Switching characteristics of submicron cobalt islands

R. D. Gomez[a] and M. C. Shih
Department of Electrical Engineering, University of Maryland, College Park, Maryland 20742

R. M. H. New
IBM Almaden Research Center, 650 Harry Road, San Jose, California 95123

R. F. W. Pease
Department of Electrical Engineering, Stanford University, Stanford, California 94305

R. L. White
Department of Material Science and Engineering, Stanford University, Stanford, California 94305

(Received 2 January 1996; accepted for publication 14 March 1996)

The magnetic characteristics of $0.2\times0.4\times0.02\ \mu m^3$ cobalt islands were investigated using magnetic force microscopy in the presence of an applied field. The islands were noninteracting and showed a wide variety of single and multidomain configurations. The distribution of magnetization directions supports earlier models which suggest that crystalline anisotropy plays a dominant role in establishing a dispersion of easy axis directions about the long axis of the particles. The magnetic evolution, involving rotation and switching of individual islands, was observed at various points along the microscopic magnetization curve. A magnetization curve of an ensemble of islands was derived from the images and compares remarkably well with macroscopic $M-H$ measurements.
 [S0021-8979(96)07312-4]

I. INTRODUCTION

Submicron magnetic particles have become of increased interest in recent years both because of their potential as high-density magnetic storage media and because they provide a vehicle for exploring the switching dynamics of single-domain particles. This interest has been spurred by the recent development of techniques for synthesizing magnetic nanoparticles of controlled size and spacing and the parallel development of high-resolution tools for characterizing the magnetic structure of these particles.[1–3] We report here the use of such a high-resolution tool, magnetic force microscopy (MFM), to image the magnetic structure of polycrystalline cobalt islands. In particular we report high-resolution images taken in the presence of a magnetic field, allowing one to observe in detail and to compare the switching processes in individual magnetic nanoparticles.

We have used direct write electron-beam lithography to synthesize submicron thin-film islands of both polycrystalline cobalt and epitaxial [110] iron. The iron particles remain single domain up to sizes as large as $1\times3\times0.02\ \mu m^3$, but the polycrystalline cobalt islands show a rich and complex magnetic structure down to dimensions on the order of $0.15\times0.2\times0.02\ \mu m^3$.[4,5] This article describes observations on $0.2\times0.4\times0.02\ \mu m^3$ polycrystalline cobalt islands which are large enough to readily exhibit this complex magnetic behavior.

II. MFM IN THE PRESENCE OF AN APPLIED MAGNETIC FIELD: A STUDY OF SUBMICRON MAGNETIC PHENOMENA

The apparatus for our experiments consists of a commercial Nanoscope III scanning probe microscope and a custom-built C-shaped electromagnet positioned so that the sample being scanned lies in the air gap. By adjusting the current delivered to the electromagnet, a well-controlled magnetic field can be applied parallel to the sample surface. With this arrangement magnetic fields up to ±2500 Oe can be obtained, and thermal drifts due to resistive heating are low enough to permit a specific area to be imaged without difficulty. More detailed descriptions of the electromagnet and its use are given elsewhere.[6]

Using this apparatus, a series of MFM images was taken with successive values of externally applied magnetic field to understand how the magnetic configuration of the islands changed with the field. By this means, the magnetic features of the islands, some as small as 25 nm, were apparent and the evolution of these features was monitored as each island progressed through various magnetization states.

It has been shown previously how different MFM images can be manifested on the same sample, depending upon the magnetic orientation of the probe.[6] For the apparatus described above, both the probe and sample are subject to the horizontal field during imaging, and both can have their magnetizations states altered by sufficiently strong fields. It is thus important to anticipate the effects due to variations of the probe and distinguish them from those that reflect actual changes in the sample magnetization.

For probes magnetized perpendicular to the sample surface, along the z direction, the cobalt islands (most of which are approximately magnetized in plane) should appear as bright and dark regions with intensity corresponding to the distribution of magnetic charges or north and south poles. For very large horizontal fields applied in the x direction, we might expect the tip magnetization to rotate so as to partially align itself with the field, and the magnetic image would then depend on the x component of the sample fields rather than the z component. In this case, the intensity of the magnetic

