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Domain Walls in Thin Ni-Fe Films*

Abstract: Observations of domain walls in Ni-Fe films as a function of thickness demonstrate the strong influence of magnetic stray fields on the wall structure, hence on the coercivity for wall motion. In order to reduce the stray-field energy, the Bloch walls in films thicker than 1000 Å are subdivided into sections with alternating polarity which are separated by Bloch lines. In thinner films, the domain walls are of the Néel type. The position of Bloch lines in such walls is indicated by crosswalls. The motion of Bloch lines in an applied field can be observed particularly easily on scratches in negative magnetostrictive material; such scratches display properties corresponding to Néel walls. Crosswalls are also present at the ends of domains and around holes in the film material. A crosswall is distinguished from ordinary domain walls by the continuous change of the angle of magnetization along both sides of it.

Introduction

The properties of domain walls are the key to many problems in the study of ferromagnetic materials and their applications. For example, detailed knowledge of domain-wall characteristics, such as wall energy and the variation of magnetization across the wall, is necessary for theoretical explanations of coercive force, switching speed, and energy losses in magnetization reversal processes.

Domain-wall investigations of thin ferromagnetic films are especially attractive, because the particular geometry of thin films ensures that the domain configuration observed directly at the surface of the metal is unchanged throughout the body of the material. Observational techniques, such as the magneto-optical Kerr effect and the Bitter technique, are simple.

In general, the energy of a domain wall consists of the following: exchange energy, anisotropy energy (caused by crystal, stress, or induced anisotropy), magnetostrictive energy and the magnetostatic energy stored in the demagnetizing field of the free magnetic charges along the domain wall. The latter portion plays an important part in determining the variation of the magnetization across the wall. In bulk material it causes the walls to run in such a way that the normal component of magnetization is constant across the wall, i.e., the component of magnetization parallel to the wall rotates in the plane of the wall. This leads to the absence of free magnetic poles

in the material. The wall energy is made up of contributions only from anisotropy, exchange and magnetostrictive energy. Such walls are called Bloch walls, in contrast to Néel walls.

Complications arise when the wall intersects the surface of the sample. The existing free magnetic charges modify the wall structure near the surface. The attempt to calculate these deviations in detail leads to the equations of micromagnetics¹ for the variation of magnetization across the wall. Since these equations can be treated only by extensive numerical methods, even in the simplest case of magnetization reversal in an infinite cylinder by a homogeneous external field, the problem of a domain wall intersecting a surface seems too complicated for this treatment.

In the case of thin films, the short distance between the two surfaces makes this problem of the variation of magnetization in the surface region very important. No exact treatment of the phenomena influenced by domain wall properties is possible without knowledge of how the free magnetic poles at the surface influence the variation of magnetization and the energy in the domain walls.

Néel² avoided the question of magnetization variation in domain walls by assuming that the pole distribution in a 180° domain wall is the same as that of a long cylinder with an elliptical cross section $a \cdot D$, magnetized normal to the film plane. Its long axis corresponds to the film thickness D , while the short axis is associated with the wall thickness a . Then the magnetostatic energy E_m^B per

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cm² of a Bloch wall is derived from the demagnetizing factor $N=4\pi a/(a+D)$ as

$$E_m^B = \frac{1}{2} N a J_s^2 = \frac{2\pi a^2 J_s^2}{D+a} \quad (1)$$

The total domain-wall energy γ can be derived by minimizing the sum of exchange energy $\frac{8A}{a} = \frac{\gamma_0}{2} \frac{a_0}{a}$, anisotropy energy $\frac{aK}{2} = \frac{\gamma_0}{2} \frac{a}{a_0}$ and magnetostatic energy E_m^B in the wall,

$$\gamma = \frac{\gamma_0}{2} \left(\frac{a_0}{a} + \frac{a}{a_0} \right) + E_m^B,$$

with respect to the wall thickness a . $\gamma_0=4\sqrt{AK}$ and $a_0=4\sqrt{A/K}$ are the values for bulk material with A = exchange constant and K = anisotropy constant.

For 80-20 Ni-Fe alloys with $4\pi J_s^2/K=5 \cdot 10^3$ (J_s = saturation magnetization), the values of γ/γ_0 and a_0/a have been calculated as functions of the film thickness D and are plotted in Fig. 1 (Curves 1). The magnetostrictive energy can be neglected in these calculations because of its small value in 80-20 Ni-Fe alloys.

If the magnetostatic energy becomes very large in the case of very thin films, another form of domain wall is expected, in which the magnetization rotates in the plane of the film. Such a wall is called a Néel wall. In this form the axes of the elliptical cross section are interchanged so that the magnetostatic energy of the free poles inside the material is

$$E_m^N = \frac{2\pi a D J_s^2}{D+a} \quad (2)$$

The corresponding reciprocal thickness and total energy of the Néel wall shows a calculated thickness dependence which is also plotted in Fig. 1 (Curves 2).

Of special interest is the critical thickness, where the

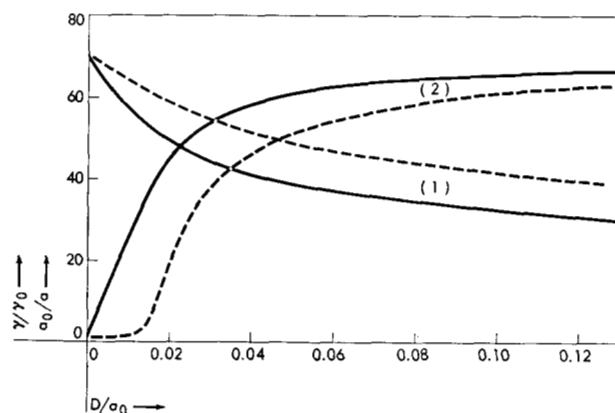


Figure 1 The domain wall energy γ (—) and the reciprocal wall thickness $1/a$ (---) for Bloch (1) and Néel (2) walls plotted as a function of film thickness D .

