SIGNAL PROCESSING FOR PROBE STORAGE

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ABSTRACT

Scanning-probe data storage is emerging as a viable alternative to conventional data storage offering ultra-high density, low access-times, and low power consumption. One probe-storage technique utilizes thermomechanical means to store and retrieve information in thin polymer films. In this paper we describe the readback signal path and characterize the thermomechanical-based probe-storage recording channel. It is shown that this channel exhibits a particular nonlinear behavior at high storage densities or high recording power that is, the energy per unit time used to write a bit of information. A simple model is proposed that accurately captures the characteristics of this nonlinearity. Experimental results from single-probe recording setups are used throughout the paper to verify the validity of this model and identify its relevant parameters.

1. INTRODUCTION

Ever since the invention of the scanning probe microscopy, it has been recognized that scanning probes are useful not only for imaging surfaces at the atomic scale but also for the development of ultrahigh areal-density storage devices. Probe-based storage technologies can be regarded as natural candidates for extending the physical limits that are being approached by conventional magnetic and optical storage as well as semiconductor nonvolatile memories.

In the past decade, conventional data-storage technologies, such as magnetic recording and solid-state flash memory, have increased their storage densities by 60-100% per year, leading to spectacular decreases in cost per GByte. It is widely recognized though, that the areal density of magnetic storage will eventually reach a limit imposed by the well known superparamagnetic effect, conjectured to be on the order of 250-300 Gbit/in^2 for longitudinal recording and somewhat higher for perpendicular recording. Other techniques, such as thermally assisted magnetic recording or the use of patterned media offer the promise of even higher areal densities, but practical implementation appears to be difficult. In the case of semiconductor flash memory, the challenges are predominately in lithography and in particular to achieve flash-cell scaling below the 65 nm technology node.

There is a wide variety of methods for creating nanometer scale marks on surfaces. The thermomechanical probe-based data-storage approach described in [1, 2] combines ultrahigh density, small form factor, and high data-rates by means of highly parallel operation of a large number of atomic force microscope (AFM) probes. Digital information is stored in a completely different way than on magnetic hard disks, optical disks, and transistor based memory chips. Ultimate locality is provided by a tip, and as storage medium polymer films are being considered.

In this paper we consider the readback channel for a single cantilever, scanning a storage field where bits are written as indentations or no indentations in a polymer storage medium by a thermomechanical recording technique. First, the principles of thermomechanical recording and in particular the read and write operations are presented. Then, the readback signal path is described and the thermomechanical probe-storage read channel is characterized. It is shown that at ultrahigh areal densities, i.e., 300 Gbit/in^2 and higher, the read channel can be modelled very accurately by a simple nonlinear model with a second-order nonlinearity. Moreover, it has been observed that increasing the linear density has a more profound effect on channel nonlinearities than increasing the track density. The remainder of the paper is devoted to presenting various experimental results on the effect of the recording conditions on the magnitude of the nonlinearities. This work demonstrates that a simple model can capture the nonlinear effects in the readback signal, enabling effective detection schemes for enhancing the performance of thermomechanical recording at densities as high as 1 Tbit/in^2 [3].

2. THERMOMECHANICAL WRITING AND READING

In thermomechanical probe-storage the writing and reading transduction are achieved through the use of an integrated write/read cantilever probe. This probe comprises separate resistive heaters for reading and writing, and a capacitive platform for electrostatic force application [3]. The main body of the cantilever consists of Si with a high phosphorous doping concentration, while the two resistive heaters are regions of lower doping. A sharp tip protrudes from the write heater so that the tip can be efficiently heated when current flows through the write heater. During writing, a voltage pulse is applied across two of the cantilever terminals to heat the write heater and tip and, simultaneously, another voltage pulse is applied to the substrate of the polymer medium to create a local force between tip and polymer film. As a result, a nm-sized indentation is formed on the polymer medium, representing an encoded '1' symbol.

Reading is achieved by exploiting the high temperature sensitivity of the resistivity of doped semiconductors [1]. In particular, a constant voltage is applied to the read heater, which is located at a certain distance from the tip. As the tip is scanned across the polymer medium, following the contours of previously written indentations, it moves vertically resulting in spacing variations between the hot read resistor and the polymer film. These spacing variations induce changes in the heat flow through the air gap between heater and medium, which lead to temperature and resistance changes in the heater, modulating the heater current. The evolution of the heater current is translated to a voltage waveform through a current-to-voltage converter, and this waveform serves as the analog readback signal.

