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Field dependence of the switching field for nonellipsoidal single domain particles

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Experimental data on a model system of a two-dimensional array of single domain garnet particles, switching by incoherent rotation, are presented to show that the switching field of individual particles, H_{sw}, and the coercivity of the major hysteresis loop for ~1000 particles, H_c, depend on the previously applied saturating field. For the system measured the asymptotic, ''true'' value of H_c in large fields is 321 Oe, in contrast with $H_c = 225$ Oe, measured in an applied field of $H_{\mathrm{sat}} = 188$ Oe, i.e., the smallest field adequate to close the major loop. Statistical data were collected on switching of a single particle, with an asymptotic value of $H_{\mathrm{sw}} = 150$ Oe. After the application of $H_{\mathrm{sat}} = 160$ Oe H_{sw} decreased to 111 Oe. Due to the nonellipsoidal shape of the particles, a significant canting of the magnetization near corners and edges persists up to very high fields. The torque, due to these canted magnetic moments, facilitates premature switching in lower fields. It is proposed that defects are responsible for the irreversibility of the process. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1452250]

I. INTRODUCTION

A promising medium for future extreme high density magnetic storage consists of regular two-dimensional (2D) arrays of single domain particle bits in the shape of rectangular platelets or cylinders. Other magnetic devices, such as magnetic random access memories (MRAMs) and sensors, are also based on small magnetic particles. Critical parameters of such elements are the switching field, its dispersion, and its stability. In this work we show that the value of the switching field depends on the highest magnetic field, applied before switching. Previous micromagnetic simulations show that the magnetization of nonellipsoidal particles does not reach complete saturation even in fields much higher than the field necessary to close the hysteresis loop. Significant canting of the magnetization near corners and edges persists up to very high fields.[1–3] The canting angle near the corners for a square-column garnet particle with an aspect ratio of thickness/length = 1/20 in an applied field of $4\pi M_s = 160$ G can reach ~40°. Although the canting is reduced as the saturating field is increased, the saturation is still not perfect even in a field of $10^*4\pi M_s$. Upon a decrease in the field from $H_{\mathrm{sat}} > 0$, the torque, due to these canted magnetic moments, facilitates premature switching. As a result, the switching field will depend on the previously applied saturating field.

The dependence of the coercivity on the magnetic field was demonstrated earlier for the case of dynamic magnetization processes.[4] In our case the magnetization process is quasistatic, and dynamic effects can be excluded. Similarly, time dependent magnetic aftereffects are also excluded, due to the very high anisotropy barrier that prevents thermal excitation at room temperature.[5,6] All measurements were performed on major hysteresis loops, so minor loop accommodation effects are also excluded.[7] However, earlier we have observed the dependence of coercivity on the applied field for another family of epitaxial garnet films. In that case the domain wall coercivity did depend on the field, resulting in erroneous switching by domain wall motion during device operation. Strict control of the saturating field did solve the problem.[8]

The switching process of the model system of the two-dimensional array of *magnetically* small, single crystal, single domain garnet particles was investigated in detail earlier.[9,10] The average switching field, measured on many individual single particles, H_{sw}, corresponds to the major loop coercivity, H_c, as expected for a Preisach-type system.[7] The switching field for the system investigated has a large statistical dispersion $H_{\mathrm{sw}} = 285 \pm 85$ Oe.[10] Similarly broad distribution has been reported for other patterned systems,[11] in which manufacturing defects have a high probability. However, even in these exceptionally high quality epitaxial garnet single crystals, very weak, localized crystalline defects exist, and it was shown that they are responsible for the broad distribution of the switching fields.[12]

II. EXPERIMENT

Measurements were performed on a regular square array of particles, etched in a single crystalline epitaxial magnetic garnet film, grown on a nonmagnetic GGG substrate. The size of the particles is 42 μm × 42 μm × 3 μm, separated by 12 μm wide grooves. The 5×5 mm^2 sample contains about 10^4 particles.

The squareness of the major hysteresis loop of the sample is $M_r/M_s = 1$. The magnetization, $4\pi M_s = 160$ G, is

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very low compared to the high uniaxial anisotropy field, $H_u = 2.1$ kOe. As a result, the particles are strongly uniaxial with $Q = H_u/4\pi M_s > 10$, ensuring that there are only two stable magnetic states, either "upward" or "downward" along the easy axis, normal to the film plane. All magnetic fields were applied along the easy axis.

Switching of the whole system proceeds by consecutive switching of individual particles. Each particle has a rectangular hysteresis loop. The hysteresis loops, upward and downward switching fields (H^+ and H^-) of individual particles and groups of particles, were measured magneto-optically in a Faraday effect optical magnetometer.

