Experimental observation of the optical spin transfer torque

P. Némcé, E. Rozkotová, N. Tesařová, F. Trojánek, E. De Ranieri, K. Olejník, J. Zemen, V. Novák, M. Cukr, P. Malý and T. Jungwirth

The spin transfer torque is a phenomenon in which angular momentum of a spin polarized electrical current entering a ferromagnet is transferred to the magnetization. The effect has opened a new research field of electrically driven magnetization dynamics in magnetic nanostructures and plays an important role in the development of a new generation of memory devices and tunable oscillators. Optical excitations of magnetic systems by laser pulses have been a separate research field the aim of which is to explore magnetization dynamics at short timescales and enable ultrafast spintronic devices. We report the experimental observation of the optical spin transfer torque, predicted theoretically several years ago, building the bridge between these two fields of spintronics research. In a pump-and-probe optical experiment we measure coherent spin precession in a (Ga, Mn)As ferromagnetic semiconductor excited by circularly polarized laser pulses. During the pump pulse, the spin angular momentum of photo-carriers generated by the absorbed light is transferred to the collective magnetization of the ferromagnet. We analyse quantitatively the observed magnetization dynamics triggered by the optical spin transfer torque using independently determined micromagnetic parameters and magneto-optical coefficients of the studied (Ga, Mn)As.

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The coupled precession dynamics of the magnetization orientation $\mathbf{M}$ and the photo-carrier spin density $s$ is governed by the equations

$$\frac{d\mathbf{M}}{dt} = J \frac{\mathbf{M} \times s}{\hbar}$$

$$\frac{ds}{dt} = \frac{JS_{\text{Mn}}c_{\text{Mn}}}{\hbar} \mathbf{s} \times \mathbf{M} + \frac{P\mathbf{n}}{\tau} - s$$

where $J$ is the carrier–Mn moment exchange coupling constant ($\approx 50 \text{meV nm}^{-2}$ for holes and $\approx 10 \text{meV nm}^{-3}$ for electrons in (Ga, Mn)As), $S_{\text{Mn}} = 5/2$ is the Mn local moment, $c_{\text{Mn}} \approx 1 \text{nm}^{-3}$ is the typical Mn moment density, $\mathbf{M}$ is the unit vector of the magnetization orientation, $P$ is the rate per unit volume at which carrier spins with orientation $\mathbf{n}$ are optically injected into the ferromagnet, and $\tau$ is the photo-carrier spin lifetime.

In the geometry of our experiments, with normal incidence of light propagation, and these carrier spins interact with ferromagnetic moments on Mn via exchange coupling. When the ferromagnetic Mn moments are excited, this can be sensitively detected by probe laser pulses owing to the strong magneto-optical signals in (Ga, Mn)As.

The steady-state spin density given by equation (2) is oriented in the plane of the ferromagnetic film and perpendicular to the magnetization vector. The physical interpretation of this result is that the rate of the out-of-plane tilt of $s_{0}$ due to precession around the exchange field produced by the ferromagnetic Mn moments before they relax. In the corresponding regime of $\tau J S_{\text{Mn}} c_{\text{Mn}} / h \gg 1$, the steady-state spin density of photoelectrons obtained from equation (1), by neglecting the last term, is

$$s_{0} \approx \frac{hP}{J S_{\text{Mn}} c_{\text{Mn}}} (\mathbf{n} \times \mathbf{M})$$

The steady-state spin density given by equation (2) is oriented in the plane of the ferromagnetic film and perpendicular to the magnetization vector. The physical interpretation of this result is that the rate of the out-of-plane tilt of $s_{0}$ due to precession around the exchange field produced by the ferromagnetic moments is precisely compensated by the rate of photo-injection of out-of-plane oriented electron spins. From equation (1) we see that $s_{0}$ exerts a torque on the Mn magnetization vector, given by

$$\frac{dS_{\text{Mn}} c_{\text{Mn}} \mathbf{M}}{dt} \approx P\mathbf{M} \times (\mathbf{n} \times \mathbf{M})$$

