Recording Processes in Perpendicular Patterned Media Using Longitudinal Magnetic Recording Heads

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***Abstract*—Experimental study of the recording processes in patterned magnetic media is presented. The reading of patterned media using spin-valve elements is compared to the signal levels from magneto-resistive sensors. Writing and reading of patterned columnar media at high areal densities is demonstrated. A new experimental technique has been developed that allows precise determination of the location of the write gap poles with respect to the patterned media column during the write process. Implications for patterned media write synchronization and the write head field requirements are discussed.**

***Index Terms*—Magnetic nanostructures, patterned media.**

I. INTRODUCTION

IN THE PAST four decades the magnetic recording industry has consistently achieved areal densities beyond expectations, and is currently advancing at rates of up to 100% increase per year. This progress has been achieved by parallel improvements in all key areas of storage system parameters. These include the reduction in the flying height between a spinning disk and slider, more sensitive read transducers, smaller and better decoupled magnetic media grains, and higher fields and field gradients from the write heads. While most of the above parameters might be further improved by engineering developments to accommodate the need for higher areal densities, there is a fundamental physics problem inherent in the media grain size. Once the grains become $\leq$10 nm, thermal fluctuations can flip the magnetization orientation of each grain on a time scale shorter than the ten years required for a standard hard drive use. Current media was initially predicted to show signs of thermal instability at densities around 50 Gb/in^2 [1], [2], and experimental evidence of this effect has been reported [3], [4].

Patterned magnetic media has emerged as one of the possible solutions to preventing the superparamagnetic problem. In patterned media, the information is stored in individual isolated single domain magnetic particles [5], [6]. Using a patterned media approach, the particles forming the basic storage units would be approximately an order of magnitude larger than the thermally unstable grains. They would therefore allow the progress toward densities of 100 Gb/in^2 and beyond in conjunction with continuous engineering improvements in the other key components.

We have previously fabricated and characterized viable recording model sample based on the single bit per column perpendicular patterned media. Complete description of the fabrication procedure is described elsewhere [7], [8]. Following the sample fabrication, we demonstrated that individual magnetic columns could be controllably written into one of the two possible magnetic states, and then read back using AMR read heads [9]. In our patterned media recording studies, we use the technique of Scanning Magneto-Resistance Microscopy (SMRM) [10]. The sample is positioned and scanned on a high-resolution piezoelectric stage. A conventional slider on a suspension is brought into contact with the sample, and the sample is scanned in a raster fashion under the magneto-resistive element.

In this report, we first present imaging of patterned magnetic media by a GMR spin-valve read sensor, and compare the resolution and signal levels to the AMR read transducer. The columns in the sample are 170 nm in diameter, 900 nm tall, and 2 μm apart on a square lattice [9]. This density is much lower than what can be achieved by our electron beam lithography [11], but is set by the narrowest AMR read element width available to us. The column array was rotated 45 degrees with respect to the SMRM scan direction in order to resolve the columns imaged by the AMR sensor. Fig. 1 shows the four images that compare the reading of the two stable column states by the AMR and Spin Valve sensors. Fig. 1(a) and (b) images are taken by a 2 μm wide AMR sensor with a 240 nm read gap. MR resistance was $\sim$35 Ohms and the bias current 7 mA. Fig. 1(c)–(d) show the SMRM images of the same sample imaged with a 0.8 μm wide Spin-Valve read element with a 200 nm read gap. The GMR element resistance was also $\sim$35 Ohms, but 5 mA bias current was used in order to prevent excessive heating. The narrower cross track response is evident in the Spin-Valve image. Fig. 1(e) compares the voltage levels between the two images, and demonstrates the expected higher signals in the Spin-Valve image.