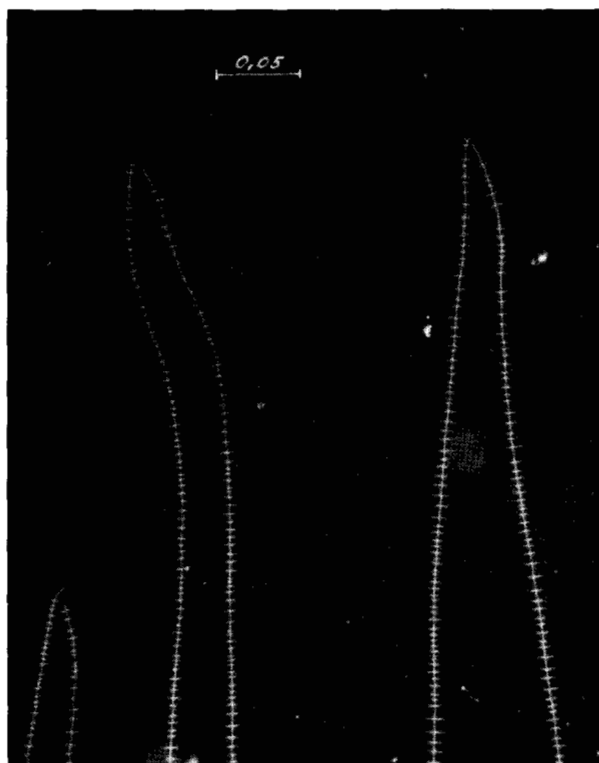


Figure 2 Domain walls in a Ni-Fe film about 800 Å thick, showing the typical cross-tie structure.

energy curves intersect and both types of walls have the same energy. In the first approximation the critical thickness,

$$D_k = \frac{1.8\sqrt{A}}{J_s} \quad (3)$$

is determined only by the exchange constant and the saturation magnetization. The anisotropy energy makes no contribution. The transition from Bloch to Néel wall must take place in the neighborhood of this critical value. No information on the way in which this transition takes place can be obtained from Néel's considerations.

In applying Formula 3 it must be kept in mind that the approximation by an elliptical cylinder is very rough. Kaczer³ and Stephani⁴ have repeated the calculations for other pole distributions, but without essential differences in the results for the critical thickness.

The purpose of this paper is to describe experimental investigations into the processes taking place in the transition region between Bloch and Néel walls, where the domain walls have their highest energy. In particular, evidence will be given that the peculiar domain-wall configurations ("cross-tie" walls) observed in thin films (Fig. 2) and described by Huber, Smith, Goodenough⁵ and by other authors⁶ are typical for Néel-type walls. They are caused solely by the effect of the high magnetostatic field of the free poles along the Néel walls, if the film thickness approaches the transition point.

Domain-wall configurations as a function of film thickness

Reliable results showing the influence of stray fields on domain-wall configuration can be obtained only if thin-film samples can be produced which vary solely in thickness. To circumvent the well-known difficulties of reproducibility in thin-film behavior, the films for these investigations were evaporated in a single process, producing a wedge-like, continuously increasing thickness from a few angstroms to about 2000 Å. Such a thickness distribution can be easily obtained by using a rotating mask or a fixed mask with a suitable geometry.

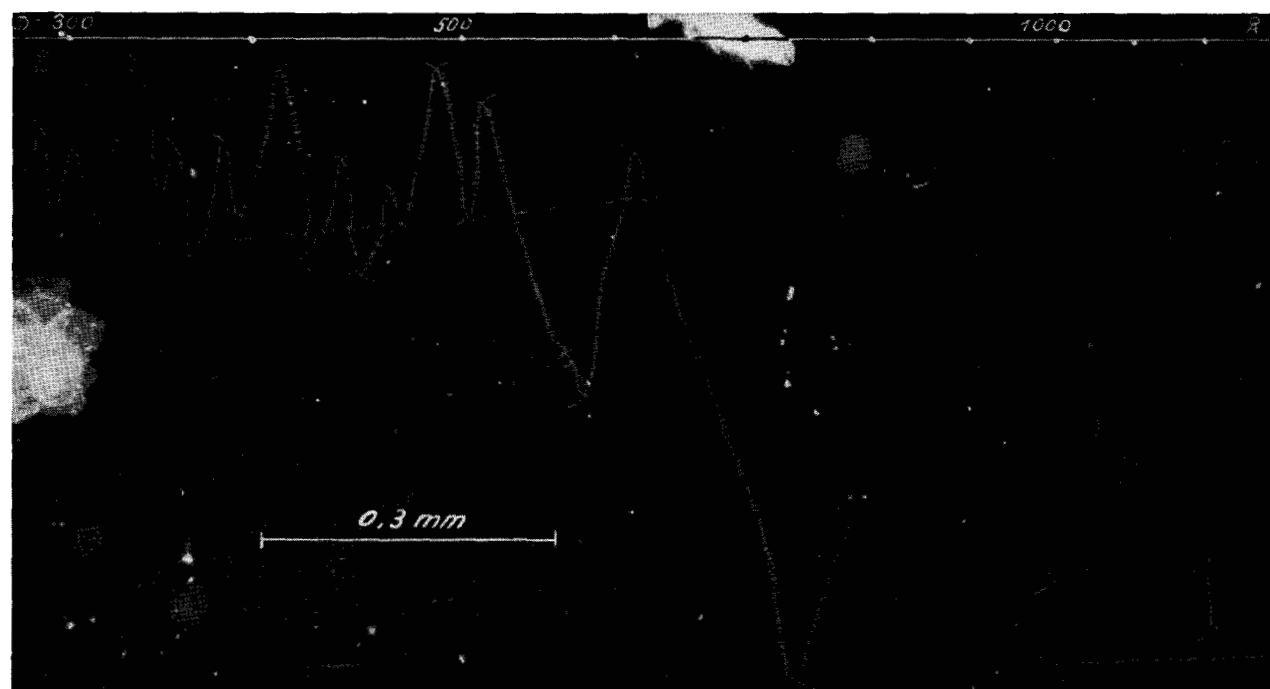
The 80-20 Ni-Fe alloy was condensed on optically flat glass substrates at about 300°C in a vacuum of $<10^{-6}$ mm Hg. A magnetic field of about 100 oersteds was applied parallel to the substrate plane during evaporation in order to produce a uniaxial anisotropy with an easy direction either perpendicular to or parallel to the thickness gradient. Since in 80-20 Ni-Fe alloys the magnetostriction and the crystal anisotropy are very small, and the effects of the anisotropies in the crystals are averaged out due to the small size (200 to 300 Å) of the irregularly orientated crystals, the induced uniaxial anisotropy field H_K of the order of 5-6 oe, is predominant in determining the magnetic behavior of these films. That is, the films behave magnetically like a single crystal with only one anisotropy axis. The reversal of the magnetization in the easy direction takes place only by the growth of 180° domains which are nucleated at the edges by means of the stray field there. The domain walls can be driven by a dc field of the order of 1 oe parallel to the easy direction

