Fabrication of single-domain magnetic pillar array of 35 nm diameter and 65 Gbits/in.^{2} density

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(Received 20 June 1994; accepted 31 August 1994)

Using electron beam nanolithography and electroplating, arrays of Ni pillars on silicon have been fabricated. The effects of plating current and feature size on the plating rate were investigated. The pillar arrays have a period of 100 nm and the pillar diameters are uniform and as small as 35 nm. 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. If each pillar were to represent one bit of information, the density of the pillar arrays would be 65 Gbits/in.^{2}—over two orders of magnitude greater than the state-of-the-art magnetic storage density. The ultrahigh density, together with the single-domain formation, make these pillar arrays very attractive for high-density magnetic storage devices and fundamental magnetics studies.

I. INTRODUCTION

To explore new high-density magnetic storage media and improve our understanding of magnetics, new fabrication techniques for producing closely packed nanoscale magnetic structures are required. The highest packing density is achieved when the magnetic structures are oriented perpendicular to the substrate and thus form a perpendicular magnetic recording media. 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 and magnetization direction of the magnetic grains have a broad continuous distribution; the spacing between the grains varies and is uncontrollable; and each bit is stored over at least several magnetic grains.

In this article, we report the development of a process for fabricating ultrahigh-density arrays of single-domain magnetic pillars for perpendicular magnetic recording media using electron beam nanolithography and electroplating of nickel, a ferromagnetic material. Due to its nanoscale size and shape anisotropy, each pillar is a single domain with magnetization perpendicular to the substrate. We will discuss the factors that are important to the plating of nanoscale pillars such as plating current and feature size.

II. FABRICATION OF MAGNETIC PILLAR ARRAYS

Our fabrication process involves electron beam lithography and electroplating. The reason for using plating is that the popular lift off process cannot be used for high aspect ratio vertical structures. In the lift off process, gradual accumulation of materials at the orifice of each resist template opening during the deposition will eventually close the opening; as a result, the maximum pillar height is about the size of the template opening and large shape anisotropy is difficult to achieve.

A schematic of the process is shown in Fig. 1. A plating base of 10 nm chrome and 50 nm gold was evaporated on a silicon substrate. A high resolution electron beam resist, polymethyl methacrylate (PMMA), of 950 K molecular weight was then spun onto the substrate. The thickness of the PMMA was either 130 or 720 nm depending upon the desired pillar height. Dot arrays with diameters from 35 to 75 nm and spacings from 50 to 1000 nm were exposed in the PMMA using a high resolution electron beam lithography system that has a beam diameter of 4 nm and an accelerating voltage of 35 kV. The electron beam lithography system is a converted scanning electron microscope (SEM) and has been reported elsewhere.[6] The exposed PMMA was then developed in a cellosolve and methanol solution creating a template for the electroplating process.

The nickel plating process used a nickel sulfamate type plating bath. Such type of plating bath is known to produce films with low internal stress as compared to other types of nickel plating baths such as Watts, all chloride, or sulfate.[7] Low stress deposits are required to fabricate ultrahigh-density arrays of nanomagnetic pillars that have high aspect ratios. The nickel sulfamate plating bath consists of 367 g/ℓ nickel sulfamate [$Ni(SO_3NH_2)_2 \cdot 2H_2O$] and 30 g/$\ell$ boric acid in water yielding a pH of 4. The bath was heated to 50 °C and mechanically agitated at a stirring speed of 100 rpm. The optimum stirring speed for micron scale features was found to be between 100 and 125 rpm. Stirring speeds lower than this resulted in only shallow filling of the template features and speeds higher than this resulted in rough film surfaces. During the plating, the plating current was kept constant by using a current source. The stress in the deposited nickel was tested by plating 0.5 μm thick nickel squares with an area of 25 μm^2. No cracking of the film was observed, except slight bowing at the edges, indicating that the stress was low. After electroplating, the PMMA template was removed in an oxygen ashing process leaving the nanomagnetic pillar arrays.

The nickel plating rate was found to be related to the plating current, the feature size, and the total plating area. The effect of plating current on the plating rate of nanoscale pillars with 720 nm PMMA is shown in Fig. 2. As expected, the plating rate generally increases linearly with plating current. However, at low plating current the plating rate is not a linear function of the current.

