Understanding Sources of Errors in Bit-Patterned Media to Improve Read Channel Performance

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The limitations of current lithographic techniques result in a variation of the geometry of the fabricated islands in bit-patterned media. These variations give rise to jitter in the replay waveform that has a detrimental effect on the recovery of stored data. By analyzing experimental bit-patterned media, we show that the presence of lithography jitter can be quantified in terms of variations in the size and position of the islands, which can be seen to be Gaussian-like in nature. In addition, the amount of jitter increases as the periodicity and size of the islands reduces, confirming that lithography jitter will be a significant source of noise in any future storage system incorporating bit-patterned media. By using a comprehensive read channel model we demonstrate that a novel trellis structure offers improved read channel performance in the presence of island position variations.

***Index Terms*—Bit-patterned media, jitter, magnetic recording, noise, trellis, Viterbi.**

I. Introduction

BIT-PATTERNED media is seen as one technology suitable for achieving storage densities in excess of 1 Tb/in^2 (155 Gb/cm^2) in future magnetic recording systems [1], [2]. However, the fabrication of bit-patterned media is technically challenging, and whilst some promising fabrication approaches exist, their applicability at such densities have yet to be proven [2]. More importantly, lithographic techniques are unable to fabricate uniform island arrays over large areas cost effectively, and the resulting island arrays have a large variation in island geometry. The result of this variation in island geometry is the introduction of jitter in the replay signal and variations in the amount of inter-symbol-interference (ISI) present, which has a detrimental effect on the performance of the read channel [3]. In addition, any island geometry variations also pose a problem for recording [4].

Recent work investigating read channel designs for bit-patterned media has shown that the effect of lithography jitter may be alleviated through the application of low-density parity-check (LDPC) coding schemes [3]. However, by identifying the type of island variation prevalent in bit-patterned media, it may be possible to improve the data recovery process without the need for additional coding schemes. Here, we demonstrate that the variation in island geometry can be quantified in terms of variations in island size and position and we investigate the effect that such variations have on the read channel performance in bit-patterned media storage systems. We then propose a modified trellis design that can be shown to improve the bit-error-rate (BER) performance in the presence of position jitter, without the need for additional coding schemes.

The paper is structured as follows. Section II outlines the analysis of island variations in experimental media. Section III describes the replay and read channel simulations used to perform the data recovery analysis in the presence of lithography jitter, and Section IV outlines the new trellis design proposed to offer improved BER performance.

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II. Jitter Analysis of Experimental Media

In order to understand the nature of the variation in island geometry in bit-patterned media, images of experimental media produced at Manchester have been analyzed. The media produced consist of arrays of islands fabricated in Co/Pt multilayer thin films using electron-beam lithography and Ar ion milling. The complete fabrication process is discussed in [5] and is summarized here. First, the deposited Co/Pt thin film $(10\ \mathrm{nmPt}/[0.4\ \mathrm{nmCo}/1\ \mathrm{nmPt}]_{15})$ was coated with a C overcoat in order to form a hard mask for milling. Electron-beam lithography was then used to expose nanostructures in a PMMA resist layer. After development, the patterned resist was then coated with a Ti layer, which was then removed by lift-off to reveal islands of Ti on the C overcoat. Transfer of the pattern to produce a C hard mask was achieved by O_2 plasma etch. Finally, Ar ion milling was used to produce the patterned islands.

Island arrays of nominal pitch 100, 80, 60, and 50 nm were produced and then imaged using a LEO 1530 Gemini scanning electron microscope. The resulting images were then processed, using the MATLAB image processing toolbox, to determine the approximate size (in terms of the island length along track) and down track pitch of the fabricated islands. Figs. 1 and 2 illustrate probability density functions for the variation in measured island diameter (Fig. 1) and island pitch (Fig. 2) for the four island arrays investigated. Table I lists the statistical properties of the island arrays analyzed.

