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Nanosecond Switching in Thin Magnetic Films*

Abstract: A special pulse equipment including a pulse-sampling oscilloscope with an over-all response time of 0.35 nanosecond (10^{-9} sec) for the observation of the nanosecond flux change in thin permalloy films is described. Film switching signals as short as 1 nanosecond have been obtained and are discussed with respect to the underlying processes. Inverse switching time versus driving-field curves have been plotted for films of different thicknesses. They show that thinner films switch faster than thicker ones. The slopes of these curves have characteristic values in the nanosecond region of about 10^8 per oersted-second. Coherent rotation and oscillation of the magnetization have been clearly detected by picking up the flux change transverse to the driving field.

Thin permalloy films with uniaxial anisotropy may behave like a single magnetic domain; flux-changes are then possible by a mere domain rotation. Switching times of about 1 nsec (10^{-9} sec) for such a "coherent" rotation of the magnetization of the film subjected to a magnetic field pulse have been predicted based on an evaluation of the results of ferromagnetic resonance experiments by the Landau-Lifshitz equation.[1,2] The experimental problem is characterized by the display of the very short signals induced by the rapid flux-change, the length of which lies beyond the time resolution of conventional measuring instruments. By means of oscilloscopes with distributed amplifiers and by travelling wave oscilloscopes, film switching times had been observed down to 10 nsec and 3 nsec.[3,4] Even these advanced techniques, however, did not permit a more detailed investigation of the very fast flux-change processes. In this paper, film switching measurements are reported, carried out by an improved technique based on a pulse-sampling oscilloscope with an over-all response time of 0.35 nsec.[5]

Experimental techniques

A magnetic field pulse is generated in a 50-ohm strip transmission line by the discharge of a 50-ohm cable over a coaxial mercury relay (Fig. 1). The rise time of the field pulse is equal to or smaller than the response ime of the oscilloscope. A strip-line, consisting of two equal plates, has been selected because the magnetic field inside the plates is sufficiently homogeneous.[6] The strip-line is short circuited. Because of the reflected wave, the magnetic field is doubled as compared with the matched case. At the other end of the cable this reflected wave is absorbed by a matching network. The diode D serves to disconnect the matching resistor R_M from the cable during the charging time between the pulse intervals. In order to compensate for the response time of the diode an rc network is provided.

In addition to the pulse field, dc fields and reset fields can be set up in the plane of the film by two pairs of Helmholtz coils. The earth's magnetic field is cancelled by such a dc field.

The longitudinal flux-change of the film, the flux change in the direction of the pulse field, is picked up by a wire placed in the symmetry axis of the strip-line (Fig. 2a). The voltage induced by the air flux is cancelled by symmetrical termination of the wire by four resistors. Disturbances picked up from the electrical field of the pulse are reduced by the short-circuiting of the strip-line.

The transverse magnetic flux-change, the flux-change perpendicular to the pulse field, is linked by a wire placed normal to the axis of the strip-line (Fig. 2b). Since no air flux is picked up, one end of the wire can be short circuited for the reduction of capacitive disturbances. The remaining disturbances have been minimized by the use of a thin, resistive pick-up wire. An additional small wire above it has been found useful for capacitive compensation.[7] The signals are repetitively produced at a rate of about 50 cps and fed to the pulse-sampling oscilloscope over type RG 19 U wideband cable with a delay of about 140 nsec.[8] The signal delay is necessary because of the delayed generation of the sampling pulse. The synchronization pulse for the sampling oscilloscope is de-