We also present in this report the experimental method developed to study the writing process in perpendicular patterned media. In order to investigate the recording process, we devised a method to precisely determine the write element location with respect to the patterned media column during writing. It was discovered during the recording experiments that when the reader is monitored while the pulsing of the writer is performed, a

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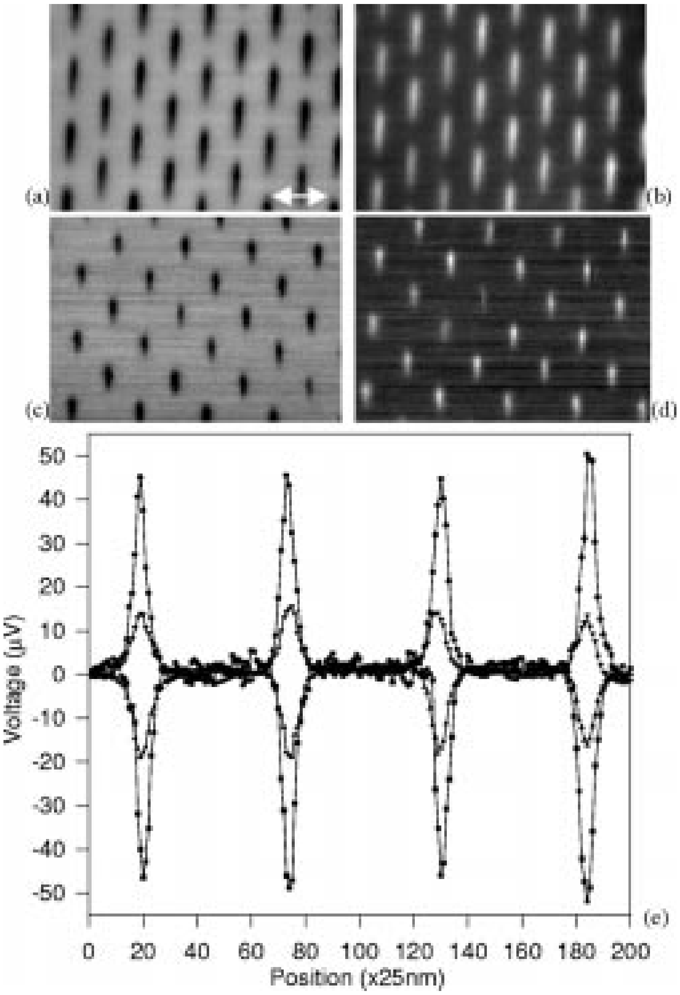

Fig. 1. Comparison of AMR and spin-valve imaging. (a) and (b) show the columns in two stable magnetization states. (c) and (d) show the same sample imaged by the spin-valve sensor. Narrower cross track response is apparent. Fig. 1(d) shows the comparison of AMR and spin-valve read signals. Scale bar is 2 μm.

transient signal is observed in the MR read voltage. This allowed precise marking of the writer position, since the distance from the write poles (where the writing happens) and the reader (where the transient voltage is observed) can be precisely measured by scanning electron microscopy (SEM). There are four possible write configurations in perpendicular patterned media using longitudinal magnetic recording write heads.

Fig. 2 summarizes the possible configurations using the write-pulse/MR-read transient method we developed. Fig. 2(b) and (c) demonstrate the first two possible cases. Fig. 2(a) shows a linescan of two patterned media columns imaged by an AMR sensor without any write pulse being applied to the write head. In this example, the column on the right is the column that one intends to write. The initial state of that column is down as indicated by the arrow. There are two possible ways of rewriting this column into an up state. Fig. 2(b) shows the diagram of the writing with the front pole of the writer, and the direction of the field indicated in order to orient the column in the correct direction. When the pulse is applied to the write head that is in the position with respect to the column shown in Fig. 2(b), the MR element experiences a transient signal due to the pick up from the write pulse. Since the MR element is located several microns behind the writer, the transient voltage appears adjacent to the first column and points in the negative direction, as indicated by the sharp transient in the data. The second possible way of rewriting the column in the up state is by writing with the second pole, but applying the current in the opposite direction, as indicated in the schematic of Fig. 2(c). Since the pulse now appears later in the linescan, the transient in the MR voltage appears closer to the written column, as shown by the sharp pulse in the linescan. One also observes that the transient pulse now points in the opposite direction than the transient pulse of Fig. 2(b), indicating a current of opposite polarity.

