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Writing and reading bits on pre-patterned media

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We have written and read back bits on perpendicular pre-patterned media prepared by electron-beam lithography. Using a contact tester equipped with a standard longitudinal head, we are able to write different bit lengths on $100 \times 200 \text{ nm}^2$ dots spaced 100 nm apart. These tests demonstrate the role played by the distribution of the coercive fields of the dots during the write process. Signal-to-noise ratios (SNRs) are obtained by numerical analysis and are found to be on the same order of magnitude as in continuous perpendicular media, but remain constant at decreasing bit lengths. This property of the SNR is due to a partial reduction of transition noise. The potential to pattern these media with nanoimprint lithography and their good recording performance make them candidates for ultrahigh density recording. © 2004 American Institute of Physics. [DOI: 10.1063/1.1644341]

Patterned media are a promising route to increase the areal density in magnetic storage devices toward 1 Tbit/in² because they allow one to increment the superparamagnetic limit that appears in conventional media at similar densities.¹ The fabrication of arrays at 100 Gbit/in² and beyond has been currently demonstrated by lithographic² and nanoimprint techniques,³ as well as by self-organization of magnetic particles⁴ and patterning by irradiation.⁵ In the present approach, we decouple the lithographic patterning of the substrate (Si), which is extremely well controlled in microelectronics, from the deposition of the magnetic material ([Co/Pt] multilayer).⁶ The pre-patterning of Si is achieved by direct electron-beam lithography or by nanoimprint followed by reactive ion etching techniques. Nanoimprint may become the preferred technique because of its resolution (feature size about 10 nm has been demonstrated⁷), low cost, and potential to produce large areas of dots in circular patterns. In this letter, we report on writing and reading experiments of individual dots on pre-patterned arrays using a write/read contact tester. Recording properties such as signal-to-noise ratio (SNR) and transition position jitter are analyzed.

The magnetic medium is deposited by magnetron sputtering and consists of a [Co/Pt] multilayer exhibiting uniaxial perpendicular anisotropy of $K \sim 1.5 \times 10^6 \text{ J/m}^3$, with an average saturation magnetization of $M_S \sim 300 \text{ kA/m}$. Since the deposition is performed after the Si pre-patterning, the medium covers the top of the dots, as well as the sidewalls and the trenches between the dots. We have previously reported on the magnetic exchange coupling, which can appear between dots depending on sputtering conditions and on the geometric arrangement of the dots (i.e., the ratio between spacing and height).⁸ In this study, the dots are all decoupled and exhibit single-domain magnetic behavior. Figure 1(a) shows a magnetic force microscopy (MFM) image of an array of $100 \times 200 \text{ nm}^2$ dots, spaced 100 nm apart, scanned after a perpendicular alternating demagnetization cycle. The black and white contrast is associated with the up and down magnetic states for each perpendicularly magnetized, single-domain dot. Figure 1(b) shows a hysteresis loop measured by

magneto-optical Kerr effect (MOKE) of the same dot-array. The average coercive field is $H_C \sim 0.25 \text{ T}$. Since the dots are always observed to be in single-domain state (see Fig. 1, for instance), this implies that the magnetization reversal in each individual dot is very sharp, that is, nucleation followed by easy propagation of the reversal throughout the dot. The hys-

