ALL-OPTICAL SWITCHING

Three rules of design

By following three empirical rules it is possible to design and fabricate magnetic heterostructures or even devices whose magnetization can be controlled by means of circularly polarized femtosecond laser pulses, instead of applied magnetic fields.

Alexey V. Kimel

The logical bits that form the basis of magnetic memory devices are encoded by setting the magnetization vector of individual magnetic domains either 'up' or 'down'. The recording of one bit therefore corresponds to magnetization reversal, and conventionally this is achieved by using an external magnetic field. However, the idea of developing a magnetic material that can be controlled with the help of light has long intrigued scientists in research areas ranging from semiconductor physics[1] to organic chemistry[2]. The development of lasers able to generate sub-100 fs optical pulses has made optical control of magnetism especially appealing, as it promises to revolutionize magnetic recording and information processing technologies by pushing their operational frequencies into the terahertz range[3].

Writing in *Nature Materials*, Stephane Mangin and colleagues report a major step forward in the development of magnetic materials suitable for all-optical switching[4]. In particular, they demonstrate a general strategy for designing and fabricating magnetic heterostructures for which it is possible to control their magnetizations by means of circularly polarized femtosecond laser pulses instead of pulses of magnetic field.

The possibility of reversing the magnetization of a metallic film solely by means of light was demonstrated in 2007 for a thin film of the ferrimagnetic amorphous alloy GdFeCo (ref. 5). Using a short, circularly polarized laser pulse, the direction of this optomagnetic switching was solely determined by the helicity of the pulse itself. Naturally, the discovery of this helicity-dependent all-optical switching (HD-AOS) raised a number of questions, chief among which was the generality of this phenomenon. Were there any other materials capable of displaying HD-AOS?

The theoretical framework for describing the mechanism responsible for HD-AOS in a system as complex as a multi-sublattice amorphous alloy is still the subject of intense debate[6,7]. Rather than relying on predictions from theory, Mangin *et al.* followed a set of empirical rules that they derived from earlier studies of HD-AOS in GdFeCo (ref. 6). The authors searched for optomagnetic switching in materials, heterostructures or multilayers satisfying the following three criteria. First, they looked for systems consisting of two magnetic sublattices (or layers) that were antiferromagnetically coupled (Fig. 1a). Second, they required that the magnetizations of the two magnetic sublattices (or layers) have different temperature dependencies such that a compensation temperature T_M is present, at which point the total magnetization is zero (Fig. 1b). And finally, they ensured that the medium exhibited perpendicular magnetic anisotropy (Fig. 1c).

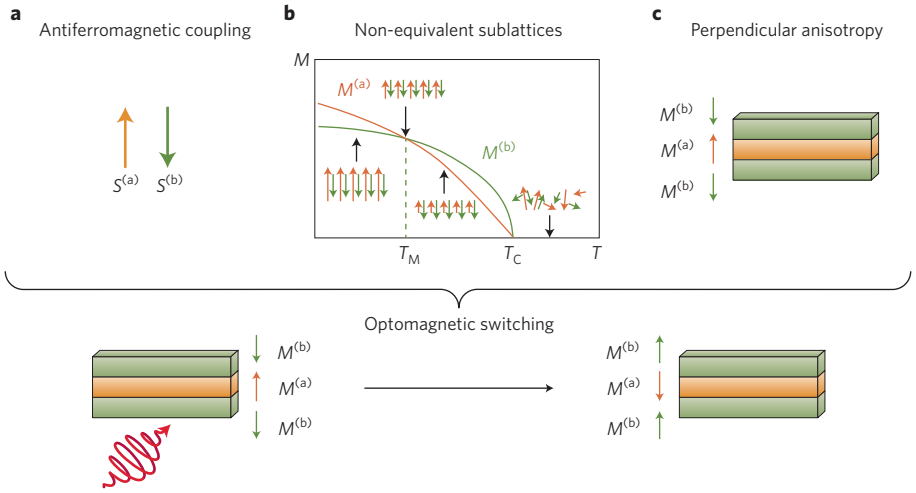

Figure 1 | Three requirements for achieving optically switchable magnetic films. **a**, Antiferromagnetic coupling between spins $S^{(a)}$ and $S^{(b)}$. **b**, The spins between the two sublattices having different size. **c**, Perpendicular anisotropy. T_C is the Curie temperature, and $M^{(a)}$($M^{(b)}$) is the net spin $S^{(a)}$($S^{(b)}$) per unit volume (generally referred to as the magnetization).

Mangin and colleagues' first result was to show that, provided they satisfied these three criteria, HD-AOS is also present in other amorphous rare-earth transition-metal alloys beyond GdFeCo, such as Tb_xCo_{1-x}, Dy_xCo_{1-x} and Ho_xFeCo_{1-x}. However, the authors also investigated the influence of atomic ordering on HD-AOS, by examining multilayers in which each one of the layers contained only rare-earth (Gd, Tb, Ho) or transition-metal (Fe, Co) atoms. Although taken individually these layers do not have a T_M, the multilayers can be fabricated in such a way that the rare-earth and transition-metal layers are coupled antiferromagnetically. As a result, the whole structure acquires a compensation temperature and, by satisfying the second criterion described above, also displays HD-AOS. These findings not only confirm the importance of the presence of a compensation temperature in the medium, but also reveal that HD-AOS is not limited to amorphous alloys. To observe the switching it is simply necessary that the whole heterostructure has a magnetic compensation point — achieving compensation on shorter length scales isn't necessary.

