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Remanent state studies of truncated conical magnetic particles

M. Hwang[a)]
Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

M. Redjdal and F. B. Humphrey
Department of Electrical and Computer Engineering, Saint Mary's Street, Boston University, Boston, Massachusetts 02215

C. A. Ross
Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

The remanent state of truncated conical particles is investigated as a function of their size, aspect ratio, and anisotropy, using a micromagnetic model based on the Landau–Lifshitz–Gilbert equation. Particles with a base diameter smaller than three times the exchange length show a ''flower'' state, while larger particles show a ''vortex'' magnetization state. The critical size for this transition increases with increasing anisotropy. Small flower-state particles show abrupt reorientation from out-of-plane to in-plane magnetization at a critical aspect ratio of 0.9. For vortex-state particles, the axial remanence gradually increases as the aspect ratio increases, and high aspect ratio particles have significant remanence even at larger diameters. [DOI: 10.1063/1.1361271]

I. INTRODUCTION

The equilibrium magnetization structure of a magnetic particle depends on its size, shape, and the strength and symmetry of its magnetic anisotropy. Most micromagnetic analysis has been carried out on particles with ideal shapes such as ellipsoids, cubes, and cylinders.[1–4] However, there is now a variety of experimental data available for magnetic particles made by evaporation and lift-off processes. These particles tend to have tapered profiles (i.e., the particle width decreases as the particle becomes taller) because the holes in the lithographically defined template become smaller as the evaporation process proceeds. This leads to particles with truncated pyramidal or conical shapes, whose side-wall angle depends on the angular distribution of the arriving flux of the evaporant. In this article, a three-dimensional numerical micromagnetic model is used to investigate the remanent states of truncated pyramidal particles and to compare these states with the behavior of cylindrical particles.

II. MICROMAGNETIC MODELING

A three-dimensional micromagnetic model[5] based on the direct integration of the Landau–Lifshitz–Gilbert (LLG) equation in a Cartesian lattice is used to obtain the remanent states of truncated pyramidal particles. The particle is represented by $N_x \times N_y$ cubic elements in the xy plane for the base of the particle. Along z, perpendicular to the base, N_z elements represent the height. The magnetization is constant in magnitude but may vary in direction from one element to another. Initially, all the magnetic moments are aligned with z, the axial direction of the particle, and then the magnetization is relaxed in the absence of external field to generate the remanent state. The effective field H_{eff} is first calculated as the sum of the applied external, magnetostatic, exchange, and anisotropy fields. The LLG equation is then solved for each element until the maximum angular precession ($dm/dt = \gamma H_{\mathrm{eff}}$, with γ, the gyromagnetic ratio, $= 0.0179$ $\mathrm{Oe}^{-1}\,\mathrm{ns}^{-1}$) in the system is below 10^{-5} GHz, i.e., $H_{\mathrm{eff}} < 6 \times 10^{-4}$ Oe.

Particles were modeled as cylinders, truncated cones, or pyramids by stacking up either circles or squares made from cubic elements. The volume of the particle was divided into between 6000 and 16 000 elements, with $N_x = N_y = 23$ or 31, and $N_z = 14$–35 depending on the desired aspect ratio. The angle between the sidewalls and the base plane was fixed at 72° for the conical or pyramidal particles. Length scales are normalized with respect to the exchange length $\lambda_{\mathrm{ex}} = \sqrt{A/M_s}$, where A is the exchange constant and M_s the saturation magnetization.[2] The size of the cubic elements was kept below 0.5 λ_{ex} even for the largest size particles to ensure robust computations. Even though the surfaces are represented by discrete steps due to the cubic mesh, with the discretization size equal to 1/31 or 1/23 of the particle diameter, the surface roughness was smaller than λ_{ex} for all the particle sizes modeled. Thus, the surface roughness is not expected to introduce significant error into the calculation.[4] Since initial calculations on truncated cones showed similar results to truncated square-based pyramids, only results on truncated pyramids are presented in this article. An exchange constant of $A = 10^{-6}$ $\mathrm{erg\,cm^{-1}}$ was used for both Co and Ni particles. A saturation magnetization M_s of 484.1 and 1420 $\mathrm{emu\,cm^{-3}}$ was taken for Ni and Co, respectively, so the exchange length was 20 nm for Ni and 7 nm for Co. A uniaxial magnetocrystalline anisotropy K_u from zero to 3.0×10^6 $\mathrm{erg\,cm^{-3}}$ parallel to the particle axis was included. Another micromagnetic model based on iterative methods[6]

