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


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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.

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During the last decade (III,Mn)V ferromagnetic semiconductors 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, e.g., spin injection, electrical control of ferromagnetism, very large magnetoresistance, tunneling 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 Ga₀.₉₈Mn₀.₀₂As epilayer. It was deposited on a (001) GaAs substrate followed by a 3 µm Al₀.₃Ga₀.₇As 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/cm². 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
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 photoexcitation, 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 as (1), (2), (3), and (4). This occurs provided $|H| < K_c$ ($K_c$ 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 $\varphi=41^\circ$ 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 $H_{41}=-H_{12}$ and $H_{42}=-H_{23}$ 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:

$$\frac{H_{ij} \cdot M_J - H_{ij} \cdot M_I}{2} = \varepsilon.$$  

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

$$H_{23} = \tan(\varphi + 45^\circ),$$

and obtain in our case $\varphi=41^\circ$.

When the field sweep is limited to $H_{02} < H < H_{23}$, 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.

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the pump spot. In addition, one should note that a strong point to an inhomogeneous distribution of Mn ions within fluences. These observations conclusively demonstrate that applying ultrashort optical pulses we can manipulate the magnetization in Ga_{0.98}Mn_{0.02}As 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, \( \tau = 100 \) 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 \( \tau_R > \tau \). The rate at which one can rewrite a bit of information is given by \( \frac{R_{\text{write}}}{1} = \frac{1}{\tau + \tau_R} \approx \tau^{-1} \), and one must know \( \tau_R \) for a reliable estimate of this rate. For a massively parallel memory \((N\rightarrow\infty)\), the recording rate \( \frac{R_{\text{write}}}{N} = NT_{\text{tot}} = \tau^{-1} \); i.e., \( \tau_{\text{write}} \) is determined by the excitation time only. In this theoretical limit, one may achieve \( \tau_{\text{write}} = 10 \) 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 magneto-optical 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.

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**FIG. 2.** (Color online) Minor hysteresis loops of the Ga_{0.98}Mn_{0.02}As 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).

**FIG. 3.** Polarization rotation of the linear magnetic dichroism of our Ga_{0.98}Mn_{0.02}As sample after excitation with a single optical pulse, plotted between 110 and 130 mJ/cm\(^2\), while \( P < 110 \) mJ/cm\(^2\), Pump fluence, \( P \) (mJ/cm\(^2\)).

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