Magnetic Nanostructure Hysteresis Loop Calculation for Modified Thin Film Multi-layer by Ion Irradiation

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Abstract—The nonlinear dependence of magnetization on direction of the applied magnetic field and history is described by statistical domain behavior using phenomenological adaptive parameters (like: g [1], h [A/m], k [J/m^3], and q that are related to anisotropy, saturation field, static hysteresis loss, and pinning site density). The loop simulation data could be used also as parameters for thermal stability equation to calculate the relaxation time of the stored information on any magnetic nano particles (dots) of patterned magnetic media.

1. Introduction

Magnetic nanostructures are subjects of growing interest because of their potential applications in high density magnetic recording media and their original magnetic properties [1]. Multilayer thin films (like Co/Pt) are well known for their high magnetic anisotropy, and the origin of this high magnetic anisotropy has been the subject of interest for many researchers [2]. Demands for the continuous increase in the data storage density bring the challenge to overcome physical limits for currently used magnetic recording media [3]. Patterned magnetic media could be a way of realizing ultra high density storage media. Recently, demonstrations of areal recording density over 60 Gb/in^2 in both longitudinal and perpendicular magnetic recordings have been successfully made [4]. Determining the properties of small magnetic structures is extremely important for the development of data storage devices [5]. Better understanding of the micromagnetic processes in magnetic recording media is essential for developing novel materials for future ultrahigh density recording [6]. Good understanding of the noise mechanism in magnetic recording is required for developing heads and media for future applications [7].

In perpendicular recording, the magnetization pattern corresponding to the bits is provided perpendicular to the plane of the medium. The information is being stored in vertical domains or other structures of uniform magnetization [8]. The magnetic properties of an ultra thin multilayer can be patterned by controlled ion beam irradiation [9]. The basic step in this technique is to control the changes in the magnetic properties induced by the irradiation process.

In magnetic materials two characteristic length scales have to be considered [10]:

- at the atomic level, nearest neighbour exchange interaction is dominating,
- at a mesoscopic level, the domain wall width is the characteristic length dominating the magnetization reversal.

When the physical dimensions of a system become comparable to the interatomic spacing, strong modifications of the intrinsic magnetic properties (ordering temperature, magnetic anisotropy, spontaneous magnetization) are expected.

Micromagnetic modeling of the behavior of a nanostructured film beautifully describes the magnetization process, but requires a high calculational effort and long computation times. Furthermore, it is difficult to predict changes of the macroscopic physical behaviour due to variation of parameters. Phenomenological models, on the other hand, are very useful to simulate the behaviour of the magnetic material under the influence of varying parameters, especially when the parameters are based on physical constants.

2. Experiments

An assembly of ferromagnetic amorphous nanoparticles has been prepared by heavy ions irradiation of paramagnetic YCo_2 thin films [11, 12]. Several irradiation experiments carried out on YCo_2 samples have shown that fluences on the order 10^{12} U ions/cm^2 causes changes in magnetic properties of the samples [12]. Important changes are reported to take place after the irradiation:

- change of spontaneous magnetization, coercivity and initial susceptibility [12], and
- a distinct change of the anisotropy perpendicular to the film plane [11].

3. Energetic Model

The magnetic behaviour of magnetic moments is mainly described by the well known equations of Schrödinger (exchange interaction) and Landau, Lifshitz, and Gilbert (dynamics of magnetization reversal). Above this fundament is the shell of the physical constants describing spontaneous magnetization, anisotropy, magnetostriction, etc. The energetic model (EM) is designed as an interface between this shell and the macroscopic hysteresis phenomenon, able to predict many magnetic properties due to the relation of the parameters with the physical constants. The EM has been applied for different magnetization processes and materials [13–17].

The hysteresis of the magnetization M depending on the applied field H is described by the following equations, with the spontaneous magnetization M_s, the geometrical demagnetizing factor N_d, and the following phenomenological parameters:

1. g [1] related to anisotropy, reversible processes;
2. h [A/m] related to saturation field H_s, reversible processes;
3. k [J/m^3] related to static hysteresis loss, irreversible processes;
4. q [1] related to pinning site density, irreversible processes.

In the cases of large domains, the microscopic constant c_r describes the influence of reversal speed. The sgn(x) function provides the correct four quadrant calculation (with the related magnetization $m = M/M_s$):

$$H = H_d + \mathrm{sgn}(m)H_R + \mathrm{sgn}(m - m_o)H_I\,. \tag{1}$$

The first term of Eq. (1) describes linear material behaviour, using the demagnetizing field

$$H_d = -N_d M_s m\,, \tag{2}$$

the second term represents non-linear behaviour using the reversible field

$$H_R = h\Big[\big((1+m)^{1+m}(1-m)^{1-m}\big)^{g/2} - 1\Big]\,, \tag{3}$$

including saturation at a field $H_s(M_s)$, and the third term describes hysteresis effects like initial susceptibility χ_0, remanence M_r, coercivity H_c, static losses, and accomodation, using the irreversible field

$$H_I = \left(\frac{k}{\mu_0 M_s} + c_r H_R\right)\left[1 - \kappa\exp\left(-\frac{q}{\kappa}\left|m - m_o\right|\right)\right]. \tag{4}$$

