# Magnetization Reversal in Permalloy Films

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Magnetization reversal in 80 Ni-20 Fe Permalloy films, which is completed in the course of monotonic variation of field, has been investigated with AC fields 60 to  $700 \times 10^3$  cps. Measurements of the magnetoresistance effect are utilized to see whether the reversal is due to wall motion or rotation. All the reversals observed in this experiment are due to the wall motion. As dH/dt before the noticeable onset of the reversal increases, the effective field driving the reversal increases and eventually exceeds  $H_k$ . These results are interpreted in terms of the local deviation of the magnetization, and the threshold field for non-uniform rotation is estimated.

#### 1. Introduction

In the experiments on the magnetization reversal in soft ferromagnetics with a pulse field, the reversal would for the most part be driven by the constant field of the pulse. However, aspects of the reversal might depend on the shape of the field versus time curve during the rise time, since the reversal would begin, in principle, at the threshold field smaller than the height of the pulse field. Fields during the rise time are given by  $\int (dH/dt)dt$ , so that the magnitude in dH/dtmight be strongly dependent on the aspect of the reversal. Then, some aspects of the reversal would be revealed by applying the continuously increasing fields with various magnitudes in dH/dt.

In the present work, the magnetization reversal in Permalloy films, which is always completed in the course of a monotonic variation of field, has been investigated with not only slow-rise-time pulse fields having dH/dt 10<sup>4</sup> to 10<sup>6</sup> Oe/sec, but also AC field corresponding to dH/dt  $3 \times 10^3$  to  $7 \times 10^7$  Oe/sec. Then, the average field driving the reversal, the effective coercive force, as well as the notable threshold field are detectable.

#### 2. Experimental

The films used were prepared by vacuum deposition of 80Ni-20Fe at normal incidence onto the glass substrate heated at 200°C in the presence of field 100 Oe. The thickness is about 1500 Å and the size is about 1 cm  $\times 1$  cm. The induced anisotropy field  $H_k$  is 3 to 4 Oe and the wall coercive force,  $H_w$ , is 1 to 1.5 Oe;  $H_k$  was determined by measure-

ments of a linear hysteresis loop in a low AC field and also of the magnetoresistance effect<sup>1) 2)</sup> ( $\Delta R$ ), and  $H_w$  was determined by a quasi-static measurement of  $\Delta R$ .

The reversal behavior is almost the same in all the films. The results which will be given hereafter concern *R*-492 film,  $H_k=3$  Oe and  $H_w=1.5$  Oe.

In the present experiment, measurements of  $\Delta R$  are employed in addition to those of the flux  $\phi_{\parallel}$  and the time derivative of  $\phi_{\parallel}$ ,  $\dot{\phi}_{\parallel}$ . In Permalloy films,  $\Delta R$  depends practically on the rotation alone; that is, it is represented by  $\Delta R = (R_{\parallel} - R_{\perp}) \cos^2 \theta$ , where  $\theta$ is the angle between the directions of the magnetization and the measurement of the resistance, and  $R_{\parallel}$  and  $R_{\perp}$  are the resistances when  $\theta = 0$  and  $\theta = \pi/2$ , respectively. In the present films,  $(R_{\parallel} - R_{\perp})/R_{\perp} \simeq 2 \times 10^{-2}$ .<sup>1)</sup>

### 3. Results and Discussion

In Fig. 1 are shown  $\phi_{\parallel} - H$ ,  $\phi_{\parallel} - H$  and  $\Delta R - H$  curve observed in 10 kcps field with  $dH/dt = 6.3 \times 10^6$  Oe/sec which is applied along the easy direction. Here, the measurement of  $\Delta R$  is made perpendicularly to the easy direction. The flux reversal in  $\phi_{\parallel} - H$  curve or the switching signal in  $\phi_{\parallel} - H$  curve is essentially due to wall motion. This is definitely confirmed by a break in  $\Delta R - H$ curve. The break roughly corresponds to the onset of the flux reversal in  $\phi_{\parallel} - H$ curve and  $\Delta R$  at the break is only about 10% as large as  $(R_{\parallel} - R_{\perp})$  which stands for uniform rotational reversal. Such a small maximum in  $\Delta R$  can hardly be expected even if the reversal results from nonuniform rotation.<sup>3)</sup> Then the field at the break,  $H_b$ ,

may be taken as the noticeable threshold for wall motion reversal.