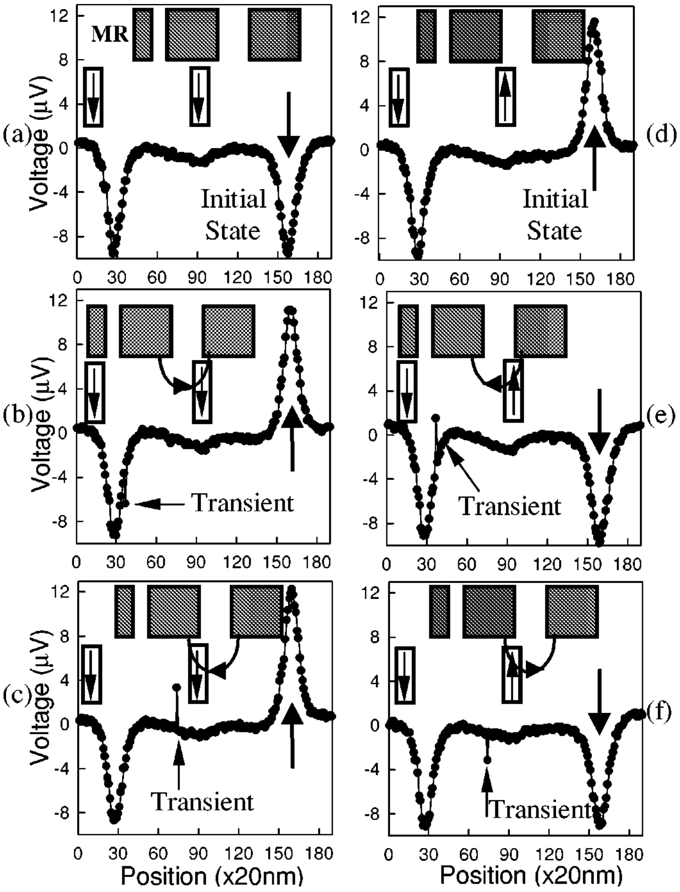

Fig. 2. (a)–(c) show the write configurations that reverse the column from the down to the up state. (d)–(f) show the write configurations of reversing the column from the up to the down state.

In addition to writing the column into an up state from the initial down state, two other symmetric possibilities exist for recording the column into a down state from an initial up state. This is experimentally demonstrated in the Fig. 2(d)–(f). The image of Fig. 2(d) shows the initial state where no pulsing occurs, with the column on the right in the up state, as indicated by the arrow. Again, there are two possible ways of rewriting this column into a down state. Fig. 2(e) shows the writing of the column into a down state using the front pole of the writer, as indicated by the schematic. The corresponding transient pulse in the MR voltage again appears at the same location as in Fig. 2(b), but opposite in direction due to the opposite direction of the current through the write coil. The last writing

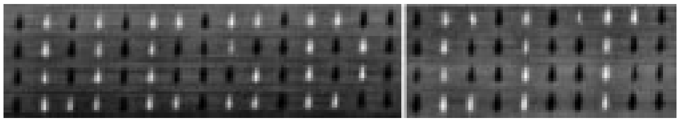

Fig. 3. Image of patterned magnetic media recorded so that the up columns in the image, appearing white, spell out the letters of UCSD and CIT.

configuration is shown in Fig. 2(f), where the column is again rewritten into the down state from an initial up state. This time the writing is performed by the back pole of the writer, and the opposite current direction than in Fig. 2(e), as indicated by the figure schematic. Again, the transient occurs later in the linescan, due to the closer distance of the MR element and the written column. One again observes that the location of the transient pulse in Fig. 2(f) is the same as the location of the transient pulse of Fig. 2(c), but the transient pulse is in the opposite direction due to the opposite direction of the current through the write coil.