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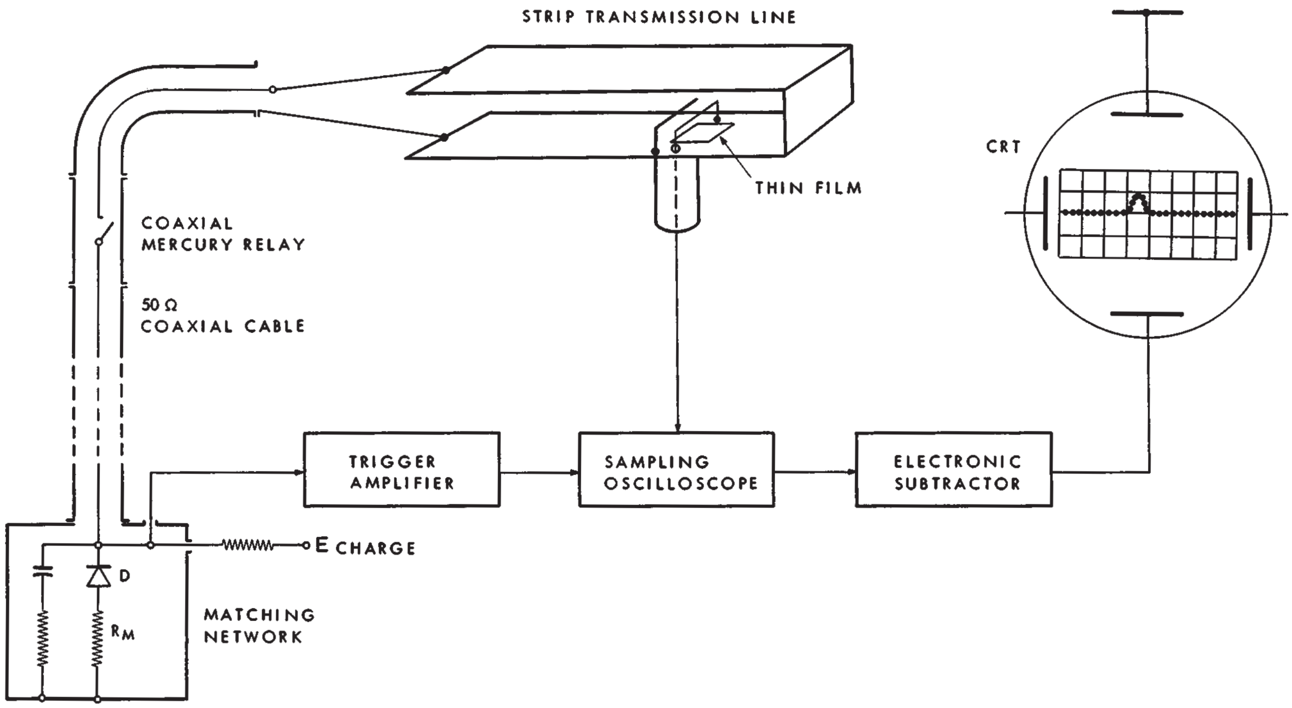
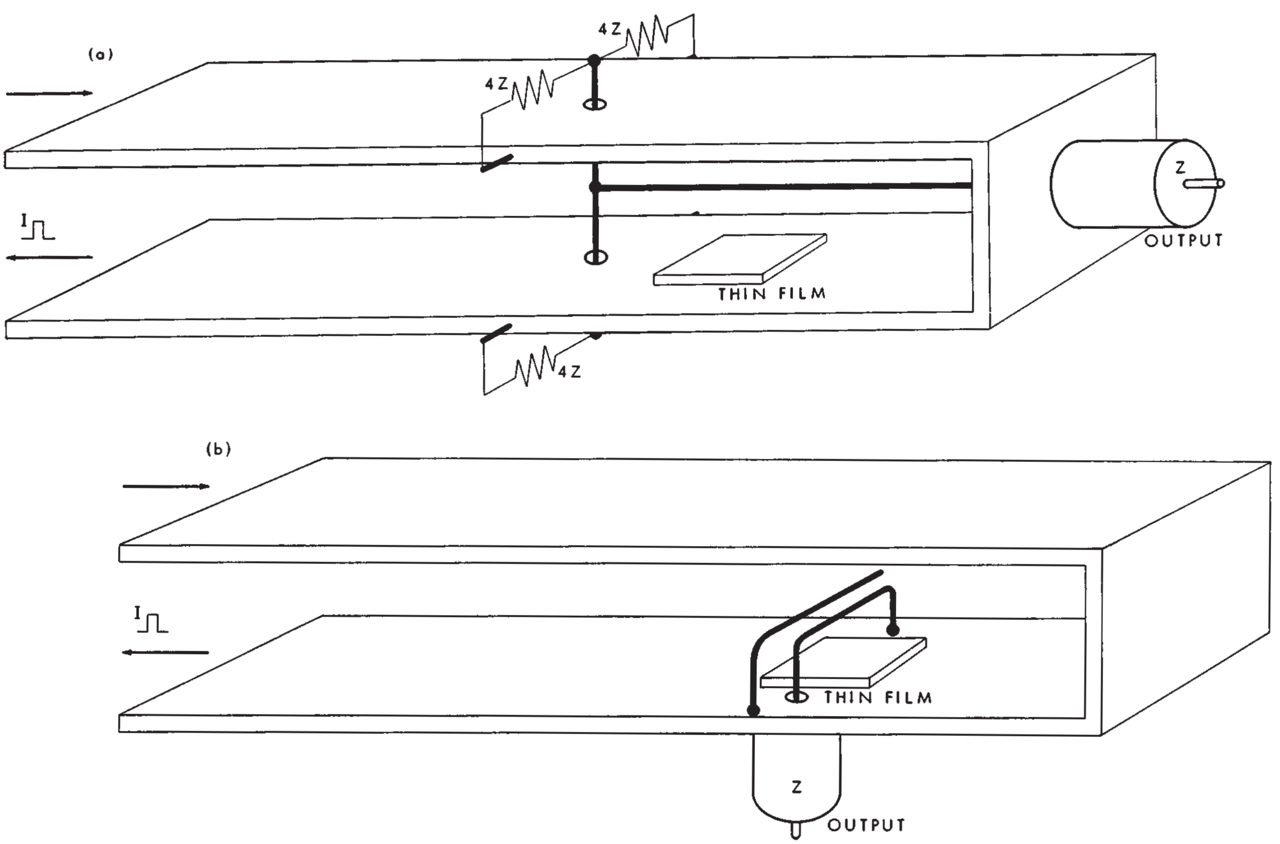
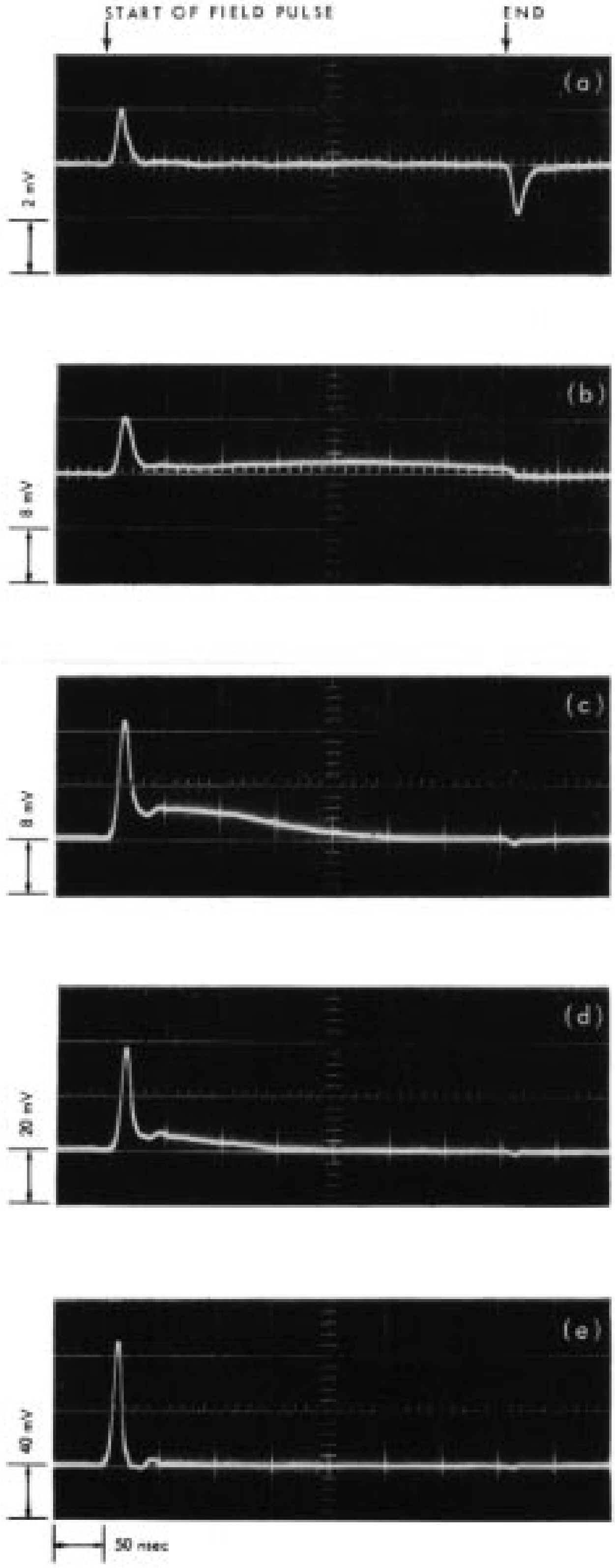