It should be noted that small reversible rotation which increases with the field is observed until the field reaches  $H_b$ . Such a rotation might be attributed to the actual existence of local deviations of magnetization from point to point in the film. It was ascertained, from measurements of the transverse flux, that the reversible rotation occurs locally half and half in the left-handed and the right-handed direction, respectively. The average local deviation of magnetization at remanance is estimated as  $6^{\circ}$  to the easy direction from the static measurement of  $\Delta R$ .

As will be mentioned later,  $H_b$  is increased with increase of dH/dt. The rotation till  $H_b$ , however, is always almost reversible;



Fig. 1.  $\varphi_{\parallel}-H$ ,  $\dot{\varphi}_{\parallel}-H$  and  $\Delta R-H$  curves in 10 kcps with dH/dt, 6.3x10<sup>6</sup> Oe/sec.





that is, every  $\Delta R$  observed till  $H_b$  lies on almost the same curve, independently of the magnitude in dH/dt. Therefore, the average reversible rotation angles are computed from  $\Delta R$  at different  $H_b$  with the relation  $\Delta R/(R_{\parallel} - R_{\perp}) = \sin^2 \alpha$ , where  $\alpha$  is the angle beween the magnetization and the easy direction. In this computation, amounts of the reversed domains are neglected, since they are negligibly small compared with the whole volume of the film. The computed values are plotted as curve a in Fig. 2.

In Fig. 2 are also given curves b and c which are calculated in terms of the simple rotation model on the magnetization lying in the direction deviating 6° to the easy direction and when the uniaxial anisotropy fields in the direction are 3 Oe and 6.3 Oe, respectively. According to the calculation, the irreversible rotation takes place at the rotation angle 31°, independently of magnitudes of the anisotropy field.

In a real film, therefore, it might be presumed that irreversible rotation also occurs at the critical angle 31°. Thus, the threshold field for the rotation reversal is estimated as 4.8 Oe corresponding to the critical angle in curve a. This rotational reversal should, in principle, be nonuniform rotation, since the reversible rotation occurs locally and in both directions before the onset of the irreversible rotation, as mentioned previously.

From the comparison between the shapes of curve a and curves b and c, it is understood that the effective anisotropy field increases with increase of the applied field. Internal local fields and exchange fields which result from the local deviation of magnetization would be responsible for the increase of the effective anisotropy field, although "locking"<sup>40</sup> or "buckling"<sup>50</sup> mechanism may also possibly be responsible. The increase of the effective anisotropy field with increase of the applied field, therefore, would be attributable to the fact that the local deviation of magnetization increases gradually with increase of the applied field.

The observed reversal is essentially due to wall motion even for the fields above 4.8 Oe. The reason is evidently attributed to the fact that the switching time is much smaller for wall motion than for nonuniform rotation in the range observed.

In Fig. 3  $H_b$  is shown as a function of dH/dt.  $H_b$  increases with increasing dH/dt and eventually it exceeds  $H_k$  which corresponds to the threshold for uniform rotation; that is, the film appears to behave just like the so-called inverted film<sup>4)</sup> for  $H_b$  in excess of  $H_k$ . The increase in  $H_b$  with dH/dt is, in principle, attributable to the fact that as dH/dt is increased the time to reach a certain field becomes smaller, so that the



Fig. 3. Relation between  $H_b$ , the notable threshold field for the reversal, and dH/dt.

amounts of the reversed domains are smaller at that field. This is based on the assumption that the wall velocity is proportional to  $(H-H_w)$  and also the number of walls available for growth is increased as a function of  $(H-H_w)$ . However,  $H_w$  must be increased with increase of the applied field, because it would depend on something like *transfixing* or *nailing* of wall motion. This would result from interactions between the walls and the locally deviated magnetization in the unreversed domains and would increase with the applied field. This increase in  $H_w$  must be more responsible for the increase in  $H_b$ with dH/dt.

