Micromagnetism in mesoscopic epitaxial Fe dot arrays

Y. B. Xu, A. Hirohata, L. Lopez-Diaz, H. T. Leung, M. Tselepi, S. M. Gardiner, W. Y. Lee, and J. A. C. Bland[a)]
Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom

F. Rousseaux, E. Cambril, and H. Launois
L2M/CNRS, 19 Avenue Henri Ravera, 92220 Bagneux, France

The domain structures of epitaxial Fe (20 nm)/GaAs(100) circular dot arrays (diameters from 50 to 1 μm) were studied with magnetic force microscopy. A transition from a single domain to a multidomain remanent state was observed upon reducing the dot diameter beneath 10 μm in dot arrays with the separation twice the dot diameter. When the separation is reduced to half the dot diameter, the single domain states were found to ''collapse'' into stripe-like multidomain states due to local dipole coupling between dots. Micromagnetic simulations further suggest that for ultrathin Fe dots of less than about 2 nm thickness the diameter does not have a significant influence on the domain structures due to a dramatic reduction of the dipole energy. © *2000 American Institute of Physics.* [S0021-8979(00)47608-5]

INTRODUCTION

While polycrystalline ferromagnetic elements[1–5] continue to attract attention for the study of magnetic domain structure and magnetization processes in mesoscopic elements, mesoscopic dots and wires fabricated from epitaxial films are becoming increasingly important.[6–10] The epitaxial magnetic elements have a well-defined magnetocrystalline anisotropy and are much less influenced by defects in contrast with polycrystalline structures. Epitaxial structures therefore provide an opportunity to control the domain structure via the competing magnetic anisotropy and dipolar fields. For example, the domain width in hexagonal-close-packed (hcp) Co dots was tuned by changing the thickness of the dots.[6] The correlation between the reduction of thickness and the increase of coercive fields has been demonstrated in submicron-size epitaxial Fe dots.[10] In our previous studies,[7] the domain structures of Fe (100) square dots on GaAs have been studied using Lorentz microscopy. A transition from single domain to multidomain remanent states is observed upon reducing the element size beneath about 50 μm due to a competition between the in-plane dipolar fields and the magnetocrystalline anisotropy field. A recent study by Stamm *et al.*[8] demonstrated that two-dimensional Co dots in the thickness range of 2–10 ML grown on Cu(100) adopt a single domain state regardless of their lateral size. In addition to the fundamental interest of studying the domain configurations in mesoscopic magnets, the stabilization of the single domain state is important for magnetic data storage as well as the next generation of spin electronic devices.[11,12] We have recently carried out a systematic study of micromagnetism in epitaxial Fe(100) dot arrays grown on GaAs(100) by molecular beam epitaxy and patterned by e-beam lithography. In addition to the lateral size of the dots, parameters such as the separation, and thickness as well as the element shape need to be considered. In this article, we highlight the effect of the diameter and separation, as well as that of thickness on the domain structures.

SAMPLE PREPARATION AND MFM IMAGING

The starting magnetic material is a high quality epitaxial body-centered-cubic (bcc) Fe film of 20-nm-thick grown by molecular beam epitaxy on GaAs(100) at room temperature.[13] The cubic anisotropy is dominant, but with the presence of a uniaxial anisotropy, in this film as shown by *in situ* magneto-optical Kerr effect measurements. The film was then capped with a 4-nm-thick Au layer to prevent oxidation before removal from the growth chamber. The Fe dot arrays were fabricated using electron-beam lithography (JEOL JBX5D2U) operated at 50 KeV and ion beam etching with an intermediate metallic mask of Al made by a lift-off process. The diameter d of the circular dots was varied from 50 to 0.2 μm. Two sets of dot arrays of different separation s were fabricated, one with $s=2d$, and the other with $s=0.5d$. The square dot arrays have total sizes of about 200–500 μm with the edge parallel to the $\langle 110 \rangle$ directions. Figures 1(a) and 1(b) show large scale micrographs of the 10 μm dot arrays with 20 and 5 μm dot separation, respectively. The domain structures were studied in the remanent state using magnetic force microscopy (MFM) after saturating the magnetization along one of the easy axis $\langle 100 \rangle$ directions. A commercial Si tip coated with CoCr was used for the MFM imaging.