Figure 1 **Block diagram of the equipment for fast switching measurement.**

Figure 2 **Strip transmission line with longitudinal pick-up (a) and transverse pick-up (b).**





rived at the matching network of the discharge cable and not at the strip-line, in order to avoid distortion of the leading edge of the magnetic field pulse.

The picked-up disturbances, which are mainly periodic, have been reduced by electronic subtraction of the disturbing signal from the disturbed switching signal, both of which are generated alternatingly. The disturbing signal alone is produced by applying the field pulse while the film is completely saturated and, therefore, causes no flux-change. A complete storing of the two wave forms—disturbed and disturbing signal—is not necessary as the sampling oscilloscope allows a point-by-point subtraction.[9]

Switching signals longer than 10 nsec have been measured with high sensitivity by means of a Tektronix 517-A oscilloscope used in connection with a Type 206 Spencer Kennedy 300-mc distributed amplifier. While the maximum sensitivity of the equipment with the sampling oscilloscope is at present 30 mv/cm at sufficient signal-to-noise ratio, a sensitivity of 2 mv/cm can easily be obtained with the Tektronix 517-A setup.

Results and discussions

The flux-change of numerous permalloy films of thicknesses between 700 A and 5000 A and of various anisotropy fields H_K has been investigated. In most experiments a pulse field H_S is applied parallel to the easy direction and, simultaneously, a dc magnetic field H_T parallel to the hard direction. During the pulse intervals a reset field is provided oppositely to the pulse field.

• *Longitudinal signal*

Figures 3a to 3e show the longitudinal signals for increasing pulse fields H_S and constant transverse field H_T for a typical film (1 × 1 cm) observed with the 517-A oscilloscope.

Starting from low driving fields, we first notice a small positive pulse at the leading edge of the field pulse and a similar negative pulse at the trailing edge of the field pulse (Fig. 3a). These two pulses can be attributed to a small reversible rotation of the magnetization.

