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Slow magnetization dynamics of small permalloy islands

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The conditions that lead to specific domain configurations and the associated switching characteristics of small permalloy islands were studied by using magnetic force microscopy. By measuring a large number of particles, it was established that islands that have nonzero remanent moments (nonsolenoidal) exist in one of three distinct configurations, namely: (a) true single domain, (b) quasisingle domain with edge closure patterns, and (c) multidomain with nonuniform internal magnetization. The configuration depended upon the island width as well as the aspect ratio. Islands that are 310 nm wide or less are true single domain particles at low aspect ratios (~1.87) and higher, while islands wider than 500 nm always exhibited edge closure domains even for very large aspect ratios. In the range between 310 and 500 nm, the onset of single domain behavior was a function of the aspect ratio and thickness. Our studies involving *in situ* applied field similarly revealed the mechanisms of the reversal processes for each of the configurations, which correlated quite well with the values of the switching fields. [S0021-8979(00)37308-X]

I. INTRODUCTION

In previous work, we studied the domain configurations of mesoscopic size permalloy elements[1] and characterized the motion of the domain walls as a function of applied magnetic field.[2] It was verified that the remanent configurations of 25 nm thick islands with lateral dimensions on the order of microns can be classified into seven unique configurations depending upon the aspect ratio. Four of these were solenoidal, i.e., closure patterns formed to produce a zero net moment; while the rest were nonsolenoidal and exhibited finite net magnetic moments.[3] The distinction between the solenoidal patterns were related to the number of domains and the presence of crossties and other inclusions, while the differences among the nonsolenoidal configurations reflected either pure single domain character or the presence of multidomains at the edges and in the interior regions. In the present study, we are interested in ascertaining the conditions that lead to specific domain formation and in understanding the switching behavior as a function of field application along the easy axis.

The samples consisted of arrays of rectangular NiFe islands with lateral dimensions ranging from 50 nm to 4 μm, and had well-defined aspect ratios. The thickness ranged from 23 to 80 nm. They were deposited on Si substrates using thermal evaporation and patterned using e-beam lithography and lift-off.[4] The samples were imaged using the magnetic force microscopy (MFM). In the switching experiments, an in-plane magnetic field was applied while imaging with the MFM, which was sequentially varied to induce the magnetization reversal. Some samples were comprised of arrays of identical islands, which were used to obtain the statistical distribution of certain parameters such as switching field and domain characteristics. Details of the sample preparation and experimental techniques are described elsewhere.[4]

II. RESULTS AND ANALYSIS

Representative MFM images of the three unique configurations that exhibit the so-called nonsolenoidal remanent configurations are shown in Fig. 1. All three contain distinctive bright and dark contrasts near the edges denoting the presence of magnetic charges.

Figure 1(a) is a classic manifestation of a single domain (SD) particle.[5] The featureless interior region indicates a uniform magnetization that is oriented parallel to the long axis of the island, and magnetic charges are formed at the ends due to the discontinuity of the magnetization at the surface.

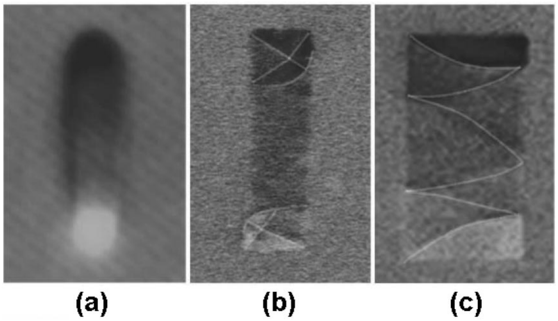

FIG. 1. Characteristic structures of nonsolenoidal patterns: (a) single domain (0.37 μm×1.34 μm), (b) edge closure (0.5 μm×2 μm), (c) complex structure (2 μm×4 μm).

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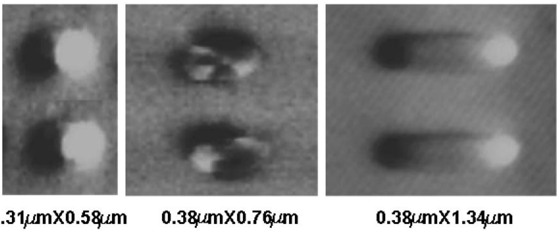

FIG. 2. Comparison of single and multidomain pattern formation in submicron permalloy elements. This shows the sensitivity of single domain formation with the particle width.

