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UNDER RAMP EASY-AXIS FIELDS IN THIN Ni-Fe FILMS

by

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Chapter 1

INTRODUCTION

High-speed flux reversal at low reversing fields has long been considered an attractive feature of thin Ni-Fe films for potential computer memory and digital logic applications. Reversal times between 1-10nsec at reversing fields of the order of 3.0 Oe are commonly observed for 1 cm-diameter circular films of 80% Ni-20% Fe composition and of thickness near 1000Å. In the absence of external fields, Ni-Fe films fabricated by vacuum deposition in the presence of a large dc field in the substrate plane tend to remain uniformly magnetized along a direction referred to as the easy-axis which is usually coincident with the original dc field direction during fabrication. Currently the origin of this so-called induced uniaxial anisotropy is uncertain. For reasons made clear in Chapter 2, the minimum easy-axis reversing field is called the domain-wall motion coercive field \( H_w \); and the field required to saturate the film along the hard-axis, which is by definition perpendicular to the easy-axis, is called the anisotropy field \( H_K \).

Extensive investigation of magnetization reversal in thin, uniaxially-anisotropic, vacuum deposited, Ni-Fe films ranging in thickness between approximately 100-10,000Å has been reported in the literature (e.g. ref. 1). Reversal time is ordinarily measured from the switching
voltage waveforms exhibited by a pair of orthogonal flux derivative sensing coils tightly encircling the film. Disparate definitions of reversal time measured from the easy-axis switching voltage waveform have led to confusion in the literature. Results are most often presented in the form of curves of reciprocal electronic reversal time, hereafter designated as $\tau_e$, versus magnitude of easy-axis step field $H_x$ with hard-axis bias field $H_y$ as a parameter. Piecewise linearization of these curves usually suggests the existence of three different flux reversal processes classified according to relative reversal time as low-speed, intermediate-speed, and high-speed. In this laboratory, the results of experiments on magnetization reversal under pulsed and ramp easy-axis fields have led to the formulation of a new kinematical model for intermediate-speed switching as a domain boundary propagation phenomenon originating from the film edges. Further, it is shown that reversal times characteristic of this process may be from 3 to 5 times longer than the values measured electronically in conventional pickup coil systems.

Low-speed flux reversal for $H_x$ slightly higher than domain-wall motion coercive field $H_w$ is believed to consist of nucleation of domain tips at the easy-axis extremities of the film, longitudinal (easy-direction) domain-tip motion to form stripe domains parallel to the easy-axis, and transverse (hard-direction) expansion of stripe domains by parallel domain-wall motion to complete the switching. Parallel or lateral domain-wall motion has been observed by many [2] to obey the empirical relationship $v = m_1(H_x - H_w)$, where $v$ is
transverse velocity and $m_1$ is by definition the lateral domain-wall mobility.

High-speed switching with $\tau_e$ of the order of 1 nsec for $H_s$ near the irreversible threshold fields defined by minimization of the total energy $W = K \sin^2 \theta - \bar{M}_0 \cdot \bar{H}_a$, where $\theta$ is the angle between magnetization $\bar{M}_0$ and easy-axis, $\bar{H}_a$ is applied field, and $K$ the anisotropy constant, is believed to occur by single-domain coherent rotation of the magnetization throughout the film. Comparison of the empirically determined locus of irreversible threshold fields with the theoretical astroid locus defined by minimization of $W$ and simultaneous monitoring of orthogonal easy-axis and hard-axis flux derivatives during reversal tend to lend credence to the hypothesis of coherent rotation.

Flux reversal at intermediate speeds ($10 \text{ nsec} < \tau_e < 100 \text{ nsec}$) is least understood. Although this region of the switching curves is sometimes presumptuously designated as the region of "incoherent rotation", evidence of high-speed propagation phenomena has been cited as a possible mechanism for intermediate-speed switching. "Labyrinth propagation" has been discussed by Smith and Harte [3], and "dynamic walls" propagating 10 to 100 times faster than normal Bloch or Néel walls are reported by Stein [4]. Localized nucleation of a high-speed wavefront having nominal velocity of $10^7$ cm/sec is described by Jaeklin [5]. The requirement of moderate $H_T$ appears to be a feature common to all three phenomena. A correlative presentation of the phenomenology of high-speed domain-boundary propagation under interrupted pulse and uninterrupted ramp applied magnetic fields is the primary aim of this dissertation.
When a thin magnetic film is situated appropriately between crossed polarizers, the differential phase shift between left and right circularly polarized monochromatic waves reflected from the film plane results in an intensity contrast between regions of opposite magnetization via the Kerr magneto-optic effect in the material. Dynamic Kerr magneto-optic photography of fast flux reversal has not yet been reported, and the kinematics of intermediate-speed switching has proved difficult to infer from indirect electronic sensing data. Thus the controversial but widely employed quasi-static procedure of examining remnant flux patterns with a Kerr magneto-optic display system before and after application of a pulsed field seems at present to be the optimum available technique for investigating high-speed propagation phenomena.

An experimental effort to extend the interrupted-pulse, velocity-field characterization to higher fields and velocities has produced a more complete and quantitative description of high-speed propagation phenomena for applied fields and total switching times well into the region of "incoherent rotation". In particular, for $H_\|$ well above $H_\$ but below the anisotropy field $H_K = 2K/M_O$, a pair of "zig-zag walls" composed of connected domain tips extended in the hard-direction is observed to switch approximately 100% of the film by longitudinal motion beginning at the easy-axis edges. For threshold fields near the theoretical astroid value, well-defined propagation fronts originating at the film edges have been observed and their velocities carefully measured. The resulting velocity-field data is used to predict with good accuracy the results of experiments on uninterrupted reversal under
a ramp field $H_s = st$ for $s$ up to $5 \times 10^6$ Oe/sec. Influence of position and geometry of flux derivative sensing coils upon measurements of switching time associated with longitudinal domain-boundary propagation is discussed both theoretically and experimentally. It is found that for $H_e = 0$, electronic switching times measured in conventional pickup coils can be considerably shorter than true value. Finally, results in this laboratory are compared with the literature, and suggestions for further experimental and theoretical exploration are offered.
Chapter 2

PROPAGATION PHENOMENA UNDER PULSED EASY-AXIS FIELDS

2-1. Introduction

Propagation phenomena under pulsed easy-axis fields $H_g$ of amplitude from $H_w$ up to $2H_k \approx 8$ Oe and duration from 3 nsec to 50 $\mu$sec have been examined by Kerr magneto-optic observation of the remnant flux patterns before and after application of the field. Although the magneto-optical approach is favored over less direct electronic techniques, the possibility of dynamic relaxation effects demands a cautious interpretation of results. Thus the quasi-static velocity-field characterization is presented below with an awareness that its ultimate validity lies in the accuracy with which it describes uninterrupted switching, as discussed in Chapter 3. A more detailed account of the experiments described in this chapter is given by K. D. Savage [6].

2-2. Film Fabrication

Single-layer and magnetostatically-coupled two-layer planar films of nominal 82-18 Ni-Fe composition, vacuum-deposited and annealed in the presence of a 34 Oe dc field in the substrate plane have been investigated in this study. A permalloy source of approximately non-magnetostrictive composition is evaporated onto Corning 0211 glass substrates ($CTE = 7.2$ ppm/deg.C) at temperature of 300 deg. C and a pressure of $10^{-6}$ Torr. Evaporation rates up to $100$Å/sec. are obtained in a diffusion pump system using resistance source-heating by a tungsten boat element; slower rates of 5-20Å/sec are achieved in an
ion-pump system employing electron bombardment source-heating. During deposition, film thickness is manually controlled via a commercial quartz crystal oscillator thickness monitoring system. Final film thickness after deposition is determined magnetically by comparison of the vertical deflection of the 20 Hz hysteresis loop of film under test with that of an interferometrically or mechanically measured standard of the same composition and planar dimensions.

Single-layer films fabricated as described exhibit \( H_k \) of 3-5 Oe and \( H_w \) of 1-2 Oe; while two-layer films separated by a 100Å SiO layer have similar \( H_k \) and typical \( H_w \) of 0.2 Oe, as measured from the 20 Hz hysteresis loop. Film thickness ranges from 150-2000Å of permalloy per layer. A final 500Å SiO coating is deposited on all films for enhancement of Kerr magneto-optic contrast.

2-3. Experimental Technique

Low-level excitation requiring many long duration pulses for appreciable switching is accomplished with a pair of 2 inch-square, 4-turn coils spaced for optimum uniformity in Helmholtz fashion. Rise and fall times of 50 nsec and a minimum width at full amplitude of 100 nsec are achieved with this drive system illustrated schematically in Fig. 2.1. For total reversal times in the range 5-100 nsec, a shorted, double-strip transmission line section having 0.5 nsec rise and fall times and 3 nsec minimum width capability is used to generate the required fields. The transmission line section constructed of two 0.500 inch-wide brass strips spaced 0.066 inches apart for nominal characteristic impedance of 50 ohms is powered by a delay-line pulser
Fig. 2.1. Kerr magneto-optic and electronic systems schematic.
capable of charging voltages up to 500 volts. Between pulses the strip line is opened for optical inspection of the flux patterns from which velocity measurements are made.

