Large area high density quantized magnetic disks fabricated using nanoimprint lithography

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A new low-cost, high throughput method was developed for fabricating large area quantized magnetic disks (QMDs) using nanoimprint lithography (NIL), electroplating, and chemical mechanical polishing. Perpendicular QMDs with a density of 18 Gbit/in.^{2} and good uniformity over an area of 4 cm$\times$4 cm (total 45 Gbit) have been achieved, as well as longitudinal QMDs of 30 Gbit/in.^{2} The NIL molds for the perpendicular QMDs were fabricated using double NIL with a grating mold. The magnetic properties of both types of QMDs were studied by magnetic force microscopy. © *1998 American Vacuum Society.* [S0734-211X(98)15406-9]

I. INTRODUCTION

Quantized magnetic disks (QMDs) are a new paradigm for magnetic data storage that can overcome the storage density limit of conventional thin-film magnetic disks by several orders of magnitude.[1,2] A QMD consists of discrete magnetic single domain islands uniformly embedded in a nonmagnetic disk; each island has only two possible magnetizations, equal in magnitude and opposite in direction (Fig. 1). Fabrication of QMDs generally requires use of a lithography that has sub-100 nm resolution. Previously, we demonstrated QMDs with a density of 65 Gbit/in.^{2} fabricated using *e*-beam lithography.[3] However, like other conventional ultrahigh resolution nanolithographies, e-beam lithography is too expensive to be used for the commercialization of QMDs because of its low throughput, which takes several days to fabricate even a penny size 65 Gbit/in.^{2} QMD. It is important, therefore, to develop a low-cost, high throughput, nanopatterning technology.

One alternative way to pattern QMDs is to use interference lithography.[4,5] Interference lithography has many advantages as well as a number of challenges. One of the challenges is that the dose profile of interference lithography is sinusoidal, making it difficult to precisely control the feature size, particularly when patterns are pillars or a via array. The other is that for high resolution an antireflection coating (ARC) layer is needed, which is insolvable in most common solvents, thus increasing processing complexity.

Nanoimprint lithography (NIL) is a new approach to patterning QMDs. It is a sub-10 nm resolution lithography tool with high throughput and low cost.[6,7] In NIL a resist is patterned by physically deforming its shape with a mold rather than by changing the resist chemical structure with radiation. Although the fabrication of NIL master molds requires the use of other lithography techniques and could be expensive, the low-cost, rapid replication of NIL and long lifetime of the molds will keep the cost of each QMD low.

II. FABRICATION OF NIL MOLDS

The NIL molds for QMDs consist of large area pillars of a period of 190 nm and a height of 180 nm, which were fabricated in two steps. First, a grating mold was fabricated using interference lithography (wavelength 351 nm). Second, the grating mold was used in a double NIL process to fabricate pillar molds for QMDs. Each pillar has a square cross section and vertical sidewall, rather than a round cylindrical shape. Using our current process the uniform area of a pillar mold is 4 cm$\times$4 cm, and is limited by the area of our interference lithography tool which produced the grating mold. Our discussions here focus on the fabrication and properties of QMDs, while the fabrication of the grating and pillar molds will be reported elsewhere.[8]

III. FABRICATION OF LARGE AREA PERPENDICULAR QMDs USING NIL

A perpendicular QMD structure consists of a high-density array of nanoscale single domain nickel pillars embedded in a SiO_2 film with a smooth top surface. The fabrication of such disks includes the following steps shown in (Fig. 2). First, a thin metal plating base was deposited on a silicon wafer, then a SiO_2 film, followed by a 200 nm poly(methylmethacrylate) (PMMA) film. The SiO_2 layer is the nonmagnetic layer; its thickness determines the final height of the nickel pillars. The PMMA serves as the NIL resist. Second, a pillar mold was used to pattern a via array in the PMMA film using NIL. Then O_2 reactive ion etching (RIE) was used in the NIL for pattern transfer, which anisotropically etched the via array into the entire PMMA thickness. Third, a 20 nm Cr layer was evaporated at a glancing angle on the top of the PMMA to provide an additional mask for etching the SiO_2. Fourth, CHF_3 RIE etched the via array into the SiO_2 and stopped at the plating base. The etching had a pressure of 2 mTorr, a power of 150 W, and a CHF_3 gas flow of 15 sccm. During the final several seconds of the etching, O_2 was added into the plasma to remove the passivating layer produced in the etching process on the bottom and sidewall of the SiO_2 vias, which can affect the uniformity of the subsequent elec-