RESULTS AND DISCUSSION

Figure 2(a) shows the evolution of the domain configuration with dot diameter in dot arrays with the separation twice that of the diameter. The interparticle dipolar coupling is often believed to be negligible when the ratio of the separation to the diameter is larger than 1.[14] The evolution of the domain configuration with the diameter shown in Fig. 2(a) can thus be compared with our previous work[7] on square

a)Electronic mail: jacb1@phy.cam.ac.uk

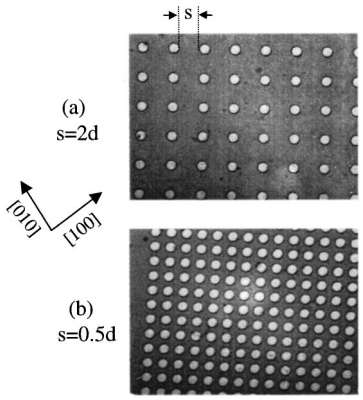


FIG. 1. Large-scale micrographs of the circular dot arrays with dot diameter $d=10\ \mu$m and separation s (a) $s=2d$, and (b) $s=0.5d$.

dots to show the influence of the geometry. It was found that in square dots of 15 nm thickness multidomain states were created when the size was reduced beneath about 50 μm. Here the lack of contrast in the MFM images of the 50 and 20 μm dots in Fig. 2(a) shows that the single domain state in circular dots can persist down to 20 μm due to the strong magnetocrystalline anisotropy of the epitaxial Fe films. It is unlikely that the different critical size values for the transition from single domain to multiple domain states in circular and square dots, respectively, is due to their slightly different thickness. The much smaller critical size for the circular dots as compared with that of the square dots suggests that the high symmetry favors the stabilization of a single domain state. With further decreasing diameter, it is expected that a second transition from a multiple domain to a single domain state will occur. In this case the total energy required to form any domain wall across the dots will be higher than that of the single domain state when the dot size is reduced beneath a certain value. The MFM images in Fig. 2(a) suggest that single domain states are stabilized in the 1 μm Fe dots, although the exact value of the critical diameter for the second transition remains to be determined. It should be noted that

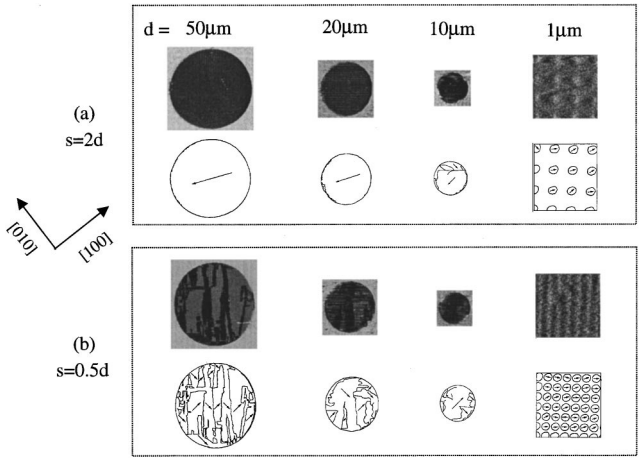
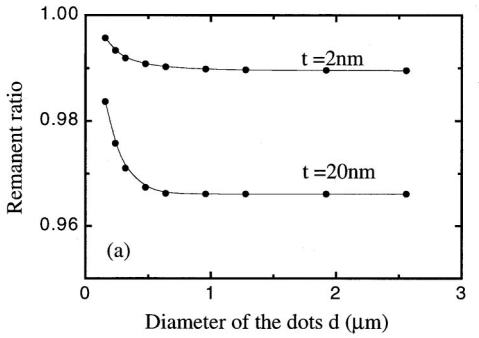


FIG. 2. MFM images and schematic diagrams of the domain configurations of the dots arrays of two different diameter d to separation s ratios, (a) $s=2d$, and (b) $s=0.5d$.



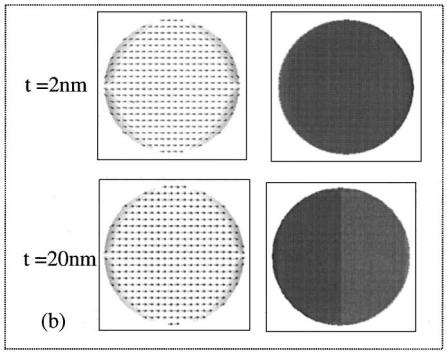


FIG. 3. (a) Computed values of remanence for isolated dots of thickness $t=2$ and 20 nm and different diameters. (b) The magnetization configurations (left) and the simulated MFM pictures (right, corresponding to $\nabla\cdot\mathbf{M}$) for the dots of $d=1.28\ \mu$m, $t=2$ nm, and 20 nm, respectively. In the left plot, the gray scale corresponds to the component along the applied field axis and the magnetization vector in one of each 12 computational cells is represented, whereas in the right one $\nabla\cdot\mathbf{M}$ is represented on a gray scale.

in the single domain states the magnetization is not aligned precisely parallel to the ⟨100⟩ directions, due to the presence of the uniaxial anisotropy.[13]

Figure 2(b) shows the evolution of domain configurations with dot diameter in the dot arrays with the separation half that of the diameter. We would like to emphasize that the dots in Figs. 2(a) and 2(b) were fabricated following exactly the same procedures and their only differences are the different separations. The most striking feature is that the single domain states of the 50 and 20 μm dots in Fig. 2(a) collapse into multidomain states. This demonstrates that local dipolar coupling between dots via the edges are strong enough to switch the domains. The coercivity of the continuous Fe film is about 20 Oe[13] and the stray field 10 μm away from a 20 μm dot was estimated to be larger than 25 Oe[15] for example. The detailed domain structures are determined in principle by the spatial distribution of the stray field due to all the dots in the array. This stray field distribution is expected to be anisotropic, i.e., corresponding to the structural anisotropy, related to the structure of the dot arrays such as the geometrical configuration and array periodicity. The stripe-like patterns shown in Fig. 2(b) as well as the rotation of the magnetization direction way from the ⟨100⟩ axis might suggest the importance of such a structural anisotropy in the dot arrays.

