Optical spin transfer torque driven domain wall motion in ferromagnetic semiconductor

A. J. Ramsay, 1 P. E. Roy, 1 J. A. Haigh, 1 R. M. Otxoa, 1 A. C. Irvine, 2 T. Janda, 3 4 R. P. Campion, 5 B. L. Gallagher, 5 and J. Wunderlich 1 4

1 Hitachi Cambridge Laboratory, Hitachi Europe Ltd., Cambridge CB3 0HE, UK
2 The Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK
3 Charles University in Prague, Faculty of Mathematics and Physics, Ke Karlovu 5, 121 16 Prague 2, Czech Republic
4 Institute of Physics ASCR, v.v.i., Cukrovarnická 10, 162 53 Praha 6, Czech Republic
5 School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK

(Dated: September 23, 2014)

We demonstrate optical manipulation of the position of a domain wall in a dilute magnetic semiconductor, GaMnAsP. Two main contributions are identified. Firstly, photocarrier spin exerts a spin transfer torque on the magnetization via the exchange interaction. The direction of the domain wall motion can be controlled using the helicity of the laser. Secondly, the domain wall is attracted to the hot-spot generated by the focused laser. Unlike magnetic field driven domain wall depinning, these mechanisms directly drive domain wall motion, providing an optical tweezer like ability to position and locally probe domain walls.

Recent work advocating the use of mobile magnetic domains for memory 1 and logic 2 applications has sparked renewed interest in the physics of domain wall motion. A key element in these research efforts is the controlled propagation of domain walls driven by electric currents 3 5. This occurs via spin transfer torque where, due to an exchange interaction with the magnetization, a non-collinear injected carrier spin can exert a torque on the magnetization. Recently, it has been demonstrated that a spin transfer torque can also be applied optically 6. In that experiment, the optical spin transfer torque was used to induce precession 7 10 of the magnetization in a thin-film of GaMn<0.09As with an in-plane easy axis.

Here we consider a similar material, Ga0.94Mn0.06As0.91P0.09, with an out-of-plane easy-axis. In this case, the optical spin transfer torque induced by a circularly polarized laser at normal incidence is not expected to act in the bulk. However at a domain boundary, the magnetization has an in-plane component, allowing a local torque that results in a domain wall motion with a polarization dependent direction. We demonstrate this helicity dependent optically induced domain wall motion by exposing a single domain wall to a train of above bandgap picosecond laser pulses, and identify the optical spin transfer torque as the dominant helicity dependent mechanism driving the domain wall motion. In addition, we observe a second helicity independent effect that attracts the domain wall to the center of the focused Gaussian laser spot due to local heating of the magnetic material. During laser exposure the domain wall moves towards a final position where the effects of the optical spin transfer torque and the thermal gradient are balanced and the domain wall motion is stationary. This interpretation is confirmed by numerical simulations based on the Landau-Lifshitz-Bloch equations. The optical control of domain wall motion provides a tool for applying local rather than global stimuli; and to provide ultrafast excitation of a domain wall.

The wafer consists of a 25-nm thick film of Ga0.94Mn0.06As0.91P0.09 on a GaAs substrate. The annealed sample has a Curie Temperature of 106 K. The addition of P results in an out-of-plane easy-axis via tensile growth strain 11. To study domains constrained to one spatial dimension, the wafer is fabricated into 4 × 60 μm bars oriented along the [110] and [110] crystallographic directions. Further details of the sample can be found in ref. 12.

The sample is mounted in a cold-finger cryostat at 92 K. A small out-of-plane magnetic field can be applied using an electro-magnet. The magnetic domains are imaged using a Kerr-microscope. A mode-locked Ti:sapphire laser provides a source of 140-fs optical pulses at an 80-MHz repetition rate. The sample is excited with an exposure time of > 4 ms using a mechanical shutter. After a 10-m single-mode fiber, dispersion stretches the pulses to approximately 4-ps. A polarizer and quarter-wave plate define the polarization following the fiber launcher. The laser is focused to a spot with a Gaussian intensity profile with a full width at half maximum of w = 5 μm.

To prepare a magnetic domain we use thermally assisted magnetization reversal by laser excitation. First the magnetization is saturated using a negative magnetic field, Bz = −15 G, large compared with the coercive-field, Bc = 4 G. The field is then slowly ramped to a slightly positive value, Bz = +0.9 G. The bar is illuminated for τn = 200 − 400 ms at a high power of 94 mW with the write-pulse. Figure 1(a-c) present typical differential Kerr images of the resulting domains. The domains are uniform and have the same contrast as domains formed by tuning the external magnetic field, indicating...
that a single domain is formed.

