MICROMAGNETIC SIMULATIONS AND APPLICATIONS

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1 Introduction

The thermal stability of magnetic media and magnetic storage elements becomes important with decreasing size of the magnetic structures [1]. The calculation of the thermal stability requires the estimation of transition rates between stable equilibrium states of the magnet. The calculation of transition rates needs a detailed characterization of the energy landscape along the most probable path which is taken by the system from its initial state to a final state. The energy landscapes of micromagnetic systems drastically depends on the microstructure of the magnet and may contain many local minima. Using the finite element method it is possible to represent complex geometries and grain structures. The combination of the finite element method and an algorithm for finding the minimum energy path provides a tool to calculate the energy barriers in large scale micromagnetic systems.

2 Numerical Methods

The following numerical methods are used for the simulation of magnetic elements:

- MCS/Patran to create the finite element mesh
- software package VODPK to perform a time integration
- finite element program library DIFFPACK
- hybrid FE/BE method for the open boundary problem
- Treecode for the long range magnetostatic interaction
- hierarchic matrices for speeding up the FE/BE method
- AVS for visualization of the results

The simulations (especially large models) were carried out partly on the following servers of the computational center of TU-Vienna (*ZID*): sc.zserv, fe.zserv, cfd.zserv and fpr.zserv.

3 Applications

3.1 ENERGY BARRIERS IN MAGNETIC RANDOM ACCESS MEMORY ELEMENTS

Minimum energy paths and energy barriers are calculated for the free data layer in MRAM (magnetic random access memory) elements using a recently developed method [2] which combines the CINEB method [3] (climbing image nudged elastic band method) with finite element micromagnetics. The method calculates the magnetic states along the most probable reversal paths for applied fields below the zero temperature switching field.

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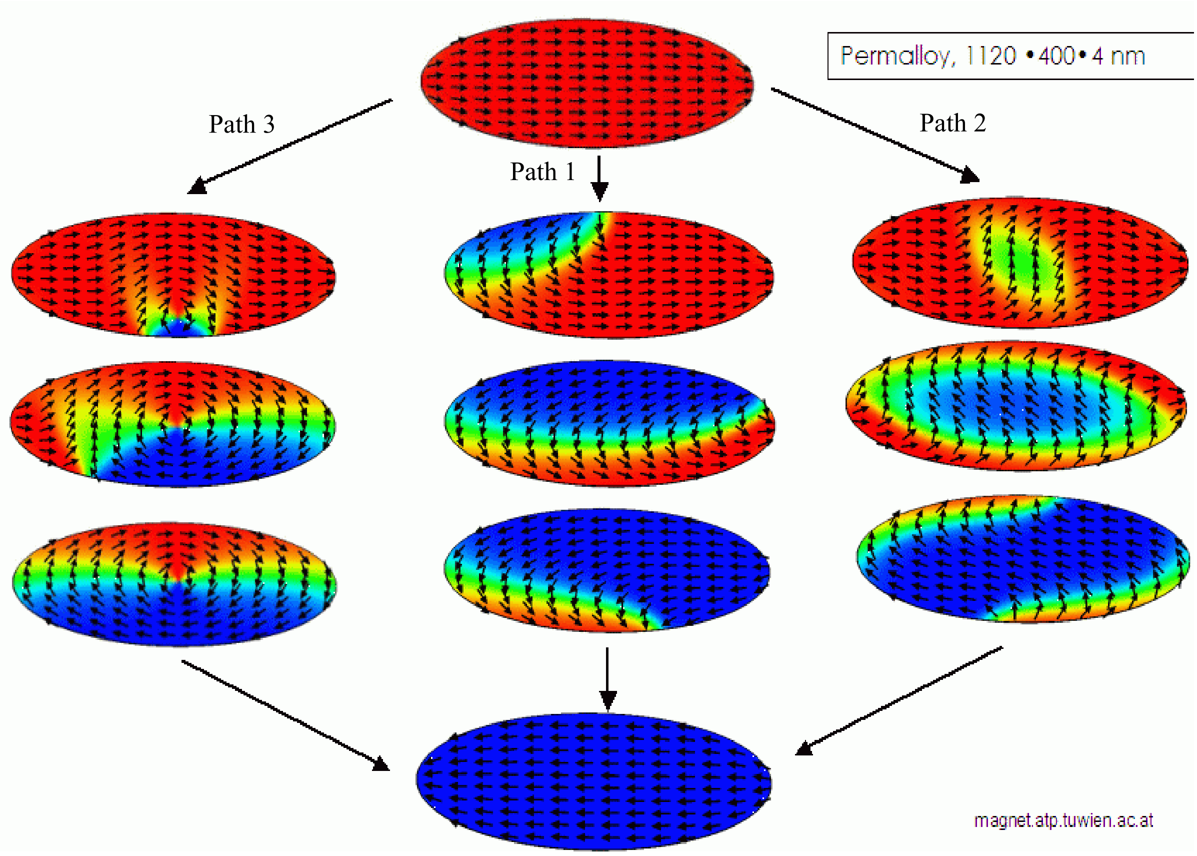

Figure 1. Three Minimum energy paths for the thermal reversal of a thin NiFeCo MRAM element are found between the two stable states. In Paths 1 and 2 the magnetization stays in plane crossing a single barrier. In path 3 a two step reversal mode is found passing a metastable state (vortex in the center).

