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# Observations of the Fine Structure of Domains and Reversible Rotation of the Magnetization in Thin Permalloy Films by the Faraday Effect

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A microscopic Faraday effect apparatus is described by means of which the fine structure of the domain configurations in thin permalloy films has been observed. The direction of the magnetization in cross-tie domain walls and other configurations has been deduced from their light, dark or grey appearance and known polarizer angles. A method of using the Faraday microscope is presented to show how this device may be used to observe the reversible rotation of the magnetization in small areas of the film at rates of DC to 50 Mc/sec. The Faraday microscope was used to find the anistotropy constant over a 1 mm$^2$ area of a permalloy film and it was found to be $K=1600$ ergs/cm$^3$.

## 1. Introduction

The gross appearance of the domain structure in thin ferromagnetic films as observed by the Farady magneto-optic effect has already been reported[1,2,3]. The fine structure of the domain walls in these films may also be observed directly by this technique and conclusions may be drawn as to the direction of magnetization in the cross-tie walls and in various domain configurations.

For oblique transmission of polarized light through semitransparent permalloy films below 1000 Å in thickness, a rotation of the polarized light occurs which is proportional to the magnitude and direction of the component of magnetization along the transmitted beam. This rotation is many times that obtained by the reflection of polarized light in the magneto-optic Kerr effect so that much improved contrast is available. For such thin films it does not seem energetically possible for volume domains to occur, therefore, the same domain structure exists all the way through the film.

## 2. Experimental

The apparatus used for microscopic Faraday observations is similar to that described by Fowler, *et al.*[4] for magneto-optic Kerr observations of domains in iron whiskers and is shown in Fig. 1. The photomultiplier shown in the photograph is used for obtaining optical hysteresis loops and for observations of rotation of the magnetization as described below and is interchangeable with eyepiece or camera.

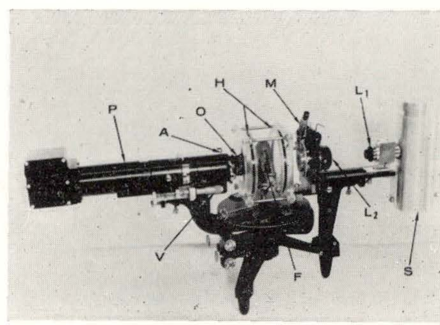


Fig. 1. Faraday Microscope, S-point source, $L_1$-first image forming lens, $L_2$-second image forming lens, M-polarizer manipulator, H-helmholtz coils, F-inclined film, O-objective lens, A-analyzer prism, V-vernier focus control, P-photomultiplier.

The film was inclined at an angle of 45° to the vertical axis and polarizer angles were measured with a precision of $\pm 2$ minutes of arc. The photographs presented were all taken on one 5 mm. film spot; however, the features described are representative of those found in 50 or more such films. The thickness of this particular film spot (81 Ni–19 Fe permalloy) was measured by the Tolansky interference method using a very narrow line filter (15 Å halfs-width) and found to be 490 $\pm 20$ Å.

The procedure by which domains were introduced was as follows. With the film spot in a single domain state and the easy axis horizontal, a small permanent magnet was approached at an angle of about 45° to the easy direction until the film broke up into an interesting domain structure. The magnet was then removed so that the domain structure represented a relatively stable demagnetized state under the influence of stray fields at the most. The effect of these stray fields was negligible because the film could then be rotated freely without disturbing the domain configuration under observation.

### 3. Cross-tie Domains

If the analyzer prism is set at about 35 minutes from extinction with respect to the vertical polarizer and the film is rotated so that the domain walls are horizontal, there is maximum contrast between the areas on both sides of the domain wall and cross-ties cannot be seen. However, as the film is rotated towards the position where the domain walls are vertical, the cross-ties appear to "grow" out of the wall. Fig. 2 is a photograph made when the domain wall direction was 32° from the vertical. In this position, the cross-ties are almost fully developed in length.

