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# Effects of magnetic relaxation times on the shielding of a polarized electromagnetic pulse

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The shielding of a polarized electromagnetic pulse by a ferromagnetic thin film is calculated in the case where the magnetization is perpendicular to the incident field's polarization. The effects of anisotropy, domain interaction, saturation, hysteresis, and magnetization response time are considered. Results show that best shielding occurs when the response time of the ferromagnetic film is the inverse of the rise time of the pulse. At its optimum frequency, a ferromagnetic alloy shields better than a copper film of the same thickness.

## I. INTRODUCTION

In a previous paper,<sup>1</sup> hereafter referred to as I, we have considered the penetration of an electromagnetic pulse through a ferromagnetic conducting thin film in the case where the magnetization ( $M$ ) of the material had a characteristic relaxation time  $\tau$ . In I the magnetic state of the film was represented by an average magnetization parallel to the incident  $H$  field which follows an idealized  $M$ - $H$  curve (including saturation and hysteresis) with a time delay  $\tau$ . In this phenomenological theory, the response time of the magnetization represents the domain-wall mobility. Starting from Maxwell's equations, we derived a solution for the diffusion equation in terms of the magnetic field intensity ( $H$ ). An iterative routine was used to converge the  $H$  field internal to the film to its final value. We showed that  $\tau$  had a significant effect on the shielding factor and that a film with a relaxation time on the order of the rise time of the incident pulse shields best.

Extending the results of I to the case where the incident electromagnetic pulse (EMP) is polarized perpendicular to the film magnetization vastly increases the complexity of the problem. The initial effect of the incident  $H$  field is to cause the film magnetization to precess. The damping of the precession until the magnetization lies along the incident field plays the role of the relaxation time  $\tau$  of I. An additional factor is introduced by the uniaxial anisotropy which will try to restore the magnetization to its original equilibrium orientation after the pulse is past. Finally, the effect of demagnetization and the magnetostatic interaction between the individual domains must be accounted for.

In this paper we abandon the phenomenological  $M$ - $H$  behavior of I and model the interaction directly through the Gilbert equation of motion.<sup>2</sup> The response of the material is introduced through the Gilbert damping parameter  $\alpha$ . The effects of anisotropy, demagnetization, and magnetostatic interaction are included in constructing the free energy.<sup>3</sup> The resultant effective  $H$  field is found by taking the gradient of the free energy with respect to  $M$ . The diffusion equation is applied to this effective  $H$  field by subdividing the film into

layers of different magnetization. Maxwell's equations give the condition of the continuity of  $H$  across the boundaries.

## II. FORMULATION

We consider a linearly polarized field incident on a multidomain thin film as shown in Fig. 1. The  $H$  field is reduced to one component  $H_y$ , and  $M$  in the domains is oriented in the  $+z$  and  $-z$  directions. The free-energy equation is given by<sup>3</sup>

$$F = -H_y(y_1M_{1y} + y_2M_{2y}) + (K/M^2)[y_1(M_{1x}^2 + M_{1y}^2) + y_2(M_{2x}^2 + M_{2y}^2)] + \frac{1}{2}N_x(y_1M_{1x} + y_2M_{2x})^2 + \frac{1}{2}N_{xx}(y_1M_{1x} - y_2M_{2x})^2 + \frac{1}{2}N_{yy}(y_1M_{1y} - y_2M_{2y})^2. \quad (1)$$

The film demagnetization parameters are  $N_x = 4\pi$ ,  $N_y = N_z = 0$ ; the demagnetization factors of the individual domains are given by  $N_{zz} = 0$ ,  $N_{xx} = N_{yy} = 2\pi$ , and  $N_2 = (1 - y_1)$ .

The first term in the free-energy equation is the magnetization energy for the two domain regions. The second term is the uniaxial anisotropy energy, and the last three terms form the total demagnetizing energy. The last two terms in Eq. (1) follow since the domains have  $x$  and  $y$  dimensions much smaller than the  $z$  dimension.