By studying a large number of such particles, we verified that the formation of single domain particles has a very strong dependence on the particle width as well as aspect ratio. To illustrate the effect of the width, Fig. 2 shows two ensembles of noninteracting islands, prepared under identical conditions but with slightly different sizes. The smaller islands have dimensions 0.31 μm$\times$0.58 μm$\times$0.035 μm (aspect ratio=1.87), while the larger islands have dimensions 0.38 μm$\times$0.76 μm$\times$0.035 μm (aspect ratio=2). The difference in domain characteristic is quite striking: one clearly sees that despite having lower aspect ratios, the smaller islands are exclusively single domain. This suggests that the width is primarily responsible for the difference, and we can assign 310 nm as the critical width for the formation of single domain at low aspect ratios in these islands. We further examined islands with 23 and 55 nm thicknesses of similar sizes, and found the same critical width. The multidomain character of the 350-nm-wide particles persists even as the length increases, but eventually reverts into single domain behavior when the aspect ratio reaches a specific value, which depends upon the thickness. These transitions occur at the lengths: 0.97 μm (AR=2.43) for 23 nm thickness, 1.34 μm (AR=3.62) for 35 nm thickness, and 1.57 μm (AR =4.13) for 55 nm thickness. The trend in forming single domains is towards increasing aspect ratio with increasing thickness. However, we also discovered that single domain (SD) formation occurred at a much lower aspect ratio (2.95) for thickness of 80 nm. This anomaly may arise from the crossover from Néel to asymmetric Bloch wall types.[6]

The magnetization of the SD particles is bistable and the MFM measurements with applied field merely show the reversal of the bright/dark contrast in the middle of the scan whenever the switching field is reached. More interestingly, by counting the number of domains that switched as a function of the field, we were able to form the switching field distribution of the islands. The switching distributions were symmetric and peaked functions. For the islands in which measurements were made, namely, 1.34 μm$\times$0.37 μm (AR =3.62) and 2.21 μm$\times$0.37 μm (AR=5.9), the curves were centered at 40 and 120 Oe, respectively, with nearly identical spread (FWHM) of about 40 Oe.

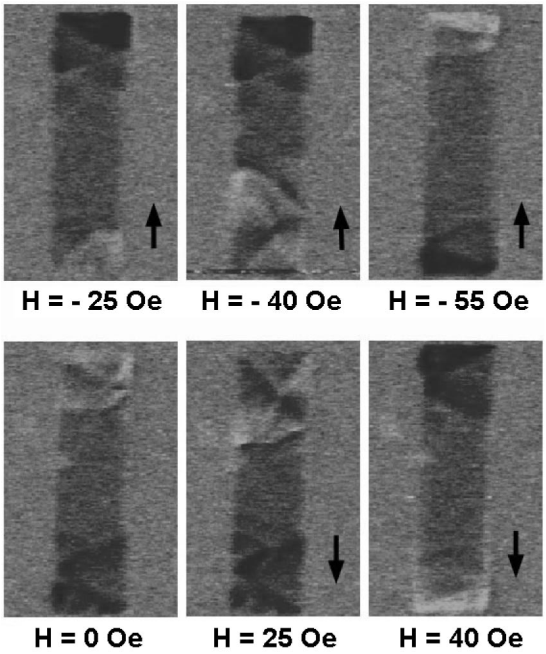

FIG. 3. Magnetization reversal mechanism of a 1 μm$\times$4 μm permalloy island with closure end domain structures. (Arrows indicate the direction of applied field.)

By considering other islands, we identify another important demarcation with regards to single domain behavior. Islands having width equal to or larger than 0.5 μm were never observed to be true single domain particles. Instead, the patterns exhibit uniformly magnetized internal regions bounded by closure domains at the ends. This pattern has been identified previously by using Lorentz electron microscopy,[3] and a representative MFM image is shown in Fig. 1(b). We analyzed islands up to 4 μm long, and determined that the structure and size of the closure domains are invariant with length. Increasing the length merely increased the interior area where the magnetization is constant. In contrast to the SD particles, these particles do not possess perfectly rectangular magnetization loops since the process of switching occurs gradually with applied field.[3] Representative images of a complete cycle involving two switching events are shown in Fig. 3. The onset of the switching commences by the migration of the edge domain walls towards the middle of the island. Wall motion starts at roughly 25 Oe lower than actual switching field and continues with increasing field until the spontaneous reversal. Switching is evident as the reversal of contrast of the closure domains, which diminish in size with increasing field. In the two events illustrated in Fig. 3, the switching fields are −55 and 40 Oe. The fact that the fields are not equidistant to zero suggests some induced anisotropy in the films or some hysteresis in our electromagnet.

