The impact of in-plane grains on HAMR performance and THMap metrics

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An important source of noise in the Heat Assisted Magnetic Recording (HAMR) medium results from structural defects or magnetic defects of the FePt grains. One origin of this noise is the in-plane grains with easy axes pointing in-plane instead of out-of-plane. While the presence of these grains has been confirmed in the literature through experiments, there is a lack of understanding of how these grains can impact the HAMR performance and THMap metrics. In this modeling study, we first evaluate the impact of in-plane grains on the HAMR performance. We then model the THMap process to understand the effect of in-plane grains on magnetization mean, variance and the readback signal mean, variance. We also compare the signal, noise, low frequency SNR (LF SNR) and jitter captured through micromagnetic simulations to values obtained from an analytical DC noise model. Finally, we use analysis with correlation length for magnetization to explain the relationship of the magnetostatic interactions between grains and signal variance as a function of in-plane grains. This work establishes the performance impact of in-plane grains, the effect on specific THMap metrics and explains the relationship between the magnetostatic interactions between grains and signal variance through correlation length analysis .

Index Terms— HAMR, in-plane grains, noise, jitter, LF SNR, RTS, THMap, micromagnetic simulations, analytical model

I. Introduction

In the last two decades, efforts surrounding the Heat Assisted Magnetic Recording (HAMR) process have focused on improving the Signal to Noise Ratio [1, 2], reducing noise (jitter) [3-5] and alleviating erasure from overlapping data tracks [6, 7]. These efforts have allowed the technology to be commercialized in a 30TB drive. The next step is to ensure viability of the technology for the next couple of decades. Media noise is the most important noise source in HAMR, and a major contributor to this noise is in-plane grains. The distribution of these grains is difficult to control, and they are ubiquitous irrespective of the fabrication process parameters. This study establishes the impact of in-plane grains through HAMR micromagnetic simulations. We use the THMap methodology to calculate noise (readback signal variance) due to the in-plane grains in the absence and presence of magnetostatic interactions and compare the results to an analytical noise model. Finally, through autocovariance analysis, we explain both the behavior of the noise curve for different proportions of in-plane grains in the presence of magnetostatic interactions and the reasons why these trends deviate from the analytical noise model.

II. Micromagnetic Simulations And THMap Method

We use the micromagnetic technique described previously [8-10] to simulate discretized single layer media with magnetic grains. We've explained results from our HAMR Micromagnetic model in a digest published previously [11]. In this current work, simulations with the HAMR micromagnetic model show that in-plane grains reduce the Areal Density Capability (ADC) by 30 Gbpsi for every 1% increase of in-plane grains. The ADC loss occurs due to a reduction of the Linear Density (LD), which results from an increase in jitter, decrease in Low Frequency SNR (LFSNR), and a decrease in reader SNR. Simulations indicate that in-plane grains have almost no effect on track squeezability, and that the loss in LFSNR occurs because of the increase in noise power due to the presence of in-plane grains and impacts both the center of the bit and the transition. In addition to recording simulations, we run simulations of the THMap method [12]. First, the simulated media is initialized in a negatively saturated state by applying a high field in negative (-1) direction. This is followed by band erase at a particular temperature and an applied field (T & H respectively). The final magnetization state for each grain is then convolved with the reader sensitivity function to generate the readback signal.

III. Analytical Noise Calculation

We provide analytical expressions for the DC signal and DC noise power as a function of the proportion of in-plane grains [13] via a derived statistical model. The orientation of the grains' magnetization is described by binomial statistics. Let R be the proportion of out-of-plane grains. Of the R out-of-plane grains, a proportion p has their magnetization up and a proportion q=(1-p) have their magnetization down.

We extend the model to arbitrary reader point spread functions [13, 14] and include noise that arises from the grains' random positions. The expression for the average DC signal becomes:

$$\langle Signal \rangle = H_1 . pf . (M_g t_g) . R(2p-1) \qquad (1)$$

where H_1 is the head signal sensitivity pre-factor, *pf* the medium packing fraction, M_g the average grain out-of-plane magnetization and t_g the grain thickness. H_1 is proportional to the integral of the reader sensitivity function ϕ (x,y).

The expression for the signal variance is:

$$var[Signal] = H_2 . pf . A_{grain} . (M_g t_g)^2 \left[\left(1 + \left(\frac{S_{corr}}{S_{area}}\right)^2\right) \left(4.\ R^2 . p . (1-p) + R.(1-R) + \left(R(2p-1)\right)^2\right) - \left(R(2p-1)\right)^2 \right] \qquad (2)$$

where H_2 is the head noise sensitivity pre-factor, A_{grain} the average grain area, S_{corr}/S_{area} is the grains spatial correlation ratio that depends on the random granular structure of the medium [13]. H_2 is proportional to the integral of ϕ^2(x,y). Details behind the derivations of equations (1) and (2) will be provided in a separate publication.

