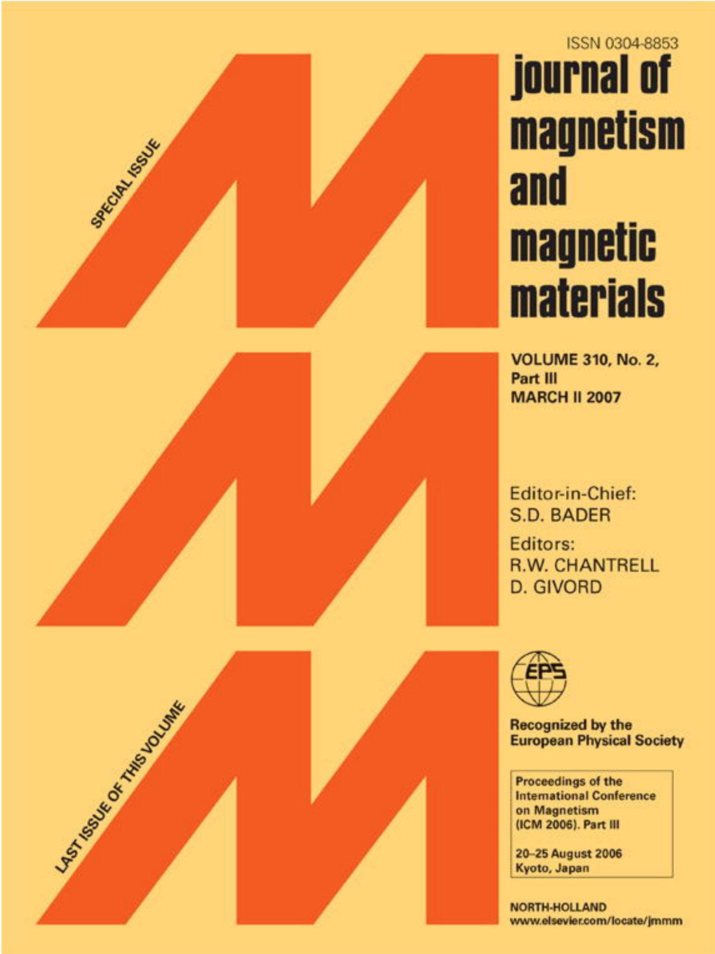
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Magnetic characterization of regularly aligned Y-shaped permalloy arrays

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Abstract

Regularly aligned arrays of submicron-sized Y-shaped permalloy ($Ni_{80}Fe_{20}$) structures buried in silicon wafers have been fabricated. Spin distributions of the surface have been observed using a magnetic force microscope (MFM) and analyzed by a micromagnetic simulation based on the Landau–Lifshitz–Gilbert equation. In widely-spaced linear arrangement of dots, two magnetic poles on the ends of two of three arms and a multi-domain structure in the remaining arm were observed. On the other hand, in the closely-spaced honeycomb arrangement regularly aligned magnetic poles appeared at the ends of all arms and no multi-domain structures appeared and the 'spin ice' states were confirmed at each vertex site of the Y-shaped dot.

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Keywords: Magnetic structure; Micromagnetic simulation; Damascene technique; Magnetic force microscope

Understanding of magnetic spin structures in ferromagnetic dots of nanometer or sub-micrometer size is essential for manipulation of nonvolatile magnetic memories and spintronic devices [1]. The spin structures of square, rectangular, and circular dots with symmetric geometry have been extensively studied [2–4]. We have been investigating magnetic structures of regularly aligned arrays of square, rectangular and cross-shaped permalloy dots buried in a silicon wafer fabricated using the damascene technique with a help of electron-beam (EB) lithography [5,6].

In the present study we focused on arrays of Y-shaped ferromagnetic dots composed of three arms, the ends of the arms forming the vertices of a triangle lattice, in which a spin frustration phenomenon is expected to arise. Dimensions of arms are 300 nm in width, 1.4 μm in length and 100 nm in depth. We prepared two different arrays: (a) a widely-spaced linear arrangement with a dot pitch of as long as 6 μm; and (b) a closely-spaced arrangement with a separation of 400 nm to make a honeycomb pattern. Details of the fabrication procedure have been described elsewhere [6].

Spin structures were investigated using an SII Nanotechnology model Nano-Navi/E-sweep magnetic force microscope (MFM) system with a low-moment probe, which is capable of high sensitive detection using a specially designed Q-control system in high vacuum [7].

Fig. 1(a) shows an MFM image of one of Y-shaped dots for the widely-spaced arrangement after applying an external magnetic field (H) of 80 Oe. Black and white spots are observed on the ends of two arms, solid gray area of the arms representing a single domain structure. In the remaining arm, a multi-domain structure composed of four chained closure domains with 90°-walls is formed as shown in Fig. 1(b).

A micromagnetic simulation based on the Landau–Lifshitz–Gilbert (LLG) equation was carried out. The LLG micromagnetic simulator [8] was modified to correspond to three-dimensional (3D) geometry created by a generic 3D-CAD system. The equation was numerically solved using the fourth-order Runge–Kutta method for high accuracy.