2-4. Experimental Results

Kerr magneto-optic sequences of three distinct propagation phenomena observed throughout this investigation are displayed in Fig. 2.2. For \( H_s \approx H_w \), a mixture of mechanisms is illustrated in Fig. 2.2, A-E, for a circular film. Connected domain tips form a pair of "zig-zag walls" which reverses a central band parallel to the easy-axis by longitudinal propagation, whereupon the remainder of the film is switched by parallel wall motion. For \( H_s \) well above \( H_w \) but below the theoretical astroid value, the zig-zag wall pair is observed to switch approximately 100\% of the film as shown for the triangle in Fig. 2.2, S. Note that both parallel wall mobility \( m_1 \) and zig-zag wall mobility \( m_z \) defined by

\[
v_z = m_z (H_s - H_w)
\]

may be measured from the sequence of Fig. 2.2, A-E. Empirically it is found that \( m_z \propto m_1 / \tan \theta \) where the tip half-angle \( \theta \) is an average over many tips measured from Bitter patterns; for single films, \( \theta \) ranges from approximately 16° to 10° for film thickness from 150Å to 2000Å. Typically \( m_z \approx 2m_1 / \tan \theta \) which suggests that the lateral mobility of one flank of a domain tip perpendicular to itself is nominally twice \( m_1 \); however, no domain-tip flank mobilities are measured in this work. Measured values of \( m_1 \) are in general agreement with the literature [2] with a sharp reduction observed in both \( m_1 \) and \( m_z \) for cross-tie walls; typical \( m_z \) is \( 1 \times 10^5 \) cm/sec-Oe, while
Fig. 2.2. Domain-boundary propagation for circular film 
\(H_w = 1.5 \text{ Oe}, H_k = 4.0 \text{ Oe}, D = 700 \text{ Å}\) and triangular film \(H_w = 1.6 \text{ Oe}, H_k = 4.0 \text{ Oe}, D = 1300 \text{ Å}\) for various pulsed easy-axis fields \(H_g\) and hard-axis bias \(H_c\): A-E respectively 5, 10, 20, 30, 60 pulses with \(H_c = 0\) and \(H_g = 2.5 \text{ Oe}\) by 1 \(\mu\text{sec}\); F-J respectively 1, 2, 3, 4, 5 pulses with \(H_c = 0\) and \(H_g = 5.0 \text{ Oe}\) by 150 \(\text{nsec}\); K-N respectively 1, 2, 3, 6 pulses with \(H_c = 0.4 \text{ Oe}\) and \(H_g = 4.0 \text{ Oe}\) by 150 \(\text{nsec}\); 0, single pulse with \(H_c = 0.4 \text{ Oe}\) and \(H_g = 4.2 \text{ Oe}\) by 150 \(\text{nsec}\); P-R respectively 1, 2, 3 pulses with \(H_c = 0\) and \(H_g = 5.0 \text{ Oe}\) by 160 \(\text{nsec}\); S, 10 pulses with \(H_c = 0\) and \(H_g = 3.3 \text{ Oe}\) by 180 \(\text{nsec}\); T, single pulse with \(H_c = 0.04 \text{ Oe}\) and \(H_g = 5.3 \text{ Oe}\) by 160 \(\text{nsec}\).
values as low as $2 \times 10^4 \text{ cm/sec-Oe}$ are measured for cross-tie walls. Lower wall energies in two-layer films give rise to longer, sharper tips (smaller $\theta$) resulting in higher $m_z$; typical $m_z$ values for two-layer films are near $3 \times 10^5 \text{ cm/sec-Oe}$.

For $H_s$ above a sharply defined threshold roughly corresponding to the theoretical astroid value, a novel type of longitudinal domain-boundary propagation at velocities much higher than for the zig-zag wall is observed in single films. Both threshold fields and apparent domain-boundary mobility for this process show critical sensitivity to transverse bias $H_t$, mechanical alignment with drive field $H_s$, the magnetization distribution at the film edges, and overall film uniformity. Mechanical alignment between easy-axis and applied field is achieved by optimizing the symmetry of the flux pattern left after partial switching with $H_t = 0$. The consistently well-defined propagating fronts observed for $H_t = 0$ are shown in Fig. 2.2, F-J, for the circular film and in Fig. 2.2, P-R, for the triangle. Edge effects are revealed in a comparison of the shapes of the propagating boundaries in these two sequences. The effect of a dc hard-axis bias $H_t$ is shown in Fig. 2.2, K-0, for the circle and in Fig. 2.2, T, for the triangle. For $H_t = 0$, the circular film tends to switch in quadrants, with longitudinal propagation occurring in all four quadrants. For $H_t \neq 0$, propagation is enhanced in one pair of diametrically opposite quadrants and suppressed in the other, the choice of quadrants being determined solely by the polarity of $H_t$. Longitudinal propagation in the triangular
film for $H_L = 0$ proceeds in such a way as to maintain geometrical similarity with the triangle. For $H_L \neq 0$, propagation from one edge is enhanced, the choice of edge again determined by the polarity of $H_L$.

Quantitative characterization of the phenomena described above is presented in the empirical velocity-field plots of Fig. 2.3 and 2.4 in which the easy-axis component of propagation velocity is plotted against amplitude of easy-axis field $H_s$ for typical single and two-layer films with normalized hard-axis bias field $h_t = H_t/H_k$ as a parameter. For both single and two-layer films, the initial slopes at low fields corresponding to domain-tip and zig-zag wall motion reflect the observation that propagation velocity is altered only slightly in magnitude (significantly in direction) by hard-axis bias field $H_L$. The relation $m_2 \propto m_1 / \tan \theta$ is found to hold rather well at low fields for both single and two-layer films. Both threshold field and apparent domain-boundary mobility for the anomalous high-speed mode of propagation in single films show strong dependence upon $H_L$. For $H_L = 0$, a typical piecewise mobility of $10^6$ cm/sec-Oe is measured. In two-layer films, flux patterns appear to indicate that above an apparent threshold between $H_w$ and $H_k$, high-speed reversal occurs by longitudinal propagation of disjoint domain tips moving at anomalously high velocity followed by a small percentage of parallel wall motion. Typical mobility values of $10^7$ cm/sec-Oe cannot be explained by the observed static tip angles, and the apparent threshold shows no simple correlation with either $H_w$ or $H_k$. The well-defined propagation
Fig. 2.3. Easy-axis component of velocity vs. easy-axis field $H_s$ for single-layer film ($H_w = 1.2$ Oe, $H_K = 3.0$ Oe, $D = 1760 \, \text{Å}$) and 2-layer film ($H_w = 0.4$ Oe, $H_K = 3.5$ Oe, $D = 750\, \text{Å}$ per layer).
fronts observed in single films for $H_s$ near the theoretical astroid value have not been detected in two-layer films over the range of $H_s$ used in these experiments.

Velocity measurements at the highest fields obtained in the strip line system are presented in Fig. 2.4 for the single film of Fig. 2.3. At these field levels, the propagation fronts as observed statically appear to lose definition and to widen significantly, especially in the case of moderate transverse bias $H_L$. In such cases, an average easy-axis component of velocity is measured. Single field pulses at varying width rather than multiple pulses of constant width are used in making high-field velocity measurements in order to maintain a constant start condition. Static flux patterns similar to the fine-structured stripe-domain patterns left after static hard-axis demagnetization are observed with Bitter patterns. This suggests longitudinal propagation of a very wide wall of field-dependent width within which the magnetization is turned in the hard direction. Dynamic relaxation into the fine-structured stripe-domain pattern might then occur over a region in the vicinity of the moving wall upon removal of the pulsed field $H_s$.

In the following chapter, uninterrupted magnetization reversal under an applied ramp field of the form $H_s = st$ with $s$ up to $5 \times 10^6$ Oe/sec is studied electronically in light of the propagation phenomena observed magneto-optically. Knowledge of these effects gained from the pulsed field experiments is used to good advantage in planning the ramp field experiments, especially in regard to location and geometry of pickup coil which is discussed in considerable detail in Chapter 4.
Fig. 2.4. Easy-axis component of velocity vs. easy-axis field $H_s$ for the single-layer film of Fig. 2.2 at high velocity.
PROPAGATION PHENOMENA UNDER RAMP EASY-AXIS FIELDS

3-1. Introduction

Pragmatically, the legitimacy of the quasi-static, interrupted-pulse characterization of Chapter 2 must be tested by the measure of its conformity with empirical data on uninterrupted reversal. Direct Kerr magneto-optic observation of uninterrupted switching is, of course, precluded at present by the short switching times involved. Hence an appeal is made to the less direct procedure of electronically sensing flux changes with an orthogonal pair of probing coils as reported by numerous researchers [1]. In this chapter, the results of experiments on uninterrupted magnetization reversal under sinusoidal fields of 30 Oe p-p at frequencies up to 50kHz are presented.