[a]Electronic mail: mel@lps.umd.edu

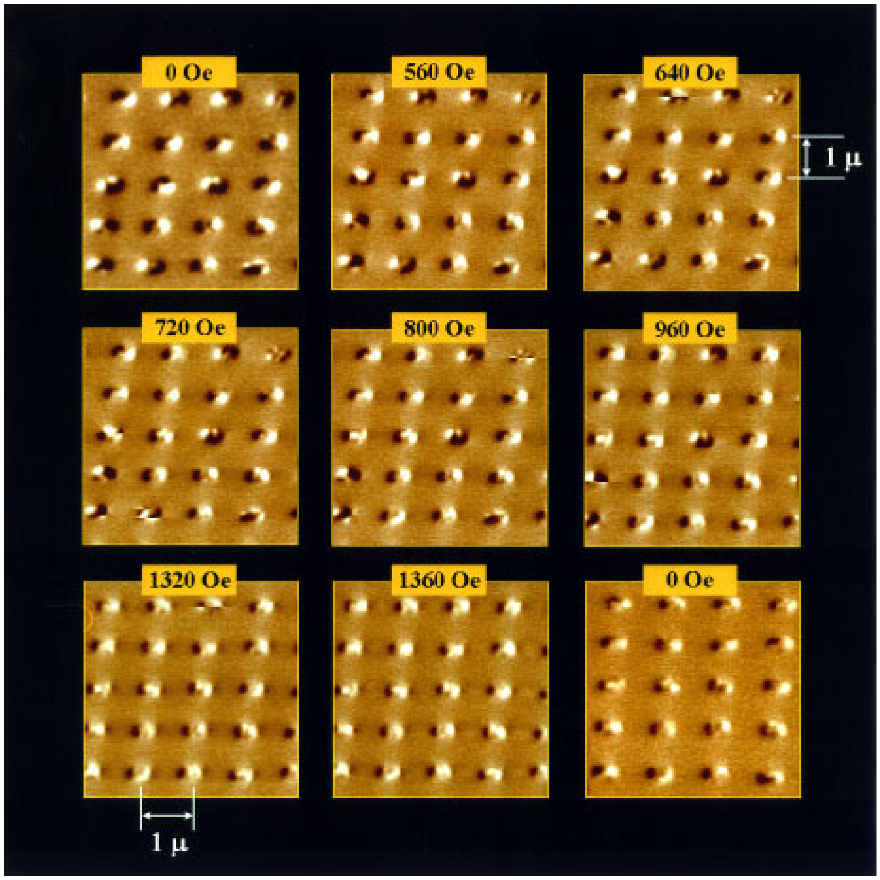

FIG. 1. Microscopic magnetic evolution of $0.2\times0.4\times0.02$ μm^3 cobalt islands with magnetic field.

images would correspond more closely to the x component of the magnetization rather than the magnetic charge distribution. Thus, uniformly magnetized islands would appear either uniformly bright (or dark, depending upon the magnetization state), with subtle darkening (brightening) at both ends. For intermediate fields, with a tip only partially reoriented, the magnetic image would be a mixture of x- and z-component images. Clearly, if the coercivities of the tip and sample are comparable, the interpretation of the images becomes quite complicated. To circumvent these difficulties, we carefully selected probes which have coercivities higher than the sample switching fields and kept the external fields below 1400 Oe. The images presented here were obtained under these conditions, and subtle probe-induced effects can be discerned only at the largest applied fields.

III. SYNTHESIS AND STRUCTURE OF THE COBALT NANOPARTICLES

Hexagonal polycrystalline films 200 Å thick were deposited at room temperature by dc magnetron sputtering upon a 500 Å chromium undercoat on an oxidized silicon substrate. The chromium underlayer was used to impart a texture to the cobalt film, so that the c axes of the cobalt grains were in plane and randomly oriented. Direct write electron-beam lithography and a multistep masking and milling process were used to pattern islands with feature sizes down to 0.1 μm.[7] We have reported elsewhere that cobalt islands smaller than