For the initial magnetization, beginning with $M = 0$, $H = 0$, we set $m_o = 0$ and $\kappa = 1$. The function κ describes the influence of the total magnetic state at points of magnetization reversal. Therefore, κ (previous value κ_o) depends on the unit magnetization reversals $s = |m - m_o|$ up to this point of field reversal (m_o is the starting value of m at the last field reversal) with the simplification $e^{-q} \ll 1$:

$$\kappa = 2 - \kappa_o \exp\left[-\frac{q}{\kappa_o}\left|m - m_o\right|\right]. \tag{5}$$

The calculation always starts with the initial magnetization curve and m is increased stepwise (the stepwidth determines the desired resolution of the calculation), which gives the corresponding field by Eq. (1). At a point of field reversal κ is calculated by Eq. (5) and m_o is set to the actual value of m at this point. Then m is decreased stepwise until the next reversal point, etc.

3.1. Identification

The identification of the EM with measurements or data sheets can be done easily. At given M_s and N_d the parameters are directly calculated from special points of the hysteresis loop. Considering reference conditions, the index 0 is to indicate that the identification is done at a temperature $T = T_0$ without applied mechanical stress σ, using the following equations:

$$k_0 = \mu_0 M_s H_c \tag{6}$$

$$q_0 = \frac{M_s}{H_c}\frac{1 - N_d\chi_0}{\chi_0} \tag{7}$$

If χ_0 is not available one can also use the total static losses $w_l = \int_{-M_s}^{+M_s} H\mathrm{d}M + \int_{+M_s}^{-M_s} H\mathrm{d}M$ corresponding to the area of the closed major loop (upper and lower branch of hysteresis)

$$w_l = 4k\left(1 - \frac{2}{q}\right) \tag{8}$$

and we can write the equation for q_0 as

$$q_0 = \frac{8\mu_0 M_s H_c}{4\mu_0 M_s H_c - w_l}\,. \tag{9}$$

These relations allow even an estimation of M_s (at $c_r \approx 0$), using Eqs. (6), (7), and (9) to

$$M_s = \frac{2\chi_0 H_c}{1 - N_d \chi_0} + \frac{w_l}{4\mu_0 H_c}\,. \tag{10}$$

Furthermore, q_0 can also be determined by the reduced remanence m_r of the upper branch of a loop with the measured reduced maximum magnetization m_m. Using f_q as a factor related to m_r,

$$f_q = \left[(1+m_r)^{1+m_r}(1-M_r)^{1-m_r}\right]^{g_0/2} - 1\,, \tag{11}$$

we identify q_0 as

$$q_0 = \frac{2}{m_m - m_r}\ln\frac{2H_c}{H_c - h_0 f_q + N_d M_s m_r} \tag{12}$$

By using f_g as a factor related to m_g which is the reduced magnetization at $H = H_g$, in the knee of the lower branch of the hysteresis,

$$f_g = \frac{1}{\ln\sqrt{(1+m_g)^{1+m_g}(1-m_g)^{1-m_g}} - \ln 2}\,, \tag{13}$$

hence g_0 is

$$g_0 = f_g \ln\frac{H_g - H_c - N_d M_s m_g}{H_s - H_c - N_d M_s} \tag{14}$$

Using f_c as a factor related to m_r and m_m,

$$f_c = 1 - 2\exp\left[q_0\frac{m_r - m_m}{2}\right], \tag{15}$$

the microscopic constant describing the domain (grain) geometry ratio becomes

$$c_r = \frac{f_q \frac{H_s - H_c - N_d M_s}{M_s \exp g_0 \ln 2} - f_c \frac{H_c}{M_s} + N_d m_r}{\left(f_q \frac{H_s - H_c - N_d M_s}{M_s \exp g_0 \ln 2} + f_c \frac{H_c}{M_s}\right) - N_d m_r} \tag{16}$$

Finally, the identification equation of h_0 is

$$h_0 = \frac{H_s - H_c - N_d M_s}{(c_r + 1)(\exp[g_0 \ln 2] - 1)} \tag{17}$$

If H_s is not available, one can estimate H_s from the measured maximum field H_m at m_m using the approximation $H_s \gg H_c + N_d M_s$. Using f_h as a factor related to m_g and m_m

$$f_h = \frac{\ln\sqrt{(1+m_m)^{1+m_m}(1-m_m)^{1-m_m}} - \ln 2}{\ln\sqrt{\frac{(1+m_g)^{1+m_g}(1-m_g)^{1-m_g}}{(1+m_m)^{1+m_m}(1-m_m)^{1-m_m}}}} \tag{18}$$

we find

$$H_s = (H_m - H_c - N_d M_s m_m)\left(\frac{H_m - H_c - N_d M_s m_m}{H_g - H_c - N_d M_s m_g}\right)^{f_h}\,. \tag{19}$$

If N_d of the experimental arrangement is unknown then it can be estimated roughly by the differential susceptibility χ_c at coercivity of a measured hysteresis loop:

$$N_d \approx \left.\frac{1}{\chi_c}\right|_{H=H_c}\,. \tag{20}$$

If N_d of the sample is rather large so that the magnetization curve is strongly sheared ($M_r N_d > H_c$), then it can be necessary to identify g_0 and c_r by the backsheared curve ($N_d = 0$).

