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Computer calculation of the Lorentz microscopy image and magnetic domain structure of weakly ordered FePt:C thin film

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A computer calculation technique of Lorentz microscopy image was developed and was applied to the analysis of the Lorentz microscopy image and magnetic domain structure of a weakly ordered FePt:C thin film for recording media. The magnetic domain structure was, at the as-deposited (random) state, a vortex network structure and evolved into the islandlike elongated reverse domain structure at the dc-demagnetization state, via a featherlike ripple structure at the remanent state. The magnetization reversal occurred not by the domain wall motion but by the local magnetization rotation to form a series of local vortices leading to the formation of reverse domains. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2746078]

Magnetic thin films for recording media have been subject to intensive studies in an effort to develop high density recording media.[1,2] However, the magnetic domain structure of the magnetic thin films for recording media, using Lorentz transmission electron microscopy (LTEM), has rarely been subject to intensive studies despite its importance in controlling the media noise.[2,3] Most of LTEM works were confined to soft magnetic thin films.[4] This is partly because the LTEM image of a magnetic thin film for recording media is often complex and difficult to interpret because of lack of information on the magnetization distribution.[5]

The purpose of the present work was thus to computer calculate the LTEM image and magnetic domain structure with an objective of providing a useful analytical tool for the interpretation of the experimentally observed LTEM image. The calculated image was compared with the LTEM image observed in a weakly ordered FePt:C magnetic thin film for recording media to test its feasibility and to analyze the magnetization reversal mechanism in the magnetic thin film for recording media.

Micromagnetic simulation was performed using the program package OOMMF (the object oriented micromagnetic framework).[6] In the simulation, the unit cell size was $20 \times 20 \times 20\ \mathrm{nm}^3$ and the film dimension was $8\ \mu\mathrm{m} \times 8\ \mu\mathrm{m} \times 20\ \mathrm{nm}$. The unit cell was assumed to stand for a single crystal. The crystalline easy axis was randomly distributed in three dimensions. The basic parameters used for micromagnetic simulation of a weakly ordered FePt:C magnetic thin film are shown in Table I. The simulations were performed for three different magnetization states, i.e., as-deposited, remanent, and dc-demagnetization states.

The LTEM image contrast in Fresnel mode was computer calculated using the magnetization distribution pattern obtained from the micromagnetic simulation. For this purpose, we have used the contrast model proposed by McVitie and Cushley.[7] In this model, the magnetization variation through the film thickness was assumed to be negligible and the magnetic field out of the specimen was ignored.

Equiatomic FePt thin film intercalated with four carbon layers (40 at. % C) was magnetron sputter deposited on the thermally oxidized Si substrate at 300 °C under 5 mTorr of Ar in a vacuum chamber of 1×10^{-6} Torr. The magnetization and hysteresis curves were measured using a vibrating sample magnetometer. The magnetic domain structure was observed in the Fresnel mode using a high resolution Lorentz transmission electron microscope of Tecnai F30. Samples were observed in three different magnetization states, i.e., at as-deposited state, remanent state, and dc-demagnetized state.

The LTEM image of a weakly ordered FePt:C thin film was calculated using a technique developed in the present work (Fig. 1). The contrast line, whether it is bright or dark, arises from the ripple boundary, where the magnetization direction changes abruptly. The nature of contrast, i.e., bright or dark, is determined by the rotation sense across the boundary. The vortices[8] were found at the crossing points of the same (i.e., bright-bright or dark-dark) contrast lines, whereas the cross-ties[8] were found at the crossing points of the two different contrast lines. The result of calculation thus indicated that the magnetic domain structure at the as-deposited state [Fig. 1(a)] consisted of two interweaving vortex networks. The formation of a network of the vortex of one sense (say, bright contrast) inevitably forms a vortex of antisense (dark contrast) at the center of the network of bright contrast. This leads to the formation of the other vortex network, seen as dark contrast lines, interpenetrating into the vortex network in bright contrast line [Fig. 1(b)].

The remanent state [Fig. 1(c)] showed a typical featherlike ripple structure with the ripples running perpendicular to the applied field. The bright and dark contrast lines, although visible faintly, tended to appear alternatively. This arises from the fact that the rotation sense across the ripple boundaries has to be reversed alternatively in order to maintain a constant overall magnetization direction perpendicular to the ripple boundaries. The calculation [Fig. 1(d)] further showed that the dc-demagnetization state essentially consisted of an islandlike elongated domain structure. All the islandlike

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TABLE I. Basic parameters used for micromagnetic simulation of a weakly ordered FePt:C thin film for recording media.

Film geometry (μm)	Grain geometry (nm)	M_s (A/m)	K_u (J/m^3)	A (J/m)	Film texture
$8\times8\times0.02$	$20\times20\times20$	1.15×10^6	2.5×10^5	2.7×10^{-11}	3D random

elongated domains were bounded by a pair of bright and dark contrast lines in the same order. This suggested that these islandlike elongated domains are the reverse domains, in which the sense of magnetization inside the domains is opposite to that of the outside region, which was actually confirmed by inspection of the magnetization pattern.

In order to understand the magnetization reversal mechanism, the LTEM image has been calculated at various demagnetization steps along the course of dc demagnetization (Fig. 2). A featherlike ripple structure running perpendicular to the demagnetization field became distinctive at the remanent state. On further increasing the reverse field, a small vortex (i.e., bright dot at the center of crossing bright lines) nucleated at the ripple boundaries [Fig. 2(b)], suggesting that local magnetization rotation occurred. The formation of a localized small vortex forced the magnetization units in a local region, adjacent to the vortex, to rotate parallel to the direction of the reverse field. This, in turn, led to the formation of a second localized small vortex, with the antisense, displaced in a direction perpendicular to the reverse field [Fig. 2(b)]. The formation of a second localized vortex now triggers the nucleation of a third localized vortex near the first vortex and so on. The repetition of this procedure will lead to the formation of an elongated reverse domain parallel to the reverse field [Fig. 2(c)]. The boundaries with the same contrast consisted of vortices with the same sense. Thus, in the present example, the vortices with the bright contrast appeared at the lower boundary and those with the dark contrast were seen at the upper boundary [Fig. 2(d)]; cross-ties were found in between the two vortices with the same sense. Closer inspection indicated that the width of elongated reverse domains was enlarged by the annihilation of old vortices and nucleation of new vortices of the same rotation sense.

To recapitulate, the mechanism by which the elongated closure domain forms is the repeated nucleation of a pair of localized small vortex with the antisense of rotation along the perpendicular direction to the reverse field and of a pair of localized small vortex with the same rotation sense along the parallel direction to the reverse field. The boundary with reverse contrast consisted of vortices of the opposite rotation sense. The propagation of elongated reverse domains was effectuated by the annihilation of old vortices and formation of new vortices at the domain boundaries. The process of annihilation and new formation of vortices did not occur coherently and the boundaries of elongated reverse domains were generally rough and irregular [Fig. 2(c)]. This reversal mechanism is essentially similar to what has been discussed from the result of the micromagnetic simulation study of Co-based alloy thin film for magnetic recording media by Zhu and Bertram.[8]

In order to confirm the calculation result, a weakly ordered FePt:C thin film was fabricated and its magnetic domain structure was studied using a high resolution Lorentz transmission electron microscope. The TEM observation and electron diffraction pattern indicated that the grain orientation was almost random as expected and the measurement of magnetic hysteresis curve showed small in-plane coercivity (415 Oe) with a similar out-of-plane coercivity.

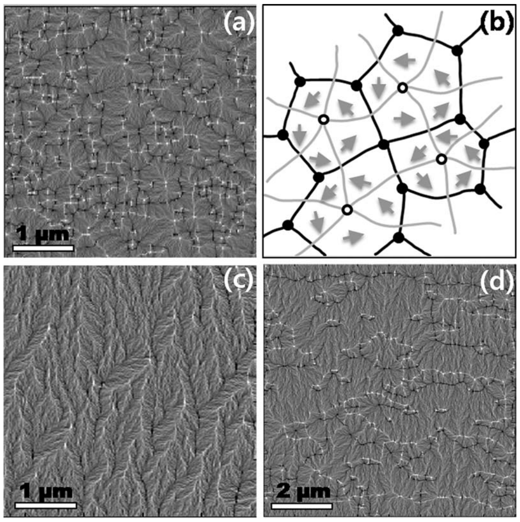

FIG. 1. Calculation of Lorentz microscopy images of a weakly ordered FePt:C thin film at various magnetization states: (a) as-deposited state; (b) schematic diagram of (a); (c) remanent state; (d) dc-demagnetization state. Filled and open circles in (b) stand for vortices with clockwise and anticlockwise rotation senses, respectively, and arrows represent the magnetization direction. The reverse field points leftwards in the horizontal direction.

