Perpendicular quantized magnetic disks with 45 Gbits on a $4\times4\ cm^2$ area

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Quantized magnetic disks consisting of an array of single domain Ni pillars with a density of 18 Gbits/in.^{2} were fabricated using nanoimprint lithography (NIL) and electroplating. The total disk area, limited by the NIL mold, is $4\ cm\times4\ cm$, leading to a total 45 Gbits. Magnetic force microscope (MFM) images show that all pillars 70 nm in diameter and 400 nm in height are single domain. The magnetostatic interaction between adjacent pillars is fairly strong. The pillars have an average switching field of 360 Oe and can be switched by a MFM tip with a large magnetic moment.
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I. INTRODUCTION

The data storage density of conventional magnetic thin film media is limited by the superparamagnetic limit, interbit exchange coupling, bit edge noise, and tracking. All of these limitations can be eliminated or alleviated if the continuous thin film media is replaced by quantized magnetic disks,[1,2] also called patterned media, in which each bit of information is stored in a single domain magnetic island. Inside each island, all ferromagnetic grains are strongly coupled by exchange and magnetostatic interaction, so that they behave collectively during magnetization reversal. Outside the island, a nonmagnetic material completely eliminates the exchange coupling between islands. As a result, the ultimate theoretical storage density of such a medium, determined by the superparamagnetic limit of the islands, will be 6000 Gbits/in.^{2} for Co.

Previously, quantized magnetic disks (QMDs) with a 35 nm pillar diameter and a density of 65 Gbits/in.^{2} were demonstrated.[3] However, the disk area was limited to the order of 100 μm^2 due to the low throughput of e-beam lithography. Therefore, to commercialize QMDs, a low cost, high-throughput nanopatterning technology must be developed. Nanoimprint lithography[4] is a very promising technology to pattern QMDs. It has demonstrated sub-10 nm resolution patterning with high throughput.[5] At present, nanoimprint lithography (NIL) can replicate nanoscale patterns over a 4 in. wafer within a few minutes. In this article, we will present the fabrication of large area nickel perpendicular QMDs using NIL and electroplating, and their characterization using an atomic force microscope (AFM), a magnetic force microscope (MFM), and a vibrating sample magnetometer (VSM).

II. FABRICATION OF NI PILLAR ARRAY

The fabrication of QMDs with an array of nanoscale high-aspect-ratio nickel pillars embedded in a nonmagnetic SiO_2 matrix consists of four major steps: substrate preparation, patterning, electroplating, and chemical mechanical polishing (CMP).

In substrate preparation, a thin metal plating seed layer was first deposited on a silicon wafer, then a SiO_2 film, and, finally, a 200-nm-thick layer of polymethyl methacrylate (PMMA) was spun as the NIL resist. The SiO_2 layer is the nonmagnetic layer to embed the Ni pillars, and its thickness determines the final height of the nickel pillars. In patterning the substrate, a hole array was formed in PMMA using NIL with a grid mold. The grid mold was fabricated by a double NIL process with a grating mold that was fabricated using interference lithography (the details of the mold fabrication are described elsewhere).[6] O_2 reactive ion etching (RIE) was used to etch the holes into the entire PMMA thickness. Then 20 nm Cr was shadow evaporated on the PMMA as an additional RIE mask, since PMMA has poor etching selectivity relative to SiO_2. Finally, the hole array pattern was transferred into the SiO_2 layer using RIE. The PMMA/Cr etching mask was removed after etching. During electroplating, the current was kept constant, and the solution was stirred continuously in order to uniformly fill the holes. Because Ni has a relatively high magnetostriction coefficient and thus is sensitive to stress, we chose nickel sulfamate-based plating solution for its low stress property. Finally, CMP was used to remove the over-plated Ni and to gain a smooth surface. The slurry contains 20 nm diameter silica particles as abrasive particles and its *p*H can be adjusted by adding diluted nitric acid to the original alkaline slurry.

III. RESULTS AND DISCUSSION

The properties of QMDs were characterized using scanning electron microscopy (SEM), AFM, VSM, and MFM. Figure 1(a) shows a pillar array having pillars which are 110 nm in diameter, 240 nm in height, and a 190 nm period. For this feature size, all holes are successfully filled and the pillars are very uniform with nearly vertical sidewalls. The surface is very smooth with Ni pillars recessed about 3 nm from