Optically assisted magnetization reversal has previously been reported in highly resistive GaMnAs using relatively low power HeNe laser excitation [13, 14] or a single 80-pJ 100-fs laser pulse [15]. There, the polarization independent magnetization reversal was attributed to a reduction in the coercive field due to the photo-carriers smoothing the pinning potential of the low (<1%) Mn-content material. We attribute the laser induced domain nucleation at small applied fields to thermally assisted magnetization reversal and note a helicity dependent threshold. The helicity dependence of magnetization reversal has not yet been reported in a magnetic-semiconductor, but has been studied intensively in ferromagnets such as GdFeCo [16].

In the first experiment, the [1Ì0]-bar is excited with a write-pulse to prepare a magnetic domain. The bar is allowed to cool, and the magnetic field is reduced to $B_{ext} \sim 0$ G. The sample is excited by a series of weaker pulses (34 mW, $\tau_p = 10$ ms), below the threshold for domain nucleation. To detect any changes in the domain wall position, a differential Kerr image is recorded for each exposure. The laser starts at a position outside the domain, then it is stepped to the left until the domain wall is located. The laser then excites the domain wall at randomized positions within 4 $\mu$m of the domain wall position. Figure 1(a), where $\sigma^+$-excitation is used, the final domain is larger than the initial domain, indicating that the laser moves the domain wall to the right. By contrast, in the case of fig. 1(c), where $\sigma^-$-excitation is used, the domain has been completely erased. This indicates that the laser mostly moves the domain wall to the left. In fig. 1(b), using linear polarization the domain is relatively unchanged.

To look in more detail, fig. 1(d) presents examples of domain shifts with respect to the laser position for linear polarization. On average, the final domain wall position is independent of the start position. If the laser spot does not overlap with the domain wall, no shift in the domain is observed. In fig. 1(e) the displacement of the domain wall is plotted against the initial position of the domain wall with respect to the laser spot. The result is a straight line of gradient -1, indicating that a domain at arbitrary initial position $x_i$ moves to an position where the domain wall is stationary. For linear polarization, the domain wall is attracted to the hot-spot of the laser. A similar observation has recently been reported for domain wall in CoPt [16]. For $\sigma^\pm$ circular polarization, the final position of the domain wall is shifted from $-0.9 \mu$m to $(+0.7, -2.7) \mu$m relative to the center of the laser spot, respectively. This demonstrates that the direction of laser induced domain wall motion depends on the helicity of the laser.

To get a better gauge of the relative strength of the helicity dependent and thermal terms of the domain wall motion, the laser is positioned at the domain wall and the final position is measured as a function of external magnetic field $B_{ext}$. The data is presented in fig. 2. For a $\sigma^\pm$-polarized laser the equilibrium position $x_0$ is shifted by $\pm 2 \mu$m with respect to the case of linear polarization. The gradient is relatively independent of polarization. For small external magnetic fields the final position of the domain wall can be described by $x_f = x_0 + aB_{ext}$,
where \( x_0 \) is the stationary position at \( B_{\text{ext}} = 0 \). We note that for larger external magnetic fields, \((\sim 1.5 \text{ G})\), the non-illuminated domain wall can also move as a result of optical excitation of the lower wall.

In the case of an optical spin transfer torque acting on the right-hand Néel (Bloch) domain wall \([12]\) with magnetization \( \downarrow \parallel \uparrow \), the unit magnetization-vector at the boundary is \( \hat{n}_{DW} = \hat{x}(\hat{y}) \). Above bandgap excitation with \( \sigma^\pm \) polarization creates photo-carriers with a spin-density \( s \propto \hat{n} = \pm \hat{z} \). Due to the exchange interaction, the carrier-spin experiences many sub-ps period precessions about the quasi-stationary magnetization vector (period \( \sim 10 \text{ ns} \)) during the \( 10^6 \) of ps spin-lifetime of the carriers. This results in a time-averaged carrier-spin density along \( s_0 \propto \hat{n} \times \hat{m}_{DW} = \pm \hat{y}(\mp \hat{x}) \). This kicks the magnetization-vector at the boundary in a direction \( \hat{m}_{DW} \propto \hat{m}_{DW} \times \hat{s}_0 = \pm \hat{z} \) moving the domain wall to the right/left, as observed. Hence, optical spin transfer torque can explain the helicity dependence of the direction of domain wall motion.