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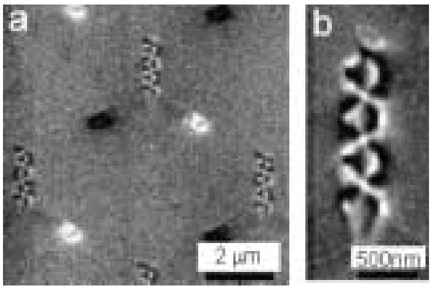

Fig. 1. (a) MFM image of the Y-shaped permalloy dot array for widely-spaced arrangement after applying H of 80 Oe and (b) magnified image of multidomain structure

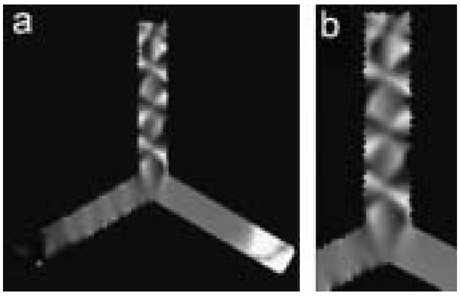

Fig. 2. (a) Calculated z-component force gradient image of an isolated Y-shaped permalloy dot and (b) magnified image in arm with multi-domain structure.

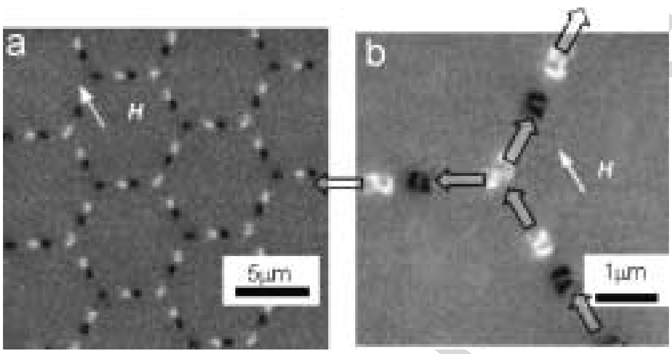

Fig. 3. (a) MFM image of Y-shaped dots after applying H of 80 Oe for honeycomb arrangement and (b) magnified image of a specific dot with block arrows showing spin flow.

The force gradient interacting between an MFM probe and the Y-shaped dot was calculated using the mathematical expression given by Garcia et al. [9].

Figs. 2(a) and (b) show images of the z-component force gradient simulated for an isolated Y-shaped permalloy dot of approximately the same size as the fabricated dot. Details of the simulation are described elsewhere [6]. The calculated images are in excellent agreement with the MFM observations. A single domain structure appears in each of two arms and a multi-domain structure is formed in the remaining arm. Two of the arms show single domains due to the shape anisotropy in arms and the exchange energy in the crossing point of the three arms. The remaining arm can take either a single domain in the 'in' direction, a single domain in the 'out' direction, or a multi-domain structure. Under the weak interaction between adjacent dots, a multi-domain structure is stabilized to minimize the magnetostatic energy.

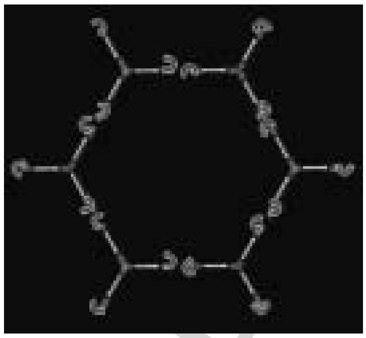

Fig. 4. Calculated magnetization configuration of Y-shaped dots for honeycomb arrangement.

Fig. 3(a) shows an MFM image of the closely separated array and Fig. 3b the magnified image of a specific dot after applying H of 80 Oe. Regularly aligned magnetic poles are observed at the ends of all arms and no multi-domain structures appeared. Magnetic poles show polarity reversal between opposing dots. The estimated spin flow in a specific dot is illustrated by arrows in Fig. 3(b). The spin flow conforms to the "two-in, one-out" or "one-in, two-out" rule around the vertex, which corresponds to the 'ice rules' of the honeycomb network of permalloy [10], and is similar to the 'spin ice' states in the artificial frustrated ferromagnetic islands [11].

Fig. 4 shows a calculated magnetization distribution for a honeycomb array composed of six Y-shaped dots separated by 400 nm, where the dot was designed as 200 nm in width, 40 nm in depth, and $20 \times 20 \times 20\,nm^3$ elementary volumes. Single domains are formed in all arms and vortices appear at the ends of the arms. The chirality of vortices shows a mirror reflection at the ends of all arms, which suggests the existence of a significant magnetostatic interaction.

In conclusion, spin structures were investigated in regularly aligned arrays of the Y-shaped permalloy dots using MFM measurements and a micromagnetic simulation. In the widely separated array, a heterogeneous spin structure appeared. In the closely separated honeycomb array, regularly aligned magnetic poles with opposite signs are observed, which suggests a significant magnetostatic interaction between dots. The calculated spin structures are in good agreement with the experimental MFM images.

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