Magnetic Domains by the Longitudinal Kerr Effect*

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Rotation of the polarization plane of obliquely incident light reflected from a polished ferromagnetic surface is successfully employed to reveal the antiparallel domains lying in the surface of a large single crystal of silicon iron. This Kerr magneto-optic effect is the basis of two methods of domain observation which are described in detail: (1) the optical probe method in which a small, focused beam of plane polarized light scans the crystal surface before being reflected into a photomultiplier tube located behind the Nicol prism analyzer, and (2) the photographic method in which the crystal surface is broadly illuminated with polarized light and the reflected beam is photographically recorded after passage through the analyzer. The truly saturated character of the domains is demonstrated, and the directions of the domains are assigned without ambiguity. Domain wall movement and Barkhausen discontinuities are revealed in photographs taken as the crystal is subjected to a changing magnetizing field. Possible applications and limitations of the method are discussed.

INTRODUCTION

THE domain structure of single ferromagnetic crystals has been vividly demonstrated by several investigators using the powder-pattern technique, and a great deal of information has been obtained concerning the behavior of surface domains under various conditions of pressure, tension, and applied magnetic fields.[1] In that technique the colloidal particles become strongly concentrated at regions of the surface where the magnetic field gradient is large. This may occur at the Bloch walls separating domains in the case of flux closure configuration (all domains parallel to the surface), and also in cases where flux closure does not exist and domains come to an abrupt end at the crystal surface. Thus the boundaries of the surface domains are clearly outlined. The direction of magnetization in each domain is not usually determined, but Williams and his collaborators[2] have managed to infer it by means of a clever "scratch technique" combined with a study of wall movement with applied field. It has been noted that the powder-pattern method becomes difficult to apply to crystals with low anisotropy.

This investigation was undertaken with a view to establishing an alternative method for revealing domain structure that would complement the powder-pattern method. In the several cases of the Kerr magneto-optic effect, the rotation of the plane of polarization of reflected light has a magnitude and a sense that depend upon the amount and direction, respectively, of the magnetization at the surface.[3] Since domains are regions of saturated magnetization, the possibility exists that adjacent domains will be revealed in contrasting intensity when they are illuminated with plane polarized light and observed by reflection through a suitably oriented analyzer, if the problems inherent in detecting a microscopic Kerr effect can be overcome.

The macroscopic Kerr effects are of three types: (1) the polar case having the magnetization normal to the reflecting surface, (2) the longitudinal case with the magnetization vector parallel to the surface and in the plane of incidence, and (3) the transverse case where the magnetization vector in the surface is normal to the plane of incidence. In all of these, the rotation is dependent in various ways upon the angle of incidence, the direction of light vibration, and the wavelength of the light, and is accompanied by an added circular component which is generally weak and becomes negligibly small for incident light vibrations parallel or perpendicular to the plane of incidence. For saturated iron the value of the rotation for the normal polar case is about 20 minutes; for the longitudinal case it is zero at normal incidence and reaches a maximum of about 5 minutes at 60° incidence; for the transverse effect the rotation is about the same as for the longitudinal case. The available data are not too meaningful, however, since they were obtained for different samples and often without mention of the intensity of magnetization or the wavelength of the light employed.[3]

The normal polar effect with its relatively large rotation offers the best chance for successful observation of domains, and the most likely surface having the required antiparallel normal domains is a basal plane of hexagonal cobalt cut normal to the single axis of easy magnetization. Employing a special metallographic microscope, Williams, Wood, and Foster[4] succeeded in photographing the mottled domain structure typical of such a cobalt surface.