For switching confined to sufficiently small argument of the experimentally tractable sine wave, the latter may be adequately approximated by an excitation of the mathematically more tractable ramp form, \( H_s = st \). The error \( E \) in making this approximation is no greater than \( E \approx (\theta^2/6) \times 100\% \), where only the first two terms in the small argument expansion of the sine wave are included, and \( \theta \) should be taken as the value of the argument near the end of reversal. Since \( E \approx 2.6\% \) for \( \theta = \pi/8 \), the maximum argument observed experimentally, it is assumed that magnetization reversal occurs under the influence of a ramp drive field of the form \( H_s = st \) with \( s \) up to \( 5 \times 10^6 \) Oe/sec, the apparatus limit.
3-2. **System Details**

Experimentally, the applied field $H_s = 15 \sin 2\pi ft \text{ Oe}$ is obtained by passing a sine wave of current through a 50-turn, flat, rectangular solenoid $5.5 \text{ cm} \times 5.5 \text{ cm} \times 1.4 \text{ cm}$ producing 10 Oe/amp and designed [7] for field uniformity to within 1% over the volume of a circular film 1 cm in diameter. The field coil has a self-resonant frequency of 2.5 MHz and self-inductance of 39 $\mu$H. During switching, the thin film flux derivative is sensed with a 1-turn pickup coil, the position and geometry of which are described in 3-3. Thin film, 1-turn pickup coil, and 1-turn compensation coil of opposite phase to pickup coil for cancellation of the drive field flux derivative are positioned inside the field coil. Cancellation is effected by manually positioning the compensation coil, which has larger component of area normal to the drive field than the pickup coil, near the edge of the field coil at a point of reduced flux density.

Dual-trace sampling and real time CRO's are used in parallel to monitor displays of switching voltage $\phi_g$ and flux $\phi_s$ versus either $H_s$ or time as illustrated in the system schematic of Fig. 3.1. Field signal $H_s$ is derived from a 1-ohm sampling resistor in series with the field coil. Flux $\phi_s$ is obtained by RC-integration of the time-stretched $\dot{\phi}_s$ available at the analog output jack of the sampling CRO. Dual-trace vertical and horizontal real time preamplifiers afford four-channel real time capability as shown in Fig. 3.1.

Since all data presented in this chapter is obtained from X-Y displays of $\dot{\phi}_s$ versus $H_s$, consideration of electronic phase shift
Fig. 3.1. Ramp field switching system schematic.
between vertical and horizontal signals becomes important. If phase shift \( \pm \varphi \) is present in the system, then an event occurring at time \( t_e \) and field \( H_e = H_m \sin \omega t_e \) appears to occur at a different field value \( H'_e \) given by

\[
H'_e = H_m \sin(\omega t_e \pm \varphi) = H_m \sin(\sin^{-1} H_e / H_m \pm \varphi),
\]

which for small \( \varphi \) becomes

\[
H'_e \approx H_e \pm \varphi \sqrt{H_m^2 - H_e^2}.
\]

For \( H_m^2 = (15 \text{ Oe})^2 \gg H_e^2 \), as is usually the case, the phase-induced error is approximately \( 1/4 \text{ Oe/deg.} \), an alarmingly large figure. Such large field errors caused by relatively small phase shifts necessitate precautionary measures to ensure that intrinsic system phase shift is within tolerable limits, e.g. less than \( \pm 0.5 \text{ deg.} \), corresponding to field error within approximately \( \pm 0.1 \text{ Oe.} \). Operationally, electronic phase shift in the system is conveniently divided at the CRO horizontal preamplifier input into two distinct sources: (1) phase shift between actual field and derived field signals up to the horizontal preamplifier input, and (2) phase shift between horizontal preamplifier input and horizontal deflection plates of the CRT. The latter source is easily eliminated by ensuring that sampled and real time X-Y displays are identical over the frequency range of the measurements. Thus the real time system, with which data is most conveniently taken, consisting of a pair of Tektronix Type 3A1 plug-in preamplifiers in a Type 564 storage oscilloscope is readily verified to be phase shift free up to \( f = 50 \text{ kHz} \) by parallel monitoring with the dual-trace sampling system. Phase shift
up to the horizontal preamplifier input is investigated with the system of Fig. 3.2 in which a Lissajous figure is formed from the time derivatives of true and derived field signals. With no film in the pickup coil, the time derivative of true field is sensed in the uncompensated coil, amplified, and applied to the vertical channel of either sampling or real time CRO. The derived field signal is differentiated to within 0.3 deg. of phase shift by choosing a differentiator time constant \( RC = \frac{T}{1000} \) , where \( T \) is the sine wave period and \( R \) is the resistance presented by the terminated length of transmission line. After amplification, the resulting signal is applied to the horizontal channel of the CRO forming a Lissajous figure which, in the absence of system phase shift, displays a phase shift of 0.3 deg. with respect to the vertical signal, a value barely measurable from the pattern. The two techniques described above reveal that the system of Fig. 3.1 possesses intrinsic electronic phase shift less than 0.3 deg., i.e. less than the differentiator phase shift, up to \( f = 50 \text{ kHz} \).

In regard to both phase shift and field calibration, caution must be exercised in the selection of sampling resistor \( R_s \). Commercially available 1-ohm, noninductively wire-wound resistors are observed to have sufficient residual series self-inductance to cause phase leads \( +\phi \) in (3.2) of several degrees at \( f = 50 \text{kHz} \), indicating switching thresholds higher than true value. The sampling resistor used throughout this study is a parallel network of ten 10-ohm Corning C-5 glass tin oxide film resistors, each 1/2 watt rated at 70 deg.C with temperature coefficient of 100 ppm/deg.C from -55 deg.C to +175 deg.C.
Each resistor must dissipate only $\frac{1}{2}(1.5/10)^2 10 = 0.1125$ watts, so that the resistance change resulting from the small observed temperature rise is negligible.

3.3. Experimental Technique and Results

In view of the nature of the rather well-defined propagation fronts described in Chapter 2, particular attention must be focused on both position and geometry of the voltage-sensing pickup coils. Dynamic tracking of the propagating boundary across the film surface is accomplished with a pickup coil coplanar with the film so as to sense flux changes associated with the vertical component of stray field as illustrated schematically in Fig. 3.3. As shown, a straight segment of small diameter wire is extended in the transverse direction, displaced from the film surface by its insulation thickness, and returned at a point of low flux density. Application of an easy-axis field $H_s = st$ with $s$ sufficiently large launches a pair of fast propagating domain boundaries from the film edges as discussed in Chapter 2. As the disturbance passes under the straight wire segment, a voltage maximum occurs. For smaller $s$, the less well-defined zig-zag wall produces a voltage peak coincident with its average arrival; and for still smaller $s$, the arrival of disjoint domain-tips followed by parallel wall motion appears as an initial voltage peak followed by a long and noisy trailing edge. A tracking sequence for the fast front is shown in Fig. 3.3, (A)-(D) in which pickup-loop voltage is displayed against $H_s = st$ for fixed $s$ and four different locations of the probing wire from the film edge. Since time and magnetic field are
Fig. 3.3. Pickup coil voltages vs. $H_g = at$ for 1cm diameter circular films; A-D: $s = 4.5 \times 10^6$ Oe/sec, $H_w = 1.5$ Oe, $H_k = 4.0$ Oe, $D = 700$ Å, horizontal scale = 0.5 Oe/div with centerline at 5.0 Oe; E-G: $H_c = 0, 0.4, 0.8$ Oe respectively and $s = 2.3 \times 10^6$ Oe/sec, $H_w = 1.3$ Oe, $H_k = 3.5$ Oe, $D = 820$ Å, horizontal scale = 0.5 Oe/div with centerline at 3.5 Oe.
equivalent to within the scale factor \( s \), a shift \( +\Delta X \) in probe wire position appears as an increase \( +\Delta H \) in the field at which the voltage peak occurs, corresponding to a propagation time \( \Delta t = \Delta H/s \) as illustrated in the sequence. Figure 3.3, (E)-(G) are X-Y displays of easy-axis and hard-axis voltage versus \( H_s = st \) with and without transverse bias \( H_t \) for fixed \( s \) and \( X = r \), the film radius. Noteworthy in these displays are the reduction in threshold field and the appearance of large hard-axis signals with increasing bias \( H_t \).

