MR Head Response from Arrays of Lithographically Patterned Perpendicular Nickel Columns

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***Abstract*—We report, for the first time, the MR head response from lithographically patterned perpendicular nickel columns. Electron-beam lithography is used to fabricate arrays of Ni columns, 400 nm tall and 150 nm in diameter spaced 2.1 μm apart, embedded in SiO_2. The sample surface is planarized with a chemical mechanical polish. The technique of Scanning Magnetoresistance Microscopy (SMRM), in which a magnetoresistive (MR) head is raster-scanned in contact with a sample, is used to investigate the MR head response from the Ni columns. Single columns can be "read" with a 0-peak MR voltage of 60-70 μV. Unexpectedly, we find that the magnetic field due to the bias current in the MR head is enough to switch the columns during scanning, which results in a "dibit-like" MR response. By scanning in the presence of a small (~21Oe) external magnetic bias field, the columns can be imaged in either their "up" or "down" magnetic states.**

I. Background and Motivation

Recently, there has been a growing interest in exploring the feasibility of a patterned magnetic media as an alternative for high density data storage [1-3]. Such a medium would consist of lithographically defined single domain perpendicularly oriented magnetic particles embedded in a non-magnetic matrix, and a single particle would correspond to one information bit. Thus, patterned media could achieve much higher densities than conventional longitudinal thin film media where each bit cell must contain hundreds of magnetic grains.

Previous reports have demonstrated the ability of fabricating arrays of Ni columns embedded in SiO_2 [1,2]. The morphology of these Ni structures has been characterized by techniques such as scanning electron microscopy (SEM) and atomic force microscopy (AFM). However, thus far, magnetic characterization has been limited to magnetic force microscopy (MFM). We present here, for the first time, additional magnetic characterization using commercial magnetoresistive (MR) heads.

To do this, we use the technique of Scanning Magnetoresistance Microscopy (SMRM) in which an MR head is statically positioned with respect to a sample, and then raster-scanned with the slider in contact [4]. The MR voltage is then recorded as a function of position.

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II. Array Fabrication and Polishing

The fabrication process for our samples has been described in detail elsewhere [1]. Briefly, we use electron-beam vector scan lithography to pattern a resist-coated (PMMA) diced piece of silicon wafer, and the Ni columns are deposited electrochemically. We have previously reported on the fabrication of ultra-high density arrays of nanoscale Ni columns, 20 nm diameter, 100 nm tall, and 100 nm center-to-center spacings, embedded in PMMA [5]. These arrays demonstrate that structures can be fabricated at very high densities (>65G-columns/in^2), but they proved to be difficult to characterize, especially with regard to their magnetic properties.

More recently, and in the present work, we focus on larger columns at lower densities (150 nm diameter, 400 nm tall, 2.1 μm center-to-center spacing) embedded in SiO_2 [1]. We have switched to SiO_2 because it is a hard, polishable material which is more suitable as a practical storage medium than PMMA which is relatively soft. The column-to-column spacing allows us to characterize the response to individual columns using MR heads with track widths of 2.8 μm.

It is difficult to determine when to stop the Ni electroplating, and so we generally overplate which causes the Ni to "mushroom" out onto the surface of the SiO_2. In order to raster-scan an MR head with the slider in contact with these samples, the surfaces had to be planarized using a chemical mechanical polish (CMP). This was necessary to remove the Ni "mushroom" tops as well as to remove any other hard contamination, scratches, or defects which would result in too large a head/sample separation. We used a polishing slurry which consists of a liquid dispersion of 20-30 nm colloidal silica spheres at a concentration of 28%, and with a pH of 11.3 [6].