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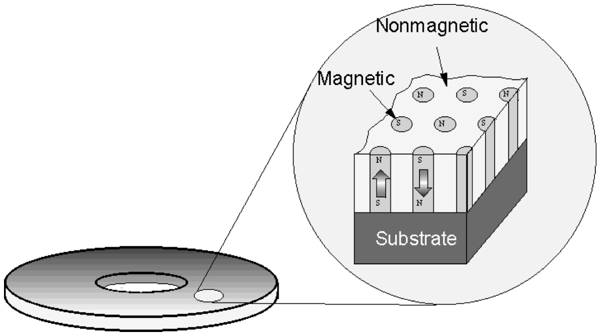


FIG. 1. Schematic of a quantized magnetic disk. A QMD consists of discrete single magnetic domain bits uniformly embedded in nonmagnetic disks; each bit has only two possible magnetizations (equal in magnitude but opposite in direction).

troplating. Fifth, nickel was electroplated through the holes. Finally, chemical mechanical polishing (CMP) was used to remove the excess nickel from the top of the SiO_2 layer to achieve a smooth surface.

IV. RESULTS AND DISCUSSIONS OF LARGE AREA PERPENDICULAR QMDs

In NIL, a press with two parallel plates was used. A typical pressure for NIL is 100 lb/cm^2, and the temperature is 175 °C. The scanning electron microscopy (SEM) picture in Fig. 3 shows a 190 nm period via array patterned in PMMA using NIL by a daughter QMD mold. The via array has little defect count and is uniform over an area of 4 cm×4 cm, which was limited by the molds size. The low defect is due to the fact that the NIL process is a self-cleaning process. The mold release agent on the mold makes dust weakly bound to the mold. But a molten resist acts like glue to the dust, taking it away from the mold. A ''dirty'' mold will become completely clean after just a few imprints. The vias shown in Fig. 3 do not have sharp corners, because it is imprinted by a daughter mold. The round corners came from the lift-off process that is used to make the daughter mold.

Electroplating of the nickel was carried out in a nickel sulfamate based solution with a pH value in the range of 3.0–4.5. The temperature was 50 °C and the current density was 10–30 mA/cm^2, which gave a plating rate of 200–600 nm/min. The as-deposited nickel had a rough surface and looked dark due to the large grain size. The hysteresis loop, measured by vibrating sample magnetometer (VSM), showed that the saturation magnetization of the as-plated Ni film was very close to that of bulk Ni, and the coercivity of the Ni film was about 100 Oe. We can also plate bright

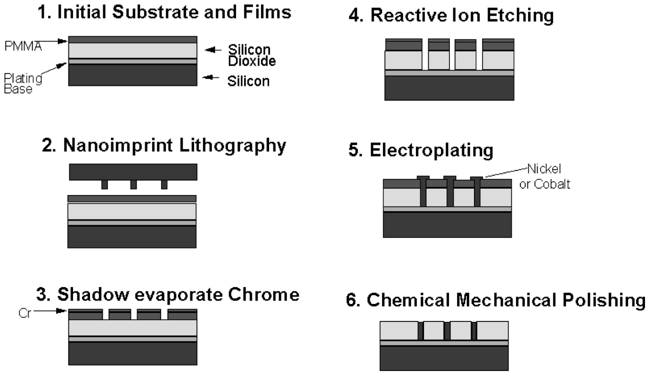


FIG. 2. Schematic of the QMD fabrication process.

