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Bloch Wall Motion in Ferromagnetic Films
Excited by Fast-rising Hard-axis Pulses

by

Chia-hsiung Lin

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Thesis Director's Signature:

A handwritten signature in dark ink, appearing to read "Henry C. Banner", is written over a horizontal line.

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Chapter 1

Introduction

The potential use of ferromagnetic films as memory devices for computers has prompted tremendous research into their basic properties. A particularly attractive feature of these films is the speed with which the magnetization can be reversed at relatively low drive levels. The development, however, has been somewhat delayed for the following reasons:

- 1) the difficulty in manufacturing thin films with identical characteristics,
- 2) the insufficient knowledge of flux reversal process,
- 3) the destruction of information by domain creeping.

Of particular importance is the third. Many workers have engaged in this research,⁽⁵⁻¹⁵⁾ yet no satisfactory model has been proposed, especially when Bloch walls are prevalent. The present work was largely motivated by that of Feldtkeller and Stein on "wall streaming"⁽¹⁶⁾ and of Kusuda, Konishi, and Sakurai on "worm motion".⁽¹⁷⁾ In Chapter 2 will be found a theoretical calculation for Bloch wall motion excited by hard-axis pulses. The corresponding experimental results are presented in Chapter 3. Chapter 4 deals with creeping; an alternative explanation involving the gyromagnetic nature of magnetization is presented.

1.1 Comparison between the Motions of Domain Walls Produced by Easy-axis and Hard-axis Pulses

Ni-Fe films thicker than $900 \text{ \AA}$ when subjected to a magnetic field less than H_k , uniaxial anisotropy field, reverse their magnetization by domain wall motion. The motion of a Bloch wall is determined uniquely by the wave form and the direction of the applied field. The easy-axis field

causes normal domain wall motion, which will be described in the following paragraph. Fast rising pulses, however, applied along the hard direction induce a more complicated motion: it will be described in the second paragraph.

If a magnetic field $\vec{H}$ is applied parallel to a Bloch wall, the field favors one of the adjacent domains, which should therefore grow at the expense of the neighboring domains. At the moment of application, the spins in a Bloch wall precess around $\vec{H}$; hence there is a rotation of the spins out of the plane of the wall, and this results in a large demagnetizing field perpendicular to the wall. The subsequent motion of the spins is to precess around this demagnetizing field, which causes the wall to move in transverse direction. The wall velocity in this field can be well described⁽¹⁸⁾ by

$$\frac{dy}{dt} = \frac{w\gamma}{\pi\alpha} (H - H_c) \quad (1-1)$$

where y is the coordinate perpendicular to the wall, γ is the gyromagnetic ratio, w is the wall thickness, α is the phenomenological damping constant, and H_c is the characteristic coercive force of the wall. Note that the direction of the motion is independent of the direction of spins in the wall as indicated in Fig. 1-1-A.

When a fast rising pulse, however, is applied perpendicular to a Bloch wall, the wall motion is determined by the directions of the spins in the wall and in the surrounding domains and also on the direction of $\vec{H}_1$. Thus, as shown in Fig. 1-1-B, the direction of motion under this excitation depends on the two possible directions of the spins in the wall. The wall velocity for this pulse field, which will be derived in Chapter 2, can be written as:

Fig. 1-1 The dependence of the direction of motion on the rotation of wall spin by the application of (A) a field along the Bloch wall, and (B) a fast rising pulse field perpendicular to the wall.

$$\frac{dy}{dt} = \frac{w\gamma}{\pi\alpha} \frac{\dot{\theta}_c/\gamma - H_c}{\cos\phi_f} \quad (1-2)$$

Here θ_c is the angle between the magnetization at the wall center and the axis perpendicular to the film plane; ϕ_f is the angle between the domain magnetization and the axis perpendicular to the plane of the wall. A detailed treatment of the mechanism of gyromagnetic origin will be given in the following chapters; no attempt will be made at this time to give a more detailed explanation.

There are three important differences between both phenomena, namely,

- 1) the demagnetizing field produced by wall spin is responsible for domain wall motion in easy-axis fields, while that induced by the discontinuity of magnetization in the wall and the surrounding domains is responsible for domain wall motion in transverse pulse fields,
- 2) The domain magnetization plays no part in wall motion for fields in the easy direction while it is the origin of the motion for fields in the hard direction,
- 3) the direction of motion is independent of the direction of spins in the wall for easy-axis excitation while it depends on the two possible directions of the spin for hard-axis excitation.

1.2 Experimental Set-up

1.2.1 Sample Preparation

In order to achieve consistent experimental results, it is necessary to use samples with reproducible characteristics. The procedure of film fabrication for this work was established experimentally after many trials

and samples made by following identical procedure are quite reproducible as far as their electromagnetic properties are concerned.

81%-19% Ni-Fe alloy was chosen for the film material because of its small crystal anisotropy and magnetostriction. The films were evaporated onto glass substrates at 300°C in the presence of a uniform field of 40 oe produced by a pair of Helmholtz coils outside the vacuum chamber. Deposition is performed in pressures less than 5×10^{-6} torr. With tungsten boat as a heating element, the evaporation rate of $50 \text{ \AA}/\text{sec}$ was found to give the best results. Permalloy metal in quantities larger than actually needed was evaporated in order to maintain composition of the film as close as possible to 80%-20% Ni-Fe.

A dynamic measurement of film thickness is usually desirable. Thus the thickness was continuously monitored by a crystal oscillator whose frequency was determined by the mass of Ni-Fe evaporated onto the crystal during the deposition. The calibration was made by a M-H loop tracer after deposition.

One hour of annealing in magnetic field at 300°C is included in our procedure after the evaporation. The films were naturally cooled to room temperature and were then carefully examined by a low frequency (200 cps) M-H loop tracer. The hard-axis hysteresis loops reveal the constricted characteristics typically associated with Bloch-Néel wall transition of the wall structure. The film parameters were found to be:

H_c 0.7 to 1.6 oe;

H_k 3.5 to 5.0 oe;

angular dispersion less than 1° .

In order to observe the films by Kerr magneto-optic apparatus, a thin

layer of SiO₂ was deposited on the film surface as a coating to increase the Kerr rotation. A thickness of about 600 Å is found to give the best contrast.

1.2.2 Experimental Technique

Three methods were used for observation of domain boundaries. They are Kerr magneto-optic apparatus, sampling oscilloscope and XY recorder system, and Bitter pattern technique.^(1,3,4) Kerr magneto-optic apparatus is mostly used for observations and measurements because of its ability of clear display of domain pattern and its fast response to the change of domains. When the overall characteristics is desired, sampling technique is utilized. Bitter pattern method greatly limited by its slow response to following the wall motion, is used only when the wall structure is studied.

a) Kerr Magneto-optic Apparatus

When linearly polarized light is reflected (Kerr effect) or transmitted (Faraday effect) by a ferromagnetic sample, the plane of polarization is rotated through an angle which depends on the direction of magnetization in the sample. A thin film usually consists of domains with antiparallel magnetization and an analyzer can be adjusted in such a way that the light reflected or transmitted through one kind of domain is extinguished. In our observation, we used only the Kerr effect because the Faraday effect is limited to the thicknesses less than 400 Å.

A schematic diagram of this set-up is shown in Fig. 1-2. A high intensity light source and high quality polaroid filter were used to supply the linearly polarized light. The reflected light when passed

Fig. 1-2 Schematic diagram of Kerr magneto-optic apparatus and sampling oscilloscope-XY recorder system.

through an analyzer gave a domain pattern by filtering action. The pattern can be observed by a telescope or a closed-circuit TV system. A thin layer of SiO₂ as mentioned above of about 500-600 Å coated on the film surface improves the contrast.

A mercury pulser and 50-Ω strip line with a window close to the short-circuited end were used to give pulses of very short rise and fall times. The rise time of the pulses could be changed by using a rise time integrator at the output of the pulser, while the fall time could be changed by adding a simple R-C series network at the end of discharge line. The rise time T_r was always smaller than the fall time T_f . The pulse repetition rate was 50-300 pps. In case that a very uniform field was needed, a delta-shaped strip line was used. This was especially useful when uniform domain motion was to be observed.

b) Sampling Oscilloscope and XY Recorder System

This method was used to detect the domain wall motion by picking up the change of the transverse (easy-axis) signal whose amplitude was proportional to the net easy direction magnetization. The slow variation of signal induced by the sidewise wall motion allowed the detection and recording of the motion as amplitude variation of the transverse signal at a fixed sampling point of the sampling scope. The sampling point was fixed at about $3T_r$ from the wavefront of the drive pulse. This method gave an overall picture of magnetization variation but failed to detect the cases when the net variation of flux was zero though individual walls were still moving. A combination of this technique and Kerr magneto-optic apparatus as shown in Fig. 1-2 served the purpose appropriately

because it yielded information concerning the motion of individual walls and the overall behavior of the film simultaneously.

c) Bitter Technique

As mentioned before, this technique is not suitable for domain wall motion observation, yet it is a very powerful method for the study of domain wall structure. In this work it was used to determine the wall structure.

A drop of the suspension containing fine ferromagnetic colloidal particles was placed on the film and squeezed to a thin layer by a microscope cover glass. The particles in the suspension are so small that they perform Brownian motion. When the particles come close to the domain wall, they are attracted by the stray field which is associated with the wall. The resulting particle concentration above the walls can be observed by a microscope.