We now argue against the two other candidate mechanisms that could give rise to a helicity dependent shift of the domain wall position. Firstly, the circular dichroism of the material can lead to a difference in photo-carrier density and temperature across the domain wall. This would cause the domain wall to move towards the hot region, as observed for linearly polarized light. In the case of negative saturation magnetic field, the magnetization \( \downarrow / \uparrow \) either side of the right-hand domain wall is \( \downarrow \uparrow / \uparrow \downarrow \), where \( \uparrow / \downarrow \) indicates the direction of the total angular momentum of the lowest energy heavy-hole state, responsible for the magnetic circular dichroism \([20]\). In the case of \( \sigma^\pm \)-polarized excitation, a photo-hole of angular momentum \( \downarrow (\uparrow) \) is added, and the resulting thermal gradient is \( \text{hot/cold}(\text{cold/hot}) \) causing the domain wall to move left/right, respectively. This is the opposite to what is observed. Furthermore, the majority of the light, \( > 95\% \), is absorbed below the 25-nm film of GaMnAs. Therefore, the heating of the sample should be relatively independent of the dichroism. Hence, the circular dichroism is not the dominant mechanism. Secondly, the laser can generate an effective magnetic field along the optical axis due to the inverse Faraday effect. However, recent studies have shown that compared to the optical spin transfer torque, the inverse Faraday effect is weak in dilute magnetic semiconductors \([8]\). These conclusions were made on the basis of spectroscopic measurements showing that the peak in the Kerr rotation was not coincident with that in the measured torque.

To further test our understanding, we investigate the power, and wavelength dependence of the final domain wall position, \( x_0 \). The results are presented in fig. \[3\] Figure \(3(a) \) plots the power dependence of \( x_0 \). Assuming the domain wall moves until reaching a position where the power density \( P \text{e}^{-x^2/\sigma_0^2} \) is below the threshold \( P_{\text{th}} \) for domain wall motion, a manual fit to \( x_0 \approx \)
\( x_0^{(lin)}(\nu) \pm w_{eff} \sqrt{\ln\left(\frac{P}{P_{th}}\right)} \) is made. The threshold power is 
\( P_{th} = 12(17) \text{ mW} \) for \( \sigma^\pm \)-polarization respectively. This 
equates to an effective current density (photon flux \( \times e \)) of 
\( J_{\text{max}}^{th} \approx 0.25 \text{ GA.m}^{-2} \). We note that this is similar to 
the threshold current density measured for electrically 
driven domain wall motion in the same wafer \cite{12}. The 
effective width of the Gaussian temperature profile is less 
than the laser spot-size, \( w_{eff} \approx 1.9 \mu m < w \). This is 
attributed to a power-threshold that is lower at the hot-spot. 
Due to the power threshold, we conclude that the 
domain wall is moving in a flow regime \cite{12} driven by an 
optical spin transfer torque.

Figure 3(b) presents the wavelength dependence of \( x_0 \), 
which peaks at 785 nm. Domain wall motion is only 
observed for above band-gap excitation verifying that the 
domain wall is driven by photo-generated carriers. The 
generation of spin may become less effective at higher 
photons energies due to increased spin relaxation. 
In this wavelength regime, the circular dichroism increases 
monotonically with wavelength \cite{21}, further ruling out 
circular dichroism as the dominant source of the helicity 
dependent term.

![FIG. 4: (a) Schematic of magnetization at a Néel wall and 
direction of the optical spin transfer torque. (b) Initial position 
of domain wall and and laser spot intensity profile. (c) 
Subsequent domain wall motion following application of 80 MHz 
train of laser pulses. For linear polarization, the domain 
wall moves to the center of the laser spot. For circular 
polarization (\( \sigma^\pm \)) the additional spin transfer torque slows down 
(speeds up) the domain wall motion, shifting the final position 
by \( \pm 0.5 \mu m \). The average speed over the first \( 0.25 \mu s \) is 
about \( v_{lin} \approx 5 \text{ ms}^{-1} \) or \( 60 \text{ nm/pulse} \); and \( v_+ \approx 6 \text{ ms}^{-1} \), and 
\( v_- \approx 4 \text{ ms}^{-1} \).

To estimate the expected shifts in the domain wall 
following laser excitation, simulations using a 1-D 
micromagnetic Landau-Lifshitz-Bloch (LLB) model \cite{22}, 
including the demag field \cite{23}, were performed with pa-
rameters given in \cite{24}. In the case of linear polarization, 
a temperature increase proportional to the time-averaged 
intensity is assumed with an amplitude \( \Delta T = 13 \text{ K} \) 
\cite{3}, and a base temperature of 92 K. This modifies the 
magnitude of the equilibrium magnetization \( M_{eq}(T) \) \cite{25} 
scaling the exchange stiffness and magnetic anisotropy-
effects of the internal fields, resulting in a free-energy 
well for the domain wall. As shown in fig. \cite{4(b)}, for 
the [110]-bar, the Néel wall is initially at a position of 
\( +3.5 \mu m \) from the center of the laser spot. When the tem-
perature profile is switched on, the domain wall moves to 
the center of the hot-spot on a microsecond timescale, as 
shown in fig. \cite{4(c)}.

