Letter to the Editor

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Partial-Switching Processes in Thin Magnetic Films

In a previous experiment[1] it was shown that *complete rotation* of the magnetization in thin NiFe films, lasting only a few nanoseconds, can take place when rapidly rising field pulses of sufficiently high amplitude are applied. In this experiment the film remained in the single-domain state during the flux reversal, which is in contrast to static-switching experiments where the film splits up into many domains during the process.[2] This Letter discusses *partial-switching* processes which occur when rapidly rising field pulses with amplitudes just beyond the rotational threshold are applied to the film. In this case the film is also split up into fine domains. This is interpreted as being caused by inhomogeneities of the magnetic properties of the film. Further, an unexpected creep effect occurs for field pulses with amplitudes somewhat below the wall coercive threshold H_c, which is attributed to partial wall motion starting from the edge domains of reversed magnetization.

Incomplete rotation

The magnetic films under investigation were prepared by evaporation of 80/20 NiFe onto a heated glass substrate in the presence of a dc magnetic field, inducing uniaxial anisotropy. The film size was between 5 and 10 mm diameter, and between 80 nm and 150 nm (nanometers) in thickness.

Magnetic field pulses rising within 0.3 nsec were applied to the magnetic films in the plane of the film at various angles with respect to the easy axis. The amount of flux switching by fast rotation was measured in the direction of the applied field as a function of field amplitude. Generally it consists of a reversible part and an irreversible part. The measurement equipment used is described in detail in Ref. 1.

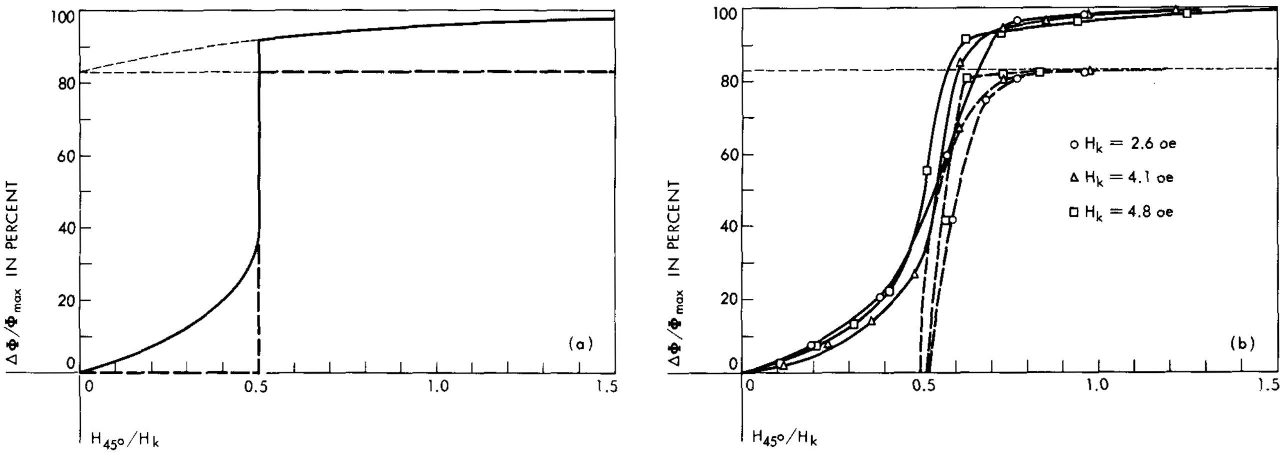
In Fig. 1a the theoretical rotational flux change is plotted versus drive field amplitude when the field is applied at 45° with respect to the easy axis. The switched flux is normalized with respect to the amount of flux for complete rotation, and the drive field is normalized with respect to the anisotropy field $H_K = 2K/M$. Here K is the anisotropy constant and M is the magnetization. This plot is derived from the Stoner-Wohlfarth model for rotational reversal

Figure 1 **Rotational flux reversal for driving fields at 45° to the easy axis. (a) Theoretical rotational flux change. (b) Experimental results for three film samples.**

The films were reset to the single domain state after each drive pulse.

