PHYSICAL REVIEW VOLUME 104, NUMBER 3 NOVEMBER 1, 1956

Magnetic Domains in Evaporated Thin Films of Nickel-Iron*

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(Received July 23, 1956)

The longitudinal Kerr magneto-optic technique proves to be well suited for the observation of domains in evaporated ferromagnetic thin films. In a series of six films of NiFe ranging in thickness from 20 000 angstroms to 500 angstroms, domain patterns have been photographed in all but the two thickest. Many features of domain structure, familiar in bulk single crystals, have been observed in the films. Certain unusual features of domain behavior appear characteristic of the thinnest specimens and have also been photographed. Complexities in many of the patterns, uncorrelated with change of film thickness, are probably due to uncontrolled physical factors connected with the manufacture and the preservation of the specimens. The necessity of careful control of such factors for quantitative domain investigation is emphasized.

INTRODUCTION

SINCE the appearance of the theoretical paper of Kittel,[1] thin ferromagnetic films have been the subject of considerable study.[2–8] This interest has undoubtedly resulted from the fact that the films, being essentially two-dimensional, offer considerable promise of elucidating certain problems of magnetic theory whose interpretation is difficult for matter in bulk. The interest has been further heightened, of course, by the possibility of practical application of ferromagnetic films to information storage.

Various studies of the magnetization curves and measurements of certain magnetic properties of thin films have seemed to indicate that domain configurations depend in general upon the thickness and the constants of the film in the manner predicted by Kittel, but no direct observations of domain patterns were reported until a recent research note described domains in an evaporated film of NiFe observed with the Kerr magneto-optic technique.[9] We have thus felt justified in continuing our research in an exploratory fashion with the hope of learning what features of thin-film domain behavior are similar to those of matter in bulk, and what features, if any, are different.

EXPERIMENTAL PROCEDURE

The technique for observing domains by the longitudinal Kerr magneto-optic effect has been fully described in a previous paper,[10] and the method was employed for this investigation with little modification. Some improvement of the photographic field of view has been achieved through the use of a 7-inch $f/2.5$ Kodak Aero-Ektar lens and an analyzer of larger aperture. A controlled, uniform, longitudinal magnetizing field was provided at the specimen by a solenoid designed to allow observation by oblique reflection. Although we have observed domain structure in films of other materials, we decided to restrict our present survey to the films of NiFe (80% nickel) generously furnished to us by the magnetics group at the Naval Ordnance Laboratory, Corona. This material has small coercivity, low anisotropy, and small magnetostriction; more important, its Kerr effect is reasonably large resulting in good contrast between adjacent domains whenever they exist. Each film was evaporated to the desired thickness in the presence of a magnetic field of 128 oersteds directed across the width of the microscope cover glass that serves as a substrate. The dimensions of the film surfaces are 1 in.$\times 2\frac{1}{4}$ in., but evidence of fringing of the magnetic field near the ends led us to restrict our field of observation in most cases to a center area approximately 1 in.$\times$1 in. The specimens observed, each evaporated in identical fashion, had thicknesses of 20 000, 10 000, 5000, 2500, 1500, and 500 angstroms, respectively.

OBSERVATIONAL RESULTS

It was our hopeful expectation to observe in this set of films some well-defined features of domain behavior that would correlate in a clear progressive way with the film thickness. Although certain general facts about the effect of thickness could be concluded, very different features have often appeared in two apparently identi-

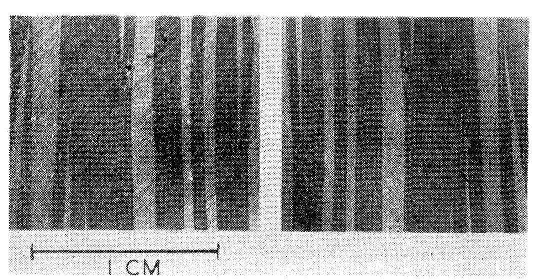

FIG. 1. Photographs of the top and bottom surfaces of a portion of a thin-film specimen 5000 A thick. The specimen was turned over about an axis parallel to the center domain.