When H_S exceeds the coercive force H_c for wall motion, the first short pulse is followed by a long pulse, while the negative pulse at the end of the field pulse has almost disappeared (Fig. 3b). The increase in the amplitude of the first short pulse can be explained by an initial rotation of the magnetization by an increased angle, according to the theory of the rotational model.[10] The second long pulse is due to wall motion. The decrease of the amplitude of the short pulse at the end of the pulse field also follows from static theory, as the major part of the magnetization has been reversed.

Figure 3 **Longitudinal switching signals for constant transverse field H_T=0.5 oe and different pulse fields H_S, recorded by equipment with 7-nsec response time.**
Film 215 B2; 80/20 Ni-Fe; 1500 A; H_c=1.7 oe; H_k=3.0 oe; H_S=1.6 oe, 2.9 oe, 3.2 oe, 3.6 oe, and 5.0 oe, respectively, in (a) to (e).

For increasing H_S, the length of the second pulse decreases while its amplitude increases. At the same time the amplitude of the first peak grows considerably larger (Figs. 3c and 3d). Evidently, while an increasing part of the film switches by fast rotation, the remaining part, which becomes smaller and smaller, still switches by wall motion or possibly by slow incoherent rotation.[11,12]

Finally, the first peak becomes dominant, i.e., the film switches mainly by coherent rotation (Fig. 3e).

When we investigate the film switching by means of the sampling oscilloscope, we notice that the first peaks of the switching curves in Fig. 3 are not fully resolved by the 517-A oscilloscope. These peaks are much shorter and much higher, as is shown, for example, in Fig. 4. The lengths of these first peaks, which seem to be independent of H_S in Fig. 3, are of the order of 1 to 2 nsec, and change considerably with respect to the applied torque ($\mathbf{M} \times \mathbf{H}$). Figure 4 shows characteristic switching curves obtained by the sampling oscilloscope for various pulse fields and constant transverse field. Because of the still low signal-to-noise ratio of the sampling oscilloscope, only the high first peak of the switching signal, but not the smaller second one, can be displayed at present.

The delay between the start of the pulse field, and the 10 percent value of the output pulse for the short switching times, is less than 1 nsec. The delay decreases as expected when the pulse field H_S is increased.

- *Switching time*

If we define the switching time τ as the time interval between the 10 percent values of the signal peak amplitude, it becomes obvious from Figs. 3 and 4 that two switching times exist, whether we consider the peak amplitude of the first (fast) or the second (slow) part of the signal. In Fig. 5 the inverse switching time $1/\tau$ versus pulse field H_S is plotted for three films of different thicknesses and about the same anisotropy field H_K, based on the definition of τ given above. The curves in the lower parts of the pictures result from the slow, second pulse signal observed by the 517-A oscilloscope. The curves in the upper parts of the pictures are obtained from the first, fast signal observed by the sampling oscilloscope.

Obviously the two branches of each $1/\tau$ versus H_S curve for constant transverse field H_T originate from at least two different reversal mechanisms in the film. At low pulse fields, wall-motion or incoherent rotation are dominant, at high pulse fields, fast coherent rotation is dominant: each reversal mechanism is obeying a different $1/\tau$ versus H_S law.

Another definition of the switching time would be based on the time interval between the 10 and 90 percent value of the total flux-change. Such a definition leads to a continuous transition between the two branches of the $1/\tau$ versus H_S curves in Fig. 5, but entails a more difficult measurement.

A comparison of Figs. 5a, 5b and 5c shows that thinner films switch faster, with respect to coherent rotation, than thicker films. Moreover, we noticed that thinner

