Engineering materials for all optical magnetic recording

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The possibilities of manipulating magnetization without any applied magnetic field have attracted the growing attention of researchers during the last fifteen years. From the discovery of spin transfer torque switching [1], the effect of electric fields on magnetic devices [2] to magnetization switching using femto- or picosecond pulsed lasers [3,4] the manipulation of magnetization on ultra-short time scales has become a fundamentally challenging topic with implications for magnetic data storage. At CMRR we have an ongoing theory, modeling and experimental project to both probe the underlying physics of so-called all-optical magnetization switching (AOS) using circularly polarized light pulses and develop new materials classes that will enable applications of this phenomenon. Here we describe recent optical manipulation of the magnetization of carefully engineered magnetic materials and devices. We demonstrated that AOS can be observed not only in very particular rare-earth transition-metal alloys [3,4] but also in a variety of materials (alloys, multilayers and complex structures). In particular we show for the first time AOS for a rare-earth free heterostructure system. This is a breakthrough for application since it provides materials "compatible" with spintronic applications for data storage, memories and logic.

The use of laser pulses for magnetization switching is particularly interesting since femto-second laser pulses can reverse magnetization which is 1000 to 10 000 times faster than switching magnetization by magnetic fields [5] or spin-polarized current pulses [6]. Moreover this process is reported to be very energy efficient [7]. Here we report on engineered materials ranging from amorphous ferrimagnetic alloys to coupled transition-metal ferromagnetic heterostructures. The fact that ferromagnetic layers such as Co, [Co/Pt] and Co/Ni may be switched opens the use of AOS in spintronic devices. Figure 1 shows an example or controlled reversal of magnetization by polarized light which can be used to write on a magnetic media.

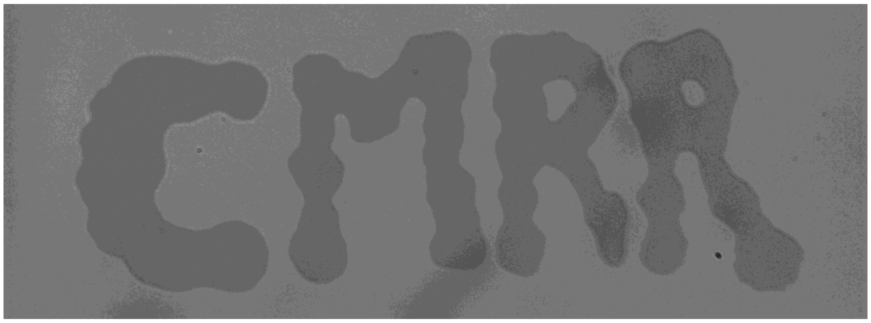

Figure 1 Magnetic image of a saturated $[Co(5Å)/Tb(4\ Å)]_{x28}$ *multilayer film, where pulses of circularly polarized light were used to reverse the magnetization of certain areas. The full size of this image is about 100* μ*m long.*

Three classes of materials with perpendicular magnetic anisotropy (PMA) have been studied 1) rare-earth (RE) –transition metal (TM) alloys 2) RE-TM multilayers and 3) synthetic ferrimagnets (SFI) which are made of two ferromagnetic layer showing two different temperature behaviors and which are antiferromagnetically coupled through an Ir interlayer. This latter structure was designed to mimic the magnetic properties of ferrimagnetic material. To study the magnetization response to femtosecond laser pulses we used a set-up similar to that shown schematically in Fig. 2. The pulse duration is about 100 fs with a repetition rate of 1 kHz. Helicity of the beam is controlled by a quarter wave-plate, which allows to transform linear polarized light of the laser beam into circularly left- or right-polarized light. The average LASER power can reach 1W.

