Micromagnetic Modelling of Advanced Bit Patterned Magnetic Recording Structures

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1. Introduction

The main objective of the studies of micromagnetic modelling has been laid in 2007 on the simulation of the magnetization reversal properties and the complex hysteresis behaviour of magnetic materials in the view of magnetic recording applications, and spanning length scales from the atomic level to the continuum and picoseconds to long time stability. The research activities should combine the modelling of intrinsic magnetic properties on the atomistic level and hysteresis properties including switching modes and times on mesoscopic level together with the functional behaviour of magnetic devices on the macroscopic level, such as recording devices, spintronic, magneto-elastic sensors, biomedical devices, etc. Novel concepts for recording media and recording head design can be tested virtually. The guidelines for systems development can be drawn from the simulations results. Hard disk storage at high densities has to overcome a fundamental limit. With decreasing bit size thermal stability can only be achieved in recording media with highly coercive small structural units such as grains, particles or patterned elements. Magnetic recording in patterned magnetic elements addresses individual physical entities to store one bit of information. The effective volume of a structural unit in bit patterned media is much larger than the grain volume in thin film granular media. Thus thermal stability can be achieved at moderate coercivities. The switching field required to write the bits can be produced by single pole magnetic recording heads.

2. Method

Recording simulation software is required to take into account the detailed microstructure of a magnet and the interactions between the different magnetic parts of magnetic device. The micromagnetic software solves the equation of motion for the magnetization of an entire magnetic device. For example in magnetic recording simulations, the input for the simulations are the detailed microstructure of the recording media, the geometry of the write head, the layer stack and shield geometry of the read head, the intrinsic magnetic properties and the current wave form of the write current. Macropsopic properties like current wave form, read back voltage, transition jitter are input/output of a multiscale simulation that treats the functional behaviour of a recording system while taking into account the microscopic magnetization processes during recording and read back. The multiscale simulation process is illustrated in Figure 1.
Figure 1. Multiscale simulation of high density magnetic recording systems. The characteristic length scale ranges from 10μm in coils to 1 nm size features in the data layer.

Figure 2 illustrates the matrix compression technique used for fast multiplication of matrices arising from the boundary element method, which is used to calculate the interaction fields between the write head and the storage media. Due to the small distance between the head’s air bearing surface and the patterned elements it is required to take into account the mutual interaction between head and magnetic islands.

Figure 2. Fast boundary element method used for the calculation of magnetostatic interactions. Left hand side: The nodes are renumbered and grouped together so that nodes with consecutive numbers are located next to each other and form a cluster. Right hand side: Corresponding block structure of the interaction matrix. The large off-diagonal blocks can be approximated by low rank matrices. After [1].

2. Results of the write process of ion-irradiated Bit Patterned Media

The media is composed of several hundred well decoupled Co-Pt grains with an average diameter of 7 nm and a height of 15 nm. It is assumed that the ion irradiation affects the magnetic anisotropy but keeps the magnetization unchanged. The recording simulations were performed using a fully integrated micromagnetic simulation package. The background region that is regarded to be irradiated triggers the magnetic switching of the bits. Thus some degree of intergrain exchange between bits and background is needed to reduce the write field. However, the intergrain exchange leads to spin waves. It is found that the spin waves may
cause adjacent tracks erasure. In the simulations it is assumed that ion irradiation affect only the uniaxial anisotropy. The hard magnetic properties ($K_U = 10^6 \text{ J/m}^3$) are assigned to the grains within a recording bit whereas zero magnetocrystalline anisotropy is assigned to the irradiated region. The bit size was $30 \times 30 \text{ nm}^2$ that corresponds to 180 Gb/in$^2$. The material parameters for the recording media are as following: The saturation polarization $J_s(\text{bit}) = J_s(\text{irradiated}) = 0.8 \text{ T}$ and the exchange stiffness $A_{\text{exch}} = 10 \text{ pJ/m}$. In order to account for a possible change of the intergrain exchange, the intergrain exchange stiffness $A_{\text{int}}$ is varied from 0.07 to 1.13 pJ/m of $A_{\text{exch}}$ and the damping parameter is assumed to be $\alpha = 0.02$. The bits are arranged $2 \times 2$ with 60 nm pitch along the tracks and 45 nm spacing between tracks.

