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Review of Wall Creeping in Thin Magnetic Films

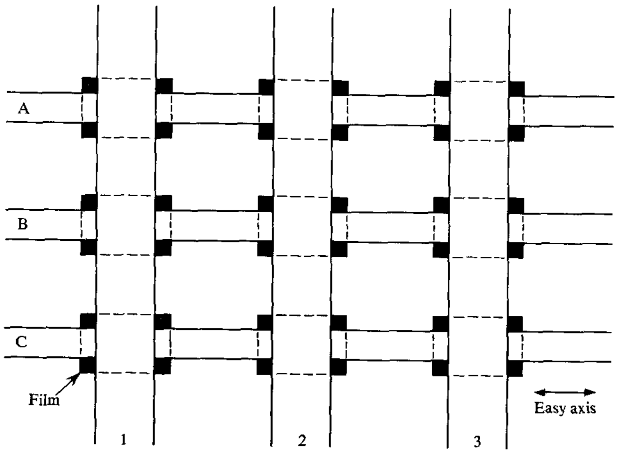
Abstract: Domain wall creeping in thin magnetic Ni-Fe films has been studied as a function of the film thickness, field pulse amplitude, duration and repetition frequency, and bias fields in the hard direction. The experimental results are reviewed and compared with the three existing theories, which ascribe wall creeping to a) Bloch line motion, b) wall structure changes, and c) changing magnetic charges along the walls, respectively. Based on the first theory, methods are indicated by which a reduction of creep sensitivity of magnetic films might be obtained.

Introduction

The most generally known mode of operation of a thin film memory uses unipolar field pulses in the hard direction and positive or negative field pulses in the easy direction for writing.[1] The field pulses in the hard direction are applied by means of word lines A, B or C (Fig. 1) parallel to the easy axes of the film elements. The return current usually flows through a metallic ground plate beneath the film elements. The word field causes the magnetization of an element to rotate towards the hard direction. At the trailing edge of the word pulse, at the moment when the magnetization is about to turn back to one of the easy directions, a positive or negative bit field pulse is applied in the easy direction by means of the bit lines 1, 2 or 3 (Fig. 1) and a binary ONE or ZERO is stored. For proper operation of the memory, it is necessary to determine whether or not the information in a certain element is disturbed when information is repeatedly stored on adjacent word lines. When, for instance, a ZERO is stored in the film elements A_2 and C_2 and a ONE is being written into element B_2, the elements A_2 and C_2 experience the full ONE bit field in the easy direction and a small stray word field due to word line B in the hard direction. When a ONE is written into B_2 only once, the information in A_2 and C_2 will hardly be affected. However, when in B_2 a ONE is stored repeatedly, for instance 10^6 times, in a poorly designed memory, it is rather certain that the information in A_2 and C_2 will be completely disturbed. This disturbance of information is caused by a process called wall creeping, which has been the subject of many publications in recent years. In order to design a good film memory it is necessary to have some knowledge of the physics of this reversal process.

Reversal behavior of magnetic films is usually described on the basis of the theoretical critical curve H_r for rotation (Fig. 2). The curve gives the field, as theoretically calculated,[2] necessary to rotate the magnetization irreversibly. When the field in the easy direction at which magnetization reversal actually occurs is measured as a function of a field in the hard direction, the critical curve for wall motion H_w is found. This curve intersects with the curve H_r and for large, hard-direction fields a third critical curve H_{pr} is found. For large, hard-direction fields, on application of a field in the easy direction at H_{pr}, a process called partial rotation occurs which is followed at H_w by wall motion, as discussed in a previous publication.[3]

Figure 1 Schematic illustration of a memory plane with word lines A, B and C, and bit lines 1, 2 and 3.



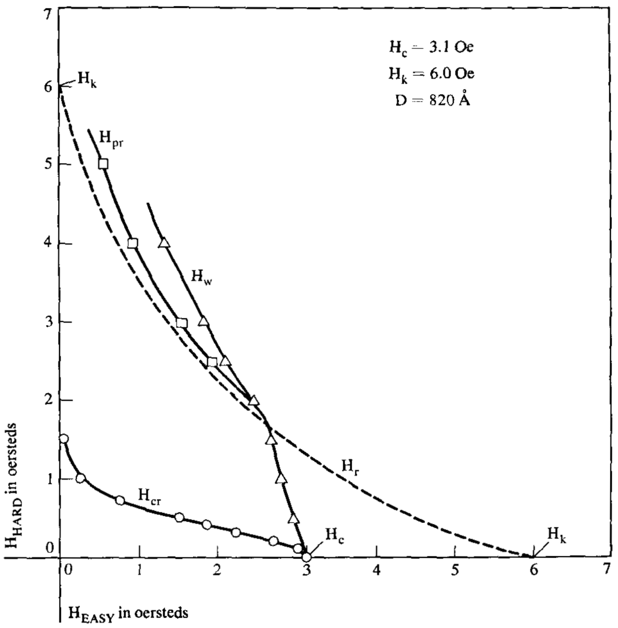


Figure 2 Critical curves for wall motion H_w, partial rotation H_{pr}, and wall creeping H_{cr} as compared with the theoretical critical curve for rotation.

The field in elements A_2 and C_2 consisting of the full bit field and the stray field due to word line B is normally much smaller than H_w or H_{pr} and, therefore, it is expected that information disturbance cannot occur. However, measurements of the disturb sensitivity of film elements do not confirm this expectation. When a film element is observed with the Bitter technique, while a small pulse field in the hard direction and a dc field in the easy direction antiparallel to the magnetization in the element are applied, it is found that the small edge domains always present at the edges of the element start to grow slowly. Subsequently, long walls parallel to the easy axis are formed which in turn creep sidewards, completing the reversal process (Fig. 3). The time in which this reversal is completed depends on the amplitude and frequency of the hard-direction pulse field and the magnitude of the dc field in the easy direction.

For the construction of a memory it is important to know the maximum field combination H_{cr} for which wall creeping still does not occur, even when more than, for instance, 10^6 pulses are applied. Figure 2 shows this curve as measured in an 820 Å film. In a properly designed memory, the resulting fields in A_2 or C_2 (Fig. 1) due to writing-in in element B_2 must be smaller than H_{cr}. This requirement is not easy to satisfy if simultaneously a high bit density is required.

As is well established today,[4] wall creeping occurs only when the applied field has an ac or pulse component in the hard direction and a dc component in the easy direction. One can, therefore, speak of *field-activated wall creeping*, in contrast to thermally activated or ultrasonically activated creeping.

Thermally activated wall creeping is a reversal process occurring in films as well as in bulk material, when a dc field slightly smaller than the wall motion coercive force H_c is applied parallel to the easy direction. When the energy increase related to a small movement of the wall (Barkhausen jump) is comparable with kT, a finite probability exists that this movement will take place without the necessary increase of the applied field. In normal Ni-Fe films with relatively small H_c's, the magnetostatic coupling along the wall seems to allow only large Barkhausen jumps, so that thermally activated wall creeping does not occur. However, in films with relatively large H_c's this kind of creeping is observed.[5-9]

Up to now, it has not yet been determined how far thermally activated creeping can endanger the operation of a thin film memory.

Ultrasonically activated wall creeping is found to occur in magnetic materials when dc fields below H_c are applied and the specimen is subjected to some kind of ultrasonic agitation. Haacke et al.[10] glued Ni crystals to quartz crystals, and observed the motion of Bloch walls when the quartz oscillated at 1 Mc/s. Ultrasonically activated wall creeping has not yet been studied in thin films, though it is not impossible that this reversal process can also occur, for instance, in non-zero-magnetostrictive films.