and can be observed by means of the Kerr effect. Since the coercive force for wall motion was also found to be a function of the thickness, it was necessary to use a small permanent magnet to bring the domain walls into positions suitable for observation. Then the Bitter technique,⁷ using a normal light microscope with dark-field illumination, was employed to make the domain walls visible for detailed investigations. The film thickness was determined by the Tolansky multiple-beam interference method.

Figure 3 shows domain walls in a wedge-shaped film with a thickness gradient perpendicular to the easy direction of magnetization. The thickness varies from 300 Å at the left to 1200 Å at the right. It is apparent that the domain walls change their character with film thickness. This picture clearly demonstrates the dominating importance of the demagnetizing field of the domain walls on their structure and behavior, and it seems clear that the domain walls in the thick portion of the film are of the Bloch type, which is accompanied by free magnetic poles at the film surface. In the thin part of the film, however, domain walls of another type are found with a much denser powder track which can be identified as Néel walls with free magnetic poles inside the material. They continue unchanged to film thicknesses of 100 Å and lower. Consequently, the region between these two extremes, in which the "cross-tie" structure first observed by Huber, Smith and Goodenough⁵ appears, should correspond to the transition region in Fig. 1 where the curves for the wall energies intersect.

In general it can be expected that changes in the wall energy will influence the coercive force, so that anomalies in the coercivity in the transition region would not be

Figure 3 Domain walls in a wedge-shaped film, showing change of character with film thickness.



surprising. The experimentally found coercive force for wall motion in the same wedge-shaped film as in Fig. 3 is shown in Fig. 4 as a function of thickness. In the same figure the number N of crosswalls counted on each mm length of domain wall is also plotted.

Starting with the thicker end, the coercive force at first increases with decreasing thickness owing to the enlarged stray-field energy of Bloch walls. Néel's hypothesis⁸ that the coercivity can be derived from the resistance of inhomogeneities in the film thickness to domain wall motion, leads to a $D^{-4/3}$ law for the coercive force. This law is found not to apply in the range between 200 to 1500 Å available in our wedge-like films. It can be imagined that the influence of the demagnetizing field, which radically changes the wall configuration in the transition region, already has an appreciable effect on the magnetization distribution in the walls in the 1000 Å region. The corresponding variation in the pole distribution would give rise to another thickness dependence of the wall energy and therefore to another law for the dependence of the coercive force on film thickness.

Furthermore, Fig. 4 shows the coercivity decreasing as soon as the crosswall structure begins to build up. This characteristic may be a consequence of the reduction of the magnetostatic stray-field energy by crosswalls. Beyond this region the crosswalls again disappear, and the coercivity is now associated with the resistance to motion of Néel-type walls through the film.

Other samples were prepared with the easy direction of magnetization parallel to the thickness gradient. When a domain wall is brought into the film, parallel to the easy direction, all variations of the wall configuration with the film thickness can be continuously observed on a single wall. Figure 5 shows a Bitter picture of such a sample at a higher magnification so that more details can be detected in the domain-wall structure.

The direction of the stray field at the film surface explains why the Bloch wall track in the thick part is so poorly formed compared with the Néel walls in the thin part. In the case of Néel walls the free magnetic poles lie inside the material. The ferromagnetic powder particles at the film surface can be used for easy flux closure and precipitate, therefore, more readily in this region than in the stray-field of a normal Bloch wall with field lines perpendicular to the film plane.

The changes of the domain-wall character with decreasing film thickness observed in Fig. 5 make the following interpretation obvious. Above 1000 Å, the Bloch walls are divided by one-dimensional "Bloch lines"¹¹ into right-handed and left-handed sections for reduction of the magnetostatic energy. In other words, the spin direction at the wall center is perpendicular to the film surface and points upwards or downwards, respectively, in the different sections. Williams and Goertz⁹ have also found this wall modification in 0.35-mm thick permivar sheets with uniaxial anisotropy. The period of alternation was about 0.1 mm here. Shtrikman and Treves¹⁰ gave a theoretical treatment of this type of Bloch wall. The Bloch wall can be imagined as being similar to a thin sheet, the

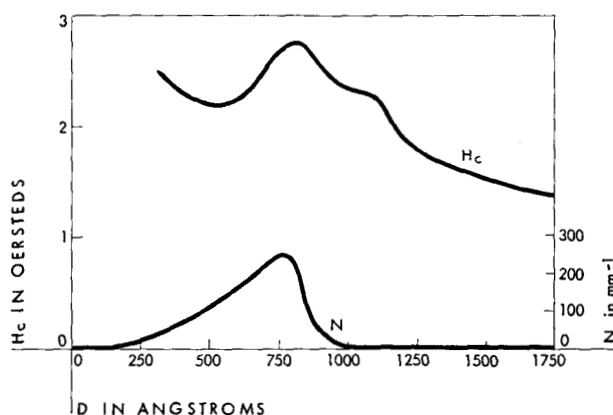


Figure 4 Coercive force H_c and crosswall density N , as a function of film thickness.