If the probe wire is positioned at the center of the film corresponding to \( X = r \), the film radius, a voltage peak marking a propagation distance \( X = r \) occurs at some field value \( H_r \). Accurate mechanical alignment between applied field, easy-axis, and the plane of the pickup coil is achieved by maximizing \( H_r \) for large \( s \) and \( H_t = 0 \). For the high-speed domain-boundary and the zig-zag wall, this peak marks essentially the end of switching, whereas appreciable switching by parallel wall motion occurs after the peak for disjoint domain-tip motion. As suggested by the velocity-field curves of Fig. 2.3, for switching confined to any linear segment approximated by \( v = m(H_s - H_0) \) and \( H_s = st \), then \( X = (m/2s)(H_s - H_0)^2 \) which yields \( H_r = H_0 + \sqrt{2rs/m} \) for the field value at the voltage peak. In Fig. 3.4, empirical curves of \( H_r \) versus \( \sqrt{s} \) for \( s \) up to \( 5 \times 10^6 \) Oe/sec are plotted for both single-layer and two-layer films with and without transverse bias \( H_t \). Extrapolation to \( s = 0 \) consistently yields \( H_w \) for both single-layer and two-layer films. Although the qualitative correspondence between
Fig. 3.4. Field at peak signal, $H_x$, vs. $\sqrt{s}$ for the films of Fig. 2.3.
the curves of Figs. 2.3 and 3.4 is apparent, a more quantitative connection may be established by noting that the model predicts that
\[ \int_0^r \varepsilon_d H = s \int_0^r dx = rs. \]
Thus graphical integration of the empirical velocity-field plot yields a predicted curve of \( H_r \) versus \( \sqrt{s} \). Predicted and experimental curves are compared in Fig. 3.5, wherein the accuracy with which the interrupted-pulse characterization can describe uninterrupted switching is demonstrated for ramp field slopes up to \( 5 \times 10^6 \) Oe/sec. Note that the deviation from linearity exhibited by the curves of \( H_r \) versus \( \sqrt{s} \) for \( H_t = 0 \) at large \( s \) reveals that propagation velocity is not linear in applied field \( H_s \) for large \( H_s \).

The detailed connections between the propagation phenomena examined in Chapters 2 and 3 and the switching curves of \( 1/\tau \) versus \( H_s \) reported in the literature are extremely complicated. In the following chapter, the influence of location and geometry of flux derivative sensing coils upon the measurement of switching times associated with longitudinal domain-boundary propagation is considered both theoretically and experimentally.
Fig. 3.5. Field at peak signal, $H_x$, vs. $\sqrt{s}$ from Fig. 3.4 compared with $H_x$ vs. $\sqrt{s}$ predicted from Fig. 2.3 for $H_T = 0$. 

\[ \sqrt{s} \times 10^{-2} \text{(oe/sec)}^{1/2} \]

$H_x$ (oe)
Chapter 4

INFLUENCE OF POSITION AND GEOMETRY OF SENSING COIL

4-1. Introduction

Numerous researchers have reported the results of experiments on high-speed flux reversal under applied step fields (e.g., ref. 1) in the form of curves of reciprocal switching time \(1/\tau_e\) versus magnitude of easy-axis step field \(H_s\) with hard-axis bias field \(H_t\) as a parameter, where \(\tau_e\) henceforth designates the electronically measured switching time to be compared with true switching time \(\tau_t\). Electronic switching time \(\tau_e\) is most often defined operationally as the time required for easy-axis flux \(\varphi_s\) to switch from 10% to 90% of twice the maximum flux linked by the pickup coil. Thus by its own definition \(\tau_e\) is dependent upon the sensitivity of the flux derivative sensing coil to the stray field of the film. This spatial sensitivity to stray field characteristic of the particular pickup coil used is herein suggested as a primary source of discrepancy between electronic and true switching times associated with the longitudinal domain-boundary propagation phenomena described in Chapters 2 and 3. In this chapter, a purely kinematical model describing the flux change associated with longitudinal domain-boundary propagation in single films for \(H_t = 0\) is developed as a dynamic extension of Oguye's static result [8] for \(\varphi - H\) loops. Although the special case \(H_t = 0\) is not of paramount interest and is chosen for conceptual ease of modeling, many of the concepts developed for this case are qualitatively applicable within obvious restrictions to the cases \(H_t \neq 0\) and two-layer films. Electronic switching time \(\tau_e\)
is shown to be shorter than true switching time $\tau_c$ by a spatial sensitivity factor relating pickup coil position to film size. Limited experimental evidence in support of the calculations is presented.

4-2. The Model

As discussed in 2-4, the most well-defined propagating boundaries observed magneto-optically occur in single-layer films with $H_c = 0$. From an intuitive perspective, the philosophy of the model about to be presented is best appreciated in light of the Kerr magneto-optic sequence of Fig. 2.2, F-J. Domain boundaries separating regions of head-on magnetization originate at the easy-axis extremities of the film with the characteristic quadrantal symmetry of Fig. 2.2, F., which is believed to be a reflection of the magnetization distribution at the film edges. Since the magnetization distribution along the easy-axis edges has least hard-axis component in a small region about the easy-direction symmetry axis, i.e. the easy-axis diameter in the circular case, a narrow central band of the film parallel to the easy-axis is subjected to less torque upon application of antiparallel $H_s$ and hence has higher threshold for propagation than the remainder of the film. After propagation a short distance, the net result, depicted in Fig. 2.2, G, is a pair of domain boundaries which separate regions of head-on magnetization and which are substantially straight and parallel to the hard-axis but for the lagging central region.

An idealization of such a process and the location and geometry of a particular flux derivative sensing coil for probing it are modeled for a rectangular film in Fig. 4.1. For mathematical expediency, the
Fig. 4.1. Model for longitudinal domain-boundary propagation

for $H_t = 0$. 

$\lambda = M_0 D$
boundaries between regions of head-on magnetization are regarded as a pair of mobile magnetic line charges in the plane of the film parallel to the hard-axis. Within domains, the rectangular film is assumed to be uniformly magnetized parallel to the easy-axis, and flux reversal occurs by longitudinal propagation of the line charge pair from the edges to the center of the film. Consider the pickup coil of Fig. 4.1, which senses flux changes associated with the component of stray field perpendicular to the film plane. For $T \approx W$, $R \rightarrow \infty$, and $y \approx D/2$, approximately one-half the film flux, $\Phi_o/2$, is linked by the loop, while for $T \ll W$ and $y \gg D/2$, some fraction of $\Phi_o/2$ is linked. Intuitively it is suspected that an infinite line charge approximation may be used in calculating the flux linked by a pickup coil satisfying the criteria $T \ll W$, $y \ll L$. Magnitudes and locations of the four required infinite magnetic line charges, two mobile and two stationary, are specified in Fig. 4.1, (C). Pickup loop flux, switching time, and voltage associated with the infinite line charge distribution of Fig. 4.1, (C) are calculated below. But for a constant factor of 2, the results for the flat pickup loop of Fig. 4.1 and the more common arrangement of pickup loop encircling substrate and film are identical for given $T$ and $y$. That is, if $\Delta \Phi$ is the flux closing between $D/2 \leq y' \leq y$, then the flat loop links $\Phi = \Phi_o/2 - \Delta \Phi$; and the loop encircling film and substrate (same $y$) links $\Phi = \Phi_o - 2\Delta \Phi = 2(\Phi_o/2 - \Delta \Phi)$. In practice the latter arrangement is preferable since it furnishes larger signal behind smaller self-inductive reactance resulting from smaller cross sectional area.
4.3. **Flux, Switching Time, Switching Voltage, and Energy Losses**

(a) Flux

Since the infinite line charge approximation reduces the flux calculation to two dimensions, it is reasonable to anticipate for the flat pickup coil of Fig. 4.1 a flux function of the form

\[
\phi_s = \frac{\phi_0}{2} \cdot \frac{T}{W} \cdot f(x, y, t, \eta)
\]

\[\text{where } -1 \leq f(x, y, t, \eta) \leq +1\]

(4.1)

where the film flux \( \phi_0 = \mu_0 M_0 D \omega \), and the displacements are defined in Fig. 4.1. Of immediate interest is the explicit form of \( f(x, y, t, \eta) \).