In the present paper, only field-activated creeping will be discussed. Wall creeping was first observed[11] in 1962 and since then has been discussed in many papers. Today, three rather different theories exist on the mechanism of this process.

◆ *Bloch line motion theory*

The first theory is based on the assumption that Bloch line motions during crosstie-Néel wall and Bloch-Néel wall transitions, which occur under the influence of the ac or pulse field in the hard direction, are responsible for wall creeping.[12,13]

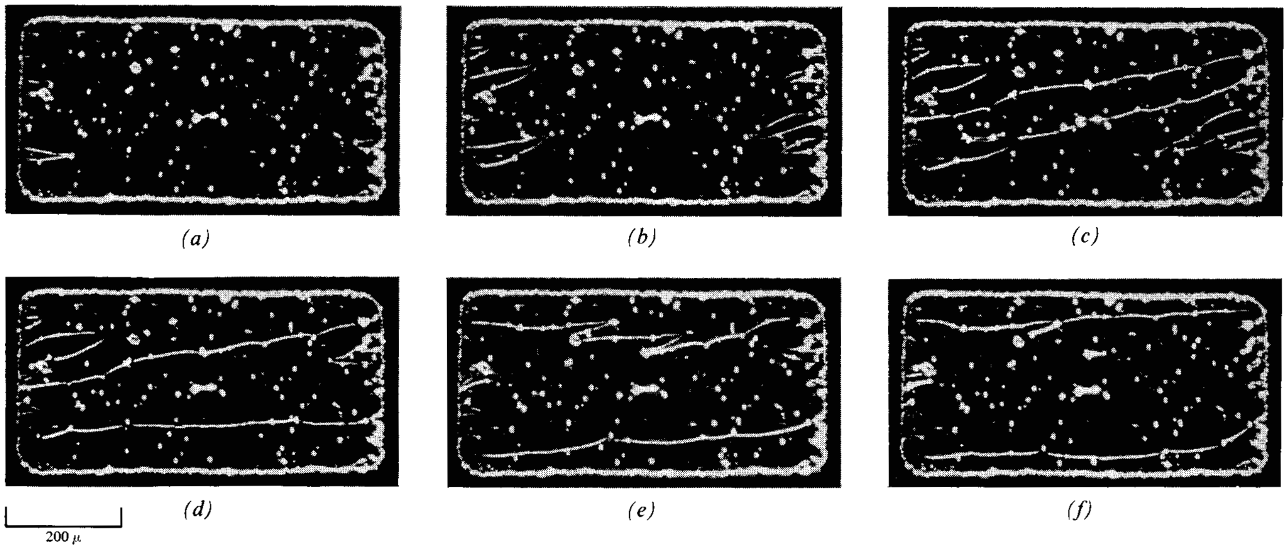
◆ *Wall structure change theory*

The second theory is based on the assumption that, due to the fields in the hard direction, the structure of the walls and consequently also the wall motion coercive forces change.[14]

◆ *"Lever" theory*

The third theory makes the varying magnetic charges on the walls, due to the hard direction fields, responsible for wall creeping.[15,16]

In the first part of this paper, experimental results typical for wall creeping are presented. In the second part, the three theories are discussed with the most emphasis on the



(a) (b) (c)

(d) (e) (f)

Figure 3 Bitter pictures of wall creeping in thin film memory elements.

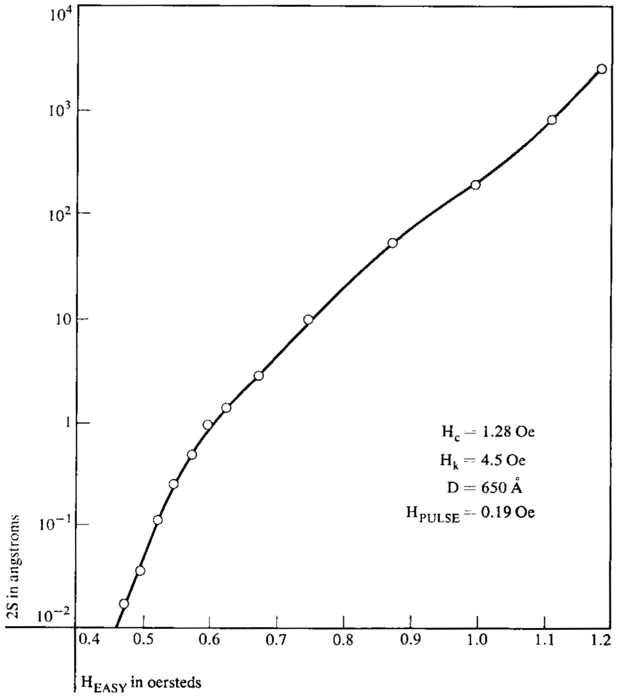
Bloch line motion theory. In the concluding section means are indicated by which the disturb sensitivity of film memory elements might be improved.

Experimental results

Today, general agreement exists on the fact that wall creeping can occur only when a varying field (ac, pulse, manually switched) is applied in the hard direction and a dc or pulse field with proper phasing in respect to the hard direction field is simultaneously applied in the easy direction. For instance, wall creeping is observed when a hard-direction pulse field and an easy-direction dc field are applied. Creeping also occurs when a pulse field is applied under an angle to the easy direction. However, wall creeping does not occur when a dc field is applied in the hard direction together with a pulse field in the easy direction. Neither is wall creeping observed when pulse fields are applied in both the hard and easy directions in such a manner that the rising and trailing edges of the short pulse field in the easy direction fall between the rising and trailing edges of the longer hard-direction field pulse.[4]

When a wall is observed by means of the Bitter technique while the specimen is subjected to an easy-direction field, and a field in the hard direction is switched on and off, it can be clearly seen that small wall jumps occur only at that moment when the field is switched on or off, and not thereafter or between. When an ac or pulse field is applied, the jumps follow one another very rapidly, so that the impression of wall creeping is produced.

Figure 4 Wall movement $2S$ per hard-direction field pulse as a function of the field in the easy direction.



The curve of most interest to the designer of a film memory is the critical curve H_{cr} for wall creeping (Fig. 2). This curve gives the largest pulse and dc field combination for which no wall creeping yet occurs. Since measurements on small memory elements are obscured by effects such as shape anisotropy and demagnetizing fields, it is preferable to measure H_{cr} on large films. The curve of Fig. 2 and all following results are obtained by observing, by means of the Kerr magneto-optic effect, a domain wall in the center of a 1 cm^2 film subjected to a dc field produced by Helmholtz coils, and a pulse field produced by a properly terminated stripline beneath the film. With the same setup using a measuring ocular, the wall creep velocity

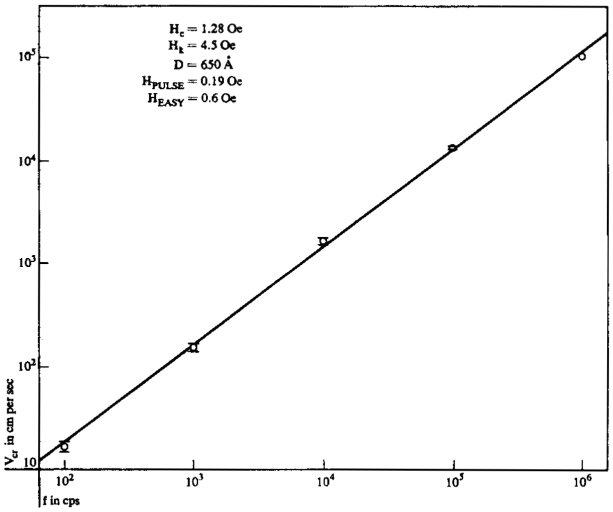


Figure 5 Wall creep velocity as a function of pulse repetition frequency for constant hard- and easy-direction fields.

can be measured for different fields.[17] From this creep velocity, the wall movement $2S$ per single pulse can be calculated. Figure 4 shows the value $2S$ as a function of the dc field in the easy direction for a given hard-direction pulse field. It is interesting to note how fast the distance $2S$ increases with increasing easy-direction field.