[a)] Electronic mail: minha@mit.edu

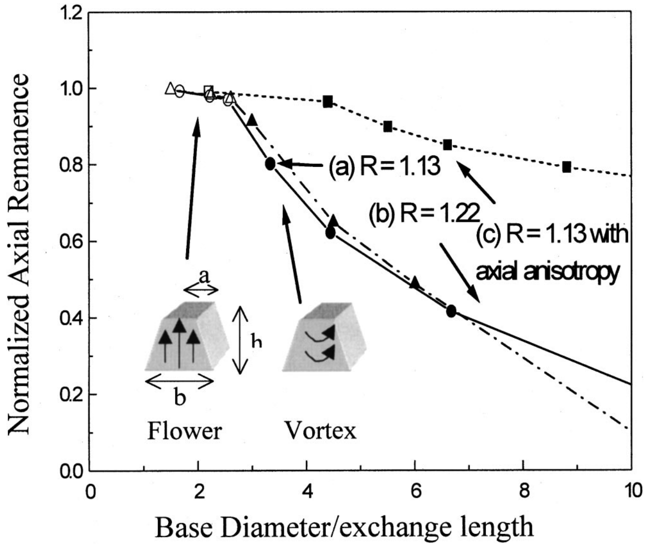

FIG. 1. Calculated axial remanence for truncated pyramidal particles after axial saturation, as a function of normalized base diameter. (Open dots: flower state, closed dots: vortex state) (a) Aspect ratio $R=1.13$, $a/b=0.35$, zero anisotropy; (b) $R=1.21$, $a/b=0.22$, zero anisotropy; (c) $R=1.13$, $a/b=0.33$, with axial anisotropy corresponding to 3.0×10^6 erg cm^{-3} for Co particles.

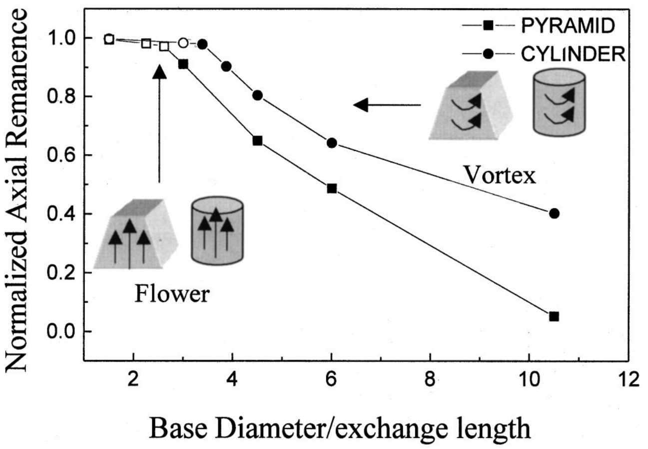

FIG. 2. Calculated axial remanence for truncated pyramidal particles and cylindrical particles with aspect ratio $R=1.13$, as a function of normalized base diameter. (Open dots: flower state, closed dots: vortex state)

was used to determine the reorientation of the remanent magnetization direction from axial to in plane as a function of aspect ratio.

III. RESULTS

A. Effect of particle size on remanence

Particles are approximated as truncated square-based pyramids with height h, base diameter b, and top diameter a, and the aspect ratio is defined as $R=h/b$. First, the effect of size will be considered. In Fig. 1, axial remanence is shown as a function of normalized diameter b/λ_{ex} for three cases, (a) an aspect ratio of $R=1.13$ and $a/b=0.35$ with zero anisotropy, (b) a taller and sharper particle with $R=1.22$ and $a/b=0.22$ with zero anisotropy, and (c) the same geometry as (a) but with an anisotropy field, defined as $2K_u/M_s$, of 4191 Oe along the axis, corresponding to $0.66K_u$ of pure Co. This particular value was chosen for comparison with experimental results on evaporated Co particles.[7]

For tall particles with $R>0.9$, the squareness S, which is defined as axial remanence divided by saturation moment, is almost constant at 1.0 until the diameter b reaches a critical value above which S begins to decrease. For the zero anisotropy case, shown in Figs. 1(a) and 1(b), the critical diameter is $3\lambda_{\mathrm{ex}}$. Below this diameter, an ''out-of-plane flower'' state exists where the squareness is very close to 1 and the magnetization is almost parallel to the axis except for small deviations at the corners. Above the critical diameter, a helical vortex develops along the central axis of the particle and the magnetization vectors become tilted into the sample plane. This helical vortex develops first near the base of the particle, and extends through the particle as the particle size increases, leading to a gradual decrease in S. Even larger particles ($b>\sim10\lambda_{\mathrm{ex}}$) show multidomain states. The addition of uniaxial anisotropy parallel to the axis of the particle, as in Fig. 1(c), makes the flower-to-vortex transition occur at larger critical diameters and increases the axial remanence of vortex states significantly.