For circular polarization, the optical spin transfer 
torque is described by an additional effective field in 
the LLB equation, \( H_{\text{eff}}^{\text{OSTT}} = \frac{J_{\text{eff}}}{\mu_0 M_{eq}(T)} s \), due to the 
exchange field exerted by the carrier spin density \( s \) on the magnetization. An additional rate equation \cite{8} 
is used to describe the time-evolution of the spin: 
\( \dot{s} = (J_{eff}(T)/\mu_0 \hbar) \mathbf{m} \times \mathbf{s} + R(t) \mathbf{n} \times \mathbf{s}/\tau \), where \( R(t) \mathbf{n} \) 
describes the spin pumping rate due to laser excitation, 
and \( \tau \approx 30 \text{ ps} \) is the carrier spin-lifetime \cite{8}. The 
spin pump rate is treated as a \( \nu_{\text{rep}} \approx 80 \text{ MHz} \) train of square 
pulses of duration \( \tau_L = 4 \text{ ps} \), proportional to the in-
tensity profile of the laser, and an effective pump-rate 
\( \nu_{\text{rep}} \tau_L R_{\max} = 0.8 \text{GA.m}^{-2} \mu m \), which assumes an 
sorption length of \( \approx 1 \mu m \) in GaAs \cite{26}. The different 
polarization cases \( \sigma^\pm \) are controlled by direction of the 
carrier-spin \( \mathbf{n} = (0,0,\mp 1) \) respectively. In the simula-
tions shown in fig. \cite{4(a)}, the domain wall moves to an 
ostationary position \( x_0 \) shifted by \( \pm 0.6 \mu m \) with respect to 
the center of the laser spot, reproducing the observed helicity 
dependence of the sign of the shift. The effect of the 
OSTT on the domain wall is illustrated in fig. \cite{4(a)}.
Initially, the injected carrier-spin is aligned along the \( z \)-
axis. The precession around the exchange field due to 
the magnetization is fast compared to the carrier-lifetime 
\( 0.4 \text{ ps} \) vs \( 30 \text{ ps} \), and the time-averaged carrier spin 
aligns along the \( \hat{y} \times \mathbf{n} \times \mathbf{m} \) axis. For the example of a Néel 
wall, the carrier spin applies a torque on the magnetization, 
kicking the magnetization in the \( \pm \hat{z} \) direction. 
Following the kick, the magnetization precesses around 
the internal fields moving the domain wall. For the case of 
80-MHz repetition rate considered here, the domain wall 
is still moving when the next laser pulse strikes, leading to 
a steady-state motion where the magnetization pre-
cesses around an equilibrium state that is intermediate 
between a Néel and a Bloch wall. We note that similar 
domain wall motion is observed and calculated for the 
Bloch-wall of the [110] bar.

To summarize, we observe shifts in a magnetic domain 
wall position following above bandgap excitation with a 
train of picosecond laser pulses. Two main driving 
terms are identified and reproduced in micromagnetic simul-
tations. The first helicity dependent term results from spin-
polarized photo-carriers exerting a spin transfer torque
on the domain wall. The second helicity independent term attracts the domain wall to the laser hot-spot due to a free energy well resulting from a reduction in the local magnetic moment. Laser manipulation of domain wall position provides a tool for local rather than global control of domain wall motion. It provides an experimental route to investigate domain wall motion following ultrafast, rather than nanosecond, kicks to the spin transfer torque. By isolating laser induced magnetization reversal from domain wall propagation, these techniques should provide insights into magnetization reversal.

We acknowledge funding from European Metrology Research Programme within the Joint Research Project EXL04 (SpinCal), and Hitachi Europe Ltd.

