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All-Optical Switching of Magnetic Tunnel Junctions with Single Subpicosecond Laser Pulses

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The magnetic tunnel junction (MTJ) is one of the most important building blocks of spintronic logic and memory components for beyond-CMOS computation and communication. Although switching of MTJs without magnetic field has been achieved by charge and spin current injection, the operation speed is limited fundamentally by the spin-precession time to many picoseconds. We report the demonstration of ultrafast all-optical switching of an MTJ using single subpicosecond infrared laser pulses. This optically switchable MTJ uses ferrimagnetic Gd(Fe,Co) as the free layer and its switching is read out by measuring its tunneling magnetoresistance with a $\Delta R/R$ ratio of 0.6%. A switching repetition rate at MHz has been demonstrated, but the fundamental upper limit should be higher than tens of GHz rate. This result represents an important step toward integrated optospintronic devices that combines spintronics and photonics technologies to enable ultrafast conversion between fundamental information carriers of electron spins and photons.

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The control of magnetism without using magnetic fields enables the integration of spintronic devices in a large scale for memory, computation, and communication in the beyond-CMOS era [1–7]. Mechanisms including spin torque transfer [8], spin Hall effect [9], and electric field or strain-assisted switching [10,11] have been implemented to switch magnetization in various spintronic devices. However, their operation speed is fundamentally limited by the spin-precession time to longer than 10–100 ps [12–14]. Such a time constraint severely limits the possible operating speed of spintronic devices, and therefore, overcoming it is critical for the prospective development of spintronics.

Ultrafast optical manipulation of the magnetism in magnetic materials is both fundamentally intriguing and practically important as it can achieve magnetization reversal without the application of a magnetic field and faster than the spin-precession time, which sets the operation speed limit of most spintronic devices [15,16]. More recently, all-optical switching (AOS) with subpicosecond laser pulses has been achieved in a plethora of material systems ranging from ferrimagnetic alloys of rare-earth elements and transition metals (RE-TM) such as Gd(Fe, Co), TbCo, and TbFe [17–21], to synthetic ferrimagnetic multilayers of RE-TM [22] and ferromagnetic multilayers of Co/Pt and Co/Ni [23]. Among those, the Gd(Fe,Co) system stands out as its magnetization reversal can be achieved with single laser pulses as short as a few tens of femtoseconds [24,25]. In contrast, switching of other materials is through the cumulative heating effect of multiple laser pulses and therefore much slower [21]. Briefly, optical switching of Gd(Fe,Co) is achieved by ultrafast heating of the material by laser pulses to a highly nonequilibrium state. Because the Gd sublattice demagnetizes slower than the Fe, Co sublattices, the antiferromagnetically coupled system forms a transient ferromagnetic state within the subpicosecond and relaxes spontaneously to the reversed magnetization state after cooling down [25].

AOS has been extensively explored for its prospects of enabling ultrafast magnetic recording and operation of spintronic devices. Nevertheless, there has not been any demonstration of AOS in realistic spintronic devices, such as magnetic tunnel junctions (MTJs) [26–28]. Since previous studies of AOS have been performed only on a single magnetic layer, how additional magnetic layers affect the AOS phenomenon remains unknown. In this Letter, we develop a perpendicularly magnetized MTJ employing Gd(Fe,Co) as the free layer. We demonstrate all-optical switching of an MTJ, without using any external magnetic field, but rather with single subpicosecond infrared laser pulses. The switching is read out electrically through measuring the tunneling magnetoresistance (TMR). We further demonstrate the MHz repetition rate of switching Gd(Fe,Co) film, which is limited by our instruments, but the fundamental upper limit of this rate should be higher than tens of GHz, as it has been revealed by previous time-resolved studies [25]. The demonstrated picosecond switching time of an MTJ by AOS is 2 orders of magnitude faster than that of any other switching methods.

