SPINTRONICS

Perpendicular all the way

A conventional material used in magnetic tunnel junctions with in-plane magnetization can also be magnetized perpendicularly, offering new possibilities for high-performance memory and logic circuits.

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Magnetic tunnel junctions (MTJs) are thin-film structures consisting of two conducting magnetic layers separated by a very thin insulating barrier. Because of the tunnel magnetoresistance (TMR) effect, MTJs experience a large difference in resistance — a high TMR ratio — between states in which the layers are magnetized parallel and those in which the magnetization is antiparallel. This, and the fact that the direction of the magnetization can be switched by an external magnetic field, have made MTJs of standard use in modern magnetic hard-disk drives and magnetoresistive random-access memory (MRAM), a new type of non-volatile memory. A commonly adopted material for MTJs is the CoFeB–MgO multilayer system, which produces a giant TMR ratio with in-plane magnetization. Writing in Nature Materials, Ohno and colleagues show that this soft magnetic material can also be magnetized perpendicular to the film plane when incorporated into an MTJ (Fig. 1a).

Perpendicular magnetization in this material results in high-stability magnetization at room temperature, important for long-term data storage.

Thin multilayered films that show large out-of-plane magnetocrystalline anisotropy — preferential alignment of the magnetization along the crystallographic direction perpendicular to the film plane — and that also impose a large energy barrier to magnetization switching, permit stable
magnetization states at room temperature in thin-film elements of less than only 10 nm in diameter. Moreover, these magnetization states are expected to be readily altered using spin-transfer torque, a new mechanism for magnetization switching that makes possible spin transfer torque MRAM (STT-MRAM). This has led to intense worldwide efforts to realize STT-MRAM with perpendicularly magnetized layers. The focus of the efforts has been on complex multilayers of magnetic transition elements such as Co and Ni, or Co and Fe with heavier non-magnetic elements like Pt and Pd. These materials are known to have perpendicularly magnetic anisotropy (PMA), and are already employed in hard disks as perpendicular magnetized recording media. However, they are far from ideal for STT-MRAM, because they tend to form poor MTJs. Known materials with PMA have a crystal structure that does not match well with the body-centred cubic (bcc) lattice formed by MgO. Furthermore, they often have poor spin–transport characteristics: the heavy elements in the material lead to strong spin–orbit scattering that causes spin-flips, and also large damping of the magnetic moments. Thus, they are far from ideal for STT-MRAM.

The surprising discovery that CoFeB becomes Fe-rich, enhancing the PMA. It is possible that the CoFeB/MgO interface has not been studied theoretically, their electronic structure predicted to have a large PMA based on their magnetic dipole interactions for layer thicknesses of about 1 nm (~3 monolayers of CoFeB).

The work goes further to demonstrate the incorporation of this interface anisotropy in a device. A perpendicularly magnetized CoFeB-MTJ device is shown to have a large magnetoresistance (>100%). When these stacks of layers are patterned into 40-nm-diameter circular devices, spin current switching is observed for relatively low currents, ~50 μA. The PMA leads to an energy barrier to switching (denoted as U in Fig. 1b), sufficient to permit long-term data storage. In combination, these are very impressive results. Previous research had shown that it is possible to achieve larger magnetoresistance, comparable switching current densities, and thermal stability, but not all three at the same time.

The work by Ohno and colleagues opens new possibilities for high-performance STT-MRAM, and also poses basic questions. First, it is not clear what the origin of the PMA is. Although Fe/MgO interfaces were predicted to have a large PMA based on their electronic structure, the CoFeB/MgO interface has not been studied theoretically, and its structure and composition has not yet been characterized. To form the MTJ, the layers are annealed and the elements in the layers can diffuse. Indeed, boron is known to diffuse in the CoFeB layer. And it is possible that the CoFeB/MgO interface becomes Fe-rich, enhancing the PMA. It is therefore clear that studies of the nature of the interface are needed to correlate structure and properties in these materials.

Another question is related to the fact that CoFeB films show low damping. However, in the devices fabricated by Ohno and colleagues, which have very thin CoFeB layers, the damping is strongly enhanced, and the origin of this enhancement is not well understood. In acquiring a PMA, the damping apparently becomes comparable to other thin-film materials with PMA, which typically have large distributions in their magnetic properties that may lead to variations in device characteristics. Do such distributions exist in CoFeB–MgO bilayers? To answer this question, further studies of films and device arrays are necessary. In addition, the switching speed and energy are critical metrics for applications. In perpendicular spin-valve junctions, magnetization-switching with pulses as short as 0.3 ns has been demonstrated, with energies of 0.1 pJ in thermally stable elements. However, the ultimate switching speed of CoFeB–MgO requires further study and optimization. Devices with non-collinear magnetizations can switch even faster, without nanosecond incubation delays seen in collinearly magnetized structures. Nonetheless, there is great potential for perpendicularly magnetized CoFeB–MgO devices. It should be straightforward to increase their anisotropy further to permit stable magnetization states in even smaller magnetic elements, for example, by adding a Pt/CoFeB interface. If lower damping can be achieved, we may then consider mechanisms to increase the switching current to minimize magnetic disturbances when reading the device resistance, which would be, in perspective, a real switch for STT-MRAM development.

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References

Additional information
The author declares competing financial interests: Spin Transfer Technologies, LLC is developing orthogonal spin-transfer MRAM under a license from New York University (NYU). The author may receive a portion of NYU’s license income.