NANOSECOND REMAGNETIZATION OF MAGNETIC FILMS ACCOMPANIED BY MAGNETOSTATIC INTERACTION OF MAGNETIZATION INHOMOGENEITIES

1. PHYSICAL PREMISES AND CALCULATION PROCEDURE

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One factor which affects the nanosecond remagnetization of magnetic films is the presence of magnetization inhomogeneities. Attempts have been made to take into account the inhomogeneity associated with the scatter in the directions of the easy axes of various regions of the film [1, 2], but the agreement with experiment has been poor [3, 4]. In particular, agreement with experiment requires an implausibly large (15°) angular spread of easy axes [2].

Another source of magnetization inhomogeneities is the fine structure of the magnetization. It is very difficult to take this factor into account quantitatively, even in the static case [5], and it is impossible in the dynamic case without important simplifications.

Both qualitative [6] and quantitative [7] attempts have been made to analyze this problem by means of simplified models. In this paper we will develop one of these models by taking into account new factors, and we will analyze the behavior of a film under various remagnetization conditions and for various film parameters. In writing the equations and in choosing the numerical solutions we will strive for generality, so the results can be used to further refine the model.

To evaluate the components of the torque acting on each region of the fine structure (subdomains), we adopt a highly simple magnetization distribution. We assume that in the subdomains the magnetization deviates from the average magnetization direction by an angle $\pm\Delta\Theta$; $\Theta_{1,2} = \Theta \pm \Delta\Theta$, where $\Theta = (\Theta_1 + \Theta_2)/2$. Here the subscript 1 and the upper sign refer to the advanced regions, while index 2 and the lower sign refer to the retarded regions.

In its initial state, we assume the fine structure to be longitudinal ripple with boundaries running normal to the average magnetization direction. We assume as in [7] that during a remagnetization the angle β between subdomain boundaries and the hard axis can change. We neglect possible boundary displacement during nanosecond remagnetization (which lasts up to 10-15 nsec), and we neglect the change in the boundary energy.

We will use the following procedure to find the magnitude of the magnetostatic interaction among subdomains.

The magnetic charge density at a boundary is

$$M\,[\cos(\Theta_1-\beta)-\cos(\Theta_2-\beta)] = 2M\sin\left(\frac{\Theta_1+\Theta_2}{2}-\beta\right)\cdot\sin\frac{\Theta_1-\Theta_2}{2},$$

where M is the saturation magnetization of the film. The average field which this charge exerts on each subdomain is determined from the demagnetizing factor N.

For a uniformly magnetized band (or subdomain); N can be easily calculated by replacing the magnetization by the equivalent surface current and using the field calculated for a planar coil (see, e.g., [8]). After simplifications based on the thinness of the film, we find

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$$N = 4\pi - 8\left[\frac{1}{\Gamma}\ln(1+\Gamma^2) - \operatorname{arctg}\Gamma\right] \cong \frac{8}{\Gamma}(1 + 2\ln\Gamma), \qquad (1)$$

where $\Gamma = 2l/D$; l is the ripple wavelength; and D is the film thickness. The last of this equation holds for the case $\Gamma > 20$, as is usually true in films.

With $\Gamma = 20$, 40, and 80, N takes on values 2.8, 1.7, and 0.98, respectively.

The effect of the neighboring subdomains is taken into account, according to [2], by multiplying N by $\pi/4$.

The torque exerted by this field on the subdomain magnetization is

$$\pm\frac{\pi}{2}NM^2\sin\left(\frac{\theta_1+\theta_2}{2} - \beta\right)\cdot\sin\frac{\theta_1-\theta_2}{2}\cdot\sin(\theta_{1,2}-\beta).$$

A torque tending to oppose remagnetization is assumed positive.

For the dimensionless torque (i.e., the torque divided by $M \cdot H_K$, where H_K is the anisotropy field), the coefficient of the trigonometric function is $p = \pi MN/2H_K$. For typical films, having M = 800 G, H_K = 2-5 Oe, D = 0.05-0.2 μ, and l = 2-5 μ, p varies from 100 to 2000.

The concept of a ripple relaxation time τ_r, associated with the rate at which boundaries rotate, was introduced in [7] without a specific definition. This relaxation time can apparently be defined on the basis of a phenomenological equation for the viscous rotation of a boundary: $\dot\beta = (\Theta - \beta)/\tau_r$, where $\dot\beta$ is the time derivative of β. In [7], τ_r was determined to be 1.1 ± 0.2 nsec. However, this determination is not very reliable, and in analyzing the solutions we will vary τ_r over a broader range.

We can estimate the other terms of the ripple torque acting on a subdomain in the following manner: we assume that the film in its initial state is subjected to a constant field h_y along the hard axis. From the condition for a static equilibrium of the subdomain, we find the initial internal torque of the ripple to be

$$T_{01,2} = h_y\cos(\theta_0 \pm \Delta\theta_0) - \frac{1}{2}\sin 2(\theta_0 \pm \Delta\theta_0) \cong \mp(1 - h_y^2)\sin\Delta\theta_0, \qquad (2)$$

where Θ_0 and $\Delta\Theta_0$ are the initial values of Θ and $\Delta\Theta$. The last equation here takes into account the conditions $\Delta\Theta_0 \ll 1$ and $\sin\Theta_0 = h_y$.

