Magnetic Domain-Wall Racetrack Memory

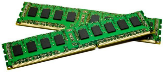
David Boelke, Edilbert Christhuraj, Jan-Christopher Cohrs,
Niklas Herff, Stefan Jeske, Paul Luckner

Aachen, June 9, 2017

Introduction

Actually two widely used techniques to store information:

- HDD (hard disc drives) is slower
- RAM (random access memory) is much more expensive



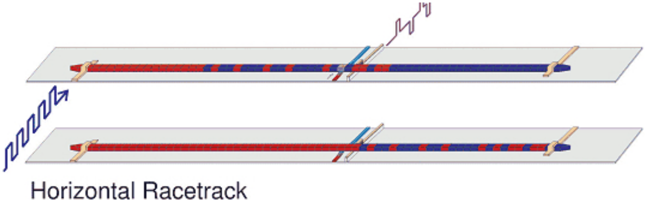
$\rightarrow$ the aspiration is a new type of memory which combinates both positive parts

Introduction

new approach: *"racetrack memory"*

$\rightarrow$ consists of a ferromagnetic nanowire

(reading and writing by fixed elements)

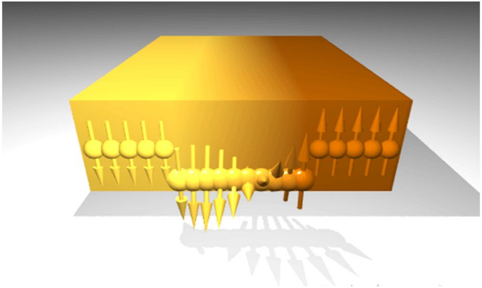


Introduction

In the nanowire:

- electrons with spins
- align along an external magnetic field
- system of spins with same alignment form = ”domain”
- ”domain-wall between two opposite domains

Bloch wall



Mathematical description

The configuration of the spins $\vec{\mathbf{m}}$ is described by the Landau-Lifshitz equation

$$\frac{\partial \vec{\mathbf{m}}}{\partial t} = -\vec{\mathbf{m}} \times H - \alpha \vec{\mathbf{m}} \times \vec{\mathbf{m}} \times H. \tag{1}$$

To obtain the quantity of interest $\vec{\mathbf{m}}$ we have to solve equation (1). Solving (1) is equivalent to minimizing the energy functional given by

$$E_{LL}[\vec{\mathbf{m}}] = E_a[\vec{\mathbf{m}}] + E_e[\vec{\mathbf{m}}] + E_s[\vec{\mathbf{m}}] + E_z[\vec{\mathbf{m}}]. \tag{2}$$

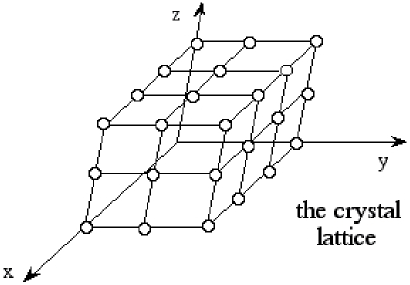
The H denotes the variational derivative of E_{LL}.

Mathematical description - Anisotropy Energy

The structure of the crystalline lattice initiates a preferred orientation for the spins, which is given by the equation

$$E_a[\vec{\mathbf{m}}] = \frac{K_u}{M_s^2} \int_\Omega \left(m_2^2 + m_3^2\right) d\mathbf{x} \tag{3}$$

with K_u - material parameter and M_s - constant length of the vector field $\vec{\mathbf{m}}$.



Mathematical description - Exchange Energy

- Includes the special characteristic of a ferromagnetic material
- Spin experiences an exchange field by the spins directly next to it
- Spin alignment in the same direction

It is described by the equation

$$E_e[\vec{\mathbf{m}}] = \frac{C_{ex}}{M_s^2} \int_\Omega |\nabla \vec{\mathbf{m}}|^2 d\mathbf{x} \tag{4}$$

The C_{ex} is the exchange constant.