The influence of the earth's magnetic field was eliminated by a compensating field supplied by three pairs of Helmholtz coils arranged perpendicularly to each other in every set-up mentioned above.

Chapter 2

Mathematical Model for the Sidewise Motion of Bloch Wall Excited by Transverse Pulse Field

Two kinds of domain wall motions for thin Ni-Fe films in Bloch wall region exist when a pulse field is applied along the hard-axis of the film, namely, 1) wall creeping and 2) wall streaming or domain parade.

Creeping is due to the combination of an easy-axis bias field and hard-axis pulses. Because of the existence of a field component parallel to the wall, the direction of motion is predetermined. As a result the domains favored by this field will grow at the expense of the others.

Wall streaming occurs even if no field component parallel to the wall exists, thus no adjacent domain is favored. The direction of motion is determined by the spin rotation in the domain wall relative to the magnetization direction in the surrounding domains and the applied field. In both phenomena, creeping and streaming or parade, the walls, if they are of Bloch type, propagate along the hard direction when a very fast rising pulse field is applied to the hard-axis of the film. This suggests that the same mechanisms cause both types of motion if the film is of the appropriate thickness to possess Bloch walls.

In this chapter we will explore and formulate a mathematical model based on Bloch-Néel wall transition and gyromagnetic behavior of Bloch wall spins to explain these phenomena. To begin with, we will discuss the Bloch-Néel wall transition and then mathematical formulation will follow and lead to the equation of motion for the spin at the wall center. This approximation is necessary in order to avoid calculation of extreme complexity. The equation was solved by the aid of a computer. The results

show a quite satisfactory agreement with the experimental data given in Chapter 3 and Chapter 4.

2.1 Bloch-Néel Wall Transition

As discussed in the last section, both wall streaming and creeping are observed when the film is in Bloch wall region. Streaming, however, has never been detected when the film thickness is less than $900 \text{ \AA}$ where cross-tie and Néel walls are more favorable. This means that the spins in the wall, which rotate in the film plane, are not affected by the application of hard-axis pulse field when no effective easy-axis bias exists. Bloch wall structure is responsible for both streaming and creeping.

As proposed by Middelhoeke,⁽¹⁹⁾ the transition from a Bloch wall to a Néel wall can occur when a field larger than a certain strength is applied along the hard-axis. This combined with the fact that wall streaming occurs only in the Bloch-wall regime suggests an interesting feature of spin behavior in the Bloch wall. If a step field with rise time T_r whose strength is larger than Bloch-Néel wall transition field is applied perpendicularly to a Bloch wall, the wall will move under this excitation until the transition is complete. However, the Bloch-Néel wall transition is gradual rather than abrupt. If the applied field $H_{\perp}$ is smaller than the transition field H_{B-N} , the wall has both a Néel and a Bloch components. Therefore the wall is neither a Bloch nor a Néel wall, but a hybrid of the two.

To discuss the gradual change of the wall structure the coordinate system of Fig. 2-1-A is used. The arrangement of the film with respect

Fig. 2-1 (A) Coordinate system, (B) film arrangement, (C) variation of $\vec{M}$ within the wall, and (D) components of $\vec{M}$ used in the analysis.

to the coordinate system is given in Fig. 2-1-B where x-y plane is the film plane and x-z plane the wall plane. The direction of easy magnetization is in the plane of the film along x-axis. The magnetization $\bar{M}$ is assumed to have a constant magnitude throughout the film but is allowed to vary in orientation as function of y only. The total energy density is taken to be the sum of four contribution: the anisotropy energy, the Zeeman energy, the demagnetization energy and the exchange energy. The uniaxial anisotropy energy density is given by

$$E_{an} = K_1 (1 - \sin^2 \theta \cos^2 \phi) \quad (2-1)$$

the Zeeman energy by

$$E_z = -MH_1 \sin \theta \sin \phi \quad (2-2)$$

and the exchange energy by

$$E_{ex} = A [(\nabla \theta)^2 + \sin^2 \theta (\nabla \phi)^2] \quad (2-3)$$

where K_1 is the anisotropy constant, H_1 is the applied hard-axis field and A is the exchange constant. The demagnetization energy is given by the equation

$$E_d = -\frac{\mu_0}{2} \int \bar{M} \cdot \bar{H} dV \quad (2-4)$$

where

$$\bar{H} = \frac{1}{4\pi} \int_V \frac{\rho_m \hat{r}}{r} dV + \frac{1}{4\pi} \oint_S \frac{\sigma_m \hat{r}}{r^2} dS$$

is the demagnetizing or stray field due to an effective volume pole density $\rho_m = -\nabla \cdot \bar{M}$ in the volume V and effective surface pole density $\sigma_m = \bar{M} \cdot \hat{n}$ on the surface S of V, where $\hat{n}$ is the outward unit vector normal from S. $\bar{r} = r\hat{r}$ is the vector distance from the pole density point

to the field point. As pointed out by Brown and LaBonte,⁽²⁰⁾ the net magnetostatic energy due to interactions of surface charge and volume charge is zero. The magnetostatic energy splits into two independent parts which can be approximated by assuming the wall to be uniformly magnetized over the whole width w of the wall. Therefore the demagnetization energy is given by

$$E_d = \frac{1}{2\mu_0} \frac{w}{w+D} M_{ez}^2 + \frac{1}{2\mu_0} \frac{D}{w+D} M_{ey}^2 \quad (2-5)$$

where D is the thickness of the film, M_{ez}^2 and M_{ey}^2 are given by

$$M_{ez}^2 = \frac{1}{w} \int_{-\frac{w}{2}}^{\frac{w}{2}} M^2 \cos^2 \theta \, dy \quad (2-6A)$$

$$M_{ey}^2 = \frac{1}{w} \int_{-\frac{w}{2}}^{\frac{w}{2}} M^2 (\sin \theta \sin \phi - \sin \phi_f)^2 \, dy \quad (2-6B)$$

The first term in (2-5) is the energy due to the surface charge of the wall while the second term is given to account for the energy due to the discontinuity of magnetization in the wall and the surrounding domains, i.e. the volume charge. The total energy is thus obtained as

$$\begin{aligned} E_T &= \int_{-\frac{w}{2}}^{\frac{w}{2}} (E_{an} + E_z + E_{ex} + E_d) \, dy \\ &= \int_{-\frac{w}{2}}^{\frac{w}{2}} \left[K_1 (1 - \sin^2 \theta \cos^2 \phi) - M H_{\perp} \sin \theta \sin \phi + A (\nabla \theta)^2 + A \sin^2 \theta (\nabla \phi)^2 \right. \\ &\quad \left. + \frac{M^2}{2\mu_0} \frac{w}{w+D} \cos^2 \theta + \frac{M^2}{2\mu_0} \frac{D}{w+D} (\sin \theta \sin \phi - \sin \phi_f)^2 \right] dy \\ &= \int_{-\frac{w}{2}}^{\frac{w}{2}} E(\theta, \phi, \theta', \phi') \, dy \end{aligned} \quad (2-7)$$

where $E(\theta, \phi, \theta', \phi')$ is the equivalent total energy density of the wall.

The proper way to solve this wall problem is to minimize the total energy

by means of a variational calculation in which the variation of the total energy with respect to θ and ϕ is to be made zero. Thus

$$\frac{\delta E}{\delta \theta} = \frac{\partial E}{\partial \theta} - \frac{d}{dy} \left(\frac{\partial E}{\partial \theta'} \right) = 0 \quad (2-8A)$$

and

$$\frac{\delta E}{\delta \phi} = \frac{\partial E}{\partial \phi} - \frac{d}{dy} \left(\frac{\partial E}{\partial \phi'} \right) = 0 \quad (2-8B)$$

where $\theta' = \frac{\partial \theta}{\partial y}$, and $\phi' = \frac{\partial \phi}{\partial y}$

This states that the torque is everywhere zero, which is a necessary condition for a stable structure of a wall.

Instead of solving these coupled nonlinear equations which are mathematically very complicated, we shall assume a wall structure with components of magnetization in the wall given by

$$M_x = M \cos \phi_f \tanh \frac{\pi y}{W} = M \sin \theta \cos \phi \quad (2-9A)$$

$$M_y = M [1 - M_x^2 - M_z^2]^{\frac{1}{2}} \quad (2-9B)$$

$$M_z = M \cos \theta_c \operatorname{sech} \frac{\pi y}{W} = M \cos \theta \quad (2-9C)$$

where θ_c , ϕ_f are the corresponding angles in the wall center and in the domains respectively (Fig. 2-1-C).

