

Writing Bits of Longitudinal Quantized Magnetic Disk Using Magnetic Force Microscope Tip

Linshu KONG, Rick C. SHI, Peter R. KRAUSS and Stephen Y. CHOU

Nanostructure Laboratory, Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455, USA

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Longitudinal quantized magnetic disks (QMDs) consisting of discrete single domain Ni bars on a silicon substrate with a density of nearly 2 Gbit/in.² were fabricated. A magnetic force microscope (MFM) tip with a large magnetic moment has been used to successfully write individual bits of the QMD by simply positioning the tip near one end of a Ni bar. It was found that the MFM tip can write each individual bit perfectly without writing the neighboring bits. This is attributed to the fact that the magnetization of each QMD bit has only two stable quantized values and therefore the writing process is quantized.

KEYWORDS: quantized magnetic disks, magnetic force microscope, electron-beam lithography, single domain, switching field, writing process

1. Introduction

In the epic of information and multimedia, demands for higher data storage density escalate drastically. Whether the storage density of commercial magnetic disks can reach 10 Gbit/in.² is under debate.¹⁾ One thought is that for a storage density significantly higher than 10 Gbit/in.², a new magnetic disk paradigm is needed. Quantized magnetic disks (QMDs) are such a potential candidate.^{2,3)} QMDs based on patterned magnetic thin film have pre-fabricated, discrete, single-domain magnetic elements uniformly embedded in a non-magnetic disk. Each single-domain element has a uniform, well-defined shape and a pre-specified location, and has only two possible stable magnetization states: equal in magnitude but opposite in direction. Each magnetization direction of a single-domain element can represent a bit of binary information. A QMD of a vertical magnetization uses pillars, and a QMD of longitudinal magnetization uses bars.

QMDs are expected to have several advantages over the conventional disks such as spontaneous self-quantization of each bit's magnetization, isolated transition region between bits which allows high data packing density and near zero transition noise. Moreover, QMDs will help to overcome the superparamagnetic limits.

The main purpose of this work is to experimentally write data in QMDs. Micromagnetic simulation has shown that the writing process in a QMD is quantized.⁴⁾ Previously, magnetic force microscope (MFM) tips were used to write magneto-optical recording media,⁵⁾ and were found to be able to flip Permalloy bars.⁶⁾ In this paper, we present the experimental demonstration of writing each individual bar in a nearly 2 Gbit/in.² longitudinal QMD using a MFM tip. We will also discuss the unique properties of such writing.

2. Fabrication and MFM Tip Characteristics

The highest data storage density in a QMD fabricated so far is 65 Gbit/in.² using vertical magnetization.⁷⁾ For the purpose of clear demonstration and due to the limitation of our current MFM tip, in this paper we focus on writing individual bits of a longitudinal QMD with lower

density. The longitudinal QMD is made of discrete single domain Ni bars with a 100 nm width, 400 nm spacing and length varying from 300 nm to 700 nm, which corresponds to nearly 2 Gbit/in.² density.

The Ni bars were fabricated using electron-beam lithography and a lift-off technique.^{8,9)} In the fabrication, rectangular patterns were exposed in a thin film of polymethyl methacrylate (PMMA) on a silicon substrate with high-resolution electron-beam lithography. The exposed PMMA was removed in a development process, resulting in rectangular trenches in the PMMA. 35-nm-thick Ni was evaporated onto the entire sample. Finally, the sample was immersed in acetone which dissolved the PMMA template, lifting off the Ni that was on the PMMA and leaving the isolated Ni bars on the substrate. Figure 1 shows a scanning electron micrograph of the Ni bars. We used a Nanoscope III from Digital Instruments to carry out the MFM measurement. MFM observation shows that each as-deposited Ni bar is a single domain, and the switching field of these Ni was found to be about 350 Oe.¹⁰⁾

The MFM tips used in this experiment were made in house by coating a magnetic thin film on commercial Si SPM tips. The uncoated Si tips have pyramidal structures with 10–15 μm height and cone half angle of about 20°. The cantilevers are 221 μm long, 25–28 μm wide and 2.2–3.5 μm thick. The resonant frequencies are 58–93 kHz, the spring constants are 1.1–4.5 N/m, and the tip radii are about 10 nm.