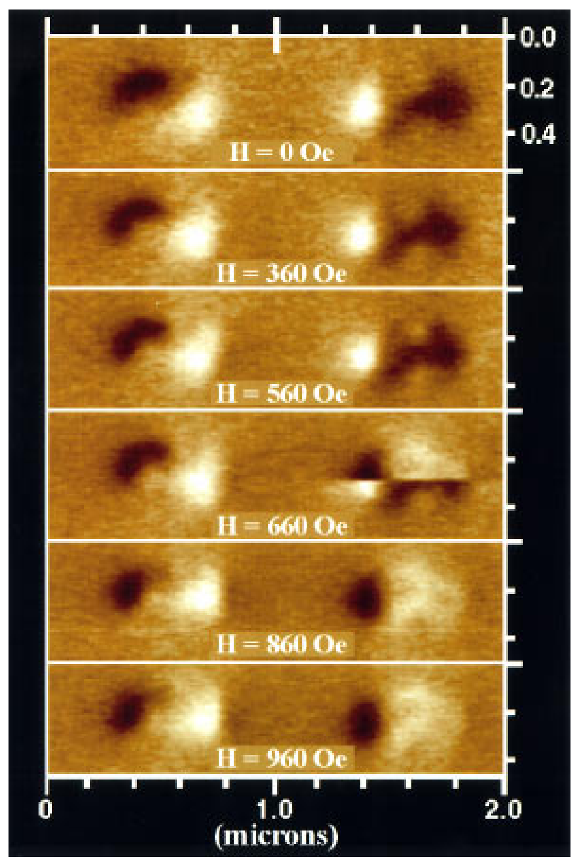

FIG. 2. Enlargement of islands (1,1) and (1,2) of Fig. 1 showing rotation and switching processes.

about 0.15 μm are mostly single domain,[4] but islands 0.2 $\times$0.4 μm^2 show a rich variety of magnetic configurations; observations of these magnetic configurations are the subject of this article.

To understand the complex behavior of the polycrystalline cobalt islands we examine some of the magnetic parameters involved. For a uniformly magnetized 0.2$\times$0.4$\times$0.02 μm^3 cobalt particle magnetized along its long axis, the demagnetizing field is approximately 500 Oe. The same particle magnetized along the shorter in-plane direction would have a demagnetizing field of 1400 Oe. Normally the difference in these two fields tends to keep the magnetization oriented along the long axis of the island; however, this tendency is often thwarted to some degree by the magnetocrystalline energy of the film. For cobalt, the magnetocrystalline anisotropy field for an individual grain (given by $2K_u/M$, where K_n is the uniaxial anisotropy constant and M is the magnetization) is roughly 6300 Oe much larger than the demagnetizing fields mentioned above. For a polycrystalline island composed of many grains, the crystalline energy will average to zero if enough grains are included in the island. For our particles the number of grains is finite and not very large. For a very small uniformly magnetized island, the expected total net anisotropy of an island can be calculated by treating the computation of the net anisotropy field as a random walk problem: The randomly oriented magnetocrystalline anisotropy from each grain adds to the fixed shape anisotropy. The result is a dispersion of the net ''easy'' magnetization direction about the long axis of the particle. This calculation and experimental confirmation of it have been reported previously.[8]

The situation in the cobalt islands reported here is much more complex than contemplated by the above calculation because the assumption of uniform magnetization is less well justified for larger islands. The MFM images of these islands indicate that many if not most of them have a multidomain structure. Much of this tendency to break up into domains is due to the magnetic inhomogeneity of the polycrystalline cobalt film. In such a film, we expect exchange across grain boundaries to be weaker than within a grain, so the formation of domain walls at grain boundaries may be energetically inexpensive. Even within a cluster of strongly exchange coupled grains, the magnetization will rotate so as to align itself with the strong local magnetocrystalline anisotropy. The exchange length root K/A, where A is the ''exchange stiffness'' and K is the axial anisotropy constant, figures prominently in calculations of domain-wall widths and provides an estimate of the distance over which spins will twist against the exchange field to align themselves with a magnetocrystalline anisotropy field. For cobalt the exchange length is 100 Å, smaller than most grains, so we expect magnetization ripple on this scale even for films with strong intergrain exchange coupling.

Because of the strong magnetocrystalline anisotropy of cobalt, and the random orientations of the grains in a polycrystalline film, the magnetization can never be completely uniform. Therefore, in the context of this article, our use of the term single domain is not a rigorous one: We apply it to islands which are almost uniformly magnetized and contain no obvious domain walls. In this sense, a single recorded bit on a hard disk is also single domain, even though there is magnetization ripple within the bit.

IV. OBSERVED MAGNETIC CHARACTERIZATION OF COBALT ISLANDS

Figure 1 shows the MFM images of an array of cobalt islands and traces their behavior as a magnetic field of increasing magnitude is applied along the long axis of the islands. The islands are initially in an ac demagnetized state, and we believe that the island spacing is sufficiently large that the interaction between islands is negligible. We see, in the demagnetized state, a variety of magnetic configurations. The single-domain islands show a bright spot on one end and a dark spot on the other. Clearly, many of these particles are multidomain, and even the single-domain islands show significant variation in their magnetic configuration. Figure 2 is an enlarged image of two single-domain islands. Quite obviously the detailed magnetic configuration of these two particles is quite different, as evidenced by the concentration or diffuseness of their poles and by the differing separation of poles. These differences presumably are manifestations of the small deviations or ripple in magnetization discussed above.

