Magnetic structure of cross-shaped permalloy arrays embedded in silicon wafers

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Abstract

This paper describes the observed magnetic structure and the micromagnetic simulation of cross-shaped, permalloy (Ni\textsubscript{80}Fe\textsubscript{20}) arrays embedded in silicon wafers. The nano-scale-width, cross-shaped patterns were fabricated using the damascene technique, electron beam lithography, and chemical mechanical polishing. The magnetic poles were observed as two pairs of bright and dark spots at the ends of the crossed-bars using a magnetic force microscope. The force gradient distributions were simulated based on micromagnetic calculations and tip’s stray field calculations using the integral equation method. This process of calculation successfully explains the appearance of the poles and complicated spin structure at the crossing region.

It is critical to understand the spin structures and magnetic switching behavior of nano-scale patterned magnetic elements for application in high-density data storage devices, nonvolatile magnetic memories, and magnetic logic gates. The spin structures of square, rectangular, and circular dots have been extensively studied [1]. We have investigated regularly aligned magnetic patterns of square (1 × 1 \textmu m\textsuperscript{2}), rectangular (300 × 100 \textmu m\textsuperscript{2}), and circular (100 \textmu m in diameter) arrays with a thickness of 150 nm and a pattern separation of 300 nm embedded in silicon wafers [2]. These patterns were successfully fabricated using the damascene technique, electron beam (EB) lithography, and chemical mechanical polishing (CMP). However, the spin structures for more complicated geometries with a branch have not yet been adequately investigated. We focused on cross-shaped arrays of permalloy (Ni\textsubscript{80}Fe\textsubscript{20}) in order to clarify their spin structures.

Fig. 1 shows the mask patterns of the cross-shaped arrays. Two kinds of structures termed CROSS\textsubscript{1} (200 nm in width, 3 \textmu m in length with a separation of 3 \textmu m) and CROSS\textsubscript{2} (100 nm in width, 1.5 \textmu m in length with a separation of 1.5 \textmu m) were fabricated. EB resist films (ZEP520) spin-coated on a silicon wafer were exposed. The wafer with the patterned resist films was dry-etched by RIE using CF\textsubscript{4} gas, and pit arrays of about 150 nm in depth were formed on the wafer. Permalloy films were deposited on to the pit arrays using...
an electron beam evaporator, and the films outside the pit were polished out by CMP.

The remanent state of these nano-scale arrays was observed using an SII Nanotechnology model SPI-4000/SPA300HV magnetic force microscope (MFM) system with a low-moment probe (having a 24-nm-thick Co–Cr–Pt coated tip) using a specially designed Q-control in high vacuum, after applying a magnetic field of 20kOe in the direction toward the tip from the sample.

Figs. 2(a) and (b) show MFM images for CROSS1 measured in high vacuum with a low-moment tip (a) in \(10 \times 10 \mu m^2\) scan area and (b) in \(1.5 \times 1.5 \mu m^2\) scan area.

\(\frac{\delta F_z}{\delta \zeta_{\text{tip}}} = \int_{\text{sample}} \nabla^2 H_{\text{tip}} \cdot M_{\text{sample}} \, d^3r + \int_{\text{sample}} \frac{\partial H_{\text{tip}}}{\partial z} \frac{\partial M_{\text{sample}}}{\partial z_{\text{tip}}} \, d^3r,\)  

\(1\)
where $H_{\text{tip}}$ is the stray field from the tip at the sample volume element, $M_{\text{sample}}$ is the magnetization of a sample volume element at equilibrium, and $z_{\text{tip}}$ is the tip–sample distance. The values of $H_{\text{tip}}$ and $M_{\text{sample}}$ are considered to change corresponding to the tip–sample interaction. The magnitude of the coercive force ($H_c$) for a 24-nm-thick Co–Cr–Pt coated tip is about 650 Oe. Therefore, the influence of a sample’s stray field on the magnetization of the hard magnetic tip is considered to be approximately constant. On the other hand, the influence of a tip’s stray field on the magnetization of the soft magnetic sample, that is, $\delta M_{\text{sample}}/\delta z_{\text{tip}}$ included in the second term of Eq. (1), is considerably large. However, in this work, this term was excluded to save calculation time.

Fig. 5 shows the schematic structure of the MFM probe model for calculating $H_{\text{tip}}$ at the sample’s volume element.

Fig. 6. (a) Force gradient distribution of cross-shaped permalloy pattern and (b) with magnetization distribution at crossing region.
element. The MFM probe’s tip (tip diameter \( d = 30 \text{ nm} \)) is coated with Co–Cr–Pt (thickness \( t = 24 \text{ nm} \) and \( H_c = 650 \text{ Oe} \)). The \( H_{\text{tip}} \) distributions were calculated using an integral equation method.

Fig. 6 shows the force gradient distributions of a cross-shaped pattern. Two pairs of bright and dark spots were obtained at the ends of the crossed-bars, as shown in Fig. 6(a). Furthermore, as shown in Fig. 6(b), bright and dark contrasts appeared on each side of a slanted boundary (the dotted line) in the crossing region, consistent with the experimental MFM image shown in Fig. 2(b), even though the size of the simulated pattern is different from that of the CROSS1 pattern shown in Fig. 2(b).

In conclusion, cross-shaped permalloy arrays embedded in silicon wafers were fabricated using the damascene technique, and their spin structures were investigated using MFM measurements. The force gradient distributions for a cross-shaped pattern were simulated based on micromagnetic calculations and tip’s stray field calculations using the integral equation method. This process of calculation successfully explains the important features of MFM images; i.e., appearance of magnetic poles at the bar ends, and the complicated spin structure at the crossing region.

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References