* Supported by the Office of Naval Research.
[1] Charles Kittel, Phys. Rev. **70**, 965 (1946).
[2] H. König, Naturwiss. **33**, 71 (1946).
[3] A. Drigo and M. Pizzo, Nuovo cimento **5**, 196 (1948).
[4] E. C. Crittenden and R. W. Hoffman, Revs. Modern Phys. **25**, 310 (1953).
[5] M. J. Klein and R. S. Smith, Phys. Rev. **81**, 378 (1953).
[6] W. Reinke, Z. Physik **137**, 169 (1954).
[7] L. E. Collins and O. S. Heavens, Phil. Mag **45**, 283 (1954).
[8] R. L. Conger, Phys. Rev. **98**, 1752 (1955).
[9] C. A. Fowler and E. M. Fryer, Phys. Rev. **100**, 746 (1955).
[10] C. A. Fowler and E. M. Fryer, Phys. Rev. **94**, 52 (1954).

cal specimens and even in the same specimen at two different times. Such behavior reflects the very sensitive dependence of the state of the system upon factors in the manufacture and the preservation of the specimen that are uncontrolled and perhaps unknown. It certainly points up the necessity of fool-proof controls for assuring absolute uniformity of the evaporated films in order to make a quantitative study of the dependence of the domain behavior upon any specific parameters.

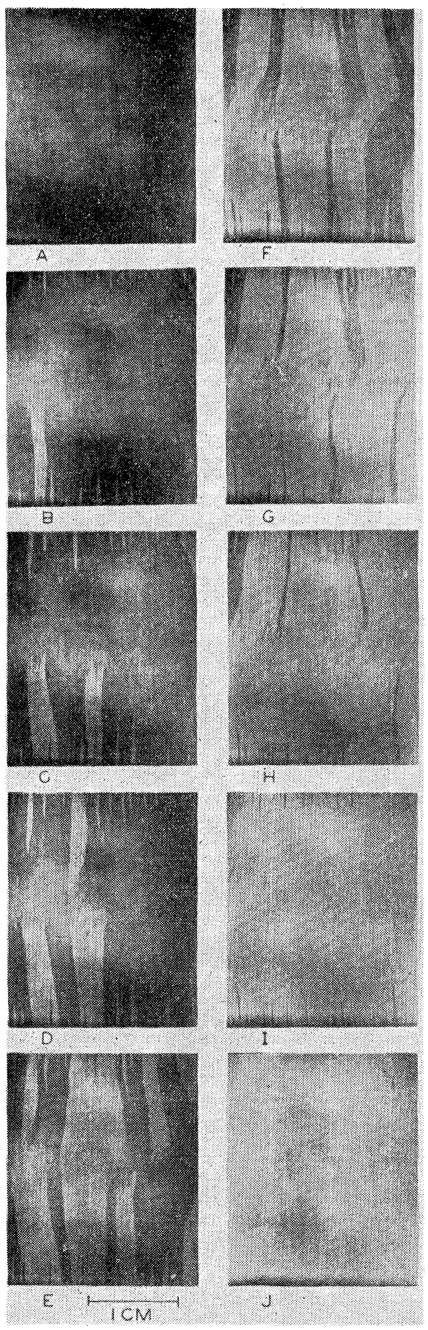

FIG. 2. Ten steps in the complete magnetization reversal of a 2500 A specimen. The light areas indicate magnetization directed toward the top of the page, the dark areas toward the bottom.

