Micromagnetic Modeling of Writing and Reading Processes in Magnetic Recording

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Outline

- Overview of magnetic recording process
- Overview of technology development of magnetic recording
- Computational micromagnetics
- Micromagnetic writing process
- Micromagnetic reading process
- Future work
Head Structure

Figure 2. MR and GMR head structures.

From IBM Web
Recording Process

Figure 9
(a) Longitudinal magnetic recording. (b) Type 1 perpendicular recording, using a probe head and a soft underlayer in the medium. (c) Type 2 perpendicular recording, using a ring head and no soft underlayer.

Technology Development of Magnetic Recording at Seagate

- AMR (anisotropic magnetoresistance) heads, 1-3Gb/in², 1997.
- Regular GMR (giant magnetoresistance) heads, 5Gb/in², 1998.
- Synthetic anti-ferromagnetic (SAF) biased GMR heads, 6Gb/in² and beyond, since 1998.
- Perpendicular recording, may achieve areal density of 500Gb/in² – 1000Gb/in². Seagate demonstrated 60Gb/in² last year.
- Thermal assisting magnetic recording, proposed by Seagate Research.
Scaling Laws for Magnetic Recording*

- If the magnetic properties of the materials are constant, the magnetic field configuration and magnitudes remained unchanged even if all dimensions are scaled by the factor $s$ (for example $s=1/2$), so long as any electrical currents are scaled by the factor $s$. Areal density of recording system increases by $(1/s)^2$ after the scaling.

<table>
<thead>
<tr>
<th>Density (Gb/in$^2$)</th>
<th>Sensor width (um)</th>
<th>Sensing layer thickness (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.8</td>
<td>80</td>
</tr>
<tr>
<td>20</td>
<td>0.4</td>
<td>40</td>
</tr>
<tr>
<td>80</td>
<td>0.2</td>
<td>20</td>
</tr>
</tbody>
</table>

- Difficulties with the linear scaling law
  - Super-paramagnetic limit: media grain size is too small such that it is thermally unstable.
  - Current density must then scale as $1/s$, temperature in the head increases.
  - Sensing layer gets too thin.
  - Head-to-media separation is too small.

Use uniform rectangular discretizations for both media and reader stack. Magnetization $\mathbf{M}$ is uniform in each cell.

Magnetization damping follows Landau-Lifshitz-Gilbert Equation

$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\lambda}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}})$$

$\gamma = $ the gyromagnetic ratio of the free electron spin

$\lambda = $ damping constant
Effective Magnetic Field

\[ H_{\text{eff}} = H_{\text{demag}}(M) + H_{\text{anisotropy}} + H_{\text{exchange}} + H_{\text{external}} \]

\[ H_{\text{demag}}(r_i) = \sum_j N(r_i - r_j)M(r_j) \]

\[ N(r_i - r_j) = (1 / \Delta V) \int n_j dS_j \int G(r_i - r_j)n_i dS_i \]

\[ H_{\text{exchange}} = (2A / Ms) \nabla^2 M, \text{ or in discretized form,} \]

\[ H_{\text{exchange}}(r_i) = (A / MsD^2) \sum_{j=nn} [M(r_j) - M(r_i)] \]

\[ H_{\text{anisotropy}} = (H_k / M_s)k(k \cdot M) \]

- \( H_{\text{demag}} \) is the volume averaged demag field within a cell.
- \( G \) is the scalar Green’s function. It is \( 1/r \) in free space. The integrals for demag tensor \( N \) can be carried out analytically for uniform rectangular cells in free space. The convolution of \( N \) and \( M \) can be calculated using FFT in this case.
Lindholm field is obtained by linear superposition of the approximate solution for an infinite permeability, finite gap wedge. [IEEE Trans. Magn., Vol.13, 1460(1977).]
M-H loop of Perpendicular Media

- Saturation field increases when the exchange constant $A$ decreases.
- Nucleation field decreases when $A$ decreases.

Media anisotropy easy axis is oriented within 15° cone to the perpendicular direction.

- $M_s=350\text{emu/cm}^3$, $H_k=15\text{kOe}$, grain size=7nm, media thickness=25nm.