The validity of this choice of magnetization distribution along the direction of wall width can be checked by considering the limiting cases, namely, Bloch and Néel walls. For $\theta_c = \phi_f = 0$ the direction cosines α_1 , α_2 , and α_3 of the magnetization vector with respect to x, y, and z axes have the following behavior:

$$\begin{array}{lll}
y: & -\infty & 0 & \infty \\
\alpha_1: & \pi & \longrightarrow & \frac{\pi}{2} & \longrightarrow & 0 \\
\alpha_2: & \frac{\pi}{2} & \longrightarrow & \frac{\pi}{2} & \longrightarrow & \frac{\pi}{2} \\
\alpha_3: & \frac{\pi}{2} & \longrightarrow & 0 & \longrightarrow & \frac{\pi}{2}
\end{array}$$

This describes the Bloch wall. For $\theta_c = \frac{\pi}{2}$

$$\begin{array}{lll}
y: & -\infty & 0 & \infty \\
\alpha_1: & \pi - \phi_f & \longrightarrow & \frac{\pi}{2} & \longrightarrow & \phi_f \\
\alpha_2: & \frac{\pi}{2} - \phi_f & \longrightarrow & 0 & \longrightarrow & \frac{\pi}{2} - \phi_f \\
\alpha_3: & \frac{\pi}{2} & \longrightarrow & \frac{\pi}{2} & \longrightarrow & \frac{\pi}{2}
\end{array}$$

This describes the Néel wall. The calculation of energy for those two limiting cases also prove this point. The most important condition to be proved, however, is that the exchange torque for both limiting cases is zero at the wall center. The exchange torque is given by

$$\begin{aligned}
T_{ex} &= \frac{\delta E_{ex}}{\delta \theta} \\
&= 2A \sin \theta \cos \theta \left(\frac{\partial \phi}{\partial y} \right)^2 - 2A \frac{d^2 \theta}{dy^2}
\end{aligned} \tag{2-10}$$

Using the assumption given by equation 2-9A, B, and C, we obtain

$$\begin{aligned}
\frac{d^2 \theta}{dy^2} &= \left(\frac{\pi}{w} \right)^2 \frac{\cos \theta_c \operatorname{sech}^2 \frac{\pi y}{w}}{(1 - \cos^2 \theta_c \operatorname{sech}^2 \frac{\pi y}{w})^{3/2}} \left[(\operatorname{sech} \frac{\pi y}{w} - \tanh \frac{\pi y}{w}) (1 - \cos^2 \theta_c \operatorname{sech}^2 \frac{\pi y}{w}) \right. \\
&\quad \left. - \cos^2 \theta_c \operatorname{sech} \frac{\pi y}{w} \tanh \frac{\pi y}{w} \right]
\end{aligned}$$

and

$$\begin{aligned}
\frac{\partial \phi}{\partial y} &= - \left(\frac{\pi}{w} \right) \\
&\times \frac{\cos \phi_c \operatorname{sech}^2 \frac{\pi y}{w} (1 - \cos^2 \theta_c \operatorname{sech}^2 \frac{\pi y}{w}) - \cos^3 \phi_c \tanh^2 \frac{\pi y}{w} \operatorname{sech}^2 \frac{\pi y}{w}}{(1 - \cos^2 \theta_c \operatorname{sech}^2 \frac{\pi y}{w} - \cos^2 \phi_c \tanh^2 \frac{\pi y}{w})^{3/2} (1 - \cos^2 \theta_c \operatorname{sech}^2 \frac{\pi y}{w})}
\end{aligned}$$

Hence

and

$$\left. \frac{d^2 \theta}{dy^2} \right|_{y=0} = \left(\frac{\pi}{w} \right)^2 \cot \theta_c$$

$$\left(\frac{\partial \phi}{\partial y} \right)^2 \Big|_{y=0} = \left(\frac{\pi}{w} \right)^2 \frac{\cos^2 \phi_f}{\sin^2 \theta_c}$$

With these results we obtain the exchange torque at the wall center; thus

$$T_{ex} \Big|_{y=0} = -2A \left(\frac{\pi}{w} \right)^2 \cot \theta_c \sin^2 \phi_f \quad (2-11)$$

For a Bloch wall $\phi_f = \theta_c = 0$, $T_{ex} \Big|_{y=0} = 0$. For a Néel wall, although $\theta_c = \frac{\pi}{2}$ so that $\cot \theta_c$ approaches infinite, $\sin^2 \phi_f$ tends to zero faster; hence $T_{ex} \Big|_{y=0} = 0$. Therefore, we conclude that this assumption is reasonable, although a justification at points other than the wall center is not available.

To obtain a stable structure of the wall, total torque is required to be zero at the wall center. That is the torques due to the demagnetization field

$$\bar{H}_d = -\hat{j} \frac{M}{\mu_0} \frac{D}{w+D} (\sin \theta_c - \sin \phi_f) - \hat{k} \frac{M}{\mu_0} \frac{w}{w+D} \cos \theta_c \quad (2-12A)$$

$$\text{and applied field } \bar{H}_a = \hat{j} H_L \quad (2-12B)$$

should be balanced by the exchange torque given by equation 2-10. Hence

$$\bar{M} \times \bar{H} + \bar{T}_{ex} = 0$$

which gives

$$\begin{aligned} & \left(\frac{M^2}{\mu_0} \frac{D-w}{D+w} \right) \sin^2 \theta_c - (MH_L + \frac{M^2}{\mu_0} \frac{D}{D+w} \sin \phi_f) \sin \theta_c \\ & - 2A \left(\frac{\pi}{w} \right)^2 \sin^2 \phi_f = 0 \end{aligned} \quad (2-13)$$

The wall width w should be determined by minimizing the total energy with respect to w . This minimization is difficult to perform. For a given film, w is independent of ϕ_f for Bloch wall, although not for a Néel wall. In the latter case, however, the variation is not large, especially

around the thickness range we consider. Therefore we assume a constant wall width here for mathematical simplicity.

By solving equation 2-13 for $\sin \theta_c$, we obtain

$$\sin \theta_c = B \sin \phi_f \quad (2-14)$$

where

$$B = \frac{(MH_k + \frac{M^2}{\mu_0} \frac{D}{D+W}) + [(MH_k + \frac{M^2}{\mu_0} \frac{D}{D+W})^2 + 8A \frac{M^2}{\mu_0} \frac{D-W}{D+W} (\frac{\pi}{W})^2]^{\frac{1}{2}}}{\frac{2M^2}{\mu_0} \frac{D-W}{D+W}} \quad (2-14A)$$

This constant determines the rate of transition from a Bloch to a Néel wall.

If $B = 1$ no transition should occur, and if $B = \infty$ a transition should occur and in fact be completed as soon as a hard-axis field is applied.

Usually of course B lies between these two extremes. Contrary to our gradual Bloch-Néel wall transition along the line $1 < B < \infty$, Middelhoek's theory predicts that the Bloch-Néel transition is along the line $B = 1$ at first, and then $B = \infty$ as soon as the hard-axis field corresponding to

ϕ_{fc} , the critical angle for Bloch-Néel transition, is reached; this is shown in Fig. 2-2-A. Fig. 2-2-B gives graphically the relationship between θ_c and ϕ_f for $T = 2w, 4w$, and $8w$, using the typical values for permalloy film; $H_k = 5 \text{ oe} = 398 \text{ amp-turn/m}$, $M = 1 \text{ weber/m}^2$, $\mu_0 = 4\pi \times 10^{-7} \text{ henry/m}$, and $A = 10^{-11} \text{ joule/m}$. The curves show that for a given film thicker than $900 \text{ \AA}$, there is a critical angle ϕ_{fc} that depends on the thickness, such that for $\phi_{fc} < \theta_c$ the wall is of the pure Néel type; for $\phi_{fc} > \theta_c > 0$ the wall has components of both Bloch and Néel whose ratio changes continuously as a function of applied field; and for $\theta_c = 0$ the wall is of Bloch type. The existence of the mixed wall has been proven by using Lorentz microscopy.⁽²¹⁾ Note that as the ratio, D/W , increases the transi-

Fig. 2-2 Theoretical calculation of Bloch-Neel wall transition.

tion curves are shifted closer to the line of pure Bloch wall. For a bulk material $D/W \rightarrow \infty$, $B \rightarrow 1$, the transition is negligible until $H_1 \lesssim H_k$.

2.2 Qualitative Theory of Wall Streaming and Wall Creeping

When a fast rising pulse field along the hard-axis is applied, the response times for magnetization in the walls and the domains are quite different if the films are thicker than $900 \text{ \AA}$. Upon the application of this field, the magnetization in the domains initially precesses around the field axis, thereby leaving the film plane; then it precesses around the demagnetizing field and finally reaches a stable direction within the film plane with the help of intrinsic damping of the precession. This is practically a coherent rotation^(22,23) so that the magnetization can closely follow the applied field except for the extremely fast pulses ($T_r = 0.5 \text{ ns}$) and reaches its stable position very fast.

Within a wall the magnetization also precesses around the field axis but no additional demagnetizing field perpendicular to the film plane is thereby established because the increase of the magnetization component normal to the film plane in some location is compensated by the decrease of the other location. With no help from the demagnetizing field, the magnetization undergoes a slow motion to its final position.

This difference in response time causes the magnetization within the wall to delay that of the domains and results in the discontinuity of magnetization component normal to the wall plane. A very large demagnetizing field normal to the wall plane is thereby established within the wall by these volume charges. It is this field which helps the wall magnetization to precess and results in the displacement of a Bloch wall along the hard

direction.

The dependence of the Bloch wall motion on the time rate of change of pulse can also be explained by this model. When the rise time is short, the delay, and therefore the demagnetizing field, are large; the motion then is more pronounced. When the rise time is increased, the magnetization within the wall begins to be able to catch up with that of the domains. This streaming motion becomes weaker and finally stops if the rise time is so long that the equilibrium is almost always assumed. In the next section a quantitative theoretical treatment based on this model and Bloch-Néel wall transition will be given from which it is possible to estimate the movement per pulse under different conditions, especially the rise time dependence.