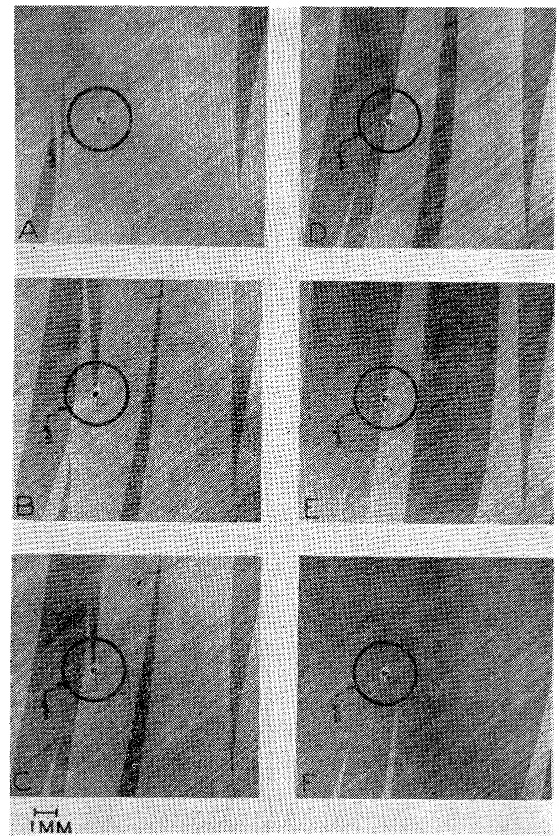

FIG. 3. Development and movement of domain walls in the vicinity of an inclusion in a 5000 A specimen.

A photographic survey of the several specimens has revealed magnetic domain patterns that can be classified rather naturally into two groups, (a) relatively simple configurations closely resembling in pattern and behavior the domains observed in the surfaces of large single crystals, and (b) complex domain patterns that differ strikingly from the well-known configurations in single crystals having surfaces parallel to principal planes.

Simple Domain Patterns with 180° Walls

In certain specimens the patterns consisted of straight or slightly curving antiparallel domains aligned more or less parallel to the direction of the field applied during evaporation and indicating an induced anisotropy. All of the photographs in this report are oriented with that "longitudinal" direction as vertical on the page.

In no case where surface domains were observed was there any evidence that each domain did not extend completely through the film. The Kerr technique is perhaps unique in permitting domain observation of the underside of the film through the glass backing.

In Fig. 1, showing the top and bottom surfaces of a portion of one film specimen, an almost perfect mirror-image pattern results from turning the specimen over about a longitudinal axis. The minute change of pattern at one extremity was the result of a minor wall-shift. It is interesting to note that the diagonal surface imperfections, so evident in the photograph of the upper exposed surface, are completely missing in the smooth underside of the film.

The process of magnetization reversal in the specimens of 5000 A and 2500 A thickness proved not unlike that observed in single crystals having a single direction of easy magnetization. Upon reducing the magnetizing field to zero, small spike-shaped domains of reverse magnetization appear at either edge. With increasing reverse field these grow longer, then broader, until the specimen becomes completely magnetized when the field has reached about one oersted. Figure 2 is a series of photographs showing ten steps of this reversal process in a 2500 A film. Although the hysteresis loops for these specimens are relatively square,[8] the photocell monitor reveals that the reversal proceeds by small discontinuous steps; however, the entire process is considerably smoother and less sporadic than that shown by any single crystal specimen we have observed. This relatively unimpeded motion of the domain walls probably results from the good homogeneity of the film and the paucity of retarding nonmagnetic inclusions.

A large inclusion in the form of a 0.3-mm hole scratched in one of the 5000 A specimens strikingly reveals its "sticky" attraction for a domain wall in the magnetization sequence illustrated in Fig. 3, where the successive steps in the movement of a wall across the inclusion are clearly seen. Figure 4, depicting the same surface area at an early stage in another magnetization reversal, shows several spike domains of reversed magnetization almost at their inception. They are very

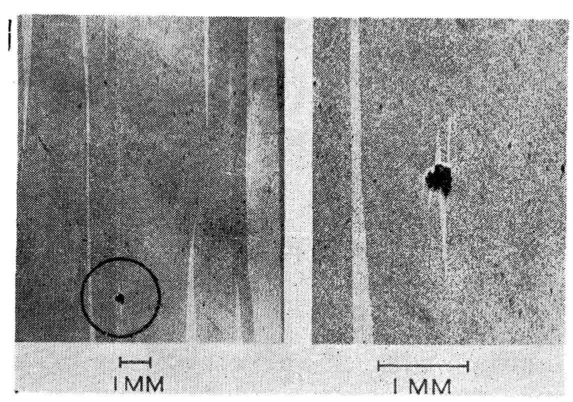

Fig. 4. A "thread" domain extending across the surface of a 5000 A film. A nearby inclusion is encircled. The photograph on the right is an enlargement of the inclusion showing spikes of reversed magnetization.