Statistical measurements of single-particle switching fields were performed by selecting an arbitrary particle, saturating it in a large field, then traversing its square hysteresis loop, detecting H^+ and H^-, then systematically decreasing the maximum magnetic field above the closure of each consecutive hysteresis loop (H_{sat}). The switching field is defined as $H_{\mathrm{sw}} = (H^+ - H^-)/2$, i.e., the half width of the loop, thus excluding possible interaction effects between particles. This series of measurement was performed in a solenoid with optical access. The optical system made possible visual observation together with electro-optical detection of the switching process of individual particles. Major loop data were also obtained magneto-optically. The hysteresis loop of about 1000 particles was measured in the field of an electromagnet. After saturating the system in H_{sat}, the major loop coercivity was determined as a function of the magnetic field above the end of the hysteresis loop (H_{sat}). After traversing a full cycle, the next H_{sat} was reduced with respect to its previous value. Magneto-optical methods are preferred to vibrating sample magnetometer (VMS) measurements, because the very large paramagnetic contribution from the GGG substrate introduces significant measurement errors.

III. RESULTS AND DISCUSSION

Magneto-optic measurements prove that the switching field of the system of single domain particles, and of individual particles on a 2D array, depends on the previously applied saturating field. Figure 1 shows the measured major loop data. The switching field was reduced upon a reduction of the saturating field. The largest $H_c = 321$ Oe was measured in $H_{\mathrm{sat}} = 1504$ Oe. The data were fitted to nonlinear transition and kinetic equations (TABLECURVE), using a robust minimization technique with 300 iterations. The best fit was obtained for a cumulative Gaussian function.

$$H_c = a + (b/2)\{1 + \mathrm{erf}\,[(x-c)/(\sqrt{2}d)]\},$$

where $a + b = 317$ Oe is the height of the transition curve, $c = 414$ Oe is the center of the transition, and $1.35d = 386$ Oe is the width of the transition. This form indicates a simple mechanism of sequential switching of the elements of the array, as expected. The degrees of freedom adjusted $r^2 = 0.98$ for the fit, taking into account the small number of data points. For the large ensemble of particles the asymptotic, the "true" value of the coercivity, $H_c = 317$ Oe, can be achieved only at $H_{\mathrm{sat}} \approx 1600\ \mathrm{Oe} = 10 * 4\pi M_s$. The smallest value of coercivity, $H_c = 225$ Oe, was measured for the smallest $H_{\mathrm{sat}} = 188$ Oe to ensure closure of the major loop. The field sensitivity is strongest around $H_{\mathrm{sat}} = 414$ Oe, with $dH_{\mathrm{sw}}/dH_{\mathrm{sat}} = 0.165$. It should be noted that other, similar transition type functions (sigmoid, lognormal, Weibull) gave a fit very close to that of the Gaussian.

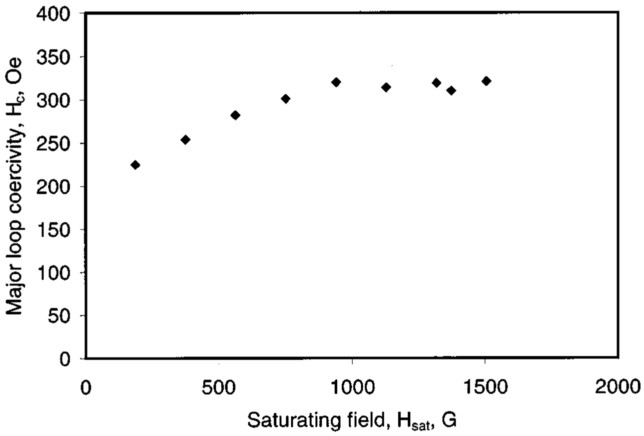

FIG. 1. Dependence of the major loop coercivity H_c on saturating field H_{sat}, applied along the easy axis of the particles, for a group of ~1000 particles.

Figure 2 shows the statistical average values of the switching field for a selected representative single particle. The asymptotic (highest) value, $H_{\mathrm{sw}} = 152$ Oe, can be measured after saturation in $H_{\mathrm{sat}} \geqslant 600$ Oe. The switching field was reduced upon a reduction of the saturating field, because the stronger canting in lower saturating fields makes the magnetization easier to switch. The lowest, $H_{\mathrm{sw}} = 111$ Oe, was measured in $H_{\mathrm{sat}} = 160$ Oe. The numerical fitting procedure, like in the case of the major loop, yielded several similar functional forms (Gaussian, cumulative, sigmoid, etc.) with $r^2 = 0.95$. The field dependence of the selected particle is strongest around the center of the curve, $H_{\mathrm{sat}} = 340$ Oe, with field sensitivity of $dH_{\mathrm{sw}}/dH_{\mathrm{sat}} = 0.14$.

