Ballistic electron magnetic microscopy studies of magnetization reversal in Co/Cu/Co trilayer films

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We have used ballistic electron magnetic microscopy to image, with nanometer resolution, the magnetization behavior of Co/Cu/Co trilayer films in the presence of a magnetic field. Films prepared both by thermal evaporation and by magnetron sputtering have been studied. In each case we have observed both large, ~500 nm, domain structures, and much smaller, apparently randomly dispersed, regions of magnetic misalignment between the Co layers that persist to fields >100 Oe. We find the details of the ballistic electron transport through the films to be different on small length scales, ~50 nm, for the two types of growth methods. © 2000 American Institute of Physics.

Driven by the discovery and application of the novel transport properties of magnetic multilayer systems, there has been a great deal of interest in the magnetic structure of thin ferromagnetic films. While much information on the micromagnetic properties of these films has been gained from modeling their transport properties and magnetization curve behavior,¹ there has been little direct investigation of the relative magnetization alignments of ferromagnetic films in multilayer stacks in a magnetic field. Techniques that can directly image the magnetic structure of films are of limited resolution, or cannot be used in the presence of a magnetic field.² There have, therefore, been limited microscopy studies of the magnetization reversal processes in thin films, and none that have been able to look at the relative magnetic orientation between a surface and buried layer. Here we present results from ballistic electron magnetic microscopy (BEMM)³ measurements taken on Co/Cu/Co trilayers, showing their magnetization behavior in complete field cycles.

In BEMM, a variation of ballistic electron emission microscopy (BEEM),⁴,⁵ 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 a hot-electron current Iₜ into the film under typical constant-current feedback conditions. A small fraction of the injected electrons (typically <10%) will travel ballistically through the multilayer film and into the underlying semiconductor substrate. The current flowing into the semiconductor is then measured (the collector current, Iₑ) and displayed as a function of the position of the tip, creating a BEMM image. Hence, a BEMM image is a spatial map of ballisitic current through the multilayer film. Contrast in these images is due to local variation in the relative magnetization alignment between the Co films. When the films are ferromagnetically (F) aligned, Iₑ is maximum, whereas when the films are antiferromagnetically (AF) aligned, Iₑ is minimum. This results from a large difference in the hot-electron attenuation lengths for majority and minority electrons.⁶

The samples used in this study consist of Co/Cu/Co trilayer films grown on a H-terminated Si(111) substrate that have been precoated with a Cu (9 Å)/Au (75 Å) layer. We use the Au to form a high-quality Schottky barrier interface and the Cu to seed the Co layer. The two Co layers are separated by a ~45 Å Cu spacer layer, leaving them only weakly coupled by indirect exchange.⁷ Samples will we discuss here were grown both by thermal evaporation and by magnetron sputtering. The thermal deposition was carried out in an ultrahigh vacuum (UHV) with the pressure remaining <5×10⁻¹⁰ Torr during evaporation, and the samples then vacuum transferred to a room-temperature UHV-BEMM chamber for study. For the sputtered samples, we first evaporated an Au layer on the Si surface. We next sputter deposited the Cu seed layer and ferromagnetic trilayer, and then overcoated this with a Cu (9 Å)/Au (25 Å) layer. The final Au layer prevents oxidation of the sample while being transferred through atmosphere to the BEMM chamber. Sputtering Au directly onto the H-terminated Si substrate routinely gives devices of poor quality, in that their zero-bias resistances are typically more than 100 times lower than evaporated films and their low voltage characteristics deviate significantly from the expected behavior predicted by thermionic emission.⁸

Shown in Figs. 1(a)−1(h) is a series of typical large area (2.5×2.5 μm²) BEMM images from an evaporated Co (30 Å)/Cu (45 Å)/Co (30 Å) trilayer film taken at a fixed position in a varying H applied parallel to the film plane with a tip bias Vᵣ = −1.5 eV. The series begins by showing the magnetic structure with the film in the as-prepared state, with no field having been applied. In these Co/Cu/Co trilayers we typically find magnetic domains with a characteristic length scale of ~500 nm, but we also see magnetic structure on much smaller length scales. For instance, in Fig. 1(a) within a region of a given overall alignment, small regions ~100 × 100 nm² having the opposite alignment are regularly observed, as are very thin (<100 nm) fingerlike structures. In Fig. 1(b), we show the magnetic structure of the film in an applied field of H=30 Oe. While much of the region is magnetically aligned, there is still a large AF-aligned region in the left part of the image. As the applied field is increased
misaligned regions do not reappear in the same places in different field cycles, they cannot be caused by a localized antiferromagnetic coupling between the Co layers, nor are they correlated with individual grains in the films, which are \(~10\,\text{nm}\) in size. We conclude that these small, misaligned regions, which appear to strongly influence the details of the magnetization behavior, arise randomly from the interplay of the various magnetic interactions, both dipolar and exchange, that are acting between and within the ferromagnetic layers.

