Ultrafast magnetization reversal by picosecond electrical pulses

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Spintronic devices that work on the principle of manipulation of a magnetic bit by spin currents, through spin transfer torque (STT) or spin orbit torque (SOT), are attractive because of the low switching power of with these techniques and the non-volatility of magnetic bits, which leads to near-zero off-state power consumption. However, STT and SOT based devices are limited by the precessional switching speed of the ferromagnets, and so far, the record switching speed is of the order of ~100 ps [1]. For comparison, silicon based field effect transistors have speeds <5 ps [2].

GdFeCo, a ferrimagnetic alloy, is of great interest for high speed memory applications as it was shown that its magnetization toggles in picosecond timescales upon being excited by a femtosecond laser pulse, a phenomenon termed as All-Optical Switching (AOS) [3]. Such high-speed magnetization dynamics have heretofore required optical laser pulses or free-space terahertz irradiation, thereby making integration on-chip impractical.

Our work aims to bridge the on-chip integrablity and scalability of conventional spintronics with the high speed of AOS by exciting the conduction electrons of GdFeCo with ps electrical pulses [4]. Previous AOS experiments on GdFeCo have shown that heating the electrons to high temperatures in ps timescales is crucial for magnetization reversal [3]. We have previously demonstrated that AOS in GdFeCo for laser pulsewidths up to 15 ps [5]. It should therefore be possible to toggle the GdFeCo magnetization with successive ps electrical pulses.

We fabricated low-temperature GaAs based photoconductive Auston switches with gold transmission lines in the coplanar stripline (CPS) configuration (Fig 1a). Sputter deposited Ta(5nm)/$Gd_{30}Fe_{63}Co_7$(20 nm)/ Pt(5 nm) multilayers are patterned at the transmission line load. Upon irradiation with 100 fs optical pulses from a regeneratively amplified Ti-sapphire laser (800 nm wavelength), the Auston switch generates 9 ps electrical pulses that flow through the GdFeCo load with a peak current density of $\sim 7 \times 10^8$ A/cm^2. Magneto-optical Kerr effect (MOKE) microscopy images indicate that the GdFeCo load toggles magnetization with each electrical pulse, just as with optical pulses (Fig 1b).

We then performed time-resolved MOKE experiments to study the magnetization dynamics of GdFeCo following excitation by the electrical pulses. The amplitude of the electric pulse was varied by changing the bias voltage of the CPS. For electrical pulses with absorbed energy densities less than 1.24 mJ/cm^2 (with respect to the surface area of GdFeCo), the GdFeCo only demagnetizes, followed by magnetization recovery. At 1.3 mJ/cm^2, the GdFeCo switches its magnetization within 10 ps of the arrival of the electrical pulse (Fig 2a). An optical pulse with a similar heating pulsewidth (6.4 ps) appears to need a higher critical absorbed fluence of 1.65 mJ/cm^2 to drive AOS in the same GdFeCo film (Fig 2b). The magnetization recovery following irradiation with the optical pulse is also slower than with electrical pulse. We believe that the spin currents arising from the Pt and Ta layers sandwiching the GdFeCo following an electrical pulse might lead to the lower energy and faster recovery time in the electrical pulse toggling experiments.

The energy density required to switch the magnetization in our device is 13 aJ/nm^3. For a cell size of (20 nm)^3, which is typical for memory devices, switching should be possible with as low as ~4 fJ of energy (peak current of 3 mA). The Auston switch is not necessary to generate ps electrical pulses; the demonstration of 5-ps gate delay with 45-nm CMOS technology [2] indicates that sub-10 ps pulses can be generated on-chip with existing CMOS electronics.

In conclusion, we have demonstrated ultrafast magnetization reversal of GdFeCo in 10 ps with 9 ps electrical currents. Our results show the potential for the realization of ultrafast, non-volatile and low energy spintronic devices.