The similarity in the kinetics of the switching sequence of a large number of particles, and that of the statistical average of many measurements for a selected single particle is

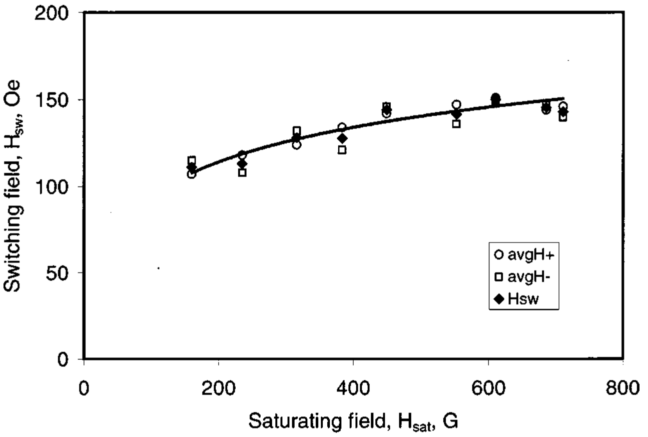

FIG. 2. Dependence of the statistical average switching field of a selected particle, H_{sw}, on the saturating field, H_{sat}, applied along the easy axis of a given particle.

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intriguing. The major loop coercivity, which corresponds to the mean value of the Gaussian distribution of the switching fields of individual particles,[7] is reasonably well reflected in the Gaussian cumulative form of the field dependence. The similar functional form for Fig. 2 might be attributable to the statistical average of data points, which would also follow a Gaussian distribution. However, magnetization switching of an *individual* particle, with no domains and domain walls, but having a nonuniform magnetization distribution, still takes place suddenly as the applied field reaches the limit of instability.[1] At first glance, for a system, or a particle, with a square hysteresis loop $(M/M_s=1)$, the magnetization distribution in any given field along the descending branch of the hysteresis loop before switching should be the same because along this branch the M/M_s measured is equal to 1. Thus, the onset of instability, i.e., H_{sw} is not expected to depend on H_{sat}. However, because of the canted magnetic moments at the corners and edges of the rectangular particle $M_z/M_s < 1$ for finite H_{sat}. According to micromagnetic calculations,[13] between $H_{\mathrm{sat}}=800$ and 750 Oe the component of the magnetization along field M_z decreases by about 0.5%, hardly noticeable on the measured loops. For an ideal particle and a quasistatic magnetization process, even in this case, the system would come to equilibrium at each field value, always arriving at the point of instability with the same magnetization distribution, without the observed field dependence of the switching field. Obviously, an irreversible contribution is needed to explain the observed phenomenon. In the previously published case of the field dependence of the coercivity, the irreversibility, was caused by wall pinning at the defects, i.e., by the typical coercivity mechanism.[8]

It was shown in Ref. 12, that the switching field is highest for defect-free particles. For a particle with a defect, the ''true'' switching field for inhomogeneous rotation is reduced due to the reduced local internal field at the defect. The localized weak crystalline defects (stress fields from the GGG substrate, impurities, dislocations at the substrate/film interface, etc.) in these seemingly perfect single crystalline epitaxial garnet particles are responsible not only for the broad distribution of the switching fields, but for the locally reduced anisotropy too. It seems reasonable to assume that the locally reduced internal fields contribute irreversibility by *locally* minimizing the free energy and optimizing the magnetization distribution. The defect forms an energy barrier by locally stabilizing, ''pinning'' the magnetization distribution, corresponding to the actual applied saturating field. For a larger $H_{\mathrm{sat}}=H1$ the pinned, frozen canting of the magnetic moments around the defect will be smaller than for a lower $H_{\mathrm{sat}}=H2$, $(H2<H1)$. Consequently, the torque from the same H_{sw} field, which would initiate switching for the less uniform magnetization distribution, resulted by $H2$, will not be sufficient to initiate switching from the more uniform state, frozen by $H1$. Higher H_{sw} is required for higher H_{sat}, in accordance with the observation.

The manufacturing process of MRAMs, patterned recording media, or heads is expected to produce a large number of identical small magnetic elements with high yield. Any physically small and magnetically weak defect can lead to a broad distribution of switching fields. The problem of the field sensitivity of the switching field due to the nonuniform magnetization distribution around the defects remains a challenge to the technology. This effect should be considered in designing the optimum bias field and its homogeneity for a magnetic recording system, or for any mass produced magnetic device based on noninteracting particles, or on a patterned array of small particles.

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