The results in Table I show that there is a significant variation in the size (diameter) and position (pitch) of the fabricated islands. The distributions show that these variations are Gaussian-like in nature, which agrees with an analysis of island size variations in island arrays of increased diameter and period [6]. In addition, as the pitch of the islands is reduced, the calculated standard deviations increase. Hence demonstrating that variations in island size and position will be a significant source of jitter noise in any future ultrahigh-density storage system incorporating patterned media.

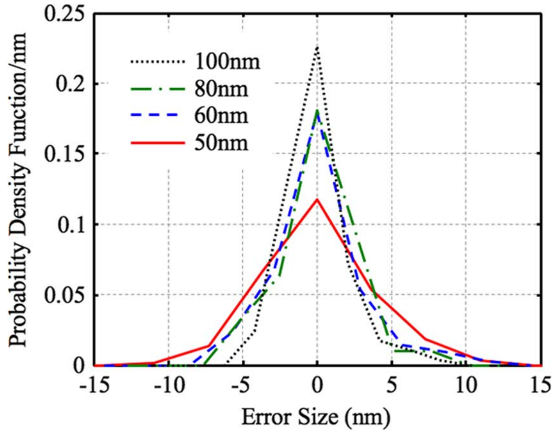

Fig. 1. Distributions for the variation in island size for four island arrays of nominal island period: 100, 80, 60, and 50 nm.

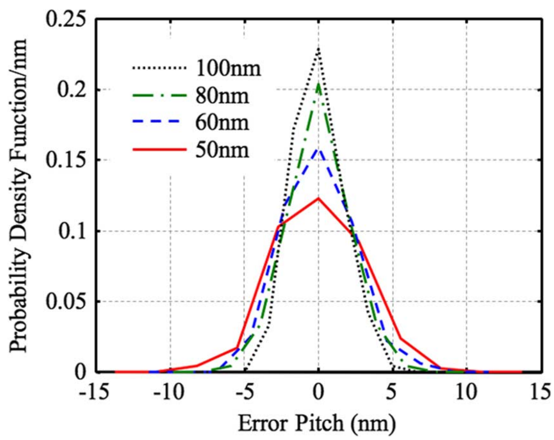

Fig. 2. Distributions for the variation in island pitch for four island arrays of nominal island period: 100, 80, 60, and 50 nm.

TABLE I
ISLAND SIZE AND PITCH STATISTICS

Array Nominal Pitch	No. of islands	Mean Island Diameter	Island Size σ	Island Pitch σ
100nm	140	39.42nm	2.08nm (2.1%)[1]	1.65nm (1.7%)[1]
80nm	117	34.08nm	2.55nm (3.2%)[1]	1.96nm (2.4%)[1]
60nm	150	32.43nm	2.86nm (4.8%)[1]	2.29nm (3.8%)[1]

III. READ CHANNEL SIMULATION

A comprehensive read channel simulation has been developed in order to investigate the effect that the two sources of island jitter have on the ability to recover stored data. The complete read channel model, written in the MATLAB environment, consists of simulations of the replay process using a conventional giant magneto-resistive (GMR) read sensor, and the data recovery process in a conventional partial-response maximum-likelihood (PRML) read channel. A complete description of the simulations is given in [3], [7], and [8].

The replay model uses a 3-D implementation of the reciprocity integral to simulate the replay waveform from the GMR read sensor. The use of a 3-D model allows the 3-D geometry of both the recording medium and the GMR read sensor to be taken into account. In addition, it also allows the effects of the finite track width and inter-track interference to be accounted for, which is important in the case of bit-patterned media, where the written track width is determined by the width of the fabricated islands and not the width of the record head.