Mathematical description - Zeeman Energy

This energy is the effect of an external field $\mathbf{H}_e$ applied such that the spins tend to align with it

$$E_Z[\vec{\mathbf{m}}] = -\mu_0 \int_\Omega \mathbf{H}_e \cdot \vec{\mathbf{m}} d\mathbf{x}. \tag{5}$$

Mathematical description - Stray Field Energy

The stray field energy is given by

$$E_s[\vec{\mathbf{m}}] = \frac{\mu_0}{2} \int_\Omega \vec{\mathbf{m}} \cdot \nabla U d\mathbf{x}, \tag{6}$$

- Magnetic permeability of vacuum $\mu_0 = 4\pi \cdot 10^{-7} N/A^2$.

$$\nabla^2 U = \begin{cases} \nabla \cdot M, & \text{in } \Omega \\ 0, & \text{else} \end{cases}$$

- Magnetostatic potential

$$U(\mathbf{x}) = \int_\Omega \nabla N(\mathbf{x} - \mathbf{y}) \cdot \vec{\mathbf{m}}(\mathbf{y}) d\mathbf{y} \tag{7}$$

In the formulation of U, N is the Newtonian potential

$$N(\mathbf{x}) = -\frac{1}{4\pi} \frac{1}{|\mathbf{x}|}. \tag{8}$$

Strategy

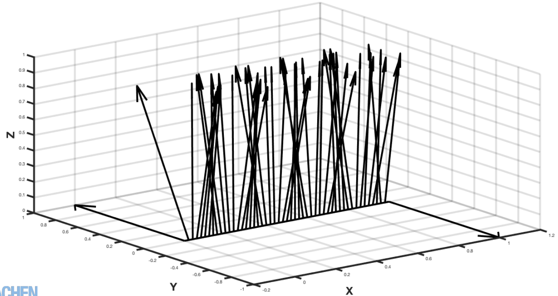
To minimize the energy it was suggested to use a fixed-point iteration

$$\vec{\mathbf{m}}^{n+1} = \frac{h^n}{|h^n|}.$$

h is the derivative of the energy functional.

$$\mathbf{h} = -q(m_2\mathbf{e}_2 + m_3\mathbf{e}_3) + \epsilon\nabla^2\vec{\mathbf{m}}_i - \nabla U + \mathbf{H}_e.$$

this lead to oscillations, so we damped the itteration and came up with a different method

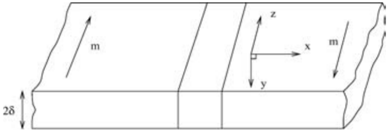


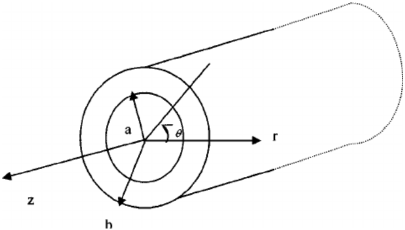
$$\vec{\mathbf{m}}^{n+1} = \frac{\vec{\mathbf{m}}^{n} + \Delta t h^{n}}{\left|\vec{\mathbf{m}}^{n} + \Delta t h^{n}\right|}.$$

Reduced Model for Stray Energy

Goal: From 3D to 1D

Potential: $U(x) = \nabla \cdot (N * M)(x)$ over Ω
Ansatz: $M(x) = M(x_1)$





Individual Energies

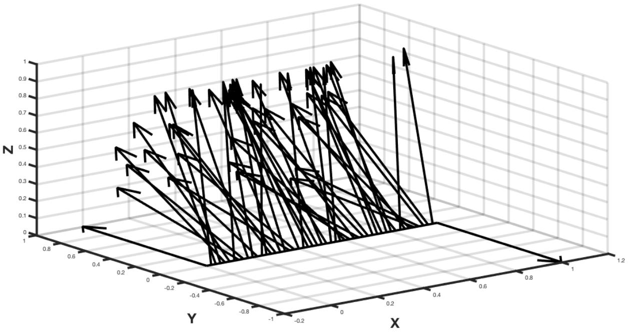
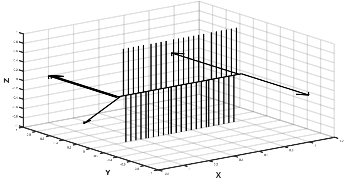
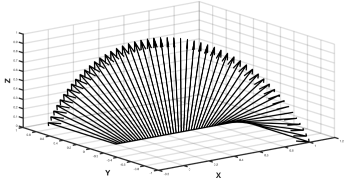