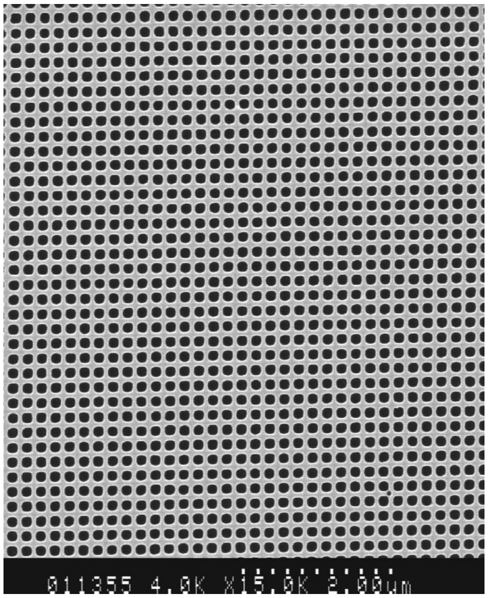
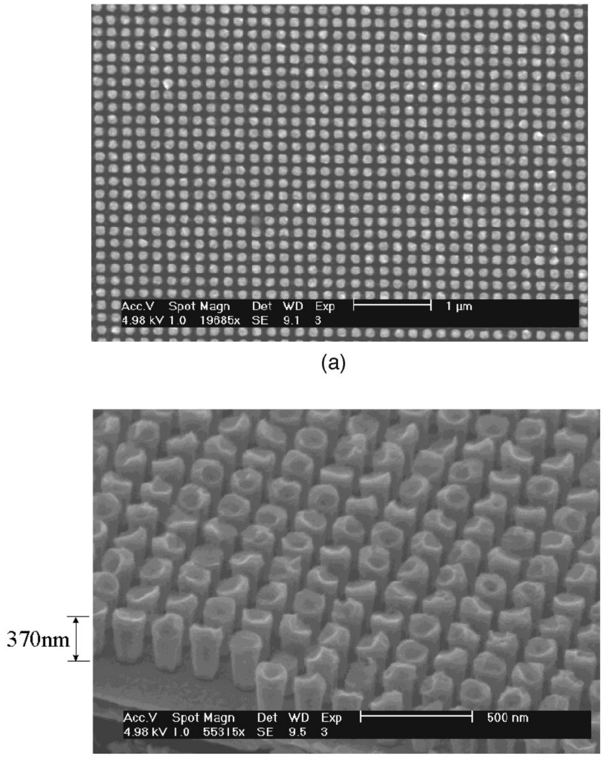


FIG. 3. SEM picture of a 190 nm period square via array on PMMA fabricated by single NIL using a pillar daughter mold.



(a)

(b)

FIG. 4. SEM pictures of a 18 Gbit/in.^{2} large area perpendicular QMD fabricated using NIL. Each bit is an electroplated pillar. (a) Top view. (b) The SiO_2 was stripped off in order for the Ni pillars to be seen more clearly.