The equation of motion with damping in the Gilbert form is<sup>2</sup>

$$\frac{1}{\gamma} \frac{d\mathbf{M}}{dt} = (\mathbf{M} \times \mathbf{H}) - \frac{\alpha}{\gamma M} \mathbf{M} \times \frac{d\mathbf{M}}{dt}. \quad (2)$$

Using the vector identity

$$\mathbf{M} \times (\mathbf{M} \times \mathbf{H}) = (\mathbf{M} \cdot \mathbf{H})\mathbf{M} - M^2\mathbf{H}, \quad (3)$$

we find

$$\frac{d\mathbf{M}}{dt} = \frac{\gamma}{1 + \alpha^2} \left( \frac{\alpha}{M_0} [(\mathbf{M} \cdot \mathbf{H})\mathbf{M} - M^2\mathbf{H}] + (\mathbf{M} \times \mathbf{H}) \right), \quad (4)$$

where  $\gamma$  equals  $ge/2mc$ , and  $\alpha$ , the Gilbert damping parameter, is defined from the Ferromagnetic resonance (FMR) linewidth equation as

$$\Delta H = 2(f/\gamma)\alpha. \quad (5)$$

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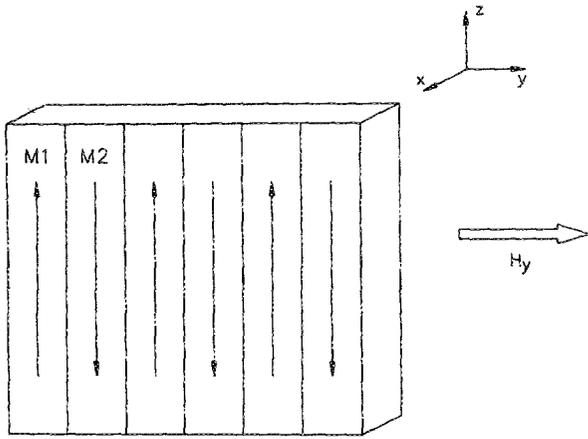


FIG. 1. Magnetic film considered in paper. The domains M1 and M2 are  $10\ \mu\text{m}$  wide and extend the entire thickness of the film. The EMP is incident in the  $x$  direction with the magnetic field polarized in the  $y$  direction.

$\Delta H$  is one-half the field full width at half maximum of the FMR absorption at frequency  $f$ . A typical value of  $\gamma$  is  $2.92\ \text{MHz/Oe}$  for metallic magnetic films<sup>4</sup> and  $\alpha$  is typically equal to 0.03. In this analysis, we will assume an  $\alpha$  varying from one decade below to one decade above the typical value of 0.03 ( $0.003 < \alpha < 0.3$ ).

The effective internal field, the sum of the fields in the domains, is obtained by calculating the negative gradient of the free energy  $F$ :

$$\mathbf{H} = \mathbf{H}_1 + \mathbf{H}_2 = -\nabla_1 F - \nabla_2 F,$$

$$\nabla_{1,2} = \frac{1}{M} \left( \frac{d}{d\alpha_x} \hat{a}_x + \frac{d}{d\alpha_y} \hat{a}_y + \frac{d}{d\alpha_z} \hat{a}_z \right)_{1,2}. \quad (6)$$

$\alpha_x$ ,  $\alpha_y$ , and  $\alpha_z$  are the directional cosines of  $M$  with respect to the  $x$ ,  $y$ , and  $z$  axes and  $\hat{a}_x$ ,  $\hat{a}_y$ , and  $\hat{a}_z$  are unit vectors in the  $x$ ,  $y$ , and  $z$  directions. The subscripts 1,2 outside the parentheses indicate the domain regions that are under consideration. When we derive the effective internal field for one domain, we get

$$H_{1x} = 2 \left[ -H_A M_{1x} / 2M_0 - N_x (M_{1x} + M_{2x}) / 4 - N_{xx} (M_{1x} - M_{2x}) / 4 \right],$$

$$H_{1y} = 2 \left[ -H_A M_{1y} / 2M_0 - N_y (M_{1y} + M_{2y}) / 4 - N_{yy} (M_{1y} - M_{2y}) / 4 + H_0 / 2 \right], \quad (7)$$

$$H_{1z} = 2 \left[ -N_z (M_{1z} + M_{2z}) / 4 \right],$$

where  $H_A = 2K/M_0$ ,  $M_0$  is the saturated magnetization value, and  $H_0$  is the driving (EMP) field. The internal effective field defined in Eq. (7) is a function of the anisotropy field and the magnetization in both domain regions as well as the driving EMP field. The net components of the magnetization in the  $x$  and  $z$  directions are zero when calculated over the two domains, and only the  $y$  component remains in the analysis.

### III. BOUNDARY CONDITIONS AND DIFFUSION EQUATION

From Maxwell's equations the boundary condition at the front surface is

$$H_0(0,t) - \frac{1}{\sigma Z_0} \frac{dH_0(0,t)}{dy} = 2H_i(0,t), \quad (8)$$

where  $H_i$  is the incident EMP field,  $H_0$  is the internal field, and  $Z_0$  is the impedance of free space. Since the conductivity of the film is large compared to the remaining parameters of the equation, the second term of the equation can be dropped, and the internal field at the front surface of the film becomes equal to twice the incident field. At the back surface of the film, a distance  $d$  away from the front, the equation of the field is as follows:

$$H_0[d,t - (d/v)] = H_t, \quad (9)$$

where  $H_0$  and  $H_t$  are the internal and transmitted field through the film back surface, and  $v$  is the wave velocity inside the film.