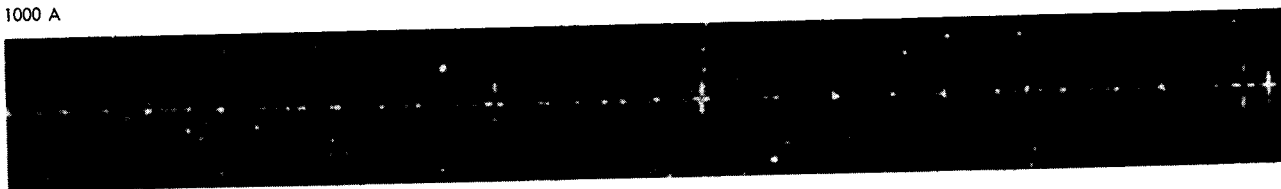
length of which is so small in one direction that the demagnetizing field has sufficient energy to divide the sheet into domains with alternating directions of magnetization. That which is a domain wall in the sheet corresponds to a Bloch line in the Bloch wall, and the spins in its centerpart are aligned perpendicular to the plane of the Bloch wall. The length of the sections with a single spin direction in the wall, i.e., the distance between the Bloch lines, is derived by them to be proportional to the thickness of the sample.

Deblois and Graham¹¹ observed in 50- μ iron whiskers that the Bloch lines, which separate the sections of left-hand and right-hand walls, can be shifted by an external field applied parallel to the plane of the Bloch wall. This is similar to the process of wall motion in thin films.

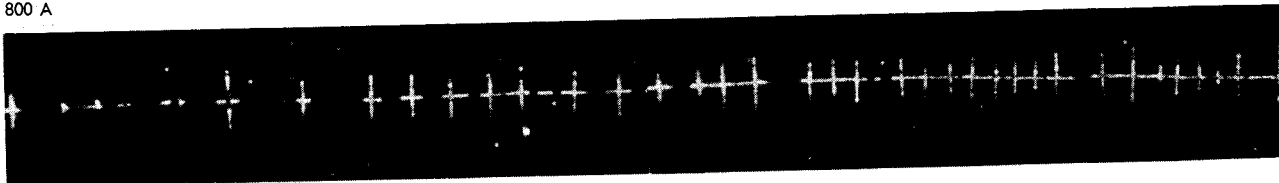
With decreasing thickness of the sample, the period of the alternations decreases because the demagnetizing energy becomes smaller the more frequently the Bloch wall is subdivided. On the other hand, the increasing number of Bloch lines increases the exchange part of the wall energy, so that a lower limit for the period of the subdivisions is to be expected.

In the part of the sample (Fig. 5), with a thickness around 1000 Å, the shape of the Bloch wall is, of course, more similar to a long cylinder with the magnetization perpendicular to its axis than to a thin film. The energy of the demagnetizing field depends only slightly on the distribution of the spins around this axis. Bloch and Néel wall configurations have approximately the same energy; therefore the 180° Bloch lines degenerate to 90° lines, which now separate longer sections of Bloch walls from Néel wall sections, as sketched in Fig. 6. The widely spaced Néel wall sections may be identified in Fig. 5 by the heavier precipitation of particles separated by a few microns. With decreasing film thickness, Néel walls become more and more favorable with respect to their magnetostatic energy than the Bloch wall sections. The latter become shorter and are finally reduced to 180° Bloch lines which now subdivide the Néel walls into left- and right-hand sections. The transition continues down to 700 Å and is demonstrated by the disappearance of

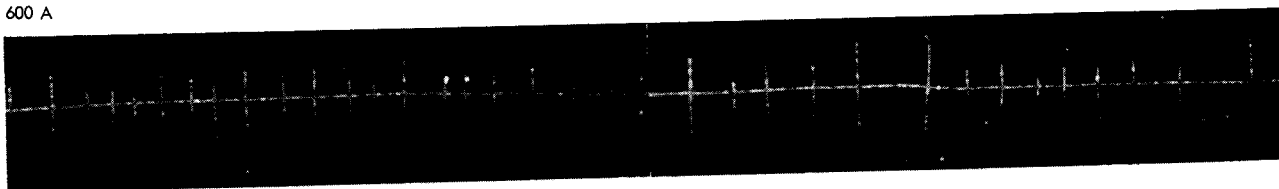
1000 A



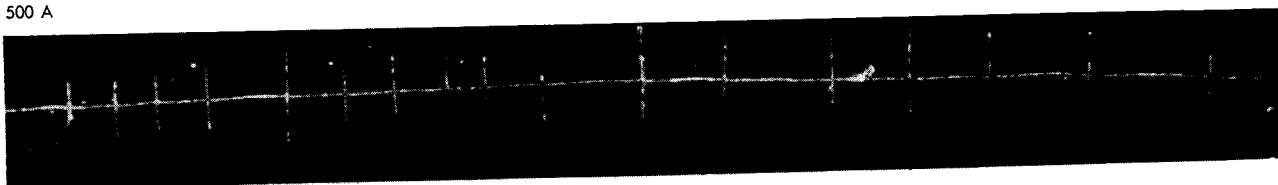
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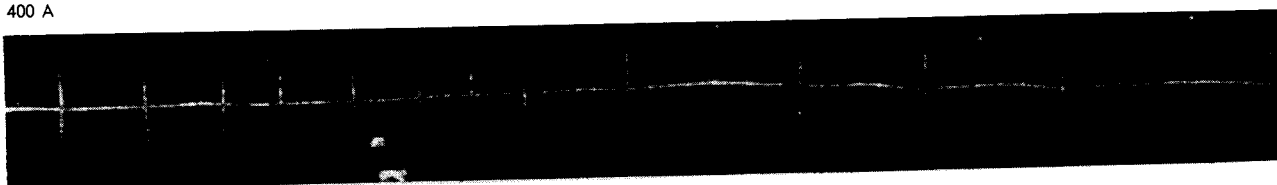
600 A