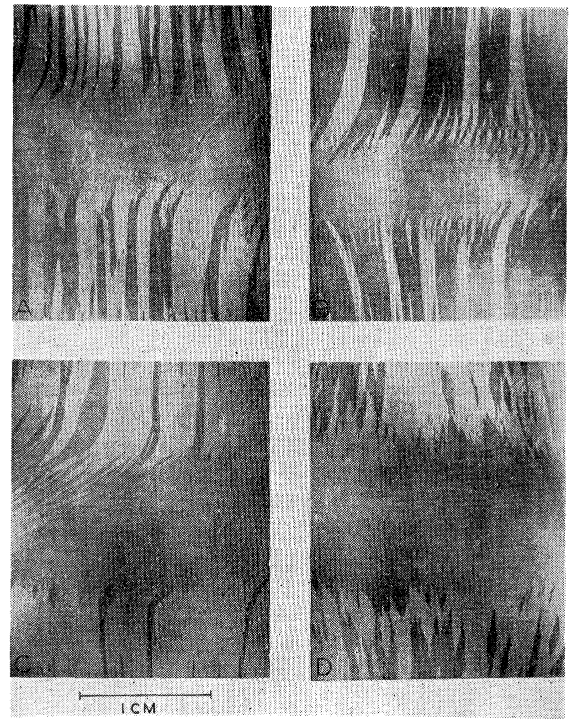

Fig. 5. Patterns in four films of different thicknesses after being demagnetized by means of a decreasing alternating field. The thicknesses are (A) 5000 A, (B) 2500 A, (C) 1500 A, (D) 500 A.

similar to those observed by Williams and Goertz[11] in a polycrystalline Perminvar ring, and utilized by Goodenough[12] in his theoretical treatment of coercive force. Figure 4 also includes a long threadlike domain extending the entire width of the specimen but less than 0.1 mm wide at its narrowest point. These "thread" domains, seldom observed in bulk specimens, are characteristic of many of the thin film patterns.

Complex Patterns

The degree of magnetization of a specimen in our setup is continually monitored by photoelectric means. With the aid of the monitor, a net zero magnetization can be attained either by demagnetizing the sample with a decreasing alternating field or through a partial magnetization reversal with the required coercive field. The domain configurations in these two cases differ noticeably, and this difference becomes an extreme one in the case of the thinnest films. Figure 5 shows the surfaces of four films of different thickness after demagnetization by an alternating field. The four photographs are quite similar in appearance, each showing antiparallel domains extending from the edges in to a center belt that has little visible structure. However, this photographic similarity proves to be largely apparent and coincidental.

[11] H. J. Williams and M. Goertz, J. Appl. Phys. **23**, 316 (1952).
[12] J. B. Goodenough, Phys. Rev. **95**, 917 (1954).

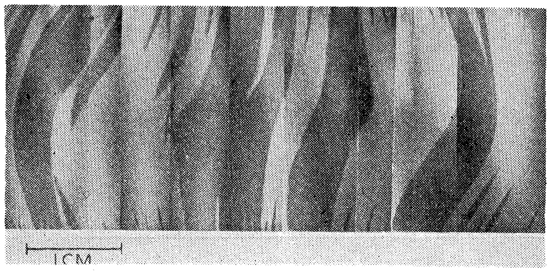

FIG. 6. A composite photograph of the entire surface of the 2500 A film of Fig. 5(B), taken under the same conditions but twelve months earlier.

Close examination of the patterns of the two thicker films [Fig. 5(A) and 5(B)] reveals that the center belt is edged with small reversal spikes and these decrease in size toward the center of the belt until they become unresolved. Their magnetization direction seems to remain parallel to the principal domains, inasmuch as photographs of these specimens after they were rotated 90° in the longitudinal Kerr arrangement showed almost no structure.[13] Moreover, the appearance of the central belt in these two specimens has apparently been a result of "aging." Photographs taken several months earlier showed no such break in the pattern, which in fact first appeared as a small break and then expanded with time. Figure 6 is a composite photograph of the entire surface of the same 2500 A film [see Fig. 5(B)] taken twelve months earlier, before we had improved the photographic field of the Kerr technique. The gradual appearance of such a central belt certainly suggests that the specimen is acquiring minute inclusions. Such inclusions might result from oxidation, or the film under tension on the substrate may have developed microscopic holes as time passes. However, the permeability of the center area, as evidenced by the amount of field required for a full Kerr-effect reversal, seems not to have changed appreciably, nor does a microscopic examination of the surface reveal any obvious changes correlated with the center belt. The value of the film's electrical resistance, recorded at the time of evaporation, also has not measurably changed. Nevertheless, it is very possible that none of these tests is sufficiently sensitive to detect the altered structure.