Further, it is evident that the creep velocity must be proportional to the pulse repetition frequency f if the magnetic fields are not changed. This is demonstrated in Fig. 5.

As creep occurs only during the rising or trailing edges of the pulse, the wall creep velocity should be independent of the pulse length. This is indeed found experimentally, as shown in Fig. 6. Also, the critical curve for wall creeping H_{cr} is not much affected by the pulse length.[4]

For the memory designer it is of interest to have films with large H_{cr} values. To characterize the creep sensitivity of films it is practical to take the maximum pulse field amplitude H_t divided by the anisotropy field H_k for a dc field equal to $\frac{1}{2}H_c$, for which no creep yet occurs (inset Fig. 7). This is allowed because H_t is proportional to H_k for films with the same H_c's and thicknesses as is shown by Beeforth.[4] When the value H_t/H_k is plotted as a function of film thickness, it is found that, for films thinner than about 400 Å, the creep sensitivity is much less, a result also observed by others[15,18] (Fig. 7). As the output signal of such films is very low, their use in film memories is still very difficult in spite of their low disturb sensitivity.

Another method to obtain large H_t/H_k values is to use films with high wall motion coercive forces H_c. The critical curves for wall motion H_w and for wall creeping H_{cr} join in H_c. It is, therefore, reasonable to assume that, when H_c of the film is increased, H_t/H_k will also be larger, which is indeed observed.[19] However, too large H_c's are generally connected with large angular dispersion of the easy axis, which is a disadvantage from the point of view of memory application.[20]

A final parameter of interest is the pulse rise and fall time. Not too much data on this point are available, but it seems that its effect, at least on the critical curve for creep, is not very large.[4,21]

Creep theories

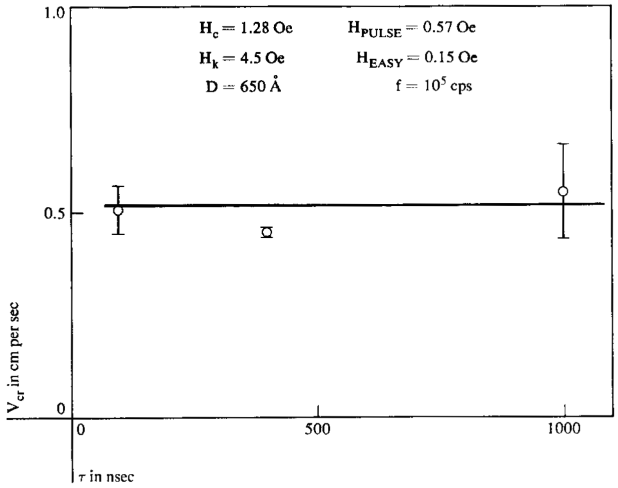
a) Bloch line motion theory

1) Introduction

In the first publication on wall creeping[11] a 1260 Å film was investigated. It was found that for hard-direction pulse fields larger than about $\frac{1}{3}H_k$, wall creeping became more pronounced. As this is about the field at which Bloch-Néel wall transitions occur, it was suggested that some connection between these transistions and creeping could occur. In a later publication[12] results on thinner films were also reported, which showed that in films in which crosstie walls occur, creeping is also observed and, in contrast to the 1260 Å film, also for fields much smaller than $\frac{1}{3}H_k$. As in thin films, a hard-direction field causes the motion of Bloch lines in a crosstie wall, it was suggested that Bloch line motions might also be responsible for wall creeping in thin films.

As Bloch-Néel wall transitions also occur by means of the motion of some kind of Bloch lines (90° lines) the Bloch line motion theory can be generally formulated to state that the motion of Bloch lines or other lines taking place during wall transitions of some kind under the influence of a hard-direction field will cause wall creeping, if

Figure 6 Wall creep velocity as a function of pulse duration for constant hard- and easy-direction fields.



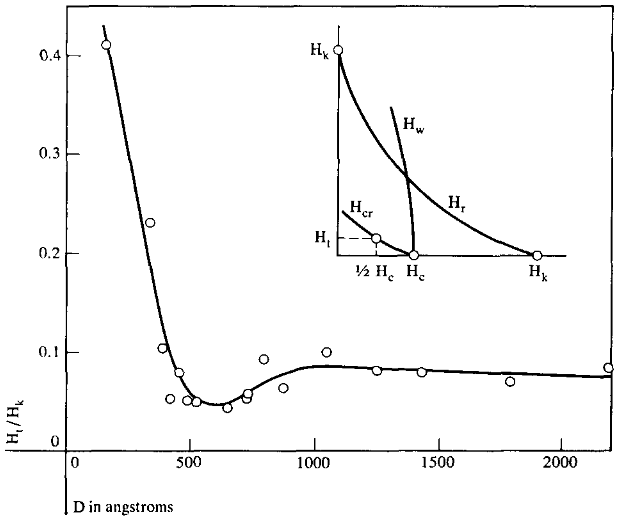


Figure 7 Creep sensitivity H_t/H_k, as defined in the inset, as a function of film thickness.

simultaneously a field is applied in the easy direction.[13] Films in which no Bloch lines or other lines occur, because they are too thin or of a special structure (double films[22,23]) or because a dc field is applied in the hard direction,[13] will not exhibit wall creeping. In order to know for what fields and film thicknesses wall creeping can be expected, it is necessary to know the kinds of wall and lines occurring in a particular film.[24,25]

2) *Wall transitions*

Three methods are available to obtain this kind of information: 1) the Bitter technique, 2) Lorentz microscopy and 3) a sensitive *B-H* loop tester.

With the first two methods, the walls are observed directly and the fields at which wall transitions occur can easily be determined. The methods are very easy, though not fast, for films thinner than 1000 Å. Figure 8 shows the wall transitions as a function of film thickness and the hard-direction field. The diagram will be discussed later. The third method enables also the determination of wall transitions in films thicker than 1000 Å and functions as follows. The *B-H* loop in the exact hard direction of a film is practically always open, but closes down to a straight line when the driving field amplitude is reduced.[26] If now the non-integrated signal is amplified and observed it is found that, at certain fields, small signal bumps occur which are due to wall transitions. When a wall transition occurs, the magnetizations in small, thin parts of the domains adjacent to the walls are also affected, which leads to the small signal. Figure 9 shows the wall transition diagram as observed with the *B-H* loop tester. The agreement with the other visually obtained diagram is rather satisfactory. The crosstie-Néel wall transition could not be detected with the *B-H* loop tester method, probably because this transition is rather gradual. Most transitions in both diagrams are indicated by vertical lines. The Bitter technique shows that the wall transitions do not occur abruptly in the whole film but are spread out over a certain field range. With the *B-H* loop tester, this effect demonstrates itself as a certain width of the signal bump.