For surfaces having no normal component of magnetization, such as the prism faces of the cobalt crystal or the three principal planes of a cubic iron crystal, the longitudinal or transverse effects must be employed. By using the longitudinal Kerr effect at 60° incidence, we were able to detect photoelectrically and photographically the several antiparallel domains

* Supported by the U. S. Office of Naval Research.
[1] R. M. Bozorth, *Ferromagnetism* (D. Van Nostrand Company, Inc., New York, 1951), pp. 532–538.
[2] Williams, Bozorth, and Shockley, Phys. Rev. **75**, 155 (1949).
[3] *International Critical Tables* (McGraw-Hill Book Company, Inc., New York, 1929), first edition, Vol. VI, p. 435.
[4] Williams, Foster, and Wood, Phys. Rev. **82**, 119 (1951).

in a (100) surface of a demagnetized single crystal of silicon iron.[5]

EXPERIMENTAL PROCEDURE

The specimen, a single crystal of 4 percent silicon iron, grown and cut by Mr. J. G. Walker of the Bell Telephone Laboratories, was used for all of the work reported in this paper. It is primarily a rectangular slab, $1.7\times1.4\times0.3$ cm, with edges parallel to the cubic axes, the two large surfaces being (100) planes. However, certain corners and edges had been cut obliquely to reveal such planes as (110), (111), etc., thus leaving the two (100) surfaces, on which most of our observations were made, with somewhat different contours. The crystal was electropolished until the surfaces were relatively free of working strains as indicated by a disappearance of the maze pattern. The powder patterns then showed the (100) surface srtucture to consist of a number of domains always parallel to the long [010] edge when the specimen was demagnetized.

In order to control the magnetization, the crystal was simply laid flat on one surface of a closed magnetic circuit, where the stray field was sufficient to magnetize the crystal to saturation when the magnetizing current reached about 100 ma. ($H\approx5$ oersted.)

The Optical Probe Method

Success in observing the domain structure was first achieved by scanning across the (100) face in the [001] direction with a small polarized light-probe and recording photoelectrically the intensity of the reflected light after passage through a nearly crossed analyzer. Adjacent antiparallel domains, rotating the polarization plane slightly to right or left, respectively, cause the intensity transmitted through the analyzer to increase or decrease accordingly. The setup is shown schematically in Fig. 1, where a 60° incidence was chosen to give the maximum Kerr rotation. The source is an AH4 General Electric mercury arc whose operation on 60-cycle ac permits simple amplification of the modulated signal. The short-focus probe lens L_1 forms a diminished image of the small source-aperture upon the crystal surface after which the light is rendered parallel by a second lens L_2. Both the polarizer and the analyzer are good quality Nicol prisms of 17-mm aperture. The signal, received by a 1P21 photomultiplier tube, is suitably amplified and recorded on a recording potentiometer. In practice we have found that satisfactory results can be obtained with the incident electric vector either parallel or perpendicular to the plane of incidence; however, ambiguity with the transverse Kerr effect is avoided by polarizing the electric vector perpendicular to the incidence plane, for which direction the transverse effect is zero.

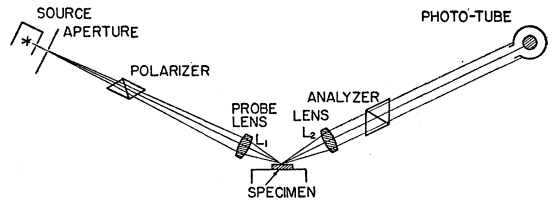

FIG. 1. Experimental arrangement for observing domains by scanning with a polarized optical probe.

By magnetizing the crystal to saturation first in one direction and then the reverse, the intensity of the light reaching the photocell can be made to differ by as much as 20 percent when the analyzer is set at approximately 1° from extinction and the very critical optical system is in perfect alignment. A signal (Kerr reversal)-to-noise ratio of about 100 has been achieved, allowing detection of polarization rotations as small as 10 seconds.

To permit scanning, the motion of the magnet and its specimen is controlled by a micrometer screw, and this is coupled through matched Selsyns to the chart movement of the recording potentiometer. Such a scan across the demagnetized crystal does not give directly the "square-wave" curve typical of antiparallel domain configuration for the same reason that a scan across the saturated specimen does not yield a constant signal. Plane polarized light, reflected obliquely at a metal surface and examined through a nearly crossed analyzer, is an arrangement utilized by metallographers to accentuate every surface irregularity. Thus in this case, the minute pits, scratches, and imperfections cause the curve of the saturation scan to fluctuate strongly, but the *difference* between the magnetically saturated and the demagnetized scans reveals the domains as expected. Figure 2 shows a typical corrected curve.