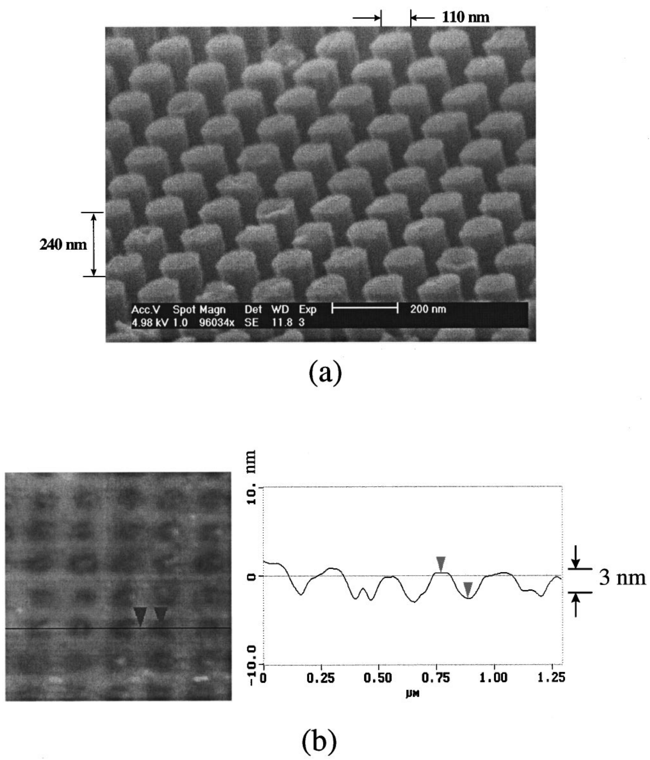

FIG. 1. (a) A SEM picture of a 18 Gbits/in.^{2} large area QMD. The SiO_2 was stripped in order to show Ni pillars more clearly. (b) An AFM image of the same QMD before stripping SiO_2, showing Ni pillars were recessed about 3 nm below the SiO_2 surface.

the SiO_2 surface [Fig. 1(b)]. Since SiO_2 is a good polishing stop layer, we expect that the pillar height is nearly the same as the SiO_2 thickness before CMP and the surface of the 4 cm$\times$4 cm disk is flat. A smooth and flat topology is essential for very low flying height recording.

The hysteresis loop of the large area pillar array measured by a VSM is shown in Fig. 2. The pillars of this particular disk have a diameter of 70 nm and height of 400 nm. Since all pillars are single domain (see below), the average switching field is equal to the coercivity which is 360 Oe. If curling is assumed to be the magnetization reversal mechanism, and if the exchange constant is assumed to be

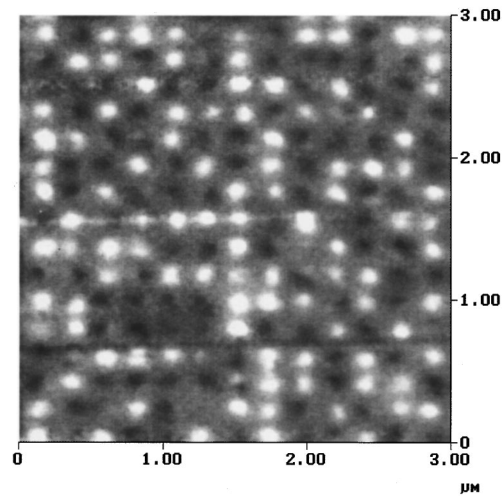

FIG. 3. MFM image of a QMD with 18 Gbits/in.^{2} density. Each bit consists of a 70 nm diam single domain nickel pillar uniformly embedded in 400-nm-thick SiO_2. The pitch between pillars is 190 nm.

5×10^{-7} erg/cm for Ni, we can calculate the switching field according to Aharoni's formula.[7] The result is 270 Oe for the current pillar dimension, which is similar to the value obtained from the experiment. Furthermore, the shape of the hysteresis loop is approximately a sheared square. This is a characteristic of strong interpillar interaction,[8] as a near square hysteresis loop is expected for an uncoupled pillar array. To reduce the magnetostatic coupling effect, the switching field of the pillars should be increased. This can be achieved by either reducing the pillar diameter, by increasing the pillar aspect ratio, or by replacing Ni with a magnetically harder material such as Co.