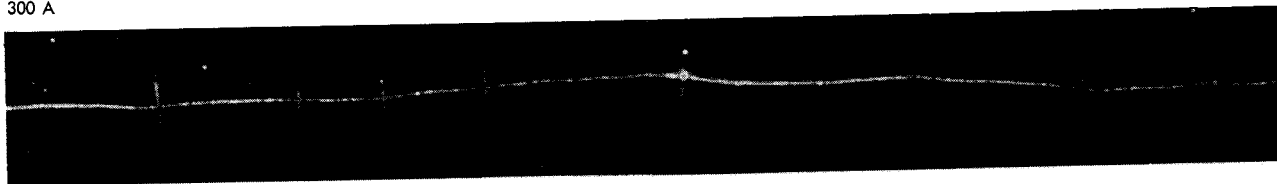
500 A



400 A



300 A



250 A

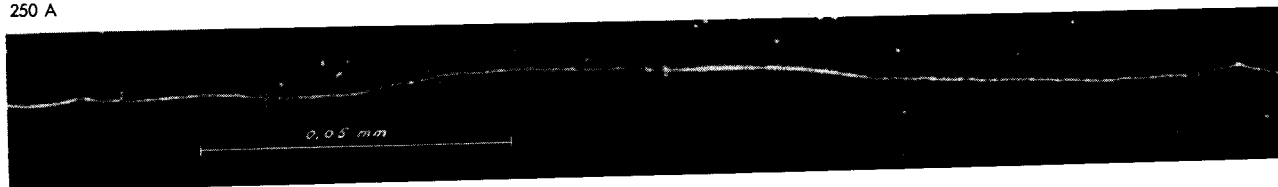


Figure 5 Map of a continuous 180° domain wall which runs parallel to the thickness gradient. The thickness decreases continuously from left to right in each strip.

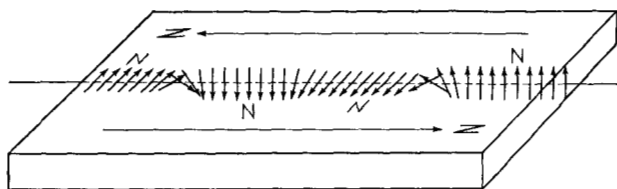


Figure 6 Sections of Bloch type and Néel type walls alternating in the domain walls at about 1000 Å film thickness. They are separated by 90° Bloch lines.

the weakly developed powder tracks between the dense Néel wall sections.

In the region of 900 Å, the sections of Néel walls are already quite long and reduce the magnetostatic energy by alternating the north or south poles at the flanks of the wall inside the film. The flux closure between these poles runs alternately with or against the magnetization of the surrounding material, which is aligned in the easy direction. Because of the high energy density in the region with flux closure opposite to the magnetization, the wall sections are drawn together in isolated pairs to lower the energy density and are supplied with short perpendicular Néel wall pieces, called "crosswalls."

Figure 7a indicates the proposed spin configuration of the paired Néel sections appearing around 900 Å. The primary process is the reduction of the magnetostatic energy of the longer Néel wall pieces by subdivision into two sections with alternating polarity corresponding to the process described before by Shtrikman and Treves for Bloch walls. But the difference is that for Néel walls the subdividing Bloch lines are decorated by crosswalls whenever the flux closure runs through the material opposite to the general direction of magnetization in the easy direction. For Bloch walls, however, the flux is closed through the air between free magnetic poles on the film surfaces, and therefore it cannot give rise to the development of crosswalls.

In the region below 700 Å, the domain walls are only Néel type with a Bloch line density which decreases with the film thickness, in contrast to the behavior of Bloch lines in Bloch walls. The distances between the crosswalls are experimentally found to increase between 900 and 300 Å, following a D^{-2} law.

Figure 7b indicates the spin configuration for the regular wall structure observed around 600 Å for which Huber, Smith and Goodenough⁵ gave the first interpretation and suggested the name "cross-tie" walls.

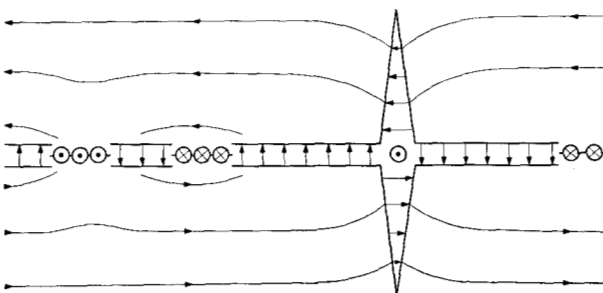
Around 400 Å the domain walls retain their polarity unchanged over relatively long distances of a few hundredths of a millimeter (Fig. 7c). This is a consequence of the reduction of the influence of free magnetic poles with decreasing film thickness.

Below a film thickness of 300 Å the subdivision of the Néel walls by Bloch lines disappears, because the possible gain in magnetostatic energy is smaller than the additional exchange energy needed for the formation of Bloch lines.

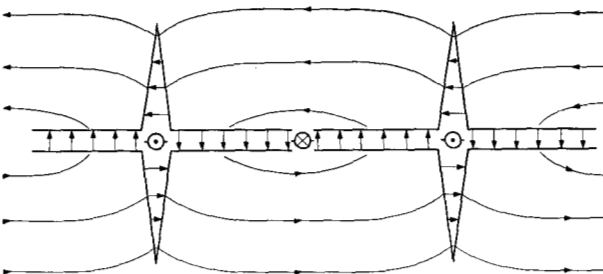
In the area around 150 Å and thinner, double Néel walls can be formed by applying an alternating field (50 cps) (Fig. 8). Their properties are described by Williams and Sherwood.¹² A theoretical treatment of this phenomenon is given by Kaczer¹³ and Behringer.¹⁴

For the transition between Bloch and Néel walls, it is obviously difficult to define a critical thickness which can be compared with the value obtained from Formula (3). If a value for the critical thickness must be derived from Fig. 5, then perhaps a value around 1000 Å would be most plausible, because the sections of Bloch and Néel walls here have about the same length and, consequently, about the same energy. When an 80-20 alloy with a magnetization of $4\pi J_s = 10^4$ gauss and an exchange constant of $2 \cdot 10^{-6}$ erg/cm is used, Formula (3) yields a critical thickness of 320 Å, which is too small by a factor of about 3.5. It may be of interest to point out here that, in the case of pure iron films, the critical thickness for

a) 900 Å



b) 600 Å



c) 400 Å

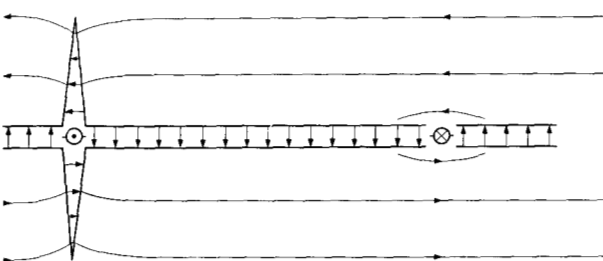


Figure 7 Variation of the magnetization around the crosswall structure as observed in Fig. 5 at several film thicknesses.