Figure: Randomly initialized magnetization vectors with fixed BC

Individual Energies



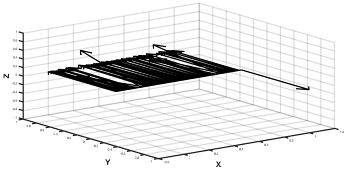
: Anisotropic Energy



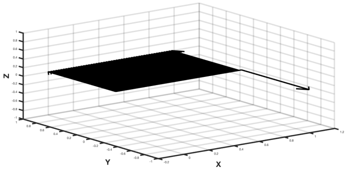
: Exchange Energy

$$E_a[\vec{\mathbf{m}}] = \frac{K_u}{M_s^2} \int_\Omega \left(m_1^2 + m_2^2\right) \mathrm{d}\mathbf{x} \qquad E_e[\vec{\mathbf{m}}] = \frac{C_{ex}}{M_s^2} \int_\Omega |\nabla \vec{\mathbf{m}}|^2 \, \mathrm{d}\mathbf{x}$$

Individual Energies



: Stray Energy

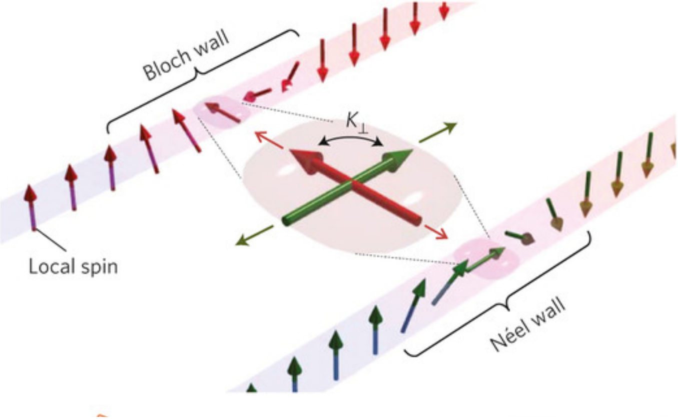


: Zeeman Energy

$$E_s[\vec{\mathbf{m}}] = \frac{\mu_0}{2} \int_\Omega \vec{\mathbf{m}} \cdot \nabla U \,\mathrm{d}\mathbf{x}$$

$$E_Z[\vec{\mathbf{m}}] = -\mu_0 \int_\Omega \mathbf{H}_e \cdot \vec{\mathbf{m}} \,\mathrm{d}\mathbf{x}$$

Neel and Bloch Domain Walls



Neel and Bloch Domain Walls

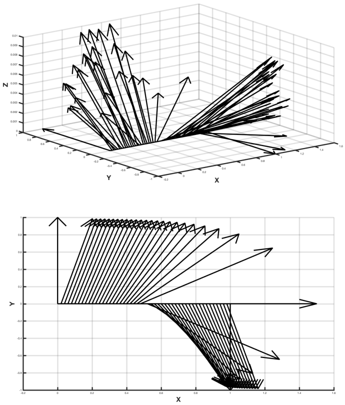


Figure: Initial Conditions

Neel and Bloch Domain Walls

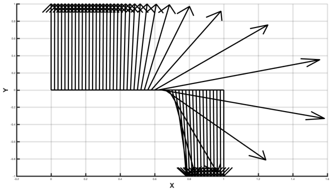


Figure: Neel wall

- Different initial conditions were used
- Neel type wall profile is approximated for both cases

Neel and Bloch Domain Walls

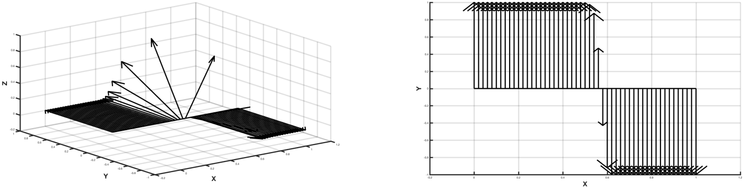


Figure: Bloch Wall

- Usage of a different initial condition
- Bloch type wall profile is approximated

What we did

- Importance of memory storage
- A new fixed point scheme to calculate the magnetization of a nanowire that minimizes the energy functional.
- Influence of the different kinds of energy on spin configuration
- Visualized qualitatively Blooch and Neel Walls.
- More reliable $\rightarrow$ Leads to expected results.

But...

- Only the steady state equation.

Next course of action

- Solution for the dynamic case
- Develop a strategy to control and to move domain walls
- Applying external magnetic field or external current
- Determine critical values
- Crucial to maintain the external fields below the critical value
- Exceeding $\rightarrow$ loss of information.