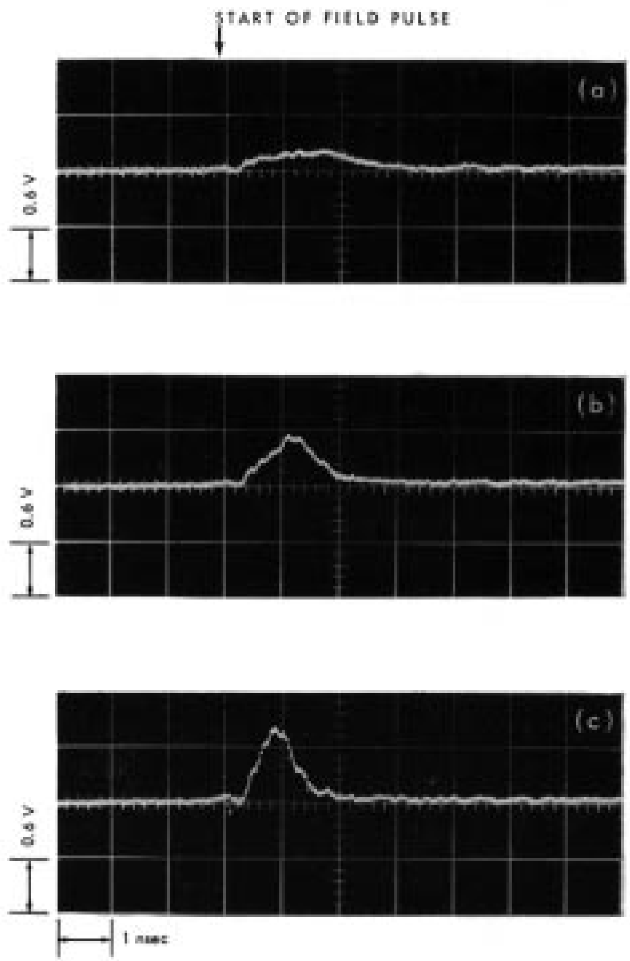


Figure 4 **Longitudinal switching signals for constant transverse field H_T=0.5 oe and different pulse fields H_S observed by sampling oscilloscope with 0.35-nsec response time.**
Film 215 B2; 80/20 Ni-Fe; 1500 A; H_c=1.7 oe; H_k=3.0 oe; H_S=3.8 oe, 5.0 oe, 7.5 oe, respectively, in (a), (b) and (c).

films show a smaller transition region between dominant wall-motion and dominant coherent rotation. These findings are substantiated by numerous measurements on films of various preparation parameters. Eddy currents, and a possible increased inhomogeneity of thicker films, can account for this fact. Moreover, in thicker films, the demagnetizing field in the plane of the film is increased and gives rise to a deviation from the single domain structure which may, in turn, hinder the coherent rotation.

Eddy currents are generated in the film itself by the coherent rotation of the magnetization. They flow in opposite directions at the upper and lower parts of the film, and cause a magnetic field which counteracts the rotation of the magnetization. It is estimated that this field, which is inhomogeneous over the cross section of the film, is sufficient to influence the switching times in our case for films thicker than about 2000 A.

As a result of the low signal-to-noise ratio, the experimental error of the switching times for fast, coherent rotation is rather high, so that the exact shape of the curves in Fig. 5 is still uncertain. Work is in progress to further decrease the noise level, and to extend the measurements to higher pulse fields. If we assume straight lines for these curves, we obtain slopes of approximately 10^8 per oersted-second.

- *Transverse signal and coherent rotation*

Investigation of the transverse flux-change clarifies the question as to whether or not the magnetization rotates in a coherent mode. The theoretically expected flux changes in longitudinal and transverse directions for coherent rotation can be deduced from the rotational model.[10] For example, if the initial and final directions of the magnetization are almost parallel to the easy direction, then in the transverse direction we can expect first a positive pulse, caused by the rotation of the magnetization into the hard direction, followed by a negative pulse, which is due to the rotation of the magnetization from the hard direction into the final position. Each of the voltage - time integrals of the positive and the negative parts of the transverse signal, equal in magnitude, has to be one-half of the total longitudinal voltage - time integral.

Figure 6 shows three pairs of longitudinal and transverse output signals, each pair for the same driving conditions.

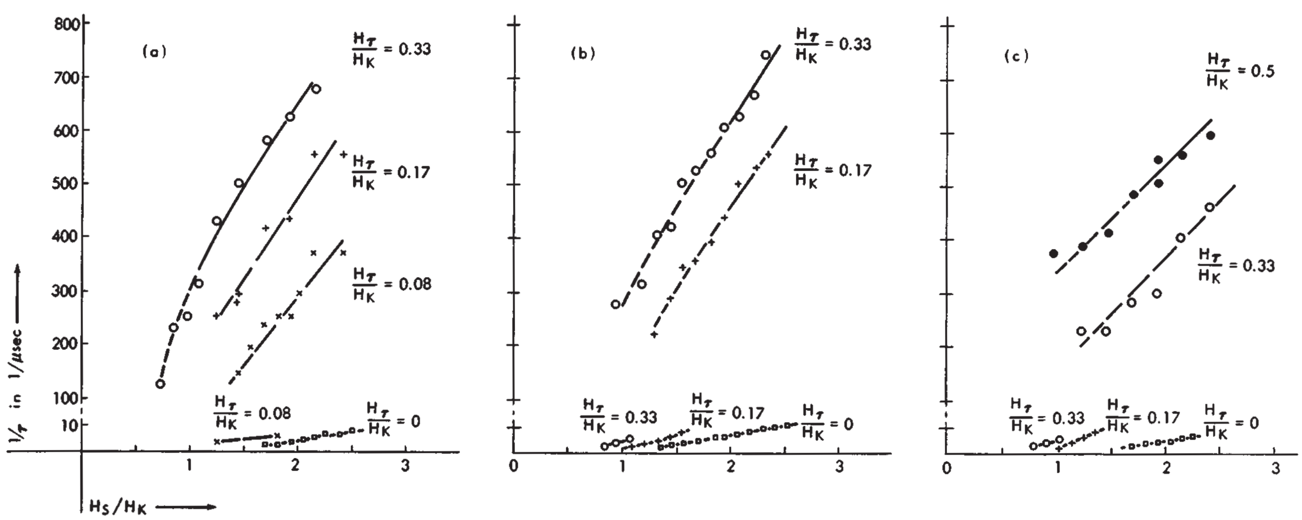
In Figs. 6a and 6b, a pulse field H_S slightly larger than H_K is applied in the easy direction with a small dc field H_T in the hard direction. The voltage - time integral of the first peak of the transverse output signal in Fig. 6b and that of the longitudinal signal in Fig. 6a, taken over the same period of time, show that not the entire magnetization is turned into the hard direction, which means that no complete coherent rotation takes place. Inspection of this first peak by the sampling oscilloscope reveals that it is not fully resolved in Figs. 6a and 6b, but lasts only about 2 nsec.