3.2. Calculation

The calculations have been done as following: At a given $N_d = 0.47$, the parameters $g_0 = 5.24$, $h_0 = 2.79\,\mathrm{kA/m}$, $k_0 = 1.10\,\mathrm{kJ/m^3}$, and $q_0 = 8.79$ are identified for the perpendicular hysteresis at $\Phi = 5\cdot 10^{12}\,\mathrm{ions/cm^2}$ with $M_s = 20\,\mathrm{kA/m}$. In the next step we vary only M_s in order to calculate the hysteresis of the other irradiation cases. Using Eqs. (6) and (7), we find the dependencies

$$H_c = \frac{k_0}{\mu_0 M_s} \tag{21}$$

and

$$\chi_0 = \frac{\mu_0 M_s^2}{k_0 q_0 + \mu_0 M_s^2 N_d} \tag{22}$$

which strongly affects the shape of the hysteresis Curve.

4. Conclusions

The rapid development of magnetic recording leads to a large increase of the bit density. Multilayer thin films with a perpendicular magnetic anisotropy devices may play an active role in the development and establishment of future storage technologies. Patterning magnetic media is a potential solution for ultrahigh density magnetic recording [18]. Ion beam modification of magnetic layers may be the possible future of ultra high density magnetic recording media.

After ion irradiation of YCo_2 thin films with different fluence values, the measured magnetizazion curves clearly show a perpendicular aniyotropy [11]. The shape of the hysteresis loops depends strongly on M_s, which is predicted by the EM. It turns out that H_c is inversely proportional to M_s and χ_0 is proportional to M_s^2, if N_d is neglected. As the EM parameters are also related to anisotropy it will be possible also to calculate the direction dependence of these magnetization curves, which is subject to further work.

REFERENCES

1. Jamet, M., W. Wernsdorfer, C. Thirion, D. Mailly, V. Dupuis, P. Mélinon, and A. Pérez, *Phys. Rev. Lett.*, Vol. 86, 4676, 2001.
2. Yamada, Y., T. Suzuki, H. Kanazawa, and J. C. Osterman, *J. Appl. Phys.*, Vol. 85, 5094, 1999.
3. Lapicki, A., K. Kang, and T. Suzuki, *IEEE Trans. Magn.*, Vol. 38, 2589, 2002.
4. Papusoi, C. and T. Suzuki, *J. Magn. Magn. Mater.*, Vol. 240, 568, 2002.
5. Kirk, K. J., J. N. Chapman, and C. D. W. Wilkinson, *J. Appl. Phys.*, Vol. 85, 5237, 1999.
6. Kisker, H., N. Abarra, Y. Yamada, P. Glijer, and T. Suzuki, *J. Appl. Phys.*, Vol. 81, 3937, 1997.
7. Phillips, G. N., T. Suzuki, K. Takano, and M. Takahashi, *J. Magn. Magn. Mater.*, Vol. 193, 434, 1999.
8. Suzuki, T., *Magneto-Optic Recording Thin Films, in: I. M. H. Francombe (Ed.), Handbook of Thin Film Devices Magnetic, Vol. 4, Magnetic Thin Film Devices*, Academic Press, 2000.
9. Ferre, J., C. Chappert, H. Bernas, J.-P. Jamet, P. Meyer, O. Kaitasov, S. Lemerle, V. Mathet, F. Rousseaux, and H. Launois, *J. Magn. Magn. Mater.*, Vol. 198, 191, 1999.
10. Noziéres, J. P., M. Ghidini, N. M. Dempsey, B. Gervais, D. Givord, G. Suran, and J. M. D. Coey, *Nucl. Instr. and Meth. in Phys. Res. B*, Vol. 146, 250–259, 1998.
11. Givord, D., J. P. Noziéres, M. Ghidini, B. Gervais, and Y. Otani, *J. Magn. Magn. Mater.*, Vol. 148, 253–259, 1995.
12. Solzi, M., M. Ghidini, and G. Asti, *Magnetic Nanostructures*, Vol. 4, 123, 2002.
13. Hauser, H. and P. L. Fulmek, *J. Magn. Magn. Mater.*, Vol. 133, 32, 1994.
14. Fulmek, P. L. and H. Hauser, *J. Magn. Magn. Mater.*, Vol. 157, 361, 1996.
15. Hauser, H. and R. Grössinger, *J. Appl. Phys.*, Vol. 85, 5133, 1999.
16. Andrei, P., L. Stoleriu, and H. Hauser, *J. Appl. Phys.*, Vol. 87, 6555, 2000.
17. Grössinger, R., H. Hauser, M. Dahlgren, and J. Fidler, *Physica B*, Vol. 275, 248, 2000.
18. Devolder, T., C. Chappert, Y. Chen, E. Cambril, H. Launois, H. Bernas, J. Ferre, and J. P. Jamet, *J. Vac. Sci. Technol. B*, Vol. 17, 3177, 1999.