Fig. 1 shows an AFM image of a polished sample along with the corresponding MFM image. In order to probe the field derivatives that a head would experience at a fly height of 100nm, the MFM tip was scanned at a height of 100nm from the surface (LiftMode™). The small particles, such as the one indicated by the arrow in the AFM image, have heights of 20-30nm. Because of this, we believe that they are silica spheres leftover from the polishing slurry. The rms surface roughness of the SiO_2 in-between the Ni columns is ~0.7 nm. As expected, the Ni, which is soft compared to the SiO_2, tended to be preferentially removed during the polish, leaving the tops of the Ni columns ~10 nm below the surface of the SiO_2. The column-to-column nonuniformity seen in the AFM image is prob-

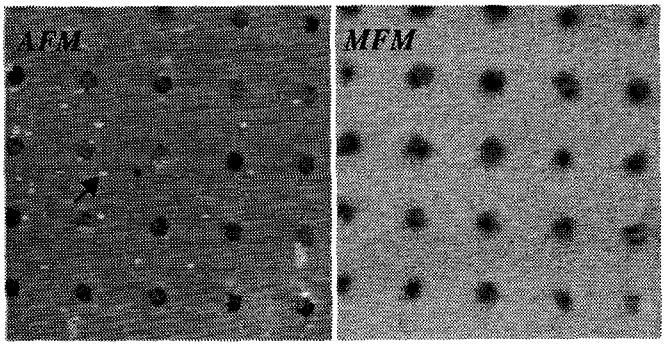

Fig. 1. 10 x 10 μm AFM and MFM images of a portion of the array of Ni columns after polishing.

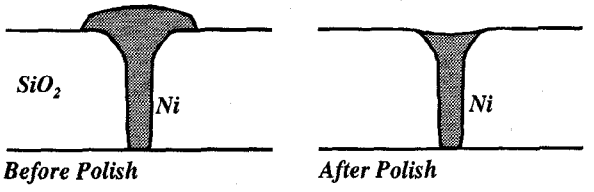

Fig. 2. Schematic of the estimated Ni column profiles before and after polishing. These profiles are derived from SEM images of Ni columns which were removed from the SiO_2.

ably due to nonuniformities during the dry etch processes. For example, the column in the upper right corner is severely receded from the surface, and it has, therefore, a weaker MFM signal. It is likely that this was caused by an insufficiently etched hole in the SiO_2.

Our best estimate of the actual profile of the Ni columns before and after polishing is shown schematically in Fig 2. SEM images of Ni columns which have been extracted from the SiO_2 reveal that they have a "thumbtack" shape. We believe that these profiles are defined during the reactive ion etching of the SiO_2, and this is why the column diameter appears to be ~400 nm in the AFM image.

III. MR Head Response

Fig. 3(a) shows an SEM image of a 50 x 50 μm array of Ni columns. The MR head response to the same array is shown in the Scanning Magnetoresistance Microscopy (SMRM) image in Fig. 3(b). For this image we used a soft adjacent layer (SAL) biased AMR head with a track width of 2.8 μm and a shield-to-shield spacing of 300 nm, and, for reasons described below, we scanned the sample in the presence of an external vertical magnetic bias field of 21 Oe. This field is produced using a sample holder with a small electromagnet which was calibrated with a Hall probe. The head is oriented horizontally with respect to the image, and at a 20° skew angle with respect to the array. The head/sample magnetic spacing is defined by the height of contaminants on the surface and is estimated to be 50-100 nm. The two images are well-correlated as is seen, for example, by the Ni defect encircled in both images.

Fig. 4 shows a 10 x 10 μm portion of the array in Fig. 3 at the indicated values of external field. Individual columns appear as horizontal bars due to the convolution of the spatial head response with the flux from the columns. Fig. 4(d) shows

