Picosecond Spintronics for On-Chip Memory Applications

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Conventional spintronic devices, such as spin-transfer-torque magnetic-resistive random-access memory (STT-MRAM) and spin-orbit torque (SOT)-MRAM, are promising due to their non-volatility, high density, energy-efficiency, and high endurance. STT-MRAMs are now entering into the commercial market, however they are limited in write speed to the ~10 ns timescale, which is quite slow compared to ubiquitous static RAM. Improvement in the write speed of spintronic devices can significantly increase their usefulness as viable alternatives to the existing CMOS-based devices. In this talk, I will discuss the prospects of ultrafast spintronics as a pathway to high-performance, energy-efficient, nonvolatile embedded memory in digital integrated circuit applications.

The field of ultrafast magnetism was first discovered[1] in 1996 with the observation of sub-ps magnetization quenching of a Ni thin film upon irradiation with fs laser pulses. Subsequently, helicity-independent all-optical toggle switching (HI-AOS) of magnetization in GdFeCo ferrimagnets was discovered and explained[2] in 2011. Ultrafast manipulation of magnetization using fs optical pulses is of particular interest as the magnetization dynamics are much faster than conventional magnetic precessional dynamics that limit MRAM speed. Surprisingly, HI-AOS is found to be a purely thermal process, in which the role of the laser pulse is simply to heat the electronic system to a high temperature, well out of equilibrium with the lattice. Under these transient non-equilibrium conditions, lasting for just picoseconds, the ultrafast magnetization dynamics occur.

We have demonstrated that picosecond pure charge current pulses are effective at initiating ultrafast magnetization switching. We excite picosecond electrical current pulses using photoconductive switches and utilize transmission line structures to carry the pulses to magnetic devices. With these ultrashort electrical excitations, we confirm that ultrafast electron Joule-heating can trigger magnetic toggle switching in GdFeCo, in a process very similar to HI-AOS[3] (see Figure 1). We have also recently demonstrated programmable ultrafast SOT magnetic switching in ferromagnets.[4] These purely electrical ps magnetic switching mechanisms are suitable for on-chip integration with CMOS, opening up the possibility of ultrafast, high density magnetic memory.

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[1] E. Beaurepaire, et al., Phys. Rev. Lett. **76**, 4250 (1996).

[2] I. Radu, et al., Nature **472**, 205 (2011).

[3] Y. Yang, et al., Science Advances **3**, E1603117 (2017).

[4] D. Polley, et al., arXiv:2211.08266

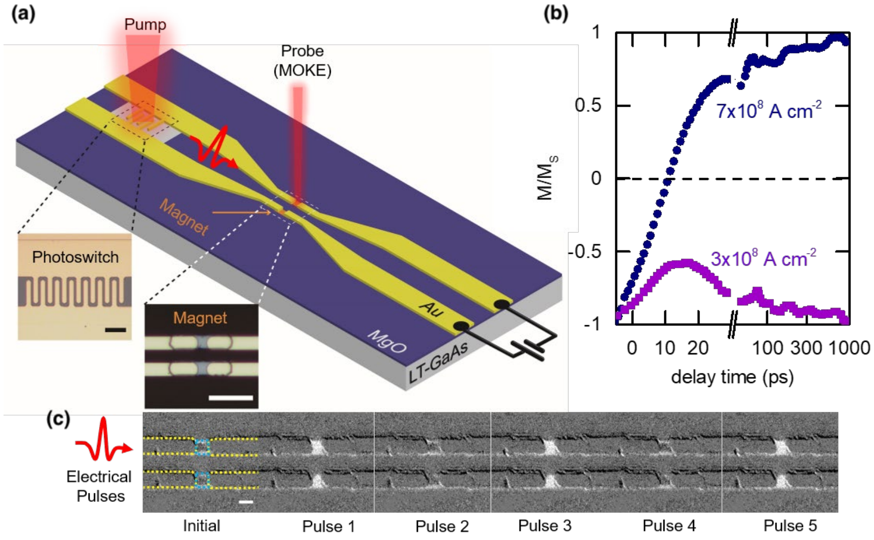

Figure 1: Ultrafast switching of GdFeCo with 9 ps duration electrical pulses. (a) Schematic of the electrical switching experiment. The photoswitch is illuminated with laser pulses while being biased with a dc source. (b) Magnetization dynamics of GdFeCo is monitored with time-resolved magneto-optic Kerr effect (MOKE). With sufficient electrical pulse amplitude, the GdFeCo magnetization switches in ~10 ps. (c) Differential MOKE images of GdFeCo coplanar strip (CPS) waveguide 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 bar, 5 mm. (c) Time-resolved dynamics after excitation with current densities below and above the switching threshold.