3. THE READ PATH

During the read process the cantilever resistance attains different values depending on whether the tip moves into an indentation or not. The relative variation of the read heater resistance is on the order of 10^{-5}/nm. For a typical indentation depth of 5-10 nm, the relative resistance change is 5×10^{-5} to 10^{-4}. This small resistance change translates to a small voltage variation in the readback waveform. Thus, the information carrying signal can be viewed as a small signal superimposed on a very large offset signal. One of the main functions of the read channel is to accurately estimate and remove the offset from the readback waveform to avoid the need for high resolution analog-to-digital conversion.

The read signal path is illustrated schematically in Fig. 1. The read sensor of the cantilever is shown as a variable resistor. A second resistor with a tunable resistance is driven by the same voltage source as the read sensor. This resistor is tuned to coarsely match the average value of the resistance of the read sensor when it is heated at the read temperature [2]. As a result, the signal at the output of the first adder has a smaller dynamic range, as the bulk of the offset signal is removed. The purpose of the second adder is to eliminate any residual offsets present in the readback signal, through a feedback loop. In particular, the readback signal with a possible residual offset is first lowpass-filtered and then amplified to enhance the information carrying part. An integrator is used to estimate the DC content of the signal which is subtracted through a feedback connection from the lowpass filter input. Consequently, the signal $r(t)$ at the output of the second amplifier is offset-free. An analog-to-digital converter (ADC) then samples $r(t)$ at the rate $1/T_s$ which is asynchronous to, and typically higher than, the symbol-rate $1/T$. A typical sequence of samples $r_n = r(nT_s)$ is shown in Fig. 2. Note that indentations on the polymer medium give rise to negative peaks in the readback signal, whereas the signal waveform amplitude hovers around the zero value outside of an indentation.

In the digital domain the sequence at the output of the ADC is first synchronized to the symbol-rate. This is accomplished through a timing recovery loop and an interpolator, which are schematically represented by the sampling rate converter (SRC) in Fig. 1. The timing loop comprises a second-order PLL driven by an error signal derived by the positions of zero-crossings of the derivative of the readback signal. Finally, the synchronous output of the interpolator is filtered and passed to a binary threshold detector to produce estimates of the stored symbols. The purpose of the digital filter f_k is to eliminate rapid DC fluctuations at the detector
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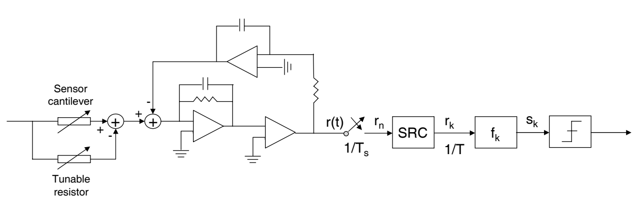


Fig. 1. Block diagram of the read signal path.

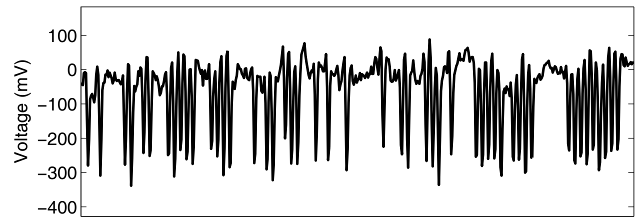


Fig. 2. Example of readback waveform.

4. CHANNEL CHARACTERIZATION

In thermomechanical probe storage information is stored on a polymer film in the form of indentations corresponding to encoded '1' symbols, whereas '0' symbols correspond to the absence of indentations. During readback of the stored information, indentations (1's) are mapped to a different nominal signal amplitude than no indentations (0's). This is a form of binary amplitude modulation. The continuous-time readback signal, after lowpass filtering, sampling and re-synchronization to the symbol-rate, as shown in Fig. 1, is translated to a discrete-time sequence r_k which may be expressed as:

$$r_k = \sum_{i=-\infty}^{\infty} a_i g_{k-i} + n_k, \tag{1}$$

where $a_k \in \{0, 1\}$ is the encoded information sequence, g_k is the compound impulse response of the write and read channels, and n_k is additive noise.