The Photographic Method

The photographic setup, which is quickly obtained by changing a few components in the optical probe arrangement, is illustrated schematically in Fig. 3. A condensing lens is introduced and the probe lens is

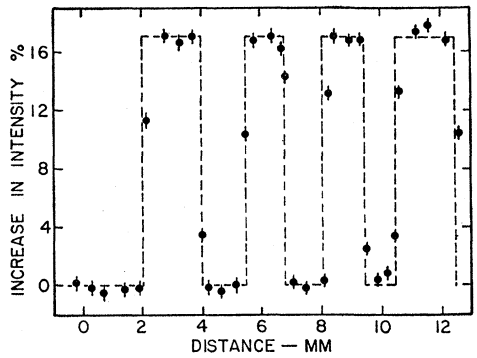

FIG. 2. Plot of a scan across the (100) surface of the crystal with a 0.5-mm probe. The ordinate is percentage increase of the light transmitted through the analyzer as the demagnetized crystal is magnetized to saturation.

[5] C. A. Fowler, Jr., and E. M. Fryer, Phys. Rev. **86**, 426 (1952).

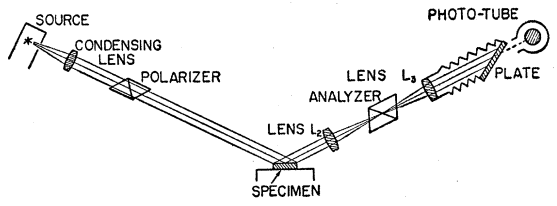

FIG. 3. Experimental arrangement used for photographing the domains of the silicon iron crystal.

removed so that the incident beam is essentially parallel. The lens L_2 and a second positive lens L_3, separated by essentially the sum of their focal lengths, constitute a compound camera objective which is focused on the crystal surface. Inasmuch as the object surface is oblique to the camera axis, the image plane is tilted at an angle that depends upon the orientation of the object plane and upon the linear magnification. For the unit magnification we have employed with the silicon iron specimen, the film holder is tilted at the same angle as the crystal surface. The analyzer is located at the point where the beam is most constricted, assuring maximum passage of light. The photocell, employed in this case as a monitor for checking the conditions for photographing domains, is shown in position behind the camera.

With this apparatus and using Eastman Contrast Process Ortho film, we obtained photographs of the domains in the silicon iron specimen with a 2-minute exposure when the illumination was unfiltered light from the mercury arc.[5] Our earliest photographs were noticeably fuzzy and unsharp at the domain edges. This can be attributed to the large local variations of intensity, mentioned in the previous section, which often exceed the contrast between adjacent domains. We have managed to circumvent this difficulty by a technique that is equivalent to correcting the scan curve. A film positive is made from a negative of the crystal magnetized to saturation. This "reversed flat" is carefully superposed on the domain photograph negative and a print made from the combined pair, thus tending to cancel the undesirable local fluctuations while leaving the Kerr domain variations. A detailed description of this "noise-reduction" technique and the limit to which it can be pushed when sufficient care is taken in balancing exposures will be published elsewhere.[6]

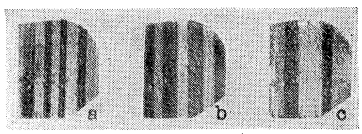

FIG. 4. Three different domain configurations of the demagnetized specimen. The crystal was demagnetized in each case by a 60-cycle alternating field of decreasing amplitude, but the duration of the demagnetizing process decreased from (a) to (b) to (c).

[6] Fowler and Fryer, J. Opt. Soc. Am. 44, 256 (1954).

RESULTS

It should be remarked at the outset that it is possible visually to see the domains and watch them disappear as the specimen is magnetized to saturation, provided that the observer adapts his eyes to the dark. However, because of the low over-all intensity, visual observation is very unreliable.

