Observation of magnetization reversal of thin-film permalloy nanostructures using ballistic electron magnetic microscopy

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We have imaged the magnetization reversal process of thin-film permalloy (Ni$_{80}$Fe$_{20}$) nanostructures using ballistic electron magnetic microscopy. Their switching behavior is often influenced by the formation of end domains and the subsequent domain-wall propagation under application of a magnetic field. Occasionally, this process leads to the formation of a 360° domain wall that is stable in fields which would otherwise switch the structure. The resulting state of the nanostructure in zero-applied field is very different from the near-single-domain state typically observed. The magnetization of the structure can show abrupt changes in a fixed magnetic field.

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An understanding of the switching behavior of nanostructured magnetic elements is essential to their development for applications such as magnetic random access memory and magnetic-field sensors. While magnetic nanostructures have been studied by employing more conventional magnetic imaging techniques such as magnetic-force microscopy, Kerr microscopy, Lorentz microscopy, and holography, these studies have generally focused on the behavior of high coercivity media. Here, we investigate much thinner and softer materials presently of interest for use in tunnel-junction- and spin-valve-based devices. Specifically, the magnetization reversal process of permalloy (Py) thin films patterned into shapes of “diamonds” and “rectangles” (1.5×0.3 $\mu$m$^2$) is studied. The magnetic states of the structures are imaged as a function of magnetic field $H$ applied along their easy axis by ballistic electron magnetic microscopy (BEMM). We also report the observation of domain-wall “creep” where the magnetization direction of a structure is found to change with time in fixed $H$.

In BEMM, a variation of ballistic electron emission microscopy, multiple thin ferromagnetic films separated by nonferromagnetic spacer layers are grown on a semiconductor substrate. A scanning tunneling microscope (STM) tip is then used to locally inject current into the multilayer film under typical constant current feedback conditions. A fraction of the injected electrons (typically, <10%) travel ballistically through the multilayer film and are collected into the underlying semiconductor substrate. This current $I_c$ is then measured and displayed as a function of the position of the tip to create a BEMM image. Hence, a BEMM image is a spatial map of ballistic current transport through the multilayer film. Contrast in these images is due to local changes in the relative magnetization directions of the ferromagnetic films. When the magnetization directions are parallel, $I_c$ is a maximum, whereas when the magnetization directions are antiparallel, $I_c$ is a minimum. This results mainly from an asymmetry in the inelastic mean-free paths between the majority and minority electrons in ferromagnetic films.

The samples investigated here are Si(111) substrates on top of which continuous layers of Au 70 Å/Cu 12 Å/Co 25 Å/Cu 50 Å are evaporated before a Py (45 Å) nanostructure is deposited. The structure is defined using a stencil-mask technique where a suspended silicon-nitride membrane (~150×150 $\mu$m$^2$), having holes of a desired shape etched in it, is used as a physical mask to define the pattern of the deposited nanostructures. The fabrication of the mask is performed using standard electron-beam lithography techniques and subsequent reactive ion etching to create holes in the membranes. Following the deposition of the continuous films, the silicon-nitride membrane is brought to within a few microns of the substrate surface and laterally registered to the 100×100 $\mu$m$^2$ device area. The Py is then deposited to form the nanostructures. Since each membrane has an array of structures patterned into it, a single nanostructure can be easily found. The end-to-end spacing of these structures is about 2 $\mu$m in order to keep the dipolar interactions between them negligible. The entire deposition process is carried out in an ultra-high-vacuum (UHV) environment with the substrate kept nominally at room temperature and in zero-magnetic field. The samples are studied in an attached room-temperature UHV STM/BEMM chamber.

Shown in Figs. 1(a)–1(h) is a series of BEMM images of a single diamond-shaped nanostructure in a varying $H$ applied parallel to its easy axis. Before the series begins, the magnetization directions of both the Py structure and underlying continuous Co film are saturated by applying $H$ ~250 Oe along the long axis of the structure. A smaller switching field is then applied along the same axis in order to investigate the reversal process as the relative alignment between the two layers changes from parallel (P) to antiparallel (AP) and back again. The switching field must be kept below ~25 Oe in order to avoid inducing domains in the underlying Co film. It has recently been shown that the stray fields from domain walls in one of the layers can induce local magnetic changes in the other as well. Therefore, to ensure that the contrast seen in the images can be unambiguously attributed to magnetic changes in the patterned Py structure,

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it was always checked that full magnetic P and AP alignment between the films could be obtained in each field cycle (except where noted below).