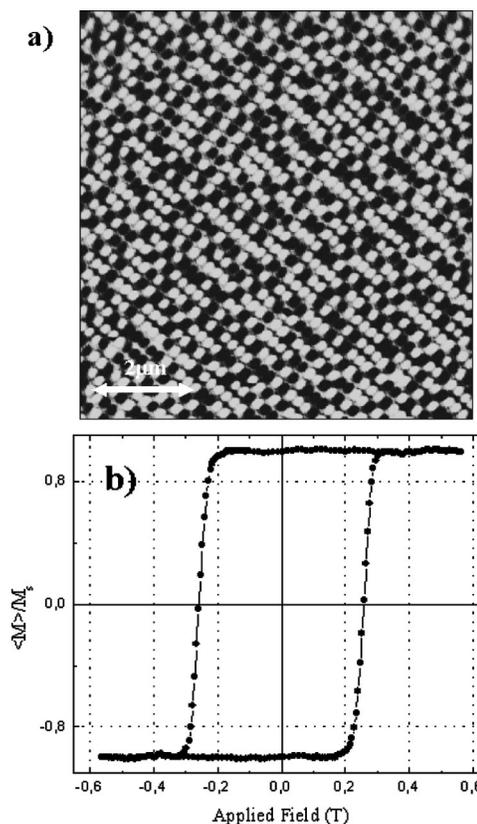


FIG. 1. (a) MFM $8 \times 8 \mu\text{m}^2$ image of a magnetic dot-array with $100 \times 200 \text{ nm}^2$ dots with an edge-to-edge spacing of 100 nm and dot height of 300 nm. The white and black contrast represents the up and down magnetization directions, respectively. (b) MOKE hysteresis loop of the array of dots covered with 1.8 nm Pt/[0.5 nm Co/1.8 nm Pt]₈ perpendicular multilayer medium.

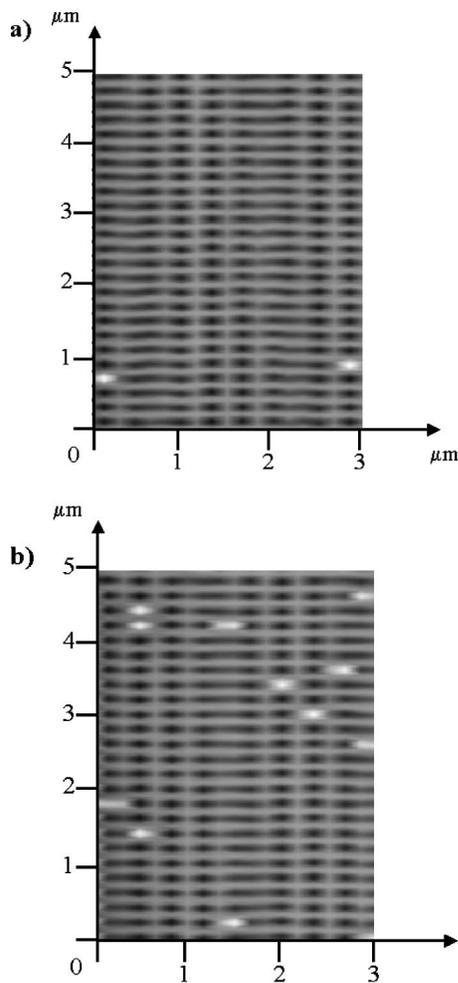


FIG. 2. Read-back amplitude after a dc erase with (a) $I_w = 8$ mA and (b) $I_w = 12$ mA. The contrasts are as in Fig. 1(a).

teresis loop of each individual dot must therefore be very square. Consequently, the observed width of the measured hysteresis loop ($\Delta H_C \sim 0.1$ T) represents the width of the distribution of switching field. The latter can be ascribed to variations in the density of defects from dot to dot.⁹

Recording tests were carried out with a contact tester¹⁰ equipped with a longitudinal head. The head is mounted on a piezoelectric stage and placed in contact with the patterned area. The full-scale lateral displacement of the stage is $5 \mu\text{m}$ in one direction (x) and $13 \mu\text{m}$ in the other (y). The smallest programmable step size is 1 nm. A capacitive sensor controls the displacement of the stage. The write gap of the head is 100 nm, and the write track width 250 nm. The remanent magnetization configuration after writing is measured by the giant magnetoresistive read head. The change in reader resistance is proportional to the perpendicular stray field emanating from the medium.

We first performed dc-erase tests with several values of the write current I_w . The results of two dc-erase tests are shown in Fig. 2. For $I_w = 8$ mA, only two dots are not reversed [the white dots in Fig. 2(a)]. In this case, I_w is insufficient to reverse the dots in the upper tail of the coercive field distribution. When I_w is increased to 12 mA [see Fig. 2(b)], several dots are observed in a nonreversed state. Actually, these dots have the smallest coercive fields in the distribution. This can be understood by considering that, be-