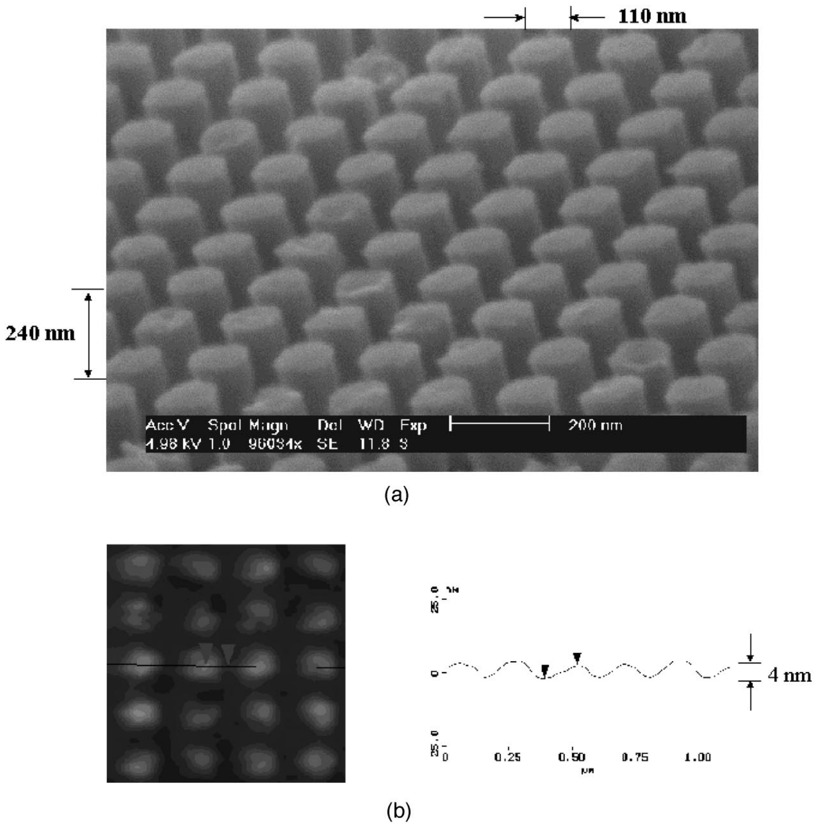


FIG. 5. (a) SEM picture of an 18 Gbit/in.^{2} large area perpendicular QMD fabricated using NIL. Each bit is an electroplated pillar. The SiO_2 was stripped off in order for the Ni pillars to be seen more clearly. (b) AFM image of the 18 Gbit/in.^{2} large area perpendicular QMD. The image shows a surface roughness of 4 nm.

nickel with a smooth surface by adding additives to reduce the grain size. But this organic additive may deteriorate the magnetic properties. As shown in Fig. 4(a), the electroplating is uniform. To examine the sidewall of the nickel pillars, SiO_2 was removed [Fig. 4(b)]. The nickel sidewall seems to conform to the SiO_2 template and no voids were found. For a uniform area of 4 cm×4 cm and a density of 18 Gbit/in.^{2}, the total number of bits of a QMD are 45 Gbit.

To make a smooth top surface, extra nickel above the SiO_2 surface was polished away using CMP. The slurry con-

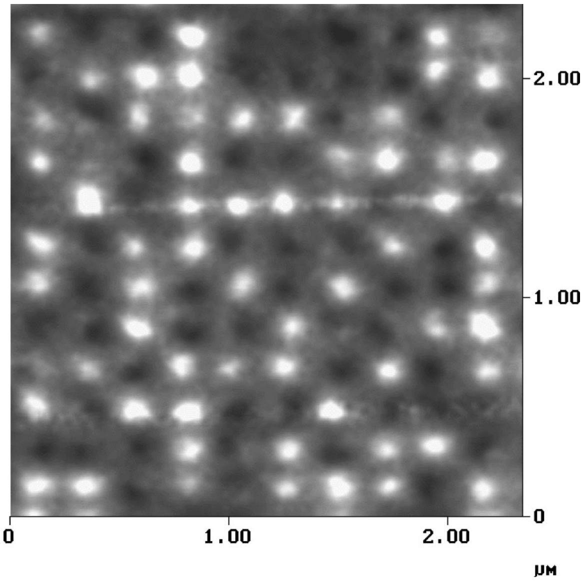


FIG. 6. MFM picture of a 18 Gbit/in.^{2} large area perpendicular QMD. There is one magnetic pole at every nickel pillar. That means every bit is a single domain.

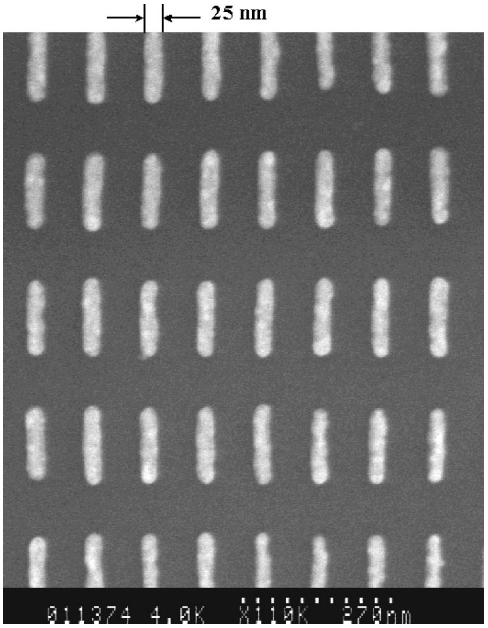


FIG. 7. SEM picture of a 30 Gbit/in.^{2} large area longitudinal QMD fabricated using NIL.

