Domain wall switching with a gradient of perpendicular anisotropy

Pieter Visscher, Zhihong Lu, and W. H. Butler

Department of Physics and Astronomy
The University of Alabama

This project was funded by NSF-DMR 0213985.

Summary

We formulate a one-dimensional model of a perpendicular-media grain in which we can prove a theoretical limit: varying the anisotropy profile can reduce the coercivity by at most a factor of 4, compared to a Stoner-Wohlfarth (uniform-M) particle with the same energy barrier, $M_s$, and length. We demonstrate an anisotropy profile that essentially achieves this limit.
Background: Beyond coherent switching

**Exchange spring media (ESM)**

- Basic concept (Victora et al)
- Simple 2-layer model
- Multiple layers (Suess et al)
- Continuum limit: continuously varying anisotropy $K(z)$

One grain of a two-layer exchange coupled medium switching by domain wall motion (figure borrowed from Dieter Suess)
Energy landscape

Describe energy landscape by $E(m_z)$ (constrained minimum energy per unit area at external field $H=0$, allowing $M(z)$ to vary arbitrarily except that $m_z \equiv \int_0^L M_z(z)dz$ is constrained.

WHY?
Tells everything about the quasistatic behavior. The external field $\mu_0 H$ necessary to hold a value of $m_z$ is the slope $dE/dm_z$ at that value.

Proof:
Energy at fixed $m_z$ and fixed nonzero external $H$ is $E(m_z,H) = E(m_z,H=0) - \mu_0 m_z H$, and $E$ is flat at the chosen point.
As we increase $H$ from zero, when it reaches the initial slope $m_z$ starts to increase. After it reaches the inflection point, $H >$ slope so it switches suddenly.
Discrete model

\[
E = \sum_{i=1}^{N} aK_i \sin^2 \theta_i + \sum_{i=1}^{N-1} a \frac{A_i}{a^2} \cos(\theta_{i+1} - \theta_i) - \sum_{i=1}^{N} a \mu_0 M_i H \cos \theta_i
\]

Computer program minimizes E with respect to all variables \( \theta_i \) while holding \( m_z \) constant.
Example: Stoner-Wohlfarth particle (limit as exchange $A \rightarrow \infty$)

Coherent reversal of uniaxial grain

\[ E = K \sin^2 \theta \]

Zeeman energy

\[ -\mu_0 HM_z \]

Smaller slope

E including Zeeman

\[ E = K(1 - M_z^2/M_s^2) \]

Slope $\frac{\partial E}{\partial M_z} = \mu_0 H$ is the field necessary to increase $M_z$
System with small exchange \((A << KL^2)\)

Switches by domain wall motion. Use thin-wall approximation

Assume:
- uniform system
- infinite system (or DW far from ends)

then
- can calculate magnetization profile \(\theta(z)\) exactly
- DW energy = \(4 \sqrt{AK}\)
- width = \((A/K)^{1/2}\)

Slope at top is zero: no field necessary to move domain wall.
Theorem I

For fixed energy barrier (per unit area) and fixed total magnetic moment per unit area $M_s L$, the smallest possible coercivity is $\frac{1}{4}$ of that of a Stoner-Wohlfarth (infinite-exchange, coherently switching) particle.

Caveats

If we allow arbitrarily long grains, we can make the coercivity as low as we want.
How close can we get to this theoretical limit?

In the thin-wall approximation, $E \sim (AK)^{1/2}$, so $E \sim z$ requires $K(z) \sim z^2$ (Suess, 2006). Numerical computation of $E$ (no thin-wall approximation) gives:
Measuring $K(z)$ experimentally

If $K(z)$ increases faster than $z^2$, $E(m_z)$ will increase faster than linearly, so domain wall will be stable:

Thus $E(m_z)$ is the integral of $H(m_z)$, the hysteresis loop: indirectly, we can extract $K(z)$ from the hysteresis loop, wherever it is increasing fast enough.
Conclusions

• The $E(m_z)$ energy plot is a very useful way to view switching -- it allows us to view coherent and domain-wall switching on the same basis.

• We have derived a theoretical limit on the coercivity improvement achievable by domain-wall switching: $\frac{1}{4}$ of a suitably defined Stoner-Wohlfarth value.

• This limit can be approached very closely.
THE END