The following explanation of these curves is suggested: The first short spike is caused by the rotation of the magnetization from the initial direction θ_1 towards the hard direction into the direction θ_2. This rotational process is not completed but is followed by magnetization reversal by wall motion into the final direction θ_3. Evidently the transverse component of the magnetization in direction θ_3 is smaller than in direction θ_2, which explains the long negative tail of the curve in Fig. 6b.

This model is further supported by partial switching experiments. If the pulse field is switched off before the reversal process is completed, short, negative spikes appear in the transverse and longitudinal signals at this moment.

The effect that no complete coherent rotation takes place, although H_S is larger than the threshold field for rotational switching, may be due to the spread of the value of the anisotropy field H_K and to the spread of the easy direction in the film. The indicated value of H_K equal to 3 oe has been obtained from the slope of the *MH* loop in the hard direction for small driving fields according to the standard procedure and can be regarded as an average value only.[1] If we inspect the *MH* loop for large driving fields, however, we notice that saturation is only gradually approached for fields larger than this average value H_K. Those parts of the film with higher anisotropy

Figure 5 **Inverse switching time $1/\tau$ vs normalized switching field H_S/H_k for three films of different thicknesses.**
(a) Film 230 B3; 80/20 Ni-Fe; 1100 A; H_c=1.8 oe; H_k=3.0 oe.
(b) Film 215 B2; 80/20 Ni-Fe; 1500 A; H_c=1.7 oe; H_k=3.0 oe.
(c) Film 159 B3; 80/20 Ni-Fe; 2500 A; H_c=1.2 oe; H_k=3.0 oe.



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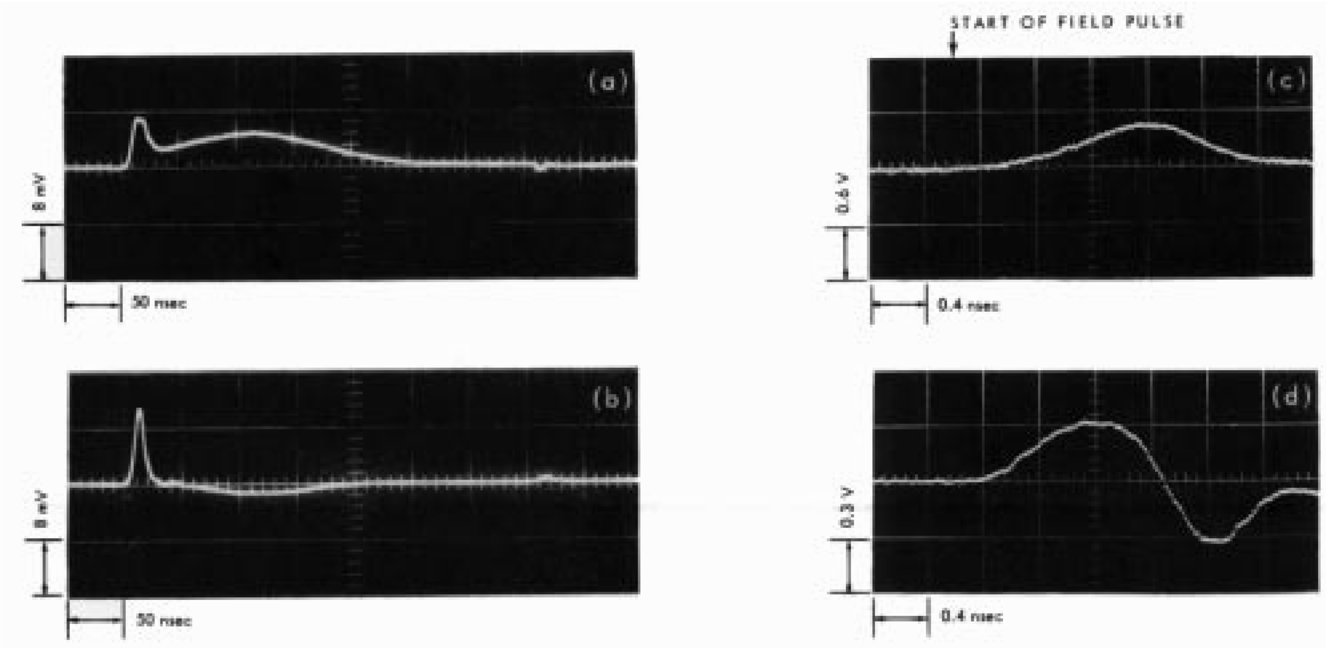