Two types of MFM tips were used. One was the writing tip which had a large magnetic moment and was coated by sputtering Co. We used the tips with different thickness Co film to scan the fabricated Ni bars with length of 700 nm, and determined the phase shift $\Delta\Phi$ (i.e., MFM response) from the captured image. Figure 2 shows the MFM response of the tips as a function of Co film thickness. It can be seen that the tip with 60-nm-thick Co film has the largest MFM response. This is consistent with the results published in previous papers.¹⁰⁾ We used the tip with 60-nm-thick Co film to write the Ni bars. The other tip, with 20-nm-thick Co film coated by e-beam evaporation, was used as the reading tip since it will not change the orientation of the bars.

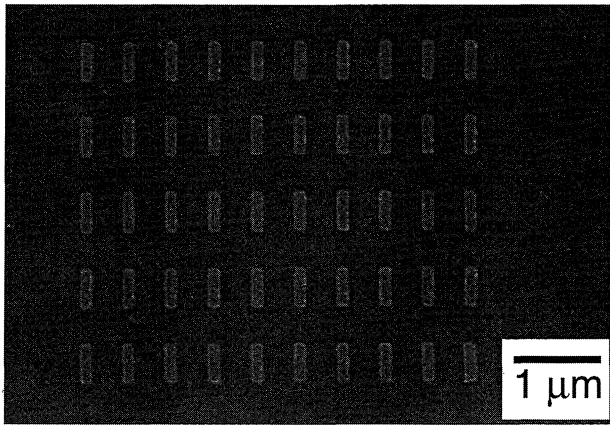


Fig. 1. SEM micrograph of Ni bars in a 1.6 Gbit/in.² QMD.

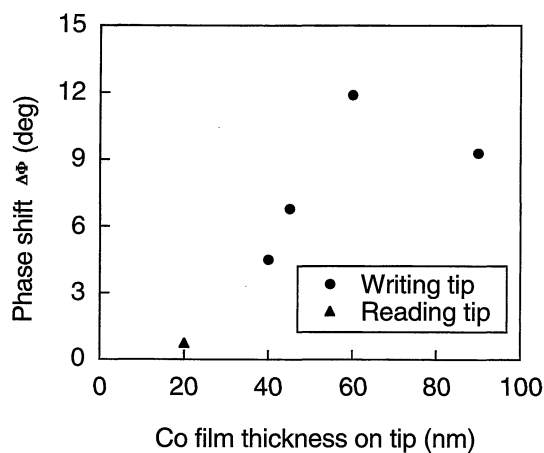


Fig. 2. MFM response vs. Co film thickness on MFM tip.

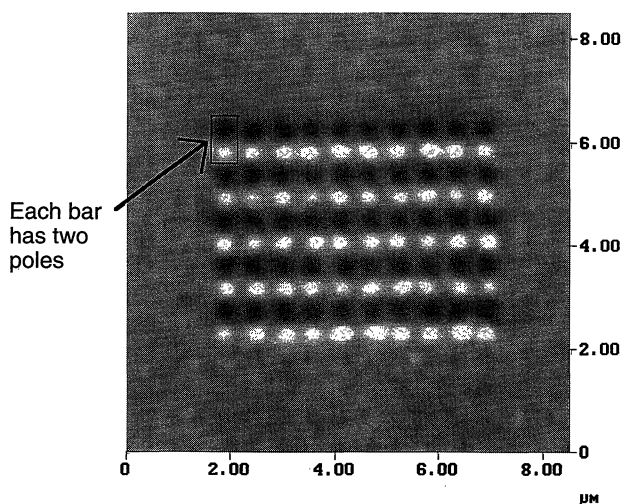


Fig. 3. MFM image of the same bars shown in Fig. 1. The image was obtained by the reading tip right after the sample was scanned from bottom to top by the writing tip.

