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Thin Film Switching by Non-Coherent Rotation

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Further study of the switching process in thin permalloy films has emphasized the importance of the role played by non-coherent rotation in the course of magnetization reversal. For switching fields applied near the hard and easy axes such a non-coherent rotation governs the reversal process and in the case of partially switched films is responsible for the presence of cross-tie domain walls.

A model in which non-coherent rotation is initiated by a spacially periodic variation of the easy axis direction has allowed the calculation of hard and easy axis switching fields and the geometrical properties of the hysteresis loops.

Numerous Bitter pattern observations for different conditions of applied field are easily interpreted from the proposed model and the calculations which it permits are in good experimental agreement.

Introduction

The hysteresis process in thin uniaxial ferromagnetic films for driving fields applied about the hard and easy axes is observed to be in disaccord with the theory of simple, uniform rotation described by the Stoner-Wohlfarth equations.[1] Hard axis hysteresis loops are, in general, not linear as expected on this basis. Those for which the remanent magnetization is zero exhibit an abrupt change in slope before remanence is reached; in hard axis loops for which the remanent magnetization is not zero, there is a discontinuous change in the magnetization as in the case of easy axis switching. Easy axis hysteresis loops, although of the predicted rectangular shape, usually indicate magnetization reversal to occur at a field value lower than the anisotropy field, $H_k = 2K/M$, as calculated by assuming a simple rotation.

Further study of hard and easy axis hysteresis has shown that the rotation is non-coherent and it is purpose of this communication to present a model for such a rotational process which seems to more accurately describe the observed switching characteristics.

Hard Axis Hysteresis

The magnetization in a thin uniaxial ferromagnetic film initially saturated along the hard axis is found to be in a multi-domain state upon removal of the applied field.[2,3] The multi-domain state, in which the sense of rotation is opposite in adjacent domains, is excited by a non-coherent rotation of the magnetization toward the easy axis as the applied field is reduced from saturation. The magnetization at the center of the intervening domain walls remains along that hard direction in which the film was initially saturated. There is an increase in the energy of these walls, caused by the rotation of the domain magnetization, so that, for the non-coherent rotation to continue unimpeded to saturation in the opposite hard direction, a reversal of the wall magnetization is necessary. This reversal takes place by a rotation of the wall "spins" out of the plane of the film, thus characterizing the hard axis switching process by a Néel to Bloch to Néel transition of the domain walls formed by the initial non-coherent rotation of the magnetization.

If the reversal of the wall "spins" begins before remanence is reached, the transition is gradual so that the domain walls at remanence are of the Bloch type and the remanent magnetization zero. If the re-orientation of the wall magnetization occurs after remanence, the value of the retentivity being then determined by the balance between domain and domain wall energies in zero applied field, the Néel to Bloch to Néel transition is sudden and results in a discontinuity in the switching curve, seen as squareness of the hard axis loop.

* This paper was read by R. Vautier.

In the quantitative description of this process the domain energy is taken to include the anisotropy energy and the magnetic energy of the applied field, H. For the domain wall energy only magnetostatic and exchange energies need to be considered, as shown by Néel.[4] For walls spaced a distance D apart, the total average energy, per unit volume of film, is then

$$\varepsilon = K\sin^2\theta - MH\sin\theta + \frac{\varepsilon_{\text{wall}}}{D}, \qquad (1)$$

where θ is the angle of magnetization with respect to the easy axis. The wall energy per cm^2, as a function of θ and of the angle, ϕ, that the magnetization within the wall makes with the plane of the film, may be approximated by

$$\varepsilon_{\text{wall}} = \varepsilon_N(\cos\phi - \sin\theta)^2 + \varepsilon_B\sin^2\phi, \qquad (2)$$

where ε_N and ε_B are the energies of a 180° Néel and 180° Bloch wall respectively. It is assumed here that the total wall energy varies in proportion to the magnetostatic energy of the wall.

From the minimization of these energy expressions one obtains, for the orientation of the magnetization as the applied field is reduced from saturation,

$$\sin\theta = \frac{\varepsilon_N + \frac{1}{2}MHD}{\varepsilon_N + KD}, \quad \phi = 0, \qquad (3)$$

provided no reversal of the wall magnetization occurs. Under this condition, the normalized remanent magnetization after hard axis saturation is

$$R = \left(\frac{M\sin\theta}{M}\right)_{H=0} = \frac{\varepsilon_N}{\varepsilon_N + KD}. \qquad (4)$$

For that value of applied field at which the wall magnetization begins its reversal, one finds

$$H_{sh} = -\left(\frac{\varepsilon_B/\varepsilon_N}{1-R} - 1\right)H_k. \qquad (5)$$