The Gd(Fe,Co) layer used in this study is sputtered on thermally-oxide-silicon wafers at room temperature in a magnetosputter system with a base pressure $<5\times10^{-8}$ Torr. The composition of Gd(Fe,Co) films is controlled by

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varying the sputter power of Gd and $Fe_{90}Co_{10}$ targets. As shown in Fig. 1(a), the samples have a stack structure of Ta(4 nm)/$Gd_x(Fe_{90}Co_{10})_{100-x}$(20 nm)/Ta(4 nm). The samples with Gd composition (x) in the range from 21% to 27% show good perpendicular magnetic anisotropy. A telecom-band infrared fiber laser, which outputs pulses with a wavelength centered at 1.55 μm and a pulse width of 400 fs, is used to demonstrate AOS. The laser spot diameter of 20 μm with an optical fluence of 5.8 mJ/cm^2 is used consistently throughout this work. Figure 1(b) shows a representative magneto-optical Kerr-effect (MOKE) image of a $Gd_{26}(Fe_{90}Co_{10})_{74}$ sample after scanning the laser spot across its surface. With a low repetition rate and high scanning speed, there is no overlap between adjacent pulses. It can be seen that individual bubble domains in size similar to the laser spot have been created through AOS in domains with both up and down magnetizations. AOS in our materials is independent of the laser polarization, and the laser pulses always reverse the magnetization, which is consistent with other reports on helicity-independent AOS of Gd(Fe,Co) [19]. Therefore, the linear polarization is used in all of our experiments.

We have systematically characterized Gd(Fe,Co) samples with various compositions, which are determined by Rutherford backscattering spectrometry. The coercivity (H_c) and saturated magnetization (M_s) of the samples are measured at room temperature with a vibrating sample magnetometer and are summarized in Fig. 1(c). We find the magnetization compensation temperature (T_M) is at room temperature (300 K) when the Gd compensation is around 24%. When Gd is close to the compensation point, the intrinsic exchange bias behaviors are observed in our Gd(Fe,Co) films [29]. Such behaviors are also observed in other amorphous RE-TM alloys, such as (Tb,Fe)Co [30] and DyCo [31]. AOS is observed in samples with Gd composition in the range from 22% to 26% [the purple shaded region in Fig. 1(c)], consistent with previous reports by several other groups [17,19,22,32].

We then demonstrate the magnetoelectric response of the Gd(Fe,Co) films to AOS by measuring the anomalous Hall effect (AHE). This method was previously developed by our group and others [33,34]. We patterned the film into pillars and deposited transparent electrodes made of 110-nm-thick indium tin oxide (ITO) to measure the Hall resistance. Figure 2(a) shows an optical image of a typical device with a pillar diameter of 15 μm. Using an external perpendicular magnetic field, the hysteresis loop of the anomalous Hall resistance (R_{AHE}) is measured [Fig. 2(b)]. The asymmetric R_{AHE} for the up and down magnetized states is attributed to the slight asymmetry in the electrodes' position. The observed rectangular hysteresis loop shows this device has nearly 100% remanence. We next use this Hall device to demonstrate direct electrical readout of AOS. The pillar is exposed to a train of single laser pulses with a repetition rate of 0.5 Hz [29], and the Hall resistance is measured in real

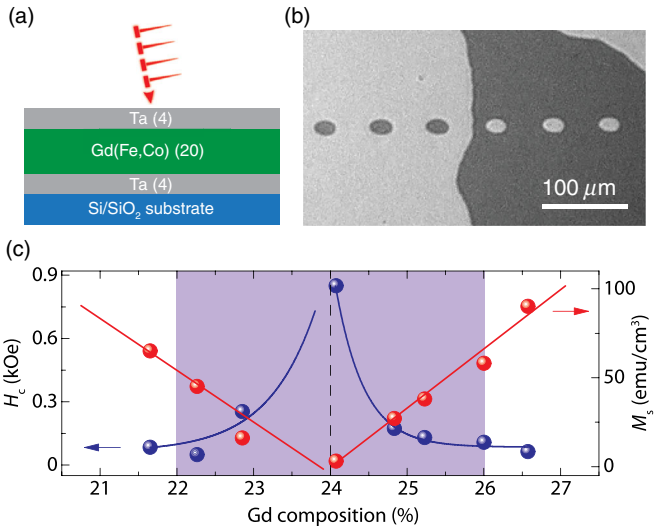

FIG. 1. All-optical switching of Gd(Fe,Co) films. (a) Schematic of Gd(Fe,Co) film structures. Tantalum layers are used as a buffer and capping to prevent film oxidation. (b) The MOKE image of single bubble domains created via AOS by scanning single subpicosecond laser pulses across the boundary between two large magnetic domains in the sample. (c) The coercivity H_c (blue symbols) and saturated magnetization M_s (red symbols) of Gd(Fe,Co) samples versus their Gd composition (x_{Gd}). Samples with Gd composition in the purple-shadowed region (22%–26%) show AOS behavior. The solid lines are used to guide the eyes.

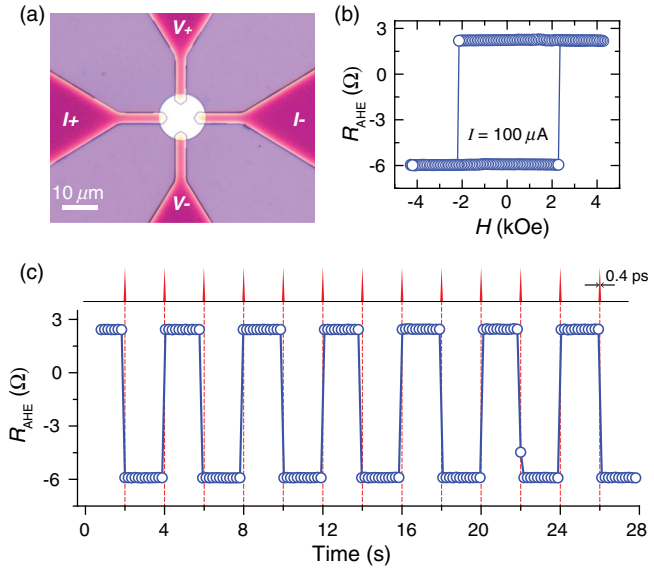

FIG. 2. Direct magnetoelectric readout of AOS in Gd(Fe,Co) film by the anomalous Hall effect (AHE). (a) Optical microscope image of a typical Hall device with pillar diameter of 15 μm and transparent ITO/Cu electrodes; (b) R_{AHE} hysteresis loop of the device measured by sweeping a perpendicular magnetic field and constant dc bias current of 100 μA; (c) R_{AHE} of the device measured during AOS by 0.4-ps single laser pulses with 0.5-Hz repetition rate. The consistent change of R_{AHE} in (b) and (c) confirms that the Gd(Fe,Co) pillar is completely switched by the laser pulses.

time. The result presented in Fig. 2(c) shows that the Hall resistance is reversed by every laser pulse. Comparing Figs. 2(b) and 2(c), it can be seen the values of R_{AHE} reversed by AOS in Fig. 2(c) are the same as in Fig. 2(b). This result indicates that every single laser pulse completely reverses the magnetization of the Gd(Fe,Co) pillar.

The above results confirm that robust AOS and magnetoelectric readout can be achieved in the Gd(Fe,Co) films. Using Gd(Fe,Co) as the free layer in an MTJ can enable the MTJ device to be switched by light only. All revealed that as soon, we design and fabricate a MTJ stack in the configuration of Ta(5 nm)/Pd(10 nm)/$[$Co(0.6 nm)/Pd(1.5 nm)$]_{\times 4}$/Co(0.8 nm)/MgO(1.8 nm)/Gd(Fe, Co)(20 nm)/Ta(4 nm), as illustrated in Fig. 3(a). The MgO layer is the tunneling barrier. The Ta and Pd layers are used as the buffer and the bottom electrodes. The Co/Pd multilayers are the fixed layer, which is optimized to obtain good perpendicular magnetic anisotropy. Notably, ITO is used as a transparent top electrode to allow optical access. Figure 3(b) shows an optical image of a representative MTJ device with a pillar diameter of 12 μm.