The writing and reading tips were magnetized in the same direction by applying a magnetic field of 8 kOe. Figure 3 shows the MFM image obtained by the reading tip right after the sample was scanned from bottom to top by the writing tip. As shown, each bar has two poles:

one light pole representing the repulsive tip-sample interaction and one dark pole representing the attractive interaction. The image indicates that each Ni bar is a single domain.

We found that when using a reading tip, the MFM image stayed the same independent of the scan direction and the scan height. This indicates the magnetic moment of the reading tip was weak and unable to switch the Ni bars. On the other hand, when using a writing tip, the magnetization of each Ni bar was reversed when the scan direction was reversed. Furthermore, all the bars were observed to have the same magnetization direction after scanning regardless of the Ni bars' initial states. This means that the magnetic field of the writing tip was strong enough to switch every Ni bar.

3. Writing Process

Before writing, the first step was to scan the writing tip over the entire sample, thereby aligning the magnetization of all the bars in the same direction. The surface topography image during the scan process was captured using the program "Capture Plane" available in our DI NanoScope III, and was used as the map for the writing step. In the writing step, we used the lithography software available in NanoScope III and selected a previously written script. When the lithography script was run in Tapping Mode (the feedback was turned off), the tip traveled according to the command in the script and relative to the plane captured above.

During the writing process, the MFM, which was under the control of the lithography script, first lifted up the MFM writing tip and then moved the tip above one end of a bar. The end of the bar initially had a magnetic pole opposite to that of the MFM writing tip. The actual writing process was simply to lower the writing tip, bringing the tip close to the bar. It was found that when the vertical distance between the tip and bar was less than 5 nm (determined from the script), the writing tip could perfectly flip the magnetization direction of the bar without flipping the neighboring bars. After writing one bar, the MFM writing tip was raised up and moved to write other bars. This process was continued until all the desired bars were written. After writing, the reading tip was used to nondestructively image the written pattern.

4. Results and Discussion

Figure 4 shows that nine bars in the 1.6 Gbit/in.² longitudinal QMD were written correctly using the MFM writing tip. Figures 5(a) and 5(b) show the written patterns of a plus sign "+" and letter "L". All the patterns shown in Figs. 4 and 5 are exactly the same as the scripts run through the lithography software. These results demonstrate that by simply lowering a MFM tip, one bit in a QMD can be perfectly written without writing the neighboring bits of the QMD.

It should be pointed out that unlike a conventional write head, an MFM tip has a very poorly defined writing field, and during the writing process the MFM does not have any feedback to track the exact tip movement. Also, the switching field of each bar is not exactly the

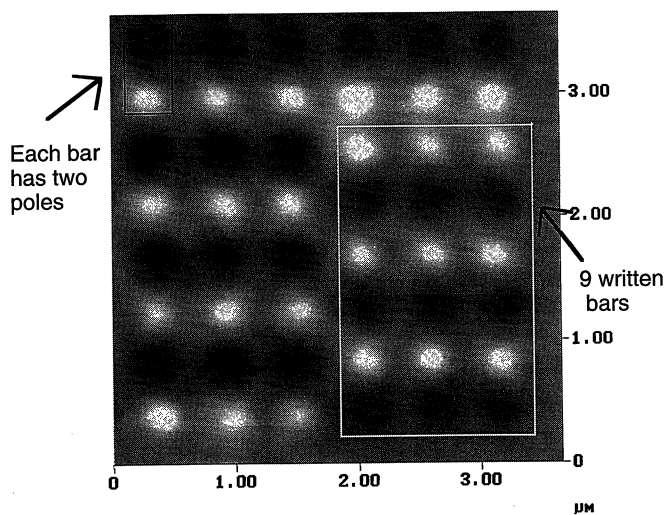


Fig. 4. MFM image of nine Ni bars written by writing tip.