Direction and Saturation of Domains

Photographs, supplemented by information from the photocell monitor, allow an unambiguous interpretation of a surface domain configuration and its changes. For example, the magnetization vector of a longitudinally oriented domain clearly has a direction that depends upon whether the domain in the photograph is light or dark. That the magnetization in a domain is truly saturated, as theoretically pictured, is demonstrated since it is observed that the optical probe when

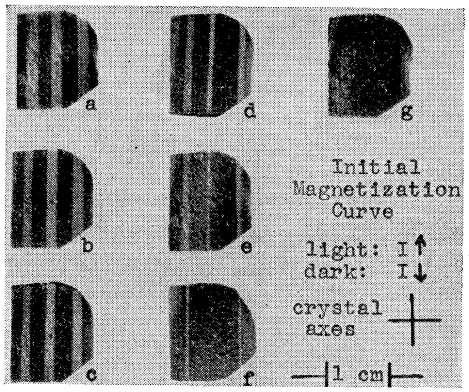

FIG. 5. Photographs of the domain behavior in the (100) surface as the applied field is increased from zero to a value sufficient to produce saturation. The field is zero in (a), whereas increasing values of H (toward the bottom of the page) are applied in (b) to (g).

located anywhere within a favorably oriented domain of the demagnetized specimen gives no change in the signal when a parallel saturation field is applied.

Demagnetized Configurations

Magnetization and subsequent demagnetization of the sample generally result in similar but not identical domain patterns. Figure 4 includes three different configurations in the top (100) surface after the crystal has been demagnetized each time by a 60 cycle alternating field of decreasing amplitude. In every case the number of domains and the uniformity of their widths were correlated directly with the slowness and uniformity of the decrease of the field. For example, Fig. 4(a) was obtained by controlling the uniform rate of fall of the demagnetizing current with an electrolytic resistor, requiring 5 minutes for the 200 ma to reduce to zero, while 4(b) and 4(c) were demagnetized with increasing speed.

Initial Magnetization Curve

A series of photographs, taken as the crystal, originally demagnetized, was subjected to a gradually increasing field, is shown in Fig. 5. The monitor indicated that the magnetization process consists of several sudden discrete changes in the magnetization (Barkhausen jumps) separated by periods of stability. Each of the photographs shown was taken immediately following such a jump. Close examination of the pictures reveals the typical sporadic movement of the domain walls as the magnetization of the crystal increases in this discontinuous manner.

Hysteresis

Figure 6 shows photographs taken as the specimen was carried through half of a hysteresis loop, that is, from saturation in one direction (a) to saturation in the opposite direction (j). After applying a saturation field, no change occurred in the pattern as the field was reduced to zero until it reached a value of about 3 oersteds in the opposite direction, at which point a dagger-like domain appeared (b) and continued to grow with increasing field until it covered the entire crystal surface in the saturated condition (j). All such series of photographs that we have taken have shown similar but not identical behavior. Both the monitor response and the photographs themselves again indicate the sporadic, Barkhausen wall motion.

Domain Closure

The configuration of the domains inside a crystal and their behavior under changing conditions of field, stress, or temperature can be studied only in terms of the surface domains. We have made a start on this problem by examining the top and bottom (100) faces of the crystal for several cases of zero or near zero magnetization (see Fig. 7). None of the pictures taken of this specimen shows any evidence of 90° closure domains in the [001] direction, which suggests an unusual reluctance to magnetization in that direction. A direct check of this peculiar anisotropy by rotating the crystal 90° and applying a longitudinal magnetizing field in the [001] direction showed no Kerr rotation for fields as high as 15 oersteds. Quite apparently an anisotropy leading to a strong preference for magnetization in the [010] direction was acquired during the process of growing this crystal or its subsequent annealing. The pairs of top and bottom photographs of Fig. 7 were obtained by turning the crystal bottom side up about a transverse axis. The close match of the stripes, dark with dark and light with light, strongly suggests that flux-closure paths for the unmagnetized state run along the top face and back along the bottom. Unfortunately those edge faces of the specimen that had not been cut oblique to the two (100) surfaces were rough or scarred to a point that precluded satisfactory photographs to show closure domains along the [100] direction at the ends. However, one photograph of one of the side faces, although of very poor quality, indicated that only two layers of domains are involved in the demagnetized specimen.