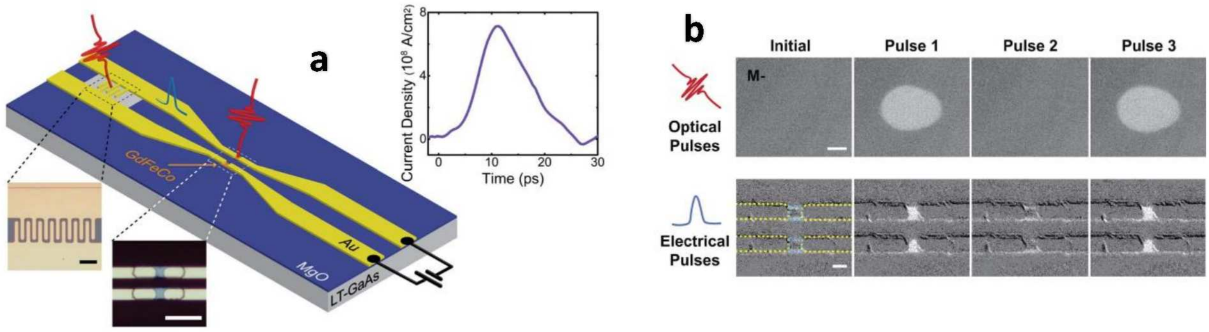

Fig 1. a) Schematic of the CPS device highlighting the Auston switch (left) and GdFeCo load (right). Scale bars, 20 µm. Inset shows the calculated electric pulse delivered to the load. b) MOKE images showing toggle switching of GdFeCo magnetization by optical (top) and electrical (bottom) pulses. Scale bars, 5µm

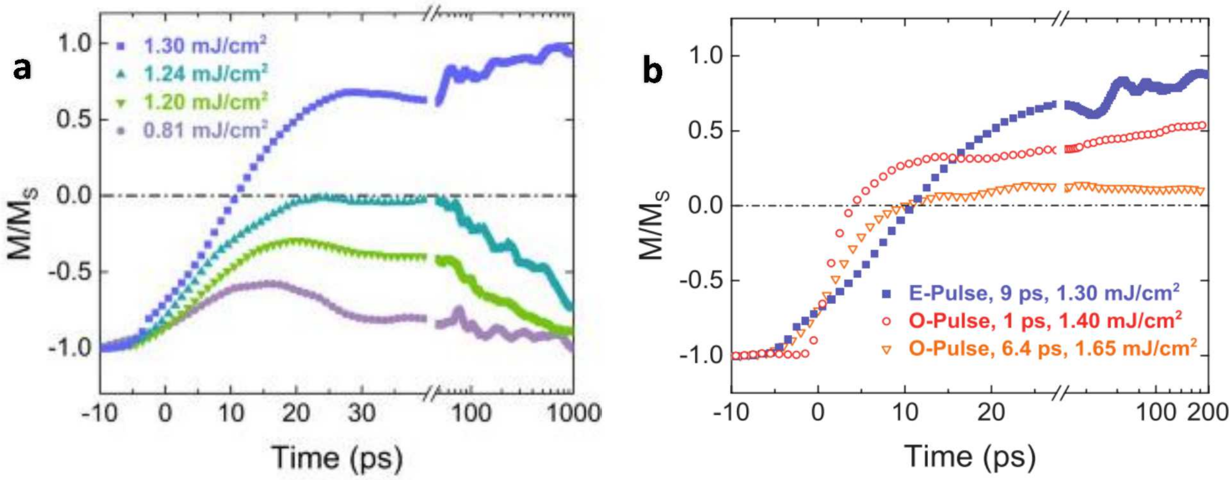

Fig 2. a) TR-MOKE traces showing magnetization dynamics of GdFeCo following excitation by 9 ps electrical pulses with different amplitudes (absorbed energies). b) Comparison of GdFeCo magnetization dynamics for excitation with electrical and optical pulses.

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