Single picojoule pulse switching of magnetization in ferromagnetic (Ga,Mn)As

A. H. M. Reid,[1,a)] G. V. Astakhov,[2] A. V. Kimel,[1] G. M. Schott,[2] W. Ossau,[2] K. Brunner,[2] A. Kirilyuk,[1] L. W. Molenkamp,[2] and Th. Rasing[1]
[1]*Institute for Molecules and Materials, Radboud University Nijmegen, Heijendaalseweg 135, 6525 AJ Nijmegen, The Netherlands*
[2]*Physikalisches Institut (EP3), Universität Würzburg, Am Hubland, 97074 Würzburg, Germany*

(Received 30 August 2010; accepted 14 November 2010; published online 6 December 2010)

The recently demonstrated photoinduced reduction of the coercive field in (Ga,Mn)As is shown to display a pronounced increase in efficiency when triggered by short laser pulses. This is due to the relaxation timescale of the effect that is measured to be about 1.5 ns. In addition, a single 100-fs-pulse with only 80 pJ of energy is found to be sufficient to write a magnetic domain. © *2010 American Institute of Physics*. [doi:10.1063/1.3524525]

Optical methods for writing magnetic information have recently gathered a considerable interest. Perhaps the two most heralded are heat assisted magnetic recording[1] and all-optical switching.[2] These rely on modifying the magnetic layers switching characteristics via a heat pulse, and then reversing via an external or an optically generated magnetic field.[3] A third method has been demonstrated in ferromagnetic (Ga,Mn)As; this is the photoinduced depinning of magnetic domains.[4] Here, the exposure to light in the visible region of the spectrum, strongly reduces their coercive field, which is the magnetic field required to switch magnetization. Unlike other optical methods, this photocoercivity effect (PCE)[4,5] occurs at low optical intensities that are easily realizable by commercial laser diodes and do not lead to excessive thermal stress on the sample. This stands in contrast to nonlinear mechanisms where high electric fields are required, thus necessitating high optical intensities, which give rise to substantial increase in temperature.[6–8]

At low temperatures, magnetization reversal is primarily governed by domain wall propagation as nucleation events are rare.[9,10] The PCE arises from the photomodification of the domain wall pinning site energies, most likely from the photogenerated holes enhancing the local exchange interaction[11,12] (although the photomodification of anisotropy could also play a role[13]), reducing the energy barrier and thus the coercive field.[14] This is evidenced in (Ga,Mn)As as the effect correlates with the onset of a strong increase in resistance at low temperatures, which corresponds to hole localization and phase separation.[15] Previous static experiments show that exposing (Ga,Mn)As to light reduces the coercive field during the exposure time (more than 60% at an illumination of approximately 1 W cm^{-2}).[4] In this letter, we demonstrate that the effect is both faster and more efficient than previously thought. Using a subpicosecond pulse, the coercive field can be reduced almost to zero in an area of approximately 100 μm^2 using only 0.08 nJ of energy. This compares very favorably with the 10–100 nJ of energy per bit written of current hard drives,[16] and even with magnetic RAM (0.15 nJ) and flash (10 nJ) solid state memories.[17] Furthermore, using a double-pulse experiment, we have found that the coercivity restores to the "in-dark" value within a few nanoseconds; this determines how fast a bit can be rewritten.

Measurements are performed on a low-doped (Ga,Mn)As layer grown by molecular beam epitaxy on (001) orientated GaAs;[18,19] note that this is the same wafer as studied in Astakhov *et al.*[4] The $(Ga_{1-x},Mn_x)As$ layer is 360 nm in thickness with a nominally Mn concentration of $x \approx 0.01$, a Curie temperature $T_C = 25$ K, and perpendicular magnetic anisotropy. It is further noted that the layer shows a sharp increase in resistivity below 5 K. In the measurement, the (Ga,Mn)As sample is mounted in a helium bath cryostat with optical access, with the measured temperature in the range of 1.5–1.6 K. A magnetic field could be applied perpendicular to the sample surface using a split-pair superconducting magnet.