The direction of the magnetization in the cross-ties may be deduced from the fact that the more nearly the magnetization is directed to the horizontal the greater will be its component in the direction of the light and the darker (or lighter) will that region be. Particularly in the upper left region of Fig. 2 periodic contrast along the wall of regions which are very dark and very light seems to indicate that the magnetization around the cross-ties can be interpreted in terms of the model proposed by Huber, *et al*[5].

As shown in Fig. 2 the films were observed to break up into narrow domains at about 45° on either side of the easy direction. The large easy direction domains show a cross-tie structure similar to that shown here for the domains at 45° to the easy direction. The domain configuration shown in Fig. 3 is a combination of easy direction domains and domains at 45° to the easy direction.

Fig. 2 also shows quasi-periodic intensity variations due to "magnetization ripple" in domains inclined at 45° to the easy direction as viewed by the Faraday effect. These have been observed by the Bitter technique[6] and by electron microscopy[7,8]. They appear to be produced by the uniaxial anisotropy in this film which is directed at about 45° to the domain wall.

### 4. Néel Walls

Fig. 3 is a photograph of domain walls as they appear when the vertical polarizer and analyzer are set almost at extinction (within 2 minutes) and the domain walls are horizontal. Under these conditions the domains on either side of the wall appear almost equally gray, because they produce equal and opposite rotations of the polarized light.


Fig. 2. Bar Domains at about 45° to the easy direction showing cross-ties and magnetization ripple.

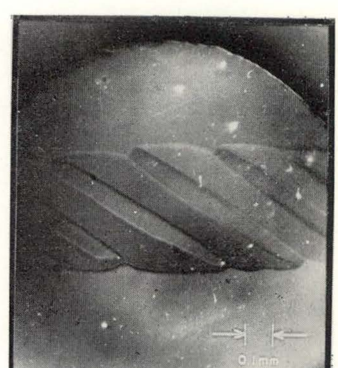


Fig. 3. "Candy-Cane" Domain—a combination of easy direction domains and those at 45° to the easy direction as viewed with analyzer and polarizer near extinction and the easy axis parallel to the page horizontal.

The walls, however, appear as dark or light lines of the same appearance as that observed by electron microscopy[7,8]. There is much evidence, both theoretical and experimental[5,9] for the existence of Néel wall segments alternating in direction at right angles to the domain wall in these thin (500Å) films. If this condition is presumed to exist in the same way in the walls on both sides of a domain, diverging or converging rays of light would strike one wall at a different angle than the next one with a corresponding change in refringence. By the Faraday effect, it is only for perfectly parallel light rays that vertical magnetization directions in the wall would result always in a dark line.

## 5. Reversible Rotation of the Magnetization

If a film spot is mounted with its easy axis vertical and inclined at 30° about the vertical axis so that the plane of the film makes an angle of 60° with the direction of the light, then the rotation of the plane of polarization $=kM\sin\theta\cdot\cos 60=k'M\sin\theta$, where $\theta$ is the angle of rotation of the magnetization away from the easy direction. For the small angles of rotation of the plane of the polarization under consideration the light output varies linearly with $\sin\theta$ reaching a maximum (or minimum) corresponding to a rotation of the magnetization of 90°. If the magnetization is caused to rotate by a field applied perpendicular to the easy direction then the familiar linear transverse hysteresis loop will result. With a film spot so mounted, the change in light output was sensed by the photomultiplier shown in Fig. 1. The photomultiplier output was measused by an electrometer millivoltmeter. Since the purpose of this experiment was to gain information that would be useful in computer memory applications, a wire drive line was placed over and under the film spot as shown in Fig. 4. Sine wave pulses, biased totally positive (or negative) were applied to the drive line in the frequency range DC to 50 Mc/sec.