In Fig. 1(f), we show the magnetic state of the same sample after we have applied a reverse field, \(H = -30\,\text{Oe}\). Here the domain walls are much less irregular than seen previously, which we find is generally the case after the initial application of a saturating field in the opposite direction. In Fig. 1(g) we show the state of the sample in \(H = -70\,\text{Oe}\). In this case, in addition to the slightly misaligned regions that are distributed throughout the image, there is a \(360^\circ\) domain wall that runs from the upper-right to the lower-left part of the image. In the bottom left of the image a double wall is seen. We were unable to change this structure with fields up to \(~100\,\text{Oe}\). Such structures are often, but not regularly, seen in our images. Sometimes they are clearly seeded by a film defect; in other cases no clear cause of the wall is detectable. In the last image of the series, Fig. 1(h), we have lowered \(H\) back to zero. The wall in the previous image seems to have led to the AF-aligned region extending from the upper-right part of the image.

Shown in Figs. 2(a)–2(b) are large area \((2.5 \times 2.5\,\mu\text{m}^2)\) scans of a sputter-deposited Co (20 Å)/Cu (45 Å)/Co (30 Å)/Cu (9 Å)/Au (75 Å)/Si (111) multilayer film is thermally evaporated. The images show the magnetic structure in (a) the as-prepared state, and in fields of (b) \(H = 30\,\text{Oe}\), (c) 40 Oe, (d) 60 Oe, (e) 0 Oe, (f) \(-30\,\text{Oe}\), (g) \(-70\,\text{Oe}\), and (h) 0 Oe. Currents are represented in a linear gray scale from 0.5 pA (black) to 2.5 pA (white). \(V_r = -1.5\,\text{V}\) and \(I_e = 5\,\text{mA}\).

to \(H = 35\,\text{Oe}\) (not shown) and \(H = 40\,\text{Oe}\) [Fig. 1(c)], this region shrinks in size while passing the same \(I_e\), indicating that the reversal process is occurring through the motion of domain walls rather than domain rotation. When we increase the field to \(H = 60\,\text{Oe}\), the sample is put into a state of near magnetic saturation, Fig. 1(d). There are still, however, regions of slight magnetic misalignment throughout the film. These are regularly seen in our samples and persist in fields up to \(~100\,\text{Oe}\) (the highest \(H\) in which we have imaged films to date). We find that these regions of slight misalignment become more magnetically misaligned and grow in size as \(H\) is reduced to zero, Fig. 1(e). In general, due to these small, persistent misalignments a sample is typically left in a state that is only \(~80\%\) saturated at \(H = 0\). As the high-field

FIG. 1. (a)–(h) Set of BEMM images \((2.5 \times 2.5\,\mu\text{m}^2)\) taken at a fixed position in a varying \(H\) field applied parallel to the film plane. The Co (30 Å)/Cu (45 Å)/Co (30 Å)/Cu (9 Å)/Au (75 Å)/Si (111) multilayer film is thermally evaporated. The images show the magnetic structure in (a) the as-prepared state, and in fields of (b) \(H = 30\,\text{Oe}\), (c) 40 Oe, (d) 60 Oe, (e) 0 Oe, (f) \(-30\,\text{Oe}\), (g) \(-70\,\text{Oe}\), and (h) 0 Oe. Currents are represented in a linear gray scale from 0.5 pA (black) to 2.5 pA (white). \(V_r = -1.5\,\text{V}\) and \(I_e = 5\,\text{mA}\).
films consisting of only a single Co layer, and is not affected by saturating the magnetization of a sputtered sample with an $H = 10$ kOe field, we conclude that it is not magnetic in nature. It may perhaps be due simply to grain to grain variations in the crystal structure of the film, e.g., different relative in-plane orientations of the (111) normal Co and Cu grains, or, we believe more likely, it may be due to an orientation-dependent intermixing at the Co/Cu interfaces as a result of the energetic sputtering process.

In Figs. 2(e) and 2(f), cross-sectional views of the collector current are shown from the sputtered and evaporated films, respectively, as taken at the positions indicated in the images above them. The collector current is seen to change by roughly a factor of 2 between the AF-aligned regions to the F-aligned regions, for both types of films. The overall current in the sputtered film is, however, about a factor of 2 less than that of the evaporated film. This strong difference in the ballistic electron current is typically seen between analogous Co/Cu/Co samples prepared by the two different methods. We note that evaporating a Cu (9 Å)/Au (25 Å) bilayer on top of the evaporated trilayer samples reduces the collector current by only $\sim 20\%$, indicating that the change in $I_c$ is a result of the method used in film growth, and is presumably an indicator of the higher defect density found in sputtered films.

The transition between regions of magnetic alignment and misalignment (domain walls) are found to occur on many different length scales in both types of films. For instance, the transition occurring on the left side of the sputtered film shown in Fig. 2(c) takes place in $\sim 10$ nm, while the transition on the right side of the image takes place over a distance of several hundred nanometers. In the evaporated film image shown in Fig. 2(d), the magnetic transition occurs over a distance of $\sim 100$ nm. We have examined both types of Co/Cu/Co trilayer films for a Co layer thickness ranging from 1.2 to 5.0 nm. In general, all samples display both very narrow and quite wide domains walls, with the most typical domain wall width being $\sim 100–200$ nm.

ACKNOWLEDGMENTS

We thank A. C. Perrella for useful discussions and assistance. This research was supported by DARPA through ONR, and by the National Science Foundation through the Cornell Center for Materials Research and through use of the National Nanofabrication Users Network.

2. For an overview see A. Hubert and R. Schäfer, Magnetic Domains (Springer-Verlag, Berlin, 1998).