Measurements are made of the magneto-optical Kerr effect (MOKE) in a confocal polar geometry (see Fig. 1). A high numerical aperture lens (NA=0.68) is mounted inside the cryostat to improve the focusing (spot diameter ≈ 10 μm). The laser source used in the experiment is a Ti:sapphire oscillator, which produced 9 nJ pulses of 100 fs at a repetition rate of 80 MHz. To reduce the number of pulses incident on the sample a "pulse picker" is employed; this is a commercially available electronic shutter that consists of a Pockels' cell placed between crossed polarizers. Due to the imperfect extinction of the pulse picker, a small

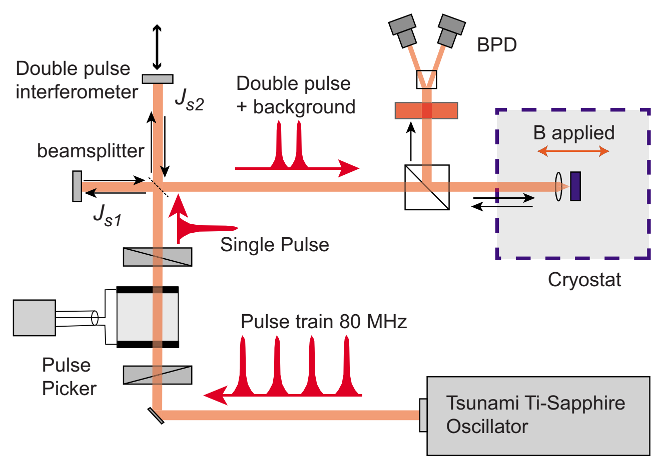

FIG. 1. (Color online) A scheme of the experimental setup.

a)Electronic mail: a.reid@science.ru.nl.

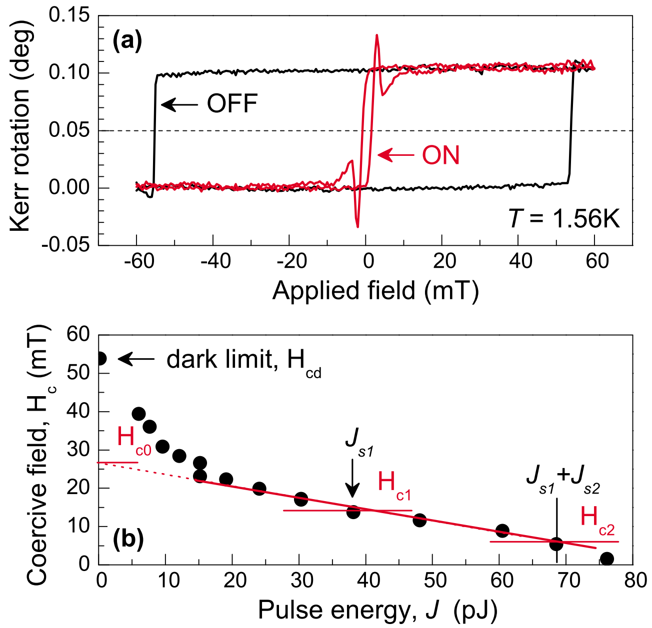

FIG. 2. (Color online) (a) MOKE measurements of magnetic hysteresis of the (Ga,Mn)As film measured with the pulse picker off and on (with $f=100$ Hz and $J=76$ pJ). (b) The measured coercive field as a function of pulse energy J. The vertical arrow indicates the pulse energy J_s used to measure dynamics of the PCE in Fig. 4.