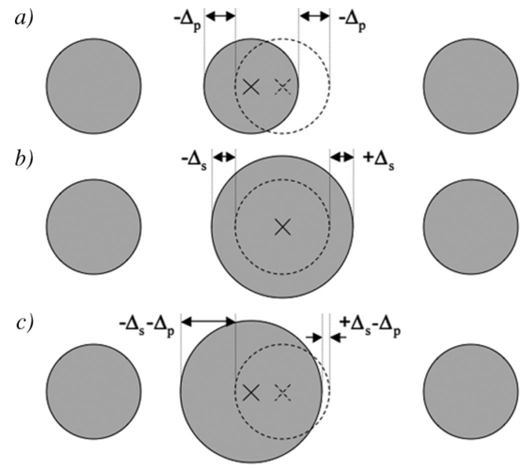

Fig. 3. Introduction of jitter in patterned media results in variations in (a) the position or (b) the size of the islands or (c) a combination of both.

The replay waveform due to a track of (assumed) random recorded data is generated by superposing isolated responses due to the leading and lagging edge of each island along the track, which have been generated using the 3-D model with a semi-infinitely long island with a semicircular end. The effect of island jitter is introduced by varying the position (in space) at which the superposition of the step responses takes place. Fig. 3 illustrates the three cases of interest for geometry variations along track only. In the case of variations in the position of an island, then the same amount of jitter, Δ_{p}, is applied in the same direction at both edges of each island, as illustrated in Fig. 3(a), which results in a shift in the island position of Δ_{p}. In the case of variations in island size, then equal jitter, Δ_{s}, is applied to each edge but in opposite directions, as illustrated in Fig. 3(b), which results in an increase in the diameter of the island by $2\Delta_{\mathrm{s}}$. Finally, Fig. 3(c) illustrates the case where there is a combination of both position and size variations.

The read channel model consists of a finite-impulse response (FIR) filter followed by a Viterbi maximum-likelihood decoder. The channel data samples are generated by sampling the simulated replay waveform at positions in the waveform corresponding to the position of the ideal centre of each island (at the ideal symbol-rate). The samples are then equalized by the FIR such that the response matches a PR target of [0.1, 1, 0.1]. Finally, the equalized samples are then passed to the Viterbi decoder in order for the recorded data to be recovered.

In the following analysis a patterned medium consisting of a single track of round islands has been assumed, with island diameter and pitch of 12.5 and 25 nm, respectively (1 Tb/in^2). The dimensions of the read sensor are the same as those listed in [3], [7].

Following the observations of experimental bit-patterned media we have adopted Gaussian distributions for the variations in island size and position, each with a standard deviation specified as 10% of the island pitch, i.e. $\sigma_{\Delta}, = 2.5$ nm, which

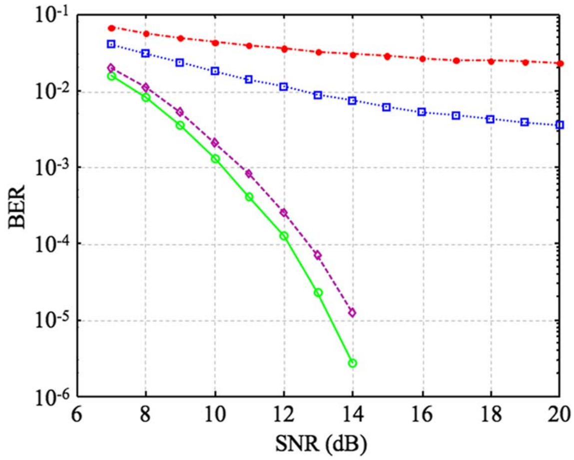

Fig. 4. BER curves for 1-Tb/in^2 bit-patterned medium in the case of no jitter (solid line), 10% island position jitter (dashed line), 10% island size jitter (dotted line), and 10% island size and position jitter (dashed–dotted line).

is appropriate considering the levels of island jitter observed in experimental media. Only island position variations along track are taken into account since the width of the read sensor is much greater than the island width. The read channel performance is evaluated using plots of BER against signal-to-noise ratio (SNR), where the SNR is defined in [3] for the case of additive white Gaussian noise (AWGN) only. Fig. 4 illustrates BER versus SNR curves for the bit-patterned medium investigated using a decoder with a standard trellis for four cases: no jitter (solid); 10% island position jitter (dashed); 10% island size jitter (dotted); and 10% island position and size jitter (dash-dot).