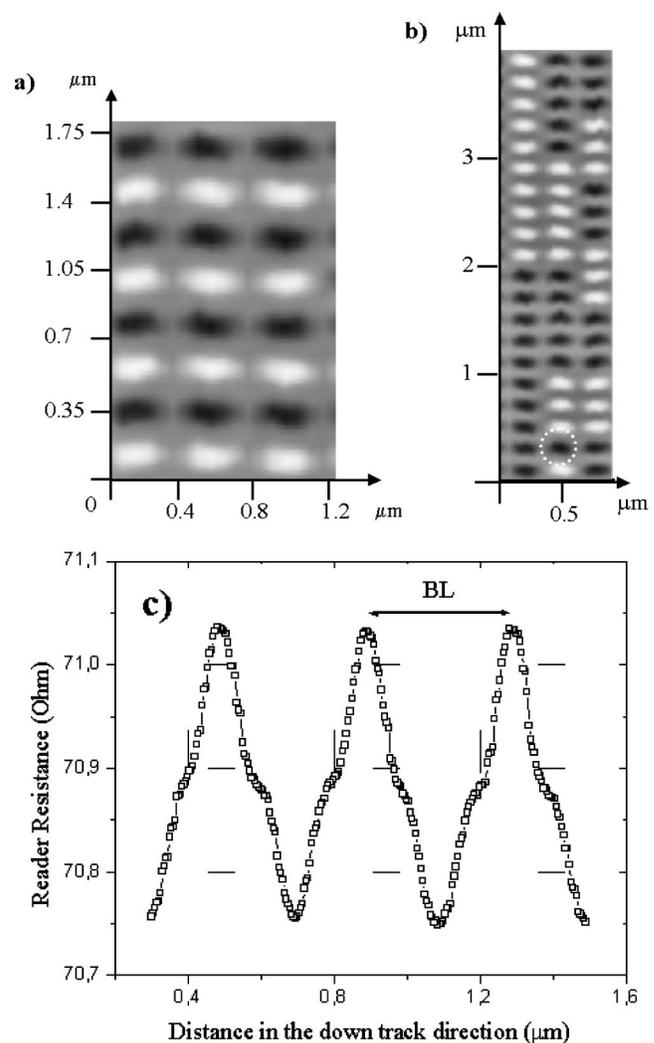


FIG. 3. Read-back amplitude after (a) writing multiple tracks of $0.2 \mu\text{m}$ BL side by side; the magnetization points up and down, alternately, and (b) writing tracks of 2.0 , 1.0 , and $0.6 \mu\text{m}$ BL, from left to right. Note the write error in the second track. The contrasts are as in Fig. 1(a). (c) Read-back amplitude line scan corresponding to (a) when the reader is scanned along the middle of a track.

cause the two writer poles have different shapes, the strength of the perpendicular field differs from one pole to the other. When the write current in the head is increased, the field generated under the two poles increases to a point where the inverted field under the larger pole (which extends over the adjacent tracks) is large enough to switch back the magnetization of low coercivity dots in adjacent tracks. This indicates that the width of the switching field distribution, as well as the use of a longitudinal head with poles extending over several tracks in the cross-track direction, can induce some errors in the dc-erase tests. This makes the proper choice of I_w difficult. The data in the remainder of the letter were taken using $I_w = 8$ mA. Other authors have explored the writability of patterned media as a function of the phase shift existing between the write pole and the center of the dots in the scan direction.¹¹ These studies lead to a similar conclusion; that is the switching field distribution and head field gradient (I_w) are limiting factors.

After dc-erasing the media, we wrote several tracks with bit lengths (BLs) ranging between 0.2 and $2.0 \mu\text{m}$. Figure 3(a) shows an example of the magnetic configuration for the

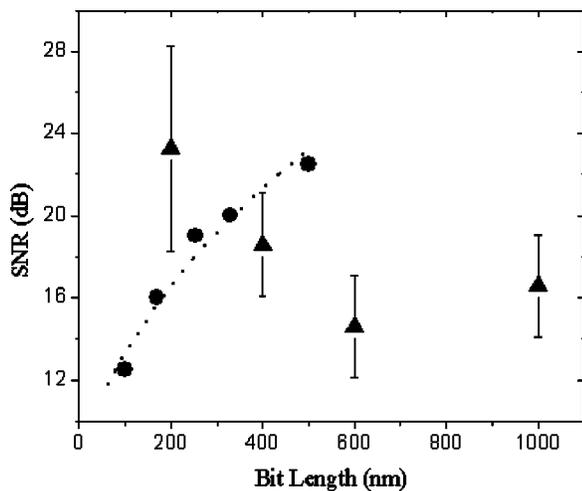


FIG. 4. SNR vs bit length for our patterned media (triangles), as well as for a continuous perpendicular [CoB/Pd] multilayer medium (circles, as taken from Ref. 13).