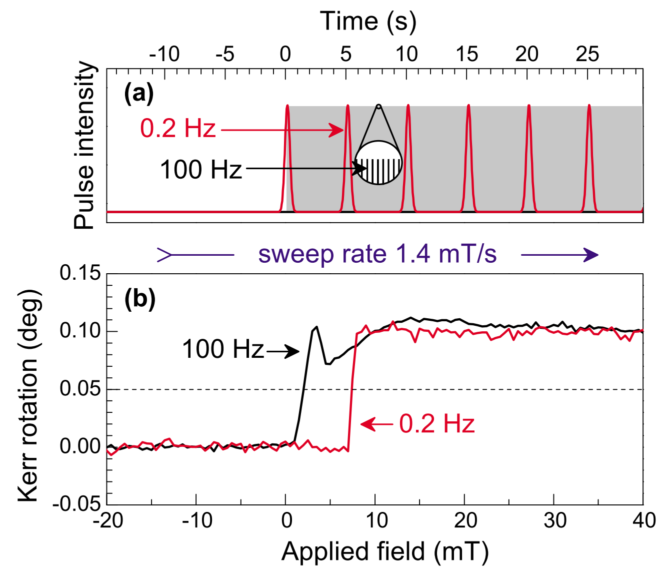

FIG. 3. (Color online) (a) Schematic representation of pulse trains with repetition rate of 100 and 0.2 Hz ($J=75$ pJ). (b) Magnetic switching observed for repetition rate of 100 and 0.2 Hz. The sweep rate of the magnetic field is 1.4 mT/s. At low repetition rates, switching is delayed until a pulse arrives.

amount of light (90 μW) is transmitted through in the "closed" position. This is employed as a quasicontinuous beam and used to measure the static MOKE signal from the sample. The Kerr rotation is detected using a balanced diode detector.

Measurements are made of static MOKE hysteresis cycles with and without incident pulses from the pulse picker. With the pulse picker switched off, a square hysteresis is recorded with a coercive field $H_{cd}=54$ mT. When 76-pJ-pulses are allowed to pass the pulse picker at 100 Hz, a large decrease in the coercive field is observed with the magnetization remaining almost unchanged [see Fig. 2(a)]. While the average power incident on the sample only increased by $<1\%$, the drop in the coercive field, almost to zero, far exceeds that observed with a continuous beam 50 times more intense. Further measurements show that the coercive field is entirely determined by the peak intensity of the incident pulse.

Figure 2(b) shows the coercive field H_c as a function of the pulse energy J. The dependence $H_c(J)$ is found to be nonlinear with a strongest decrease for $J<20$ pJ. Such a behavior is in agreement with previous static measurements.[4] For pulse energies between 20 pJ and 70 pJ, the reduction of H_c is proportional to J, $H_c(J)\approx H_{c0}+(H_{c2}-H_{c0})J/J_s$, with $H_{c0}=27$ mT and $H_{c2}=6$ mT and $J_s=70$ pJ.

The question remains, how many pulses are required to achieve a full reduction of the coercive field or a complete switching the magnetization? To explore this, the repetition rate of the pulse picker is reduced well below the sweep rate of the magnetic field (1.4 mT/s). Figure 3 shows a comparison of negative to positive field sweeps taken at pulse repetition rates of 100 and 0.2 Hz. At the 100 Hz pulse repetition rate, magnetic switching occurs at about 2.5 mT. However, at the slower pulse rate, this switching is delayed until 7.5 mT; a point that coincides with the arrival of a pulse. The magnetization is seen to fully reverse to the final state well before the arrival of the next pulse. This demonstrates unambiguously that not only is a single pulse sufficient to obtain the full reduction in the coercive field, but the duration of the reduction is also sufficiently long to obtain full switching of the magnetization.

Confirming that only a single pulse is necessary to excite the effect, we return to the question of why pulses are far more effective at generating the PCE than a continuous excitation of equal energy. This observation indicates that the coercivity reduces, following the laser pulse of energy J, to the value $H(J)$ and then recovers to the in-dark value H_{cd} on a timescale τ. The coercive field obtained in the "quasistatic" measurements of Fig. 2 is equal to the minimum value, i.e., H_{c2}. By a comparison of the energies required to generate the PCE with pulses to that required during continuous wave illumination, it is possible to estimate that τ must be in the region of nanoseconds. However, a more direct method is needed to confirm this hypothesis.