3) *Wall creeping as a function of the film thickness*

To discuss the relation between the occurrence of Bloch lines and wall creep it is practical to divide the films according to their thicknesses into four ranges: a) $0 < D < 200$ Å, b) 200 Å $< D < 400$ Å, c) 400 Å $< D < 700$ Å, and d) 700 Å $< D$. The creep behavior and occurrence of wall transitions do not, however, appear as abruptly as this division into ranges might suggest.

a) $0 < D < 200$ Å

When films of this thickness range are demagnetized with a slowly decreasing ac field along the easy direction, and are subsequently observed with the Bitter technique, it is found that the walls are of the Néel type and that the polarity of these Néel walls is constant over long distances. The Néel walls of opposite polarity are separated from each other by Bloch lines, in which the magnetization is normal to the plane of the film. If the film is now subjected to a dc field in the hard direction, the Néel wall segments in which the magnetization is parallel to the applied field, start to enlarge at the expense of the other segments. These enlargements occur by the motion of Bloch lines along the walls. At a certain hard-direction field, the whole wall is of one polarity and Bloch line free. If now the field is again reduced, the polarity of the wall remains the same.

In order to reverse the polarity of the wall, a negative field must be applied which causes the nucleation and motion of new Bloch lines. The magnitude of this field depends on the film thickness and increases for decreasing thickness, as can be seen in Figs. 8 and 9. For very thin films, even fields exceeding H_k are sometimes necessary.

When the way in which Bloch lines are removed and again nucleated is understood, creep behavior of these films can be explained. When unipolar field pulses are applied in the hard direction, a small number of pulses is sufficient to remove all existing Bloch lines. Consequently, a further application of unipolar pulse fields in the hard direction in combination with a dc field in the easy direction will not lead to wall creeping since the wall is free of Bloch lines. When bipolar pulses are applied in the hard direction, the situation is quite different. Each pulse, if large enough, will reverse the polarity of the Néel walls, a process that is accompanied by moving Bloch lines. Bipolar field pulses in the hard direction in combination with a dc

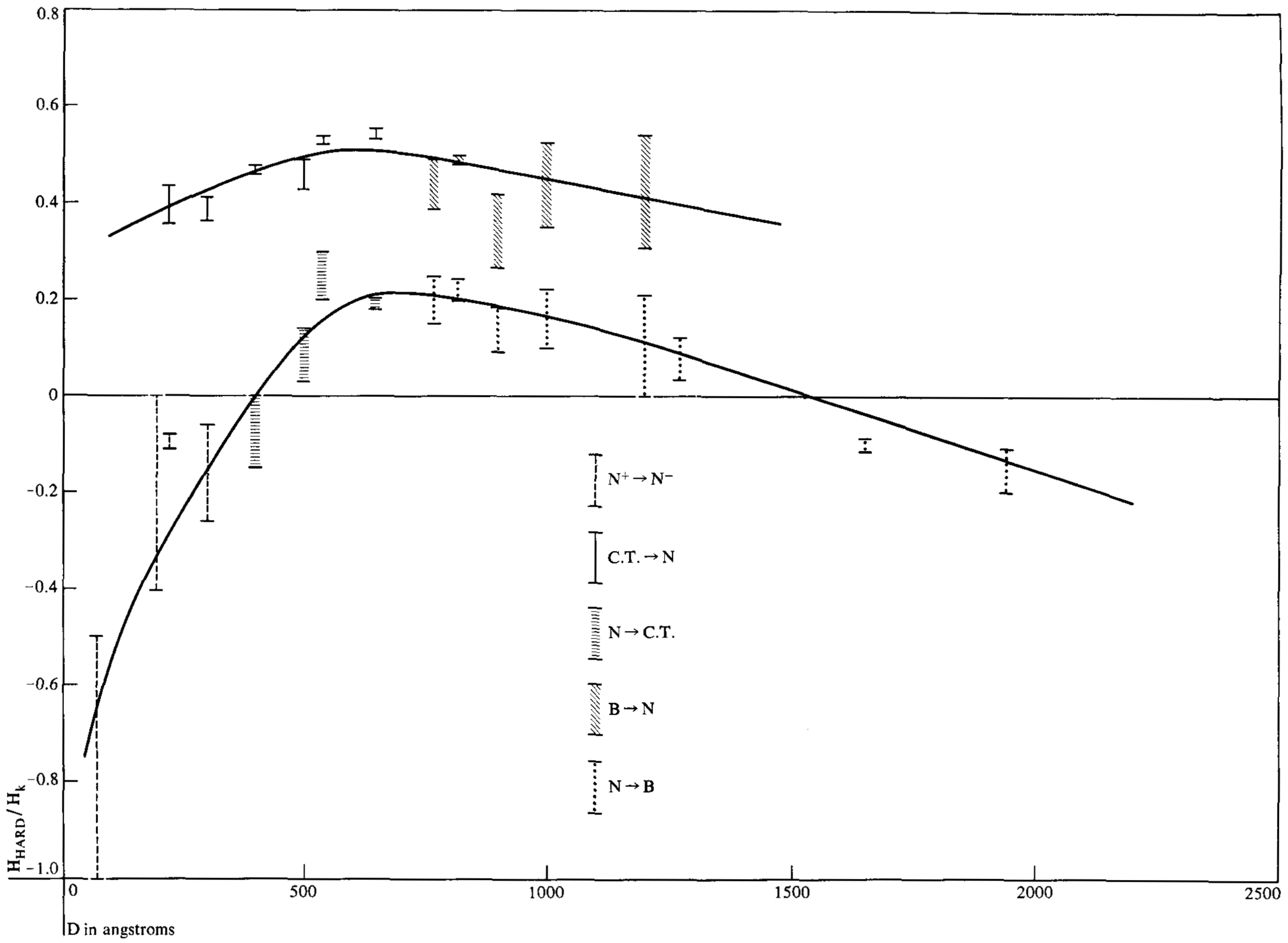


Figure 8 Diagram showing the wall transitions as a function of film thickness and hard-direction field. Results obtained with the Bitter technique.

field in the easy direction will therefore cause wall creeping in films of this thickness range. This is exactly as measured by Beeforth and Hulyer[14] though they themselves give a different explanation for this fact. As the field necessary to nucleate new Bloch lines increases for decreasing film thickness, the creep sensitivity to bipolar hard direction field pulses decreases for thinner films.

Since in the thin film memory the stray word fields due to neighboring word lines are unipolar, thin films with thicknesses below 200 Å are very suitable from the point of view of creep sensitivity.

b) 200 Å $<$ D $<$ 400 Å

When films of this thickness range are demagnetized, the walls are of the crosstie type. These crosstie walls, discussed in a previous publication,[25] are a kind of demagnetized Néel wall. They consist of Néel walls of alternating polarity separated by Bloch lines and crossties, which are also of the Néel type. When a field in the hard direction is applied, the Néel wall segments parallel to the field enlarge and the Bloch lines move together and annihilate each other. For larger fields, the whole wall is unipolar and of the Néel type. When the field is later decreased, the Bloch lines do not appear again and at zero field the unipolar Néel wall is still present. When a negative field is applied, Bloch lines are nucleated and a transition from positive to negative Néel wall occurs much the same way as observed in films of the first thickness range (Figs. 8 and 9). An intermediate crosstie wall state does not occur. When wall creeping is studied in these films, it is found that wall creep behavior depends considerably on the fields applied previous to the experiment. When unipolar Néel walls occur in the film, the creep behavior is essentially identical to that in films thinner than 200 Å. However, when crosstie walls occur in the initial state, the creep behavior resembles that of films of the third thickness range 400 Å $<$ D $<$ 700 Å.