180° domain walls was experimentally found to be of the order of 400 A, whereas Formula (3) predicts a value of 100 A, again about 3.5 times smaller.

Another consequence drawn from the experimental observations is that the applicability of a $D^{-4/3}$ law for the thickness dependence of the coercive force is in doubt. Néel's result⁸ that the wall energy increases as $D^{-1/3}$, derived from the increasing demagnetizing factor of an elliptical cylinder with decreasing thickness, is not valid. As soon as the subdivision of Bloch lines takes place, a slower increase of coercivity with decreasing thickness is to be expected. The few measurements on coercive force as a function of thickness so far reported actually give a larger¹⁵ or smaller¹⁶ deviation from this law to a lower inverse power of thickness.

Results of measurements on pure iron or nickel films¹⁷ cannot be used for comparison, because the switching process in these films seems to be much more complicated than reversal by driving 180° domain walls in Ni-Fe films with relatively high uniaxial anisotropy.

Motion of Bloch lines and crosswalls along scratches

The Bloch lines subdivide a domain wall in order to reduce the magnetostatic energy of its stray field in the same way as domain walls subdivide a thin sheet in order to lower the stray-field energy. When an external field is applied to the sheet parallel to the domain walls, the domain walls are driven into new equilibrium positions. In the same way, an external field applied parallel to the direction of magnetization inside the domain wall should cause a motion of the Bloch lines, so that the sections in the wall with magnetization parallel to the applied field grow at the expense of sections with antiparallel magnetization. This effect must be considered for the dependence of the coercive force on the angle between the applied field and the easy direction in thin films.

The movements of Bloch lines have been studied on scratches which have a magnetization distribution similar to Néel-type walls. Results are reported in this section.

Unfortunately it is difficult to observe the Bloch lines and their motion in Néel walls. If a field is applied perpendicular to such a wall, only an increasing tilting of the crosswalls with increasing field strength can be observed, as in Fig. 12. The growth of the preferred sections in the Néel wall takes place by movement of those Bloch lines which lie between the crosswalls. Certainly these Bloch lines can be detected as small points in the powder tracks⁶ within the favorable thickness region around 800 A, as shown in Fig. 5, but the observation of these points is too delicate to form a basis for a thorough investigation of Bloch line motion.

For a critical value of the applied field below the anisotropy field of the film the crosswalls suddenly disappear, i.e., the Néel wall is then homogeneously magnetized parallel to the external field. They suddenly reappear when the field strength is slightly reduced, but often with another distribution along the walls determined by the nucleation process.



Figure 8 Double Néel walls in a Ni-Fe film with a thickness of about 150 A.

We tried to circumvent the difficulties mentioned above regarding the observation of Bloch lines and looked for special conditions which might allow a more accurate determination of the Bloch line position. We found that crosswalls can also be observed along scratches in a material with negative magnetostriction, and that these crosswalls can be used for studying the properties of Bloch lines.

When a thin-film surface is wiped with a cloth, the dust particles in the cloth produce fine scratches in the surface. If the scratches run perpendicular to the direction of the magnetization, colloidal particles from Bitter's solution are attracted by the magnetic stray-field of the scratch so that the scratch appears as a fine-line track. This effect is well known and often used for determining the direction of magnetization.

If the magnetization is parallel to the scratch, nothing is normally seen. However, an interesting phenomenon occurs when the film material has a negative magnetostriction constant, e.g. a nickel-iron alloy with more than 80% nickel.

A scratch is similar to a furrow in which the material is pushed out to the sides, forming small embankments. In these ridges the material is under a pressure perpen-

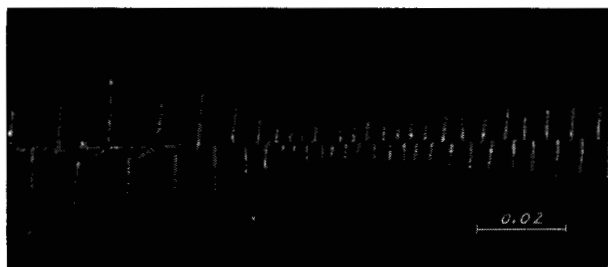


Figure 9a Crosswalls along a scratch parallel to the easy direction ($H_k=5$ oe) of a film with negative magnetostriction. They indicate subdivision by Bloch lines.

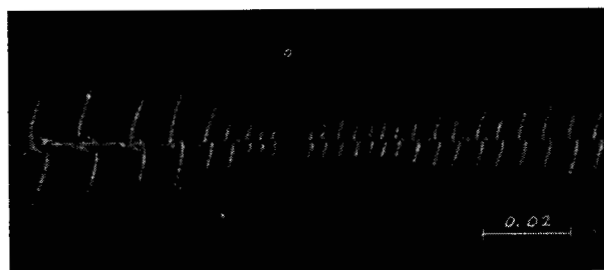


Figure 9b A magnetic field of 2 oe has been applied in the film plane and perpendicular to the scratch. The Bloch lines are shifted and the crosswalls tilted.

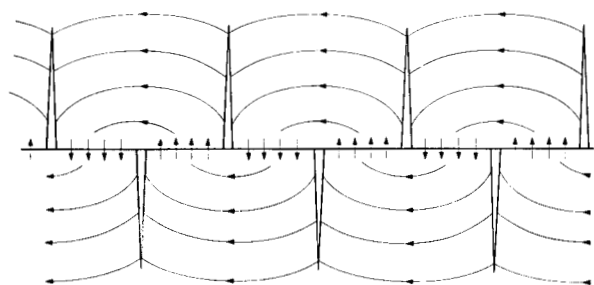


Figure 9c Variation of the magnetization around the scratch in (a).