Preliminary numerical micromagnetic simulations have been carried out on isolated iron dots of thicknesses $t=2$ and 20 nm and different diameters ranging from 160 nm to 2.56

μm. More specifically, the remanent state after saturation along one of the easy cubic axis has been computed. Figure 3(a) shows the evolution of remanence with the dot diameter for the two thicknesses. The equilibrium states are qualitatively the same in all cases and are represented in Fig. 3(b) by the simulations for dots of about 1 μm diameter. The simulated domain structures of both the 2 and 20 nm thickness dots correspond to a single domain configuration with small deviations from uniformity at the boundaries of the dot to reduce the magnetostatic energy. This is in agreement with the experimental results. The spin deviations at the edge suggest that the edge is important for the interaction between dots. It is interesting to note that the remanence of the dots with $t=2$ nm shows little dependence on the diameter. As can be seen from the gray scale patterns of $\nabla\cdot\mathbf{M}$ in Fig. 3(b) the internal demagnetization fields of the 2 nm dots are very small as compared with those of the 20 nm dots. Our micromagnetic simulations confirm that dipole interactions are negligible in ultrathin dots as has also been shown for two-dimensional Co particles on Cu (100).[8] Ultrathin ferromagnetic elements are therefore promising for magnetoelectronic devices.

CONCLUSION

The diameter, separation, and thickness dependences of the domain structures of epitaxial Fe(100) circular dot arrays were studied using magnetic force microscopy and supporting micromagnetic simulations. Upon reducing the dot diameter, the first transition from a single domain to a multidomain remanent state was observed around 10 μm, followed by a second transition from the multidomain to single domain state. When the separation is reduced to half the dot diameter, the single domain states were found to ''collapse'' into stripe-like multidomain states due to the local dipole coupling. Micromagnetic simulations suggest that for ultrathin Fe dots the domain configurations show little deviation from the single domain state as required for magnetoelectronic devices.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the EPSRC, Newton Trust (Cambridge), the Toshiba Corporation and EC-ESPRIT (MASSDOTS), and EC-TMR (SUBMAGDEV).

[1] J. N. Chapman, S. McVitie, and S. J. Hefferman, J. Appl. Phys. **69**, 6978 (1991).
[2] J. G. Zhu, Y. F. Zheng, and X. D. Lin, J. Appl. Phys. **81**, 4336 (1997).
[3] A. O. Adeyeye, J. A. C. Bland, and C. Daboo, Appl. Phys. Lett. **70**, 3164 (1997).
[4] Y. B. Xu, C. A. F. Vaz, A. Hirohata, C. C. Yao, W. Y. Lee, J. A. C. Bland, F. Rousseaux, and E. Cambril, J. Appl. Phys. **85**, 6178 (1999).
[5] R. P. Cowburn, D. K. Koltsov, A. O. Adeyeye, and M. E. Welland, Phys. Rev. Lett. **83**, 1042 (1999).
[6] M. Mehn, K. Ounadjela, J. Bucher, F. Rousseaux, D. Decanini, B. Bartenlian, and C. Chappert, Science **272**, 1782 (1996).
[7] E. Gu, E. Ahmad, S. J. Gray, C. Daboo, J. A. C. Bland, L. M. Brown, and J. N. Chapman, Phys. Rev. Lett. **78**, 1158 (1997).
[8] C. Stamm, F. Marty, A. Vaterlaus, V. Weich, S. Egger, U. Maier, U. Ramsperger, H. Fuhrmann, and D. Pescia, Science **282**, 449 (1998).
[9] J. Yu, U. Rüdiger, L. Thomas, S. S. P. Parkin, and A. D. Kent, J. Appl. Phys. **85**, 5501 (1999).
[10] O. Fruchart, J.-P. Nozières, W. Wernsdorfer, D. Givord, F. Rousseaus, and D. Decanini, Phys. Rev. Lett. **82**, 1305 (1999).
[11] G. A. Prinz, Science **282**, 1660 (1998).
[12] Y. B. Xu *et al.*, IEEE Trans. Magn. **35**, 3661 (1999).
[13] Y. B. Xu, E. T. M. Kernohan, D. J. Freeland, A. Ercole, M. Tselepi, and J. A. C. Bland, Phys. Rev. B **58**, 890 (1998).
[14] A. O. Adeyeye, J. A. C. Bland, C. Daboo, and D. G. Hasko, Phys. Rev. B **56**, 3265 (1997).
[15] E. Ahmad, Ph.D. thesis, Cambridge University, 1998.