1 Charles University in Prague, Faculty of Mathematics and Physics, Ke Karlovu 3, 121 16 Prague 2, Czech Republic, 2 Hitachi Cambridge Laboratory, Cambridge CB3 0HE, UK, 3 Institute of Physics ASCR, v.v.i., Cukrovarnická 10, 162 53 Praha 6, Czech Republic, 4 School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK. *e-mail: nemec@karlov.mff.cuni.cz.
The experimental observation of the magnetization precession in (Ga, Mn)As excited by the optical spin transfer, with the characteristic opposite phases of the oscillations excited by pump pulses of opposite helicities, is presented in Fig. 2a. In the experiment, the output of a femtosecond laser is divided into a strong (70 μJ cm⁻²), 300-fs-long pump pulse and a weak, delayed probe pulse, both of which are focused to the same spot on the measured sample. The photon energy of 1.64 eV is tuned above the semiconductor bandgap to excite magnetization dynamics by photon absorption. To observe the optical spin transfer torque we use a circularly polarized pump laser beam. The pump-induced change of the magneto-optical response of the sample is measured by a temporally delayed linearly polarized probe pulse. The magneto-optical signals shown in Fig. 2 represent the rotation of the polarization plane of the reflected probe pulse as a function of the time delay between pump and probe pulses. Lines are the theoretically calculated time-dependent magneto-optical signals. For the σ⁺ polarization of the pump pulse, the torque points in the opposite direction. The experiment was performed on the (Ga, Mn)As sample attached to a piezo-stressor at an applied bias $U = -150$ V. The probe input polarization orientation is $25°$, the temperature of the sample 35 K, the excitation laser intensity 70 μJ cm⁻², and the photon energy 1.64 eV.
polarization dependence; PKE does not depend on the probe input polarization angle whereas MLD is a harmonic function of the input polarization angle. See Supplementary Information for details on sample preparation, experimental techniques, and extensive data on a series of (Ga, Mn)As samples with a Mn doping range of 1–14%. As the period of the oscillations (0.4 ns) seen in Fig. 2a is much larger than the pump pulse duration, the action of the optical spin transfer torque is reflected only in the initial phase and amplitude of the free precession of the magnetization. The free dynamics of the magnetization is governed by the Landau–Lifshitz–Gilbert torque \( \gamma (M \times H_{\text{eff}}) \), with \( H_{\text{eff}} \) a combination of the internal magnetic anisotropy fields and external magnetic field, and by the damping term \( \gamma a M / |M| \times (M \times H_{\text{eff}}) \). Here \( \gamma \) is the gyromagnetic ratio and \( a \) is the Gilbert damping constant. The micromagnetic parameters were determined from independent magnetization measurements using both a superconducting quantum interference device and magneto-optical ferromagnetic resonance (see Supplementary Information). As the PKE and MLD coefficients were also determined for our (Ga, Mn)As materials from independent static magneto-optical measurements (see Supplementary Information), we can transform the calculated time-dependent magnetization into magneto-optical signals and directly compare them with the measured data, as shown in Fig. 2a.

In Fig. 2b we show the calculated time evolution of the polarization of the linearly polarized pump pulse with any orientation of the polarization does not excite the magnetization precession, as illustrated in Fig. 3b. The polarization-independent data obtained by summing the signals for the two opposite helicities are almost identical to the data corresponding to a linearly polarized pump pulse. They show a non-oscillatory signal that decays on a timescale at which the photon absorption is negligible. On the other hand, an excitation energy much smaller than the pump pulse duration, the action of the optical spin transfer torque is reflected only in the initial phase and amplitude of the free precession of the magnetization. The free dynamics of the magnetization is governed by the Landau–Lifshitz–Gilbert torque \( \gamma (M \times H_{\text{eff}}) \), with \( H_{\text{eff}} \) a combination of the internal magnetic anisotropy fields and external magnetic field, and by the damping term \( \gamma a M / |M| \times (M \times H_{\text{eff}}) \). Here \( \gamma \) is the gyromagnetic ratio and \( a \) is the Gilbert damping constant. The micromagnetic parameters were determined from independent magnetization measurements using both a superconducting quantum interference device and magneto-optical ferromagnetic resonance (see Supplementary Information). As the PKE and MLD coefficients were also determined for our (Ga, Mn)As materials from independent static magneto-optical measurements (see Supplementary Information), we can transform the calculated time-dependent magnetization into magneto-optical signals and directly compare them with the measured data, as shown in Fig. 2a.

In Fig. 3a we demonstrate that the previously reported inverse magneto-optical effect in (Ga, Mn)As is not contributing to our experiments in (Ga, Mn)As. The inverse magneto-optical effect does not require photon absorption, and the corresponding theory was derived and its effects observed in transparent magnetic dielectrics17. To test whether the inverse magneto-optical effect contributes in our (Ga, Mn)As samples, we tuned the energy of the pump laser beam below the semiconductor bandgap, to 1.44 eV. Here the optical spin transfer torque is not effective because of the negligible absorption. On the other hand, an excitation energy below the bandgap is favourable for the inverse magneto-optical effect. The direct PKE at 1.44 eV is comparable to, or even larger than, that at 1.64 eV, as shown in Fig. 3a. Therefore, as active excitation is above the bandgap at 1.64 eV, the inverse magneto-optical effect should be clearly detectable at 1.44 eV. No magnetization dynamics is, however, excited using an energy at 1.44 eV, from which we conclude that the inverse magneto-optical effect is not contributing in our experiments.

Pump pulses with opposite helicities trigger magneto-optical signals with opposite phases, as shown in Fig. 2a, suggesting that the optical spin transfer torque is also not accompanied by any polarization-independent excitation mechanism. Indeed, a linearly polarized pump pulse with any orientation of the polarization does not excite the magnetization precession, as illustrated in Fig. 3b. The polarization-independent data obtained by summing the signals for the two opposite helicities are almost identical to the data corresponding to a linearly polarized pump pulse. They show a non-oscillatory signal that decays on a timescale at which the photo-carrier-induced change of the sample reflectivity decays. The signal is therefore of optical rather than magnetic origin (for more details see Supplementary Information).