minimum $BL = 0.2 \mu\text{m}$. To demonstrate that magnetostatic interactions did not influence the magnetization direction, we wrote adjacent tracks with different BLs. The results are shown in Fig. 3(b). A write error is visible in the middle track, marked with a circle in Figure 3(b). This error is probably due to a larger coercive field for this particular dot or due to side erasure effect. Again, the intrinsic coercivity distribution is found to cause some problems in writing the media. Dipolar interactions, as estimated by numerical calculations, are found to be ~ 7 mT, depending on the array geometry and the magnetic layer. However, they are insufficient to influence the magnetization orientation, and do not perturb the write process or the subsequent stability of the media.

Figure 3(c) shows the down-track, read-back signal for the $0.2 \mu\text{m}$ BL pattern taken from Fig. 3(a). The read element was centered on the track. To calculate the SNR associated with the read-back signal, we estimated the cross-correlation coefficients R_{ij} between several periods, as follows:¹²

$$R_{ij} = \frac{\frac{1}{T} \int_0^T (S_i - \langle S_i \rangle)(S_j - \langle S_j \rangle) dx}{\sqrt{\frac{1}{T} \int_0^T (S_i - \langle S_i \rangle)^2 dx} \times \sqrt{\frac{1}{T} \int_0^T (S_j - \langle S_j \rangle)^2 dx}},$$

where T is the period of the read-back signal, S_i is the signal corresponding to the period labeled i , and $\langle S_i \rangle$ is the averaged value over the period T . The SNR in dB is then given by

$$\text{SNR}(dB) = 10 \log \left(\frac{\langle R_{ij} \rangle}{1 - \langle R_{ij} \rangle} \right),$$

where $\langle R_{ij} \rangle$ is the average value of the cross-correlation coefficients.

Figure 4 shows the calculated SNR as a function of BL for our pre-patterned media. Figure 4 also includes comparative data for a continuous perpendicular [CoB/Pd] multilayer media, extracted from Ref. 13. The SNR for the pre-

patterned media does not decrease with decreasing BL, in contrast to the case of continuous longitudinal and perpendicular media, in which the SNR is limited but the transition noise.¹³ At the highest linear density, the noise level is lower than in the continuous perpendicular film, without optimizing the magnetic layer for the magnetic signal. The difference can be explained by the lower dc noise and a significantly reduced transition noise. Indeed, the transitions in pre-patterned media are not limited by the granular structure of the material, but rather by the nanofabrication process, and can be made very sharp. Hence, little noise arises from spatial magnetization fluctuations in the transition area; transition noise is solely determined by the position jitter of the dots.

The transition position jitter can be extracted from the read-back signal: the jitter noise is defined as the standard deviation of the difference between the experimental positions of the read-back peaks and their theoretical positions assuming a perfectly periodic dot-array. Such an analysis yields a magnetic jitter of $\sigma_j \sim 12$ nm. Using atomic force microscopy to perform a similar evaluation, we found a topographic jitter of $\sigma_t = 6 \pm 1$ nm. This topographic jitter is determined solely by the nanofabrication process, and is therefore independent of the track width. The topographical jitter is the main contributor to the observed total jitter. Therefore, we conclude that for pre-patterned media, the transition position jitter is primarily limited by the patterning process.

In conclusion, we have investigated the write and read-back processes of perpendicular pre-patterned media, and have shown that it is possible to address individual dots in these arrays, both in the down-track and cross-track directions. The SNR is dominated by position jitter and is independent of the bit length. The overall jitter is limited by the lithographic process and is ~ 10 nm for the feature sizes investigated in these samples.

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