To this end, a second experiment has been devised. The idea is to use two almost equally intense pulses, time delayed with respect to each other, to trigger the PCE. If the two pulses, of energy J_{s1} and J_{s2}, are focused onto the same spot on the sample, with no relative delay, then the PCE generated simply corresponds to the sum of their energies $J_{s1}+J_{s2}$. However, if they are delayed with respect to each other [see Fig. 4(a)] then this need not be the case. The first pulse reaching the sample will generate a PCE associated with its intensity, but if the second pulse arrives after this effect has decayed, it cannot enhance the PCE further, only generate an equal effect. If, however, the delay between pulses t_d is less than the decay time of the PCE τ, some enhancement above the single-pulse value would be expected due to the second pulse [Fig. 4(b)]. In the linear regime [see Fig. 2(b)], and assuming an exponential decay of the PCE, the minimum value of the coercive field is

$$H_c(t_d)\approx H_{c1}+(H_{c2}-H_{c1})\exp(-t_d/\tau). \quad (1)$$

This should be equal to the coercive field obtained in quasistatic experiments of Fig. 2(a).

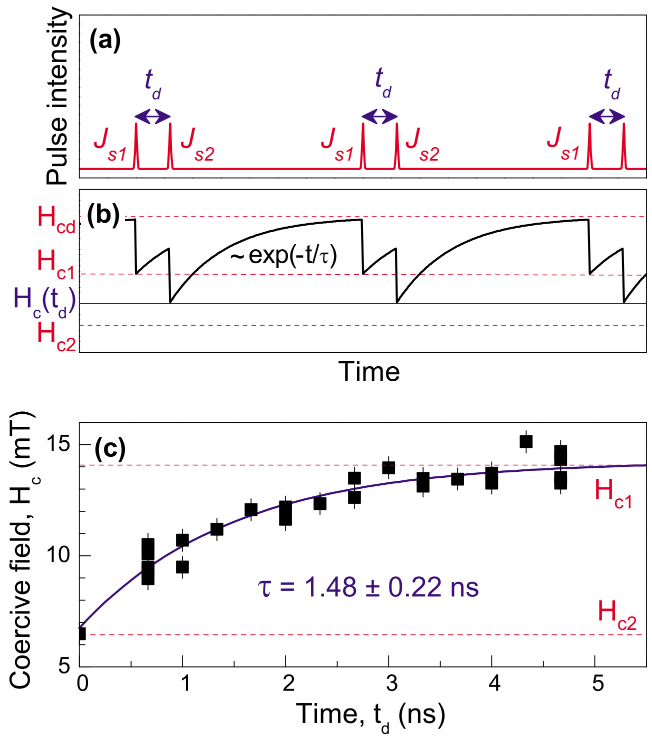

FIG. 4. (Color online) (a) Schematic representation of a double-pulse train (100 Hz) with t_d being the delay between two pulses. (b) Temporal behavior of the coercive field. $H_c(t_d)$ corresponds to the coercive field detected in the quasistatic MOKE experiment. (c) The coercive field H_c of the (Ga,Mn)As sample as a function of t_d. As the delay is increased, the coercive field is reduced toward the that observed with the individual pulses. Solid line is a fit to Eq. (1) with the time constant $\tau = 1.48 \pm 0.22$ ns.

The double-pulse experiments are performed using a beam splitter at the intersection of two interferometer arms to create pulses of nearly equal intensity with a relative time delay (Fig. 1). Again MOKE hysteresis loops are recorded. Figure 4(c) shows the measured coercive field H_c as a function of the delay between the pulses t_d for fixed pulse energies $J_{s1} = 38$ pJ and $J_{s2} = 31$ pJ. As expected, increasing the delay between the pulses causes an increase in the coercive field toward the level observed with a single pulse. The reduction of the PCE is well fitted to Eq. (1) with a time constant $\tau = 1.48 \pm 0.22$ ns. This time can therefore be taken as characteristic of the decay rate of the PCE.

Summarizing, in this letter, we have demonstrated that the photocoercivity effect in (Ga,Mn)As is a fast and efficient method for switching the magnetization direction. It has been observed that femtosecond pulses with an energy <100 pJ can reduce the coercive field in a micrometer sized area of the magnetic semiconductor from over 50 mT to less than 1 mT. Further experiments show that a single pulse is sufficient to fully reduce the coercive field, and that this reduction is sufficiently long to allow the magnetization to be switched. Using a double-pulse experiment, the photocoercivity effect can be shown to decay on a timescale of 1.5 ns.

