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# Micromagnetic simulation of hysteresis curves for Permalloy based thin films

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A computer micromagnetic simulator, based on Stonner-Wolfarth model, was used to obtain the magnetization curves and the magnetoresistive response for Permalloy ($Ni_{80}Fe_{20}$) based thin films and magnetic multilayers. The films were divided into small elements, single magnetic domains, which interact between them and with the applied magnetic field. The dimensions and the distances between elements are inspired from the films microstructure. The results of computer simulations are compared with the magnetic measurements made with a Vibrating Sample Magnetometer and the agreement concerning the shape of the hysteresis loops, coercive field and the ratio between the remanent to saturation magnetization is very good for films with the magnetic layer thinner than 100 nm. The data are very sensitive on the right choice of the parameters used for simulation.

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## 1. Introduction

Various technological applications, like magnetic read heads, magnetic memories or microcompass sensors, are explored by phenomena like anisotropic magnetoresistance effect (AMR) and giant magnetoresistance effect (GMR), that magnetic thin films and magnetic multilayers are exhibiting. These effects are related with the magnetic and structural properties of the magnetic films. The magnetic properties of the investigated structures were studied using a vibrating sample magnetometer (VSM) and by the measurements of magnetoresistive (MR) and Hall effect behaviours. In order to simplify the designing process of magnetic sensors and to get a better understanding of the processes that take place in the films when a magnetic field is applied, we used a computer micromagnetic simulator based on Stonner-Wolfarth model. The program, developed by Dr. John Oti [1], calculates the interaction between the single-domains elements and the applied magnetic field. The element's magnetic properties, such as magnetization, anisotropy, pinning fields, must be specified or selected from a library of materials. However, the results of the simulation, using a single domain structure, give data which are far from the VSM measurements even in the case of very thin films [2]. This is because the lateral dimensions (length and width) of the real structures, like magnetic sensors, are large enough to create a multi-domain configuration. Our goal was to find a better approach in using of this program in order to improve the quality of the micromagnetic simulations. For this reason, we used complex structures that consist from a number of single-domains which interact between them through magnetostatic and exchange couplings and can be subject of some pinning fields. The direction and the amplitude of the applied magnetic field are also defined.

## 2. Results and discussion

In what follows, we present the results of our micromagnetic simulations made for (i), NiFe(100 nm), (ii) NiFe(10 nm) films and (iii) NiFe(10 nm)/Cu(4 nm)/NiFe(10 nm) magnetic multilayered structure. Films with the same structures were also deposited by means of high vacuum thermal evaporation onto oxidised Si substrates. We made in-plane magnetic measurements with VSM, MR and planar Hall effects (PHE) as well in order to get a complete characterization of the magnetic properties for the investigated structures.

### 2.1. Micromagnetic simulations for NiFe(100 nm)

To perform the micromagnetic simulations we have take in account the film microstructure. The AFM measurements made on the NiFe(100 nm) film, reveal a surface with an average roughness of about 12.8 nm. The average grain size is about 1 μm [2]. From both VSM and MR measurements we obtained a coercive field, $H_C$, between 2 and 4 Oe. The ratio between the remanent to saturated value of the magnetization, $M_R/M_S$, is about 0.33. The shape of the hysteresis loop can be identified as curling reversal type in which the magnetization is known to form full or partial flux closure states [3]. To perform the simulations the film plane was divided into square elements with two values for the side length: 100 nm and 900 nm. These elements are assumed to be single-domains despite their large dimensions. The thickness of the elements was 100 nm. For simulations we used a structure of 12×12 single-domains. We present, in Fig. 1a, the

simulations results for a structure of 12×12 single-domains, 100 nm each side and 100 nm thick placed in the same plane. The magnetic field was applied in the film plane. We set three values for the distance, *d*, between each domain in the film plane: 0, 10 and 20 nm. As we can see the hysteresis curves are distorted. The curve for *d*= 0 was not presented. The strong coupling between the domains requires a magnetic field greater than 1000 Oe to saturate the film which is unrealistic. Because the single-domains are cubic in shape, the magnetization vectors are not fixed in the film plane and, for low magnetic fields, can rotate under a perpendicular direction to the film plane in order to achieve the minimum energy state and giving the shape of the hysteresis loops presented in Fig. 1(a). The coercive fields are $H_C$=120-170 Oe for *d*=10 nm and $H_C$=50-60 Oe for *d*=20 nm respectively. If the size of the square elements is now fixed to 900 nm, which was inspired from the AFM measurements, the shape anisotropy will keep the magnetization vectors in the film plane. The results of our simulations are shown in Figure 1(b), for *d*=0, 100 and 200 nm. Because of the crystalline discontinuity at the grain boundary, the inter-grain interaction will be lower than the intra-grain interaction. The result is a decreased exchange field at the grain boundary which in turn lowers the switching field. So, this crystalline discontinuity supports the idea of single-domains indentation at a given value *d*. The values of the obtained coercive fields are summarized in Fig. 1.