We then measure the tunneling magnetoresistance (R_{TMR}) of the MTJ by sweeping a perpendicular magnetic field in the range of ± 2 kOe. A clear TMR minor loop showing the low and high resistance states of the MTJ is measured, as shown in Fig. 3(e). Because the bottom Co/Pd multilayers have a lower coercivity H_c than the Gd(Fe,Co) layer, they are switched by the magnetic field while the magnetization of the Gd(Fe,Co) layer remains fixed. The MTJ in the low and high resistance state has a resistance of 98.0 and 98.6 Ω, respectively. Therefore, the TMR ratio $\Delta R_{TMR}/R_{TMR}$ is ~0.6%. The bias-voltage (V) dependent-current (I) measurement shows clear nonlinear behavior [29], which could be well fitted using Simmons' model with electric tunnel effect [35,36]. We attribute the low TMR ratio to the low quality of the MgO layer because no postdeposition annealing is performed, and to the oxidation at the MgO/Gd(Fe,Co) interface [37,38]. The relatively high noise in the TMR measurement is attributed to the poor interface between the ITO and the Ta/Gd(Fe,Co) layers [29]. Nevertheless, the device provides a sufficient TMR signal-to-noise ratio to discern optical switching of the MTJ. The AOS measurement on the MTJ is performed in a similar way to the Hall device by setting the laser repetition rate at 0.5 Hz and monitoring the TMR value with an averaging time constant of 100 ms to obtain the result shown in Fig. 3(f). It clearly shows that each laser pulse switches the MTJ between high and low resistance states. In contrast to switching using a magnetic field, the laser pulses switch the magnetization of the Gd(Fe,Co) layer that is on the top of the MTJ while the magnetization of the Co/Pd multilayers at the bottom remains fixed, as is evident in the MOKE images in Figs. 3(c) and 3(d). The change of the TMR by AOS is 0.6 ± 0.05 Ω, the same as the value in the magnetic field measurement [Fig. 3(e)]. We note that, in Figs. 3(e) and 3(f), the difference in the absolute resistance values is due to the changed probe-to-device contact resistance in two different measurement setups. The

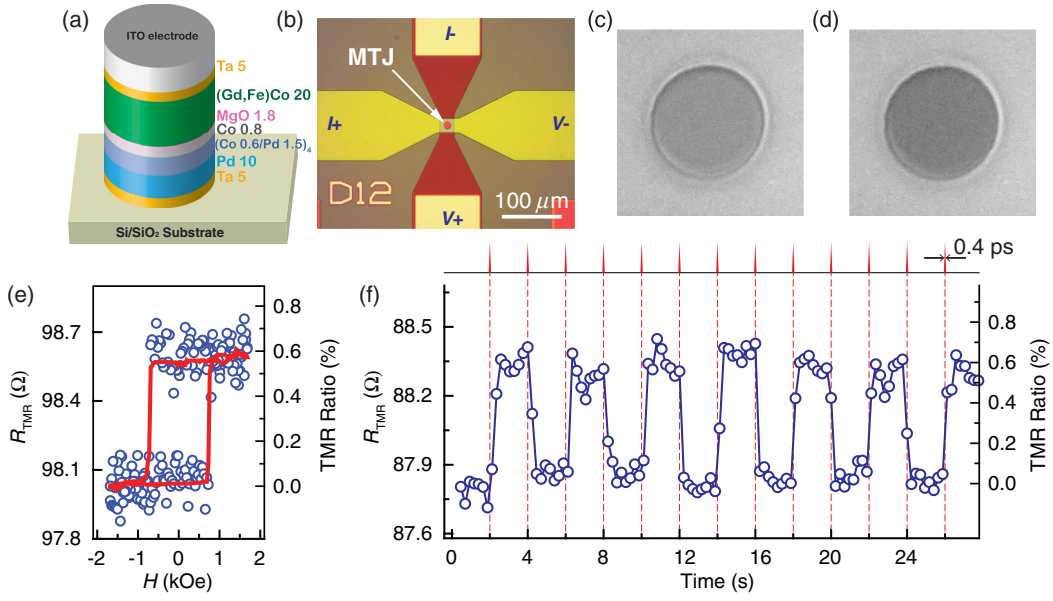

FIG. 3. AOS of an MTJ with subpicosecond single laser pulses without external magnetic field. (a) Schematic of the MTJ structure used in the experiment. (b) Optical microscope image of a typical MTJ device with ITO electrode on the top for TMR measurement. (c), (d) The MOKE images of the MTJ pillar before and after AOS by a single laser pulse, showing the Gd(Fe,Co) layer is completely switched. The pillar diameter is 12 μm. (e) The $R_{TMR}(H)$ minor loop measured by sweeping a perpendicular magnetic field, which switches the Co/Pd layers. The red line is the smoothing of the raw data (open circles). (f) R_{TMR} of the MTJ device measured during AOS by 0.4-ps single laser pulses at 0.5-Hz repetition rate. The changes of R_{TMR} in (e) and (f) have the same value of $\sim 0.6 \pm 0.05$ Ω, indicating the Gd(Fe,Co) layer has been completely switched.