In contrast, short particles ($R<0.9$) have low axial remanence. At small diameters the particle shows an ''in-plane flower'' state in which the magnetization is parallel to the base plane. Larger particles develop vortex or multi-domain structures. Some examples of these remanent states have been shown previously.[7]

To compare cylinders and truncated pyramids, the remanent states of a cylinder with $R=1.13$ were compared with those of a pyramid with the same R and with $a/b=0.35$, as shown in Fig. 1(a). The results are shown in Fig. 2. The behavior is qualitatively similar, but the flower-to-vortex transition for the cylinder occurs at a larger diameter, $3.5\lambda_{\mathrm{ex}}$, and the decrease of the remanence after the transition is more gradual compared to the pyramid.

B. Effect of aspect ratio

The effects of varying the aspect ratio on the flower and vortex states were studied for truncated pyramidal particles. For the flower states, the base diameter was fixed at $2\lambda_{\mathrm{ex}}$ and the height of the particle was changed. The particle shows a flower state at all aspect ratios but there is an abrupt transition from out-of-plane to in-plane flower states at $R=0.9$ (Fig. 3). This is similar to the critical aspect ratio analytically obtained for a uniformly magnetized cylinder, which is 0.9065.[8] Adding anisotropy along the axis of the particle reduces the critical aspect ratio.

Similar tests were performed for vortex state particles. The base diameter was fixed at $4\lambda_{\mathrm{ex}}$ or $4.5\lambda_{\mathrm{ex}}$, and the effect of aspect ratio was studied for different amounts of axial anisotropy (Fig. 4). In contrast with flower-state particles,

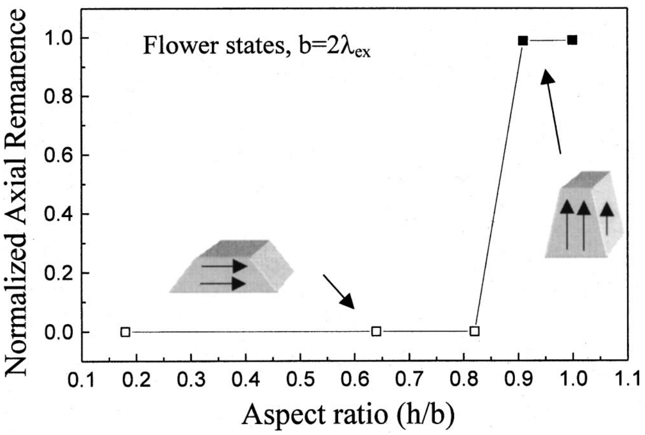

FIG. 3. Calculated remanence along the axis of the particle for a truncated pyramidal particle with $b=2\lambda_{\mathrm{ex}}$ and a taper angle of 72°, as a function of height/base aspect ratio h/b.

there is a gradual decrease in remanence with decreasing aspect ratio as the magnetization vectors become more tilted into the plane, but the remanence is still significant even for particles with aspect ratios below 0.9. Moreover, the remanence increases with increasing anisotropy.

IV. DISCUSSION

Our calculations show a transition from a flower state to a vortex state with increasing particle size. This behavior has been found in other geometries such as cubes, cylinders and prisms.[3,6] However, the fact that even vortex states can have significant axial remanence at aspect ratios below 1 should be emphasized. The flower-to-vortex transition is predicted to occur at about 60 nm diameter for Ni, and 20 nm for Co with zero anisotropy. Experimentally, arrays of conical nickel dots with a base diameter of ~80 nm have been found to show high axial remanence even for aspect ratios of 0.63,[7,9,10] and magnetic force microscopy indicates dipolar magnetization states. These experimental observations are consistent with the results of the model, which shows that even with zero anisotropy, Ni particles of these dimensions would show a helical magnetization state with significant perpendicular remanence. However, for Co, particles of 80 nm diameter are predicted to have multidomain or vortex states with very low remanence. The observation of dipolar magnetization states with high remanence in such particles[7] is interpreted as a result of perpendicular anisotropy arising from the preferred (0001) crystal orientation.

