweep and down-sweep of the hysteresis loops. As shown in Fig. 2, we now focus on. The reduction of the coercivity may be induced by heating of the sample, using either a current or laser pulse. The latter has been exploited in this work.

The essential figure demonstrating single pulse magnetization switching is Fig. 2. We measured the minor birefringence hysteresis loop of Fig. 1(d) before and after optical excitation of our Ga$_{0.98}$Mn$_{0.02}$As layer with a single ultrashort (100 fs) laser pulse. Before the photobleach, the lower minor hysteresis loop (open symbols) is measured. After a single pulse excitation in a magnetic field of 75 mT, the magneto-optical hysteresis has been turned to the upper minor loop.

When an in-plane magnetic field ($H$) is too weak to produce a rotation of $M$ away from the easy axes, only four different orientations of $M$ (two for each of the two [100] and [010] axes) are possible; in Fig. 1 these states are labeled as (1), (2), (3), and (4). This occurs provided $H \cdot M/2 \leq K_c$ ($K_c$ is the cubic anisotropy coefficient), which holds for the experiments presented in this letter. In this limit, hysteresis loops exhibit somewhat unusual multiple switching events.

The process of magnetization reversal in an applied magnetic field at an angle $\varphi = 41°$ with the [100]-axis of Ga$_{0.98}$Mn$_{0.02}$As is shown schematically in Fig. 1(a). The reversal occurs via multiple 90° switches between the states labeled 1 to 4. Consequently, after two jumps the magnetization is reversed with respect to the original configuration. This is due to the perpendicular-biaxial anisotropy, where [100] and [010] are the easy axes. The biaxial anisotropy leads to an M-shaped major hysteresis loop in the magnetic birefringence, as shown in Fig. 1(c). Two jumps, at fields $H_{12} = 6$ mT and $H_{23} = 88$ mT, are clearly seen when the magnetic field is swept from minus to plus. Similar jumps occur at $H_{34} = -H_{12}$ and $H_{41} = -H_{23}$ when the field is swept in the opposite direction.

These magnetization jumps, appearing at magnetic fields $H_{ij}$, are related to the sudden appearance of a single macroscopic domain with magnetization in the final state ($J$) oriented under 90° with respect to that of the initial state ($I$). Such a behavior is confirmed by the sharp magnetization loops which were mapped using the MLD [Figs. 1(c) and 1(d)] and found to be independent of the spot size. The fields $H_{ij}$ can be estimated through a characteristic pinning energy of such domains $E$ using the following simple equation:

$$\frac{H_{ij} \cdot M_{ij} - H_{ij} \cdot M_i}{2} = E. \tag{1}$$

Based on this equation, we were able to measure precisely the sample orientation with respect to the magnetic field direction:

$$H_{23} = \tan(\varphi + 45°),$$

and obtain in our case $\varphi = 41°$.

When the field sweep is limited to $H_0 < H < H_{23}$, two mutually reversed hysteresis loops appear instead of the major loop [see Fig. 1(d)]. These are referred to as minor hysteresis loops and characterize the magnetization switching between the states 1 and 2 (lower minor loop), as well as between states 3 and 4 (upper minor loop) as shown in Fig. 1(b).
nor loop (solid symbols). This observation clearly demonstrates that ultrafast laser excitation is able to induce far more drastic changes than just to switch the orientation of the magnetization. In the present experiment, the hysteresis loop as a whole is completely reversed.

The laser-induced switching requires the application of an external magnetic field $H_0$ and an intense optical excitation with pump fluence $P$. We have analyzed the influence of these parameters on the hysteresis reversal, finding as general tendency the larger $P$ the weaker $H_0$. For $P=150 \text{ mJ/cm}^2$ the switching was found to happen for magnetic fields $H_0>50 \text{ mT}$ [Fig. 3(a)]. In a constant magnetic field of $H_0=75 \text{ mT}$ the switching occurred only for pump fluences $P>130 \text{ mJ/cm}^2$ [Fig. 3(b)]. We did not detect any switching for pump fluences below $P<110 \text{ mJ/cm}^2$, while for $P$ between 110 and 130 mJ/cm² the switching was not complete. The deviation from ideal step-like behavior could point to an inhomogeneous distribution of Mn ions within the pump spot. In addition, one should note that a strong laser pulse may introduce large local stresses that may remain present even after heat relaxation and cannot be wiped out by moderate fields.

These observations conclusively demonstrate that by applying ultrashort optical pulses we can manipulate the magnetization in Ga₀.₀₉Mn₀.₀₂As layer between its four metastable states, which can be used for application in a magneto-optical memory. In this context, it is important to note that there are two different time scales that characterize the switching process. The first one is the excitation time, or in our case the duration of the laser pulse, $\tau=100 \text{ fs}$. The other, $\tau_R$, is the relaxation time the magnetization needs to relax into its new equilibrium state after the laser pulse is turned off. The latter may vary in a wide range, depending on the specific relaxation mechanism, and usually $\tau_R \gg \tau$. The rate at which one can rewrite a bit of information is given by $R_{\text{write}} = 1/(\tau + \tau_R) \approx \tau^{-1}$, and one must know $\tau_R$ for a reliable estimate of this rate. In order to write different bits in parallel at once, however, a total writing time $T_{\text{tot}}=N\tau+\tau_R$ is sufficient. For a massively parallel memory ($N \rightarrow \infty$), the recording rate $R_{\text{write}} = N/T_{\text{tot}} \approx \tau^{-1}$; i.e., $R_{\text{write}}$ is determined by the excitation time only. In this theoretical limit, one may achieve $R_{\text{write}} = 10 \text{ THz}$. However, it should be understood that other factors, e.g. the time required to focus at another spot, can limit memory performance.

In summary, the ferromagnetic semiconductor (Ga,Mn)As possesses a combination of magnetic and optical properties, which enabled us to demonstrate that its magnetooptical hysteresis loop can be reversed with a single 100 fs laser pulse. This hysteresis reversal occurs in an applied magnetic field and only for pump fluences above a well-defined threshold value. These observations may be adopted in ultrafast magneto-optical recording.

This work was supported in part by the EU RTD project SPINOSA, EU project DYNAMICS, the RFBR, as well as the Dutch organization for Fundamental Research on Matter (FOM), the Deutsche Forschungsgemeinschaft (DFG) and the DARPA SpinS program.


![FIG. 2. (Color online) Minor hysteresis loops of the Ga₀.₀₉Mn₀.₀₂As sample, recorded before (open symbols) and after (solid symbols) single optical pulse with a duration of 100 fs, are shown together with corresponding magnetization orientations (insets).](image-url)