The linear model of (1) appears to be quite accurate at low to moderate storage densities and/or recording power. However, at high storage densities and/or high recording power the channel exhibits a specific nonlinear behavior, called partial erasing [3]. In particular, the depth of indentations decreases when other indentations are written close to them. In a series of consecutively written indentations at a close spacing, all but the last written indentation exhibit this nonlinear amplitude loss. Moreover, the indentation written first suffers the largest reduction in amplitude, while the indentation written last exhibits an amplitude enhancement with regard to the nominal indentation amplitude. Indentations which do not have immediate neighboring indentations, also called 'isolated' indentations, attain the nominal readback amplitude. This nonlinear behavior is attributed to the write process. These observations suggest a simple two-step model of the readback signal at high storage densities or high recording power; in a first step, due to the nonlinear nature of the write process, the encoded binary information sequence a_k is mapped to a five-level sequence b_k through the following mapping:

$$b_k = a_k + (\alpha - 1) a_k a_{k+1} + (\beta) a_k a_{k-1}, \tag{2}$$

where α, β are positive real parameters taking values in $[0, 1]$. This mapping essentially reflects the partial erasing effects that have been observed experimentally depending on whether a_k corresponds to an isolated indentation or not. Table 1 lists the values of b_k for all sequences of symbols a_{k-1}, a_k, a_{k+1} with $a_k = 1$, as $b_k = 0$ when $a_k = 0$. As required, isolated '1's remain unchanged, whereas for series of consecutive '1's all but the last '1' in the series are reduced in amplitude, while the last '1' gets enhanced. The closer α gets to 0, the bigger the amount of amplitude reduction becomes. In the second step, the readback sequence is

a_{k-1}	a_k	a_{k+1}	b_k
0	1	0	1
0	1	1	α
1	1	0	$1+\beta$
1	1	1	$\alpha+\beta$

Table 1. Sequences of symbols a_k and corresponding model output b_k.

obtained as a linear transformation of b_k,

$$r_k = \sum_{i=-\infty}^{\infty} b_i g_{k-i} + n_k. \tag{3}$$

The proposed nonlinear model belongs to the class of Volterra series models [4]. By using (2) in (3) and re-arranging terms one obtains

$$r_k = \sum_{i=-\infty}^{\infty} a_i g_{k-i} + \sum_{i=-\infty}^{\infty} a_i a_{i-1} h_{k-i} + n_k, \tag{4}$$

where $h_k = (\alpha - 1)g_{k+1} + (\beta)g_k$. This is recognized as a truncated Volterra series with a second-order next-neighbor nonlinearity. As the nonlinear kernel is coupled to the linear kernel in the proposed model, it is actually a special case of the Volterra series with a smaller number of parameters.

The performance of the linear, Volterra, and simplified nonlinear models was tested on experimentally obtained readback signals from a single-probe recording setup. For the Volterra model, nonlinearities up to third-order were used. A total of 50 periods of a pseudorandom bit sequence of length 511 were recorded on a thin polymer film, with the write voltage set to an increasingly higher level every 10 periods. Higher write voltages mean higher tip temperatures, which lead to increased softening of the polymer and thus larger indentations, giving rise to increased partial erasing of neighboring indentations. The effect of additive noise on the measurements was reduced by averaging over 10 periods of the readback sequence resulting in 5 averaged sequences, one for each value of the write voltage. The parameters of the three models were estimated by applying the method of least-squares to the averaged readback sequences. The normalized mean square error (MSE) value, i.e., the difference between model output and actual sequence, was used as the quality criterion for the model fitting. Fig. 3 shows the inverse normalized MSE in dB for the three models, as a function of the write voltage. As nonlinearity in the readback signal increases with the write power, the fitting performance of the linear model deteriorates. On the other hand, the proposed model captures well the nature of the nonlinearities, as it attains similar normalized MSE levels to the more powerful Volterra model. As further evidence of the effectiveness of the proposed model, Figs. 4(a) and (b) compare the linear and first-order nonlinear kernels, respectively, of the Volterra and proposed models, at a linear storage density of 660 Kbits/inch and for a write voltage of 5.4 V. Similar results are shown in Figs. 5(a) and (b) for the linear storage density of 825 Kbit/inch. As can be seen, the new model approximates very well the more complex Volterra model with only two parameters.