——— *Flux change with field $H_{45°}$ present.*

— — — *Irreversible flux change, which remains after $H_{45°}$ has been switched off.*



processes.[3] The broken line represents the irreversible part of the magnetization reversal, i.e., the flux change that remains after the drive field is decreased to zero.

Figure 1b shows the experimental results for three film samples. The drive field pulses are applied at 45° to the easy axis. After each drive pulse the film was reset to the original single-domain state. Again the amount of irreversible flux change is given by the broken lines. These results were obtained by the following method.

The rotationally switching flux is experimentally distinguishable from the wall-motion part due to the completely different switching times of the two parts.[1] For example, Fig. 2 shows the output signal of a film switched by a field pulse of long duration. The first spike is due to rotational reversal. It is not fully resolved by the oscilloscope used, however, with respect to time. By means of a sampling oscilloscope the switching time of this spike was measured and found to be a few nanoseconds. The second part of the output signal shown in Fig. 2 is due to wall motion. In practice, the rotational flux reversal could be observed separately by using drive pulses of only 20-nsec duration.

The irreversible part of the flux change can be measured easily by applying a strong reset pulse of constant amplitude and short duration in the opposite direction after each drive pulse. The amplitude of this reset pulse is sufficiently large to reset the film in the previous single-domain state. Even when no flux has been switched by the drive pulse, only a constant reversible flux change occurs during the reset pulse. This constant amount of flux change can then be established and subtracted from the amount of total flux change, in order to determine the amount of irreversible flux change switched by the drive pulse. The anisotropy field H_K is determined by the slope of the BH curve measured under pulse conditions in the hard direction. When these measurements are carried out at different angles to the easy axis, the lines of constant switching flux in the H_x, H_y plane can be plotted. Here H_x, H_y are the field components in the easy and hard directions respectively. In Fig. 3 the lines of constant irreversibly switched flux are plotted for the first sample of Fig. 1b.

From these investigations carried out on a number of film samples, it follows that the onset of irreversible flux change occurs always somewhat beyond the theoretical threshold curve[4] $H_x^{2/3} + H_y^{2/3} = H_K^{2/3}$. However, the threshold for complete rotational flux reversal lies considerably outside of the theoretical threshold. In the region between these two threshold curves, partial switching takes place. The difference between the complete rotational threshold and the theoretical threshold varies for the different films. Attempts to relate this difference to other magnetic properties, e.g., spread of the easy axis direction and the anisotropy constant, are in preparation.

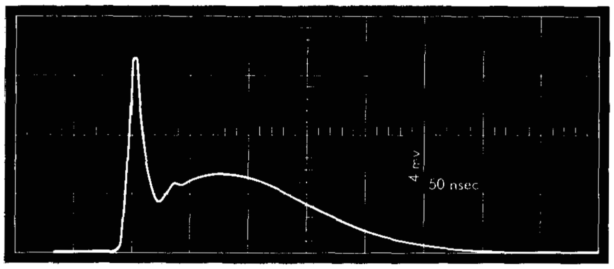


Figure 2 **Switching signal of a typical film, picked up in the easy direction.**
Field pulses of 400-nsec duration are applied in the easy axis with a small dc field in the hard direction.

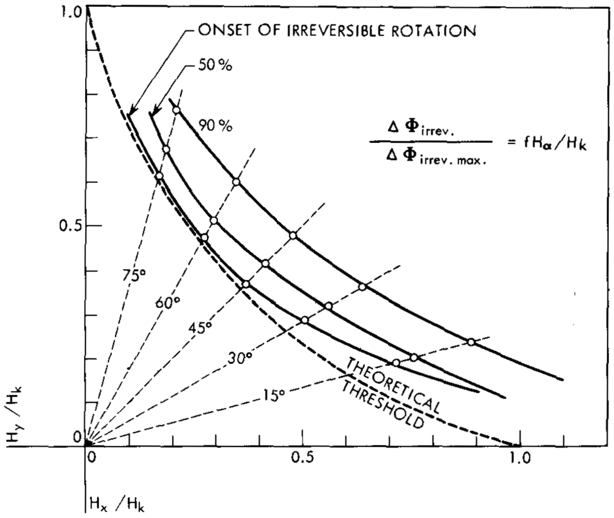


Figure 3 **Partial flux reversal in the H_x, H_y plane of the film obtained from the first sample of Fig. 1b.**

