Single-domain magnetic pillar array of 35 nm diameter and 65 Gbits/in.^{2} density for ultrahigh density quantum magnetic storage

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Using electron beam nanolithography and electroplating, arrays of Ni pillars on silicon that have a uniform diameter of 35 nm, a height of 120 nm, and a period of 100 nm were fabricated. The density of the pillar arrays is 65 Gbits/in.^{2}—over two orders of magnitude greater than the state-of-the-art magnetic storage density. Because of their nanoscale size, shape anisotropy, and separation from each other, each Ni pillar is single domain with only two quantized perpendicular magnetization states: up and down. Each pillar can be used to store one bit of information, therefore such nanomagnetic pillar array storage offers a rather different paradigm than the conventional storage method. A quantum magnetic disk scheme that is based on uniformly embedding single-domain magnetic structures in a nonmagnetic disk is proposed.

I. INTRODUCTION

Perpendicular magnetic recording media have been considered by many as the media that will offer the largest storage density. Previously, several perpendicular recording media were developed and investigated. These include Co-Cr thin films with vertical grains,[1,2] barium ferrite powder with a perpendicular *c* axis,[3] and vertical ferromagnetic pillars plated through porous Al films[4] or plastics films with nuclear radiated tracks.[5] In all these media, the diameter of magnetic grains and the magnetization direction have a broad continuous distribution; the spacing between the grains varies and is uncontrollable; and each bit of information is stored over at least several magnetic grains.

In order to explore the ultimate size of a magnetic bit and the ultimate spacing between neighboring magnetic bits (therefore storage density), to improve understanding of the fundamental magnetics, and to develop new magnetic devices of high speed and high density, we have fabricated ultrahigh density arrays of single-domain nickel pillars using electron beam nanolithography and electroplating. The unique advantage of nanolithography is that the dimension of each pillar as well as the spacing between the pillars can be well controlled and uniform. Due to small size and shape anisotropy, each pillar is a single domain with magnetization perpendicular to the substrate. Moreover, each magnetic pillar can be used to store one bit of information. In this article we will discuss the fabrication process, magnetic force microscope (MFM) measurements, and the possibilities of a novel new recording paradigm offered by these pillars.

II. FABRICATION OF MAGNETIC PILLAR ARRAYS

A schematic of our fabrication process is shown in Fig. 1. A thin gold plating base was deposited on a silicon substrate. A high resolution electron beam resist, polymethyl methacrylate (PMMA),[7] was then spun onto the substrate. Depending upon the desired pillar height, the thickness of the PMMA is typically 130 nm; however, 720 nm thick PMMA was also used in some cases. Dot arrays with diameters from 35 to 40 nm and spacings from 50 to 1000 nm were exposed in the PMMA using a high resolution electron beam lithography system with a beam diameter of 4 nm. The exposed PMMA was then developed in a cellosolve and methanol solution creating a template for the electroplating process. The sample was immersed in a nickel sulfamate type plating bath and nickel was electroplated into the template openings until the nickel thickness was near the template thickness. The plating rate, which is a function of plating current, template diameter, and template thickness, was well calibrated and was fixed at 45 nm/min for our work. After electroplating, the PMMA template was removed.

After fabrication, the pillars were examined using a scanning electron microscope (SEM) to verify the pillar dimensions. The resulting nickel pillars are uniform and have desired shape anisotropy. Figure 2 shows a SEM micrograph of a pillar array having a diameter of 35 nm, a height of 120 nm, and therefore an aspect ratio of 3.4. The pillar array has a period of 100 nm, and thus has a magnetic storage density of 65 Gbits/in.^{2} which is two orders of magnitude higher than the state-of-the-art storage. The pillars have a cylindrical shape with very smooth sidewalls.

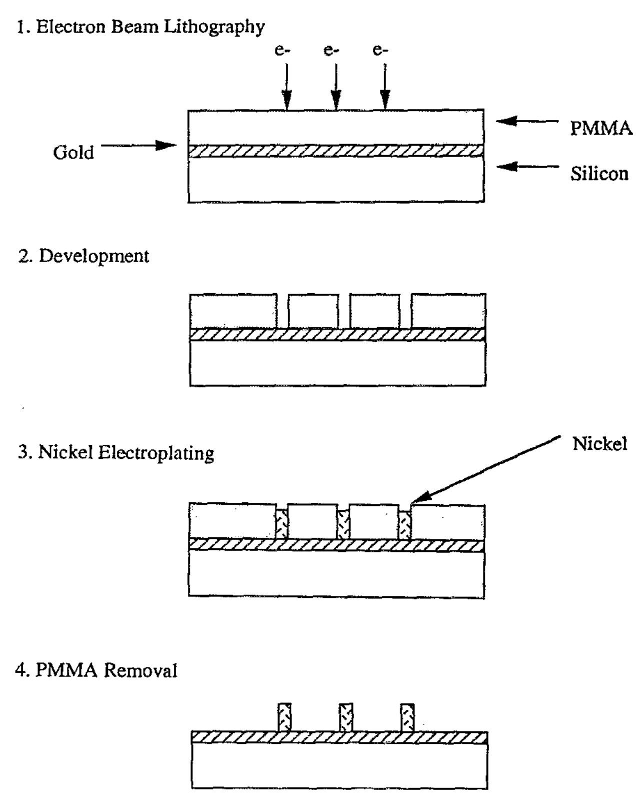

FIG. 1. Schematic of nanomagnetic pillar array fabrication process.