The nickel plating rate also depends upon the size of the

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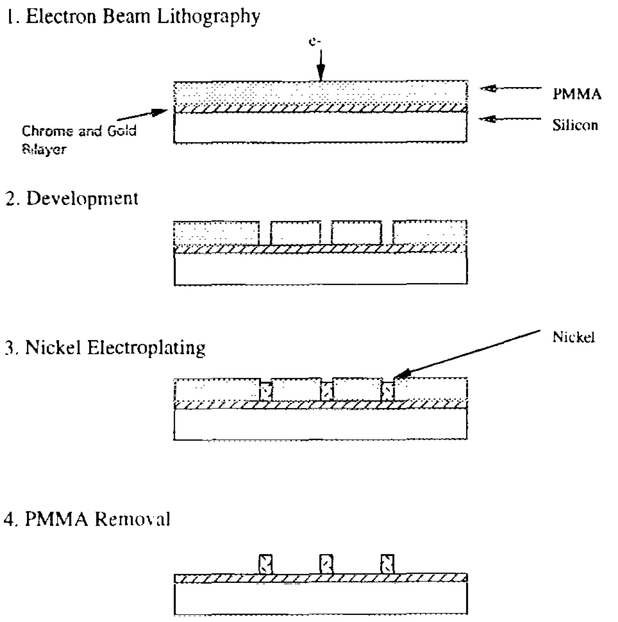

FIG. 1. Schematic of nanomagnetic pillar array fabrication process.

feature. As shown in Fig. 3, which is for a resist template thickness of 720 nm and a plating current of 36 mA, the plating rate is almost constant when the feature size is very large. But the rate increased rather rapidly with decreasing feature size below 1000 nm. This phenomena is caused by the fact that more nickel ions are supplied at the edges of a wide opening than in the middle, making the plating rate depend on the feature size.[8,9] When the isolated feature size is equal to about one-third of the resist thickness, 200 nm, the plating rate has a sudden drop, then as the feature size further decreases the plating rate increases again. Although not fully understood at this time, this phenomenon is thought to be related to competition between the process of nonlinear diffusion at the corners and the drag effects in a narrow template tube.

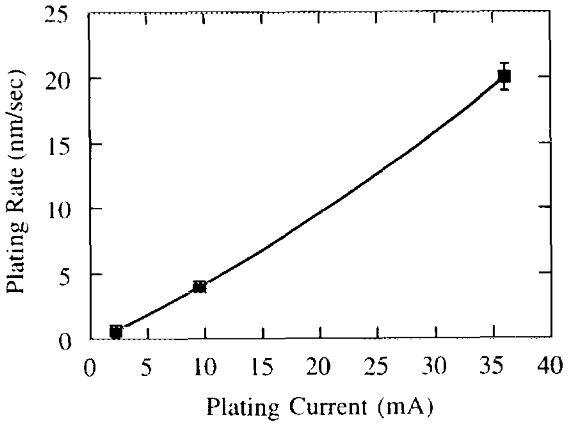

FIG. 2. Effects of the plating current on the plating rate of nanoscale pillars with an average 75 nm diam in 720 nm thick PMMA.

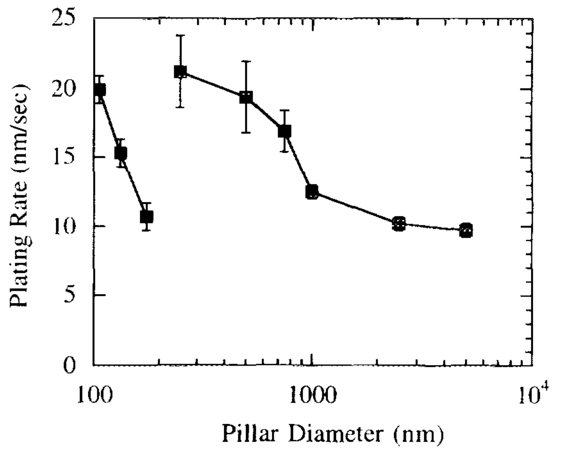

FIG. 3. Effects of the feature size on the plating rate of features in 720 nm thick PMMA.

Finally, the plating rate depends on the total area plated. The nanomagnetic structures which we were fabricating generally have very small surface areas. In order to keep the total surface area plated nearly constant for different samples, we electrically connected a sample to a metallic fixture which had a surface area many orders of magnitude larger than the electron beam exposed area on the sample thus keeping the loading factor constant. The nickel deposition rate was well calibrated and fixed at 0.75 nm/s for our work.

III. RESULTS

After fabrication, the pillars were examined using an SEM to verify the pillar dimensions. The resulting nickel pillars are uniform and have desired shape anisotropy. Figure 4 shows a SEM micrograph of a pillar array fabricated using 130 nm thick PMMA and having a diameter of 35 nm, a height of 120 nm, and therefore an aspect ratio of 3.4. The pillars have a cylindrical shape with very smooth sidewalls. The pillar array has a period of 100 nm. If each pillar stores one bit of information, then the array has a magnetic storage density of 65 Gbits/in.^{2}, which is two orders of magnitude higher than the state-of-the-art storage.

Figure 5 shows a SEM micrograph of a second pillar array that was fabricated using 720 nm thick PMMA to obtain nickel pillars with a larger aspect ratio. These pillars have an average diameter of 75 nm, a height of 700 nm (therefore an aspect ratio of 9.3), a period of 100 nm, and a density of 65 Gbits/in.^{2}. Compared with the pillars in Fig. 4, these tall pillars have a cone shaped sidewall with an angle of 1.6° from vertical. Such cone shape results from the fact that the plated Ni pillars conformed with the PMMA template that had a cone shape due to significant scattering of electrons in the thick PMMA resist during the lithography.

We have tried to fabricate pillar arrays of 50 nm period, but observed that the pillars were not completely isolated, indicating that the exposed resist openings are very close to the period resulting in very thin PMMA template walls between pillars. The minimum diameter of the template open-

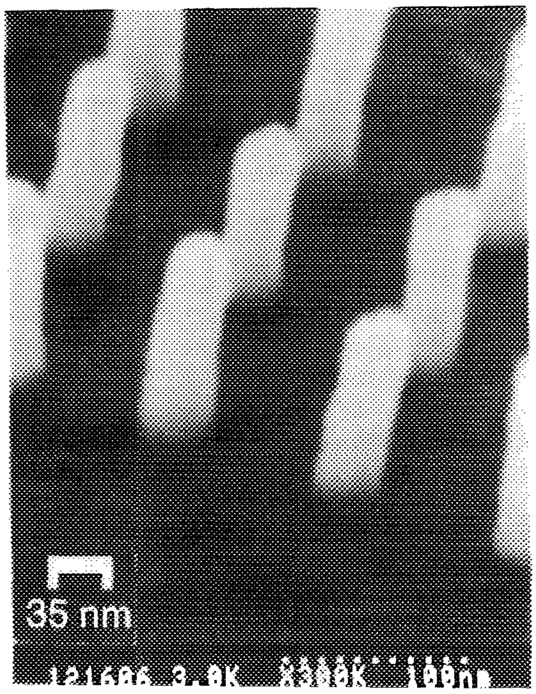

FIG. 4. SEM image of Ni pillar array of 35 nm diam, 120 nm height, and a 100 nm spacing. The density is 65 Gbits/in.^{2} and the aspect ratio is 3.4.

ings seems to be limited by the electron backscattering from the metal plating base. To reduce such electron backscattering, electroless nickel plating rather than electroplating is under consideration.

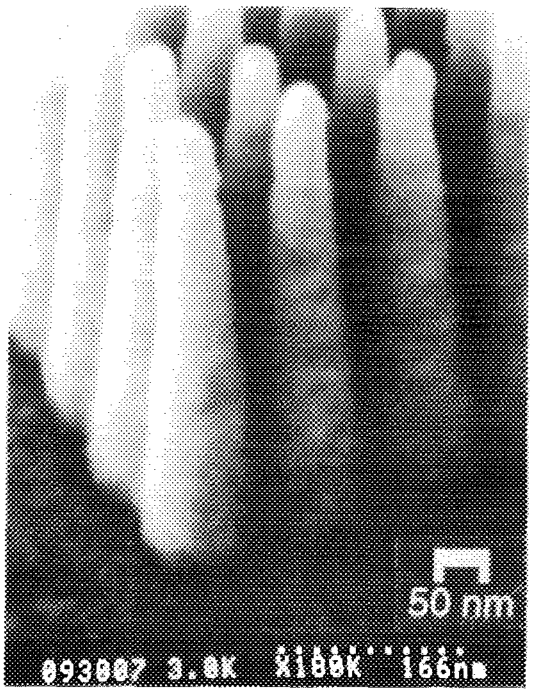

FIG. 5. SEM image of Ni pillar array of average 75 nm diam, 700 nm height, and a 100 nm spacing. The density is 65 Gbits/in.^{2} and the aspect ratio is 9.3.

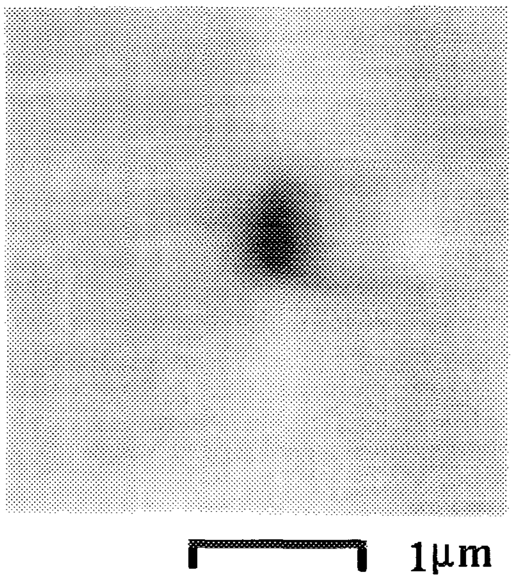

FIG. 6. MFM image of an electroplated nickel bar which is 35 nm thick, 30 nm wide, and 1 μm long.

IV. THEORETICAL ANALYSIS

Theoretical calculation indicates that each nickel pillar should be single domain. Using Aharoni's formulas, for a prolate nickel spheroid with an aspect ratio of 3.4 to be single domain, the diameter should be 52 nm or smaller.[10] In our case, the pillar diameter is 35 nm and therefore should be single domain. For a prolate nickel spheroid with an aspect ratio of 9.3 to be single domain, the diameter should be 102 nm or smaller. Thus, the pillars with a 75 nm average diameter should also be single domain.

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.[11] 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. In the single-domain pillar array, on the other hand, each bit is stored in a pillar that has only two quantized magnetization states: up or down in direction but equal in magnitude. Details of such lithographically defined single-domain magnetic recording media will be discussed elsewhere.[12]

V. CHARACTERIZATION

We have attempted to use a high resolution magnetic force microscope (MFM) operating at 300 mTorr to examine these ultrahigh-density pillar arrays, but were unsuccessful. The primary reason is that, since the topology image and magnetic image are interwined 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 electroplated nickel 35 nm thick, 30 nm wide, and 1 μm long are single domain, supporting our theoretical estimation that the nanomagnetic pillars should be single domain as well. An MFM image of such a bar is shown in Fig. 6. The white spot represents one magnetic pole and the black spot represents the other, indicating that the bar is a single magnetic domain.

Two other possible methods may be able to characterize the nanoscale magnetic pillars: scanning electron microscopy with polarization analysis (SEMPA) and magneto-optical 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 are 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.

VI. SUMMARY

Using electron beam nanolithography and electroplating, a process was developed for fabricating arrays of Ni pillars on silicon that have a diameter of 35 nm, a height of 120 nm, and a period of 100 nm. The factors that are important to the plating such as plating current, plating rate, and feature size were studied. Theoretical analysis and MFM measurements of the horizontal plated bar with equivalent dimensions indicate that, 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. If each pillar were used to represent one bit of information, the density of the pillar arrays would be 65 Gbit/in.^{2}—over two orders of magnitude greater than the state-of-the-art magnetic storage density. In this way, such nanoscale pillar array storage offers a rather different paradigm than the conventional storage method. MFM characterization of these pillars is unsuccessful at the moment due to the large aspect ratio. Characterization using SEMPA and MOKE is in progress.

ACKNOWLEDGMENTS

The authors thank J. G. Zhu for very helpful discussion, Hao Fang for MFM measurements, and Robert Guibord for his technical assistance in fabrication. This work was partially supported by the Office of Naval Research and the Advanced Research Projects Agency.

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