Ultrafast On-Chip Spintronics

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The field of spintronics involves the study of both spin and charge transport in solid-state devices. Ultrafast magnetism involves the use of femtosecond laser pulses to manipulate magnetic order on subpicosecond time scales, including helicity-independent all-optical switching. We have united these phenomena by using picosecond charge current pulses generated on-chip using an ultrafast photoconducting (Auston) switch (Fig. 1) to induce deterministic, repeatable ultrafast reversal of the magnetization of a ferromagnetic GdFeCo thin film [1]. Using 9 ps duration current pulses, the magnetization reverses in ~10 ps, which is more than one order of magnitude faster than any other electrically controlled magnetic switching, and demonstrates a fundamentally new electrical switching mechanism that does not require spin-polarized currents or spin-transfer/orbit torques. (Fig. 2) Furthermore, the energy density required for switching is low, projecting to only 4 fJ needed to switch a (20 nm)^3 cell.

This ultrafast magnetization reversal phenomenon through a nonequilibrium thermal excitation is primarily limited to Gd based ferrimagnets, such as the GdFeCo alloy used in the experiments shown in Figs. 1 and 2. In order to integrate this fast switching with a readout, a magnetic tunnel junction exhibiting high tunneling magneto resistance (TMR) is desired. Yet, the TMR value reported for devices using GdFeCo is too small (≈0.6%) for practical applications [2]. Thus, it is of great interest to switch a ferromagnet with helicity independent optical pulses, which could then be implemented as a storage layer in a high TMR memory cell.

We have shown how to transfer the ultrafast switching of GdFeCo to a ferromagnet (in our case Co/Pt multilayers) using Ruderman–Kittel–Kasuya–Yosida (RKKY) exchange coupling mediated HI-AOS of the ferromagnet layer driven by the HI-AOS of the ferrimagnet layer [3, 4]. This technique is generally applicable to other ferromagnets that could then be used for MTJ readout of the state of the switched magnetic structure with high TMR.

We also show that 6-10 ps duration electric current pulses can be used to directly and deterministically switch the out-of-plane magnetization of a ferromagnetic thin cobalt film via spin–orbit torque (SOT) [5]. The current pulses were applied to a heavy metal/ferromagnet thin film heterostructure in the presence of an in-plane symmetry breaking magnetic field. Depending on the relative current pulse and in-plane magnetic field polarities, we observe either SOT switching or an ultrafast demagnetization and subsequent recovery, but no switching. (Fig. 3) The short current pulse induces the ultrafast demagnetization of close to 30% due to transient Joule heating. This heating plays a crucial role in promoting the SOT switching in the presence of the in-plane magnetic field. Nevertheless, we also project low energy (~fJ range) for switching of a (20 nm)3 cell using this mechanism. We use a macro-magnetic simulation model coupled with an ultrafast heating model to analyze the effect of ultrafast thermal anisotropy torque (intimately related to the ultrafast demagnetization) and current-induced SOT in the observed dynamics. Good agreement between our experimental results and the macro-spin model shows that the switching dynamics are coherent rather than involving domain nucleation and growth, even though our device dimensions are as large as 4 X 5 um2.

References

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Figures

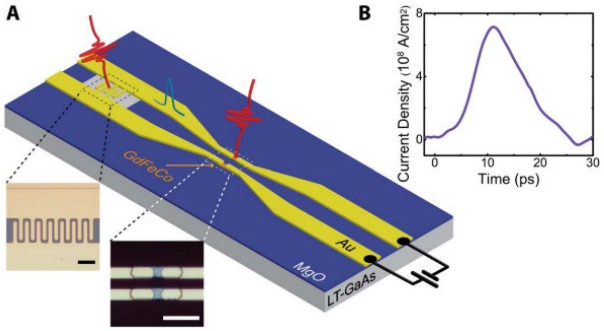

Figure 1. (A) Schematic of electrical switching experiment. The photoswitch is illuminated with laser pulses while being biased with a dc source. Magnetization dynamics of GdFeCo is monitored with time-resolved MOKE. Left: Optical image of the photoswitch. During laser illumination, photoexcited carriers in low-temperature GaAs conduct current across the gap, generating a transient electrical pulse propagating in both directions. Right: Optical image of the GdFeCo section of CPS. Scale bars, 20 μm. (B) Calculated temporal current density profile through the GdFeCo section, based on the temporal current profile measured with a Protemics Spike probe positioned 1 mm before the GdFeCo section.

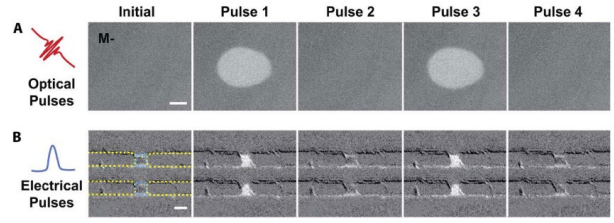

Figure 2. Single-shot optical and electrical switching of GdFeCo. (A) Differential MOKE images of bare GdFeCo film after sequential 6.4-ps optical pulse irradiation. Absorbed fluence is 1.8 mJ/cm2. After each optical pulse, the magnetization of GdFeCo toggles to the opposite direction. The contrast indicates change in magnetization. (B) Differential MOKE images of GdFeCo CPS section after sequential 9-ps electrical pulse excitation. After each electrical pulse, the magnetization of GdFeCo toggles. Yellow and blue dashed lines indicate gold CPS and GdFeCo sections, respectively. Scale bars, 5 μm.

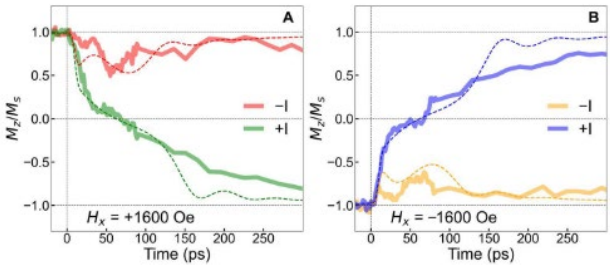

Figure 3. Ultrafast current pulse–induced magnetization switching dynamics. The approximately 9 picosecond current pulse–induced time-resolved magnetization dynamics measured in the presence of (A) positive and (B) negative in-plane symmetry-breaking magnetic field and reversing the direction of the current pulses starting from positive and negative magnetic saturation. The dotted lines show the theoretical analysis by solving a macroscopic LLG equation and combining ultrafast one-temperature heating model due to a 9-ps current pulse with a current density of $\pm 7.3 \times 10^{12}$ A/m^2.