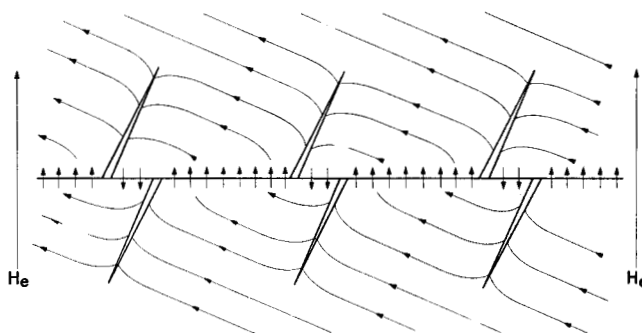


Figure 9d Variation of the magnetization around the scratch in (b).

dicular to the scratch. The corresponding stress is transmitted through the material and is maintained by the substrate. In a negative magnetostrictive material under stress, the magnetization has a preferred direction along the direction of pressure. Therefore, a scratch parallel to the easy direction of the magnetization in this material has a preferred direction of magnetization along a narrow band perpendicular to itself and consequently to the easy direction of the film. For this reason, the scratch has free magnetic poles along both flanks inside the material. If, now, the free poles along any thin band can give rise to the spin configurations and crosswalls previously discussed for Néel walls, then such structures should be observable along these scratches, too. Differences are to be expected for the following reasons: a scratch can be thicker than a Néel wall, and the magnetization on both sides of the scratch is usually parallel. This is in contrast to Néel walls, which are always surrounded by material with antiparallel magnetization.

In Fig. 9a, powder patterns are shown along a scratch in which the region of deformed material is of the order of the domain-wall thickness. It is seen that the scratch carries crosswalls similar to a Néel wall. Since the magnetization is parallel on both sides of the scratch, the

position of the high energy flux closures alternates, and so do the crosswalls (Fig. 9c). Note that now both ends of the alternating sections are marked by crosswalls, in contrast to Néel walls. Therefore, the shifting of Bloch lines by an external field can be readily observed.

In Fig. 9b, a magnetic field is applied in the film plane perpendicular to the scratch. The sections with the magnetization aligned parallel to the applied field grow at the expense of those with antiparallel magnetization. The crosswalls which indicate the location of the Bloch lines are now paired together. At the same time they are tilted at an angle. This tilting is associated with the rotation of the film magnetization out of the easy direction, which is due to the applied field (Fig. 9d).

When the external field is further increased, the crosswalls suddenly disappear (center of Fig. 9b) indicating that the scratch is now homogeneously magnetized. At the same time other scratches which run nearly parallel to the applied field develop a crosswall structure. The field strength necessary for removing the crosswalls varies in different portions of the scratch and is roughly proportional to the distance between the crosswalls in zero field. Reduction of the applied field makes the crosswalls reappear with roughly the same distance between them as

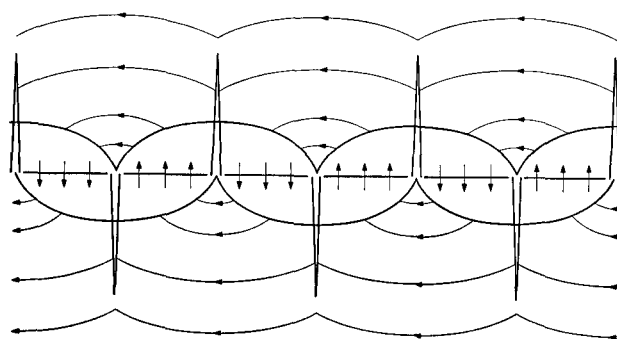
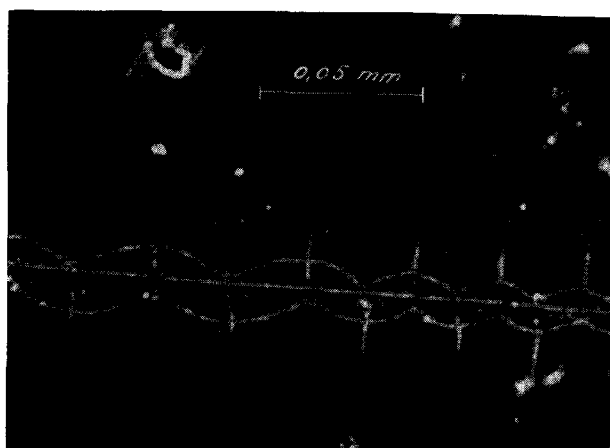


Figure 10 Powder track and variation of the magnetization around a broad scratch.
The deformed material is separated by domain walls. (The easy axis of magnetization lies on the horizontal.)



Figure 11 A domain wall meeting a scratch.
The magnetization on both sides of the scratch changes from parallel (left) to antiparallel (right). The alternating cross-walls shift into positions opposite one another.

before, but with another distribution along the scratch due to the same nucleation process taking place in Néel walls.

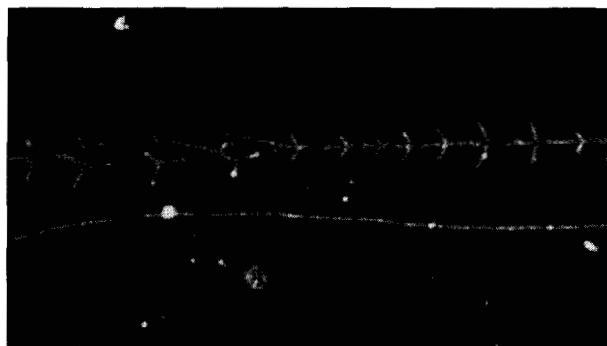
The length and distance of the crosswalls on a scratch do not depend on the film thickness, but are determined only by the magnetic character of the material and by the way in which the scratch is made. If the region of the deformed material along a scratch is much thicker than the domain-wall thickness, it can be separated from the surrounding material by domain walls (Fig. 10). The shape of the included small domain is determined by the condition that domain walls should have as few free magnetic poles as possible. This means that the component of the magnetization normal to the wall should pass unchanged through the wall. In other words, the wall will approximately bisect the angle between the directions of magnetization on either side of it. Therefore, the shape of the domains can give additional information about the distribution of the magnetization around a scratch.