The predicted transition rates are compared with an experimental work [4], which studies the thermal reversal of elliptical NiFeCo MRAM elements. Fig. 1 shows a top view of the 3D finite element model of the free layer. The long axis is 1120 nm, the diameter 400 nm and the thickness 4 nm. The material parameters of NiFeCo were used (Js=1.068 T, A=10 pJ/m, K=5.1 10^2 J/m3) with the easy axis along the long axis of the element. The minimum energy paths (MEP) were calculated as a function of a external field along the easy axis of an strength below the zero temperature switching field (= 90 Oe).

The results show three possible minimum energy paths. Two of them shows a single energy barrier where the magnetization reverses by an inhomogeneous rotation in the film plane (path1 and path2 in figure 1). The third mode is a two step reversal process which passes a metastable state where a vortex is in the center (path3 in figure1). At zero field this two step reversal by vortex motion has smaller energy barriers than the in plane process. With increasing field however, the in plane mode becomes energetically favorable. This is in agreement to the single energy barrier behavior of the observed relaxation times in the experiment.

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3.2 FAST BOUNDARY METHODS FOR MAGNETOSTATIC INTERACTIONS IN MICROMAGNETICS

Micromagnetic simulations of realistic magnetic devices require the calculation of the magnetostatic interactions between distinct magnetic parts. Hybrid finite element/boundary element (FE/BE) algorithms as originally proposed by Fredkin and Koehler are very efficient, since they require no mesh between the particles [5]. In addition the FE/BE discretization allows arbitrarily shaped structures. However the BE part of this algorithm leads to a fully populated matrix of size N^2, where N is the number of boundary nodes. As a consequence storage and CPU-time scale with N^2, which causes performance problems in structures with high aspect ratio where most nodes are on the boundary. To overcome this problem various techniques to accelerate the BE method have been proposed. In this work we compared (1) a treecode-method as used for particle simulations [6], (2) hierarchical matrices or so called supermatrices [7], and (3) the fully populated boundary element matrix.

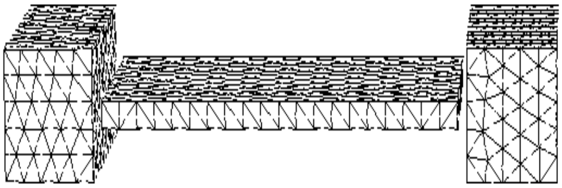

Figure 2. Surface mesh with 996 boundary nodes.

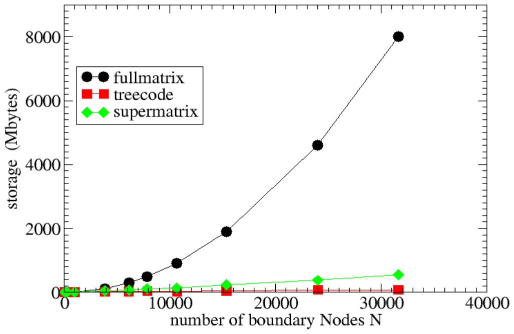

Figure 3. Storage requirements dependent on the number of boundary nodes.

The different methods are tested for a soft magnetic film stabilized by two permanent magnets. Fig. 2 gives an example of a surface mesh. The CPU-time for the setup-phase, the CPU-time for the matrix vector multiplication and the required storage are compared as a function of the number of boundary nodes. Therefore the same structure is remeshed with grids of different element size. Fig. 3 gives the memory requirement for the different methods. CPU-time tests with the full matrix method are only possible for $N < 10000$, because of the N^2-dependence and the limited memory in our workstation. We found that both, the treecode and the supermatrix approach, drastically reduce the CPU-time of the setup-phase as compared to the N^2-dependence of the full matrix method. Finally we evaluated the required CPU-time for 1000 matrix vector multiplications according to (3). Even for a small problem size, $N=10000$, the supermatrix method reduces the CPU-time by a factor of 10 as compared to the multiplication of the full matrix. With increasing problem size the speedup becomes more significant. The treecode scales with $N \times \log(N)$. The high amount of bookkeeping increases the CPU-time for matrix vector multiplications for small problems. Because of the N^2-dependence the full matrix method is not suitable for large systems. Due to the very short setup-phase the treecode method is recommended for moving parts, for example recording simulations using a fully discretized head. The supermatrix is faster in the matrix vector multiplication. So it is the method of choice for the solution of the Landau-Lifshitz-equation on a fixed grid.

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