The spontaneous formation of a single domain is critical to having each pillar store one bit information. The MFM was used to determine whether the pillars were single domain or not. MFM tips were prepared by e-beam evaporating 10–35 nm Co onto silicon tips and magnetizing them along the tip axis. During MFM phase detection, the tip was lifted 25–40 nm above the surface. No distinct poles were found in the MFM image for a pillar array with a 110 nm diameter

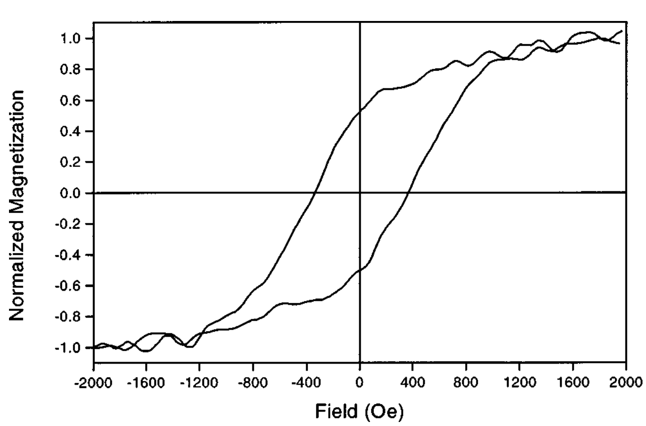

FIG. 2. A hysteresis loop of a large area 18 Gbits/in.^{2} QMD. The pillars have a diameter of 70 nm and height of 400 nm. The coercivity is 360 Oe.

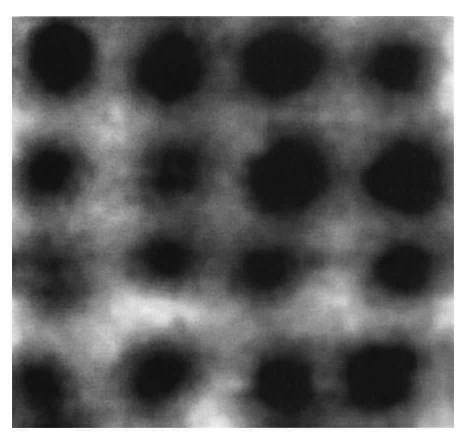

FIG. 4. MFM image of 4 by 4 bits of a Ni QMD in the remnant state. All pillars have the same polarization, indicating the switching field of each pillar is large enough to overcome interbit magnetostatic interactions.

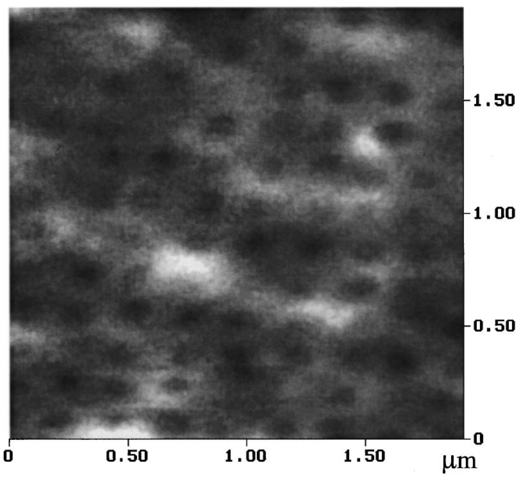

FIG. 5. MFM image of a Ni pillar array scanned with a 35 nm Co-coated MFM tip. Only dark poles are evident. This polarity is opposite to the initial state of the pillars, indicating that the field from the tip is sufficiently strong to switch every pillar.

and 240 nm height, indicating the pillars were not single domain. When we increased the pillar height to 400 nm and decreased the pillar diameter to 70 nm, a strong distinct pole array was observed in the MFM image (Fig. 3), indicating all pillars are single domain. An AFM image showed there are roughly one percent unfilled holes so some poles are missing in the MFM image. Also, it can be seen that the poles are not located exactly at the pillar sites, because of the stray field from adjacent pillars, keeping in mind that the MFM detects the force derivative rather than the force on the tip itself. In addition, despite the strong interaction between pillars, we were able to find a 4×4 pole array with the same magnetization direction in the remnant state (Fig. 4).

Finally, to investigate the feasibility of switching the magnetization of the pillars with a MFM tip, we scanned the QMD with a MFM tip coated with 35 nm Co. Only attractive dark poles were evident in the MFM image (Fig. 5), even though the pillars of the disk were initially magnetized in the opposite direction. Therefore, such a QMD could be written by a Co-coated MFM tip.

IV. SUMMARY

Using nanoimprint lithography, electroplating, and chemical mechanical polishing, large area quantized magnetic disks with a density of 18 Gbits/in.^{2}, a disk area of 4×4 cm^2 and, hence, a total storage capacity of 45 Gbits were fabricated. An AFM image of this QMD indicates the surface of the QMD is smooth. When the pillar diameter was reduced to 70 nm and the aspect ratio was increased to 5.7, all the pillars begin to form single domains. The average switching field was 360 Oe, and curling was suggested as the magnetization reversal mechanism. The magnetostatic interaction between neighboring pillars was strong enough to flip some of the pillars having relatively low switching fields. The pillars' magnetization could be switched by MFM tips coated with 35 nm Co. We concluded that such a QMD could be written and read with a high resolution single-pole-type head.

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