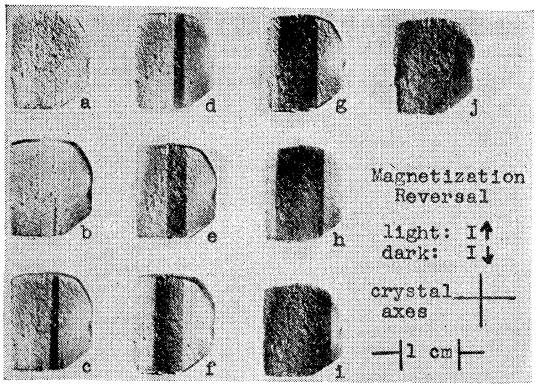

FIG. 6. Photographs of the domain behavior in the (100) surface as a strong external field, toward the top of the page in (a), is reduced to zero and then increased to saturation value in the opposite direction, (j).

A much more interesting problem is the behavior of the domains throughout the crystal as it is taken through a magnetization curve or a hysteresis cycle. Here our observations have been impeded by the unsatisfactory method of applying the magnetizing field, for with the magnetizing setup described above, it is impossible to examine more than one face without changing the field on the specimen. We have now designed a completely new magnet which permits observation of every side of the specimen without any change of the magnetizing field, and we are proceeding with the study of a crystal cut into a true rectangular slab with all edges along ⟨100⟩ directions and all faces satisfactorily polished.

CONCLUSION

The Kerr magneto-optic method is one which can complement the powder pattern method in many problems of domain investigation. In order to establish

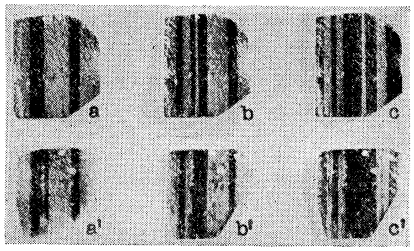

FIG. 7. Corresponding domain configurations in the top and bottom (100) surfaces of the crystal. The magnetization of the dark domains is toward the bottom of the page, and the crystal was turned from the top side (a,b,c) to the bottom (a',b',c') about a horizontal, transverse axis. The close match of dark with dark and light with light in a,a' and approximate matches in b,b' and c,c' suggest flux-closure paths.

the longitudinal effect technique, the authors have purposely restricted their investigation to the silicon iron case, so well known through the beautiful work of the ferromagnetism group at the Bell Telephone Laboratories.[2,7,8]

Certain advantageous features of the technique indicate the nature of the problems to which it is peculiarly suited.

1. The entire surface of a domain has a single characteristic intensity and is revealed as a whole rather than being merely outlined; furthermore the relative intensities of the domains indicate without ambiguity the absolute directions of their magnetization.

2. The magnitude of the magnetization at any point on a specimen is subject to rapid quantitative measurement through the optical probe technique.

3. Although a properly polished, strain-free surface is required just as with the powder technique, the need for repolishing between observations is of course completely eliminated.

4. The method is not affected by either high or low temperatures as long as the surface is preserved, so that the study of domain behavior at interesting transition points becomes a distinct possibility.

5. Since the method is by its very nature a dynamic one, certain problems concerning domain dynamics can be undertaken.

There is some question as to how suitable the method will be for studying the truly microscopic domains of polycrystalline samples. The answer probably lies in the degree to which surface imperfections in the image can be eliminated by the photographic "noise-reduction" technique.

We wish to thank H. J. Williams and R. M. Bozorth of the Bell Telephone Laboratories for the loan of the silicon iron crystal and for valuable discussions concerning the investigation. We are also indebted to Dr. Burton Henke of Pomona College for several helpful suggestions.

[7] H. J. Williams and W. Shockley, Phys. Rev. **75**, 178 (1949).
[8] Williams, Shockley, and Kittel, Phys. Rev. **80**, 1090 (1950).

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The Electrical Conductance of Pressed Powders, in Particular of Zinc Oxide*

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The electrical conductance of a pressed semiconducting material in powder form, representing a multiboundary semiconductor, is investigated. Experiments are described in which the dc conductance of the powder pressed between parallel plates in an evacuated chamber is determined for different pressures and temperatures. A model based on the change of the energy gaps with pressure is developed which accounts for the phenomena observed. Transient changes of conductance with time are observed for which only tentative explanations are suggested. Most of the experimental work refers to zinc oxide.