If $\varepsilon_B/\varepsilon_N > 1-R$, the reversal, and consequently the change in domain magnetization orientation occurs instantaneously, after remanence, at a positive value of applied reverse field, H_{sh} (Fig. 1). It should be noted that the multi-domain remanent state is characterized by Néel walls separating regions of opposite rotation even if $\varepsilon_B < \varepsilon_N$. If $\varepsilon_B/\varepsilon_N < 1-R$, the domain wall magnetization begins to rotate out of the film plane before remanence at the field H_{sh}, whereupon the slope of the linear variation of $\sin\theta$ with H changes abruptly so that the hysteresis loop exhibits zero remanence (Fig. 1). At an equal and opposite value of applied field the reversal of the domain wall magnetization is completed and the walls are once more of the Néel type. Bitter pattern studies have confirmed the Néel to Bloch to Néel wall transition in the case of pre-remanence switching; this transition, as it occurs in its discontinuous form for the case of post-remanence switching, has already been reported.[2]

Examples of possible hard axis hysteresis loops predicted by the theory and their observation by experiment are depicted in Fig. 1. Agreement is generally good for the initial part of the loops, although there seems to be a change in the multi-domain state which accompanies reversal of the domain

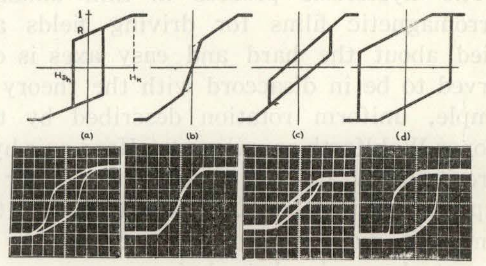

Fig. 1. Examples of several predicted theoretical hard axis hysteresis loops and their experimental observation for the parameters R, ε_B, and ε_N related as follows:
(a) $1 > 2(1-R) > \varepsilon_B/\varepsilon_N > 1-R$;
(b) $\varepsilon_B/\varepsilon_N < 1-R$;
(c) $2(1-R) > \varepsilon_B/\varepsilon_N > 1$;
(d) $1 > \varepsilon_B/\varepsilon_N > 2(1-R)$.

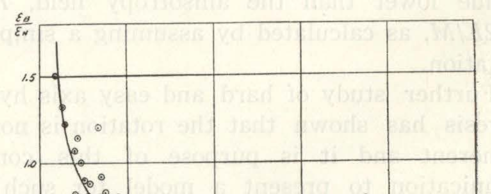

Fig. 2. The ratio, $\varepsilon_B/\varepsilon_N$, of Bloch to Néel wall energy as a function of film thickness measured in films around the 80-20 Ni-Fe composition. The calculated variation is shown by the solid curve

wall magnetization and modifies the subsequent part of the loops. A gross wandering of the easy axis could account for this effect. In Fig. 2 is shown the variation of $\varepsilon_B/\varepsilon_N$ with film thickness, as determined from the observed switching curves ($\sin\theta=1-\varepsilon_B/\varepsilon_N$ at $H=H_{sh}$), for permalloy films around the 80-20 composition along with the theoretical curve calculated for films of this composition. In spite of the scatter of the data, the agreement seems good and verifies a thickness of about 200Å as being the cross-over point for the Néel and Bloch wall energies as predicted.

Easy Axis Hysteresis

The easy axis switching process is analogous in that a similar non-coherent rotation is excited as a reversing field is applied. Separating the regions of opposite rotation, there would be narrow regions of high magnetostatic and exchange energy equivalent to the domain walls formed after hard axis saturation. These wall-like regions are the lines of "buckling" observed during the course of easy axis switching[5,6].

In accordance with this model, calculations for the case of easy axis switching have been made assuming a periodic variation of the easy axis direction to be responsible for the initiation of the non-coherent rotation and one obtains for the field necessary for reversal of the magnetization

$$H_{se}=-\left(1-\frac{\alpha}{\sqrt{2(\varepsilon_B/\varepsilon_N)}}\right)H_k \qquad (6)$$

where α is the amplitude of the angular variation of the easy axis. Experimental verification of the calculation pertaining to the easy axis case is difficult due to the problem of measuring α. Moreover, the existence of "inverted" films is not included in Eq. 6.

Switching by Wall Motion

The reversal mechanism described here assumes a rotation in unison of the domain wall magnetization toward the opposite hard axis direction. In practice, however, such homogeneity is lacking so that certain regions of the film will switch before others creating large domains (as compared to the narrow domains of the multi-domain state) of reversed and un-reversed magnetization. It is important to note that, in the case of easy axis and post-remanence hard axis switching the boundaries between the reversed and un-reversed regions must have the magnetization distribution attributed to a cross-tie wall due to the initial non-coherent rotation.[3] Further switching of the film is then effected by the movement of these boundaries. That the "buckling" lines and the domain walls of the multi-domain state should be located at the Bloch regions of these cross-tie wall boundaries follows directly from the model.

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