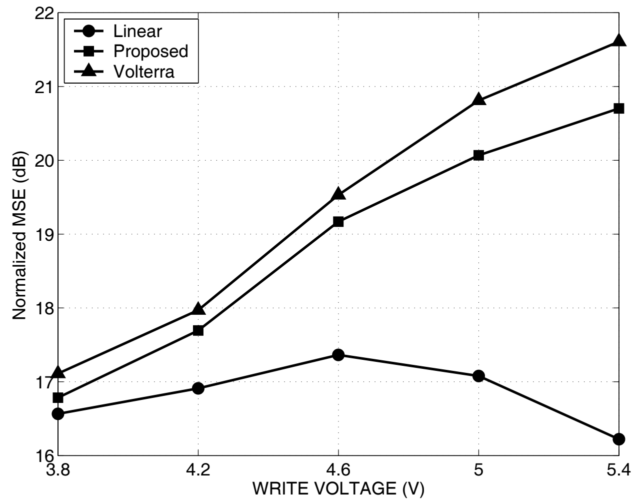
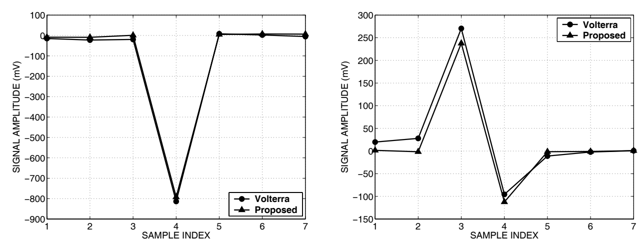


Fig. 3. Model fitting quality as a function of write voltage.

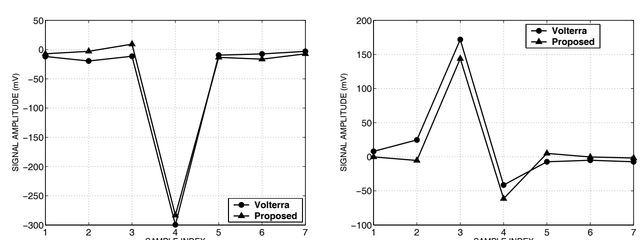


(a) (b)

Fig. 4. Comparison of (a) linear kernels, and (b) first-order nonlinear kernels at 660 Kbits/inch.

5. EFFECT OF RECORDING CONDITIONS ON NONLINEARITIES

The probe-storage channel becomes increasingly nonlinear with increasing storage density and increasing recording power. The nonlinear model introduced in the previous section can be used to quantify the amount of nonlinearity present in the readback signal as a function of these recording parameters. The effect of increasing write voltage on the model parameters α and β is shown in Fig. 6. Parameter α drops almost linearly from 0.88 to 0.7 as the write voltage increases from 3.8 to 5.4 V, while parameter β increases in a much slower rate. In general, it has been found that parameter α is more characteristic of the degree of nonlinearity in



(a) (b)

Fig. 5. Comparison of (a) linear kernels, and (b) first-order nonlinear kernels at 825 Kbits/inch.

the readback signal, while β is often of secondary importance. In the following results only the variations of parameter α are considered.

In thermomechanical writing, an indentation is formed by simultaneous heating of the tip and the application of a force between tip and polymer film. The recording power is not only a function of the write voltage, but also of the amount of the local force exerted at the polymer medium. Increasing amounts of force result in deeper and larger indentations, which affect more the depth of neighboring indentations. The effect of electrostatic force on the amount of nonlinearity in the readback signal is illustrated in Fig. 7, with the linear storage density in Kbits/inch as a parameter. Clearly, the nonlinearity increases as the electrostatic force used for writing indentations increases.

Fig. 8 shows the effect of increasing linear storage density on the value of α, with the electrostatic voltage as a parameter. For all these experimental results, the track pitch was fixed at 46 nm, and the minimum indentation pitch was varied between 46.1 and 30.8 nm, corresponding to areal densities of 304 and 456 Gbit/in^2, respectively. The value of α decreases dramatically as the storage density increases from 550 to 825 Kbits/inch, indicating higher amounts of nonlinearity.

Several other parameters of the recording process give rise to nonlinear behavior. For example, the duration of the write voltage pulses or the electrostatic voltage pulses has a similar effect, as expected. These all manifest themselves as nonlinear contributions to the readback signal, which eventually lead to detection losses if not accounted for in the detector. A simple yet accurate model of the nonlinearities present in the readback signal, such as the model introduced here, enables the design of simple detection schemes that can enhance the performance of the read channel even in the presence of adverse signal imperfections.