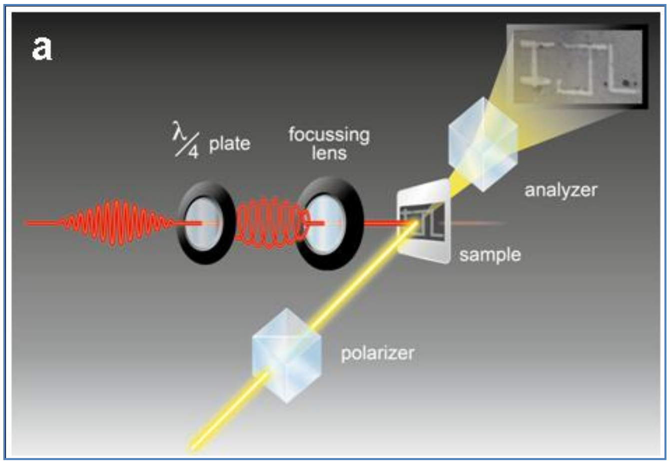

Figure 2: Experimental set-up: a Faraday imaging setup consisting of a white-light source, a crossed polarizer pair, and a CCD-camera, is used to image the magnetic domains while a polarized light is illuminating the sample. fs-amplifier running at 1 kHz at a central wavelength of 800 nm is used to provide pulse duration close to 100 fs. The pulses are circularly polarized by a zero order quarter-wave plate and focused on the sample.

Rare-earth transition-metal alloys

In RE-TM alloys the net magnetization results from the magnetization of the RE sub-lattice and of the TM sub-lattice. In our study we used heavy rare earth elements (Gd, Tb, Dy, Ho). The exchange coupling between a heavy RE and the TM sublattices is antiferromagnetic, causing ferrimagnetic ordering. Depending on the concentration and temperature the net magnetization of the alloy can be either along the RE magnetization sublattice for large RE concentrations or along the TM magnetization. For a certain composition at a given temperature (T_{Mcomp}: magnetization compensation temperature) the two sub-lattice magnetizations compensate and the net magnetization is zero. Note that due to the different Landé factor of RE and TM spins the angular momentum compensation temperature is always slightly higher than the magnetization compensation. More than 30 different alloys have been grown by sputtering Gd_xFeCo_{1-x}, Tb_xCo_{1-x}, Dy_xCo_{1-x}, Ho_xFeCo_{1-x} on a Glass/Ta(4nm) substrate and subsequently covered with Ta(4nm) to avoid oxidation. All the samples have shown strong PMA. For Tb-Co alloys the PMA is sufficiently strong to enable sub-10 nm islands to be fabricated that are thermally stable. As presented on Fig. 3, while sweeping the laser beam two types of behavior have been observed that can be defined as thermal switching (Fig 3.a) and AOS

(Fig 3.b). Thermal switching is characterized by the formation of small magnetic domains with random up or down orientation and those states are found to be independent of the helicity. This is similar to what is observed for thermally demagnetized samples. On the other hand, AOS is characterized by the deterministic magnetization reversal of the material under the beam, where the orientation of the magnetization depends on the helicity of the laser as shown on Fig 3b.

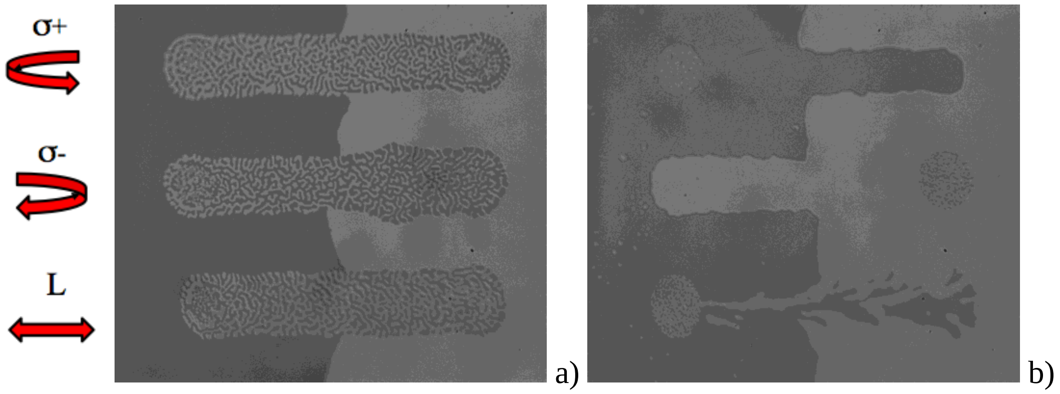

Figure 3: two different samples were studied a) [Co(8Å)/Tb(4Å)]$_{x21}$ and b) [Co(5Å)/Tb(4 Å)]$_{x28}$ for each sample three types of polarized beam were swept over the sample: from top to bottom right circularly polarized light (σ+), left circularly polarized light (σ-) and linear polarized light (L)

When trying to identify which compositions show thermal switching and which show AOS we find that AOS is observed only for a given range of compositions. (Fig.4). A careful analysis demonstrates that AOS is observed only when the alloy has a compensation temperature larger than room temperature.