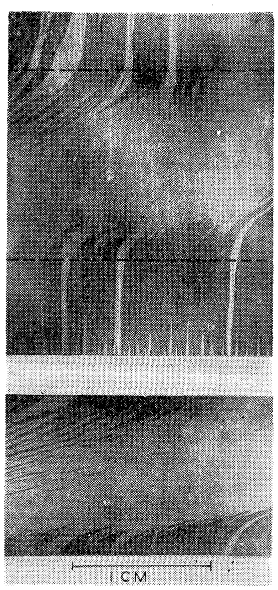

FIG. 7. Detailed structure of the central area of the 1500 A film. In the upper photograph, the longitudinal optical axis of the Kerr setup has the customary up and down direction on the page, but has a left and right orientation in the lower picture.

The center belt of the 1500 A film [Fig. 5(C)] is of a different character. In this specimen the anisotropy has the customary longitudinal direction at either edge but develops a pronounced lateral component as it winds across the center. Since the technique employed gives domain contrast proportional only to the longitudinal component, it is necessary to rotate the specimen in order to follow the structure through the central area. The result appears in Fig. 7 which clearly shows the transverse central structure characteristic of this film. Such domain behavior possibly results from an unusual stress pattern in the film.

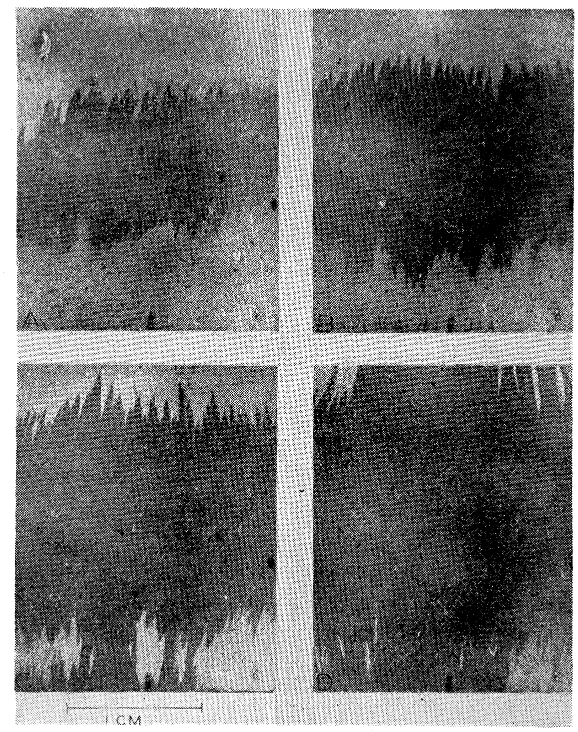

FIG. 8. Four steps in the reversal of magnetization in a specimen 500 A thick. The reversing field is directed from top toward bottom of the page and increases in magnitude from A to D.

The most interesting behavior is evidenced by the 500 A film, which is the thinnest we have studied. In good agreement with Kittel's theory this specimen prefers to exist as a single domain, and only infrequently after many attempts could it be forced into a demagnet-

[13] With the electric vector of the incident light polarized normal to the plane of incidence, the transverse Kerr effect is zero. (See reference 10.)

ized state by the alternating field technique. Figure 5(D) shows such an occurrence. Moreover, the film can be carried through a step-by-step magnetization reversal if the coercing field is controlled with extreme care, and the change of the magnetization pattern proceeds in a fashion unlike any that we have seen reported. This film, evaporated under the same field conditions as the thicker specimens, retains the same longitudinal anisotropy. However, in the reversal process, a small island of altered magnetization edged by jagged "grassy" walls first appears across the center area. With increasing longitudinal field the irregular walls move along the field direction toward the two edges of the film. Figure 8 depicts four steps in this type of reversal. The poorer quality of the photographs results from the fact that this film is semitransparent and reflections from the unmetalized surface of the glass substrate are appreciable. There is also some evidence to suggest that the dark and lighter regions in these pictures may represent something other than strictly antiparallel directions of magnetization, but only photographs taken under controlled photometric conditions and analyzed by quantitative photometric methods can accurately decide this point. The observations further showed that this type of magnetization reversal also occurs in the 1500 A specimen but not in any of the thicker ones, and thus may well be a characteristic associated with small thickness.