2.3 Mathematical Formulation of the Model

As described before, a fast rising field can induce a large demagnetizing field normal to the wall plane within the wall during its transient state. In this section we will try to formulate the model by assuming a wall structure, i.e. the spatial dependence of θ and ϕ on the coordinates, where θ and ϕ are shown in Fig. 2-1-A.

When magnetization, $\vec{M} = M \hat{r}$, is excited by an externally applied field, the following motion of the magnetization can be well described by the Landau-Lifshitz equation: ⁽²⁴⁾

$$\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{r} - \frac{\lambda}{|\vec{M}|^2} \vec{M} \times \vec{r} \quad (2-15A)$$

or by its modified form, the Gilbert equation: ⁽²⁵⁾

$$\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{r} + \frac{\alpha}{M} (\vec{M} \times \frac{\partial \vec{M}}{\partial t}) \quad (2-15B)$$

Here α is a damping constant and $\bar{\tau}$ a generalized force given by

$$\begin{aligned}\bar{\tau} &= -\bar{r} \times \nabla E \\ &= \hat{\theta} \frac{1}{\sin \theta} \frac{\delta E}{\delta \phi} - \hat{\phi} \frac{\delta E}{\delta \theta}\end{aligned}\quad (2-16)$$

Substituting the above equation and

$$\frac{\partial \bar{M}}{\partial t} = M \left(\hat{\theta} \frac{d\theta}{dt} + \hat{\phi} \sin \theta \frac{d\phi}{dt} \right) \quad (2-17)$$

into equation 2-15B, we get

$$M \sin \theta \frac{d\phi}{dt} = \gamma \frac{\delta E}{\delta \theta} + \alpha M \frac{d\theta}{dt} \quad (2-18A)$$

and

$$M \frac{d\theta}{dt} = -\frac{\gamma}{\sin \theta} \frac{\delta E}{\delta \phi} - \alpha M \sin \theta \frac{d\phi}{dt} \quad (2-18B)$$

Hence the equations of motion of the magnetization are:

$$\frac{d\theta}{dt} = -\frac{\gamma}{M(1+\alpha^2)} \left[\frac{1}{\sin \theta} \frac{\delta E}{\delta \phi} + \alpha \frac{\delta E}{\delta \theta} \right] \quad (2-19A)$$

and

$$\frac{d\phi}{dt} = \frac{\gamma}{M(1+\alpha^2) \sin \theta} \left[\frac{\delta E}{\delta \theta} - \frac{\alpha}{\sin \theta} \frac{\delta E}{\delta \phi} \right] \quad (2-19B)$$

These are the coupled nonlinear differential equations.

Since our configuration contains variation only in y direction, the variation derivatives are

$$\frac{\delta E}{\delta \theta} = \frac{\partial E}{\partial \theta} - \frac{d}{dy} \left(-\frac{\partial E}{\partial \theta'} \right) \quad (2-20A)$$

and

$$\frac{\delta E}{\delta \phi} = \frac{\partial E}{\partial \phi} - \frac{d}{dy} \left(-\frac{\partial E}{\partial \phi'} \right) \quad (2-20B)$$

Clearly the form of eq. 2-20A and B includes the contribution of the exchange energy.

2.3.1 Gyromagnetic Behavior of Magnetization in Domains

If a pulse field along the hard-axis is applied, the spins in the domains will precess first around the applied field and then around the demagnetizing field, and will finally reach a stable direction with the help of the intrinsic damping of the precession as mentioned in the last section. This fast coherent rotation of magnetization can be described by equation 2-19A and B.

The total free energy density is

$$E = K_1(1 - \sin^2\theta \cos^2\phi) + \frac{M^2}{2\mu_0} \cos^2\theta - MH_L \sin\theta \sin\phi \quad (2-21)$$

The first term on the right-hand side of equation 2-21 represents the uniaxial anisotropy energy. The second term represents the demagnetization energy and the third is the Zeeman energy. Differentiating with respect to ϕ and θ , we obtain

$$\begin{aligned} \frac{\partial E}{\partial \phi} &= K_1 \sin^2\theta \sin 2\phi - MH_L \sin\theta \cos\phi \\ &\simeq K_1 \sin 2\phi - MH_L \cos\phi \end{aligned} \quad (2-22A)$$

and

$$\begin{aligned} \frac{\partial E}{\partial \theta} &= -K_1 \sin 2\theta \cos^2\phi - \frac{M^2}{2\mu_0} \sin 2\theta - MH_L \cos\theta \sin\phi \\ &\simeq -\frac{M^2}{2\mu_0} \sin 2\theta \end{aligned} \quad (2-22B)$$

where we have used the good approximation, $\frac{M^2}{\mu_0} \gg H_L M$, $\frac{M^2}{\mu_0} \gg 2K_1$, and $\theta \simeq \frac{\pi}{2}$. Substituting equation 2-22A and B into equation 2-19A and B, we obtain

$$\dot{\phi} = -\frac{\gamma M}{\mu_0} \psi - \frac{\alpha \gamma H_L}{2} \sin 2\phi + \alpha \gamma H_L \cos\phi \quad (2-23A)$$

and

$$\dot{\psi} = -\gamma H_L \cos \phi + \frac{\gamma H_k}{2} \sin 2\phi - \frac{\alpha \gamma M}{\mu_0} \psi \quad (2-23B)$$

where $\psi = \frac{\pi}{2} - \theta$. These nonlinear coupled equations give the exact behavior of magnetization in the domains. The numerical solutions with following typical data, $\alpha = 0.01$, $\gamma = 2.21 \times 10^5$ (amp-turn/m -sec) $^{-1}$, $\mu_0 = 4\pi \times 10^{-7}$ henry/m, $M = 1$ weber/m 2 , $H_k = 5.0$ oe = 398 amp-turn/m, $H_c = 1.2$ oe = 95.5 amp-turn/m, are given in Fig. 2-3. The applied field is also shown in the same figure for comparison. This calculation shows that the magnetization in the domains rotates and rapidly attain its stable direction, $\phi = \sin^{-1} \frac{H_L}{H_k}$, thus confirming the statement made in the last section.

2.3.2 Gyromagnetic Behavior of Spins in the Walls

As discussed in the last section, the coherent rotation of the spins in the domains causes a large demagnetizing field in the wall. Therefore, the spins within the wall, which are exposed to this large time varying field, will be forced to rotate around this field and finally reach its steady state position by the help of the intrinsic damping of the precession. The angular displacement θ and velocity $\dot{\theta}$ of wall spins determine the displacement of Bloch walls.

When a hard-axis excitation is applied, the total energy density is given by equation 2-7.

$$\begin{aligned} E = & K_1 (1 - \sin^2 \theta \cos^2 \phi) - M H_L \sin \theta \sin \phi + A (\nabla \theta)^2 \\ & + A \sin^2 \theta (\nabla \phi)^2 - H_x M \cos \theta - H_y M \sin \theta \sin \phi \end{aligned} \quad (2-24)$$

where the angle ϕ_f in H_y is now a time varying function which is

Fig. 2-3 Exact solution of ϕ as a function of t . H is the applied field.

determined by equation 2-23A and B, and

$$H_z = -\frac{M}{\mu_0} \frac{W}{D+W} \cos \theta \quad (2-25A)$$

$$H_y = -\frac{M}{\mu_0} \frac{D}{D+W} (\sin \theta \sin \phi - \sin \phi_f) \quad (2-25B)$$

If the dependence of θ and ϕ on the coordinates are known, the behavior of the magnetization at any location within the wall can be determined by substituting this energy into equation 2-19A and B. The general solution of these equations can be obtained in principle by a variational method. This procedure, however, is very complicated mathematically. Therefore, instead of solving the general problem, we shall consider only the spin at the wall center; that is we shall choose a wall structure which satisfies equation 2-7A and B for the limiting cases. A reasonable choice of these functions is given in section 3.1. This approximation provides a somewhat simplified picture of the dynamics of the process by permitting us to concentrate on a uniquely defined feature of the motion, namely the movement of the wall center. Variation of free energy with respect to ϕ and θ are

$$\begin{aligned} \frac{\delta E}{\delta \phi} = & K_1 \sin^2 \theta \sin 2\phi - MH_L \sin \theta \cos \phi - MH_y \sin \theta \cos \phi \\ & - 2A \sin^2 \theta \frac{d^2 \phi}{dy^2} - 2A \sin 2\theta \frac{\partial \phi}{\partial y} \frac{\partial \theta}{\partial y} \end{aligned}$$

and

$$\begin{aligned} \frac{\delta E}{\delta \theta} = & -K_1 \sin 2\theta \cos^2 \phi - MH_L \cos \theta \sin \phi + A \sin 2\theta \left(\frac{\partial \phi}{\partial y} \right)^2 \\ & + H_z M \sin \theta - H_y M \cos \theta \sin \phi - 2A \frac{d^2 \theta}{dy^2} \end{aligned}$$