The model consists of 4 parts – recording media, field rising coil, recording head and soft under layer SUL, as shown in Figure 3a. The numbers of the nodes and the elements of each part are summarized in Table 1 below.

<table>
<thead>
<tr>
<th></th>
<th>Nodes</th>
<th>Surfaces</th>
<th>Elements</th>
<th>Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Media</td>
<td>23230</td>
<td>43226</td>
<td>44561</td>
<td>0</td>
</tr>
<tr>
<td>Coil</td>
<td>3054</td>
<td>0</td>
<td>6108</td>
<td>34</td>
</tr>
<tr>
<td>Head</td>
<td>8394</td>
<td>26174</td>
<td>13818</td>
<td>0</td>
</tr>
<tr>
<td>SUL</td>
<td>9700</td>
<td>32077</td>
<td>16710</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>44378</strong></td>
<td><strong>101477</strong></td>
<td><strong>81197</strong></td>
<td><strong>34</strong></td>
</tr>
</tbody>
</table>

Surface elements are used for calculating exchange interaction and magnetic fields, and lines are for the current that generates magnetic field on recording head. Moreover, their interactions are calculated using virtual “field box” between the elements.

![Figure 3a](image-url)
Figure 3b

Figure 3. (a) Finite element model of a perpendicular recording device for patterned media with a granular microstructure of the recording media. (b) Media model in detail. The gray scale shows the magnetization state of the media, the trapezoid and the arrow shows the cross section of the write head and its moving direction, respectively. Four bits can be identified in the white and black regions.

During the writing process the write head moves across the multilayer structure composed of the recording media, spacer and the soft under layer that returns the write field to the back yoke. The write field is generated by the current through the induction coil that surrounds the write head. We observed a maximum write field strength of 1 T. The time to establish the maximum head field after reversing the coil current is about 0.8 ns. The head velocity is 20 m/s. In patterned media the recording bits are predefined, hence the synchronization of the field and bit position becomes important [3]. Considering the head field rise, the current was activated before getting 30 nm closer to the bit in our simulation [4]. The following materials parameters are chosen for the head and the soft under layer. $J_s(yoke) = 2$ T, $J_s(tip) = 2.4$ T, $J_s(SUL) = 2$ T, and $\alpha = 0.1$. The write head and the soft under layer have a weak uniaxial anisotropy in the cross track direction, $K_U(yoke) = 800$ A/m, $K_U(tip) = 800$ A/m and $K_U(SUL) = 800$ A/m. The easy axis of the media is along the perpendicular direction of the media surface. The easy axis of the soft under layer is parallel to the surface. The Gilbert damping constant $= 0.1$ for the write head and soft under layer. The distance between head to media and media to soft under layer was 10 nm and 7 nm, respectively. The length of the trailing edge of the pole tip and the width of the pole tip is 75 nm and 115 nm, respectively (Fig. 3). Since the model consists of about 44378 nodes, 101477 elements and 81197 surface elements for interaction calculation, the macro spin assumption was used in order to save computational time. In the macro spin assumption the magnetization of each grain is assumed to be homogenous [5].
The magnetization process was observed for 9 ns. After that time the write head has passed two upper bits and has finally exit the media. The domain configuration of the media is observed during the write process. The head field changes its direction once during writing. When the field is applied, the soft magnetic region is reversed by the write field from the head. Then, the domain wall that is formed in the soft grains propagates into the hard phase.

Figure 4. Transient states during reversal of one hard magnetic islands are shown. The z-component of the magnetization is represented by the grey scale map. (a) For $A_{\text{int}} = 0.075 \, \text{pJ/m}$, the upper right bit can not be recorded. (b), successful writing with $A_{\text{int}} = 0.37 \, \text{pJ/m}$

Figure 4b shows the magnetization dynamics with $A_{\text{int}}$ is 0.37 pJ/m, which is 3.7 % of the intergrain exchange. Therefore in the case of weaker intergrain exchange coupling, a higher head field is required to write the bits. In the case of small intergrain exchange (Fig. 4a), we can see that bit writing fails. For larger exchange between the grains the upper right bit can be reversed (Fig. 4b). This writing process is similar to that of exchange spring media. The main difference between the exchange spring media and ion irradiated patterned media is the relative position of the hard magnet and soft magnet. In exchange spring media the soft
magnet is usually placed above the hard layer. If we assume that the lateral dimensions of the patterned element are larger than the domain wall width, the reversal occurs via domain wall motion. This enables us to use small $K_u$ materials. Hence, one can write with conventional perpendicular heads. Too strong intergrain exchange coupling may lead to the erasure of the adjacent tracks.

