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Fabrication and Magnetic Characterization of Embedded Permalloy Structures

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Abstract Regularly aligned array structures of square and cross-shaped magnetic dots of sub-micrometer size embedded in silicon wafers were fabricated. It was found from magnetic force microscope observation that the spin vortices of adjacent square dots showed opposite chirality to each other, probably due to magnetostatic interaction. In the cross-shaped dot arrays, magnetic poles appeared at the end of each bar and a complicated contrast was seen at the crossing point. These observations are successfully explained by a three-dimensional micromagnetic calculation using the Landau-Lifshitz-Gilbert equation.

Keywords: magnetic dot array, damascene technique, MFM, micromagnetic calculation, magnetostatic interaction

1. Introduction

Magnetostatic interaction working between nearest magnetic elements is an important issue to be elucidated in high-density magnetic devices such as magnetic random access memories (MRAM) and patterned magnetic media. In the case of nano-scale dots, the effect of the magnetostatic force is not simple because complicated spin structures appear in such small dots. Fundamental studies with both experimental and theoretical approaches are therefore necessary to elucidate the interaction.

There are a number of research works on the preparation and characterization of small magnetic arrays, most of which employ a lift-off process to prepare the patterned structures. However, magnetic force microscope (MFM) images of the uneven surface structures produced by the lift-off technique often suffer artifacts from topographic images, making detailed analysis difficult. We therefore employed the damascene technique in which an even surface is provided by a flattening process.

Regularly aligned magnetic patterns of square and rectangular dot arrays embedded in silicon wafers were prepared by the damascene technique employing electron beam (EB) lithography and CMP techniques, details of which have been described elsewhere.[1]

In this study we employed permalloy $Ni_{80}Fe_{20}$ as a magnetic material. It is known that this permalloy is not suitable for recording studies because it possesses very small anisotropy. On the other hand, this material is suitable for studies evaluating magnetostatic effects, since due to its softness it can easily be subjected to the magnetostatic effect from an adjacent dot and due to its high saturation magnetic flux density the magnetic field from the dot is relatively large.

We showed in our previous paper that a square pattern displays a closure-domain structure, which undergoes a propeller-like distortion attributed to the stray-field effect from the MFM tip. In this study we focused our attention on the magnetostatic interaction between the adjacent square dots. We also studied cross-shaped dot arrays of different sizes in order to elucidate the spin-structure at the crossing point of two bars, since such crossing points often appear in the layout of electrical resistivity measurements.

Interpretation of MFM images is not straightforward, because the MFM detects the magnetic force from magnetic materials working on the tip. Theoretical analysis is known to be effective for this purpose. We therefore carried out a micromagnetic simulation using the Landau-Lifshitz-Gilbert (LLG) equation in three dimensions and compared the results with the experimental results.

2. Experiments

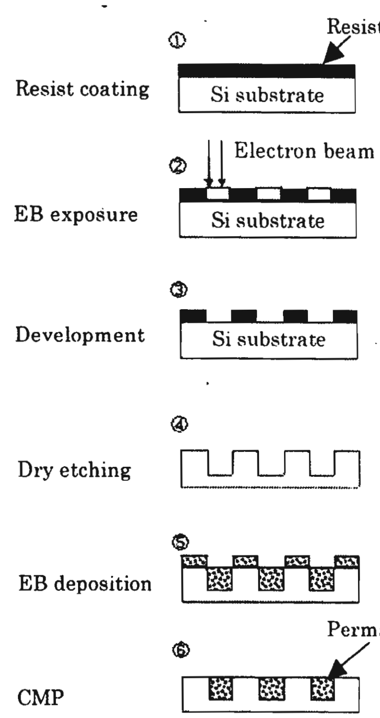

Fig. 1 Fabrication process of a permalloy dot array patterned by the damascene technique

A process flow for the fabrication of magnetic dot array structures by the damascene technique with EB lithography and CMP is schematically illustrated in Fig. 1, details of the process having been described in our previous paper.[1] By atomic force microscope (AFM) measurements, the mean-square roughness of the polished surface was determined to be less than 10 nm.

Models of the fabricated patterned square dot arrays of 1 μm × 1 μm and 300 nm × 100 nm with a separation of 300 nm are shown in Fig. 2. The patterned area is as large as 3 mm × 3 mm. Fig. 3 shows two types of cross-shaped patterns named CROSS1 (200 nm in width, 3 μm in length, and with a separation of 3 μm) and CROSS2 (100 nm in width, 1.5 μm in length, and with a separation of 1.5 μm). The thickness of all the magnetic dots after the CMP process was 150 nm on average.

Magnetic properties were measured using a vibrating sample magnetometer (VSM) (Toei model VSM-5) and an SII Nanotechnology model SPI-3800N conventional MFM with a conventional tip (having a 50 nm-thick coating of CoCrPt) in air, and an SII Nanotechnology model SPI-4000/SPA300HV MFM with a low-moment tip (having a 25 nm-thick coating of CoCrPt) using a specially designed Q-control in a high-vacuum environment. The measurements using the low-moment tips were carried out at SII Nanotechnology Inc.

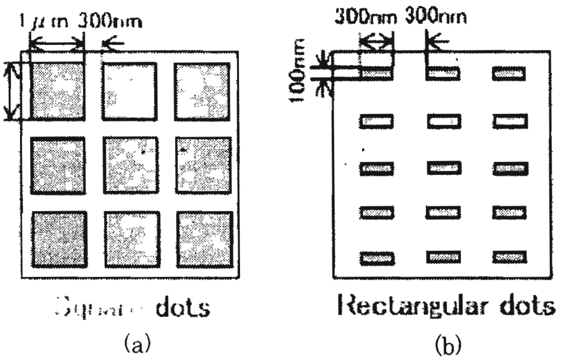

Fig. 2 Two models of fabricated patterns. (a) square dot array and (b) rectangular dot array

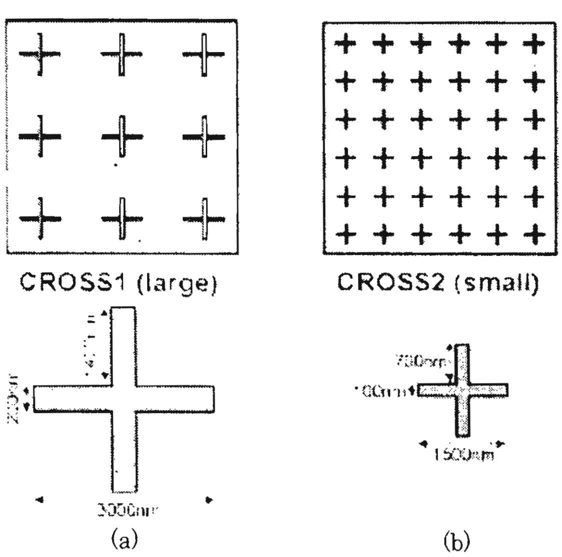

Fig. 3 Two models of fabricated cross-patterned dots: (a) CROSS1 and (b) CROSS2

3. Results and Discussion

3.1 Magnetic properties of the square dot arrays

Figure 4 shows a comparison of MFM images of square dots measured using probes with a high-moment tip in air and with a low-moment tip in a high vacuum. The propeller-like domain wall pattern, which was ascribed to the stray field from the tip in the previous paper taking into account the argument of Miltat,[2] is more clearly observed even with a low-moment tip. This means that the propeller-like pattern is not necessarily due to the MFM tip. In addition, a careful observation suggests that the directions of rotation (chirality) in the propeller-shaped domain walls of adjacent square dots show a mirror-reflection of each other, suggesting a strong effect of magnetostatic interactions between dots in the array structure.

In order to explain the MFM images observed as described above, theoretical analyses based on micromagnetic simulation were performed by solving the LLG equation, details of which will be published elsewhere. Simulation was carried out on a model structure consisting of four square dots having dimensions of 200 nm × 200 nm × 20 nm with a 50 nm separation between dots. The calculated spin structure is illustrated in Fig. 5(a), in which a closure domain structure with a 90-degree wall appears. The chiralities of the spin directions in adjacent dots are

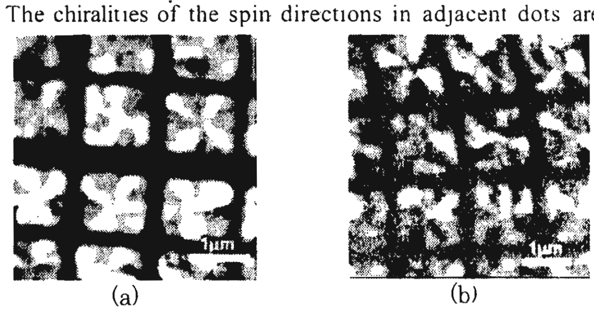

Fig. 4 Comparison of MFM images of square dots measured using probes with (a) a high-moment tip in air and (b) a low-moment tip in a high vacuum

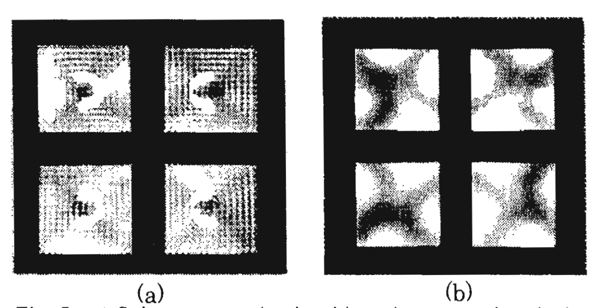

Fig. 5 (a) Spin structure simulated by micromagnetic calculation using the LLG equation and (b) force-gradient image calculated taking the tip-sample interaction into account

opposite to each other as shown by white arrows. Fig. 5(b) shows the Z-component force-gradient image taking the tip-sample interaction into account, which exhibits very good agreement with the MFM patterns shown in Fig. 4.

3.2 Magnetic properties of the cross-patterned dot arrays

Magnetization curves of the CROSS1 and CROSS2 cross-patterned dot arrays measured by VSM with the sample plane parallel and perpendicular to the magnetic field are shown in Figs. 6 and 7, respectively. In these curves it is observed that the easy axis of magnetization is not fixed either parallel or perpendicular to the sample surface.

Figures 8 and 9 show MFM images obtained using a low-moment tip of the CROSS1 and CROSS2 cross-patterned dot arrays, respectively. In each figure, (a) shows a wide-area-scan image and (b) a narrow-area-scan (zoom) image. Regularly aligned magnetic poles are observed in the MFM image of CROSS1 shown in Fig. 8(a). Dark spots appear at the left and lower ends of the crossed bars, whereas bright spots are seen at the right and upper ends. On the other hand, the MFM image of CROSS2 in Fig. 9(a) shows a different spot arrangement. Regarding the crossing point of the crossed bars, a complicated MFM image is observed at the crossing region in Fig. 8(b).

Figures 10(a) and 10(b) show a comparison of MFM images obtained using a demagnetized low-moment tip (in a high vacuum) and a high-moment tip (in air), respectively. Both figures show magnetic poles at the ends of the crossed bars. The magnetic poles of the cross-pattern array structure are aligned in the same direction in Fig. 9(a), even after the tip is demagnetized, suggesting that the magnetic alignment cannot solely be attributed to the stray field from the probe tip. It may originate from the magnetostatic interaction between dots. The smaller cross pattern shows a complicated MFM image as seen in Fig. 9(b), which may be ascribed to poorly fabricated patterns in the sample, limited by the accuracy of the present damascene process.

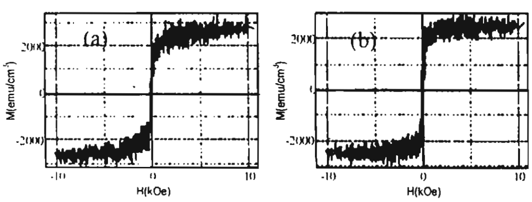

Fig. 6 Magnetization curves of CROSS1 cross-patterned dot array for the field (a) parallel and (b) perpendicular to the sample plane

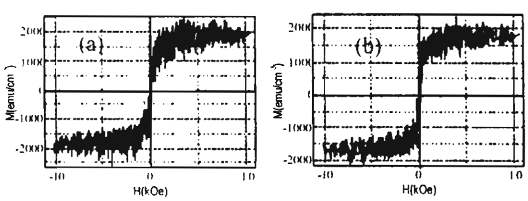

Fig. 7 Magnetization curves of CROSS2 cross-patterned dot array for the field (a) parallel and (b) perpendicular to the sample plane

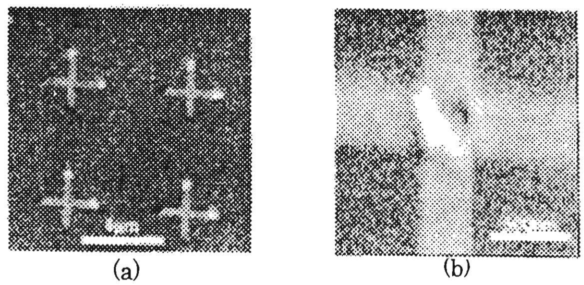

Fig. 8 MFM observations of CROSS1 cross-patterned dot array using a low-moment-tip showing (a) 4 dots and (b) a zoom image at the crossing region

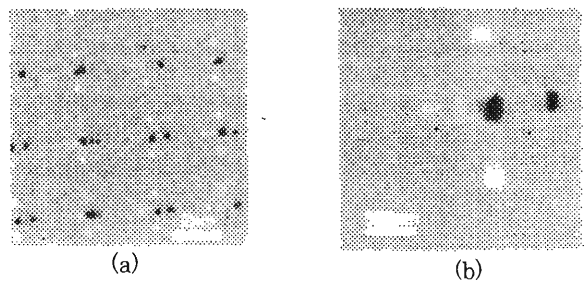

Fig. 9 MFM observations of CROSS2 cross-patterned dot array using a low-moment-tip showing (a) 9 dots and (b) a zoom image at one dot