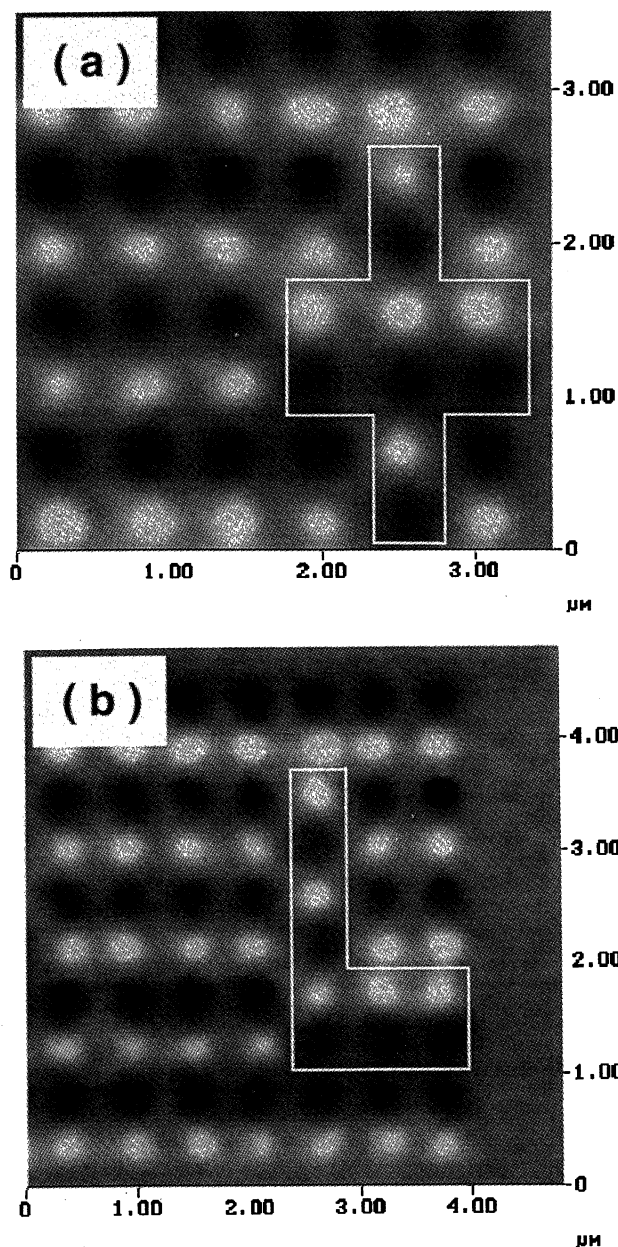


Fig. 5. MFM images of written patterns in QMD. (a) plus sign “+”; (b) capital letter “L”.

same due to fabrication limitations and magnetostatic interaction between the bars. However, even under these circumstances, the 1.6 Gbit/in.² longitudinal QMD can be written perfectly. This clearly demonstrates one of the advantages of QMD in ultrahigh density recording. Namely, the writing process in a QMD becomes quantized, meaning that either a QMD bit is written perfectly or it is not written at all. This property of QMDs may relax the requirement of the writing field.

Since the switching field for the Ni bars shown in Fig. 1 was found to be about 350 Oe, the local magnetic field produced by the writing tip should be at least 350 Oe. By varying the distance between the tip and Ni bars, we may use the experiment described above to investigate the distribution of the stray field from a MFM tip.

5. Conclusions

We demonstrated that each bit of 1.6 Gbit/in.² longitudinal QMD can be perfectly written without writing the neighboring bits using an MFM tip. The writing of QMDs with a higher density is currently being studied.

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