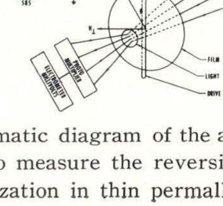


Fig. 4. Schematic diagram of the arrangement of apparatus to measure the reversible rotation of the magnetization in thin permalloy films by the Faraday effect.

At low frequencies the variation in light output could be displayed directly on an oscilloscope and at high frequencies (50Mc/sec) a sense line and a sampling oscilloscope showed that the magnetization was always in equilibrium with the drive field pulses. Since the magnetization followed the sine wave pulses exactly, and since the electrometer acts as an integrating device and measures average AC values, the amplitude of the rotation was found by doubling the electrometer reading. The electrometer was calibrated in terms of rotatation by applying a transverse field extending over the whole film spot with the Helmholtz coils shown in Fig. 1.

Using a light probe 1 mm in diameter, the the rotation of the magnetization was found to be constant with frequency up to 50 mc/sec. Also, the rotation was localized near the drive line. For example, the average rotation for a drive current of 300 m.a. at 0.5 mm from the drive line was 23° and at 1.5 mm it was 2°.

Since the magnetization is in equilibrium with the applied field pulse, the following torque equation must hold.

$$K\sin 2\theta - H_\perp M\cos\theta = 0 \qquad (1)$$

For 82 Ni-18 Fe permalloy $M=795$ gauss and for a point at 0.5 mm from the drive line the applied field was calculated as $H_\perp=3.1\times i$(amperes). The angle $\theta$ was measured as described above for values of drive current between 100 m.a. and 600 m.a. The solution of equation (1) for $K$, the effective anisotropy when plotted as functions of the measured angles is a straight line with slope $K=1600$ ergs/cm$^3$. This agrees quite well with the value found from $H_k=4.2=2K/M$, from which $K=1700$ ergs/cm$^3$.

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# Structure of Domain Walls in Thin Films

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Domain walls in single crystal films of iron, evaporated onto the (100) MgO cleavage surface, are observed by means of the Bitter pattern method. The walls in cubic single crystal films form such a simple pattern as that found in bulk crystals and always the cross-tie walls are not found. To reveal details of the colloid deposit by using electron micrograph a newly modified colloid is prepared. From the photographs thickness of the 180° and 90° Néel walls can be estimated. The uniaxial anisotropy is a necessary condition for the cross-tie formation and for the estimation of the spin angle variation in the wall and wall energy the $\mu^*$ correction should be used.

## 1. Introduction

Several researchers have investigated on the so-called cross-tie wall[1] observed in polycrystalline films with induced uniaxial anisotropy. In these polycrystalline films the type of walls observed depends on the film thickness and the cross-tie walls are found only within an intermediate thickness range under a certain magnetic condition[2),3)]. The cross-tie wall formation has been briefly explained by the wall energy increasing due to the magnetostatic effect, but it has not yet been accomplished. The magnetization process is remarkably affected by the wall structure in films.

We compared domain walls in single crystal films with cubic magnetic anisotropy with those in polycrystalline films with induced uniaxial magnetic anisotropy by the Bitter pattern observation, and investigated on schemes of the spin rotation in these walls.

## 2. Specimens

As single crystal films, a number of oriented (100) films of iron were prepared onto the (100) MgO cleavage surface, which was heated up to 450°C during evaporation. The crystalline anisotropy constant $K_1$ of these films is almost the same as that of bulk materials, according to the torque measurement. Polycrystalline films used in the study were iron evaporated on glass substrates in a magnetic field.

## 3. Optical microscopic observations

An example of the cross-tie walls observed in such polycrystalline iron films is shown in Fig. 1. On the contrary to it, domain walls in single crystal films of iron with cubic anisotropy form such a simple pattern as that found in bulk single crystals. A typical one in a (100) plane of iron crystal film 560 Å thick is shown in Fig. 2. They consist of typical 180° and 90° walls connected with the easy axes of the specimen. In our study clearly the 180° walls are thicker as the film thickness decreases, while as for the 90° walls it is not so clear, and in