It should be mentioned that the 10 000 A and 20 000 A films failed to show a domain structure. It is possible that these two specimens exceed in thickness Kittel's critical value for this alloy, provided that there exists a preferred direction of magnetization normal to the film surface induced by stress or other causes. On the other hand, investigation of evaporated films thinner than 500 A becomes increasingly difficult by the reflection method. Observation of very thin specimens by transmission appears promising, and we are at present undertaking a study of the practicability of such a technique.

PHYSICAL REVIEW VOLUME 104, NUMBER 3 NOVEMBER 1, 1956

Lattice-Scattering Mobility of Holes in Germanium

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(Received April 23, 1956)

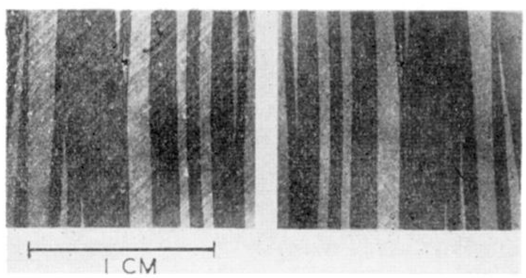
The lattice-scattering mobility of holes in germanium is calculated by using the transition probabilities for scattering by acoustical and optical phonons derived in an earlier paper, in which both the rigid- and deformable-ion models were used to determine the interaction between holes and the lattice. Coupled Boltzmann equations are considered, describing the distribution of carriers under the influence of an electric and phonon field in the two valence bands of germanium, degenerate at $k=0$. The results involve two previously described constants C_1 and C_4 which are treated as arbitrary parameters. Results are presented for several sets of these parameters and also for values of the temperature $\Theta=300°K$ and $500°K$ which might correspond to the fundamental optical frequency of the germanium lattice. The curves, $\log\mu$ *vs* $\log T$, closely resemble straight lines over the lattice-scattering range. It is possible to find values of C_1 and C_4 for both rigid- and deformable-ion models which agree well with the observed mobility if $\Theta=300°K$ but not if $\Theta=500°K$. The question as to whether these values of C_1 and C_4 are correct is not considered in this paper.

1. INTRODUCTION

THE transition probabilities for scattering of holes by acoustical and optical phonons in the two germanium valence bands degenerate at $\mathbf{k}=0$ have been calculated in an earlier paper.[1] In this treatment, the electron-phonon interaction Hamiltonian was seen to be separable into two parts: the first arises from the vibrations of the unit cell as a whole, and the second from the relative motion of the two atoms in the unit cell of the germanium lattice. The matrix elements for scattering were expressible in terms of two constants, C_1 and C_4, associated, respectively, with the two parts of the interaction Hamiltonian. The terms in C_1 describe the interaction of holes with acoustical vibrations; the terms in C_4 describe the interaction with optical and acoustical vibrations. The wave functions used to calculate the matrix elements were determined from the $\mathbf{k}\cdot\mathbf{p}$ and spin-orbit perturbations, the valence bands near $\mathbf{k}=0$ being described by spherical surfaces of constant energy and a parabolic relationship between energy and wave number, $E_s=(\hbar^2/2m_s)k^2$, where m_s is the cyclotron resonance effective mass corresponding to one of the two degenerate bands.

For the terms in C_1 the scattering was treated using both deformable and rigid-ion models. The transition probabilities were seen to have a pronounced angular

[1] H. Ehrenreich and A. W. Overhauser, Phys. Rev. **104**, 331 (1956); hereafter referred to as I.