Considering the spins at the wall center, we obtain

$$\left. \frac{\delta E}{\delta \phi} \right|_{y=0} = 0 \quad (2-26A)$$

and

$$\begin{aligned} \left. \frac{\delta E}{\delta \theta} \right|_{y=0} &= \frac{M^2}{2\mu_0} \frac{D-w}{D+w} \sin 2\theta_c - (MH_L + \frac{M^2}{\mu_0} \frac{D}{D+w} \sin \phi_f) \cos \theta_c \\ &\quad - 2A \left(\frac{\pi}{W} \right)^2 \sin^2 \phi_f \cot \theta_c \\ &= \left(\frac{\delta E}{\delta \theta} \right)_{y_c} \end{aligned} \quad (2-26B)$$

where θ_c and ϕ_f are the corresponding angles at the wall center and in the surrounding domains respectively. Substituting equation 2-26A and B, we obtain

$$\frac{d\theta_c}{dt} = - \frac{\alpha \gamma}{M(1+\alpha^2)} \left(\frac{\delta E}{\delta \theta} \right)_{y_c} \quad (2-27A)$$

and

$$\frac{d\phi_c}{dt} = \frac{\gamma}{M(1+\alpha^2) \sin \theta_c} \left(\frac{\delta E}{\delta \theta} \right)_{y_c} \quad (2-27B)$$

where y_c is y at the wall center. By combining these equations, we get

$$\frac{d\phi_c}{dt} = - \frac{1}{\alpha \sin \theta_c} \frac{d\theta_c}{dt} \quad (2-28)$$

The displacement of the wall center, which is equal to the displacement of the wall, is

$$\frac{dy_c}{dt} = \frac{dy_c}{d\phi_c} \frac{d\phi_c}{dt} = \frac{w}{\alpha \pi \cos \phi_f} \frac{d\theta_c}{dt} \quad (2-29)$$

When film inhomogeneities are considered, a local effective field,

$H_e = H_d$, can be postulated to account for the local force acting parallel to the wall. This yields

$$\frac{1}{\sin \theta_c} \frac{\delta E}{\delta \phi} = -MH_c \quad (2-30)$$

for the wall center. Then equation 2-28 and 2-29 become

$$\frac{d\phi_c}{dt} = - \frac{1}{\alpha \sin \theta_c} \left(\frac{d\theta_c}{dt} - \gamma H_c \right) \quad (2-31)$$

and

$$\frac{d\gamma_c}{dt} = \frac{w}{\pi\alpha \cos\phi_f} \left(\frac{d\theta_c}{dt} - \gamma H_c \right) \quad (2-32)$$

Integrating the latter we find the displacement per pulse to be

$$\gamma = \gamma_c = \frac{1}{\pi\alpha} \int_{t_1}^{t_2} \frac{w(\dot{\theta}_c - \gamma H_c)}{\cos\phi_f} dt \quad (2-33)$$

This integration, however, is difficult to perform analytically because

1) θ_c is a very complicated function of time and 2) the limits of the integration, corresponding to $\dot{\theta}_c > \gamma H_c$ are not known. This problem will be solved numerically by a computer in the following section.

2.3.3 Analysis of Computation Results

As the equation of the motion for the magnetization at the wall center is known, one should be able to understand the dynamic behavior of the Bloch wall in principle by solving this equation. However, the analytical solution is difficult because of the nonlinear nature of the equation itself. The problem becomes even more complicated by the presence of the angle ϕ_f in the equation. To obtain interpretable results it is necessary to use an electronic computer. With the following typical data, $H_c = 1.5$ oe = 119 amp-turn/m, $H_k = 3.5$ oe = 275 amp-turn/m, $\gamma = 2.21 \times 10^5$ (amp-turn/m - sec) $^{-1}$, $\mu_0 = 4\pi \times 10^{-7}$ henry/m, $\alpha = 0.01$, $M = 1$ weber/m 2 , $A = 10^{-11}$ joule/m, equation 2-23A and B become

$$\begin{aligned} \dot{\phi}_f = & -1.76 \times 10^{11} \psi - 3.1 \times 10^5 \sin 2\phi_f \\ & + 1.76 \times 10^5 H_L \cos \phi_f \end{aligned} \quad (2-34A)$$

$$\begin{aligned} \dot{\psi} = & -1.76 \times 10^7 H_L \cos \phi_f + 3.1 \times 10^7 \sin 2\phi_f \\ & - 1.76 \times 10^9 \psi \end{aligned} \quad (2-34B)$$

These can be solved for ϕ_f and substituted into equation 2-27 to give

$$\begin{aligned} \dot{\theta}_c = & (1.76 \times 10^5 H_{\perp} + 1.29 \times 10^9 \sin \phi_f) \cos \theta_c - 4.11 \times 10^8 \sin 2\theta_c \\ & + 2.72 \times 10^8 \sin^2 \phi_f \cot \theta_c \end{aligned} \quad (2-35)$$

The initial conditions are: at $t = 0$, $\phi_f = \psi = \theta_c = 0$. The movement per pulse is obtained by evaluating

$$y = 1.28 \times 10^{-6} \int_{t_i}^{t_2} \frac{\dot{\theta}_c - 2.64 \times 10^7}{\cos \phi_f} dt \quad (2-36)$$

The results are given graphically in Fig. 2-4. Here the movement per pulse y is plotted against $h_{\perp} = H_{\perp}/H_k$ with the rise time as parameter. There are two points of interest: 1) A slight deviation from the linearity of the curves at high field and 2) the fact that the curves are approximately parallel. The deviation of the wall motion from linearity is not surprising. This simply states that the motion of the Bloch wall depends on both rise time and field strength. However, those characteristics curves show that above a certain threshold the field strength is dominant for this dynamic problem. Since those curves are parallel to each other, one can conclude that the variation of the pulse rise time merely changes the threshold but not the general characteristics of the Bloch wall. This calculation also predicts that wall streaming is possible even when the rise time of the pulse is as long as 30 ns provided that field strength is high enough. The movement per pulse from this calculation is in the order of $10^{-7} - 10^{-6}$ m/pulse.

In real experimental situation, pulses with finite fall time are used. To account for the effect of the fall time, the only change we need to make is in the initial condition; this becomes the final value of the rising part. In other words it changes only the sign of the quantity

Fig. 2-4 Theoretical curves of movement per pulse y vs. normalized field strength $h_{\perp}$ with rise time τ as a parameter.

evaluated for the rising part. Therefore, the total movement per pulse can be inferred by subtracting the predicted motion associated with the corresponding leading and trailing edges of the pulse as illustrated in Fig. 2-5. This principle of superposition gives important information concerning the threshold and the effect of the rise and fall times. Thus, consider two pulses with the same rise time τ_1 and different fall times τ_2 and τ_3 respectively. The net effect is $\tau_1 - \tau_2$, and $\tau_1 - \tau_3$ as shown in Fig. 2-5-B. There are two points of interest: 1) The threshold is the same for both cases and 2) for a fixed rise time, the movement per pulse is larger for a long fall time pulse than for a short one. If the pulses are now changed to have the same fall time τ_3 but different rise times τ_1 and τ_2 , the results are shown in Fig. 2-5-C with $\tau_1 - \tau_3$ and $\tau_2 - \tau_3$. Contrary to the previous case, 1) the threshold is different, being higher for the slower rising pulse 2) the movement per pulse is larger for a short rise time pulse than for the long one. The theory, therefore, predicts that the threshold for wall streaming is affected only by the leading edge of the pulse while the movement per pulse is determined by both leading and trailing edges.

Another important result predicted by the theory is the threshold of wall streaming. This is accomplished by setting equation 2-36 equal to zero. The result is shown in Fig. 2-6. Note that two distinct regions are shown in this characteristic curve, 1) when $\frac{dh}{dt}$ is large, the threshold field, h_{th} , is constant and 2) when $\frac{dh}{dt}$ is small, h_{th} is a linear function of $\frac{dh}{dt}$. The first region results from the inability of the gyromagnetic motion to follow the very rapidly increasing field. The second region states that when rise time is long but still short enough to cause wall

Fig. 2-5 Illustration of the rise and fall time effects.

Fig. 2-6 Theoretical threshold curve of wall streaming: (A) exact solution, (B) approximate solution.

streaming h_{th} depends only on the slope of the applied pulse.

An alternative derivation of the threshold curve can be given analytically by a reasonable approximation. When applied field is low, equation 2-23 becomes

$$\begin{aligned} \gamma &\approx \frac{W}{\pi\alpha} \left[\int_0^{\sin^{-1}h_L} d\theta_c - \int_0^{T_r+t_0} \gamma H_c dt \right] \\ &= \frac{W}{\pi\alpha} [\sin^{-1}h_L - \gamma H_c (T_r + t_0)] = 0 \end{aligned} \quad (2-37)$$

where t_0 is the switching time contributing to the wall displacement in case of $T_r = 0$. Using the relation $T_r = \frac{h_{th}}{dh_L/dt}$, equation 2-37 becomes

$$h_{th} = \frac{\gamma H_c t_0 (dh_L/dt)}{(dh_L/dt) - \gamma H_c} \quad (2-38)$$

If $\frac{dh_L}{dt} \gg \gamma H_c$, $h_{th} = \gamma H_c t_0$, and $h_{th} \rightarrow \infty$, $\frac{dh_L}{dt} = \gamma H_c$. This is shown in Fig. 2-6-B. This approximation agrees well with the exact solution given before, except in the region $\frac{dh_L}{dt} \leq \gamma H_c$. This is not surprising because the approximation is no longer valid in this region.