The "halo" of increased current observed around the edge of the structure results from a tapering of the Py film thickness around its circumference from shadowing during the evaporation and is not magnetic in origin. The width of this taper is typically around 20 nm on a side, which is roughly the grain size in the films. Due to the short hot-electron mean-free paths in ferromagnetic films (tens of Å), this results in increased values of $I_{\text{f}}$. The highest ballistic electron current values are obtained in regions away from the deposited nanostructures, where the electrons do not transport through any Py. For clarity, this background current is saturated to black in the images and a typical gray scale used to display contrast within the Py nanostructures. We note that the small scale (~20 nm) contrast observed in the interior of the structure is due to grain-to-grain variations in the ballistic transmissivity of the films, as has been discussed elsewhere.\(^7\)

In Figs. 1(a)–1(e), the typical magnetic switching behavior of the structure is shown where its magnetization direction reverses in an applied field of ~15–20 Oe. This type of binary behavior is typically observed in these structures as well as in similar shapes of smaller dimensions and thickness.\(^\text{12}\) The reversal occurs by the seeding of a domain wall near an end of the structure and its propagation through the element. An example of this process is shown in Figs. 1(f)–1(h). The switching is fairly robust in that a given element can usually be switched back and forth many times without any deviation from this type of binary behavior or reverting to "closure" states in zero-applied field. This same structure is shown back in zero field in Fig. 1(f) after having been brought into alignment with the bottom Co layer [Fig. 1(e)]. In contrast to the typical behavior, here an "end domain" has formed on the right-hand side of the diamond where the magnetization direction is strongly misaligned with the rest of the structure. This configuration, however, does not necessarily affect its switching characteristics. As shown in Fig. 1(h), the magnetization of the diamond can still be switched by applying nominally the same field as was previously required to do so. While not shown here due to space considerations, the subsequent switching behavior is very similar to that seen in Figs. 1(a)–1(e). We note that this behavior indicates that the contrast in Fig. 1(f) results from the magnetic structure in the Py film and not the underlying Co.

While the images thus far have shown that the magnetization of the diamond structure can be controllably and cleanly switched back and forth, this is not always the case for every field reversal cycle, as shown in Figs. 2(a)–2(d). In zero field, the magnetization of the structure is aligned with the underlying Co film, Fig. 2(a). As $H$ is applied in order to begin to bring the magnetization of the structure into AP alignment with the bottom Co layer, during this particular field cycle domains form on both ends of the structure, Fig. 2(b), which grow in size as $H$ is increased. Shown in Fig. 2(c) is the magnetic state when $H = 25$ Oe, the highest field applied during this cycle. While this is a larger field than typically required to saturate the structure, here there is a region of magnetic alignment between the two films running vertically in the right side of the diamond. In Fig. 2(d), the state of the structure is shown after the field has been turned off. The magnetization of the diamond has relaxed back into a state where only roughly half of the structure is oriented in the direction of the previously applied field. We attribute the magnetic structure seen in Fig. 2(c) to a 360° domain wall in the Py at that position. As has been recently reported by Portier and Pettor-Medford in much larger tunnel-junction structures, this results from the two walls formed by the end domains having opposite chirality and coalescing to form a stable 360° domain wall.\(^\text{16}\) It has been suggested\(^\text{15}\) that a small field applied along the hard axis of these structures should serve to cause the end domains to have the same direction and, hence, walls of the same chirality. In this case the walls would annihilate upon meeting, and so would result in much better switching behavior. We will examine this situation with BEMM in the future.

We have also investigated Py films patterned into rectangles having the same dimensions (1.5 × 0.3 μm²). Their...
switching behavior is very similar to that of the diamond structures in that their magnetization direction can be switched in a nominally binary fashion in applied fields of \( \sim 20 \text{ Oe} \). However, just as was the case with the diamond structures, during the switching process occasionally a 360° wall is formed in the interior of the rectangle, which prevents the complete reversal of its magnetization. An example of this is shown in Figs. 3(a)–3(e) in somewhat more detail than was shown in Fig. 2. These images also show small regions, \( \sim 100 \text{ nm} \) in extent, which are in neither complete \( P \) nor AP alignment with the Co sense layer as is commonly seen during the reversal process, e.g., the lower middle region in Figs. 3(a) and 3(b) or the top right of Figs. 3(c) and 3(d). We note that while in these images the absolute measured current through the structure is higher, the magnetic contrast is lower than in the images shown in the previous figures. This is an example of a general trend in this system of decreasing contrast with increasing injection bias, which will be discussed in more detail elsewhere.

Domain-wall ‘‘creep’’ is sometimes, but not regularly, seen in these Py nanostructures at intermediate steps in a field cycle. An example of this is shown in Figs. 4(a)–4(c), in which three sequential images taken in a fixed \( H = 10 \text{ Oe} \) are shown. While this is a field typically too low to switch the structure, the magnetization direction changes from \( P \) to AP alignment with the underlying Co layer in the middle of the scan in Fig. 3(b) (events where the relative magnetization changes from \( AP \) to \( P \) have also been seen). We do not believe that this change is induced by a magnetic perturbation from the STM tip, as it is a nonmagnetic etched W tip. It is possible, although unlikely, that magnetic material has been transferred from the sample to the tip at some point during the scanning process. However, even if this has occurred, the amount of material transferred should at most be a few tens of atoms, which will not produce the required stray field \( \sim 10 \text{ Oe} \) to induce the switching event seen in Fig. 4(b). We also note that the current densities involved here are much too low to induce spin-transfer effects.\(^{14} \) We, therefore, conclude that it is a thermally activated switching event resulting from weak local pinning of the magnetization direction in \( Py. \)\(^{15} \) The data acquisition rate for these images is \( \sim 2 \text{ ms/pixel} \), and so does not presently allow us to measure the switching time for such an event.

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\(^{13}\)A. Arrott (private communication).