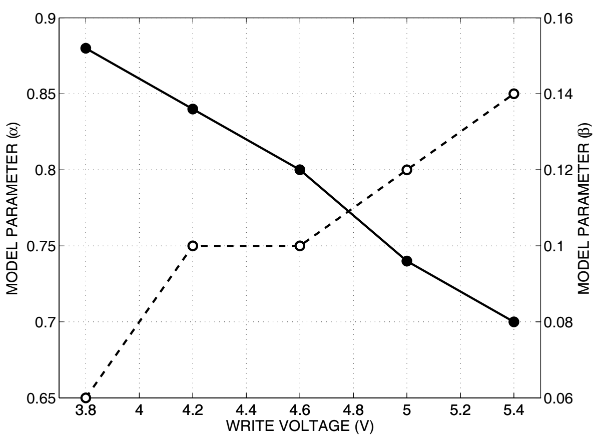


Fig. 6. Parameter α as a function of write voltage at an electrostatic voltage of 7.0 V.

6. CONCLUSIONS

The readback signal path for a thermomechanical probe-storage technique has been described. It has been shown that this probe storage channel is nonlinear at high storage densities or high recording power. A simple model was developed that accurately captures the characteristics of this nonlinearity. This model depends on only two parameters and has a memory of two symbols. Based on this

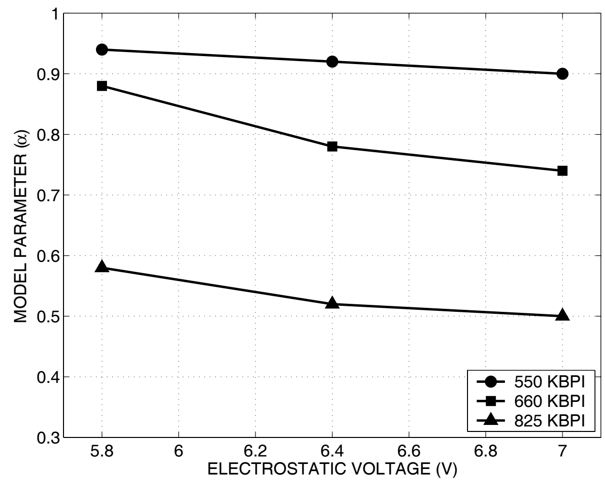


Fig. 7. Parameter α as a function of electrostatic voltage at a write voltage of 5.0 V.

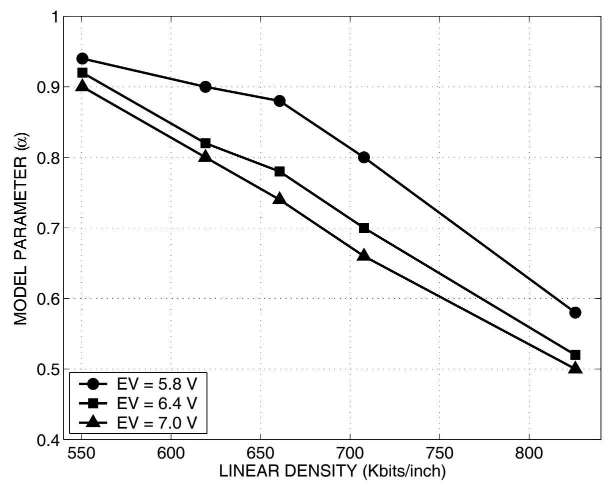


Fig. 8. Parameter α as a function of bit pitch at a write voltage of 5.0 V.

model the influence of the recording conditions on the nonlinear behavior of the channel has been quantified.

7. REFERENCES

[1] P. Vettiger, et al., “The ’millipede’-nanotechnology entering data storage,” *IEEE Trans. on Nanotechnology*, vol. 1, pp. 39-55, Jan. 2002.

[2] E. Eleftheriou, et al.,“Millipede-a MEMS-based Scanning-Probe Data-Storage System,” *IEEE Trans. on Magnetics*, vol. 39, pp. 938-945, Mar. 2003.

[3] H. Pozidis, et. al., “Demonstration of Thermomechanical Recording at 641 Gbit/in^2,” *IEEE Trans. on Magnetics*, vol. 40, no. 4, pp. 2531-2536, July 2004.

[4] M. Schetzen, “Nonlinear System Modelling Based on the Wiener Theory”, *Proc. IEEE*, vol. 69, no. 12, pp. 1557-1573, Dec. 1981.