I. INTRODUCTION

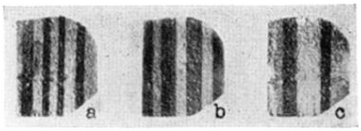
EXTENSIVE work has been done on the electrical properties of powdered and sintered materials. Recently Hausner[1] examined the properties of sintered powders containing some semiconducting constituent. Miller[2] and Hahn[3] made a detailed investigation of sintered zinc oxide powder, whereas Davis[4] examined powders of semiconductive materials, in particular aluminum oxide and zinc oxide pressed between parallel plates.

The work on sintered materials, particularly the work of Miller and his associates, showed the effect of internal grain boundaries; sintering imposes, however, certain conditions on the material resulting from the heating process which, according to the nature and pressure of the gas in which sintering takes place, produces a chemical modification of the grain surface.

The method used by Davis of compressing the powder avoids these chemical changes. Some of his results, however, are not readily accounted for in terms of a general theory. The present investigation was undertaken with the purpose of examining more closely the conditions which arise when pressing a semiconducting powder.

Kantorowicz[5] has investigated the change of electrical conductance of pressed metal powders and has shown that the conductance or reciprocal of resistance

* This work is the subject of the doctoral dissertation (Northwestern University, 1951) of Colman Goldberg and is there presented in greater detail.
† 1950–1951 Milwaukee Gas Specialty Company Fellow; now with Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania.
[1] H. H. Hausner, Electronics **21**(1), 138 (1948).
[2] P. H. Miller, Phys. Rev. **60**, 890 (1941).
[3] E. E. Hahn, J. Appl. Phys. **22**, 855 (1951).
[4] D. H. Davis, doctoral dissertation (Northwestern University, Evanston, 1951); J. C. M. Brentano and D. H. Davis, Phys. Rev. **79**, 216 (1950).
[5] O. Kantorowicz, Metallwirtschaft **10**, 45 (1931); Ann. Physik **12**, 1 1933.



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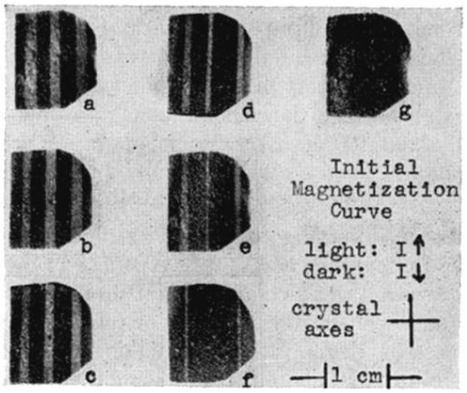

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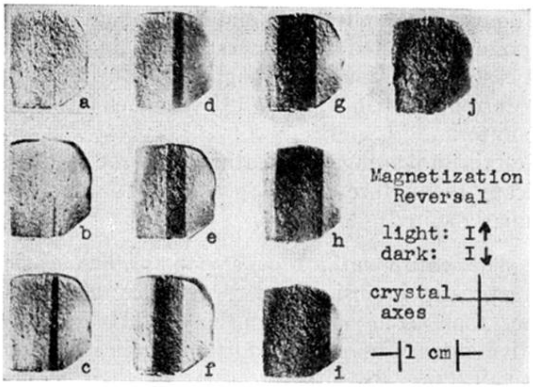
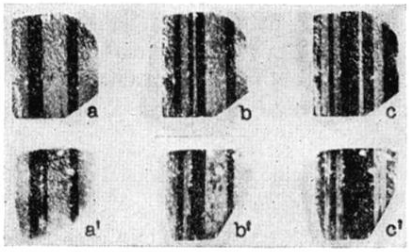


FIG. 6. Photographs of the domain behavior in the (100) surface as a strong external field, toward the top of the page in (a), is reduced to zero and then increased to saturation value in the opposite direction, (j).



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