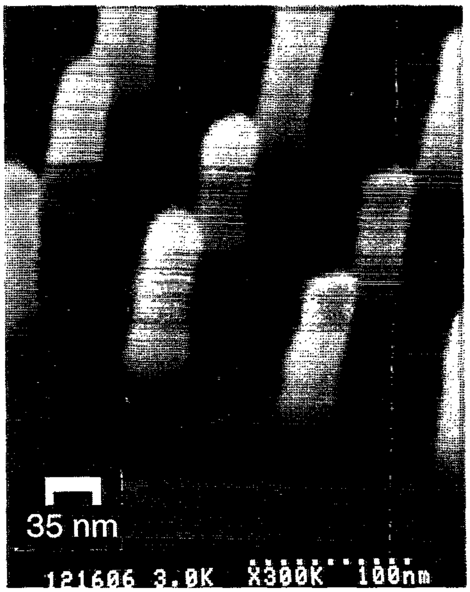

FIG. 2. SEM image of Ni pillar array of 35 nm diameter, 120 nm height, and a 100 nm spacing. The density is 65 Gbits/in.^{2} and the aspect ratio is 3.4.

Figure 3 shows a SEM micrograph of a second sample that was fabricated using 720 nm thick PMMA to obtain taller nickel pillars. These pillars have an average diameter of 75 nm, a height of 700 nm (therefore an aspect ratio of 9.3), and a period of 100 nm. Compared with the pillars in Fig. 2, these tall pillars have a cone shaped sidewall with an angle of 1.6° from vertical. Such cone shape results from the fact that during the plating, the Ni pillars conformed with the PMMA template that has a cone shape due to significant electron scattering in the thicker PMMA during the lithography.

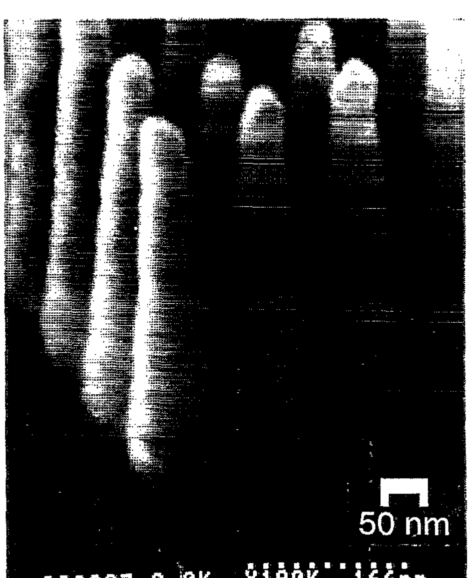

FIG. 3. SEM image of Ni pillar array of average 75 nm diameter, 700 nm height, and a 100 nm spacing. The density is 65 Gbits/in.^{2} and the aspect ratio is 9.3.

III. THEORETICAL ANALYSIS

We discuss the theoretical analysis of the nickel pillar arrays here and the characterization in the next section. First, theoretical calculation indicates that each nickel pillar should be single domain. Using Aharoni's formulas, the diameter for a prolate nickel spheroid with an aspect ratio of 3.4 to be single domain should be 52 nm or smaller.[6] In our case, the pillar diameter is 35 nm and therefore should be single domain.

Second, if each pillar is used to store one bit of information, such nanoscale pillar array storage has a rather different paradigm than the conventional storage. In conventional storage, each bit of information is stored over a number of magnetic grains which have a broad distribution in grain size, spacing, and magnetization direction. These distributions will result in the variation of the total magnetization of each bit stored and give rise to noise in reading. In the single-domain pillar array on the other hand, each bit is stored in a pillar which has only two quantized magnetization values: up or down in direction but equal in magnitude. Therefore, noise for each bit should be small. Certainly development of fabrication processes for these nanomagnetic pillar arrays is just the first step towards realization of this paradigm; methods for writing and reading information in such a media still need to be developed.

IV. CHARACTERIZATION

We have attempted to use a high resolution magnetic force microscope (MFM) operating at 300 mTorr to examine these ultra-high density pillar arrays, but were unsuccessful. The primary reason is that since the topology image and magnetic image are intertwined in MFM, the aspect ratio of our nanomagnetic pillars is so large that the topology image completely masks the magnetic image. Despite the difficulty in characterizing these nanomagnetic pillars, MFM measurements showed that horizontal nanomagnetic bars of 35 nm thickness and nanoscale widths are single domain, supporting our theoretical estimation that the nanomagnetic pillars should be single domain as well.[7]

Two other possible methods may be able to characterize the nanoscale magnetic pillars: scanning electron microscopy with polarization analysis (SEMPA) and magnetooptical Kerr effect microscopy (MOKE). Currently, we are pursuing these two studies. SEMPA analysis forms images by scanning a focused electron beam across a sample and detecting the spin polarization of secondary electrons. The magnitude and direction of the secondary electron's spin polarization is directly proportional to the magnitude and direction of the magnetization of the sample being scanned. MOKE analysis measures the magnetization of the pillars versus the magnetic field by detecting the rotation of polarization state of light reflected from a ferromagnetic sample. We have built a detection system that can detect a signal-to-noise ratio near 10^{-8} and are building a special probe station that will enable us to focus the laser beam to a diameter of 3–4 μm and position the beam to a specific location of the sample within 2 μm accuracy.

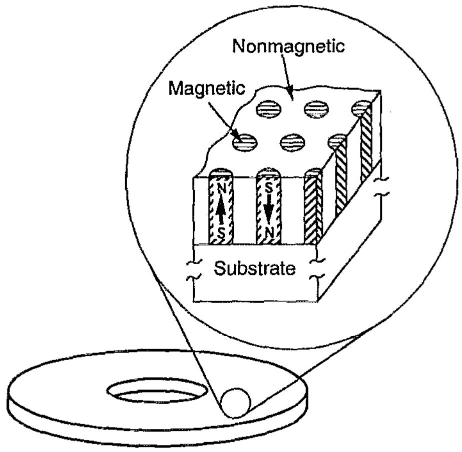

FIG. 4. Schematic of a quantum magnetic disk which consists of prepatterned single-domain magnetic structures embedded in a nonmagnetic disk.

V. QUANTUM MAGNETIC DISK

Based on these artificially patterned single-domain magnetic structures, we propose a new paradigm for ultra-high density magnetic disk: Quantum Magnetic Disk.[8] As shown in Fig. 4, a quantum magnetic disk consists of prepatterned single-domain magnetic structures embedded in a nonmagnetic disk. Each bit in the quantum magnetic disk is represented by a prefabricated single domain magnetic structure that has a uniform and well-defined shape, a prespecified location, and most importantly, a quantified magnetization that has only two states: the same in value and opposite in direction. In other words, the shape, magnetization, and location for each bit in a quantum magnetic disk are all quantized and predefined during the disk manufacturing. On the contrary, in a conventional magnetic disk where a bit is not defined at disk fabrication, the shape and magnetization of each bit have a broad distribution and the location of a bit can be anywhere on the disk. The quantum magnetic disk also differs from discrete track disk[9,10] and discrete segment disk[11,12] where the magnetization (both value and direction) of each bit can have a continuous and broad distribution.

The advantages of quantum magnetic disks over the conventional disks are apparent. First, the writing process in the quantum disk is greatly simplified, resulting in much lower noise and lower error rate and allowing much higher density. In the quantum disk, the writing process does not define the location, shape, and magnetization value of a bit, but just simply flips the quantized magnetization orientation of a prepatterned single-domain magnetic structure. The writing can be perfect, even though the head slightly deviates from the intended bit location and partially overlaps with other bits, as long as the head flips only the magnetization of the intended bit. But in the conventional magnetic disk, the writing process must define the location, shape, and magnetization of a bit. If the head deviates from the intended location, the head will write part of the intend bit and part of the neighboring bits.

Second, the quantum disk can track every bit individually, but the conventional disk cannot track all of its bits. This is because that in quantum disk each bit is separated from others by nonmagnetic material, but in the conventional disk many bits are connected. The individual-bit-tracking ability allows precise positioning, lower error rate, and therefore ultrahigh density storage.

Finally, reading in the quantum disk is much less jitter than that in the conventional disk. The reason is that in the conventional disk the boundary between bits is ragged and not well defined, but in the quantum disk each bit is defined with nanometer precision (can be less than the grain size) and is well separated from each other.

VI. SUMMARY

Using electron beam nanolithography and electroplating, arrays of Ni pillars on silicon that have a uniform diameter of 35 nm, a height of 120 nm, and a period of 100 nm were fabricated. The density of the pillar arrays is 65 Gbits/in.^{2}—over two orders of magnitude greater than the state-of-the-art magnetic storage density. Because of their nanoscale size, shape anisotropy, and separation from each other, each Ni pillar is single domain with only two quantized perpendicular magnetization states: up and down. Each pillar can be used to store one bit; such nanoscale pillar array storage offers a rather different paradigm than the conventional storage method. Certainly development of fabrication processes for such magnetic recording media is just the first step towards realization of this paradigm; methods for writing and reading information with such a media still need to be developed. MFM characterization of these pillars is unsuccessful at the moment due to large aspect ratio. Characterization using SEMPA and MOKE is in progress. Finally, based on the artificially patterned single-domain magnetic structures, a new paradigm for ultrahigh density magnetic recording media—the quantum magnetic disk is proposed.

ACKNOWLEDGMENTS

We thank J. G. Zhu for very helpful discussion and information. We also thank Robert Guibord for his technical assistance. This work was partially supported by ONR and ARPA.

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