

SPINTRONICS

Beyond the speed limit

Comb-shaped nanostrips pave the way for a fourfold velocity increase in the propagation of magnetic domain walls.

Geoffrey Beach

Today the majority of the world's digital data are stored magnetically, owing to extraordinary data density at a low cost per bit. As access to each bit is mechanical, however, magnetic storage devices remain slow and power hungry. A variety of alternative, high-performance, solid-state storage technologies are currently being pursued, and it is not yet clear whether magnetic materials will maintain their dominance in the longer term. But magnetics still have a few tricks up their sleeves. One of these is to make the bits themselves mobile. In a long, submicrometre-wide, continuous track of magnetic material, data can be represented by a series of oppositely oriented magnetic domains that are separated by domain walls. Because magnetic domain walls can be moved simply by reorienting electron spins, data could be shifted along the track to fixed reading and writing elements without mechanical motion — a solid-state analogue of today's hard disk drives¹. Beyond just storing information, entire domain wall logic architectures based on networks of magnetic tracks have been envisaged². However, one of the biggest hurdles to competitive domain-wall-based technologies is their speed, as magnetic-field-driven domain walls tend to observe a 'speed limit'³. In this issue, Lewis and co-workers⁴ demonstrate how to exceed this speed limit in a most unexpected way.

At low magnetic driving fields, a domain wall in a magnetic track translates viscously with a speed that is proportional to the field strength. However, at a critical velocity, typically of a few hundred metres per second, internal torques become so strong that the domain wall can no longer maintain a rigid internal structure. Rather, a magnetic vortex periodically nucleates near one edge of the track and moves through the domain wall towards the other side. As the vortex makes its way from side to side, strong forces drag the domain wall back and forth along the track. Any further increase of the driving field strength results in more frequent vortex nucleation, leading to an oscillatory domain wall trajectory with only a small net forward velocity (Fig. 1).

If it were possible to stop vortices from forming in the first place, the wall could in

principle be driven at much higher speeds. A number of simulations indeed point to ways of rapidly annihilating nucleated vortices^{5–7}. These include magnetic multilayer structures⁶, complex magnetic field geometries⁷ and even edge roughness of an appropriate length scale⁵. However, in all of these cases, the velocity still reaches a plateau at the critical velocity for vortex nucleation. The results of Lewis *et al.*⁴ show for the first time that it is possible to bypass this velocity limit by making a simple and elegant modification to the standard design of magnetic tracks.

In a perfectly smooth and featureless magnetic track, a domain wall has no preferred position and can be driven easily from one place to another. Lewis and colleagues have shown elsewhere⁸ that individual cross-shaped protrusions from a magnetic track can, however, act as local potential wells that can trap a domain wall

in a controllable fashion. Surprisingly, by placing a series of such protrusions in a comb-like structure, the authors have now demonstrated that rather than impeding the domain wall's motion, the traps allow it to be driven along the conduit at record speeds in excess of $1,500 \text{ m s}^{-1}$, which is four times the critical velocity in a simple track, and with no sign of vortex-mediated velocity breakdown.

When the cross-like protrusions are sufficiently closely spaced, their local potential wells overlap and the domain wall can move rapidly from cross to cross with minimal pinning. Nucleated vortices, by contrast, become trapped by each cross and are ripped away from the domain wall and annihilated before they can slow the wall down, as suggested by accompanying model simulations. The authors also point out another effect that could enhance the domain wall mobility. Shape effects tend to force the magnetization to align along the edges of straight segments. In the vicinity of each protrusion, the equilibrium magnetization hence cants away from the main track axis. The result is that over much of the structure, the change in magnetization angle after the passage of the domain wall is less than 180° . Because the local magnetic moments have a smaller angle to rotate through, the transition can occur much faster. Although the details of the motion of the magnetic reversal front are far more complex than in a uniform, straight track, the experimental consequences for the net velocity are quite clear.

The past few years have seen tremendous progress in the understanding of magnetic domain walls in confined geometries. The next stage will be to engineer domain wall dynamics by controlling wall topology; the work of Lewis *et al.*⁴ takes an important step in that direction. In the long run, however, domain-wall-based devices are more likely to rely on an entirely different drive mechanism, namely current-driven motion by means of spin momentum transfer^{9,10}. Applying magnetic fields is generally energy inefficient, and applying them locally is difficult. By contrast, passing an electrical current across a magnetic domain wall can propel the wall in the direction of electron flow at much lower input power, and at the same time

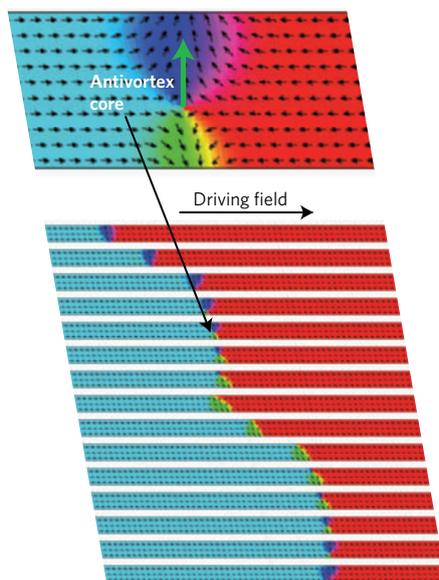


Figure 1 | Snapshots of the numerically simulated motion of a magnetic domain wall in a 150-nm wide, 5-nm thick NiFe strip under an applied magnetic field. For large driving fields, the periodic nucleation and motion of a magnetic vortex across the width of the strip leads to an oscillatory wall trajectory and a substantially lower net forward velocity. Snapshots correspond to 400-ps time steps.

provides a natural interface to conventional electronics. As the responses of a domain wall to fields and currents are fundamentally different, it is not clear whether the benefits of structural engineering would carry over to current-driven mechanisms. Nonetheless, Lewis *et al.* have shown that it is well worth thinking beyond the simple conduit structures that have been the focus of most research until now. □

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BIOMINERALIZATION

A crystal-clear view

The mechanisms of biomineralization remain hotly debated. Now high-resolution microscopy yields unsurpassed insight into mechanisms relevant both to the biomineralization of bone and teeth and to pathological mineralization.