In a second experiment after first setting the film into the single domain state, a large number of field pulses of alternating polarity, but of equal shape and amplitude, and of 20-nsec duration was applied to the film at 45° to the easy axis. Again the amount of flux switching back and forth at each pulse was measured after reaching a constant flux change for the following pulses, i.e., after applying 5 to 10 double pulses. The normalized flux change versus drive field is plotted in Fig. 4 for the same samples as in Fig. 1b. It was found that much higher field amplitudes are required to switch the same amount of flux as in the first experiment, when the film was reset to the single domain state after each field pulse.

To illustrate the mechanism of partial switching, the domain structure of a film obtained by the Bitter technique is shown in Fig. 5. This split state results when a film has been partially switched from the single-domain state by a field pulse applied at 45° to the easy axis. The structure is quite similar to that obtained by

Table 1 **Data for the seven curves in Fig. 7.**

	A	*B*	*C*	*D*	*E*	*F*	*G*	
τ_R in nsec	<0.3	<0.3	<0.3	<0.3	20	<0.3	1.2 msec	pulse rise time
τ_L in nsec	200	30	200	30	30	30	5.0 msec	pulse length
$h = (H/H_w)_{45°}$	0.88	0.88	0.5	0.5	0.88	0.88	0.88	normalized amplitude

Figure 4 **Normalized rotational flux reversal for driving fields at 45° to the easy axis after applying a number of field pulses with *alternating polarity*. Same samples as Fig. 1b.**

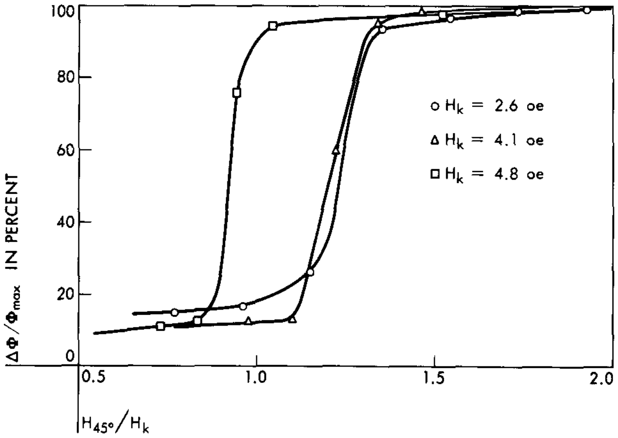
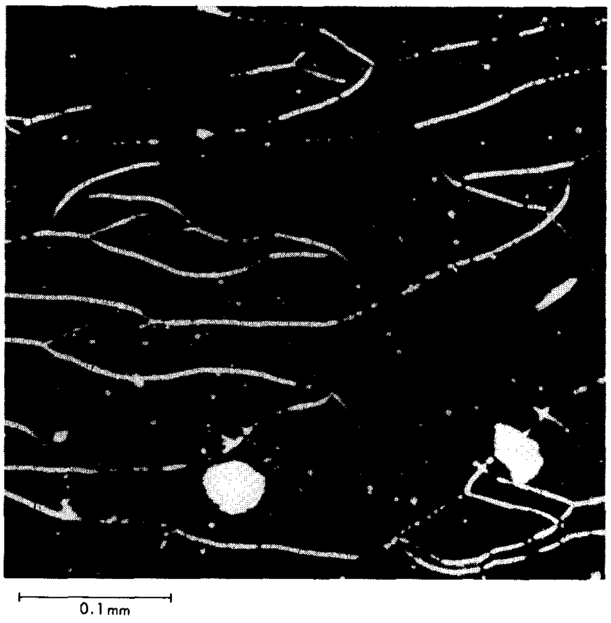


Figure 5 **Domain configuration of a partially switched film.**
The easy axis is horizontal.