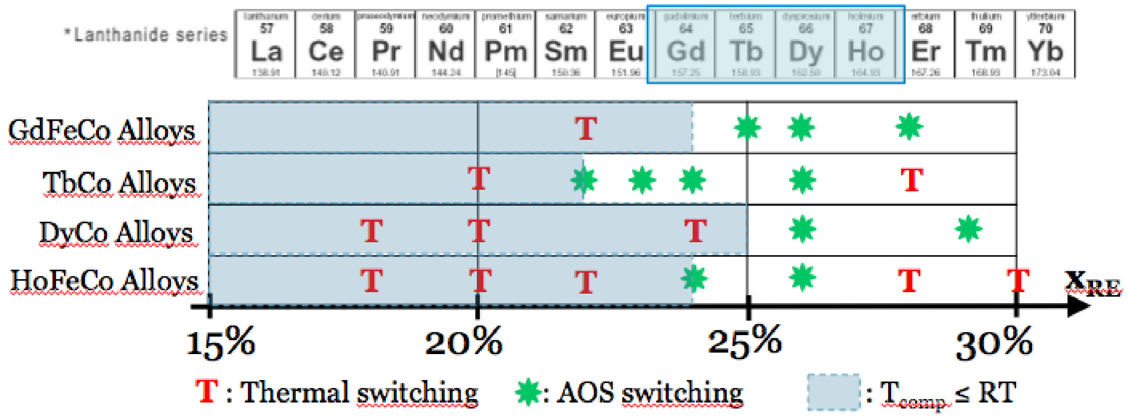

Figure 4: Types of RE-TM alloys studied for AOS as a function of the alloy concentration. Red T represents thermal switching and green stars represent AOS. The regions shaded in blue correspond to alloy compositions where the compensation temperature is below room temperature.

Rare-earth transition-metal multilayers

In order to investigate the role of the atomic order in the material we have grown multilayers such that the amount of each species stays constant but the thickness of each material varies. A $Tb_{26}Co_{74}$ alloy clearly shows AOS (volume ratio about 50/50). In multilayers with equal Co and Tb thickness AOS can be observed for a multilayer periodicity up to 5 nm as presented on Fig. 5