Exchange coupling $h_e=2A/(H_k M_s d^2)=0.23, 0.078, 0.00078$
Functions of Micromagnetic Recording Model

- Writing Model
  - M-H loop
  - Media magnetization profile
  - Media noise
  - Nonlinear transition shift

- Reading Model
  - Centered down track scan → pulse width, amplitude, symmetry
  - Multiple down track scan → track averaged amplitude profile or cross-track profile
Cross-track and Down-track Profiles

Media magnetization (perpendicular component)

2D read-back signal (collection of down-track waveforms)

Cross-track profile (averaged peak-to-peak amplitude vs cross-track position)

Comment: The cross-track profile is called a micro-track profile if the written track width is much smaller than the reader width.
GMR read sensor

- Shields are behind and in front of the stack, separated by gaps.
- \[ V=I\times R\times [1-0.5\times GMR\times \cos(\theta_{\text{free}}-\theta_{\text{reference}})] \]
Each media grain is divided into $I_g \times J_g$ ($=2 \times 2$ in the picture) cells. The media cell has the same size as the sensor cell in the cross-track direction. The media cell size in the down-track direction is usually equal to that in the cross-track direction.
Media Field: Calculation Method

- The media field is a convolution of the media-to-sensor demag tensor and the media magnetization.
- The media-to-sensor demag tensor is given by

\[ N(r_i, r_j') = \frac{1}{\Delta V} \int n_j dS_j' \int G(r_i, r_j') n_i dS_i \]

- \( G \) is the Green’s function in the shielded environment. It can be solved by the method of separation of variables and it can be expressed in terms of Fourier series expansions and Fourier integral.
- The demag tensor can be applied to arbitrary media magnetization distribution, with or without soft underlayer.
**Media Field: Green’s Function**

\[ \nabla^2 G(r, r') = -4\pi\delta(r - r') \]

\[ G(r, r') = \sum_{n=1}^{\infty} \int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y \int_{-\infty}^{\infty} dk_z \left[ A_n(k_x, r') \exp(-\kappa_n y) + B_n(k_x, r') \exp(\kappa_n y) \right] \]

\[ \times \exp(ik_x x + ik_z z), \quad y > 0, \]

\[ G(r, r') = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y \int_{-\infty}^{\infty} dk_z \left[ C_n(k_x, r') \exp(-\kappa_n y) + D_n(k_x, r') \exp(\kappa_n y) \right] \]

\[ \times \exp(ik_x x + ik_z z), \quad y < 0, \]

\[ G(r, r') = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y \int_{-\infty}^{\infty} dk_z \left[ E_n(k_x, r') \exp(-\kappa_n y) + F_n(k_x, r') \exp(\kappa_n y) \right] \]

\[ \times \exp(ik_x x + ik_z z), \quad y < y_{SUL}, \]

\[ G(r, r') = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y \int_{-\infty}^{\infty} dk_z \left[ G_n(k_x, r') \exp(\kappa y) \right] \]

\[ \times \exp(ik_x x + ik_z z), \quad y < y_{SUL}. \]

- \(x, y, z\) are coordinates normalized by \(G_s\).
- The coefficients \(A_n, B_n, C_n, D_n,\) and \(F_n\) can be derived by satisfying all interface boundary conditions and the boundary condition of \(G = 0\) at \(y = 0\) and \(x < 0\) and \(x > 1\).
Calculation of Self-demagnetization field

- Similar as the way to calculate the media field, the only difference is the Green's function.
- Results are very close to that obtained using the method of imaging. [Lei Wang et al., J. Appl. Phys., Vol.89, 7006(2001).]
- Shown on the left is the demag field in a stack of three magnetic films.
The TGMR stack is: PtMn 150A/CoFe 44A/Ru 9A/CoFe 35A/AlO 7A/NiFe 40A

W=H=1um
Magnetization Profile in Free Layer
Transfer Curves of Normal GMR Heads with PM stabilization

From 15Gb/in² to 100Gb/in², dR improves but amplitude does not improve mainly because of current constraint.
Random Telegraph Noise in GMR head

Transfer curve has a small open loop near zero or constant field.

Free layer magnetization jumps between two states spontaneously due to thermal energy.

Experimental data courtesy of J.X. Shen of Seagate
Thermal energy is large enough to overcome the energy barrier.

According to thermodynamics, the probability for the particle to jump from $E=E_1$ to $E=E_2$ is $\exp(-\frac{(E_2-E_1)}{kT})$.

Noise figures are generated by the Metropolis algorithm.
Micromagnetics with Thermal Effect

- Thermal effect is included by adding a stochastic fluctuation field to the effective magnetic field at each time interval during the integration of the LLG equation.

- The direction of the fluctuation field is 3D randomly, and its magnitude for each component is Gaussian distributed with standard deviation given by the fluctuation-dissipation theory:

\[ \sigma = \sqrt{\frac{2kT\alpha}{\gamma VM_s \Delta t}} \]

Where \( k \) is Boltzmann constant, \( T \) is temperature, \( V \) is the volume of the discretization cell, and \( \Delta t \) is the time step.
Two Possible Magnetic States from Micromagnetics

Upper branch

Lower branch

With elevated temperature of 200 degree C.
Future Work

- Finite temperature micromagnetics
- Micromagnetics with irregular meshing/grains
- Magneto-elastic interactions and magnetostriction
- Micromagnetics for large magnetic body (for example, shields)