Helmut Cölfen

Simple biominerals are composed of complex structures, which often have precise architectural order over several length scales. This amazing architecture contributes to their superior strength and toughness, allowing them to outperform synthetic materials. Biominerals rely heavily on their biological constituents, such as biomacromolecules, for regulation of mineralization. Pathological mineralization leads to the formation of undesired biominerals such as kidney stones, atherosclerosis and dental calculus. It is therefore of great importance to unravel the mechanisms that cause the formation of both desirable and undesirable biominerals in organisms. One secret of biominerals' superior material properties is their organic–inorganic hybrid structure whereby precise arrangement of the building blocks is achieved over several length scales. For example, the fracture resistance of nacre is 3,000-fold higher than that of brittle CaCO_3 (aragonite), which comprises 95% of nacre's weight. The adaptation of these building principles in synthetic models is highly attractive and can be further enhanced by synthetic chemistry^{1,2}.

To take advantage of these strategies for building better materials, a firm understanding of biomineralization mechanisms and design principles is required. As a consequence of the analytical challenges posed, these details of biomineralization remain unknown. Even in the case of bone and teeth — with studies spanning several decades focused on these issues — formation mechanisms remain ambiguous. This is demonstrated by the controversial debate surrounding whether bone mineralizes by means of ion-based or amorphous precursors. To complicate the

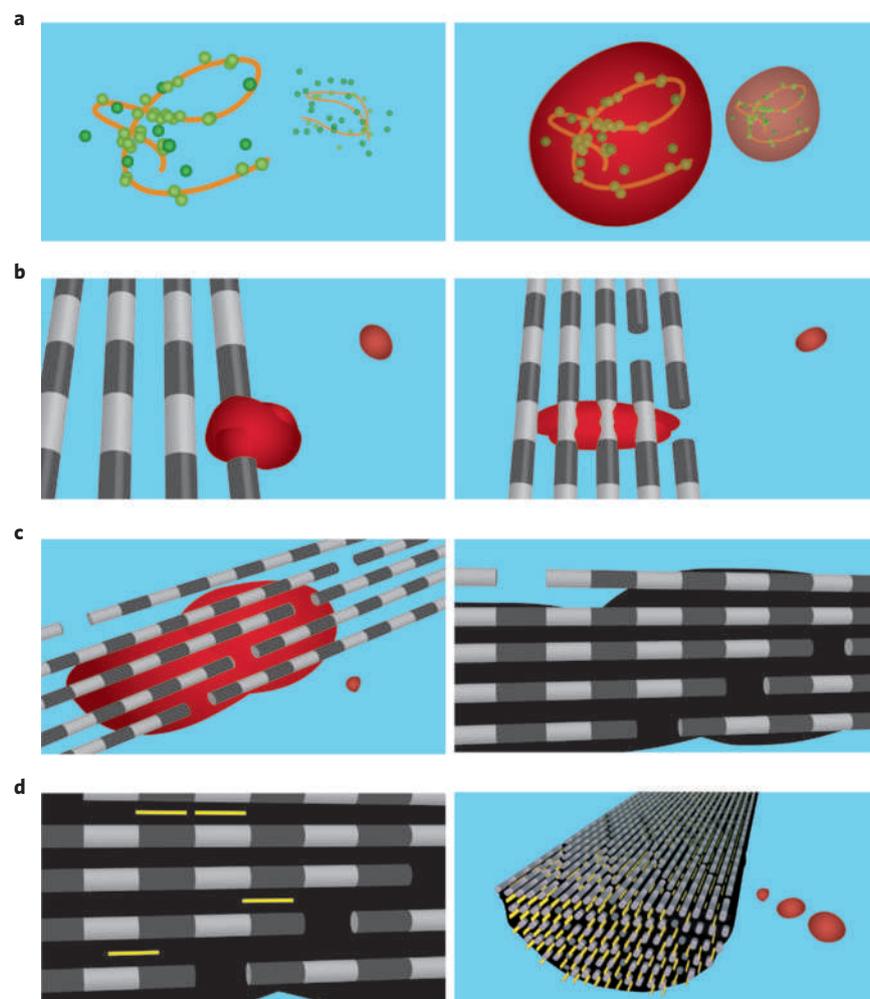


Figure 1 | Mineralization of a collagen fibril. **a**, Calcium phosphate clusters (green) form complexes with the polymer (orange line), forming stable mineral droplets. **b**, Mineral droplets bind to a distinct region on the collagen fibres and enter the fibril. **c**, Once inside the collagen, the mineral in a liquid state diffuses through the interior of the fibril and solidifies into a disordered (amorphous) phase (black). **d**, Finally, directed by the collagen, the amorphous mineral transforms into oriented apatite crystals (yellow).