The remaining point to be discussed is how far the previous considerations concerning the influence of magnetic stray fields on the distribution of spins in a Néel wall can really be applied to the conditions in and around a scratch. For this purpose in Fig. 11 is shown a scratch which is met by a domain wall at the center of the picture. The magnetization on the left is parallel on both sides of the scratch, and on the right, antiparallel. This change of magnetization from parallel to antiparallel markedly alters the Bitter pattern: the crosswalls on the right-hand side are in the same positions previously found to be typical for Néel walls. Of course the additional stress anisotropy in the scratch modifies the energy of the domain wall and therefore the length and distance of the crosswalls along the domain wall, but the basic principle leading to a crosswall structure is the same. From Fig. 11 it seems clear that the "chain" walls observed by Goodenough¹⁸ are identical with Néel walls along scratches.

This picture also indicates the position of those Bloch lines around which the flux closure is in the same general direction as the surrounding magnetization. As mentioned before, this kind of Bloch line is difficult to detect in the powder tracks of Néel walls, but is here marked by the intersections of the circular domains. This fact permits observation of the motion of Bloch lines caused by an external field in Néel walls, too, or more exactly, in a model corresponding to such a wall. In Fig. 12, the field is applied perpendicular to the scratch wall, and the growth of the wall sections magnetized parallel to the field can be observed. Compare also with Fig. 9.

With small fields, the Bloch lines are shifted over distances roughly proportional to the applied field strength. When the field is reduced to the previous value after a small increase, the Bloch lines return to the same positions with only very small hysteresis. This means the resistance to Bloch line motion along Néel walls is much lower than the resistance to Néel wall motion through the thin film. For higher values of the applied field, the cross-wall structure around the scratch disappears.

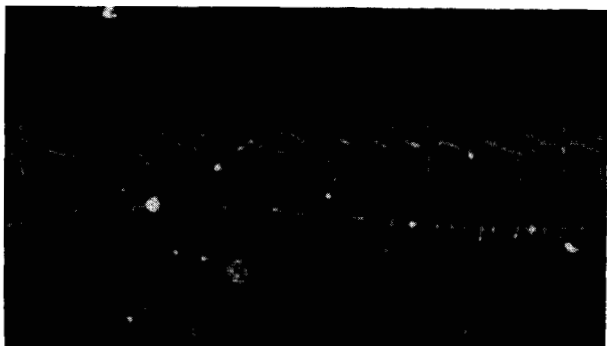
The length of the crosswalls, which runs up to a few



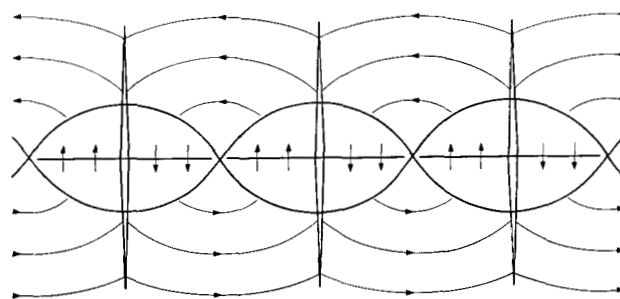
a)



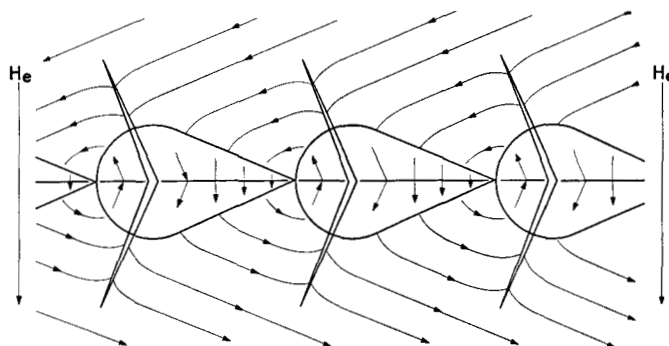
b)



c)



d)



e)

Figure 12 Shifting of Bloch lines by application of a field H perpendicular to the scratch which at the same time is a domain boundary:

(a) $H=0$, (b) $H=1.6$ oe, (c) $H=2.4$ oe. Below the scratch is a normal Néel wall seen in the photographs. (Same sample as in Fig. 9.) (d) and (e): variation of the magnetization corresponding to (a) and (b), (c), respectively.

hundredths of a millimeter, is rather surprising. The reason for this might be found in the relatively low anisotropy field of about 5 oe in these films. The high saturation magnetization of around 10^4 gauss provides all misaligned parts of material, for example within a scratch or in a Néel wall, with a strong stray-field able to turn the spins out of the easy direction over long distances in the surrounding material. By this process the free poles are distributed over a larger area and the density of air flux decreases. In this sense, crosswalls in general are not so much real domain walls as dipole lines, which outline the region of material with a magnetization turned out from the general easy direction (compare observations of

Fuller and Rubinstein¹⁹) by the influence of the stray field. Hence the ends of the domains also have these lines (see Figs. 2 and 3), indicating that the stray field around the domain ends uses a certain part of the neighboring material for lowering its air flux density. The most impressive place to observe this phenomenon in the film material is around a hole of about 0.02 mm diameter (Fig. 13). The air flux between the free magnetic poles at the borders produces a distribution of the magnetization which has a certain similarity with the distribution between two crosswalls at a Néel wall. A characteristic property of such crosswalls is the continuous change of the angle between the magnetization directions on both

sides along the wall corresponding to the local value of the stray field. Therefore they run out usually inside the film by continuous reduction of the angle between the magnetization, in contrast to the behavior of normal domain walls. If the magnetization of the film is rotated out of the easy direction by applying an external field, the position of these crosswalls is changed correspondingly.

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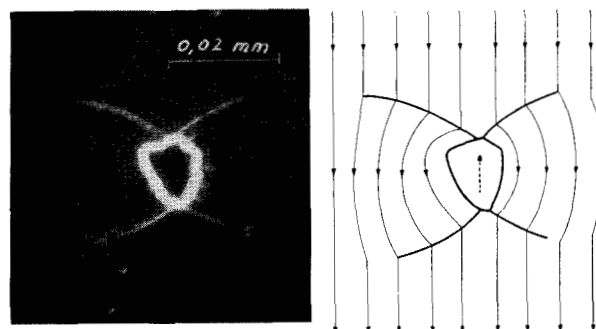


Figure 13 Flux closure around a hole in a Ni-Fe film.

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