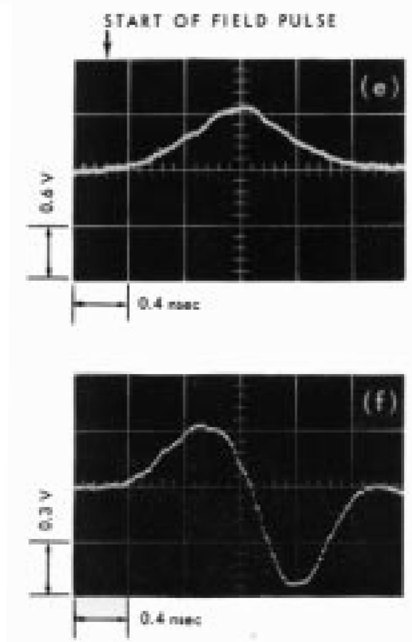

Figure 6a, b **Longitudinal (a) and transverse (b) switching signals for flux reversal by wall motion.**
H_S=4.0 oe; H_T=0.25 oe.

Figure 6 c, d **Longitudinal (c) and transverse (d) switching signals for flux reversal by incoherent rotation.**
H_S=6.0 oe; H_T=0.75 oe.

Figure 6 e, f **Longitudinal (e) and transverse (f) switching signals for flux reversal by coherent rotation.**
H_S=6.0 oe; H_T=1.25 oe.

6(a) to 6(f):
Film 215 B2; 80/20 Ni-Fe; 1500 A; H_c=1.7 oe; H_k=3.0 oe.

fields may, therefore, hinder the complete coherent rotation.

As the pulse and transverse fields are increased, the complete coherent rotation of the magnetization is more and more approached (Figs. 6c and 6d) and finally reached (Figs. 6e and 6f). From the voltage - time integrals of the longitudinal and transverse output pulses it can be concluded that the magnetization rotates in a coherent mode from the initial direction θ_1 to the final direction θ_3, which is not close to the easy direction in this case.

Discrepancies still exist with respect to the theoretically expected total flux-change and that observed by pulse measurements, caused probably by shielding effects of the strip transmission line.

• *Pulse field in hard direction*

The shortest switching times for a given pulse field H_S can be expected when the pulse field is applied at right angles to the magnetization of the single domain film; for example, when the magnetization points into the easy direction and the pulse field into the hard direction. The experimentally observed switching times are actually about 1 nsec for pulse fields of the order of the anisotropy field. Again, thicker films switch more slowly than thinner ones.

Figure 7 shows longitudinal and transverse output signals for various pulse fields applied exactly in the hard direction. During the pulse interval a pulsed reset field in the easy direction assures the single domain state of the film at the beginning of the field pulse.

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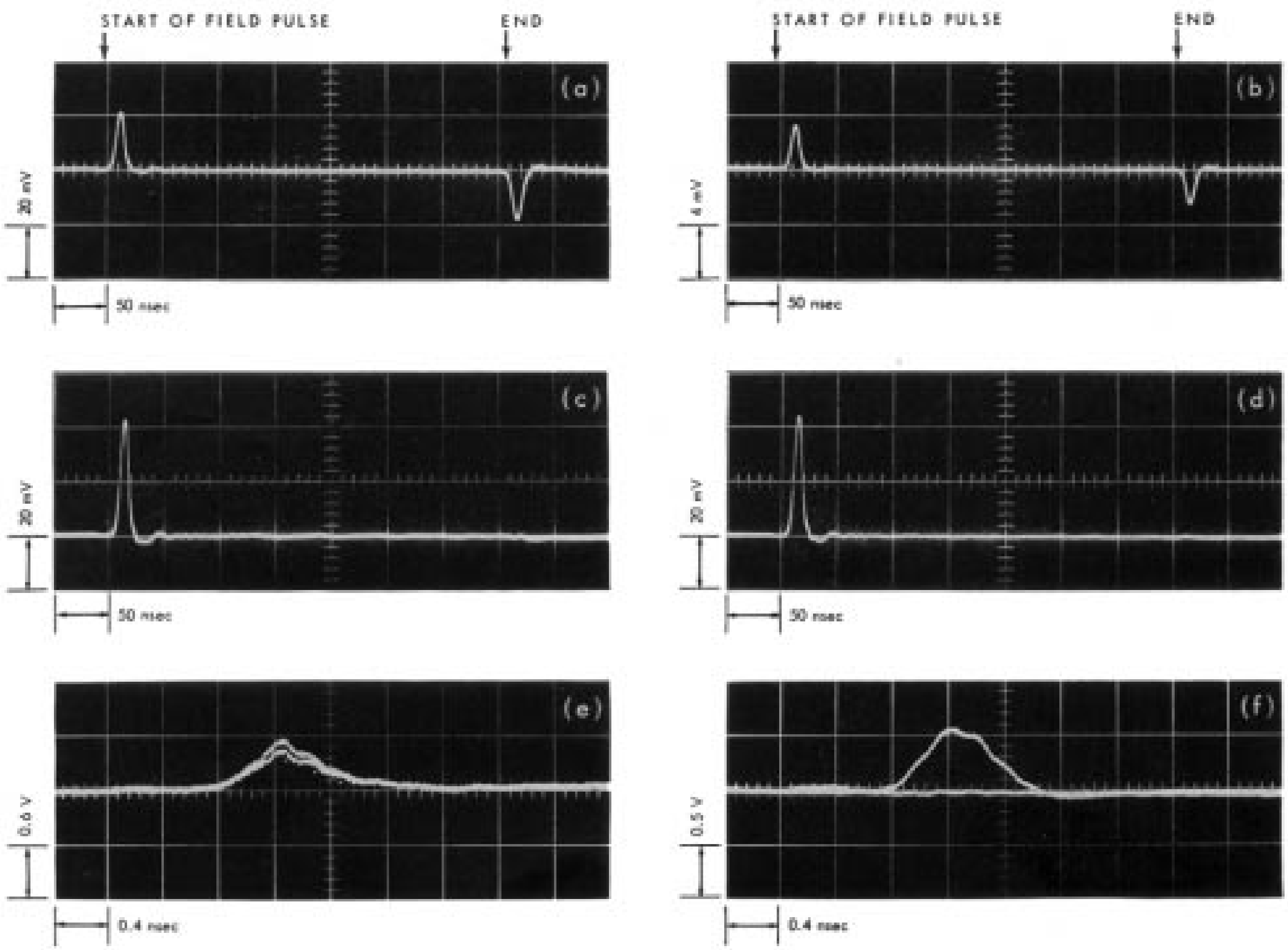
When a small pulse field $H_S < H_K$ is applied, we notice that the voltage - time integrals of the output signals at the beginning and the end of the pulse field are equal for longitudinal as well as for transverse pick-up (Figs. 7a and 7b). The ratio of the respective voltage - time integrals, moreover, agrees with the rotational model. Evidently, reversible coherent rotation of the magnetization takes place. However, for $H_S > H_K$, the transverse signal at the end of the field pulse disappears while, simultaneously, the corresponding longitudinal signal changes substantially (Figs. 7c and 7d). The latter pulse has decreased considerably in amplitude and is followed by a long and small tail, which is almost invisible.