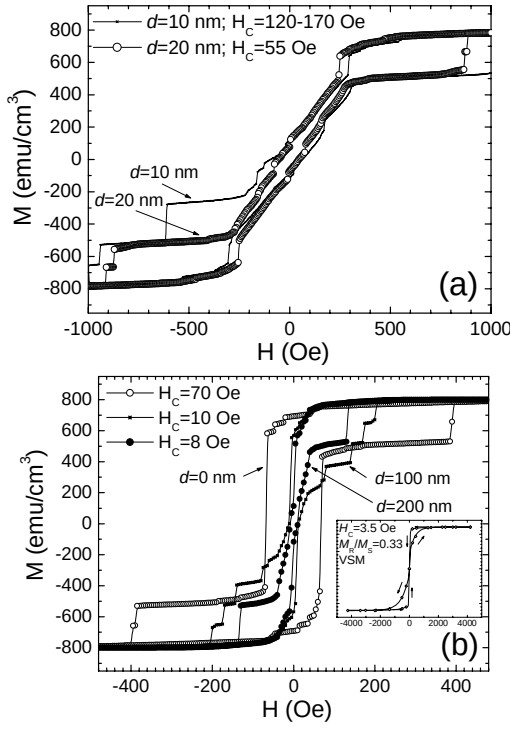


*Fig. 1. The simulated hysteresis loops for a structure of 12x12 single-domains of Permalloy, (a) 100 nm each side and (b) 900 nm each side and 100 nm thick. The magnetic field is applied in the film plane. We present, in inset, the measured hysteresis loop for a NiFe(100 nm) film.*

As we can see, for thick magnetic films (100 nm), the simulation gives only a qualitative result. The coercive field resulting from this simulation is $H_C$=8-10 Oe which is greater than the measured value that is about 3 Oe. Also, there is a difference between the experimental and calculated values for the ratio between the remanent to saturated magnetization, $M_R/M_S$. We have from simulations $M_R/M_S$=0.73 and 0.16 for *d*=100 and 200 nm respectively. For thick films, like in this case, the domain walls play a major role in the magnetization reversal process.

### 2.2. Micromagnetic simulations for NiFe(10 nm)

When the magnetic films are thinner than 100 nm, the magnetization reversal mechanism is mainly due to rotation of the magnetic moments. This is the case of the NiFe(10 nm) film. For micromagnetic simulation, the film plane was divided into 12x12 square elements with a side length of 90 nm and a thickness of 10 nm. For evaporated thin films, the effective thickness tends to be smaller than the measured one because of the discontinuous microstructure. So, the film thickness is smaller than the characteristic length of 13 nm for Permalloy [4, 5] and justifies the assumption that our elements can be considered to be single-domains. Because of the high value of the demagnetizing factor under the perpendicular direction to the film plane, we can assume a two-dimensional variation of the magnetization directions. The simulation of the magnetization curve gives the same shape for the hysteresis loops like in Fig. 1(b), for different values of the inter-grain spacing, *d*; $H_C$=60, 15, 10 and 8 Oe for *d*=0, 5, 10 and 20 nm respectively. The agreement between the experimental data and simulation is very good when we assume in the simulation an inter-grain spacing of 5 nm. In this region the material can be considerate to be non-magnetic. Fig. 2 shows the orientation of the magnetic moments, obtained by micromagnetic simulation for a 10 nm Permalloy film, at *H*=0 and for the coercive field, $H_C$=-15 Oe when the magnetic field is swept from +1000 Oe to -1000 Oe. The inter-grain spacing is *d*=5 nm. The results show a nucleation of the reversed domains at the pattern edge, Fig. 2(a), followed by lateral motion of the domain walls until the occurrence of the closure domains, Fig. 2(b), which minimize the energy of the thin film at the coercive field. The nucleation process starts at about 200 Oe when the magnetic field goes to zero from the saturated state.

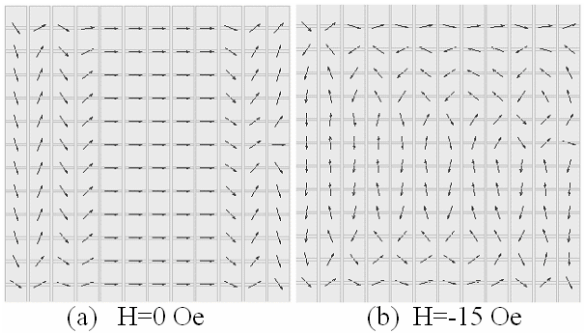


*Fig. 2. The orientation of the magnetic moments for a 10 nm Permalloy thin film when (a) H = 0 and (b) H=-$H_C$. The inter-grain spacing is d=5 nm.*