At any point \((x, y)\) in space excluding the volume of the film, the magnetic field intensity created by the distribution of Fig. 4.1, (C) is given by

\[
H_y = \frac{M_0 D}{2\pi} \left\{ \frac{y}{(x-t)^2 + y^2} - \frac{y}{(x+t)^2 + y^2} \right. \\
+ \left. \frac{2y}{(x+\eta)^2 + y^2} - \frac{2y}{(x-\eta)^2 + y^2} \right\}
\]

\[\text{and } H_x = \frac{M_0 D}{2\pi} \left\{ \frac{x-t}{(x-t)^2 + y^2} - \frac{x+t}{(x+t)^2 + y^2} \right. \\
+ \left. \frac{2(x+\eta)}{(x+\eta)^2 + y^2} - \frac{2(x-\eta)}{(x-\eta)^2 + y^2} \right\}.
\]

(4.2)
Only the first of these is needed to obtain the pickup coil flux \( \varphi_s \) which is simply
\[
\varphi_s = \int_{x}^{\infty} \mu_0 H_y(x', y') \, T \, dx'.
\]
(4.3)

Performing the integrations dictated by (4.3) yields
\[
\varphi_s = \frac{\alpha}{2} \cdot \frac{T}{W} \cdot \frac{1}{\pi} \left( \tan^{-1} \frac{L-x}{y} + \tan^{-1} \frac{L+y}{y} - 2\tan^{-1} \frac{\eta-x}{y} - 2 \tan^{-1} \frac{\eta+y}{y} \right),
\]
(4.4)

and the desired factor \( f(x,y,\eta) \) is identified by comparison with (4.1). In most laboratory arrangements, the pickup coil encircles the center of the film and \( x = 0 \) for which (4.4) becomes
\[
\varphi_s = \varphi_0 \cdot \frac{T}{W} \cdot \frac{1}{\pi} \left[ \tan^{-1} \frac{L}{y} - 2\tan^{-1} \frac{\eta}{y} \right].
\]
(4.5)

For purposes of flux calibration, it is tempting to normalize (4.5) with respect to \( \frac{\alpha}{2} \cdot \frac{T}{W} \), the maximum flux which the flat coil can link. However, since the ultimate objective is an expression for electronic switching time consistent with the operational definition used in experiments, normalization must be with respect to \( |\varphi_{\text{max}}(0,y)| \), the magnitude of the maximum flux linked by the loop for given \( (0,y) \), which is obtained by setting \( \eta = \xi \) in (4.5):
\[
|\varphi_{\text{max}}(0,y)| = \varphi_0 \cdot \frac{T}{W} \cdot \frac{1}{\pi} \tan^{-1} \frac{L}{y}.
\]
(4.6)

Normalization of (4.5) with respect to this quantity yields
\[
\varphi_N = \frac{\varphi_s(0,y)}{|\varphi_{\text{max}}(0,y)|} = 1 - 2 \cdot \frac{\tan^{-1} \frac{\eta}{y}}{\tan^{-1} \frac{L}{y}},
\]
(4.7)
from which electronic switching time is easily computed.

(h) Switching Time

For step field switching at fixed $H_s$, $\frac{d\bar{n}}{dt}$ is constant (ignoring nucleation and acceleration times), and the electronic and true switching times are respectively

$$\tau_e = \frac{\eta_{10} - \eta_{90}}{|\frac{d\bar{n}}{dt}(H_s)|} \hspace{1cm} (4.8)$$

$$\tau_t = \frac{\frac{L}{y}}{|\frac{d\bar{n}}{dt}(H_s)|} \hspace{1cm} (4.9)$$

where $\eta_{10}$ and $\eta_{90}$ are defined respectively by

$$-0.8 = 1 - 2 \cdot \frac{\tan^{-1} \frac{\eta_{10}}{y}}{\tan^{-1} \frac{L}{y}} \hspace{1cm} (4.10)$$

$$+ 0.8 = 1 - 2 \cdot \frac{\tan^{-1} \frac{\eta_{90}}{y}}{\tan^{-1} \frac{L}{y}} \hspace{1cm} (4.11)$$

according to the laboratory definition of 10% - 90% flux points. The ratio of electronic to true switching time given by

$$\frac{\tau_e}{\tau_t} = \frac{\eta_{10} - \eta_{90}}{L} \hspace{1cm} (4.12)$$

is tabulated in Fig. 4.2 for various ratios $\frac{L}{y}$ as computed from (4.10) and (4.11).
<table>
<thead>
<tr>
<th>$\frac{\nu}{\ell}$</th>
<th>$\frac{\eta_{10}}{\ell}$</th>
<th>$\frac{\eta_{90}}{\ell}$</th>
<th>$\frac{\tau_e}{\tau_t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.854</td>
<td>0.0787</td>
<td>0.775</td>
</tr>
<tr>
<td>0.1</td>
<td>0.397</td>
<td>0.0148</td>
<td>0.382</td>
</tr>
<tr>
<td>0.01</td>
<td>0.0597</td>
<td>0.00157</td>
<td>0.0581</td>
</tr>
</tbody>
</table>

Fig. 4.2. Electronic vs True Switching Time for Various $\frac{\nu}{\ell}$.

Note that the ratio $\frac{\nu}{\ell}$ behaves as a spatial connection factor between film and pickup coil and indicates the degree of flux coupling between the two. Values of $\frac{\nu}{\ell}$ greater than 1 become prohibitive for monitoring high-speed flux reversal because of increasing self-inductance, while catastrophic errors accompany values less than 0.01. Defining a switching time reduction factor by

$$f_e = \frac{\tau_e}{\tau_t}$$

leads to

$$\frac{1}{\tau_e} = \frac{\left| \frac{d^n}{dt^n} (H_s) \right|}{f_e L} = \frac{\left| \frac{d^n}{dt^n} (H_s) \right|}{L_r},$$

where the quantity $L_r = f_e L$ may be regarded artificially as a reduced film half-length. Thus, as (4.14) indicates, the particular curve $\frac{1}{\tau_e}$ versus $H_s$ for $h_t = 0$ in single-layer films is proportional to the corresponding velocity curve, e.g. the curve of Fig. 2.3 corresponding to $h_t = \frac{H_t}{H_k} = 0$, but is in error with $\frac{1}{\tau_t}$ versus $H_s$ by the factor $\frac{1}{f_e}$. 
(c) Switching Voltage

Differentiation of (4.7) with respect to time yields the switching voltage:

\[ \frac{d}{dt} \left( \frac{\varphi_N}{2} \right) = \frac{1}{\tan^{-1} \left( \frac{L}{y} \right)} \cdot \frac{y}{\eta^2 + y^2} \cdot \left| \frac{d\eta}{dt} \right| \]  \hspace{1cm} (4.15)

where the minus sign is ignored and the result is normalized with respect to 2 units, the total change in \( \varphi_N \) over one reversal. Thus \( \frac{d\eta}{dt} \), \( \eta \), and hence the switching voltage waveform depend upon the particular magnetic drive field waveform according to (4.15).

(d) Energy Losses

A quantity of considerable practical concern is the energy dissipated in the material per unit volume per magnetic cycle which, from fundamental electromagnetic theory, is given by

\[ W = \Phi \overline{H} \cdot \overline{dM} \]  \hspace{1cm} (4.16)

which amounts to the total area under the M-H characteristic of the specimen. Within the context of the model under discussion, a differential boundary displacement \( |d\eta| \) results in an average magnetization change \( dM \) in the positive x-direction of

\[ dM = \frac{4M_0}{2\zeta} \cdot |d\eta| \]  \hspace{1cm} (4.17)

and (4.16) becomes

\[ \frac{W}{2} = \frac{2M_0}{\zeta} \int_0^T H_s(t) \left| \frac{d\eta}{dt} \right| dt \]  \hspace{1cm} (4.18)
where, because of symmetry, the integral need be taken only over one reversal. For the general case of arbitrary \( H_s(t) \), numerical integration is required for evaluation of (4.18); and \( \frac{W}{2} \) is clearly dependent upon the nature of the drive field variation.

Consider now the possibility of experimental determination of (4.18) using the flat sensing coil of Fig. 4.1 satisfying the criterion \( y \approx 0 \). According to (4.4),

\[
\varphi_s \approx \frac{\varphi_0}{2} \cdot \frac{T}{W} \left[ 1 - \frac{2}{\pi} \tan^{-1} \frac{x}{y} - \frac{2}{\pi} \tan^{-1} \frac{y}{x} \right],
\]

(4.19)

and a discontinuous change \( \Delta \varphi \approx \varphi_0 \cdot \frac{T}{W} \) occurs as the propagating boundary reaches and passes \( \eta \approx x \). For \( H_s = st \), the electronic \( \varphi_s - H_s \) loop implicit in (4.19) becomes continuously narrower as \( x \) is increased between \( 0 \leq x \leq \ell \), finally closing altogether for \( x \geq \ell \).

Thus the total area \( A \) under the electronic \( \varphi_s - H_s \) loop can be caused to vary between \( 0 \leq A \leq 2\varphi_0 \cdot \frac{T}{W} \cdot H_L \), where \( H_L \) is defined similarly to \( H_E \) in 3-3. At present it is suspected that only a multi-turn sensing coil wound so as to weight flux changes everywhere in the film equally can be used for the experimental evaluation of (4.18). Unfortunately, use of such a coil is prohibited at the switching speeds of interest.