IV. THMap Results

The THMap runs are implemented using two writer fields, 250 Oe (which ensures randomization of magnetization) and 12.5 kOe (which ensures media saturation). Results are plotted for temperature T > T_c. Fig. 1(a) shows curves for the readback signal mean in the absence of magnetostatic interactions (MSI). For the low field, random orientation of grains leads to mean ~ 0, whereas the magnetization at the high field is dependent on proportion of in-plane grains. As the proportion of in-plane grains increases, the signal decreases linearly as per equation (1), as indicated by the red squares. The green lines are fits constructed based on equation (1) where 'H_1*M_rt' and 'p' are fitting factors. The value of 'p' for the higher field 12.5 kOe is 1, which indicates the saturation of magnetization in the direction of applied field. The value of 'p' for the low field is ~ 0.5, given the randomness in orientation for the grains in the presence of a low field at T > T_c.
Fig. 1(b) shows the impact of the MSI on the signal variance. Signal variance decreases when MSI are introduced (black circles to blue triangles). This is because MSI introduces anti-correlations between the magnetizations of adjacent grains. The analytical fit cannot predict the signal variance for the low field when the same fitting parameters as the high field variance fit are used with equation (2). To examine whether the impact on signal variance is purely due to the MSI (and the corresponding magnetostatic field), the magnitude of magnetostatic field is varied, and the signal variance is plotted. The impact of the field magnitude on signal variance is not linear. The comparison of the variance data with the analytical equation fit improves as the magnetostatic field magnitude is reduced. This clarifies that the mismatch between the analytical model and variance data is due to the magnetostatic field since the analytical model does not explicitly account for MSI.

V. Understanding The Impact of MSI

We employ the autocovariance function on the vertical component of the magnetization (Mz) from the micromagnetic simulations. In Fig. 2(a), we note that with stronger applied field the autocovariance function changes shape. Defining the correlation length (CL) as the zero crossing of the autocovariance function, we see that the CL changes from 8 to 3 nm when increasing the applied field from 250 Oe (blue plusses) to 12.5 kOe (red circles). Considering the CL to be equivalent to a switching unit from a noise perspective, then there are significantly more switching units to be averaged, and consequently less noise, at high field. This is consistent with the results from Fig 1 (b).
Next, we examine the effects of MSI in the context of the magnetostatic field being just another applied field. In Fig. 2(b), we note that as the MSI magnitude increases, the correlation length decreases. This makes sense given that MSI "prefer" for neighboring grains to be anti-correlated to create flux closure between them. Thus, increasing MSI means increasing anti-correlations which reduce the CL. Secondly, given that a smaller CL implies smaller switching units, more switching units to be averaged, and less noise, we can understand the trend of the 250 Oe data in Fig 2(b). The CL from the fitted curve (7.7 nm) is close to the grain pitch of the micromagnetic simulations (7.4 nm). This is reasonable since we expect the switching unit size to be roughly equal to the grain pitch if there are no fields present (except the stochastic thermal field) between the grains.

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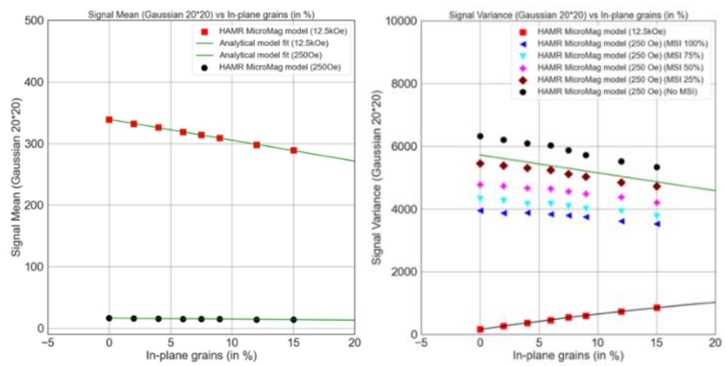
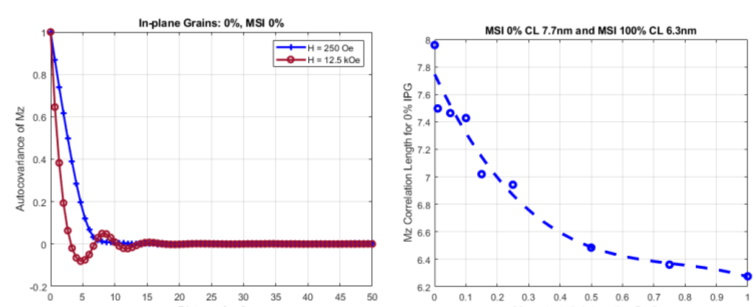


(a) (b)

Fig. 1: THMap metrics calculated from the HAMR Micromagnetic model for a Gaussian reader 20nm*20nm (a) Readback signal mean and (b) variance (for different magnetostatic fields)



(a) (b)

Fig. 2: (a) Autocovariance of Mz for no MSI and zero in-plane grains. The correlation lengths are 8 and 3nm for the two field values (b) Correlation lengths of Mz for various strengths of MSI with no in-plane grains and a 250 Oe applied field