For purposes of calculation we subdivided the  $10\text{-}\mu\text{m}$  film thickness into five equally thick layers. Each layer consists of domains  $10\ \mu\text{m}$  wide in the  $y$  direction and of infinite length in the  $z$  direction. The driving field at the surface of the first layer is determined from the boundary conditions. We used the equation of motion and the negative gradient of the free-energy equation to calculate the average internal magnetization ( $M$ ) and magnetic field ( $H$ ). The average  $M$  and  $H$  values are taken to be those at the center of the layer  $1\ \mu\text{m}$  away from the front surface. We then used the diffusion equation to solve for the  $H$  field at the back surface of the layer:

$$\frac{d^2 H}{dz^2} = \sigma \frac{dB}{dt} = \mu_0 \sigma \frac{d(H+M)}{dt}. \quad (10)$$

To determine the propagation of the pulse into the next layer we set the total effective internal field (including the effects of anisotropy, demagnetization, and domain interaction) at the back of the first layer equal to the driving field in the Gilbert's equation of motion for the next layer. This procedure is repeated for each layer of the film thickness to calculate the amplitude of the  $H$  field attenuated in the film and the transmission through the back surface of the film.

The equation of motion method defines the instantaneous magnetization of the entire domain when the material is subject to a time-dependent magnetic field. The equation of motion does not include, however, the effects of magnetization hysteresis. In this analysis, the incident EMP is not only time dependent but carries significant amount of energy that forces the magnetization to saturate. The equation of motion method, therefore, must be generalized to include the effect of remanence field. Saturation is implicit in the equation of motion because the microscopic magnetization of each domain is always  $M_0$ , the saturation magnetization. Under the influence of the driving field and the Gilbert damping the microscopic magnetization of all the domains is shifted to the  $y$  direction at which point the macroscopic magnetization is also equal to  $M_0$ . Due to hysteresis, however, once the film is saturated in the  $y$  direction, the film will not recover its original magnetization direction when the driving field is removed. We have included the effect of hysteresis by adding a remanence magnetization  $M_r \hat{a}_y$  to the magnetization of each domain at all times after the film reaches saturation. The calculated magnetization is then

scaled so that the total magnetization (including the remanence) will not exceed  $M_0$ . When the EMP pulse passes, the magnetization relaxes toward the  $z$  direction under the influence of the anisotropy term in the free energy and the equation of motion. At each stage of the relaxation, after the magnetization is calculated it is rescaled and the remanence is added. In this way the film retains a remanence magnetization in the  $y$  direction after the EMP has passed.

#### IV. RESULTS

We have applied this program for an incident EMP rising in 10 ns with a total pulse width of 100 ns (see Fig. 2). The peak amplitude of the incident pulse is equal to  $H_A$ , the anisotropy field, so the front surface field rises to  $2H_A$  from Eq. (8). The following material characteristics are assumed about the film:  $4\pi M_0 = 10\,000$  G,  $\sigma = 1.16 \times 10^6$  mho/cm,  $H_A = 5$  Oe, and  $H_r = M_0/2$  (50% remanence field). The iron-nickel alloy system could fit these characteristics. The instantaneous magnetization response and the average internal  $H$  field are calculated for three different damping constants:  $\alpha = 0.003$ , 0.03, and 0.3.

Figure 3 shows the  $y$  component of the magnetization for one domain orientation in the first layer of the film. The  $y$  component of the magnetization for the second domain orientation is the same, but the  $x$  and  $z$  components are equal in magnitude and opposite in phase. The total magnetization, therefore, is  $2M_{1y}$  in the  $y$  direction and zero in the  $x$  and  $z$  directions.

Figure 3(a) shows the  $y$  component of the magnetization in one domain for a damping parameter  $\alpha$  of 0.003. The incident field rises in 10 ns reaching a value of  $H_A$  and then drops in 90 ns. The surface field rises to twice the value of the incident field and attains the value of  $H_A$  in 5 ns. If the magnetization response were instantaneous the magnetization would reach saturation in the same time (5 ns). With  $\alpha = 0.003$ , the calculated magnetization response attains saturation in 8 ns lagging the surface field by 3 ns. Since  $\alpha$  is small, it results in an underdamped response oscillating around  $M_0$ . When the incident field drops below  $0.5H_A$  and the surface field drops below  $1H_A$ , the magnetization drops from saturation to attain its remanent value, again lagging the magnetic field by approximately 3 ns.