We now follow the magnetic behavior of these particles as the applied field is increased. The variety of behaviors observed is so great as to defy simple classification. However, if we identify the particles in Fig. 1 by their row and column (r,c), we can consider specific examples, as follows.

(1,1) This is the ''best behaved'' island (shown enlarged in Fig. 2). In zero field it is single domain with a polar axis at an angle of some 30° to the island's long axis. As the applied field increases, its axis of polarization rotates toward the applied field. Islands (3,4), (2,3), (2,4), and (4,2) have similar behavior.

(3,1) This island is multidomain in zero field. The most adverse domain coalesces with a perpendicular domain at modest fields and finally, at higher fields, the island is multidomain again with two domains of more favorably orientation appearing. Island (5,4) has similar behavior.

(3,2) This island is quasi-single domain in zero field but breaks into a more complex structure in fields above about 560 Oe.

(1,2) This island, enlarged image also shown in Fig. 2, is quasi-single domain in zero field, shows some structure in modest fields, and switches at 640 Oe. This island switched during the scan process presumably due to the fields applied by the probe. The upper and lower halves (before and after switching) can be seen to be mirror images of each other. Islands (1,3) and (5,2) also belong in this category.

(3,3) This island is multidomain at zero field and remains multidomain after switching. Island (1,4) has similar behavior.

(4,1) This island is multidomain at zero field, shows little variation with increasing field until about the switching field of 960 Oe.

(2,1), (2,2), (4,3), (4,4) These islands are either quasisingle or multidomain at zero field and aligned favorably with

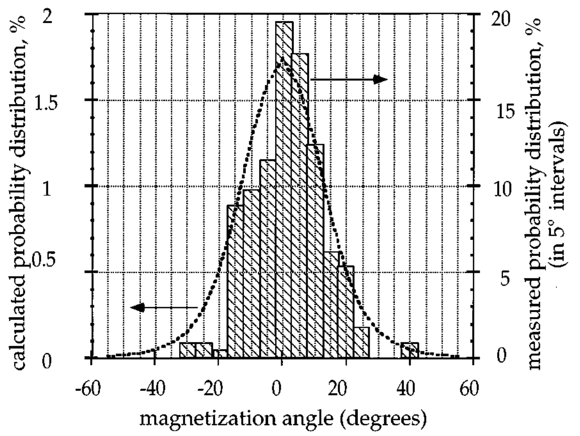

FIG. 3. Distribution of the easy axes of the islands. The histogram distribution, in 5° intervals, was derived from 80 islands at remanence; the solid curve is a recalculation based on the model from Ref. 5.

the applied field. They remain more or less unaffected by the field.

From these images, it is clear quite clear that switching was almost always induced by the scanning probe, which suggests that actual switching field for these particles is the sum of the applied field and the stray field from the probe.

The last image in Fig. 1 shows the remanent configurations as the field was brought back to zero. It is interesting to note that in some islands, particularly in multidomain islands (1,4) and (4,1), the domain configurations appear to be similar before and after applying the field. By carefully examining the two images at zero field it is clear that the external field has reversed the contrast but the domain boundaries remain virtually in the same places. This observation, although by no means definitive, is consistent with the notion that these islands are composed of a small number of weakly interacting grains. The grains switch independently and consequently preserve their intrinsic boundaries within an island.

From these few examples and by looking at the behavior of other islands in Fig. 1, we see very individualized behavior from island to island. Clearly, the random anisotropy in the grains and the weakened exchange at grain boundaries produce local environments which dominate the behavior of any given particle. We believe this is the first time such complex behavior of submicron particles has been documented, a documentation made possible by high-resolution MFM.