In the case of $A_{int} = 1.13$ pJ/m (high intergrain exchange, shown in Fig. 5b) the switching of the selected bit may induce reversal of neighbouring bits. Bits in the down track directions as well as in cross track direction may be reversed. Figure 5a shows one other type of adjacent track erasure which was observed in the intermediate intergrain exchange regime ($A_{int}$ is 0.75 pJ/m). During the first 3 ns the head field points in the +z direction. At 4 ns, when the head field already points in $-z$ direction, the magnetization of the upper right bit and its surroundings are reversed. It is very interesting to note that 3 ns later, at 7 ns, one can see that the lower left bit has reversed its magnetization. This reversal is initiated by the head field which changed its direction from $-z$ to $+z$. When the head field on the upper right bit is switched, the magnetization of the media is reversed. The soft magnet reverses earlier and the hard magnet a bit later. The reversal process excites magnetic fluctuations in the soft magnetic region. Due to the fluctuation induced by the head reversal the lower left bit reverses.
conclusion, fully integrated micromagnetics simulations were performed to simulate a polycrystalline magnetic recording layer with varying intergrain exchange. The right choice of the intergrain exchange is crucial for patterned media. A too low value leads to undesired high switching fields and lead to a reduction of the thermal stability. A too large value will induce adjacent track erasure and will reduce the signal to noise ratio. Our preliminary studies suggest an optimal value around 0.37 pJ/m. The adjacent bit / track erasure of $A_{\text{int}} = 1.13$ J/m is shown in Fig 3.

3. Track interaction of the write process of bit patterned perpendicular media

Recording simulations on bit patterned media were performed using a standard single pole head with trailing shield. The islands were of ellipsoidal shape with a length of 30 nm and a width of 7.5 nm. The centre to centre spacing was 8.98 nm. The switching field of the island is around 1 T with a minimum at a field angle of about 40 degree. The island thickness was 3 nm, the air bearing surface (ABS) to media spacing was 3 nm and the ABS to soft underlayer (SUL) spacing was 8 nm. These dimensions correspond to design point 2 of reference [2] and lead to a recording density of 2 Tbit/in$^2$. For this head media combination we calculated the maximum write margins including magnetostatic effects (interactions between the dots and head-media-head interactions). The multiscale nature of the simulation project becomes clear by looking at the write head and the patterned elements simultaneously (Figure 6).

![Figure 6. Write head and magnetic elements for bit patterned recording. The images shows a blow-up of the region below the pole tip of the head.](image)

To compute the write margins we were running the simulations several times with different initial positions of the head. To avoid any effects from the head dynamics we first computed the remanent state of the head, then cycled the head several times and finally performed the recording simulations. With a data rate of 2 GHz the head velocity used in the simulations was 17.96 m/s. From the results we conclude that the non-uniform magnetization reversal of the dots and the magnetostatic interactions between the dots narrow the write margin. Most of the dots are multi-domain for an extended time period before they reach their final magnetic state (up or down). Figure 7 shows the successful writing of bits in the centre track in an array of 3 x 12 magnetic islands.
Figure 7. Successful writing on bit patterned magnetic recording media. Magnetization reversal of the island occurs by the nucleation of an reversed domain and successive domain wall motion. The shaded area denotes the position of the pole tip of head.

Figure 8. If the initial position of the write head is moved write failures may occur because write head and bit position are far from optimal synchronization.

The write margin was found to be 1.75 ± 0.25 nm. This corresponds to 19 percent of the centre to centre spacing of the dots. Moving the head out of phase by more than 1.75 nm leads to bit errors. Bit errors especially are found for bits where the stray field from the neighbouring track is high (see Figure 8).

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References

List of publications on micromagnetics in peer-reviewed journals in 2007:


