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MFM analysis of the magnetization process in $L1_0$–$A1$ FePt patterned film fabricated by ion irradiation

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Abstract

Ga^+ ions at a dose of 0.1 at.% (1.5×10^{14} ions cm^{-2}) were irradiated by focused ion beam (FIB) onto $L1_0$ FePt films with a [001] crystalline texture normal to the film plane, and two-dimensional patterns composed of squares with high-coercivity ($L1_0$ structure, $300 \times 300\ nm^2$ and $100 \times 100\ nm^2$) separated by a soft magnetic region ($A1$ structure) 100 nm wide were fabricated. The magnetic domain structure of patterned film was observed by in-field magnetic force microscopy (MFM). In the remanent state, the domain with magnetization normal to the film surface was observed in the central part of the $L1_0$ square, while the narrow domain with reversed magnetization is at the circumference of the square. The magnetization process is discussed based on the MFM observations.

Keywords: $L1_0$ FePt film; Ion irradiation; Patterning; In-field MFM; Magnetization process

1. Introduction

Greater understanding of magnetic thermal fluctuation is important for achieving high-density magnetic storage, higher than 300 Gbit in.$^{-2}$, because grain size is decreasing towards the superparamagnetic critical size [1]. Bit-patterned media have been proposed as a possible solution to overcome the superparamagnetic effect and background noise of continuous magnetic recording media. Ferromagnetic dot arrays have been created by patterning a magnetic thin film using lithography techniques and/or assembling nanoparticles using self-organization processes [2–8]. Among the various patterning methods, ion irradiation patterning has attracted attention since the stencil mask technology permits non-contact patterning without complicated processes [9–23].

$L1_0$ FePt film with a face-centered tetragonal (fct) structure has a high magnetocrystalline anisotropy ($K_u \sim 7.0 \times 10^7$ erg cm^{-3}) caused by the atomic arrangement of alternating Fe and Pt layers along the [001] direction [24–30]. The large magnetocrystalline anisotropy of $L1_0$ FePt is considered to be suitable for a high recording density of more than 1 Tbit in.$^{-2}$ due to its good thermal stability. The effects of He^+ and Ar^+ ion irradiation on FePt and CoPt films have been studied to control the order parameter S of the $L1_0$ structure [9–11]. The conditions needed to bring about a transition from $L1_0$ to $A1$ (face-centered cubic structure) phase in FePt through B^+, Cr^+, Ga^+ and Nb^+ ion irradiation have also been studied [31].

In this paper, we report the fabrication of high-coercivity square dots ($L1_0$ structure) separated by a soft magnetic region ($A1$ structure) using Ga^+ ion irradiation. The magnetization reversal process of high-coercivity square dots is discussed based on domain observation using in-field magnetic force microscopy (MFM).

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2. Experiment

$L1_0$ FePt film (20 nm thick) was prepared by alternate sputtering of Fe (0.15 nm) and Pt (0.17 nm) onto MgO (100) substrates at room temperature. The sputtered films were annealed at 873 K for 1 h under a vacuum of $\sim 10^{-4}$ Pa using a rapid heating furnace. The composition of the films was $Fe_{52}Pt_{48}$ (at.%), evaluated by energy dispersive X-ray spectroscopy. The X-ray diffraction measurements revealed that [001] crystalline textures normal to the film plane were obtained through post-annealing. The long-range order parameter S for the $L1_0$ FePt film was calculated from the c/a ratio [32], where the values of c and a (lattice constants) were obtained from the (001) superlattice and (111) fundamental peaks, respectively. The value of S for the as-annealed $L1_0$ FePt films was about 0.8. The magnetic properties of continuous $L1_0$ FePt films were measured perpendicular to the film plane using an alternating gradient magnetometer (AGM) with a maximum field of ~22 kOe. The saturation magnetization (M_s) was ~840 emu cm^{-3}, remanent magnetization (M_r) ~810 emu cm^{-3}, coercivity (H_c) ~3.8 kOe and the perpendicular magnetic anisotropy constant (K_u) estimated from magnetization curves was $\sim 1.5 \times 10^7$ erg cm^{-3}.

The Ga^+ ions were irradiated onto the $L1_0$ FePt films by FIB under a vacuum of $\sim 10^{-5}$ Pa at room temperature. The ion irradiation was done at an accelerating energy of 30 keV and at a current of 1 pA. The Ga^+ ion beam is Gaussian in shape and the half width of the beam was set to be 50 nm in diameter.

A schematic illustration of the fabricated pattern is shown in Fig. 1a. The ion beam was scanned with an interval of 10 nm in the grid. By superposing 11 ion beams scanned in the grid, the Ga^+ ion concentration reached 0.1 at.% (1.5×10^{14} ions cm^{-2}) at the center of grid, as seen in Fig. 1b. Ga^+ ion irradiation of over ~0.05 at.% yielded a structural transition from $L1_0$ to $A1$ without surface damage [31]. As a result, the grid in Fig. 1a was converted to the $A1$ structure with in-plane anisotropy, while the central part of square (white square in Fig. 1a) maintained the $L1_0$ structure with perpendicular magnetic anisotropy. Between the gray grid and non-irradiated squares, there was a transient area of magnetic anisotropy, where the easy axis of magnetization changed gradually from perpendicular to parallel to the film plane with a change in Ga^+ concentration. This transient area is shown as the half-grayed regions in Fig. 1a. In this paper, the size of the fabricated square dot is denoted by l, which is the distance from center to center of the outermost Ga^+ ion beams, as seen in Fig. 1b. Two types of patterns were fabricated here: sample A ($l = 300$ nm) and sample B ($l = 100$ nm). The surface roughness of the irradiated area was less than 0.8 nm.

The surface morphology and magnetic domain structure of patterned dots were observed by an in-field MFM system, which is coupled with an electromagnet (maximum field of ~5.5 kOe). A home-made MFM tip with a $L1_0$ FePt film ($H_c \sim 10$ kOe) thickness of 10 nm was used. The diameter of the tip was less than 27 nm. Measurement conditions, such as the vibration amplitude of the tip (50 nm for morphology scanning and 10 nm for phase measurement), tip-to-sample distance (~20 nm), and Q factor (~3000) of the cantilever, were carefully controlled so that a resolution of about 15 nm was expected [33]. Analytical and numerical calculations were carried out with Mathematica® software. Spin configurations were simulated using a Landau–Lifshitz–Gilbert (LLG) Micromagnetics Simulator®.

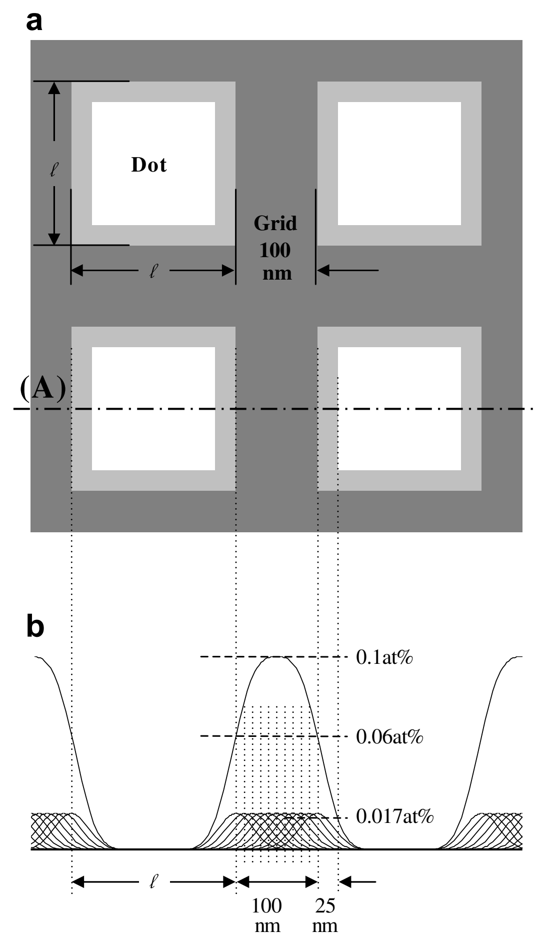

Fig. 1. Schematic illustration of designed pattern (a) and calculated spatial Ga^+ distribution at dashed line (A) (b). The Ga^+ beam was scanned at an interval of 10 nm in the grid. By superposing 11 ion beams, the Ga^+ concentration reached 0.1 at.% at the center of the grid.

3. Results and discussion

Fig. 2a shows an MFM image at the remanent state of sample A ($l = 300$ nm). Before the MFM observation, the sample was magnetized upwardly with a magnetic field of +18 kOe, while the MFM tip was magnetized downwardly by applying −18 kOe. The remanent magnetizations of square dots ($L1_0$ structure) point upward and appear as a dark contrast in the MFM image. Since the magnetization of the grid is in-plane, the grid has brighter MFM contrast