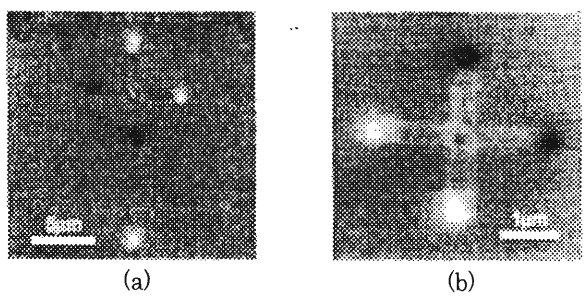

Fig. 10 MFM observations of CROSS1 cross-patterned dot array using (a) a demagnetized low-moment tip in a high vacuum and (b) a high-moment tip in air

Figure 8(b) shows a magnified image around the region of the crossing point in the cross-patterned dot array. The image is divided by a diagonal line with bright-dark contrast patterns. As shown in Fig. 10(b), an MFM image using a high-moment tip cannot resolve such a detailed structure. Here we confirm the merit of using a low-moment-tip.

In order to interpret the observed MFM images, we carried out micromagnetic simulation based on the LLG equation. The results of the simulation are illustrated in Fig. 11 Figure 11(a) shows a force-gradient image, which corresponds to the MFM image and is found to show a remarkable agreement with the experimental MFM image of Fig. 8(a). Both the theoretical and experimental images

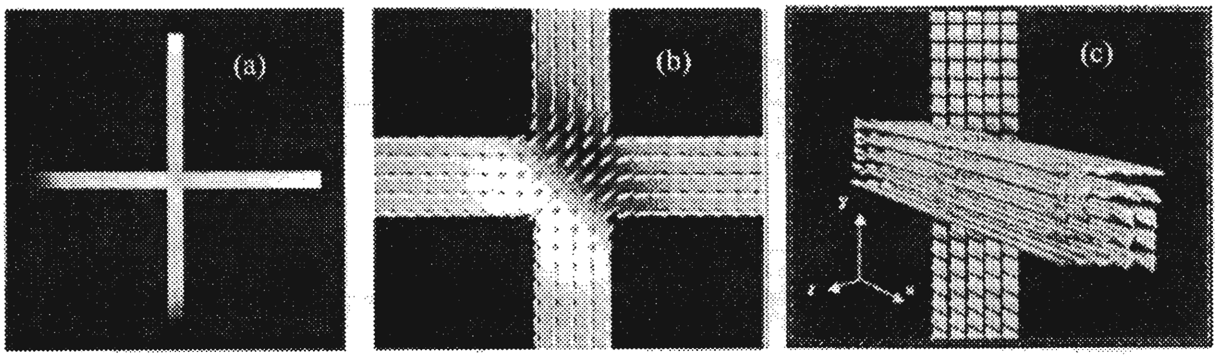

Fig. 11 Results of LLG simulation: (a) force-gradient image taking the tip-sample interaction into account, (b) spin flow image at the crossing region, and (c) vortex structure in direction x

show dark or bright images of magnetic poles at the ends of the crossed bars. Figure 11(c) shows a three-dimensional illustration of the spin structure at the end portion of the bar. By careful observation of Fig. 11(c) it is elucidated that the MFM image is due to the inclination of spins with a vortex structure only at the end of the bar. The formation of the vortex may be a consequence of the height being comparable to the width of the cross-pattern.

The spin flows are continuous in the direction toward the upper right from the lower left in the figure at the crossing region, with a vertical inclination along the diagonal line. Thus, the complicated spin structures observed by MFM at the crossing point are explained by the simulation. Evaluation of the magnetostatic interactions between crosses is an issue for future investigation.

4. Conclusions

Regularly aligned permalloy dots with sub-micron cross-shaped patterns were successfully fabricated using the damascene technique on silicon substrates.

In the square dots, magnetostatic interaction between adjacent dots gave a propeller-like distortion to the 90-degree wall pattern in the closure domain structure, creating a mirror reflection in the chirality of the wall between adjacent dots. Micromagnetic simulation elucidated that the chirality reversal was due to magnetostatic interaction of the square dots.

In the cross-pattern dots, the MFM patterns showed magnetic poles at the ends of the bars, which were aligned periodically over the observed area. A comparison of two images obtained by tips with different moment values showed that the magnetic alignment cannot be attributed to the stray field from the probe tip. Magnetostatic interaction between cross-patterned dots should therefore be taken into account. At the crossing region, the spin structure is diagonally divided into two sets of bright-dark contrast patterns.

The micromagnetic simulation perfectly explains not only the appearance of poles at the ends of the bars but also the complicated spin structure around the crossing point.

Acknowledgements

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