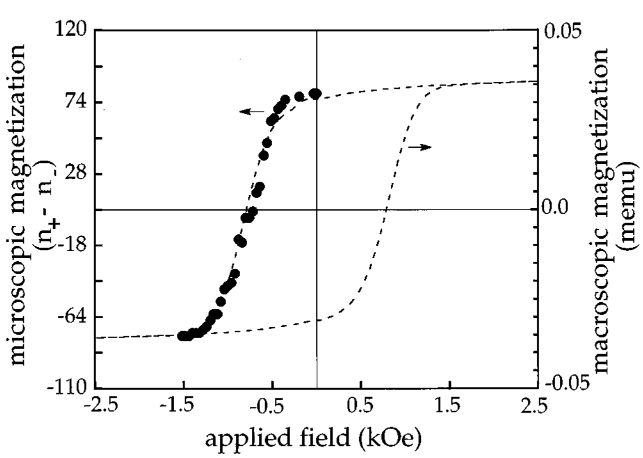

FIG. 4. Microscopic and macroscopic magnetization curves of these islands. The microscopic curve was derived from a set of 80 switching particles from the MFM images and the macroscopic curve was obtained on a 5×5 mm^2 sample using an alternating gradient magnetometer. $n_{+/-}$ denotes number of particles polarized parallel or antiparallel with applied field.

V. THE DISPERSION OF EASY AXES

We return now to the subject of the dispersion of the easy axes of the cobalt islands about the magnetostatic easy direction (the long axis of the island) caused by the failure of the individual grain anisotropies to average to zero. New *et al.*[5] have computed this easy axis dispersion and shown its dispersion for several cases having different numbers of grains or different aspect ratios. We have examined our cobalt island array to compare with this theory.

An array of $0.2\times0.4\times0.02\ \mu m^3$ islands was placed in the remanent state. In this state a substantial proportion of the islands are quasi-single domain. The polar axis of each of 94 single-domain particles was determined by drawing a line through the centers of the north and south poles of the island. The angle this polar axis made with the long axis of the island was recorded, and a histogram was constructed showing the number of islands having their axes in each 5° interval. These data are plotted in Fig. 3 together with the theoretical prediction, recalculated from Eq. (14) of Ref. 5 using a grain diameter of 200 Å. The agreement is remarkable, particularly because the assumption of uniform magnetization is only loosely justified. Nevertheless, the fit between theory and experiment confirms strongly that individual particle anisotropy is the cause of the easy axis dispersion.

VI. THE MACROSCOPIC HYSTERESIS LOOP

In this section we show that the macroscopic hysteresis loop taken on a 5×5 mm^2 array of particles can be reconstructured from microscopic hysteresis loops taken on a smaller number of particles using the MFM. The sample was placed in a remanent state by the application and then reduction of a large magnetic field along the long axes of the islands. A field of the opposite sign was then applied and increased gradually. A set of 80 islands was selected, and the field at which each island reversed was recorded. A macroscopic hysteresis loop was then constructed from the sum of these 80 microscopic observations. The microscopic data points are plotted in Fig. 4, together with the macroscopic loop measured on the whole array using a Princeton Measurements alternating gradient magnetometer. The accuracy with which the macroscopic hysteresis loop can be constructed from the microscopic data is striking.

VII. CONCLUSION

High-resolution MFM imaging of submicron polycrystalline cobalt islands, including imaging in an applied magnetic field, allows detailed observation of the magnetic structure of these islands. The strong crystalline anisotropy in the randomly oriented cobalt grains plays a dominant role in producing the complex magnetic behavior observed.

ACKNOWLEDGMENT

Part of this work was performed under NSF Grant No. ECS8920652 and JSEP Grant No. DAAH 04-94-6-0058. We are grateful to I. D. Mayergoyz and E. R. Burke for helpful discussions, and F. Lineberger for graphics support. Part of this work was conducted at the Laboratory for Physical Sciences, College Park, MD.

[1] J. F. Smyth, S. Schultz, D. R. Fredkin, D. P. Kern, S. A. Rishton, H. Schmid, M. Cali, and T. R. Koehler, J. Appl. Phys. **69**, 5262 (1991).

[2] G. A. Gibson, J. F. Smyth, S. Schultz, and D. P. Kern, IEEE Trans. Magn. **27**, 5187 (1991).

[3] M. S. Wei and S. Y. Chou, J. Appl. Phys. **76**, 6679 (1994).

[4] R. M. H. New, R. F. W. Pease, and R. L. White, J. Magn. Magn. Mater. (to be published).

[5] R. M. H. New, R. F. W. Pease, R. L. White, R. M. Osgood, and K. Babcock, J. Appl. Phys. **79**, 5851 (1996).

[6] R. D. Gomez, E. R. Burke and I. D. Mayergoyz, J. Appl. Phys. **79**, 6063 (1996).

[7] R. M. H. New, R. F. W. Pease, and R. L. White, J. Vac. Sci. Technol. B **12**, 3196 (1994).

[8] R. M. H. New, R. F. W. Pease, and R. L. White, IEEE Trans. Magn. **31**, 3805 (1995).