With this technique of observing the MR transient due to the write pulse, one has a precise marker of the MR element position at the time of the write pulse. Therefore, one can perform a variety of experiments determining the location of the write poles with respect to the position of the patterned media column, as well as determining the minimum value of the pulse current required to successfully switch the column [12]. We find that a minimum current of 2.7 ± 0.1 mA through the write coil is required for successful reversal of the column. This is possible only when the write gap is positioned precisely at the location shown in Fig. 2(b), where the perpendicular component of the field is at a maximum. The 2.7 mA current required to record 170 nm diameter columns is an order of magnitude smaller than the current required to record transitions in the thin media. This lower coercivity of patterned media is one of the potentially significant advantages with respect to the thin film media [5]. One has to be careful, however, to include the head and media dynamics issues related to the reversal process [13]. Similar study of the write process was performed with the Spin-Valve head. We observe that a minimum write current of 1.1 ± 0.1 mA is required for reversing the column when the write gap is placed precisely as shown in Fig. 2(b). This was significantly lower than the 2.7 mA value required for the AMR head. The large difference stems from two factors: a) smaller Spin-Valve head write gap dimension, which results in higher fields available from the same write currents, and b) the Spin-Valve write poles implement a higher magnetic moment material.

The precise write synchronization scheme allowed us to record both low and high areal density patterned media samples. Fig. 3 shows the SMRM images demonstrating data storage in the same low density sample used in the original patterned media data storage demonstration [9]. If one focuses on the white columns in the image, one sees that they have been written to spell out the initial letters of the respective institutions involved in this project, "UCSD" and "CIT," respectively.

Our most recent efforts are directed at pursuing increased patterned media areal density demonstrations, which are limited only by the finite width of the spin-valve sensor of ∼0.8 μm, and the ∼800 nm width of the spatial column response in the down track direction, as seen in Fig. 1(d) and (e). We have fabricated higher density structures with column diameters of 150 nm, spaced 250 nm apart in the down track direction, and 1 μm apart in the cross track direction. The description and magnetic force microscopy of this sample appear elsewhere [8]. The three $3\ \mu\text{m} \times 1.2\ \mu\text{m}$ SMRM gray scale images of Fig. 4 show various recorded data track patterns. Fig. 4(a) shows the columns oriented in the alternating up/down fashion. In Fig. 4(b) the columns are sequenced in a two-up/two-down fashion, while Fig. 4(c) shows the pattern where every third column is in the up state. The line scans of the read-back voltage are shown on the right of each image. We emphasize that while the density demonstrated is still behind the longitudinal thin film media areal density laboratory demonstration, we are not limited by the lithography, but rather by the cross track and read gap widths of the available spin-valve read sensors.

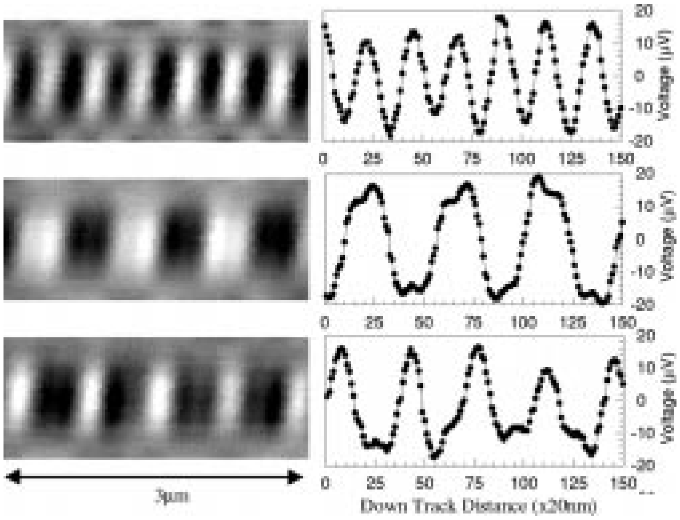

Fig. 4. Images of recorded data patterns in high density patterned media. Line scans from each image appear on the right side.

In both the reading and writing process we observe a variation in the read signal level and the required write current, and we believe that the source of this variation is due to imperfections of the columns from the fabrication process. This media and write synchronization noise [14] will have to be considered when final forms of patterned media systems are optimized in a fully operational rotating disk system.

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