The disappearance of the second transverse output signal for $H_S > H_K$ is easily explained by the fact that half of the magnetization of the film turns clockwise, and half counter-clockwise, back towards the easy direction. Inspection of the longitudinal signal gives information about the speed of this process. The first short and very small pulse of the longitudinal output signal at the end of the field pulse may be due to a rotation of the magnetization of a small part of the film in equal parts in clockwise and counter-clockwise directions. The remaining flux-change into remanence is very slow and has been found to last several hundred nanoseconds. This indicates that incoherent rotation or wall motion takes place. With respect to the underlying process it is of interest to note that no changes, or only minor changes, in the switching time occur whether this reset field is applied or not, i.e., whether the pulse field acts on a single-domain film or on one which is split up into numerous domains. This characteristic is shown in Fig. 7e, in which the signal with the larger amplitude corresponds to the case where the pulse field is applied to the single domain film, and that with lower amplitude to the case where the film is split up into numerous domains. The difference in amplitude of these two curves is a result of the remanence of the film, which amounts to about 25 percent in the split state. Figure 7f

Figure 7 **Longitudinal (a), (c), (e) and transverse (b), (d), (f) switching signals for pulse fields H_S in the hard direction with zero transverse field H_T. (Film 215 B2).**
(a, b) Reversible rotation for $H_S < H_k$. $H_S = 1.6$ oe.
(c, d) Splitting up of initial single domain for $H_S > H_k$. $H_S = 7.0$ oe.
(e, f) Comparison of first pulse for single and split-up domain. $H_S = 7.0$ oe.



depicts the corresponding transverse signals. For the split initial state, obviously, no output signal results.

• *Oscillation of the magnetization*

In some films we detected damped oscillations of the magnetization around its equilibrium direction when a pulse field is applied to the film. Figure 8, for example, shows the transverse output signal when magnetization reversal takes place when a pulse field is applied in the easy direction with a dc field in the hard direction. This oscillation can be considered as the excitation of ferromagnetic resonance by the driving pulse. With increasing driving field, the resonance frequency is increased, according to theory. The oscillations, moreover, are more pronounced the more the conditions for coherent rotation are approached.

The damping parameter λ in the Landau-Lifshitz equation has been determined by ferromagnetic resonance measurements at 500 mc/sec for the same films. The resulting λ agrees with that obtained from the decay of the observed oscillation.

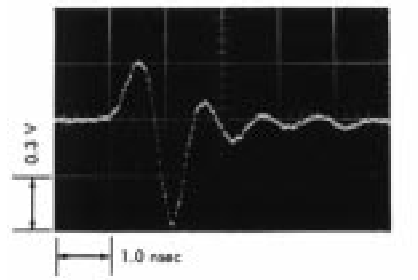


Figure 8 **Transverse switching signal shows oscillation of the magnetization for coherent rotation of the magnetization.**
Film 138a; 80/20 Ni-Fe; 1300 A; $H_c=1.75$ *oe;* $H_k=2.5$ *oe.*

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