4.4. Some Experimental Evidence

Although no rectangular films have been investigated, certain features of the model are expected to be reasonably descriptive of circular film behavior. For example, a pickup coil for which \( \frac{\eta}{\ell} \ll 1 \) is insensitive to flux changes at the film edges; and for \( \eta \approx 0 \), where
pickup loop flux changes most violently, circular and square films are indistinguishable to a pickup loop for which \( \frac{T}{W} \ll 1 \) in so far as the infinite line charge approximation is concerned.

Experimental and theoretical switching voltages for the single-layer film of Fig. 2.3 are displayed in Fig. 4.3 against a ramp drive field \( H_s = 2.5 \times 10^6 \) Oe for \( h_t = 0, \frac{V}{L} = 0.2 \), and \( T = W \). Theoretical voltage is computed point by point from (4.15) using the velocity-field characteristic of the single-layer film of Fig. 2.3 corresponding to \( h_t = 0 \), with \( \eta \) obtained by graphical integration of the same velocity-field curve as discussed in 3-3. Comparison indicates reasonable quantitative and qualitative agreement.

Notwithstanding the fact that the long switching times for reversal under the relatively slow rising ramp fields used in this study are not of particular practical interest, it is worth noting that for single-layer films with \( H_t = 0 \), the true switching time \( \tau_t \) for ramp drive field slope \( s \) is given to good approximation by

\[
\tau_t = \frac{H_r - H_s}{s} \quad (4.20)
\]

where \( H_r \) is defined in 3-3. For the example of Fig. 4.3, \( \tau_t \approx \frac{4.8 - 1.2}{2.5 \times 10^6} = 1.44 \ \mu\sec \); whereas electronic switching time \( \tau_e \approx 0.3 \ \mu\sec \) as obtained by graphical estimation of the field spanning 90% of the area under the oscillograph waveform. Such errors are typical and consistent with the results tabulated in Fig. 4.2 for step field switching. The variation of \( \frac{1}{\tau_t} \) versus \( \sqrt{s} \) as computed from (4.20) using the curve of Fig. 3.4 corresponding to \( h_t = 0 \) is plotted in Fig. 4.4 for the single-
Fig. 4.3. Experimental and theoretical switching voltages for the single-layer film of Fig. 2.3.
Fig. 4.4. Reciprocal of true switching time, $\frac{1}{\tau_t}$, vs. $\sqrt{s}$
for the single-layer film of Fig. 2.3.
layer film of Fig. 2.3. Below $s \approx 2 \times 10^5$ Oe/sec, (4.20) gives poor indication of true switching time because of the increasing percentage of lateral domain-wall motion; and for $H_t \neq 0$, the concept breaks down entirely.

4-5. Discussion

In practice, the longitudinally propagating fronts observed are neither perfectly straight, infinitesimally narrow, nor infinitely long; and the preceding calculations are expected to be in error on all three counts. The last indictment may in principle be mitigated by the requirement $T \ll W$; however, the accompanying reduction in signal level precludes its practical implementation. The first aspect of the derivation from ideality is revealed in the trailing edge of the oscillograph waveform of Fig. 4.3, as the propagating fronts mesh in the center of the film under the probe wire. A more abrupt trailing edge is expected in the ideal case. At present, little but speculation can be offered in regard to the width of the propagating front.

For $H_t \neq 0$, the less well-defined high-speed fronts propagating at an angle with respect to the easy-axis leave large percentages of the film to be switched by a fast domain-tip motion. Although the qualitative features of the model are expected to be reasonably descriptive of the propagative portion of such a process, the total switching time for this mode of reversal has little relevance to the values calculated in 4-3. A similar breakdown occurs for the two-layer film which is believed to switch at high speeds by a fast domain-tip motion followed by some percentage of lateral domain-wall motion,
In conclusion, it is not clear at present how either $\tau_t$ or $\tau_e$ can be calculated for two-layer films or single-layer films with $H_t \neq 0$.

In the fifth and final chapter, the findings described in the earlier chapters are related to pertinent results reported previously in the literature.
Chapter 5

COMPARATIVE REVIEW OF PERTINENT LITERATURE

5-1. Introduction

Currently the literature is congested with fruitless attempts to model the intermediate-speed switching process. Four of the more prominent speculations attributed to Fuchikami, Harte, Stein, and Vino-gradov are reviewed, along with their respective shortcomings, by Hagedorn [9] and will not be repeated here. Founded upon inadequate experimental evidence to begin with, most hypotheses attempt to explain quasi-static flux patterns or intermediate-speed, easy-axis switching voltage waveforms (initial voltage peak followed by long trailing edge). Many of the models postulate an initial reversible coherent rotation up to the vicinity of the irreversible threshold followed by a breakup into domains usually attributed to inhomogeneities in the magnetization distribution such as easy-axis ripple.

For example, the ripple pattern is conceived by Stein [4] to rotate reversibly with the average magnetization direction until the leading regions reach the irreversible threshold and rotate farther ahead of the lagging portions forming "dynamic walls" which complete the reversal by lateral expansion at velocities 10 to 100 times faster than normal domain-wall motion. Such a description is clearly inconsistent with the propagation phenomena discussed in Chapter 2, since the breakup into domains occurs throughout the film according to the ripple structure, with no longitudinal domain-boundary propagation from the film edges. Figure 2.2, K-O strongly suggests propagation
from the edges and is in contradiction to any such uniform breakup into domains as proposed by Stein.

"Labyrinth propagation", cited by Smith [3] as a possible mechanism for intermediate-speed switching, appears to be the proposal most apropos to the present work. In this scheme, initial reversible coherent rotation is induced by nucleation of reversed domains at the film edges where stray fields are initially highest. The resulting "labyrinth-like" domains then propagate from the film edges by sequential nucleation in a direction determined by stray fields.

In contrast to this sequential nucleation process, which behaves as a propagation phenomenon, is the sequential, rotational propagation effect reported by Jaecklin [5]. Briefly, a net easy-axis field below domain-wall nucleation threshold is applied opposite to the magnetization of a film initially saturated in the easy-direction. Subsequently, within a localized band of the film (nominally 30 mils wide) parallel to the easy-axis, the magnetization is rapidly pinned in the hard-direction by a fast rise time field of amplitude greater than $H_k$. Equilibrium is believed by Jaecklin to be established by a sequential, rotational propagation of the magnetization vector away from the pinned region. Nominal velocity of $10^7$ cm/sec is estimated from the time difference between flux derivatives sensed in two well-separated pickup coils both remote from the pinned region.

Unfortunately, little but conjecture can be offered in regard to the relevance of either of these two models to the propagation phenomena observed in this study. High stray fields at the film edges might well
supply the pinning fields required in the Jaecklin experiment, thereby
inducing longitudinal propagation by sequential rotation of the magne-
tization vector away from the film edges. Dynamic relaxation into the
fine-structured stripe-domain patterns observed after interruption of
applied field might then occur over a region in the vicinity of the
moving wall, as suggested earlier in 2-3. However, Smith has observed
identical labyrinth-like, static flux patterns and attributes the
structure to the sequential nucleation process described above. Further-
more, a third possibility might simply be high-speed domain-tip pro-
pagation involving a dynamic reduction in tip angle with an accompanying
increase in longitudinal domain-tip velocity. Because of the inherent
inadequacies in currently available experimental techniques, the advent
of dynamic Kerr magneto-optic photography must be awaited for the
resolution of the intermediate-speed switching quandary.

Space is unavailable to recount in more detail the sundry reports
of various experimental and theoretical aspects of intermediate-speed
switching that abound in the literature. The reader is referred to the
recent bibliography compiled by Chang and Lin [10]. Since the matter
of prime concern in this study is the investigation of longitudinal do-
main-boundary propagation phenomena under ramp fields, the remainder
of this chapter is devoted to a detailed comparison between the ramp
field results described in Chapters 3 and 4 and the results of per-
tinent experiments reported previously in the literature.
5-2. Previous Ramp Field Results

(a) Tatsumoto et al [11]

Magnetization reversal in permalloy films under sinusoidal fields of frequency up to \( f = 700 \) kHz, corresponding to \( s = 7 \times 10^7 \) Oe/sec, has been explored via the transverse magneto-resistance effect by Tatsumoto et al. It has been shown both experimentally and theoretically that the variation of electrical resistivity with magnetization direction in permalloy films may be described by

\[
\Delta R = (R_\parallel - R_\perp) \cos^2 \theta,
\]

(5.1)

where \( \theta \) is the angle between magnetization and direction of resistance measurement, and \( R_\parallel \) and \( R_\perp \) are the static resistances when \( \theta = 0 \) and \( \theta = \pi/2 \), respectively. If \( \Delta R \) is measured in the hard-direction, the maximum change, \( R_\parallel - R_\perp \), occurs at \( \theta = 0 \); and dynamic monitoring of \( \Delta R \) versus \( H_s \) with respect to this maximum value is expected to indicate the degree of rotational coherence of the reversal process.