quasistatic experiments[2] and it is suggested that the same mechanism of stray fields caused by partially switched domains also pertains here. From this intermediate state, the single-domain state can only be again attained either in a short time (<3 nsec) when a single pulse of short duration and large amplitude (2 to 4 times H_K) is applied, or in a relatively long time ($\geqq 1$ μsec) by wall motion switching.[5]

It is interesting to note that the partially switched state of films can be investigated by this pulse method for arbitrary values of the ratio H_w/H_r. Here H_w is the wall motion threshold, and H_r is the rotational threshold in the plane of the film. The quasistatic experiments on the split state films, however, can only be performed for ratios $H_w/H_r > 1$.

Creeping

Another partial-switching process can be observed when the film is set initially to the single-domain state and a certain number of reversing field pulses with amplitudes smaller than the wall motion threshold H_w is applied. In Fig. 6 the reversed flux is plotted as a function of the number of field pulses of 400-nsec duration applied at 30° to the easy axis for a typical film sample. The time interval between two consecutive pulses is 20 msec. The magnetization reverses completely when a few thousand pulses are applied with amplitudes far below the wall motion threshold H_w ("creeping").

Bitter pattern observations revealed that the applied pulses cause a few perpetual edge domains of reversed magnetization to increase over the film area until the magnetization is completely reversed. No flux reversal occurs, however, when only a dc field of the same amplitude is applied, even for a long period of time. Furthermore the influence of rise time and pulse length on the creep velocity is shown in Fig. 7 for another typical example. The seven curves in Fig. 7 are identified in Table 1.

The amount of reversed flux obviously increases with decreasing rise time, increasing length and increasing amplitude of the applied field pulses. When field pulses of alternating polarity are applied, the amount of reversed flux approaches only 50% of Φ_{max}.

A remarkable fact is that no creeping can be observed when field pulses are applied close to the easy axis.

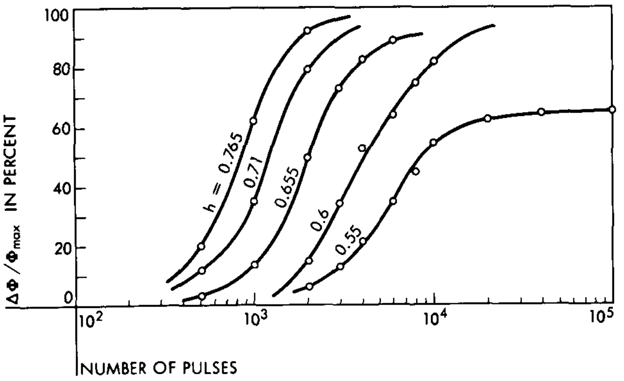


Figure 6 **Flux reversal by creeping.**

Field direction is 30° to the easy axis. Numbers on the curves are field amplitudes normalized with respect to the wall motion threshold $(H_w)_{30°}$. $h = (H/H_w)_{30°}$. *Pulse duration is 400 nsec.*

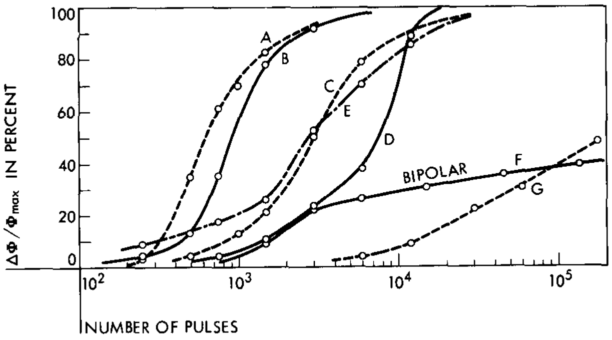


Figure 7 **Normalized flux reversal by creeping versus number of field pulses applied at 45° to the easy axis.**

Parameters are rise time, pulse duration and pulse amplitude (see text).

Although this creep effect is not completely understood, it might be due to changes in the wall thickness under the influence of fields which have components off the preferred axis. Detailed investigations concerning the mechanism of creep during partial switching are under way.

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