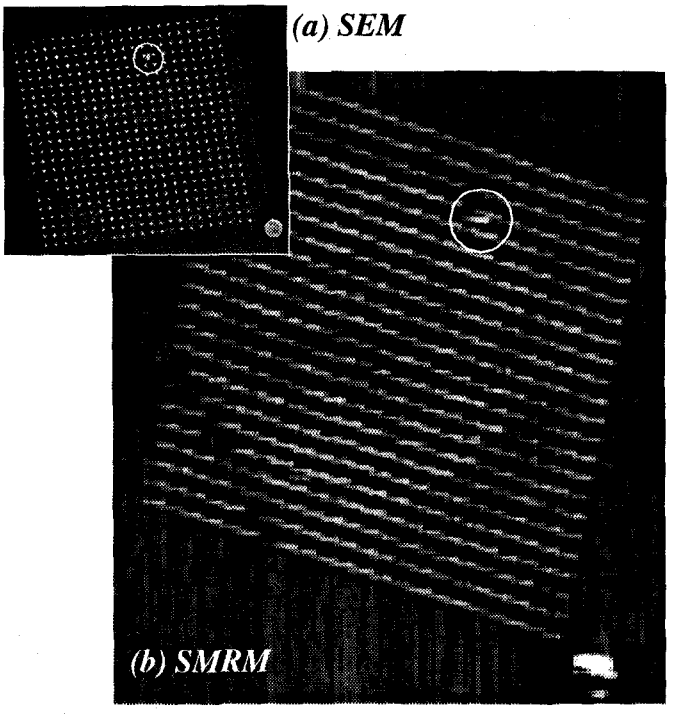

Fig. 3. (a) SEM and (b) SMRM images of the same 50 x 50 μm array of Ni columns. The large disk of Ni at the lower right corner, and the blank line in

a plot of a cut through Fig. 4(c) along the white dashed line. The variation in pulse amplitude is due to variations in Ni column geometry. The 0-peak response from a single column is in the range ~60-70 μV. As a comparison, the 0-peak response of this same head to an isolated transition in a hard disk medium ($M_r t$ = 0.55 memu/cm^2, fly height ~ 50 nm) is ~150 μV. This gives a ratio of Ni column response to hard disk response of ~65μV/150μV = 0.43.

To calculate this ratio, we estimate the flux into the head to be proportional to the magnetic charge:

$$\frac{V_{MR}^{\text{Ni column}}}{V_{MR}^{\text{isolated trans.}}} \sim \frac{\text{mag. charge (Ni column)}}{\text{mag. charge (isolated trans.)}} \sim \frac{M_s \pi r^2}{2(M_r t)W} \sim 0.28 \ ,$$

where r ≡ column radius and W ≡ track width. This calculated value is reasonably close to the measured value, especially considering the uncertainty in head/sample spacing (50-100 nm) for the Ni column data.

The SMRM images in Figs. 3 & 4 were scanned in the presence of an external vertical magnetic bias field of 21 Oe. This is because, quite surprisingly, we find that the magnetic field due to the bias current in the MR head (12mA) is strong enough to switch the columns as the head is scanned over them. The result is the bipolar, "dibit-like" MR response shown in Fig. 4(a). An external field of ±21 Oe is enough to pin the columns in either their "up" or "down" magnetic states, as can be seen in the unipolar responses in Figs. 4(b & c). The dibit response reappears at external fields below ~ ±15 Oe.

As a further demonstration that the field due to the bias current in the MR stripe interacts with the sample, we scanned the columns with opposite polarities of bias current. If the

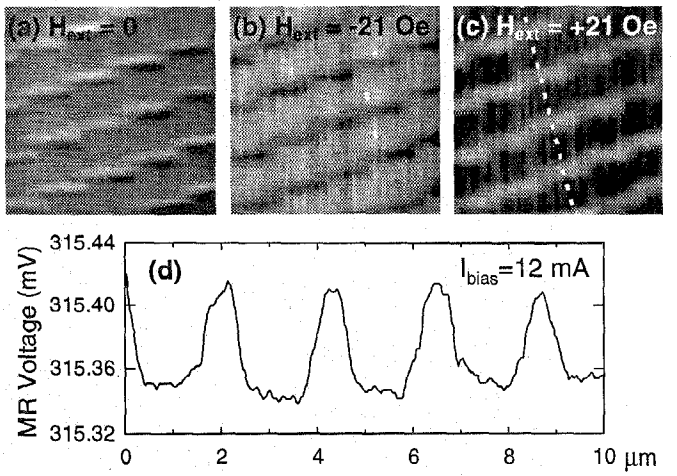

Fig. 4. 10 x 10 μm SMRM images of the Ni columns in the presence of the indicated external perpendicular magnetic bias fields. The MR response due to a single Ni column is ~60-70 μV. The plot is a cut along the dashed line indicated in (c). (a)-(d) are raw data with no filtering, averaging or other image processing.