* Electronic address: ar687@cam.ac.uk

[1] S. Parkin, M. Hayashi, and L. Thomas, Science 320 190 (2008).
[2] D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit, and R. P. Cowburn, Science 309 1688 (2005).
[3] D. C. Ralph, M. D. Stiles, and S. Bader, (eds) J. Magn. Magn. Mater. 320 1190 (2008).
[4] L. Berger, J. Appl. Phys. 55 1954 (1984).
[5] P. P. Freitas, and L. Berger, J. Appl. Phys. 57 1266 (1985).
[6] A. Yamaguchi, T. Ono, S. Nasu, K. Miyake, K. Mibu, and T. Shinjo, Phys. Rev. Lett. 92 077205 (2004).
[7] A. Mougin, M. Cormier, J. P. Adam, P. J. Metaxas, and J. Ferre, Europhys. Lett. 78 57007 (2007).
[8] P. Nemec, E. Rozkotová, N. Tesarova, F. Trojanek, E. De Ranieri, K. Olejnik, J. Zemen, V. Novak, M. Cukr, P. Maly and T. Jungwirth, Nature Physics, 8 411 (2012).
[9] N. Tesarova, P. Nemec, E. Rozkotova, J. Zemen, T. Janda, D. Butkovicova, F. Trojanek, K. Olejnik, V. Novak, P. Maly and T. Jungwirth, Nature Photon. 7 492 (2013).
[10] 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).
[11] A. W. Rushforth M .Wang, N. R. S. Farley, R. P. Campion, K. W. Edmonds, C. R. Staddon, C. T. Foxon, B. L. Gallagher, J. Appl. Phys., 104, 073908 (2008).
[12] E. de Ranieri, P. E. Roy, D. Fang, E. K. Vehstedt, A. C. Irvine, D. Heiss, A. Casiraghi, R. P. Campion, B. L. Gallagher, T. Jungwirth and J.Wunderlich, Nature Materials 12 808 (2013).
[13] 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).
[14] G. V. Astakhov, J. Schwittek, G. M. Schott, C. Gould, W. Ossau, K. Brunner, and L.W. Molenkamp, Phys. Rev. Lett. 106 037204 (2011).
[15] A. H. M. Reid, G. V. Astakhov, A. V. Kimel, G. M. Schott, W. Ossau, K. Brunner, A. Kirilyuk, L. W. Molenkamp, and Th. Rasing, Appl. Phys. Lett. 97 232503 (2012).
[16] C. D. Stanciu, A. Tsukamoto, A.V. Kimel, F. Hansteen, A. Kirilyuk, A. Itoh, and Th. Rasing, Phys. Rev. Lett. 99 217204 (2007).
[17] K. Vahaplar, A. M. Kalashnikova, A. V. Kimel, S. Gerlach, D. Hinzke, U. Nowak, R. Chantrell, A. Tsukamoto, A. Itoh, A. Kirilyuk, and Th. Rasing, Phys. Rev. B 85 104402 (2012).
[18] S. Mangin, M. Gottwald, C-H. Lambert, D. Steil, V. Uhir, L. Pang, M. Hehn, S. Alebrand, M. Cinchetti, G. Malinowski, Y. Fainman, M. Aeschlimann and E. E. Fullerton, Nature Materials 13 286 (2014).
[19] J.-P. Tetienne, T. Hingant, J.-V. kim, L. Herrera Diez, J.-P. Adam, K. Garcia, J.-F. Roch, S. Rohart, A. Thiville, D. Ravelosona, and V. Jaques, Science 344 1366 (2014).
[20] T. Dietl, H. Ohno, and F. Matsukura, Phys. Rev. B 63 195205 (2001).
[21] N. Tesarova, T. Ostatnicky, V. Novak, K. Olejnik, J. Subart, H. Reichlova, C. T. Ellis, A. Mukherjee, J. Lee, G. M. Sipahi, J. Sinova, J. Hamrle, T. Jungwirth, P. Nemec, J. Cerne, and K. Vyborny, Phys. Rev. B 80 085203 (2014).
[22] C. Schieback, D. Hinzke, M. Kläui, U. Nowak, and P. Nielaba, Phys. Rev. B 80 214403 (2009).
[23] A. J. Newell, W. Williams, and D. J. Dunlop, J. Geophys. Res. 98 B6 9551 (1993).

[24] Parameters used at zero temperature are $M_{eq}(0) = 35.57 \text{ kA.m}^{-1}$, $A = 0.3 \text{ pJ.m}^{-1}$, $K_x = 6000 \text{ J.m}^{-3}$, $K_z = 1150 \text{ J.m}^{-3}$, and intrinsic damping $\alpha = 0.01$. $J_{eff} = \frac{2}{3} J_{CMA}$. $J = 10 \text{ meV.nm}^3$, $C_{MA} = 1 \text{ nm}^{-3}$, as defined in ref. [12]. $A$, $K$, and $J_{eff}$ are scaled by $m^2(T)$, where $m_{eq}(T) = M_{eq}/M_{eq}(0)$. The cell-size is $4 \times 4000 \times 25 \text{ nm}^3$.

$m(T)$ is measured by SQUID, and estimated by a fit to a Langevin function.

[26] H. C. Casey, D. D. Sell, and K. W. Wecht, J. Appl. Phys. 46 250 (1975).