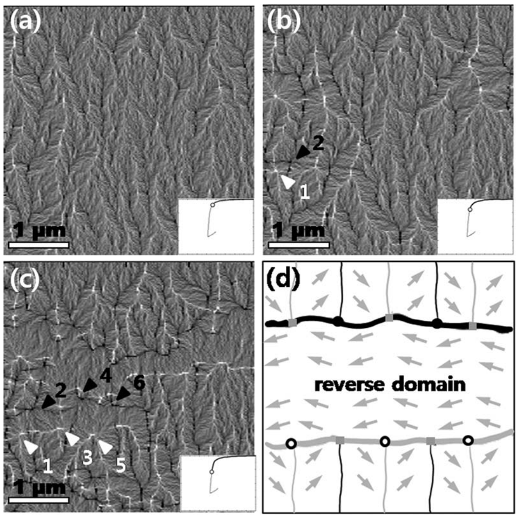

FIG. 2. Calculation of the Lorentz microscopy image of a weakly ordered FePt:C thin film at the various demagnetization steps during the dc-demagnetization process: (a) remanent state; (b) initial demagnetization state; (c) state after further demagnetization (the numbers represent the order of the formation of vortices during the demagnetization process); (d) schematic diagram of (c) showing the formation of elongated reverse domain. The filled and open circles in (d) represent the vortices with the clockwise and anticlockwise rotation senses, respectively, and filled squares represent the cross-ties.

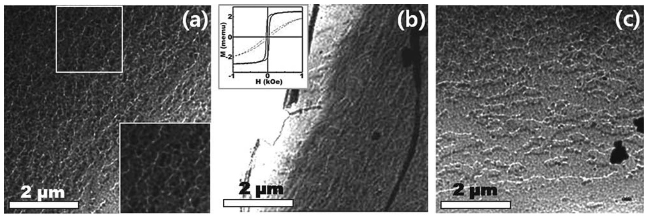

FIG. 3. Observation of the magnetic domain structure of a weakly ordered FePt:C thin film using Lorentz transmission electron microscope in Fresnel mode at various magnetization states: (a) as-deposited state; (b) remanent state; (c) dc-demagnetization state. The inset in (a) is an enlarged picture of the enclosed square area.

The LTEM observation (Fig. 3) showed that the magnetic domain structure is distinctively different depending on the magnetization state of the thin film. At the as-deposited state, the bright contrast lines appeared to show the presence of a vortex network, as seen in Fig. 1(a). However, it was difficult to clearly discern the presence of the network of the vortices in dark contrast. At the remanent state, the domain structure appeared to be a featherlike ripple structure, the bright contrast lines aligning parallel to one direction. On the other hand, at the dc-demagnetization state, the domain structure was observed to be islandlike elongated domains, which were bounded by a pair of bright and dark contrast lines, in good agreement with the calculation result [Fig. 1(d)].

In summary, the results of the present contrast calculation of magnetic domain are in good agreement with the result of the experimental observation of a weakly ordered FePt:C thin film. This showed that the presently developed technique can be utilized as an analytical tool for the analysis of the magnetic domain structure of a magnetic thin film for recording media. In addition, the present analysis strongly suggested that the magnetization reversal in this weakly ordered FePt:C thin film occurs through a local magnetization rotation to form a series of small local vortices at the domain boundaries. The propagation of reversed domains occurred not by the movement of vortices but by the annihilation of old vortices and the formation of new local vortices at the domain boundaries. This magnetization reversal mechanism is thus significantly different from the magnetization reversal mechanism in soft magnetic film, where the magnetization reversal is known to occur through a domain wall motion.[9]

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