All data presented by Tatsumoto et al concerns film \( R-492 \), a \( 1 \) cm \( \times \) \( 1 \) cm square of nominal 80-20 Ni-Fe composition, with \( H_w = 1.5 \) Oe, \( H_k = 3.0 \) Oe, and \( D = 1500 \) Å; electrical contacts are evaporated uniformly along the hard-axis edges of the film for the magneto-resistance measurement. Behavior of film \( R-492 \) is expected to resemble quite closely that of the remarkably similar single-layer film of Fig. 2.3 under given drive field conditions.

Although no detail regarding experimental technique beyond that described above is given by Tatsumoto et al, it is possible to infer from particular data the existence of certain experimental pitfalls.
which the author may not have escaped. According to an X-Y display of $\dot{\phi}_s \text{ versus } H_g = 100 \sin(2 \pi \times 10^4 t) \text{ Oe, corresponding to } s = 2\pi \times 10^6 \text{ Oe/sec, the switching voltage peak occurs at a field value } H_x = 3.5 \text{ Oe for } H_e = 0, \text{ which is approximately } 2.0 \text{ Oe lower than the corresponding value for the single-layer film of Fig. 2.3 For a peak drive field amplitude } H_m = 100 \text{ Oe, (3.2) predicts a very large field-phase error of approximately } 1.75 \text{ Oe/deg. Since the real-time oscillograph waveform display indicates that no sampling system was used, the phase response of the GRO horizontal amplifier, which corresponds to the negative sign in (3.2) and explains the reduced field value is suggested as the villain. Although mechanical misalignment between magnetization and applied field reduces switching threshold fields, the detailed shape of $\dot{\phi}_s \text{ versus } H_g, \text{ which is identical with that observed in this laboratory under conditions of near perfect alignment, tends to negate such an explanation. Positioning of the probe wire nearer to the film edges, as in Fig. 3.3, indicates apparent reduction in switching fields for a third possibility; however, in the absence of any previous knowledge of propagation phenomena, such a choice is highly unlikely. Therefore any subsequent discussion of the results of Tatsumoto et al must be interpreted with the possibility of phase shift in the experimental system.}

Since the maximum value of $\Delta R$ observed is only $10\%$ of $R_{||} - R_{\perp}$, the authors conclude correctly that coherent rotation does not occur for $H_e = 0$ and $s$ up to $7 \times 10^7 \text{ Oe/sec. One particularly enigmatic feature of the results is that the peak magneto-resistance signal
consistently appears to occur in time at the leading edge of the switching voltage waveform. Intuitively, it is suspected that the peak magneto-resistance signal occurs when the propagating fronts of Fig. 2.2, F, span the greatest breadth of film perpendicular to the current flow which is in the hard-direction. As the leading portions of the propagating fronts begin to mesh in the center of the film, where presumably the probe wire is positioned, this region begins to narrow. Thus the magneto-resistance signal passes its maximum and begins to decrease just as the switching voltage begins to change most rapidly. Note that the magneto-resistance measurement weights flux changes everywhere in the film equally.

Tatsumoto et al plot the field at peak magneto-resistance signal against $g$ for $g$ up to $7 \times 10^7$ Oe/sec. Since the relation between this value and $H_r$ of Fig. 3.4 is unknown, and the probability of system phase shift has already been exposed, no attempt is made to compare data. Furthermore, no mention is made concerning what combination of amplitude and frequency is used to achieve a particular value of $g$, so that considerable uncertainty exists as to whether or not switching is confined to a small argument of the sine wave. Finally, the authors present the rather arbitrary display of reciprocal electronic switching time against dynamic coercive field $H_c$, which is by definition the field at which $\phi_g = 0$. Although electronic switching times are comparable with those measured in this laboratory, such a display of one arbitrary quantity against another is of little value and will not be considered here. In conclusion, it is felt that the work of Tatsumoto et al would be more interesting and enlightening
with additional information regarding experimental technique. In light of the findings discussed in Chapters 2 and 3, their conclusion that coherent rotation does not occur under the given experimental conditions is believed to be correct.

(b) Hoffman et al and Lachowicz [12]

Hoffman, Turner, and Lachowicz have determined experimentally the variation of dynamic coercive field $H_c$ with $s$ ranging between $2 \times 10^3$ - $2 \times 10^4$ Oe/sec and with hard-axis bias field $H_L$ as a parameter. They conclude correctly that over the given range of $s$, magnetization reversal proceeds exclusively by domain-wall motion. All data presented relates to film No. 12 for which $H_w \approx 3.7$ Oe and $H_k \approx 10.0$ Oe, so that coherent rotation is hardly to be expected under the slow-rising ramp fields used in the experiments. Unfortunately, the premise upon which this conclusion is based, i.e. that magnetization reversal by coherent rotation should render the measured values of $H_c$ independent of $s$, is incorrect. Hoffman et al expect the $\varphi_s - H_s$ loop associated with coherent rotation to be square and bounded by the irreversible threshold fields corresponding to particular $H_L$, independent of $s$. This premise clearly ignores the influence of rotational damping, which is known to exist, on the measured values of $H_c$.

Dynamic coercive field $H_c$ is found empirically to vary as $\sqrt{s}$ with and without hard-axis bias field $H_L$ over the entire range of $s$. This $\sqrt{s}$ dependence is a fundamental manifestation of the displacement response of any viscously damped system such as $v_z = m_z(H_s - H_w)$ to
an excitation increasing linearly with time such as $H_s = st$ and is discussed relative to the present work in 3-3. Above $s \approx 10^4$ Oe/sec, zig-zag domain-wall motion begins to dominate, and a theoretical expression for $H_c$ may be obtained by setting $\phi_s = 0$ in (4.5):

$$H_c = H_w + [l - y \tan(\frac{2s}{m_z})] \frac{1}{2}, \quad (5.2)$$

For $y << l$ this reduces to

$$H_c \approx H_w + \left(\frac{2s}{m_z}\right)^{1/2}, \quad (5.3)$$

which is identical with $H_T$ in 3-3; the $s$ dependence is thus explained in terms of the characteristic velocity-field linearity of zig-zag domain-wall motion. Typical $m_z$ of $10^4$ cm/sec-Oe is computed from the slopes of the straight line plots of $H_c$ versus $\sqrt{s}$ using $2l = 5$mm, the diameter of film No. 12. Although such low values are typical in cross-tie wall films, the thickness of film No. 12 is not given; and the reduced value of $m_z$ may be dependent upon peculiar film properties ($H_w = 3.7$ Oe and $H_k = 10.0$ Oe).

In a subsequent report, Lachowicz [13] invokes constancy of the number of domain walls participating in the reversal process in order to explain the $\sqrt{s}$ dependence of $H_c$. An essentially identical model is presented in a later paper by Bourne and Walters [17]. Defining a mean free path $<d>$ as the average excursion of a Bloch wall parallel to the easy-axis during reversal, Lachowicz easily calculates the true switching time $\tau_c$ to be
\[ \tau_t = \left( \frac{2 \delta \rho}{\mu_0} \right)^{\frac{1}{2}} \text{,} \]  
(5.4)

where the notation of the present work is used, but the quantities are defined identically by Lachowicz. In view of the model of zig-zag domain-wall motion discussed in Chapter 2, the number of walls is constant and equal to two; and the original assumption of Lachowicz is valid. If \( a = m_z s \) is the domain-wall acceleration, then true switching time \( \tau_t \) is given by

\[ \frac{1}{2} a \tau_t^2 = \frac{1}{2} m_z s \tau_t^2 = \ell \]  
(5.5)

whence

\[ \tau_t = \left( \frac{2 \ell}{m_z s} \right)^{\frac{1}{2}} \text{,} \]  
(5.6)

and the mean free path \( \langle d \rangle \) of a domain-wall is identified simply as \( \ell \), the film half-length or radius. Note that the original assumption of 100\% reversal by lateral domain-wall motion, made by Lachowicz as well as Bourne and Walters, is now seen to be inapplicable except as an idealized, symbolic model. Indeed, over the range of \( s \) in which switching occurs by disjoint domain-tip motion followed by lateral domain-wall motion, the number of domain-walls is neither constant nor independent of \( s \). As \( s \) is increased until zig-zag domain-wall motion begins to dominate, the number of walls becomes constant and equal to two; and the origin of the \( \sqrt{s} \) dependence becomes clear.

Lachowicz finally gives a rather unsatisfactory phenomenological explanation of the \( \sqrt{s} \) dependence of \( H_C \) which he simply writes as

\[ H_C = H_w + C \tau_t \]  
(5.7)
which leads to

\[ H_c = H_w + C \left( \frac{2 < D >}{m} \right)^{1/2} \]  \hspace{1cm} (5.8)

where \( C \) is a phenomenological constant measured from the switching voltage waveform. In general, \( C \) is dependent upon position and geometry of pickup coil and may be identified by comparison with (5.2).