Finally, and perhaps most importantly, the authors designed and engineered heterostructures that satisfy their criteria but do not contain any rare-earth

metals. Even when the roles of the two antiferromagnetically coupled magnetic sublattices in the structures were played solely by transition metals, HD-AOS was observed, and as such the authors report the first successful demonstration of HD-AOS in rare-earth-free heterostructures.

The work by Mangin and colleagues is a remarkable contribution for understanding the mechanisms of optical control of magnetism in magnetic metals. The formulation and experimental verification of three rules to design a magnetic medium suitable for optical control of its magnetic state will drive further development of the theory of femtosecond optical control of magnetism. The possibility of designing a medium exhibiting HD-AOS provides practically limitless opportunities for fundamental studies of ultrafast optical control of magnetism. Moreover, the rare-earth-free heterostructures developed by Mangin *et al.* are compatible with modern magnetic recording and magnetic random access memory technologies, including heat-assisted magnetic recording in which sub-100 nm domains are recorded with the help of laser-induced heating. This compatibility sets an excellent starting point for applied research and development of novel technologies based on the optical control of magnetism. ❐

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References
1. Kovalenko, V. F. & Nagaev, E. L. *Uspekhi Fizicheskikh Nauk* **148,** 561–602 (1986).
2. Evans, D. F. *Nature* **176,** 777–778 (1955).
3. Kirilyuk, A., Kimel, A. V. & Rasing, Th. *Rev. Mod. Phys.* **82,** 2731–2784 (2010).
4. Mangin, S. *et al. Nature Mater.* **13,** 286–292 (2014).
5. Stanciu, C. D. *et al. Phys. Rev. Lett.* **99,** 047601 (2007).
6. Vahaplar, K. *et al. Phys. Rev. B* **85,** 104402 (2012).
7. Chimata, R., Bergman, A., Bergqvist, L., Sanyal, B. & Eriksson, O. *Phys. Rev. Lett.* **109,** 157201 (2012).

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MATERIAL WITNESS

GRAPHENE FINDS ITS PLACE

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If the commercial world is Darwinian, it's not in the sense of being a battle for supremacy. Companies, like species, coexist precisely because they don't always simply compete to be the biggest, but instead often content themselves with finding a niche. So just as the first advice for any entrepreneur would be "don't try to beat Google/Apple/Amazon", so the equivalent message for advocates of new electronic materials is "don't pretend you're the new silicon." That lesson has been amply learnt in organic electronics, where semiconducting materials initially predicted to rival the central fabric of microelectronics now instead play to their strengths for applications in optoelectronics, display technologies and interfacing with biology.

So it is with graphene. The story in which silicon is at the limits of its potential and this new contender waits to be (literally) rolled out as a cheap, robust and superior replacement is all too easily written. But no one in the field now doubts that, at least in the foreseeable future (and its fascinating fundamental physics aside), graphene must find niche applications if it is to justify all the excitement, not to mention all the funding.

But 'niche' doesn't mean small or trivial. A common consensus is that the possibilities of graphene in microelectronics are probably most profound in the burgeoning area of radiofrequency (rf) devices[1] — which means mobile devices such as smart phones, tablets and wearable electronics, as well as smart sensors and tags. Here the advantage of graphene as the substrate for charge conduction is its very high carrier mobility, which can be two orders of magnitude greater than that of silicon. This means that graphene field-effect transistors (GFETs) can be switched very fast, operating at the gigahertz speeds demanded in rf applications. Graphene's lack of a bandgap, which makes GFETs poor prospects for digital electronics because they can't be fully switched off[2], is no longer a hindrance here: rf electronics, for example to make radio receivers and amplifiers, can be an analog technology for which complete switch-off is not essential.

Much of the pioneering work in developing graphene rf circuits has happened in the IBM laboratories at Yorktown Heights in New York[3–5]. A team there has previously made GFETs from epitaxial graphene on silicon carbide that can operate at up to 100 GHz (ref. 4), and has fashioned such transistors into an integrated circuit that operates as a rf mixer[5].

That, however, was merely a proof of concept. In particular, the processing needed to complete the circuit after putting the GFETs in place degraded their performance. That's why an improvement in the manufacturing process now reported by the IBM team should be significant[6]. By making the fabrication of the GFETs the last stage in the process, they can use conventional methods without harming the delicate carbon films. That not only gives an improvement in gain performance of about four orders of magnitude but makes the whole process fully compatible with industry standards. The circuit acts as a rf receiver, capable of wireless communication at 4.3 GHz. Inevitably, the digital text used to demonstrate successful reception encoded a three-word message: 'I-B-M'. ❐

References
1. Schwierz, F. *Proc. IEEE* **101,** 1567–1584 (2013).
2. Avouris, P. & Dimitrakopoulos, C. *Mater. Today* **15,** 86–97 (March, 2012).
3. Han, S.-J. *et al. Nano Lett.* **11,** 3690–3693 (2011).
4. Lin, Y.-M. *et al. Science* **327,** 662 (2010).
5. Lin, Y.-M. *et al. Science* **332,** 1294–1297 (2011).
6. Han, S.-J., Garcia, A. V., Oida, S., Jenkins, K. A. & Haensch, W. *Nature Commun.* **4,** 3086 (2014).