Fabrication of planar quantum magnetic disk structure using electron beam lithography, reactive ion etching, and chemical mechanical polishing

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A planar quantum magnetic disk (QMD) with a magnetic storage density of 65 Gbit/in.^{2}, over two orders of magnitude greater than the state-of-the-art magnetic storage density, has been fabricated. The planar QMD structure consists of single-domain nickel (magnetic) nanopillars uniformly embedded in a SiO_2 (nonmagnetic) disk. Electron beam lithography was used to define the QMD bit's size and location, and reactive ion etching was used to form an SiO_2 template. Nickel electroplating was used to selectively deposit nickel into the template openings, and chemical mechanical polishing was used to planarize the surface. The resulting QMD consists of ultrahigh density arrays of single-domain magnetic pillars with a 50 nm diameter and 100 nm period uniformly embedded in 200-nm-thick SiO_2 and with a surface roughness of 0.5 nm root mean square. Each single-domain structure has a quantized magnetic moment and acts as a single bit to store one bit of binary information. Furthermore, a method for mass production of QMDs, the nanoimprint technique, is discussed.

I. INTRODUCTION

In a quantum magnetic disk (QMD) each bit is represented by a prepatterned nanoscale single-domain magnetic pillar or bar that was uniformly embedded in a nonmagnetic material on a disk as shown in Fig. 1. Although many QMD embodiments are possible, the particular QMD structure we report here consists of ultrahigh density arrays of nanoscale single-domain nickel pillars embedded in a SiO_2 film with an extremely smooth top surface. The size and shape of each magnetic bit is well controlled during the fabrication to ensure single-domain formation. Due to its large shape anisotropy and nanoscale size, each bit has a magnetization that is quantized along the long axis and has only two stable states: equal in magnitude but opposite in direction. Compared to ordinary magnetic disks, the QMD offers many unique advantages in writing, reading, and tracking.

Previously, we have demonstrated that nanoscale nickel structures are single magnetic domains, and that the switching field of such single-domain nickel bars can be engineered by controlling their geometric factors such as size and aspect ratio.[1] We have also developed an electroplating process for fabricating nanoscale magnetic structures.[2] In this article, we will present a QMD fabrication process which involves electron beam lithography, reactive ion etching, and chemical mechanical polishing. The fabrication process results in a QMD which consists of single-domain nickel pillars with a 50 nm diameter and 100 nm period embedded in 200 nm SiO_2 with an extremely smooth top surface with a roughness of 0.5 nm root mean square (rms). A very smooth surface is required by magnetic disk drives due to the low flying height used by magnetic recording heads. We will report the analysis of the QMD using scanning electron microscopy, atomic force microscopy, and magnetic force microscopy. Finally, we will present a low-cost process for mass producing QMD, called the nanoimprint technique.

II. PLANAR QUANTUM MAGNETIC DISK FABRICATION

The QMD fabrication process is schematically shown in Fig. 2. The fabrication process begins with a silicon substrate and the electron beam evaporation of a thin plating base of 10 nm of titanium and 50 nm of gold and an etch stop layer of 10 nm of chrome. Next, 200 nm of SiO_2 is deposited on the substrate by plasma-enhanced chemical vapor deposition (PECVD) as the nonmagnetic material that separates the bits. Then another 25 nm of chrome is deposited to be used as a dry etch mask. Finally, 70-nm-thick 950 K polymethylmethacrylate (PMMA) was spun onto the substrate.

A high resolution electron beam lithography system was used to expose dot arrays in the resist. The system used a modified JEOL 840A scanning electron microscope with a beam diameter of 4 nm. The dot arrays had periods varying from 50 nm to 1 μm and diameters varying from 35 to 100 nm. The PMMA was developed in cellosolve:methanol (3:7), and the dot array patterns were transferred into the underlying chrome layer through a wet etch. The PMMA was then

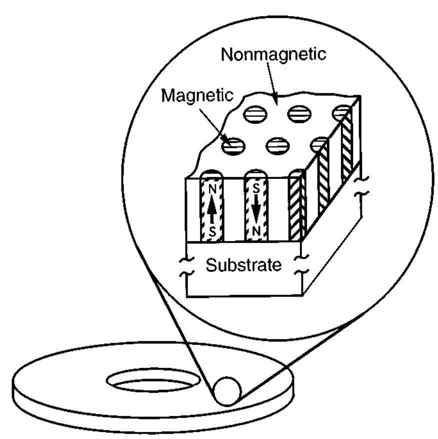

FIG. 1. Schematic of a QMD. Only the perpendicular magnetization is shown, but the disk can also be made with longitudinal magnetization.