Fig. 4 demonstrates that the introduction of jitter, whatever its source, has a detrimental effect on the performance of the read channel, and the degradation in performance arising from variations in island size is more severe than that due to variations in island position.

IV. Modified Trellis Design

The problem of position jitter in bit-patterned media storage systems is analogous to the problem of transition jitter in conventional magnetic storage systems, and results in a random shift in the position of the recorded information. Following this, we have adopted the technique described in [9] in order to propose a new trellis design to combat position jitter in bit-patterned media. The trellis design takes into account the position shift and makes an estimation based on both the state of the recorded bits and the amount of island position shift. If we consider a partial-response (PR) read channel model with only AWGN and position jitter, then the symbol-rate samples of the PR channel can be written as

$$r(k) = \sum_i b_i g(kT - iT + \Delta_i T) + n(k) \qquad (1)$$

where $b_i \in \{-1, 1\}$ denotes the magnetization of each island, $n(k)$ denotes the AWGN, T is the ideal island period, $g(t)$ is the pulse response due to the magnetization of each island as defined by the PR target, $g(kT)$ is the symbol-rate samples of the pulse response, and Δ_i denotes the position shift due to jitter that we assume follows a Gaussian distribution. As can be seen

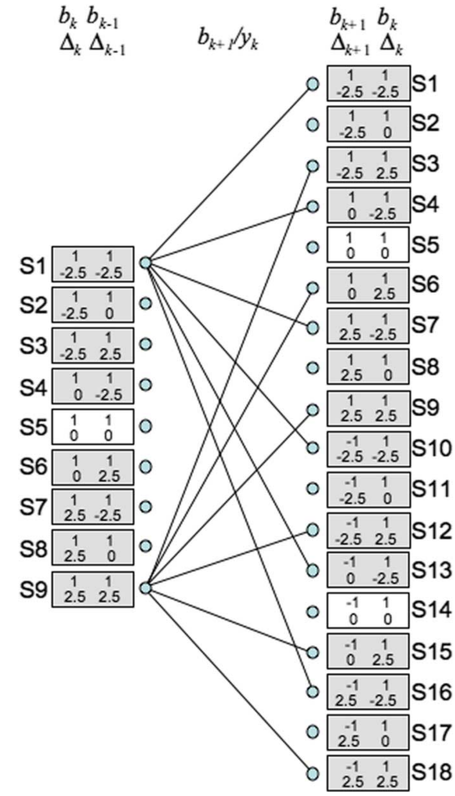

Fig. 5. Part of the proposed extended trellis structure designed to combat the effects of position jitter in bit-patterned media. Shaded blocks indicate new states.

in (1), the replay samples are calculated according to a predefined PR target sampled at the bit period plus a shift of Δ_i due to island position variations.

When using the standard trellis, the branch metric from one state to another is determined by the magnetization state of the islands and the amplitude of the pulse response, including any ISI, at the symbol-rate samples. The most likely input sequence is then chosen by comparing the channel samples with the branch metric. However, position jitter in bit-patterned media storage systems leads to a deviation from the nominal position (symbol-rate in time) of each island, which affects the detection process in selecting the most likely input sequence and introduces errors in the recovered data. Since the amount of shift in the position of each island depends on the fabrication process and is uncorrelated, then it is difficult to predict the amount of position shift for each island in advance. One way to overcome this is to approximate the amount of position shift by discrete values chosen over the range that the position jitter values span and to use these values to characterize the ideal output sample. Thus, we have proposed a modified trellis design by introducing discrete jitter values into the standard trellis structure, where we consider both state bits and the contributions of position jitter when selecting the most likely input sequence. In the modified trellis, the states are defined by both the state of the magnetized islands, b_k, and the discrete values representing a position shift of each island due to lithography jitter, Δ_k. Fig. 5 shows part of the modified extended trellis structure with the additional states introduced using this approach (shaded boxes). Also illustrated are some of the possible transitions from the states when $b_k = b_{k-1} = 1$. It can be seen that each state in the