In order to illustrate this duplex behavior, the following experiment can be performed. Two parallel fields are

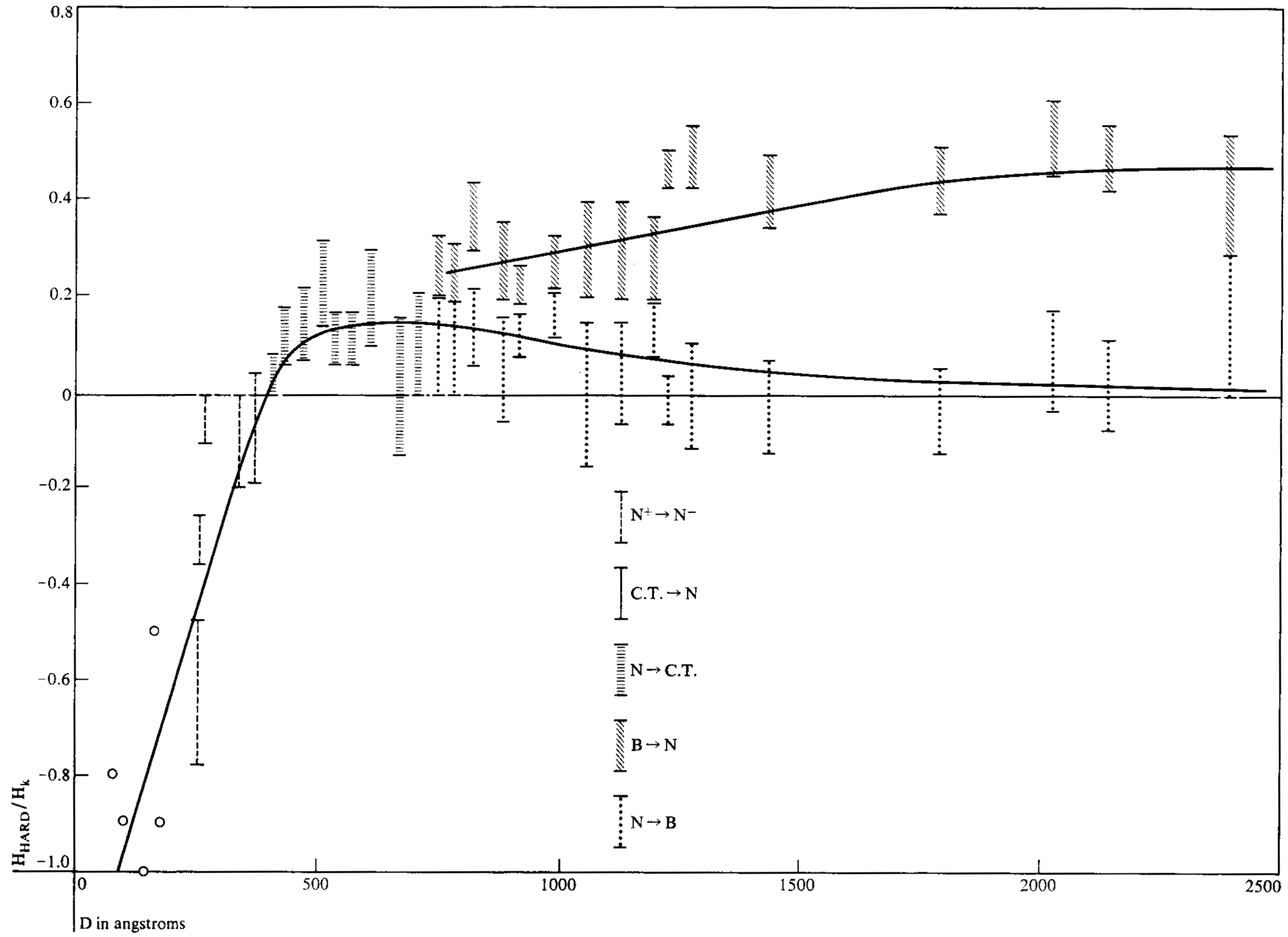
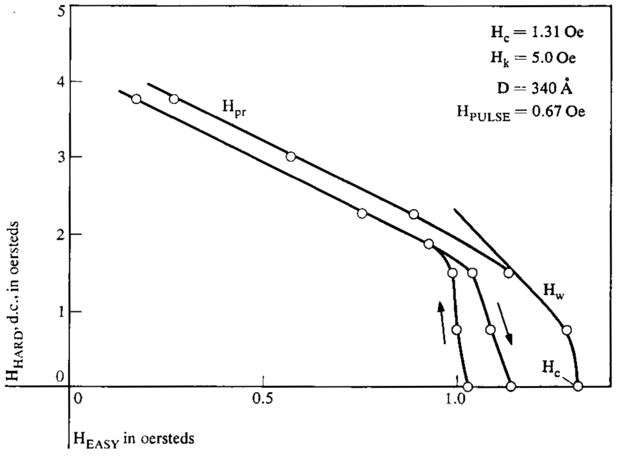


Figure 9 Diagram showing wall transitions as a function of film thickness and hard-direction field. Results obtained with the new *B-H* loop tester method. Crosstie-Néel wall transitions could not be detected, probably due to their gradual nature.

applied in the hard direction, a pulse field of fixed amplitude and a variable dc field. A measurement is then made of the strength of dc field in the easy direction at the point where wall creeping just starts to occur. This measurement is done once for increasing hard direction dc field and once for decreasing field. The initial state of the film contains crosstie walls. For increasing field, we expect to find creeping because Bloch lines are present; for decreasing field we expect no creeping, since the Bloch lines are removed. As Fig. 10 illustrates, the behavior is not as ideal as just described, but one observes that a clear difference between the two curves still exists. Probably the pulse field in the hard direction facilitates the nucleation of new Bloch lines, if the dc field is reduced. Further, it is noted that, for hard-direction fields larger than about $0.4H_k$, if only unipolar Néel walls occur no creeping is observed, thus confirming the Bloch line theory. The parallel shift of the creep curve for large fields is due to the superimposed pulse field.

Films thinner than 400 Å are reported by different

Figure 10 Creep curve obtained by applying a dc field and a fixed pulse field in the hard direction, and a dc field in the easy direction. To show the influence of the hysteresis of the wall transitions, the curve was measured for increasing and decreasing hard-direction field.



authors[15,18] to be rather creep insensitive. This characteristic is also apparent from Fig. 7; yet it must be stated that, in view of the above experiment, films of the thickness range 200 Å $< D <$ 400 Å might still prove to be unreliable as memory elements because of their duplex creep behavior.[20]

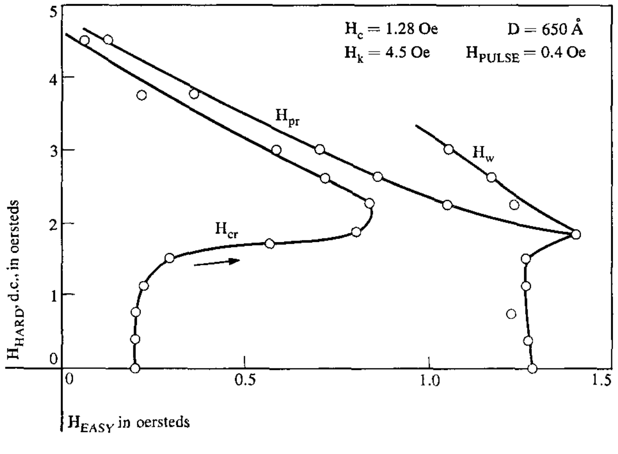
c) 400 Å $< D <$ 700 Å

When films of this thickness range are demagnetized, the walls are also of the crosstie type. The difference with respect to the thickness range 200 Å $< D <$ 400 Å is that the Néel-crosstie wall transition occurs for positive hard-direction fields (Figs. 8 and 9). This means that in these films, crosstie walls occur when no magnetic fields are applied. The difference between creep curves measured for increasing and decreasing dc hard direction as discussed for the second film thickness range is less pronounced. On the basis of the Bloch line motion theory, we expect wall creeping for hard-direction fields smaller than about $0.5H_k$ and no creeping for larger fields, since in this field range unipolar Néel walls occur. Indeed, this is experimentally observed, as illustrated in Fig. 11. The creep sensitivity of films in this thickness range is largest for films of about 600 Å, as shown in Fig. 7, where the crosstie wall is very well developed. A hugh number of Bloch lines are present and only a small field in the hard direction is necessary to cause their motion. From the point of view of disturb sensitivity, films of this thickness range are then less suitable for a thin film memory.

d) $D >$ 700 Å

Wall creeping in films thicker than 700 Å is the most difficult to explain and to bring in connection with Bloch line motion. This is due to the fact that it becomes increasingly difficult to study the wall transitions in these films with the Bitter technique or with Lorentz microscopy. In an earlier publication on wall creeping[13] a simplified wall transition diagram was presented, in which it was assumed that at zero hard-direction field unipolar Bloch walls will occur, and that when a field $H = \frac{1}{3}H_k$ in the hard direction is applied, a unipolar Bloch-unipolar Néel wall transition will occur. Further it was assumed that the Néel-Bloch wall transition also occurred at $H = \frac{1}{3}H_k$ as soon as the field was again reduced.

Figure 11 Creep curve measured as in Figure 10 for a film with crosstie walls.



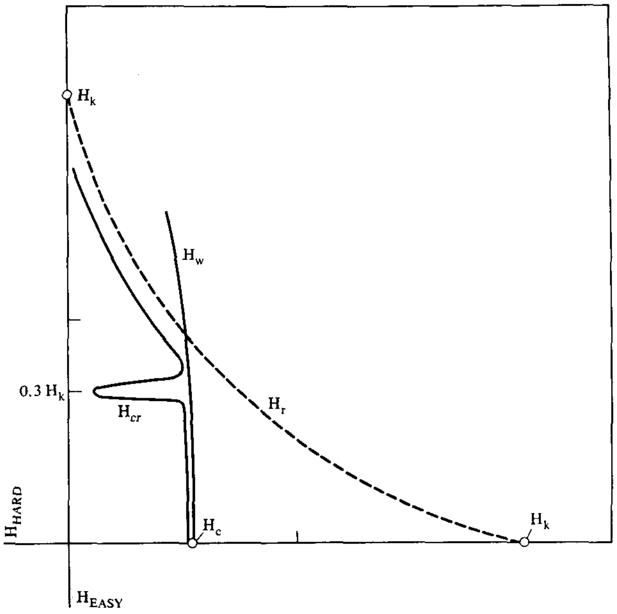


Figure 12 Creep curve as in Figure 10 for films containing Bloch walls, as theoretically expected, when creep is caused by a Bloch-Néel-Bloch wall transition at approximately ⅓ H_k.

A Bloch-Néel wall transition starts when small Néel wall segments are nucleated in the Bloch wall. These Néel wall segments are separated from the Bloch wall by so-called 90° lines[27] which move along the wall until the wall transition process is completed. The reverse Néel-Bloch wall transition starts with the nucleation of Bloch wall segments which are also separated by 90° lines from the remaining Néel walls. Also here the transition occurs when these 90° lines move along the walls. When the *B-N* wall and the *N-B* wall transitions occur at the same hard-direction field $H = \frac{1}{3}H_k$, and the creep curve is measured as indicated in Figs. 10 and 11, the result illustrated in Fig. 12 must be expected. Wall creep can occur, at least if the Bloch line motion theory is correct, only at $H = \frac{1}{3}H_k$, where 90° line motions occur. In practice, this is not found as is shown in Fig. 13. Though the curve exhibits an extremum at about $\frac{1}{3}H_k$, creep also occurs for smaller and larger hard-direction fields. To understand this behavior, the wall transitions must be investigated in more detail. At first, the *B-N* wall and *N-B* wall transitions do not occur at the same field. Roughly, the Bloch-Néel wall transition occurs between 0.3 and $0.6H_k$, whereas the Néel-Bloch wall transition takes place roughly between 0.2 and $-0.1H_k$ (Figs. 8 and 9). It is evident that this will smear out the minimum in the creep curve.

Further, it is rather improbable that unipolar Bloch walls exist if no fields are applied.

When a Néel-Bloch wall transition takes place, small Bloch wall segments are at first nucleated. For symmetry reasons, the magnetization in these segments can point up or down. When the field is further reduced, these Bloch wall segments grow at the expense of the Néel walls until the Néel wall segments reduce to so-called Néel lines. These Néel lines are visible as white points on a poorly visible Bloch wall if they are observed with the Bitter technique (Fig. 14). When the field is increased, these Néel lines immediately start to grow again.

Looking at Bitter patterns of Néel walls for large hard-direction fields, one also has the impression that these Néel walls are not homogeneous but still contain small, faintly visible Bloch wall segments. Therefore, it is perhaps better not to speak of Bloch-Néel wall, but of predominant Bloch to predominant Néel wall transitions.[28]

It is clear that for all hard-direction fields, a large number of moving 90° lines can occur. The maximum density of the 90° lines will be at about $H = \frac{1}{3}H_k$ which is reflected in the creep behavior of these films as shown in Fig. 13.

It seems that in thicker films ($D > 2000$ Å) the wall transitions are still more degenerated, so that the extreme in the creep curve practically disappears.

Figure 13 Creep curve as in Figure 10 for a film containing Bloch walls as experimentally measured. The relative minimum of H_{cr} vs H_{easy} at $H_{cr} \simeq 1.3$ Oe is due to a large Bloch line density.

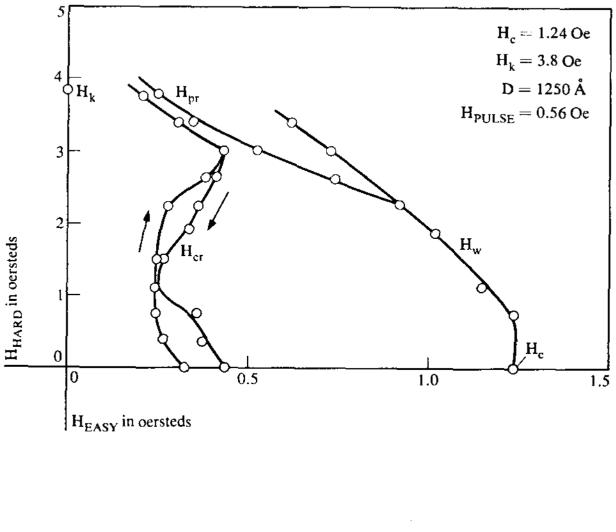


Figure 14 Bitter pattern of a Bloch wall in a 1000 Å film with Néel lines visible as bright spots. A hard direction dc field was applied of about ¼ H_k.