Polarization-independent excitations of magnetization precession in (Ga, Mn)As have been reported previously by several groups, including ourselves3–12. The experiments were interpreted in terms of changes of the magnetocrystalline anisotropy induced by the laser pulse3–12. Two mechanisms have been proposed as contributing to the transient tilt of the magnetization easy axis due to photon absorption: an increase in the temperature6,7 and an increase in the hole-density3,11,12. The samples we study in this work can also be excited by a mechanism related to magnetic anisotropy. In the measurements shown in Figs 2–4 we have intentionally suppressed this mechanism to highlight our observation of the optical spin transfer torque. We have done this by attaching a lead zirconate titanate (PZT) piezostressor to the 3.8% Mn-doped (Ga, Mn)As sample, which modifies the magnetic anisotropy of the ferromagnetic film owing to the differential thermal contraction and allows for an additional in situ electrical control of the in-plane magnetocrystalline anisotropy. (More detailed descriptions of the preparation

![Figure 3](https://example.com/fig3.png)

**Figure 3** | Absence of inverse magneto-optical effect and polarization-independent excitations. 

**a.** Energy dependence of the PKE magneto-optical coefficient. The vertical arrows indicate the photon energies \( h\nu_1 = 1.64 \text{ eV} \) (above the semiconductor bandgap) and \( h\nu_2 = 1.44 \text{ eV} \) (below the semiconductor bandgap) of the circularly polarized pump pulse that were used in the pump-and-probe measurements shown in the inset. Except for the variation of the photon energy of the pump pulse, the experimental conditions of the measurements shown in the inset are the same as in Fig. 2a.

**b.** Helicity-independent part \((\sigma^+ \sigma^-)/2\) of the signal measured at the pump pulse photon energy 1.64 eV and the pump-and-probe measurement with a linearly polarized pump pulse of energy 1.64 eV; all other experimental conditions are the same as in Fig. 2a.
The strain induced by the differential thermal contraction is $\sim 10^{-3}$. This strain significantly reduces the out-of-plane magnetic anisotropy of the (Ga, Mn)As, which leads to an approximate factor of three enhancement over the bare sample in the helicity-dependent signal induced by the out-of-plane optical spin transfer torque (see Supplementary Information). The additional piezovoltage strain, proportional to the applied bias, reaches $\sim 1 \times 10^{-4}$ for $|U| = 150$ V. These strains have a negligible effect on the out-of-plane anisotropy field and should not, therefore, affect the helicity-dependent signal induced by the out-of-plane optical spin transfer torque. In Fig. 4a we show, by comparing the measurements at large positive and negative piezovoltages, that the helicity-dependent excitation is indeed not sensitive to the piezovoltage. Also consistent with the optical spin transfer torque phenomenology, the figure shows that the amplitude of the magnetization oscillations scales with the intensity of the circularly polarized laser pulse.

Unlike the out-of-plane anisotropy, biasing the piezostressor can significantly affect the more subtle balance of the weaker in-plane anisotropy fields. We aligned the axis of the stressor at an angle $115^\circ$ from the [100] crystal direction. This is close to the easy axis of the bare sample, where the orientation is a result of the competition of the biaxial and uniaxial in-plane anisotropies in (Ga, Mn)As (see Supplementary Information). Application of a large negative piezovoltage of $-150$ V, with the measurements shown in Figs 2, 3 and 4a, deepens the minimum in the in-plane magnetic anisotropy energy such that the applied laser intensities do not produce a measurable in-plane tilt of the easy axis and, therefore, a measurable magnetization precession. As shown in Fig. 4b and c, the application of a positive piezovoltage allows us to observe the polarization-independent excitation in the same sample. Consistently, the ratio of the helicity-dependent and polarization-independent signals is proportional to the applied piezovoltage, as shown in the Supplementary Information. The helicity-dependent signal is observed throughout the series of (Ga, Mn)As materials with different Mn dopings, as we also show in the Supplementary Information. Without the attached PZT stressor, that is, with the stronger out-of-plane magnetic anisotropy field in the bare samples, the helicity-dependent signal is typically 5–20× weaker than the polarization-independent signal and was omitted in previous studies of optically excited magnetization precession in (Ga, Mn)As.

The measured oscillation frequencies and Gilbert damping constants for the polarization-independent and helicity-dependent excitations are identical. Independent of whether the excitation is due to the in-plane shift of the magnetic easy axis or due to the out-of-plane optical spin transfer torque, the precessing moments are the same in both cases. From studies of the dependence of the precession frequency on internal anisotropy and external magnetic fields, it is established that these are the precessing ferromagnetic Mn moments (see Supplementary Information and refs 3, 5–11). We conclude by pointing out that bringing the spin transfer physics into optics introduces a fundamentally distinct mechanism from the previously reported thermal and non-thermal laser excitations.

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**Author contributions**

Sample preparation: V.N., M.C., E.R. and E.D.R.; experiments and data analysis: E.R., N.T., P.N., P.M., K.O and T.J.; data modelling: P.N. and F.T.; theory: J.Z. and T.J.; writing: T.J. and P.N.; project planning: P.N. and T.J.

**Additional information**

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