Chapter 3

Bloch Wall Motion under Hard-axis Pulsing without Bias

Two kinds of domain wall motions are observed when a fast rising pulse field is applied along the hard direction of a Ni-Fe film thicker than 900 Å when it is in a demagnetizing state. One of them is the wave-like motion of domain walls which is called "wall streaming"^(16,26) or "worm motion",⁽¹⁷⁾ and the other is the uniform propagation of tip domains along the hard-axis. The latter was discovered in this laboratory and has been named "wall parade".⁽²⁷⁾ In this chapter, we will first discuss the experimental observations of streaming and parade, and then the quantitative measurements will be given to compare with the theoretical predictions of the last chapter.

3.1 Observations

One of the most important requirements for the observation of the above-mentioned phenomena, streaming and parade, is that no effective field should be applied parallel to the Bloch walls. The alignment of the film is very important for all investigations, especially when measurements are being performed. The film is adjusted within the strip line, such that domain splitting is observed if a large hard-axis field, $H_L > H_K$, is applied first and then reduced to zero.

3.1.1 Domain Parade

A pulse field applied along the hard-axis of Ni-Fe film produces a uniform propagation of domain tips which resembles a "parade" of the domains as shown in successive photographs of Fig. 3-1-A. As clearly shown in these pictures, the domains are travelling unidirectionally

(A)

Fig. 3-1 (A) Wall parade motion excited by hard-axis pulses. Pictures are taken successively at 500 pulse intervals. (Film: #7 11-28-67).

(B) Location of domain tips after the application of different numbers of pulses. This is obtained from the photographs of (A).

(B)

along the hard-axis after nucleation. Those tip domains on the left-hand side propagate downward as indicated by the triangles in the pictures while those on the right-hand side travel upward indicated by the circles in the same pictures. Those domains are finally annihilated against the film edge or merged into the big bridged domains. Careful observation also shows that those tip domains travel independently although they join together occasionally. If the position of the domains is measured and plotted against the number of pulses, which is equivalent to time, the velocity of propagation is found to be very uniform as shown in Fig. 3-1-B. The movement per pulse of the walls is of the order of 10^{-6} m/pulse for this particular situation: Film #7 11-28-67, $H_c = 1.2$ oe, $H_k = 5.0$ oe, $D = 1400 \text{ \AA}$, $\alpha_{90} \sim 1^\circ$ and pulse: $T_r = 0.5$ ns, $T_f = 30$ ns, strength = $0.36H_k$.

The most probable sites for the nucleation of these domains are at the film edges approximately in the middle of the opposite quadrants defined by the easy and hard axes. In some films, however, nucleation in other locations is observed, which is apparently associated with a random distribution of sites of easy nucleation. If these tip domains are nucleated near the center of the quadrants, only those which travel toward the easy-axis are observed. The domains that tend to travel away from the easy-axis immediately disappear against the film edge. Domains that nucleate near the easy-axis extremities in some films divide into two groups and travel away from the easy-axis and are annihilated in a normal fashion at the film edge near the center of the corresponding quadrant. This motion in contrast to wall streaming depends on the almost complete absence of Néel lines^(28,29) in the Bloch walls.

The observations of the origin of the domains participating in the parade motion may be explained by the direction of the curling of the magnetization at the film edge in the four quadrants. Two opposite quadrants are favored for the pulse field in one direction and the other two are favored for pulses of the opposite polarity. With reference to Fig. 3-2, four possibilities in the structure of a nucleated tip domain result in four types of behavior. If the spin polarities in the Bloch walls comprising the tip are the same, the tip will contract and disappear or attempt to expand. A very small easy-axis bias will suppress the nucleation of these domains. However, parade motion occurs and is easily observable in spite of the existence of the expanding domains. If the spin polarities in the wall pair are opposite — a situation which is more probable — then the tips move uniformly toward the easy-axis to give the observed parade or disappear immediately against the film edge. Therefore, even though four types of nucleated domains are possible — two with higher probability — the parade motion exists as long as some of the opposite-wall-polarity domains with appropriate signs are nucleated in the proper quadrant.

During the parade motion the total film magnetization remains essentially constant because the annihilated domain is compensated for by the nucleation of a new domain. This result is confirmed by the signal from the pick-up loop in the strip line. It is further observed in Bitter patterns that a definite closure structure is found to exist at the film edge during the parade motion. It may be assumed that the equivalent easy-axis bias field due to demagnetizing effect is very small at the

Fig. 3-2 Domain wall motion due to the application of hard-axis pulses on a Bloch wall pair. The dashed arrow represents the direction of motion.

film edge.

It should be emphasized that this uniform propagation of domain tips is very pronounced when a fast rising ($T_r = 0.5$ ns) and slow falling ($T_f \gg 20$ ns) pulse time is applied to the hard-axis of a thicker film ($D \sim 1500$ Å). This motion is more clearly displayed if a small easy-axis bias is applied to suppress the bridged domains. In films with thickness around 1000 Å, the wave-like motion is much more active and parade motion almost disappears. This occurs because for films of this thickness there is a relatively frequent change of the spin polarities of the walls by the motion of Néel lines along the walls.

3.1.2 Wall Streaming

As said previously, the wave-like motion can be induced by fast rising hard-axis pulses applied to the films in the Bloch wall region. This phenomenon was recently reported by Feldtkeller and Stein^(16,26); and Kusuda, Konishi, and Sakurai⁽¹⁷⁾; and was named by these workers "wall streaming" and "worm motion" respectively because of its appearance in visual observations.

The streaming can be best visualized by the help of a series of pictures taken successively during this motion. This is shown in Fig. 3-3 for the film #2, 2-23-68 with $H_c = 1.6$ oe, $H_k = 4.6$ oe, $D = 1170$ Å, $\alpha_{90} \sim 0.7^\circ$; and pulses with $T_r = 0.5$ ns, T_f : very long, $T_w = 50$ ns, strength = $0.36H_k$. The domains are observed to expand and shrink as long as field pulses are applied. Two basic modes of domain wall motions are involved: 1) wall displacement directed parallel or antiparallel to the pulse field, and 2) small travelling waves propagating along the domain

Fig. 3-3 Wall streaming: a wave-like motion by hard-axis pulses.
Pictures are taken successively at 250 pulse intervals.
(Film: #2 2-23-68).

boundaries. If the position y of the wall for a fixed x value is plotted versus the number of pulses, the movement per pulse is found to remain constant over a large number of pulses before it reverses the direction of the motion as shown in Fig. 3-4-A. The signal which represents the overall flux fluctuation detected by a sampling oscilloscope and XY recorder also shows the same characteristics (Fig. 3-4-B).

A domain wall in Ni-Fe films thicker than $900 \text{ \AA}$ may consist of Bloch wall sections separated by Néel lines. In order to reduce the demagnetizing field, the Bloch wall sections are alternately magnetized along their center lines in one or other of the two directions normal to the film as shown in Fig. 3-5-A. When hard-axis pulses are applied, the Bloch wall sections at both sides of Néel lines will move in opposite directions as discussed before. The lines can also be forced to move along the wall under this excitation which in turn results in a wave-like motion of the domain walls. This wave-like motion or wall streaming is very active when the thickness of the films ($900 \text{ \AA} - 1200 \text{ \AA}$) are near the cross-tie and the Bloch wall transition thickness ($900 \text{ \AA}$), because in this region cross-tie wall structure usually exists and serves as a nucleation source of Néel lines.

The behavior of Néel lines can be inferred by observing the domain wall motion. The wavy motion represents the situation under which Néel-line motion is pronounced. To determine the characteristics of Néel-line motion, the following facts are established:

- 1) With constant width and amplitude, Néel-line motion increases when the rise time is decreased if the fall time is long; and the

(A)

(B)

Fig. 3-4 (A) Position of wall y for fixed x deduced from Fig. 3-3.
 (B) The signal which represents the change of flux due to wall motion.

(A)

(B)

(C)

(D)

Fig. 3-5 Schematic diagram of a Néel line.

motion decreases when fall time is decreased with rise time kept constant. If the fall time is approximately equal to the rise time, the wavy motion practically stops, i.e., no net Néel-line motion is gained.

- 2) With constant rise time, fall time, and amplitude, the motion is weak at short pulse width, but increases with increasing pulse width. No remarkable pulse width dependence is observed with pulse widths greater than about 20 ns.

These facts can be explained by the aid of Fig. 3-5-B to D. Because the central magnetization of a Néel line lies in the film plane, its stray field causes a characteristic curvature of the local magnetization direction in its neighborhood, containing a short cross-wall (Fig. 3-5-A). If a field along the hard-axis is applied, the magnetization in the domains rotates toward the field direction. In order to remain free from magnetic poles, the cross walls have to rearrange themselves to a new orientation shown in Fig. 3-5-B. Because the reorientation corresponds to a wall motion of the cross-walls, the cross-walls may not be able to follow immediately the coherent rotation of the magnetization in the domains and thereby they become magnetically charged as shown in Fig. 3-5-C. The field of these charges may displace the Néel line, thereby facilitating the cross-wall reorientation easier, since now the mean cross-wall movement necessary for a correct reorientation is smaller (Fig. 3-5-D). This process is to be expected only if the time rate of change of the pulses, either rise or fall time, is large. In a slowly changing field, the cross-wall will have time enough to reorient without displacing the Néel lines.

The motion of Néel lines at the times of rise and fall of the pulse is similar to that of Bloch walls. Consequently, the net displacement of a Néel line should be the superposition of the displacements during the rising and falling of the pulses. This explains the first part of the experiments. The dependence of Néel-line motion on the width of the pulse shows that the time required to finish the process is less than about 20 ns. Pulses shorter than this value will affect the displacements of the lines and the motion is, therefore, suppressed.

There are two situations that favor the generation of Néel lines on which the wall streaming depends. One of these, as mentioned above, is for the films with thickness near the transition from cross-tie to Bloch walls and the other is for fields with amplitude near the transition from Bloch to Néel walls. The observation of streaming on a thicker film ($\sim 1500 \text{ \AA}$) reveals that at low field ($\approx 0.4H_k$) a uniform motion is dominant while at the field near the transition streaming is the more pronounced. If the field is increased beyond the transition, a very high density of Néel lines is generated and the motion stops.

3.2 Quantitative Experimental Results

The two basic measurements made were 1) the threshold field of the sidewise motion, and 2) the movement per pulse as a function of the applied field.

3.2.1 Threshold Condition

The threshold field, h_{th} , was determined as follows: A isolated straight single domain wall perpendicular to hard-axis was introduced

near the center of the film in order to reduce the stray field effect. The amplitude of the field was increased keeping the rise and fall times constant; the first movement of the wall was observed. The field which caused the first movement of the wall was called the threshold of the motion. The result of the measurement is given in Fig. 3-6. Here the threshold is constant when $\frac{dh}{dt} > 0.06 \text{ ns}^{-1}$, and depends linearly on $\frac{dh}{dt}$ when $\frac{dh}{dt} < 0.03 \text{ ns}^{-1}$. Comparison with the predicted curve given in the last chapter shows a very good qualitative agreement. However, the theoretical curve predicts a somewhat lower h_{th} for large $\frac{dh}{dt}$ and a higher h_{th} for small $\frac{dh}{dt}$ than the measured values. This discrepancy is presumably due to the approximation made in calculation.

3.2.2 Displacement of the Wall or Movement per Pulse

Movement per pulse was determined by counting the number of pulses needed for the Bloch wall to travel a certain distance. For this purpose it was necessary to select an isolated straight wall perpendicular to the hard direction of the film. In order to eliminate the influence of fall time, the pulse field with very long fall time was used. The result is shown in Fig. 3-7. Note that the general shape of the curves, both linearity and parallelism, agrees excellently with the predicted characteristics given in Fig. 2-4 of the last chapter. The movement per pulse is found to lie between 10^{-7} and 10^{-6} m/pulse from this experiment which is of the same order of magnitude as that predicted. The actual magnitude is about twice as large as that predicted.

One notes in Fig. 3-7 that for amplitudes greater than 0.3 the motion tends to a limit of about 10^{-6} m/pulse for very fast rise times ($T_r \sim 0.5 \text{ ns}$).

Fig. 3-6 The threshold field as a function of the rate of change of the field, $\frac{dh}{dt}$.

Fig. 3-7 Movement per pulse y vs. field strength $h_{\perp}$ ($= \frac{H_{\perp}}{H_K}$).

This may be because of the inability of the gyromagnetic motion to follow the very rapidly increasing field.

Another experiment was designed to verify the principle of superposition for rising and falling parts of the pulses. The pulse field with a very long fall time was used to measure the movement y per pulse for different rise times (Fig. 3-8-A). Then pulses of different combinations of rise time, T_r and fall time T_f , for example, $T_r = 0.5$ ns, $T_f = 10$ ns, were applied to make the same measurement (Fig. 3-8-B). If the theory is correct, the difference of the curves, that is, $T_{r1} (\neq 0.5 \text{ ns}) T_{r2} T_{f2} = 10 \text{ ns}$ of the first measurement (indicated in Fig. 3-8-B by dotted lines) should be the same as that of the second measurement (represented by solid lines in the same figure) with $T_r = T_{r1}$ and $T_f = T_{r2}$. The agreement between the theory and the actual measurements is satisfactory at low fields. However, at high field ($h_L > 0.3$), y is gradually reduced to zero instead of remaining constant as predicted. This is attributed to Bloch-Néel wall transitions. At high fields, Néel lines are created and result in wall streaming. However, those lines having the same structure as the Néel walls will hinder the Bloch walls from moving and therefore reduce the mobility of the walls. If the amplitude is increased above the field for Bloch-Néel wall transitions, the walls will completely lose their former Bloch wall polarities. As a result, a very high density of Néel lines is generated and the motion stops.

Investigation of the threshold fields of Fig. 3-8-B for pulses with different rise and fall times confirms the statement that the threshold for the sidewise domain wall motion is affected only by the leading edge

Fig. 3-8 (A) Movement per pulse for step fields with different rise times. (B) Movement per pulse for pulse fields. (Solid lines) The dotted lines are predicted from (A).

of the pulse. Therefore, we conclude that the principle of superposition is valid at low field where the density of Néel lines is negligible.

Chapter 4

Bloch Wall Motion under Hard-axis Pulsing and Easy-or Hard-axis Bias

It has been pointed out in the last chapter that wall streaming occurs only when the effective easy-axis field is zero. In this chapter, we will discuss the Bloch wall motion due to hard-axis pulses when an easy-axis bias is applied simultaneously. We will emphasize the demagnetization process of a film from its single domain state. This process is usually referred to as wall creeping.

Wall creeping occurs for films in any thickness provided that the proper combination of fields is applied. For films whose wall structure is of Néel type ($D \lesssim 400 \text{ \AA}$), bidirectional pulses along the hard-axis and easy-axis bias will result in creeping. On the other hand for either cross-tie walls ($400 \text{ \AA} \lesssim D \lesssim 900 \text{ \AA}$) or Bloch walls ($D \gtrsim 900 \text{ \AA}$), unidirectional hard-axis pulses and easy-axis bias are sufficient to produce creeping. Because creeping depends very much on wall structure, different mechanisms should be expected to explain the process. Some rather different theories have been proposed by a few authors⁽⁵⁻¹⁵⁾ concerning creeping stimulated by slowly-varying fields, yet none of them can explain all the experimental facts. In this chapter, gyromagnetic behavior of spins is used to analyze Bloch wall creeping caused by fast rising pulses.

4.1 Domain Wall Creeping

Domain wall creeping is a process of demagnetization from a single domain state brought about by an ac field applied in the hard direction and a dc field in the easy direction. This process is caused by a slow sinusoidal excitation (60 cps) or fast rising pulses ($T_r < 20 \text{ ns}$). For

the first case, creeping is associated solely with Bloch-Néel wall transitions, while for the second case, it is attributed to the gyromagnetic effects of the spins. In this work, only the latter will be considered.

Creeping can be best illustrated by a series of pictures taken successively during the process (Fig. 4-1). The film ($H_c = 1.2$ oe, $H_k = 5.0$ oe, $D = 1500$ Å, $\alpha_{90} \sim 1^\circ$) was magnetized to a single domain state (Fig. 4-1-A) by applying a large dc field along the easy-axis. In order to reduce the demagnetization energy, some tiny domains were nucleated at film edge after the field was removed. Those tips are separated by 180° wall from the main domain. The stray field in this situation is opposite to the direction of the magnetization in the main domain and tips are favored by this field. When hard-axis pulses ($T_r = 0.5$ ns, $T_f = 30$ ns, $T_w = 30$ ns) are applied, the tips grow gradually as shown in Fig. 4-1-B to D until the demagnetization state is found (Fig. 4-1-E). However, the growth of the tips may stop before the demagnetization state is reached for some cases. This can be explained by the threshold curves obtained in the following sub-section.

The most important measurements were the determination of the threshold and the movement per pulse of the domain boundaries in the hard direction.

4.1.1 Threshold Curves of Creeping

The technique for this measurement was similar to that used for measuring the threshold for streaming except that an additional dc field was applied along the easy-axis. Fig. 4-2 gives the results with rise time $T_r = 0.5$ ns, 20 ns, and 50 ns. It was found that the threshold decreases

Fig. 4-1 Wall creeping: Demagnetization process from single domain state due to hard-axis pulses. Pictures are taken successively at 250 pulse intervals. (Film: #7 11-28-67).

Fig. 4-2 Threshold field h_{th} vs. easy-axis field h_{dc} with different values of rise times.

as the bias increases and the relation was reasonably linear. The threshold curves changed drastically when the rise time was changed, being steeper for the longer rise time pulses and collapsing to the static threshold for pulses of very long rise time. However, the general shape of these curves is not influenced by the variation of rise time. All the curves converge to the point $H_{dc} = H_c$, which is not a surprising result.

Depending on the type of the easy-axis field, these threshold curves give significant information about the processes of creeping, streaming, and parade motion.

a) Demagnetizing Field Effect

When the easy-axis bias is supplied by the demagnetizing field of a single domain film, the magnetization process will depend on the amplitude of the hard-axis pulses. Imagine that the initial field combination is located at point A of Fig. 4-2, the domain tips would then propagate along the easy-axis, which would be equivalent to the propagation of domain walls along the hard-axis, thereby reducing the demagnetizing field until the threshold curve should be reached and the motion stopped. The reduction of the demagnetizing field is due to the formation of closure structure at the film edge. With the hard-axis field strength corresponding to point B, the film reaches the half-switched state, but sidewise motion practically ceases at this point. For these two cases only creeping takes place. With higher field strength, corresponding to point C, the parade and the wall streaming occur after the creeping is complete. This is well illustrated in Fig. 4-3. From a single domain state, the film is driven by fast rise time pulses along the hard-axis with an amplitude corresponding

Fig. 4-3 The demagnetization process due to hard-axis pulses with amplitude corresponding to point C of Fig. 4-2.

to point C of the same figure. No external easy-axis is as yet applied. The domain tips nucleate at the edge of the film and propagate along the easy-axis as the domains expand due to the sidewise motion of the domain wall. As this process continues, the demagnetization field continues to generate tip domains within the now expanded original tip domains; this may be seen in the successive Kerr photographs of Fig. 4-3. After many hard-axis pulses, the film will reach the demagnetized, or half-switched, state. The uniform sidewise, or parade, motion then begins and continues indefinitely. Simultaneously, with these motions walls in the film may be experiencing the typical wave-like motion or streaming. The demagnetizing field serves in these processes as an effective bias field localized along the easy-axis.

b) Easy-Axis Field Supplied Externally

If the easy-axis bias is supplied or partly supplied externally, the motion is somewhat different from that described above. Again the magnetization process depends on the amplitude of the hard-axis pulses. Consider the initial state corresponding to point A of Fig. 4-2, with applied easy-axis field H_a smaller than H' as indicated in the same figure. The magnetization process is the same as that of point A discussed in the last section where no field is applied externally. If $H_a > H'$, the domains with magnetization direction in the direction of applied field are always favored; the domains will creep until a single domain is found. The points corresponding to B and C of Fig. 4-2, have the same behavior as that of point A with $H_a > H'$. Due to the finite thickness, the magnetization is not uniform throughout the whole film. This non-uniformity gives rise to

a distribution of demagnetizing field which is higher at the film edge than at the film center. If H_a is smaller than the maximum value of this field, H_a will be balanced out at the film edge by stray field. The effective easy-axis bias is negligible and the precession motion is possible, as is proven by Kerr observation. If H_a is larger than the maximum demagnetizing field, the final state is a single domain. This suggests a method to determine the maximum demagnetizing field. This is done by supplying a dc field along the easy-axis while it is pulsing and observing the existence of tip domains. The minimum dc field at which tips completely disappear is the maximum demagnetizing field of the film. For the film #6, 3-8-68, for example, ($H_c = 1.5$ oe, $H_k = 5.0$ oe, $D = 1500 \text{ \AA}$, diameter = 1 cm) this field was determined to be 0.5 oe. The theoretical calculation by assuming a uniform magnetization over the whole wall is 0.15 oe. The discrepancy is presumably due to the simplifying assumptions.

4.1.2 Creeping Rate or Movement per Pulse

For the Bloch wall, it is believed that the major effect of the easy-axis bias, H_{dc} , is to aid the motion of the wall. Thus, two facts should be expected. One of them is a reduction of threshold and the other is an increase of creeping rate. Theoretically these facts can be explained by replacing H_c in equation 2-32 by $H_c - H_{dc}$, thus the equation reads

$$\frac{dy}{dt} = \frac{W}{\pi \alpha \cos \phi_f} [\dot{\theta}_c - \gamma(H_c - H_{dc})] \quad (4-1)$$

where the notations are the same as given before. The threshold condition

$$\dot{\theta}_c - \gamma(H_c - H_{dc}) > 0 \quad (4-2)$$

and the creeping rate

$$y = \frac{w}{\pi\alpha} \int_{t_1}^{t_2} \frac{\dot{\theta}_c - \gamma(H_c - H_{dc})}{\cos\phi_f} dt \quad (4-3)$$

reveal the above-mentioned facts by the reduction of effective coercive force. The experimental results are given in Fig. 4-4-A. Theoretical curves calculated for the same bias and experimental curve without bias are also given in the same graph. One sees, for example, that the threshold h_{th} decreases from 0.14 to 0.08 as the bias increases from zero to 0.4 oe; further the creeping rate increases by three times. The theoretical calculation shows the same trend but the numerical value is different by an order of magnitude.

The creeping rate is also measured with constant pulse field ($T_r = 2.5$ ns, $T_f \approx$ very long, $T_w = 50$ ns, strength = 1 oe) as the easy-axis bias, H_{dc} , is varied. The result (Fig. 4-4-B) indicates that the creeping rate y increases linearly with increasing H_{dc} when bias field is low, but increases very fast when H_{dc} is near the coercive force H_c and tends to the normal wall motion due to the easy-axis excitation when H_{dc} approaches H_c .

4.2 Hard-axis Bias Effect

When a dc hard-axis bias, h_{bias} , is applied superimposed on a fast rising hard-axis pulse field, h_1 , the motion of the Bloch walls is influenced because the initial condition has been changed from $\phi_f = 0$, $\psi = 0$, and $\theta_c = 0$ to $\psi = 0$, $\phi_f = \sin^{-1} h_{bias}$, and $\theta_c = \sin^{-1} (B \sin \phi_f)$. Here B is the Bloch-Néel wall transition rate defined by equation 2-14AA. The observation with $h_{bias} = 0.238$ is given graphically in Fig. 4-5-A along with the corresponding curve with zero bias. Comparison between

Fig. 4-4-A Creeping rate y vs. $h_{\perp}$ with applied easy-axis bias.

Fig. 4-4-B Creeping rate vs. H_{dc} with constant pulse field.

these two curves shows 1) the movement per pulse is increased by the application of the bias field, and 2) the threshold is somewhat higher for the case $h_{\text{bias}} \neq 0$ although it is not much affected by this field. The deviation from linearity is noted when $h_{\perp} > 0.25$, This occurs because the total field $h_{\tau} = h_{\perp} + h_{\text{bias}} = 0.48$ is close to the Bloch-Néel wall transition.

The fact that the Néel wall can not be moved by the application of hard-axis pulses suggests a method to measure the field at which the Bloch-Néel wall transition is finished. This is done more conveniently by applying both dc field and pulse field along the hard direction and observing the minimum h_{bias} which causes streaming to cease at any strength of the pulse field. Such a strength of the pulse field is necessary to ensure the threshold condition, $\theta_c - \phi H_c > 0$, is satisfied. The result is indicated in Fig. 4-5-B. The agreement between theory and experiment is excellent within the limits of the capabilities of our instruments. This justifies the Bloch-Néel wall transition theory given in section 2.1.

Fig. 4-5 (A) y vs. $h_{\perp}$ with h_{bias} applied along the hard-axis. (B) Experimental results of Bloch-Néel wall transition.

Chapter 5

Discussion

Dynamic behavior of the Bloch walls under hard-axis pulse fields has been extensively studied both theoretically and experimentally in the last few chapters. Both predicted behavior and observed results point out the following:

- 1) Threshold of the Bloch wall motion depends on the time rate of change of the pulses, $\frac{dh}{dt}$. It is constant when $\frac{dh}{dt}$ is large, and increases linearly with decreasing $\frac{dh}{dt}$, when $\frac{dh}{dt}$ is small (Fig. 3-6).
- 2) Movement per pulse increases linearly with the amplitude, h_1 , of pulse field with constant rise time at low field, when it is applied perpendicular to the Bloch walls (Fig. 3-7).

In spite of this success, the model fails to account for the decrease of the motion which finally stops after a peak is reached. This is because the theory is based on the assumption that the Bloch wall section that we have considered has only one spin rotation and is allowed to move freely. The interaction between the Bloch walls and Néel lines has been ignored.

The most significant information gained in creeping experiments is that the demagnetizing field plays an important role in determining the characteristics of the motion associated with hard-axis pulses and must be accounted for in any discussion of threshold fields.

Some weaknesses of this theory are reflected by the fact that the estimated values are somewhat lower than the measured ones. This discrepancy may possibly be due to the assumptions that 1) wall width is constant,

2) H_c represents the local force due to film inhomogeneities, and 3) the theoretical treatment was one-dimensional.^(30,31)

One obvious extension of the present work would be to improve the model by taking care of the weaknesses pointed out in the last paragraph. A reasonable assumption of the dependence of the wall width, w , on the angle between magnetization and the normal of the film plane at the wall center, θ_c , will largely improve the accuracy. Additional consideration of two dimensional walls as proposed recently⁽³²⁾ could also be possible, although it will lead to an extreme complexity of mathematical formulation. The behavior of the Bloch wall motion at higher field can be predicted only when the interaction between the Bloch walls and Néel lines is taken into account. A possible way is to treat this problem analogous to the motion of string. As regards H_c , not much can be done because of lack of knowledge on film inhomogeneities.

Experimentally, this work suggests that the future investigations should include 1) direct observation of Néel-line motion, and 2) the possibility of uniform unidirectional motion of domain rings along the longitudinal axis of permalloy wire having circumferential easy-axis and a low ratio of $\frac{H_c}{H_K}$.

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