4) *Discussion*

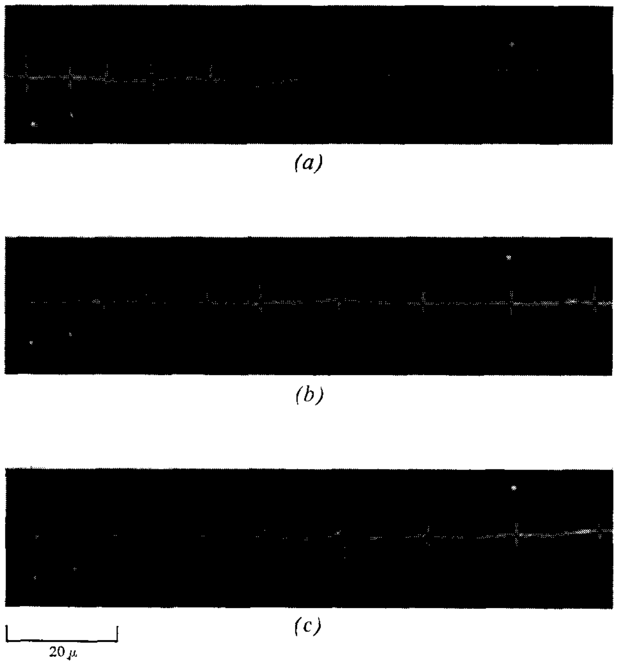
A domain wall subjected to an easy-direction field smaller than the wall motion coercive force cannot move. The essence of the Bloch line motion theory now is that, when a hard-direction field is applied which causes the motion of Bloch or 90° lines, the wall will still advance over a short distance. How far the wall will actually move depends on the number of lines present and the distance they move along the wall.

The experiments described above show that a reasonable relation between the occurrence of moving Bloch or 90° lines and wall creeping exists. Should one want to study directly the effect of a moving Bloch line on a wall, one is confronted with the difficulty that Bloch lines are too small to be directly observed. As shown by Feldtkeller et al.[29] the width of a Bloch line is only about 100 Å, and because the domain walls themselves are much wider, about 1000 Å, a Bloch line represents a strong constriction in a wall.

Though a direct proof of the correctness of the Bloch line motion theory is, therefore, not possible, some other experimental results are available which largely support the theory. First, there is the result of Fuchs et al.[30] who, by means of Lorentz microscopy, did indeed observe that a domain wall advanced after a Bloch line passed by in a 250 Å film. (Though no direct image of the Bloch line is obtained, it is possible to determine its location with Lorentz microscopy.)

In the thickness range between 200 Å and 400 Å, crosstie walls as well as Néel walls are stable in the absence of a hard-direction field. When a pulse field in the hard direction and a dc field in the easy direction are applied, it can be observed that in a film containing both types of walls only the crosstie walls containing Bloch lines start to creep.

Further support for the Bloch line motion theory is obtained if a crosstie wall is observed just before it starts to creep. If the film is not too thick and the crossties are not too close together, it is clearly seen that the wall bends the most between the crossties, due to the oscillating Bloch


(a)

(b)

(c)

Figure 15 Bending of a crosstie wall due to Bloch line motions. In (a) and (c), easy-direction fields are applied antiparallel to one another. In (b) this field is zero. The Bloch line oscillations are caused by an ac hard-direction field ($D = 350$ Å).

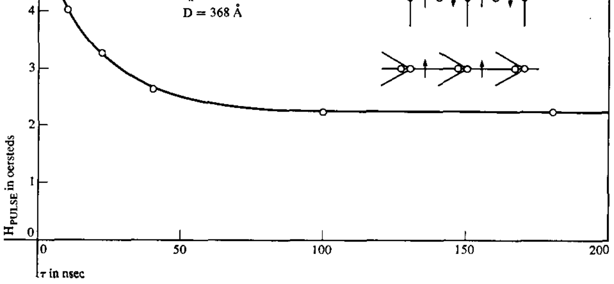
lines (Fig. 15a). When the easy-direction field is switched off, the wall straightens (Fig. 15b) and when the easy-direction field is reversed, the bending is towards the other side of the wall (Fig. 15c).

A proof for the relation between Bloch lines and creeping can also be obtained when the creep behavior of double films is observed.[23] Double films consist of two magnetic films separated by a thin nonmagnetic film. Because of the proximity of the two magnetic layers, Figs. 8 and 9 are no longer applicable. It is possible to make double films in which Néel walls occur, though in the same films when separate, Bloch walls or crosstie walls should be present. If unipolar pulse fields are utilized such films prove to be creep-free[31] much the same way as single films thinner than 200 Å. If the intermediate nonmagnetic film is thicker, the creep behavior of the double film is the same as that of a single film of the thickness range 200 Å $< D <$ 400 Å. If the intermediate film is very thick, the double film behaves as two single separate films. Double films offer a good proof for the fact that the creep behavior of a film is mainly determined by the type of wall occurring in the film.

Wall creeping in single films is also observed when very short pulses are used. When Bloch line motion is responsible for wall creeping it is necessary that the mobility of Bloch lines be sufficiently high. In order to get an impression of this mobility, the following experiment was performed. As we have discussed, crosstie walls occur in a 300 Å film if the film is demagnetized with a slowly decreasing ac easy-axis field. When subsequently a sufficiently large dc field is applied in the hard direction, a crosstie-Néel wall transition can be induced that does not reverse when the field is switched off. Instead of the dc field, a pulse field of certain duration τ can be applied. When, after application of this pulse the wall is of the Néel type, a wall transition has taken place. The pulse amplitude and duration were apparently such that the Bloch line could move across the distance a from the center between the crossties to the crossties (see inset, Fig. 16). The pulse field amplitude necessary for a crosstie-Néel wall transition as measured as a function of the pulse duration, is shown in Fig. 16 ($a = 5\mu$). It appears that in a 300 Å film the Bloch line mobility is such that for pulse durations smaller than about 40 ns, the pulse amplitude necessary for the crosstie-Néel wall transition must be increased. However, if it is realized that even small Bloch line oscillations are sufficient to cause creep, the conclusion is reached that the Bloch line velocity is large enough to cause creep even at very short pulse durations. An influence on the wall creep velocity for short pulses can be expected if we assume that this velocity depends on the distance the Bloch line moves during the pulse.[20] However measurements have indicated that the critical curve H_{cr} itself is probably not affected by the pulse duration.

Recapitulating, it can be stated that the Bloch line motion theory offers a reasonable though complicated explanation of the creep phenomena occurring in films of different thicknesses. The exact mechanism by which the Bloch line is able to reduce locally the wall motion coercive force is still not understood. If the model proposed by Green et al.[32,33] which assumes that a fast-moving Bloch line causes a magnetic field parallel to the applied easy direction field, is correct, it must be the subject of further

Figure 16 Pulse field necessary to enforce a crosstie-Néel wall transition as a function of the pulse duration. When the transition takes place the Bloch line moves along the wall across a distance a (see inset).



study. The facts that the Bloch line width is very small, and that, as observed with the Bitter technique, even very slowly moving Bloch lines can cause wall creeping, speak against the model of Green et al.

• *b) Wall structure changes theory*

The explanation as suggested by Beeforth and Hulyer[14] is based on the change of the structure of Néel walls in thin films ($D < 400$ Å) when hard-direction fields are applied. If the Néel wall consists of segments of both polarities, the field will increase the energy and the wall motion coercive force of those segments in which the magnetization is antiparallel to the field, and will decrease the energy and coercive force of the other segments. When unipolar field pulses are applied in combination with an easy-direction field, the low-energy segments can move if they are not held back by the high-energy wall segments. Motion of the whole wall can occur only when the wall motion coercive force of the high-energy segments is exceeded. However, when bipolar pulses are used, the wall segments alternate continuously between the high and low energy states, and the wall can thus move when the coercive force of the low energy wall is exceeded. Bipolar pulses would, according to this model, induce wall creeping. Though it is true that different H_c's can occur for different-poled Néel walls,[34] these differences are very small and not sufficient to explain the difference in creep behavior if unipolar or bipolar pulses are used.[33] Figure 17 shows the critical curve for wall motion of a 245 Å film for Néel walls in which the magnetization is parallel and antiparallel to the hard direction field. The difference in H_c is only very small, as can be seen. Moreover, the model fails to explain the creep behavior of thicker films and the strong dependence of the creep behavior on the wall type.