In summary, Hoffman et al and Lechowicz have investigated magnetization reversal in permalloy films under triangular fields of slope \( s \) ranging between one and two orders of magnitude lower than the minimum \( s \) used in the present work. Extrapolation of the linear plots of \( H_c \) versus \( \sqrt{s} \) to \( s = 0 \) consistently yields \( H_w \) for both single-layer and two-layer films (only single-layer films are examined by Hoffman et al), and zig-zag domain-wall motion is now suggested as the most probable mechanism. Behavior similar to the permalloy film is exhibited by both ferrite and tape-wound toroidal cores, so that the relation \( v = m(H - H_w) \) may tentatively be expected to hold for bulk materials as well as thin films.

(c) Hatfield [14]

Hatfield has examined magnetization reversal under sinusoidal easy-axis fields of amplitude up to 18 Oe and frequency up to 1mHz in thick, axially-oriented, permalloy films electroplated onto 5-mil-diameter beryllium-copper wire substrates. All data reported concerns film No. 4 for which \( H_w = 1.2 \) Oe \( H_K = 3.2 \) Oe, and \( D = 10,000\AA \). Except for the effects of the metallic substrate and the large discrepancy in film thickness, this particular plated-wire film having
easy-axis parallel to the axis of the wire is again expected to exhibit behavior similar to the single-layer film of Fig. 2.3. Eddy-current damping in thick films is expected to reduce lateral domain-wall mobility [15] and hence zig-zag domain-wall mobility, while the effect of metallic substrate is difficult to foresee.

Unfortunately, since Hatfield deliberately makes no attempt to confine switching to small argument of the sine wave, the ramp field approximation of 3-1 no longer holds, and comparison of data is impossible. Hatfield defines frequency dependent critical field $H_{c1}$ as the value of sinusoidal peak amplitude below which no reversal occurs. For peak amplitude between $H_{c1}$ and a second frequency dependent critical field $H_{c2}$, partial switching occurs; and for $H_m \geq H_{c2}$, 100% reversal is observed, all data being taken with $H_t = 0$. Thus the reversal processes studied by Hatfield occur primarily near the peak of the sine wave where $\frac{dH}{dt}$ is small, so that reversal should proceed essentially by zig-zag domain-wall motion. Analytical difficulties are encountered immediately by noting that switching time $\tau_t$ for such a process is given by

$$\tau_t = m_z \int_{H_m}^{H_m \sin \omega t} \frac{H_m \sin \omega t - H_w}{\frac{H_m}{s}} \, dt ,$$

(5.9)

which leads to an unenlightening transcendental equation in $\tau_t$. If $H_m \sin \omega t$ is replaced by $st$ in (5.9), integration yields the previous result for $\tau_t$ as in (5.6).
From the variation of $H_{c1}$ and $H_{c2}$ with frequency ranging between 1kHz - 1MHz, $H_{c2}$ is observed to increase much faster with frequency than $H_{c1}$, finally exceeding $H_k$ at a frequency of approximately 150kHz. At the lowest frequencies, $H_{c2} \approx H_n$, where $H_n$ is the field required to nucleate domain walls. $H_n$ is observed to be lower than $H_w$ at $f = 1$kHz. Thus Hatfield concludes that for $H_{c2} > H_k$, magnetization reversal occurs by incoherent rotation and for $H_{c2} < H_k$, by some form of domain-wall motion. In support of these conclusions, Hatfield presents a somewhat artificial derivation of switching time $\tau_t$ in terms of the usual phenomenological switching coefficients $S_w$ defined by $S_w = \tau_e (H_S - H_O)$, where $\tau_e$ is electronic switching time and $H_O$ is a magnetic field intercept obtained by piecewise linearization of the curves of $\frac{1}{\tau_e}$ versus $H_S$. For switching confined to small argument of the sine wave, Hatfield's expression for $\tau_t$ reduces to

$$\tau_t = \left( -\frac{2S_w}{S} \right)^\frac{1}{2}, \quad (5.10)$$

and $S_w$ is identified as $\frac{L}{m_z}$ by comparison with (5.6).

Examination of the shapes of easy-axis switching voltage waveforms at $f = 200$kHz suggests zig-zag domain-wall motion for small $H_m$ and the faster longitudinal domain-boundary propagation for large $H_m$. However the very different approach taken by Hatfield renders the effects of amplitude and frequency inseparable and precludes any comparison of data. His basic conclusions of domain-wall motion for small $s$ and some form of nonuniform rotation (which is now believed to behave as a propagation phenomenon) for large $s$ are believed to be correct.
Finally, since propagation phenomena in plated-wire films have not been studied magneto-optically in this laboratory, no firm conclusions can be drawn in regard to how the effects observed in planar films relate to the plated-wire geometry.

(d) Bourne et al [16,17]

Since the present work supersedes previous work reported by Bourne and Causey and later by Bourne and Walters, only limited consideration directed toward the clarification of certain misconceptions presented therein need be given these two reports.

In view of the observations of Chapter 2, the suggestion of essentially coherent rotation for large \( s \) and \( H_T \neq 0 \), made by Bourne and Walters on the basis of the large hard-axis signal observed under these conditions, has been attributed in Chapter 3 to propagation phenomena. Furthermore, the linear dependence of \( H_C \) upon \( s \) presented by both Bourne and Causey and later by Bourne and Walters is now believed to be attributable to phase lead in the original, wire-wound, field-sampling resistor, which has been replaced by the type described in 3-2. The true variation of \( H_C \) with \( s \) is similar to \( H_T \) versus \( \sqrt{s} \) in Fig. 3.4, and the \( \sqrt{s} \) dependence for small \( s \) stands correct as presented in both papers. Finally, it should be understood that at the time of publication of the previous two works, the authors had no knowledge of the type of longitudinal domain-boundary propagation discussed in Chapters 2 and 3.
Chapter 6

SUGGESTIONS FOR FUTURE WORK

In the present work, a purely kinematical characterization of high-speed domain-boundary propagation has been presented and suggested as the phenomenology of intermediate-speed switching. Clearly, further experimental work is needed to enhance understanding of the physical principles underlying these effects. To this end, the following items are designated as worthy of further exploration:

(a) **Dynamic Kerr Magneto-optic Photography**

High priority should be given the objective of obtaining a complete Kerr magneto-optic, photographic record of the dynamic flux patterns characteristic of uninterrupted, intermediate-speed switching. The potential of one-shot versus repetitive photography should be carefully evaluated, since considerable experimental difficulties are encountered with either technique. Development of pulsed optical power commensurate with photographic exposure times of the order of 10 nsec is currently anticipated as the most difficult problem of the one-shot approach, while synchronization of optical source with reversing field is most essential for repetitive photography which must rely upon reproducibility of the process. Generation of reversing field of sufficient amplitude and uniformity from a single strip transmission line section compatible with the optics is another obstacle in the path of this most ambitious endeavor.
(b) **Geometry and Edge Effects**

Since domain-boundary propagation is expected to originate from regions of the film subjected to most torque upon application of reversing field, the effects of film geometry and edge shape upon magnetization distribution are worthy of detailed experimental investigation. Electron microscopic observation might be used effectively in determining magnetization distribution at the edges of sufficiently small specimens of varying geometry and edge taper. Further information may be obtained from a detailed study of the effects of film geometry and edge taper upon the shapes of the quasi-static flux patterns of the propagation fronts.

(c) **Composition and Stress Effects**

Since the ideal nonmagnetostrictive composition is difficult to achieve experimentally, externally applied, nonuniform stress is observed to produce considerable alteration in both the shapes of the high-speed propagation fronts and the remnant flux patterns left after ac or dc hard-axis demagnetization. Understanding of stress effects between film and substrate and the relation between static flux patterns left after hard-axis demagnetization and magnetization distribution throughout the film are expected to shed considerable light upon the physical principles of propagation phenomena.

(d) **Magnetostatically-coupled Films**

Currently, a complete Kerr magneto-optic quasi-static characterization of propagation phenomena in two-layer films has not yet been obtained. Useful information regarding shapes of flux patterns left
after interrupted switching under pulsed fields $H_s$ near $H_k$ requires extremely narrow, fast rise time pulses since flux reversal is exceedingly rapid for fields well below $H_k$. Intuitively, two-layer films are expected to behave as their single-layer counterparts for $H_s > H_k$ and $H_t = 0$, but radically different behavior is observed for $H_s < H_k$ as discussed in Chapter 2. Present knowledge of propagation phenomena in magnetostatically-coupled films is thus inadequate and deserving of future attention.

(e) Theory

The sequential rotational propagation process suggested in Chapter 5 is attractive from the point of view of compatibility with coherent rotation theory since coherent rotation may be conceived as sequential rotation in the limit of infinite domain-boundary width. Theoretical comparison of sequential rotation as a more favorable process than sequential nucleation, if feasible, might prove to be of considerable importance toward the understanding of intermediate-speed switching as a propagation phenomenon.
REFERENCES