### 2.3. Micromagnetic simulations for NiFe(10 nm)/Cu(4 nm)/NiFe(10 nm)

To simulate the hysteresis loop for a multilayer structure (ML) we must consider the coupling between the ferromagnetic layers through the nonmagnetic layer. The structure NiFe(10 nm)/Cu(4 nm)/NiFe(10 nm) deposited by thermal evaporation presents a hysteresis loop with a coercive field $H_C$=60 Oe and a remanent to saturation magnetization ratio $M_R/M_S$=0.32 [2]. This loop shows a positive coupling between the magnetic layers which is typical for evaporated multilayered structures. To simulate the magnetization curve we used two ferromagnetic layers each consisting in a collection of 12×12 single-domains of NiFe. Each single domain is 10 nm thick and 90 nm each side. The distance between the adjacent domains is $d$=5 nm like in the previous simulation. The model was inspired from the film microstructure. The distance between this two ferromagnetic layers is set to be equal with the real interlayer thickness, $t_{Cu}$=4 nm. The coupling constant $J$, for $t_{Cu}$>1.5-2 nm, is well described by the Néel model for positive magnetostatic interlayer coupling [6]:

$$J = \frac{\pi^2}{\sqrt{2}} \frac{h^2}{\lambda} \mu_0 M_S^2 \exp\left( \frac{-2\pi\sqrt{2} t_{Cu}}{\lambda} \right) \qquad (1)$$

$M_S$ is the saturation magnetization ($M_S$=800 kA/m or 800 emu/cm$^3$ in CGS). Here $\lambda$ is determined by the grain size and $h$ by the film roughness [6]. From AFM measurements we have $h$=1.35 nm and $\lambda$=15 nm. The interlayer coupling is $J$=0.23 mJ/m$^2$ and the resulting coupling field is $H_0$=2457 A/m (31 Oe). Because of the NiFe bridges that exists trough the spacer the coupling may have local variations that exceed 31 Oe [6]. Between the top and the bottom layers we introduced coupling fields that have random values from 30 to 60 Oe. The hysteresis curve obtained from the micromagnetic simulation using these parameters is shown in Fig. 3(a). The data is normalized to the saturation magnetization. The agreement with the VSM measurement is very good both for $M_R/M_S$ ratio and for the value of the coercive field which is $H_C$=50 Oe. On the same figure we present the results of AMR and GMR calculations, in arbitrary units, in order to see the correlation with the film magnetization. The real amplitude of the GMR effect is very small because both magnetic layers are free and the coupling is a positive one. The magnetization of a magnetic layer can be fixed through exchange interaction biasing using an antiferromagnetic layer of $Fe_{50}Mn_{50}$ which produces a pinning field of about 200 Oe. The structure become FeMn/NiFe(10 nm)/Cu(4 nm)/NiFe(10 nm). We can see in Fig. 3(b) the existence of two magnetization curves and states with antiparallel magnetizations, due to pinning field. The amplitude of the GMR effect is larger for structures with the pinned layer. We introduced an offset in GMR representation in order to avoid overlaps between M and GMR loops. The correlations between the M and GMR curves are also revealed.

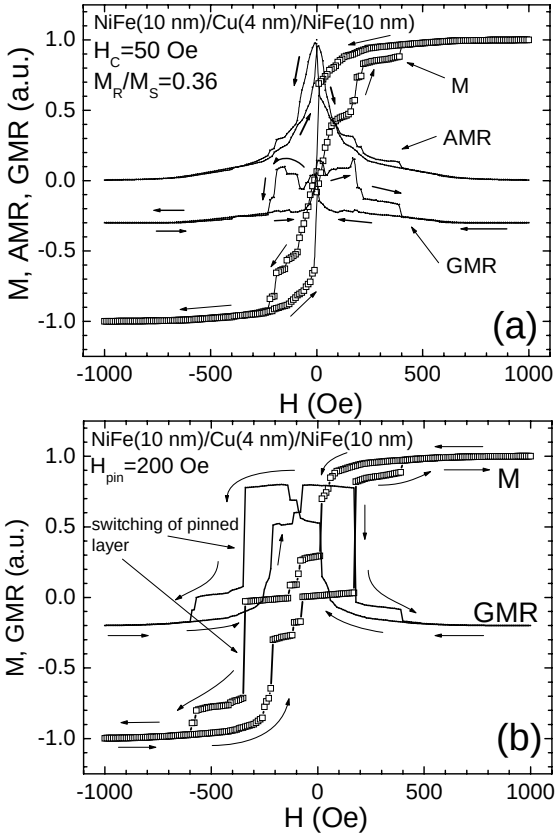


*Fig. 3. The results of the micromagnetic simulation for a Si/$SiO_2$/NiFe(10 nm)/Cu(4 nm)/NiFe(10 nm) system. On the same plot are presented (a) the hysteresis loop and the magnetic-field dependencies of the AMR and GMR effects. The effect of the pinning layer is presented in (b). The arrows are guides for the eyes.*

## 3. Conclusions

We have presented in this paper some results concerning the simulation of the magnetization curves in thin films using a micromagnetic simulator. The data are very sensitive on the right choice of the parameters used for simulation. For magnetic films thinner than 10 nm the

agreement between micromagnetic simulation and the experimental results is very good. With the same simulator we can, also, estimate the behaviour of the magnetoresistance effect in the investigated structures.

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