Overview

- Systems with inhomogeneous anisotropy (ECM, graded media) show promise for high-density recording.
- Usefulness depends critically on stability: spontaneous switching rate \( \propto f_0 e^{-E_b/k_BT} \)
- Barrier \( E_b \) is easy to calculate; pre-factor (“attempt frequency”) \( f_0 \) is not -- can’t simulate 10^20 picoseconds.

W. F. Brown (1963) used Kramers’ (1940) method to calculate rate for a coherent (single-macrospin) grain:

\[
\text{rate} = \alpha \gamma H_c \left( \frac{E_b}{\pi k_B T} \right)^{1/2} e^{-E_b/k_BT}
\]

Kramers’ method works only for 1D systems

Coercivity \( H_c \) = anisotropy field \( H_k \)

- We have developed a method to map an arbitrary domain-wall-switched system into a 1D random walk and apply Kramers’ method.
- Result for a graded medium is surprisingly similar to Brown’s:

\[
\text{rate} = \alpha \gamma H_c \left( \frac{E_b}{\pi k_B T} \right)^{1/2} \left( \frac{W}{C^{1/2}} \right) e^{-E_b/k_BT}
\]

\( W = \text{width}/\text{grain length} \)

\( C = \text{curvature} \) \( \frac{d^2E}{dm^2} \)

- New factors are of order unity -- involve domain wall width \( W \) and the barrier curvature \( C \).
- Conclusion: Previous concern that domain-wall switching leads to very high prefactors (high instability) is not warranted.

Parameters used: \( L = 10 \text{ nm}, M_s = 1000 \text{ kA/m}, K(x) = (x/L)^2 K_{\text{max}}, K_{\text{max}} = 6 \times 10^9 \text{ J/m}^3 \) (“FePt”), exchange \( A = 10^{-11} \text{ J/m} \).

Why are exchange-coupled media important?

- Increasing data density while preserving stability requires high anisotropy \( H_K \)
- The resulting high coercivity (if \( H_c > H_k \)) makes it hard to write
- We can make \( H_c << H_k \) (of hard end) with inhomogeneous anisotropy (coupled hard & soft regions, or continuously varying \( H_k \)).
- Graded media promise lowest coercivity for a given barrier height
- But we need to know stability!

Mapping to 1D system

The domain wall position is essentially determined by the total easy-axis moment \( m_x \). We can get an equation of motion for this single variable by integrating the Landau-Lifshitz equation over the grain:

\[
dm_x / dt = \mu(m_x)(H_x - H_{aniso}(m_x)) + (dm_x / dt)_{\text{micromag}}
\]

Here \( H_{aniso} \) is an internal (exchange+anisotropy) field, which can be written in terms of cell magnetizations \( M \), and computed in a micromagnetic simulation. The mobility \( \mu(m_x) \approx \alpha \gamma M \frac{\sin^2 E_b/k_BT}{M} \), where \( W \) is an effective domain wall width (in units of grain length \( L \)), also computable by simulation.

We begin the simulation at negative saturation,

\( \mu(0) \approx \frac{\alpha \gamma M}{2} \), with an initial flux density \( B(0) \approx 10^{-8} \text{ Tesla} \).

We could simulate this 1D equivalent system much faster than the actual micromagnetic system, of course, but it is still impractical for realistic barriers. However, we can get a good estimate using Kramers’ method for the switching rate of a 1D system using a Fokker-Planck equation for the probability distribution \( p(m_x), dp(m_x)/dt = -dp(m_x) \), where the probability current is

\[
\text{rate} = \frac{\rho(m_x) e^{-E_b/k_BT}}{C^{1/2}} = \frac{\rho(m_x) e^{-E_b/k_BT}}{C^{1/2}}
\]

The rate involves two integrals: one is easy,

\[
\int [1 + \exp(E_b/k_BT)] \, dm_x \approx \exp(E_b/k_BT) \int dm_x \exp(E_b/k_BT)
\]

and the other is

\[
\int \exp(-E_b/k_BT) \, dm_x \approx \exp(-E_b/k_BT) \int \exp(-E_b/k_BT)
\]

If the stability factor \( E_b/k_BT \) is large, only the \( \int \) term near the maximum will be important, and this is a Gaussian integral. In terms of the curvature

\[
C = \frac{d^2E}{dm^2}, \text{ the result is } \pi k_B T \frac{1}{E_b C^{1/2}}
\]

Putting this together into the rate, we get the expression in the overview at the far left:

\[
\text{rate} = \frac{\alpha \gamma H_c}{\pi k_B T} \left( \frac{W}{C^{1/2}} \right) e^{-E_b/k_BT}
\]

We have taken the diffusivity \( D \) to be constant in the integrals because it depends weakly on \( m_x \). It is proportional to the dimensionless domain wall width \( W \).