magnetization state of the columns switch during the scan, then the polarity of the "dibit-like" MR response would also change. As a check, we also scanned a true dibit recorded on a high coercivity (H_c = 2800 Oe) hard disk medium at opposite polarities of MR bias current. The result is shown in Fig. 5. As expected, since the field from the MR head is too weak to affect the magnetization of the hard disk medium, the polarity of the MR response is the same for both polarities of MR bias current. However, this is not true for the MR scans of the Ni columns where the polarity clearly changes.

We estimated the magnetic field produced by the bias current in the MR stripe in order to see if it is large enough to switch the columns. The head surface field at the bottom of the stripe was estimated using Ampere's law with the assumption that the shields have infinite permeability. The Karlqvist approximation was then used to estimate the field at a magnetic spacing of 100 nm. The maximum y-component of the field is ~ ±180 Oe. If we take 20 Oe as the amount of external bias field needed to overcome the interaction between the head field and the columns, then we get a value for the switching field of the columns of ~160 Oe. Even though this is a crude estimate, it appears to be reasonable when compared to quantitative measurements on isolated Ni particles with a similar diameter but larger aspect ratio [7].

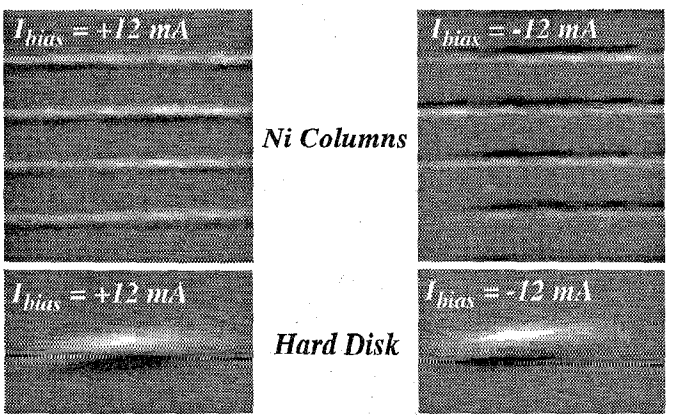

Fig. 5. The dc coupled MR head response from a 4 x 4 array of Ni columns for two polarities of MR bias current. Each of the four horizontal stripes corresponds to the MR response from a row of 4 Ni columns. The individual columns are only distinguishable in the crosstrack direction by the small horizontal modulation in the signal. Also shown is the dc coupled MR head response to a dibit recorded in high coercivity (H_c=2800 Oe) hard disk media for two polarities of MR bias current. The change in polarity in the MR response to the Ni columns indicates that the field from the MR head is switching the magnetization state of the columns during the scan.

IV. Discussion

The three main points of this paper are as follows: First, we have lithographically fabricated and characterized *polished* arrays of perpendicularly oriented Ni columns embedded in SiO_2. Second, in addition to AFM and MFM characterization, we report, for the first time, the MR head response (SAL biased AMR) to the columns. The 0-peak MR voltage from a single column is in the range of 60-70 μV at an estimated magnetic spacing of 50-100 nm, and this is a reasonable signal when compared to the signal from a hard disk medium. Third, we find that the field due to the bias current in the MR head is strong enough to switch the columns This is consistent with an estimate for the magnitude of this field, as well as with independent switching field data on similar Ni structures [7].

We have not demonstrated in this work the extent to which these columns can be considered single-domain, although we have characterized this in a previous study [7]. Future work will include the fabrication of structures with higher switching fields such as higher-aspect ratio Ni columns, and electro-plated Co columns with perpendicular crystalline anisotropy. These samples will be used to systematically switch (i.e., write) individual columns using the SMRM.

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