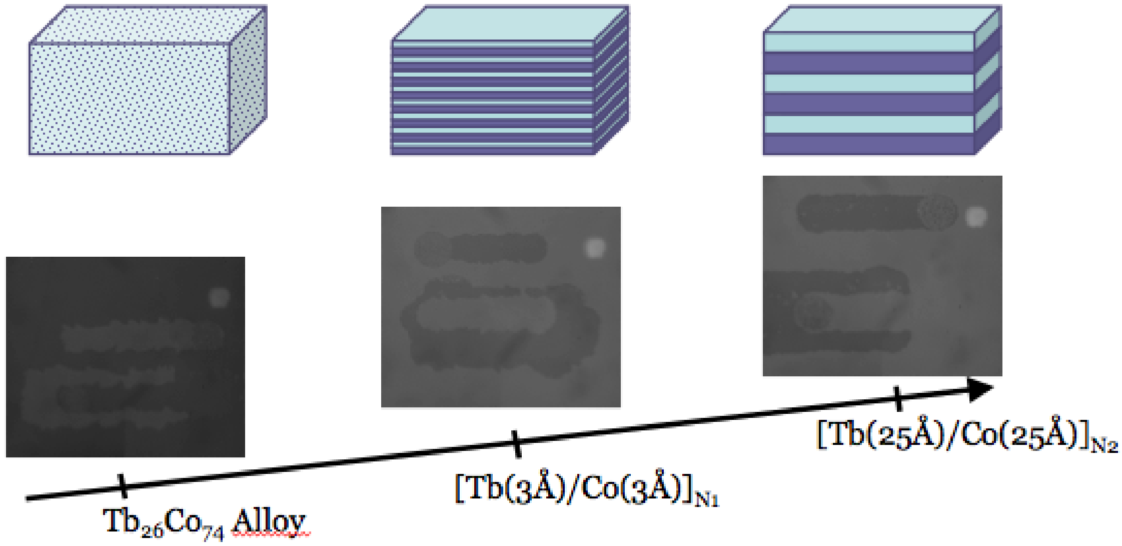

Figure 5: Polarized beam (polarized light (σ+), left polarized light (σ-)) have been swept over the sample. All optical switching can be observed for three different samples (a TbCo alloy, a *[Tb(3Å)/Co(3Å)]*$_{x42}$ multilayer and a *[Tb(25Å)/Co(25Å)]*$_{x5}$ which have identical amounts of Tb and Co

Synthetic ferrimagnetic layers

Up to now all reported studies of AOS switching have been on RE-TM ferrimagnetic alloys or multilayers. To determine if this phenomenon is unique to RE-TM based materials we fabricated synthetic ferromagnetic heterostructures that mimic the properties of RE-TM alloys. We designed magnetic multilayers of two different magnetic layers where the magnetizations of the two layers have different temperature dependence and which are antiferromagnetically coupled via a thin Ir layer. These structures have no rare-earth elements. Example structures are Ta4nm/Pd3nm/ [Co(t_1)/Ir(0.4nm)/CoPt(t_2)/Ir(0.4nm)]xN/ Pd3nm. The Ir layer thickness was chosen to maximize antiferromagnetic coupling and the surface anisotropy of the Co-Ir layers supports PMA. The thickness ratio of t_1 and t_2 are chosen such that at room temperature the CoPt layer moment is larger than the Co layer. However, CoPt has a lower Curie temperature compared to Co. Consequently, the CoPt layer moment decreases faster than the Co layer moment resulting in a compensation temperature for the structure. This class of heterostructures has been analyzed. For samples where the two magnetizations compensate at a temperature larger than room temperature AOS is observed.

From these studies we can conclude that the presence of two magnetization sublattices compensating each other at a certain temperature is a key element for AOS. The common denominator of the diverse structures showing AOS presented is that two magnetic sub-lattices showing two different temperature dependences can be magnetically compensated while heated. These results offer valuable information to understand the underlying fundamental mechanisms involved. More importantly it opens a new pathway to design complex materials using well-known thin-film techniques where the magnetization can be controlled by the application of light.

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[1] J. Katine et al Phys. Rev. Lett. 84 3149 (2000)

[2] H. Ohno, D. Chiba, F. Matsukura, T. Omiya, E. Abe, T. Dietl, Y .Ohno, K. Ohtani, Nature 408, 944 (2000)

[3] C. D. Stanciu, F. Hansteen, A. V. Kimel, A. Kirilyuk, A. Tsukamoto, A. Itoh, and T. Rasing, Phys. Rev. Lett. 99, 047601 (2007).

[4] S. Alebrand, M. Gottwald, M. Hehn, D. Steil, M. Cinchetti, D. Lacour, E. E. Fullerton, M. Aeschlimann, and S. Mangin, Applied Physics Letters 101, 162408 (2012).

[5] I. Tudosa et al. Nature 428, 831-833 (2004)

[6] D. Bedau, H. Liu, J-J Bouzaglou, A.D. Kent J.Z. Sun, J.A. Katine, Eric E Fullerton and S. Mangin, Appl. Phys. Lett 96 022514 (2010)

[7] M. Savoini[1,], R. Medapalli[1], B. Koene[1], A. R. Khorsand[1], L. Le Guyader[2,†], L. Duò[3], M. Finazzi[3], A. Tsukamoto[4,5], A. Itoh[4], F. Nolting[2], A. Kirilyuk[1], A. V. Kimel[1], and Th. Rasing[1] Phys. Rev. B 86, 140404(R) (2012)*