The authors wish to thank A. Toonen and A. van Etteger for technical support. This work is supported by the European networks Ultramagnetron (Grant No. NMP3-SL-2008-214469) and FANTOMAS (Grant No. 214810); the Dutch national organizations for scientific research FOM and NWO. G.V.A. acknowledges support from the Deutsche Forschungsgemeinschaft (Grant No. AS 310/2-1).

[1]K. Matsumoto, A. Inomata, and S.-Y. Hasegawa, FUJITSU Sci. Tech. J. **42**, 158 (2006).
[2]C. D. Stanciu, F. Hansteen, A. V. Kimel, A. Kirilyuk, A. Tsukamoto, A. Itoh, and Th. Rasing, Phys. Rev. Lett. **99**, 047601 (2007).
[3]K. Vahaplar, A. M. Kalashnikova, A. V. Kimel, D. Hinzke, U. Nowak, R. Chantrell, A. Tsukamoto, A. Itoh, A. Kirilyuk, and Th. Rasing, Phys. Rev. Lett. **103**, 117201 (2009).
[4]G. V. Astakhov, H. Hoffmann, V. L. Korenev, T. Kiessling, J. Schwittek, G. M. Schott, C. Gould, W. Ossau, K. Brunner, and L. W. Molenkamp, Phys. Rev. Lett. **102**, 187401 (2009).
[5]V. L. Korenev, Semicond. Sci. Technol. **23**, 114012 (2008).
[6]G. V. Astakhov, A. V. Kimel, G. M. Schott, A. A. Tsvetkov, A. Kirilyuk, D. R. Yakovlev, G. Karczewski, W. Ossau, G. Schmidt, L. W. Molenkamp, and Th. Rasing, Appl. Phys. Lett. **86**, 152506 (2005).
[7]A. V. Kimel, A. Kirilyuk, A. Tsvetkov, R. V. Pisarev, and Th. Rasing, Nature (London) **429**, 850 (2004).
[8]K. C. Hall, J. P. Zahn, A. Gamouras, S. March, J. L. Robb, X. Liu, and J. K. Furdyna, Appl. Phys. Lett. **93**, 032504 (2008).
[9]L. Thevenard, L. Largeau, O. Mauguin, G. Patriarche, A. Lemaître, N. Vernier, and J. Ferré, Phys. Rev. B **73**, 195331 (2006).
[10]X. Liu, W. L. Lim, L. V. Titova, M. Dobrowolska, J. K. Furdyna, M. Kutrowski, and T. Wojtowicz, J. Appl. Phys. **98**, 063904 (2005).
[11]S. Koshihara, A. Oiwa, M. Hirasawa, S. Katsumoto, Y. Iye, C. Urano, H. Takagi, and H. Munekata, Phys. Rev. Lett. **78**, 4617 (1997).
[12]A. Oiwa, T. Słupinski, and H. Munekata, Appl. Phys. Lett. **78**, 518 (2001).
[13]M. Sawicki, F. Matsukura, A. Idziaszek, T. Dietl, G. M. Schott, C. Ruester, C. Gould, G. Karczewski, G. Schmidt, and L. W. Molenkamp, Phys. Rev. B **70**, 245325 (2004).
[14]R. Friedberg and D. I. Paul, Phys. Rev. Lett. **34**, 1234 (1975).
[15]M. Sawicki, D. Chiba, A. Korbecka, Y. Nishitani, J. A. Majewski, F. Matsukura, T. Dietl, and H. Ohno, Nat. Phys. **6**, 22 (2010).
[16]A. Hylick, R. Sohan, A. Rice, and B. Jones, Proceedings of MASCOTS, IEEE Computer Society, 2008, pp. 103–112.
[17]J. P. Liu, E. Fullerton, O. Gutfleisch, and D. J. Sellmyer, *Nanoscale Magnetic Materials and Applications* (Springer, New York, 2009).
[18]H. Ohno, Science **281**, 951 (1998).
[19]G. M. Schott, W. Faschinger, and L. W. Molenkamp, Appl. Phys. Lett. **79**, 1807 (2001).