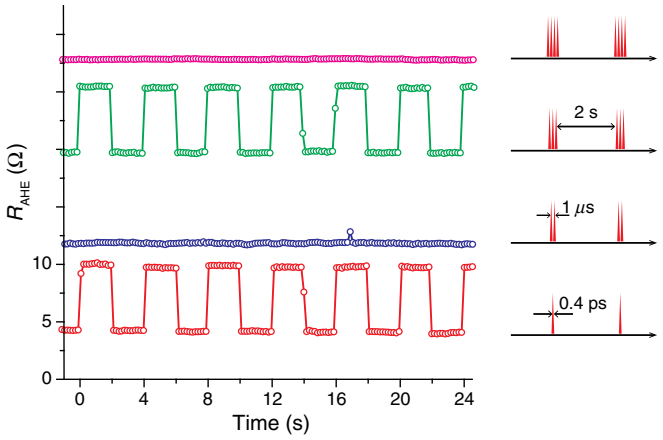

FIG. 4. Repetitive AOS of the Gd(Fe,Co) Hall device. The Gd(Fe,Co) Hall device is exposed to trains of single (red), dual (blue), three (green), and four (magenta) consecutive pulses with 1-μs pulse-to-pulse time spacing and the AHE resistance (R_{AHE}) is measured. The device is switched repetitively by the pulses: the second pulse resets the switching by the first pulse and the fourth pulse resets the switching by the third pulse. Therefore, no R_{AHE} change is measured for trains of double and quadruple pulses. The result demonstrates 1-MHz AOS repetition rate.

consistent change of the TMR value unambiguously confirms that the Gd(Fe,Co) layer in the MTJ has been completely switched via AOS. The TMR ratio in this device can be increased by exchange coupling the Gd(Fe,Co) layer with a ferromagnetic layer, such as CoFe and CoFeB [39,40], and by annealing to improve the quality of MgO layer. Our result represents a demonstration of all-optical switching of a realistic spintronic device by using ultrafast laser pulses. The demonstrated picosecond time scale of the switching is at least 2 orders of magnitude faster than other switching mechanisms [12–14].

We next demonstrate the repeatability of AOS using a Gd(Fe,Co) Hall device similar to the one in Fig. 2. The device is exposed to trains of multiple pulses with the time spacing of 1 μs, generated using a pulse picker. Our laser's base repetition rate is 1 MHz, so shorter time spacing is not possible. Figure 4 shows that, when the device is exposed to two consecutive pulses, the second pulse, 1 μs after the first pulse, switches the device again and thus resets the device to its original state. As a result, no change of R_{AHE} is observed because a measurement time constant of 20 ms is used. Similarly, when the device is exposed to three and four consecutive pulses, the third pulse switches the device again, so the change of R_{AHE} resumes, and the fourth pulse resets the device. This result demonstrates a 1-MHz AOS repetition rate of a Gd(Fe,Co) Hall device [29]. However, the fundamental switching rate of Gd(Fe,Co) should be much higher. X-ray magnetic circular dichroism and time-resolved MOKE studies of the Gd(Fe,Co) system all reveal that as soon as a few picoseconds after the laser pulse, the magnetization of both Fe and Gd sublattices have been reversed [25]. Although the system takes more than tens of picoseconds to relax to equilibrium [41], it is possible that the subsequent switching can be performed sooner than the system reaches equilibrium. Therefore, the ultimate switching rate of AOS devices could be higher than tens of GHz, which can be investigated with time-resolved measurement in future work.

In conclusion, we have integrated an optically switchable Gd(Fe,Co) film into an MTJ device and have demonstrated ultrafast all-optical switching of this spintronic device using subpicosecond laser pulses. The picosecond time scale of optical switching is 2 orders of magnitude faster than other switching methods. The use of telecom-band infrared laser sources also makes such devices compatible for integration with silicon photonics and fiber optics. Future work to improve the TMR ratio of the optically switchable MTJ and reduce the required optical fluence for switching is necessary to enable large-scale integration and practical applications. The energy per pulse required for AOS scales inversely with the device area and the efficiency of AOS also improves with the reduced device area [42]. Therefore, for an AOS device with subwavelength dimensions [43,44], femtojoule pulse energy should be sufficient to switch it. The present results pave a path toward a new category of optospintronic devices, which can directly convert ultrafast optical signals into the nonvolatile magnetic states of spintronic structures and thus may find novel applications combining photonic and magnetic technologies.

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J.-Y. C. and L. H. have contributed equally to this work.

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