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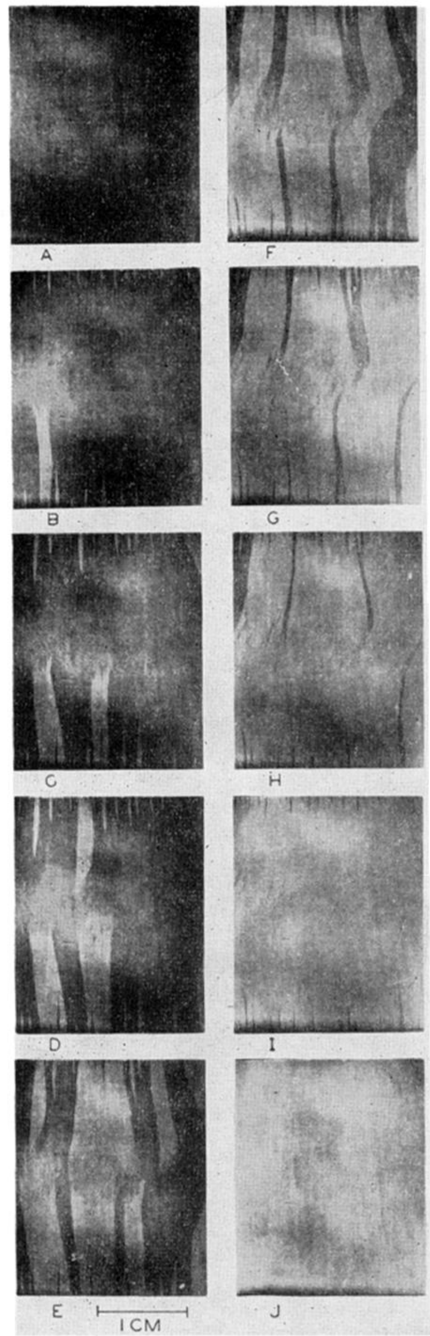
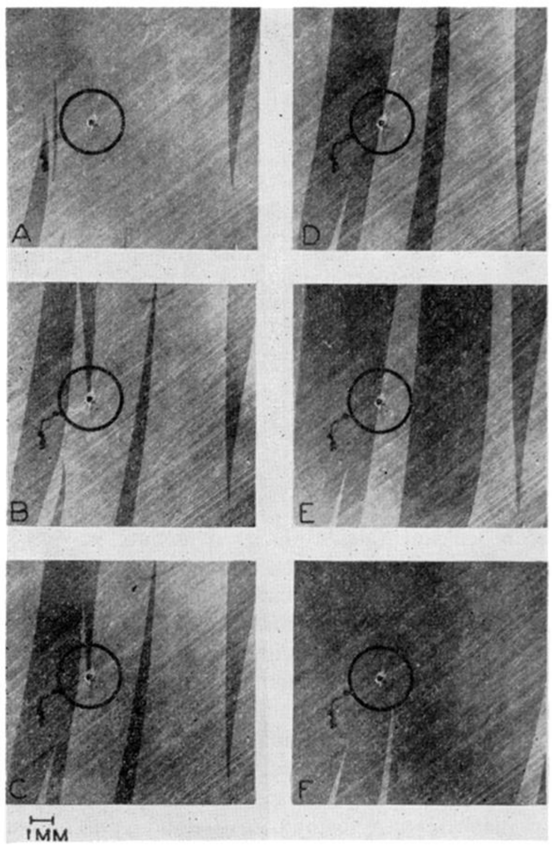


FIG. 2. Ten steps in the complete magnetization reversal of a 2500 A specimen. The light areas indicate magnetization directed toward the top of the page, the dark areas toward the bottom.