In the present films, it is presumed that many small reversed domains have already been created at both ends perpendicular to the easy direction before the field reaches  $H_w$ . This presumption is not incompatible with observations of powder patterns. The number of the reversed domains which are able to grow may be dependent on the magnitude of  $(H-H_w)$ , as mentioned previously.

In Fig. 4 are given switching curves,  $1/\tau$  as a function of  $H_c$ , where  $\tau$  is the switching

time determined as usual from the switching signal of  $\dot{\phi}_{\parallel} - H$  curve and  $H_c$  is the field corresponding to the peak in the same curve which roughly indicates the coercive force or the average field driving the reversal. As  $H_b$  is increased with increase of dH/dt, the average field driving the reversal is also increased, so that the switching curves are not significantly different from those obtained by the usual pulse field.



In the absence of a transverse field,  $H_{\perp}$ , the reversal is essentially due to wall motion in the whole observed range, as mentioned previously. In the presence of  $H_{\perp}$ , all the reversals observed are also likely due to wall motion, although the fact has not yet been the confirmed definitely. As  $H_{\perp}$  becomes greater, the reversal time becomes shorter at the same field. This seems to be attributabe not only to decreasing of the wall coercive force, but also to increasing of the number of walls with the increase in  $H_{\perp}$  at the same field.

In conclusion, the reversal process which is due to two mixed mechanisms, wall motion and nonuniform rotation, is suspected to follow the pure wall motion reversal as the field driving the reversal is increased. The experiments are being continued for solving the still uncertain problems which have been mentioned so far.

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## References

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La dourième partie est construée à l'étude de la dependance des courants de Foucaule est de la structure granulaire dans les ferrites de Ma-Za, et à une analyse détaiblée de l'action du calcium aux joints des cristaux. Du part de vue structural, l'action du calcium est deuble: 1) la presence diminue la densité des ferrites de Ma-Za. 2) il s'éprège aux joints. A cetté double action structurale du calcium correspond un double effet aux l'additiere exploréducteur, qui conduit à une diminution de la teneur ten ions l'est- aux joints. L'ansemble des conclusions est configmé par la comparaison des proprietés physico-chimiques dans les reistaux-et aux joints das cristaux de ferrites avec et sans calcium pour differentes conditions de fritager et de referidisement

The numeric and electric properties of farrites being strongly dependent upon grain structure, has led to a study of creatal growth within polycrystalline aggregates of ferrites of Ma-Za and Mi-Za. We show that all ferrites with a spinel structure should have approximately the same rate of creatal growth, irrespective of their composition, provided origoration of grain boundaries is not bindered by voids or inclusion.

In the second part of the paper a special attention is gold to the dependence of eddy currents on the grain structure in Ma-Za ferrites and then to a detailed study of the action of calcium on the grain boundaries. From the point of view of structure, the effect of calcium is twofold: 1) its presence decreases the density of the ferrites; 2) the calcium aspregates at the boundaries. Along with the twofold structural effect of calcium there is a corresponding twofold ionic effect which leads to a decrease of the Fe ions content at the grain boundaries. The set of conclusion is justified by a comparison of the physicochemical properties within the crystals and at the crystal boundaries for ferrites under various scattering and cooling conditions.

> Comme nons l'avons déjà montre" l'influence de la structure granulaire sur les propriétés des ferrites covêt une très grande importance. Deux ferrites de même composition, mais de strocture granulaire dissemblable peuvent présenter de très grandes différences dans leurs propriétés en courant faible.

None avons montre que la pernientilité dépend, toutes autres choses égules par ailleurs, du volume relabif de trois ensembles de enistrux correspondant à trois mécanismes différents d'amantation, sóparés par deux diamètres crittques  $(d_{i,k})$  et  $(d_{i,k})$  définis par le shéma ci-dessous:  $d_i$  étant le diamètre spatial d'une sphère de même volume que le cristal.

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