Figure 3(b) shows the magnetization response for a damping parameter  $\alpha$  of 0.03. The magnetization reaches

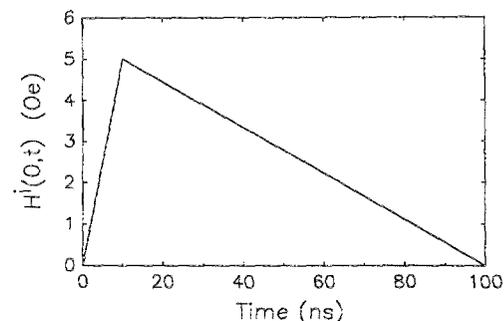


FIG. 2. Incident EMP with 10 ns rise time and 100 ns total width.

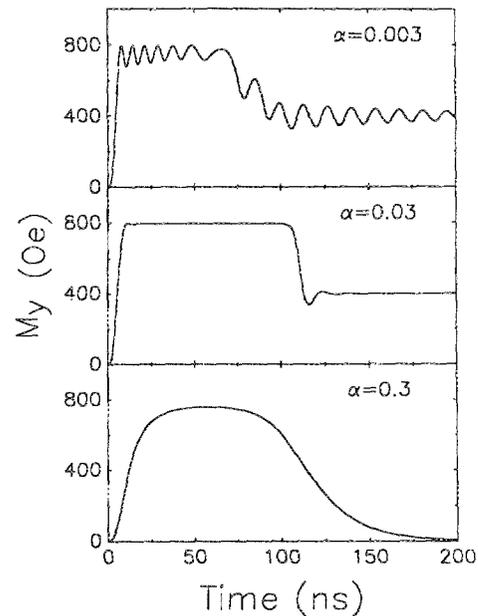


FIG. 3. Magnetization response due to incident EMP for damping parameters as shown.

saturation in 11 ns lagging the instant response by 8 ns. The response time is mildly underdamped, and the magnetization barely oscillates at its final values. Since the magnetization has attained saturation, it drops to its remanent value after the pulse has passed.

Figure 3(c) shows the magnetization response for a damping parameter  $\alpha$  of 0.3. The magnetization has a very slow response and rises to a maximum in about 60 ns and never reaches saturation. When the incident EMP drops to zero, the magnetization drops also to zero with a significant lag time.

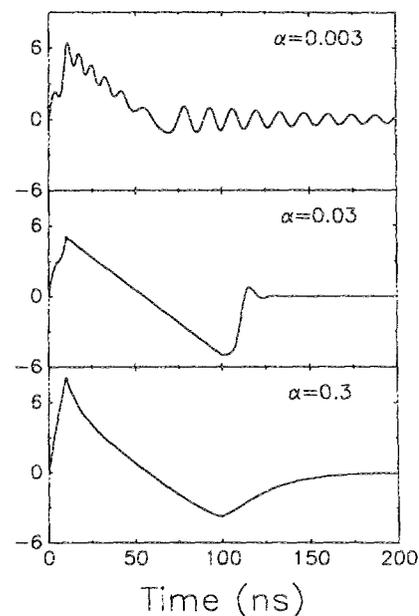


FIG. 4. Effective internal magnetic field from incident EMP for damping parameters as shown.

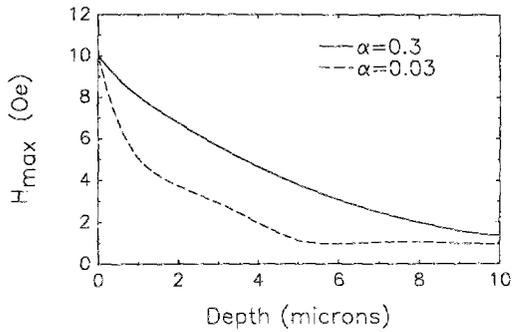


FIG. 5. Maximum internal field as a function of depth in the film for different damping parameters.

The average internal magnetic field calculated from the negative gradient of the free energy in each domain is shown for the three different damping parameters in Fig. 4. The peak values of the magnetic field are registered and found to be equal to 6.35 Oe for a damping parameter  $\alpha$  of 0.003, 5.05 Oe for a damping parameter of 0.03, and 8.1 Oe when the damping parameter is 0.3.