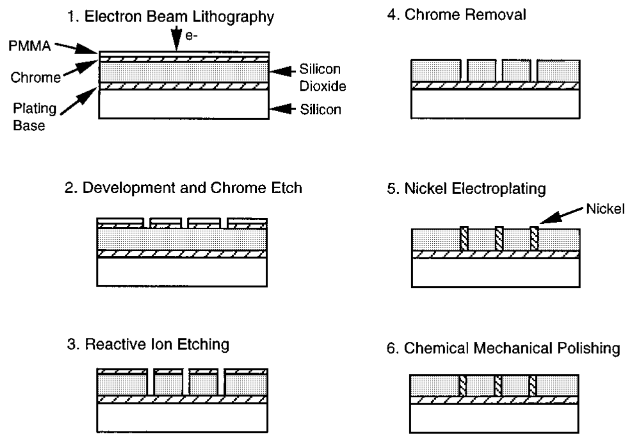

FIG. 2. Schematic of QMD fabrication process using electron beam lithography, RIE, and CMP.

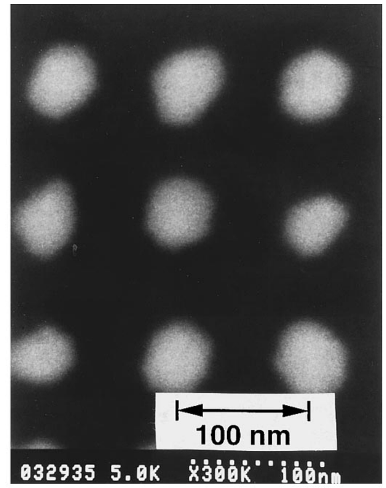

FIG. 3. SEM image of 3-by-3 bits of a QMD with 65 Gbit/in.^{2} density. Each bit consists of a nickel pillar uniformly embedded in 200 nm SiO_2 with a 50 nm diameter (aspect ratio of 4) and a 100 nm period.

removed in an oxygen plasma. Electron beam nanolithography allows precise control of the magnetic pillar geometry which greatly affects the magnetic switching properties. The minimum magnetic pillar diameter is limited to approximately 50 nm due to the isotropy of the wet chrome etch and thickness of the chrome layer. Therefore, the holes in SiO_2 have an aspect ratio of 4.

Fluorine based reactive ion etching (RIE) was then used to etch the arrays of holes through the SiO_2 down to the plating base beneath forming an SiO_2 template. The RIE process was optimized using CHF_3 and O_2 to achieve anisotropic etching for perpendicular sidewalls and high aspect ratio features. Perpendicular sidewalls are required since the magnetization switching properties depend upon the interface between the nickel pillar and nonmagnetic SiO_2 template.

A nickel electroplating process was used to selectively deposit nickel, a ferromagnetic material, into the SiO_2 template openings.[2] The process used a nickel sulfamate and boric acid plating solution with a pH of 4 and temperature of 50 °C. The process was optimized for electroplating nanoscale structures and used ultrasonic agitation for increased plating uniformity. The resulting nickel structures have very uniform sidewalls, conform to the SiO_2 template, and were slightly overplated to ensure complete filling of the template cavities. Other ferromagnetic materials, such as cobalt, could also be electroplated to obtain other magnetic characteristics.

Finally, chemical mechanical polishing (CMP) was used to remove the overplated nickel on the SiO_2 surface. The CMP used a silica based colloidal suspension with 60-nm-diameter SiO_2 particles and a pH of 9.8. The resulting surface was extremely smooth with a roughness of 0.5 nm rms. Very smooth surfaces are required by ultrahigh density magnetic disk drives that have a low flying height of less than 50 nm for reading and writing heads.

III. ANALYSIS

A QMD of 65 Gbit/in.^{2} density fabricated using this process has been investigated using scanning electron microscopy (SEM), tapping mode atomic force microscopy (TMAFM), and magnetic force microscopy (MFM). A SEM micrograph of a top view of a 3-bit by 3-bit section of the QMD is shown in Fig. 3. The micrograph shows the nickel pillars of the QMD have a 50 nm diameter and a 100 nm period. The pillars are 200 nm tall and thus have an

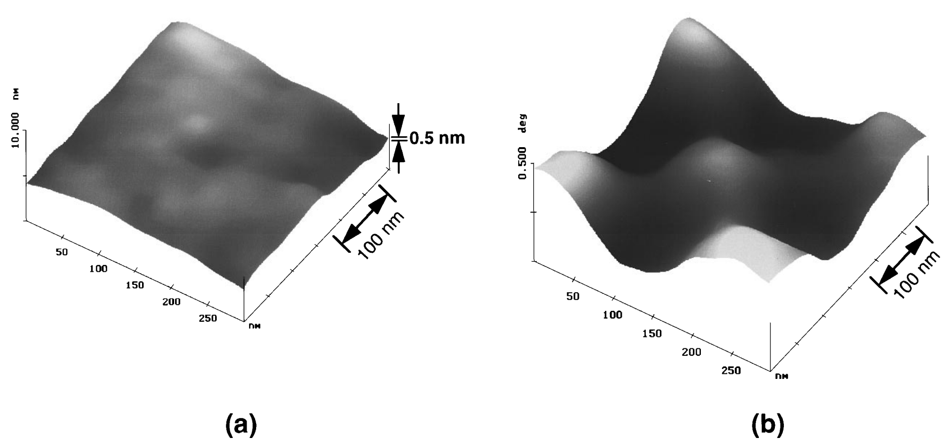

FIG. 4. TMAFM image (a) and MFM image (b) of 3-by-3 bits of a QMD with 65 Gbit/in.^{2} density. The TMAFM image shows a very smooth surface with a roughness of 0.5 nm rms. The MFM image shows an alternating pattern of magnetization directions from each bit.