We will calculate the remagnetization under the assumption that this torque remains constant during the remagnetization.

In nanosecond-remagnetization experiment, the film is placed between strips of a strip transmission line; in a first approximation these strips can be treated as infinite conducting planes. The eddy-current relaxation time in these strips is much longer than the nanosecond-remagnetization time ([9], p. 34), and the damping of eddy currents over the remagnetization time can be neglected. Then using $M_{av} = M\cos(\Theta_1 - \Theta_2)/2$ and $T_{d1,2} = \mp H_d M/H_K M \sin(\Theta_1 - \Theta_2)/2$ along with Eq. (55) of [11] for the dynamic demagnetizing field H_d, we find the torque exerted on the magnetization of each subdomain by the dynamic demagnetizing field:

$$T_{p1,2} = \mp C\sin(\theta_1 - \theta_2), \quad \text{where} \quad C = \frac{\pi MD}{H_K}\left(\frac{1}{d} + \frac{1}{2a}\right).$$

where d is the diameter of the circular film; and $2a$ is the "gap" of the strip line. As H_K is changed from 2 to 5 Oe, D from 0.05 to 0.2 μ, d from 0.5 to 1 cm, and $2a$ from 0.2 to 0.4 cm, the value of C for a flat film varies from 0.18 to 0.008.

Since the film is nonellipsoidal, the demagnetizing field at the periphery of the film is higher than the theoretical value. On the other hand, because of the finite width of the strip line, this field is lower. For this reason, C might either increase or decrease; for cylindrical films, we have C = 0.

The numerical value of the damping parameter λ, which is to be substituted into the dynamical equation, is extremely important. It was pointed out in [10] that for even a qualitative agreement between the Stein model [6] and experiment, λ must be several times greater than its value found from ferromagnetic-resonance experiments, $(1\text{-}2)\cdot 10^8$ sec^{-1}. However, analysis of experimental data [12] shows that during the initial stage of remagnetization the effective damping parameter, determined as in [4], is constant. This value (λ_{ini}) is (4-5) $\cdot 10^8$ sec^{-1} for films having a relatively low (~0.5) coercive force h_c and 2-4 times greater for films having $h_c \sim 1$. Without going into detail on the reasons for this large discrepancy between λ and λ_{ini}, we note that it is natural. Accordingly, λ_{ini} characterizes a transient, irreversible rotation of magnetization over quite large angles, while the parameter determined in linear ferromagnetic resonance corresponds to small oscillations in a specific steady-state cycle.

Uniform rotation is described in general by a two-dimensional equation [13], but for practical calculations we need take into account only the magnetization rotation in the plane of the film.

Taking these considerations into account, we see that we can calculate the motion of the subdomain magnetization by jointly solving the system

$$\ddot{\Theta}_{1,2} + 4\pi\lambda\dot{\Theta}_{1,2} + 4\pi M\gamma^2 H_K \Big[\sin\Theta_{1,2}\cdot\cos\Theta_{1,2} - h_x\sin\Theta_{1,2} - h_y\cos\Theta_{1,2}$$
$$\pm p\sin\left(\frac{\Theta_1+\Theta_2}{2}-\beta\right)\cdot\sin\frac{\Theta_1-\Theta_2}{2}\cdot\sin(\Theta_{1,2}-\beta) + T_{O1,2} \mp C\sin(\Theta_1-\Theta_2)\Big] = 0, \tag{3}$$
$$\dot{\beta} = \frac{1}{\tau_r}\left(\frac{\Theta_1+\Theta_2}{2}-\beta\right)$$

for various numerical values of the coefficients, for various initial values Θ_0 and $\Delta\Theta_0$, and for various time dependences of the fields h_x and h_y applied along the easy and hard directions, respectively. The first two equations of this three-equation system are symmetric and are written together.

The same system of equations, with $T_{01,2} = 0$, $p = 0$, h_x replaced by $h_x\cos\alpha \mp h_y\sin\alpha$ and h_y replaced by $h_y\cos\alpha \pm h_x\sin\alpha$, describes a film in which there is a spread in only the easy axes in various regions.

For brevity, we omit the six-equation system to be used to analyze the remagnetization for the case in which there is both ripple in the magnetization and a scatter in axes.

A detailed study of these equations requires the use of computers, in which connection the following circumstances must be taken into account: it would be incorrect to try to match the calculated and experimental remagnetization curves by means of a suitable choice of parameters, because of other retardation mechanisms, not taken into account in this model, the assumptions used in writing the equations, and other factors. The problem of analyzing the model consists of explaining how in principle an appreciable retardation remagnetization can be caused by the magnetostatic interaction of inhomogeneities and of relating this retardation to the shape of the average-magnetization trajectory. In addition, we can trace the effect of each of the film parameters (the thickness, the wavelength and initial amplitude of the ripple, the scatter in the easy axes, and the boundary relaxation time) on the course of the remagnetization under various conditions.

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