From these results we find that  $\alpha = 0.003$  leads to an effective magnetization response time of about 3 ns,  $\alpha = 0.03$  to a response time of about 8 ns, and  $\alpha = 0.3$  to a response time of about 60 ns. We also find that the effective internal field near the surface is smallest when  $\alpha = 0.03$ , the value corresponds to a response closest to the pulse rise time. This is consistent with the results in I.

To calculate the shielding of the film as a whole, we have to apply the result of the Gilbert equation to the diffusion equation and calculate the propagation of the field through the film. When  $\alpha$ , the damping parameter, is zero, the equation of motion gives the result that the magnetization will indefinitely precess transverse to the magnetic field direction, oscillating around the remanent value after the dissipation of the EMP. This result is unphysical. We also found that if the magnetization was underdamped the diffusion equation gave rise to unphysical oscillations. For the purpose of calculating the shielding of the film we considered two damping constants:  $\alpha = 0.3$ , corresponding to a heavily damped system (long response time), and  $\alpha = 0.03$  corresponding to a response time on the same order as the rise time of the pulse. The results are shown in Fig. 5 which plots the peak value of the magnetic field intensity reached at each depth inside the film. The peak  $H$  field at the back surface of the film, which is also the transmitted peak  $H$  field, is approximately 45% higher for a damping parameter of 0.3.

## V. CONCLUSION

We have calculated the shielding of an EMP by a ferromagnetic film including the effects of saturation and hysteresis and allowing for a finite response time for the film magnetization. A multidomain model is used which is applicable to the case when the magnetic field of the EMP is perpendicular to the magnetization. The magnetization response is determined from the equation of motion in the Gilbert form, the free energy of the multidomain structure is calculated, and the internal fields are found from the gradient of the free

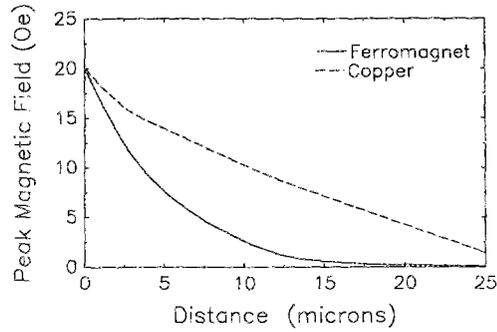


FIG. 6. Shielding of EMP peak magnetic field for a 25- $\mu\text{m}$  ferromagnetic film with parameters as given in the text compared with a copper film of the same thickness.

energy. We find that precession damping has a large effect on the shielding factor. A damping parameter corresponding to a response time on the order of the rise time of the pulse gives significantly better shielding than a much longer response time.

In the earlier work, we calculated the magnetic moment response in a ferromagnetic thin film when the incident EMP is parallel to the domain walls of the film. In this paper, we calculated the response of the magnetic moment when the incident EMP is perpendicular to the domain walls of the film. In practical situations, an incident field is more likely to be a combination of both vector fields parallel and perpendicular to the domain walls, which requires a result drawn from both analyses.

The analysis of I combined with this work form the basis for a realistic calculation of the shielding of a ferromagnetic material including saturation, hysteresis, remanence fields, and material response times. We can summarize the results of this work in Fig. 6. This figure compares the shielding of an EMP, shown in Fig. 2, by a nonmagnetic film of conductivity typical of copper with a ferromagnetic film of conductivity 1/100 that of copper, a relative permeability of 10 000, and selected for an optimum response time. These parameters are physically realizable in many ferromagnetic alloy systems. We note that the shielding of the ferromagnetic film is a factor of 20 better than the copper film for the same thickness when the response time of the ferromagnetic film is on the order of the rise time of the EMP. For EMP rise times greater than or on the order of 10 ns this method of shielding is effective in comparison to copper, since the material response time bandwidth is in the order of 300–500 MHz. For rise times much less than 10-ns copper shielding becomes more effective, since the magnetic system takes a long time to respond. These conclusions corroborate the previous results we obtained in I. Research on magnetic films to verify these conditions and to search for optimum shielding material is highly desirable.

<sup>1</sup>F. Zayek, S. W. McKnight, and C. Vittoria, IEEE Trans. Magn. **MAG-24**, 2114 (1988).

<sup>2</sup>R. F. Soohoo, *Microwave Magnetics* (Harper and Row, New York, 1985).

<sup>3</sup>F. J. Rachford, P. Lubitz, and C. Vittoria, J. Appl. Phys. **53**, 8940 (1982).

<sup>4</sup>C. Vittoria, N. C. Koon, P. Lubitz, and J. A. Geohegan, J. Appl. Phys. **55**, 1741 (1984).