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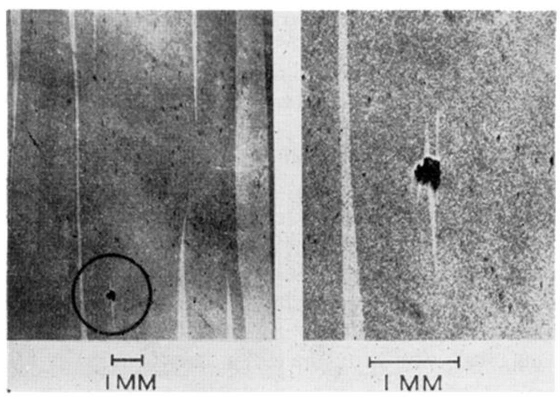

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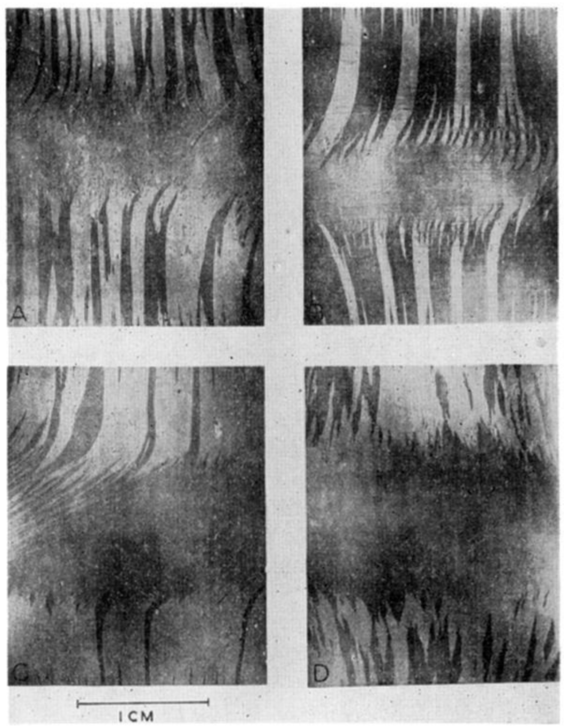

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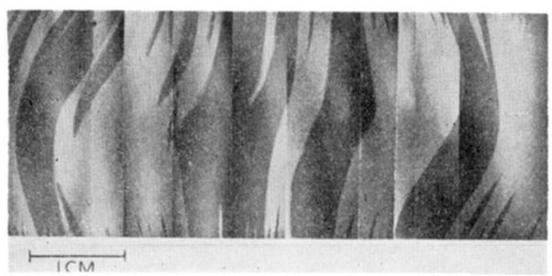
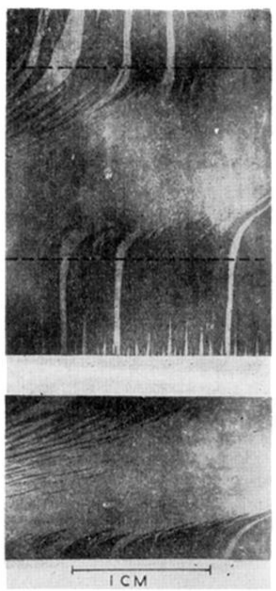


Fig. 6. A composite photograph of the entire surface of the 2500 A film of Fig. 5(B), taken under the same conditions but twelve months earlier.



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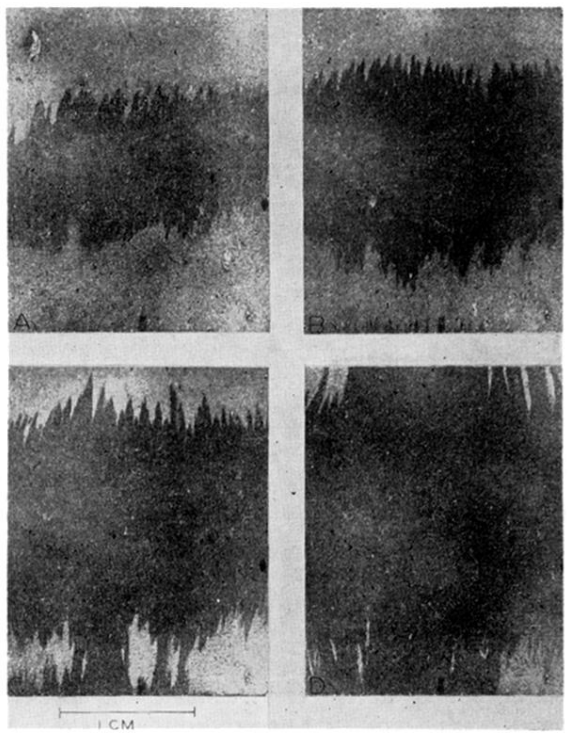

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