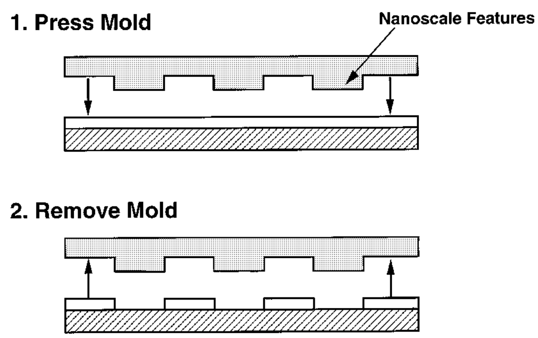

FIG. 5. Schematic of nanoimprint fabrication process.

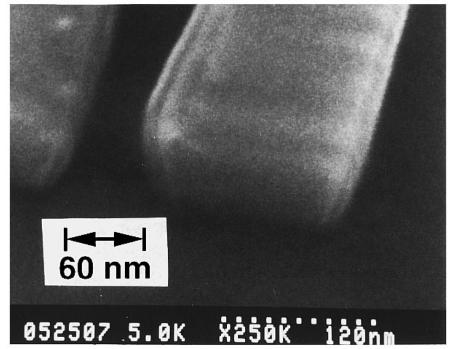

FIG. 7. SEM image of 60-nm-wide trench in 100 nm PMMA fabricated using the nanoimprint technique.

aspect ratio of 4. This period corresponds to a magnetic storage density of 65 Gbit/in.[2] which is over two orders of magnitude higher than current state-of-the-art magnetic storage densities.

TMAFM and MFM images taken simultaneously on the same area of the QMD with a Digital Instruments Nanoscope IIIa are shown in Figs. 4(a) and 4(b), respectively. The TMAFM image of a 3-bit by 3-bit section of the QMD shows that the topology of the nickel pillars is indistinguishable from that of the SiO_2. The surface is very smooth with a roughness of 0.5 nm rms.

The corresponding MFM image, on the other hand, clearly shows that each bit has a quantized magnetization orientation and the magnetic image of each pillar of the 9-bit section can be resolved. Five bits have south (bright pole) on top and the other four bits have the north (dark pole) on top. The QMD was demagnetized before imaging; therefore, the nearest neighbor bits have opposite magnetic directions. This magnetization orientation is the lowest energy state for the QMD.

IV. NANOIMPRINT FOR MASS PRODUCTION

For the mass production of QMDs, a technique which can pattern nanoscale features inexpensively must be developed. The nanoimprint technique has been proposed for this application[3] and is shown schematically in Fig. 5. First, a mold is fabricated with nanoscale features. Second, the mold is pressed into a resist film on a substrate and then removed, resulting in the nanoscale pattern being transferred into the resist film. A SEM micrograph of 25-nm-diam dots transferred into a 50 nm PMMA film using the nanoimprint technique is shown in Fig. 6. A SEM micrograph of the profile of a 60-nm-wide trench imprinted into 100-nm-thick PMMA is shown in Fig. 7. Details of the nanoimprint fabrication process and its application as a lithography process will be reported elsewhere.[4]

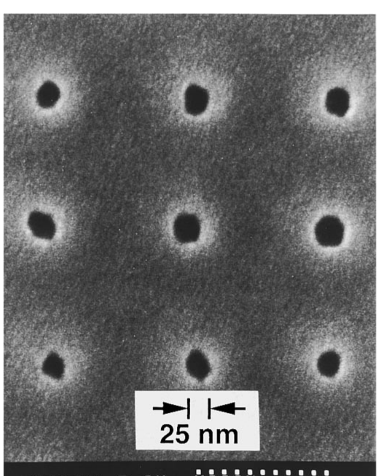

FIG. 6. SEM image of 25-nm-diam dots in 50 nm PMMA fabricated using the nanoimprint technique.

V. SUMMARY

The quantum magnetic disk is a new paradigm for ultrahigh density magnetic recording. A planar QMD with 50 nm diameter and 100 nm period nickel pillars uniformly embedded in 200 nm of SiO_2 has been fabricated using electron beam lithography, RIE, and CMP. The QMD has a magnetic storage density of 65 Gbit/in.[2]—over two orders of magnitude greater than the state-of-the-art magnetic storage density. The QMD has an extremely smooth top surface with a roughness of 0.5 nm rms. The QMD was analyzed using SEM, TMAFM, and MFM. A novel technique, nanoimprint, was discussed for the low cost patterning of nanoscale features such as those required for QMD fabrication.

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