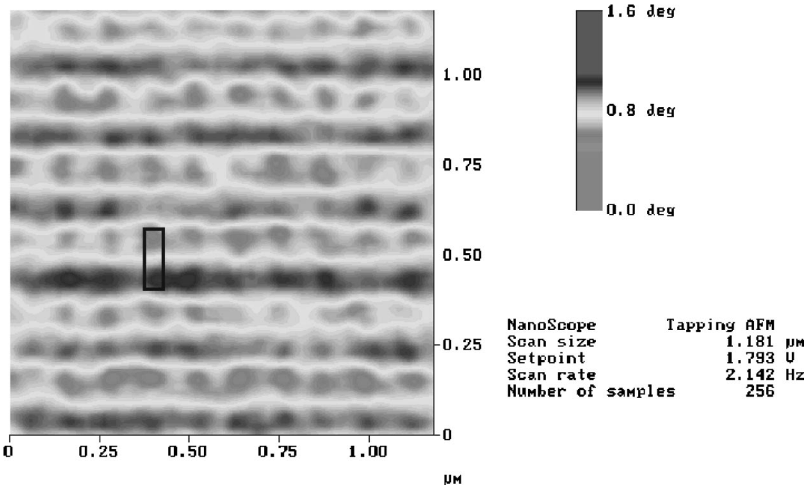


FIG. 8. MFM picture of a 30 Gbit/in.^{2} large area longitudinal QMD fabricated using NIL. Each bit contains a pair of poles, which means each bit is a single domain.

tains 20 nm diam silica particles, and has a pH value of 10.3. The polishing pressure was 0.64 psi. After CMP, the QMD's nonflat top surface became nearly flat. An atomic force microscopy (AFM) image indicates that the roughness is about 4 nm [Fig. 5(b)]. The roughness can be reduced by using an improved CMP process.

The QMDs fabricated were characterized using magnetic force microscopy (MFM). One of the key properties of a QMD is that each pillar should spontaneously form a single magnetic domain without an external magnetic field so that the magnetization of each pillar has only two possible states equal in magnitude but opposite in direction, pointing up or down. When a single domain pillar is formed, the MFM image will show either a bright pole (representative of the repulsive tip–sample interaction) or a dark pole (representative of the attractive interaction) at each pillar site.

When the pillar height is 200 nm and the pillar diameter is 100 nm, no strong single poles at pillar sites were observed in MFM images. This indicates that the pillars are not single domains primarily because the aspect ratio (pillar length to pillar diameter) is too small. When the pillar height is 300 nm and pillar diameter is 70 nm, a strong tip–sample interaction at certain pillar sites was observed in the MFM image, which reveals that some pillars formed a single domain, while some ones did not. By increasing the pillar height to 400 nm and keeping the diameter at 70 nm, a clear magnetic pole was observed at each pillar position over nearly the whole sample area observed in the MFM image (Fig. 6). That means that each Ni pillar is a single domain. In the remnant state, the north and south magnetic poles were distributed randomly. The average coercivity of each pillar is 360 Oe. The total number of defects over 4 cm×4 cm is about 1%, which is low enough for data storage applications.

V. LONGITUDINAL QMDs OF 30 Gbit/in.^{2}

In parallel to perpendicular QMDs, we also fabricated longitudinal QMDs with densities up to 30 Gbit/in.^{2} using NIL, which is much higher than what has been demonstrated previously. The fabrication involves NIL in a 140 nm thick PMMA layer on a silicon substrate and a lift off of 1.5 nm Cr and 32 nm Co films evaporated thermally. As shown in Fig. 7, each bit is a bar 25 nm wide, 140 nm long, and 75 nm apart.

MFM observations indicated that all the Co bars in the QMDs were single domains. Each bar clearly shows two opposite magnetic poles: one dark pole representing the attractive tip–bar interaction and one bright pole representing the repulsive interaction (Fig. 8). Moreover, we have successfully written longitudinal QMDs with 10 Gbit/in.^{2} density using a MFM. Error-free writings were achieved even though there was no feedback control of the writing tip and the switching field of Co bar was as high as 1020 Oe. This suggests that QMDs can, as expected, relax requirements in the design and positioning of a writing head, and are well suited for ultrahigh-density magnetic storage.

VI. SUMMARY

We have fabricated 18 Gbit/in.^{2} perpendicular QMDs (190 nm period) over a uniform area as large as 4 cm×4 cm (total 45 Gbit) using NIL, electroplating, and CMP, as well as 30 Gbit/in.^{2} longitudinal QMDs using NIL and lift off. The MFM study showed that each bit of both the perpendicular QMDs and the longitudinal QMDs is a single domain. The total number of defects over a 4 cm×4 cm perpendicular QMD is 1%, sufficiently low enough for data storage. The total uniform area can be increased to cover a 4 in. diam wafer if we improve our current interference lithography.

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