• *c) "Lever" theory*

This theory is proposed by Olson and Torok[15,16] and is based on the fact that hard-direction fields cause magnetic poles to form on the walls when their polarity reverses and when the field is also reversed. The poles occur, since due to the easy-direction field, the magnetizations in the domains at both sides of a wall do not rotate through the same angle when a field in the hard direction is applied. The magnetic poles on the wall cause a magnetic field which in some parts of the wall is parallel and in other parts antiparallel to the applied easy-direction field. The part where the extra field is parallel will advance slightly when the total field exceeds the wall motion coercive force. If the field in the hard direction is reversed, the additional stray field also changes its polarity, so that now the other parts of the wall can move. Creep will occur according to this model, when simultaneously a bipolar field is applied in the hard direction and a dc field is applied in the easy direction. The elegance of this theory is, without any doubt, that it applies to all films and does not depend on wall structures. Yet the theory fails to explain many of the experimental facts.

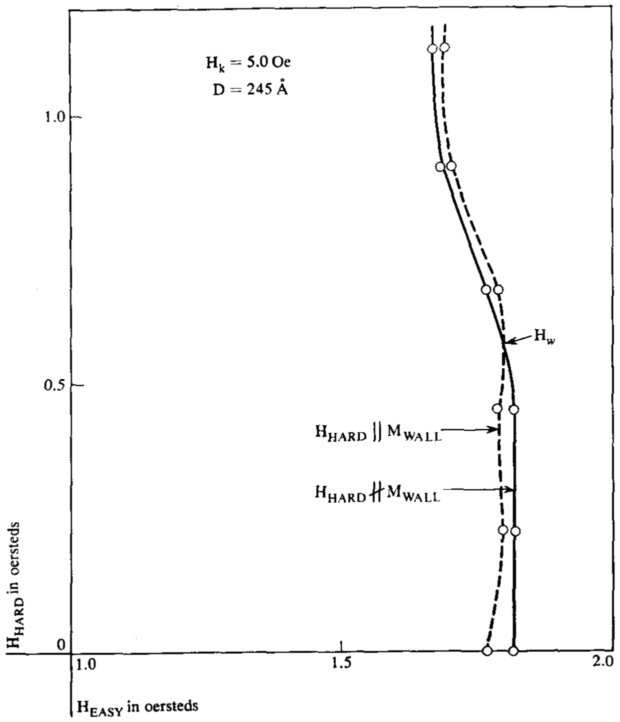


Figure 17 Critical curve for wall motion H_w measured in a 245 Å film. Each measurement was preceded by a large positive or negative hard-direction field in order to set the polarity of the Néel wall in the desired direction. The difference between H_w of different-poled walls is negligible. Solid line: M_{wall} antiparallel to H_{hard}. Dashed line: M_{wall} parallel to H_{hard}.

In films thicker than 400 Å, unipolar hard-direction pulses also induce wall creeping. This cannot be explained with the "lever" mechanism. Unipolar pulses cause magnetic charges on the wall only of one polarity. Half of the walls, therefore, never experience an additional stray field parallel to the applied field. These parts then block the total wall from moving.

For large hard-axis pulse fields, the easy-direction field necessary for wall creeping, as experimentally found, reduces almost to zero (Fig. 2). For this field combination, the magnetizations at both sides of the wall make nearly equal angles with the easy axis, so that no poles along the walls are created. According to the "lever" theory then, no creeping can occur. In other words, the "lever" theory cannot explain why critical creep curves come very close to the hard-direction field axis.

The magnetic stray field caused by the poles on the wall must be proportional to the film thickness. It can be expected, if the above theory is correct, that creep sensitivity of films would strongly increase with increasing

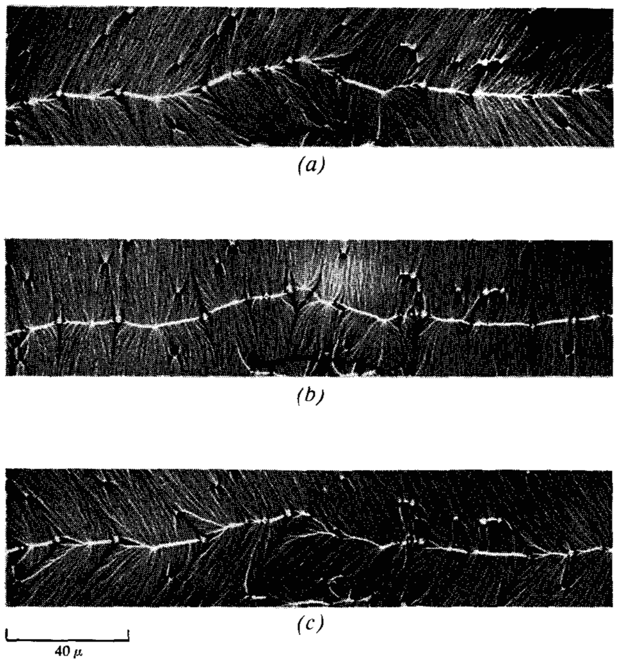


Figure 18 Lorentz microscopy pictures of a crosstie wall in a film with large hole density showing that the Bloch lines (white thickening in the center between the crossties) are unable to move when a hard-direction field (*a*), (*c*) is applied.

film thickness. Such a dependence is not found in Fig. 7. Finally the "lever" mechanism fails to explain why under exactly the same field conditions, a crosstie wall creeps and a unipolar Néel wall cannot creep, or why certain double films are creep-free.

Conclusions

Experimental observations have shown that a strong relation exists between the occurrence of moving Bloch or 90° lines and wall creeping. It is, therefore, reasonable to assume that, though the exact mechanism is not yet known, domain walls can creep only when Bloch or 90° line movements take place along the walls. The Bloch line motion theory offers a rather satisfactory explanation of the various creep behaviors as a function of film thickness. The wall structure changes and "lever" theory fail to explain much of the experimental data.

Based on the Bloch line motion theory, the following measures should be capable of improving the disturb sensitivity of thin film memory elements:

a) The memory should be designed in such a manner that stray fields due to neighboring word lines are as small as possible. This implies, for instance, larger word line distances or evaporated striplines.

b) Use of coupled films[35] in which the demagnetizing field in the easy direction is reduced, thus allowing larger hard-direction stray word fields.

c) Use of films with thicknesses below 400 Å.

d) As the creep sensitivity improves with increasing H_c, films with high H_c's should be employed. Since the bit field also increases with increasing H_c, the experiments indicate that H_c should not be much larger than H_k.

e) The application of a bias field in the hard direction causes wall transitions and a decrease of Bloch line density to occur. A bias field, therefore, can favorably influence the creep sensitivity and at the same time reduce the pulsed word field.

f) Use of double films in which creep-free unipolar Néel walls occur. Double films tend to have low H_c's and measures must be taken to counteract this tendency.

g) Use of films in which Bloch lines cannot move freely. In thin films $D < 200$ Å and in films with high coercive forces this is still partly the case. Further, it is conceivable that a huge number of small holes would also have such an effect. Figure 18 shows Lorentz picures of a crosstie wall in a film with many holes in which the Bloch lines apparently cannot move together. Creep measurements were not performed on these films.

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