Now we consider the magnetization reversal of patterns that have nonuniform internal magnetization as represented in Fig. 1(c), but nevertheless possess a net magnetic moment at remanence. This structure is ubiquitous in islands that have widths larger than 1 μm and low aspect ratio after saturation. We observed this pattern to occur even in islands with aspect ratio of 1, albeit a slight application of a negative field causes it to revert to a closure configuration. Thus, the reversal mode involves the formation of an intermediate solenoidal state. An example of this process is shown in Fig. 4 for a 3 μm $\times$4 μm pattern. The nonuniform magnetization at zero field is exhibited by the presence of several meander-

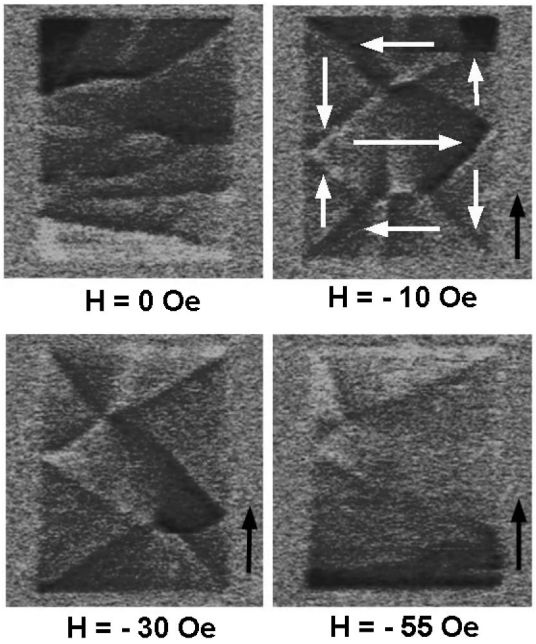

FIG. 4. Magnetization reversal mechanism of a 3 μm×4 μm permalloy island with complex internal domain structures. (Dark arrows indicate the direction of applied field.)

ing domain walls in the interior region. Despite its nonuniformity, localized dark and bright areas exist on the upper and lower portions, implying that the pattern has a nonzero net moment. This configuration, however, is unstable and it spontaneously becomes solenoidal with reverse field. Domain walls move with increasing field, as domains that are parallel with the magnetic field expand. At -10 Oe, a seven-domain configuration composed of well-defined 90° and 180° walls has emerged, and the magnetic charges at the ends have diminished. Arrows were drawn in the figure to denote the magnetization directions of the domains. The triangular domains on the 2 o'clock and 7 o'clock positions are favorable with the applied field and they expand with increasing field. The expansion occurs at the expense of the other domains, which are oriented either antiparallel or perpendicular to the applied field, and causes distortion of the patterns. The size of the central region diminishes, until the switching field is reached when the growing domains coalesce. Magnetic charges again accumulate at the end regions, and the pattern develops a net moment in the direction of the applied field. Variations of this type of switching have been observed in other islands as well. The emergence of the solenoidal intermediate state appears to be a universal attribute of relatively large islands.

Finally, we comment on the dependence of the switching fields on the domain configurations. Our results show that the switching field of single domain particles is strongly dependent upon the aspect ratio. Nearly square or circular single domain particles have switching fields of several Oe, while particles of 1:6 aspect ratio have switching fields of 120 Oe. Others have also reported switching fields of nearly 700 Oe for permalloy particles of 1:10 aspect ratio.[5,7] This could be explained on the basis of the coherent rotation model, wherein the shape-induced anisotropy term increases with aspect ratio. Others, who used *ab initio* micromagnetic calculations, also predict the strong dependence of single domain switching field with aspect ratio and the reduced width (=width/thickness).[7] The numerical calculations also predicted a state with no remanence for aspect ratio of 2.3, which was not experimentally observed for 0.41 μm×0.175 μm×0.05 μm, and the prediction for squareness deviated substantially with the experimental results at the lowest aspect ratios (<4).[7] We regard the calculations as correct in describing the hysteresis of multidomain particles, which occur for the larger particles. The prediction of zero remanence can be construed as being consistent with those particles that form solenoidal intermediate states. As far as the multidomain islands are concerned, our results show weak dependence on aspect ratio. Indeed for both of the aforementioned multidomain configurations, the switching field occurs at roughly the same value of about 50 Oe, and independent of the aspect ratio. This is reasonable since switching is induced by the movement of the closure domains. As the data suggest, the size of the end closure domains does not change with aspect ratio, so that the energy or the strength of the magnetic field to move them should be invariant with size as well. Similarly, those islands that form intermediate closure patterns are expected to have weak dependence on the aspect ratio, since the motion of 90° or 180° walls is independent of the aspect ratio. One possible factor that could affect the switching field is the number of crossties or other inclusions that appear on the domain walls. These features, of course, depend upon the size and geometry of the islands.

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