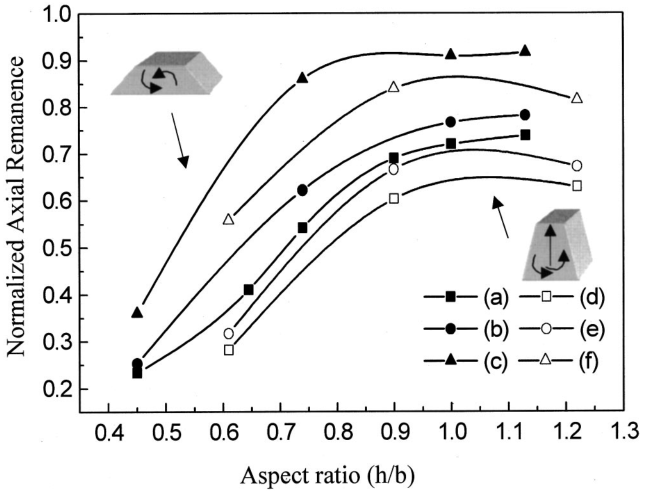

FIG. 4. Calculated remanence along the axis of the particle for truncated pyramidal particles, as a function of aspect ratio. (a) $b=4\lambda_{\mathrm{ex}}$, zero anisotropy; (b) $b=4\lambda_{\mathrm{ex}}$, anisotropy of 5×10^4 erg cm^{-3} along axis; (c) $b=4\lambda_{\mathrm{ex}}$, anisotropy of 2×10^5 erg cm^{-3} along axis; (d) $b=4.5\lambda_{\mathrm{ex}}$, zero anisotropy; (e) $b=4.5\lambda_{\mathrm{ex}}$, anisotropy of 5×10^4 erg cm^{-3} along axis; (f) $b=4.5\lambda_{\mathrm{ex}}$, anisotropy of 2×10^5 erg cm^{-3} along axis. Anisotropy values correspond to Ni particles.

The tapered particle shape, for the a/b ratios investigated here, behaves similarly to a cylinder. In particular, the transition from an in-plane to an out-of-plane flower state occurs at aspect ratios of 0.9 in both cases. This is a result of the 72° taper angle chosen in this study, which gives shapes that are not very different from a cylinder with taper angle of 90°. For completeness, an a/b ratio range from a perfect cone ($a/b=0$) to a cylinder ($a/b=1$) should be considered.

These results suggests some guidelines for the design of patterned recording media, in which data are stored in uniaxial single-domain magnetic particles for which a high remanence is desirable. A practical patterned media system would require an array of particles with density well in excess of 15 G particles cm^{-2}, implying a period below 80 nm and hence particle diameters of <40 nm. At these dimensions, the remanence of cylindrical or pyramidal particles with aspect ratio of ~1 is expected to be high for particles made from Ni or from Co with axial crystalline anisotropy. Hence the particles do not need to be highly elongated to be used as perpendicularly magnetized media. This has the advantage that switching speeds are expected to be higher for particles with aspect ratios close to 1, compared to elongated particles with aspect ratios of 2–3.[11]

ACKNOWLEDGMENTS

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[1] A. Aharoni, *Introduction to the Theory of Ferromagnetism* (Oxford University Press, Oxford, 1996).
[2] M. E. Schabes and H. N. Bertram, J. Appl. Phys. **64**, 1347 (1988).
[3] W. Rave, K. Fabian, and A. Hubert, J. Magn. Magn. Mater. **190**, 332 (1998).
[4] C. Seberino and H. N. Bertram, J. Appl. Phys. **85**, 5543 (1999).
[5] M. Redjdal and F. B. Humphrey, J. Appl. Phys. **79**, 6464 (1996).
[6] M. E. Schabes, J. Magn. Magn. Mater. **95**, 249 (1991).
[7] C. A. Ross, M. Farhoud, M. Hwang, H. I. Smith, M. Redjdal, and F. B. Humphrey, J. Appl. Phys. **89**, 1310 (2001).
[8] A. Aharoni, J. Appl. Phys. **68**, 2892 (1990).
[9] G. Meier, M. Kleiber, D. Grundler, D. Heitmann, and R. Wiesendanger, Appl. Phys. Lett. **72**, 2168 (1998).
[10] M. Farhoud, H. I. Smith, M. Hwang, and C. A. Ross, J. Appl. Phys. **87**, 5122 (2000).
[11] E. D. Boerner, H. N. Bertram, and G. F. Hughes, J. Appl. Phys. **85**, 5318 (1999).