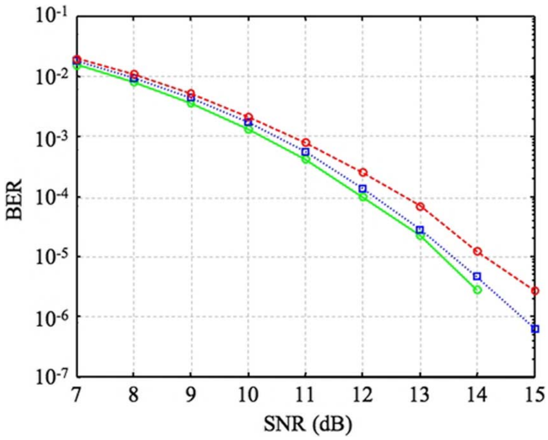

Fig. 6. BER curves with no lithography jitter (solid line) and with 10% position jitter (dashed line) using a conventional trellis, and 10% position jitter with the proposed modified trellis design (dotted line).

modified trellis represents the magnetization state of the current bit (island), the magnetization state of one or more previous bits, as well as discrete jitter values for each. The discrete jitter values are chosen depending upon the amount of jitter present. Here we have used 10% position jitter, i.e. $\sigma_{\Delta} = 2.5$ nm, so there are three discrete levels of jitter $\{-2.5\text{ nm}, 0, +2.5\text{ nm}\}$. The state branch is defined following the standard trellis with the only difference being that each state has Q branches, where Q is the number of discrete jitter levels, for each possible bit transition. Each branch metric, y_k, is calculated knowing the effect that any fixed jitter has on the amplitude of the isolated pulse response and the effect of changes in ISI due to the shift of the neighboring islands. For a PR target of length L, the isolated pulse extends over L-1 bit periods, which requires L-1 bits to represent a state in the modified trellis; in general, the total number of states is given by $2^{\mathrm{L}-1}\mathrm{Q}^{\mathrm{L}-1}$. Here, we use a PR target of length $\mathrm{L} = 3$ and $\mathrm{Q} = 3$ discrete jitter levels, which results in an additional 28 states, giving a total of 36 states in the modified trellis.

The branch metric, y_k, from the state k to the next state at $k+1$ can be calculated using

$$y_k(S_i, S_j) = \sum_i b_i . g(kT - iT + \Delta_i T) \quad (2)$$

where the variables have their usual meaning. For example, state S1 in Fig. 5 represents a current bit value of 1 with jitter of -2.5 nm and a previous bit value of 1 with a jitter value of -2.5 nm. The ideal sample from state S1 to S7 is given by

$$\begin{aligned} y_k &= b_{k-1} g\left(T + \frac{(-2.5)}{25}T\right) + b_k g\left(\frac{(-2.5)}{25}T\right) \\ &\quad + b_{k+1} g\left(-T + \frac{2.5}{25}T\right) \\ &= b_{k-1} g(T - 0.1T) + b_k g(-0.1T) + b_{k+1} g(-T + 0.1T). \end{aligned} \quad (3)$$

Fig. 6 illustrates the improvement in BER performance that is observed when adopting the modified trellis design in the presence of 10% position jitter (dotted line), compared to the use of the conventional trellis (dashed line) with the same jitter present. The use of the modified trellis design results in more than 0.5 dB improvement in allowable SNR for a BER of 10^{-5}.

V. Conclusion

Through an analysis of experimental bit-patterned media, we have shown that lithography jitter can be characterized by variations in the size and position of islands that are Gaussian in nature. Simulations show that both of these noise components affect the performance of the read channel, but the effect of size variations is more severe. We have investigated a new trellis design that aims to improve the performance of the read channel in the presence of lithography jitter. Initially, we have investigated the alleviation of the effects of island position jitter, and have demonstrated that an improvement in read channel performance can be observed. We hope to extend this work to investigate optimal trellis designs and alternative designs that offer similar improved performance with the addition of island size jitter, as well investigating reduced complexity designs.

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