nation (one or the other), as can be readily heard or seen.

The proposed variant of Bothe's experiment demonstrates simply and convincingly that radiation produced upon interaction with matter becomes manifest in the form of a flux of particles (photons).

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# *STUDY OF THE PROPERTIES OF FERROMAGNETIC FILMS IN A SPECIAL PHYSICS LABORATORY COURSE*

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THE program of a general physics course for physics-mathematics departments calls for the students to become familiar with the physical properties of ferromagnets and with magnetooptical phenomena. Until recently, laboratory experiments aimed at the study of the domain structure of ferromagnets and magnetooptic phenomena was hindered by the complexity of the experimental procedure. The recent rapid development of a new branch of ferromagnetism —the physics of thin ferromagnetic films—has made it possible to study more deeply and more pictorially properties of ferromagnets on the college level.

We have organized at the Irkutsk Pedagogical Institute laboratory experiments aimed at studying the properties of ferromagnets, using permalloy and iron films obtained by thermal evaporation in vacuum. The purpose of the experiment is to provide the students with practical familiarity with magnetic anisotropy, domain structure, reversal of magnetization, magnetic hysteresis [1], and magnetooptic phenomena [2].

The equipment used to measure the magnetic characteristics of the ferromagnetic films differs from hitherto desembed apparatus in that it is compact, made up of instruments which are regularly produced by our industry, and can be built around any polarization or biological microscope.

The research method is based on the use of magnetooptic Faraday and Kerr effects, which consist in the following [3].

Magnetooptic Faraday effect. When plane-polarized light passes through a magnetized medium, the plane of polarization is rotated. The angle of rotation of the plane of polarization in ferromagnets is $\varphi = kIl$, where k is constant, I is the magnetization of the medium, and $l$ is the thickness of the layer. The direction of rotation of the plane of polarization depends on the direction of the magnetization vector.

Magnetooptic Kerr effect. When plane-polarized light is reflected from a magnetized mirror, the plane of polarization is likewise rotated. The rotation angle depends on the magnetization of the mirror and on the relative locations of the ferromagnetic surface, the plane of incidence of light, and the magnetization vector. The angle of rotation is maximal if the magnetization vector is parallel both to the surface of the mirror and to the plane of incidence of the light (the case of the so called meridional Kerr effect). The most effective angle of incidence of the beam, at which the maximum rotation of the plane of polarization takes place, depends on the material of the mirror. For an iron mirror it amounts to approximately 60°.

The direction of rotation of the plane of polarization of the light depends in both cases on the direction of the magnetization vector. This singularity of the effects makes it possible to use them to reveal the domain structure of ferromanets. If a ferromagnetic sample, say a thin ferromagnetic film, is broken up into domains—regions with opposite magnetization directions—then the plane of polarization of light reflected (or transmitted) from neighboring domains will be rotated in opposite directions. When an analyzer is used to extinguish the light from the domains having the same magnetization direction, it becomes possible to observe visually the domain structure in the form of dark and light regions.

These methods make it possible to observe reversal of magnetization under dynamic conditions, and to obtain oscillograms of these processes if a photomultiplier is used.

## CONSTRUCTION OF SETUP

A schematic diagram of the setup for observing the domain structure and for obtaining oscillograms of

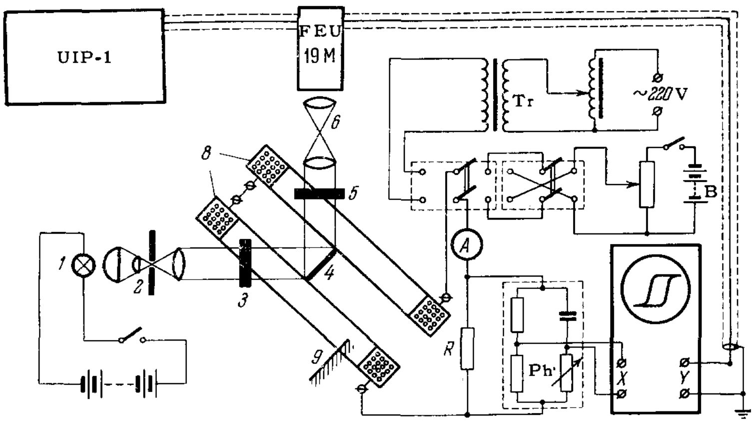


FIG. 1. Schematic diagram of setup.

the hysteresis loops of thin ferromagnetic films is shown in Fig. 1. A general view of the installation is shown in Fig. 2. When the merdional Kerr effect is used, light from a motion-picture projection lamp 1, fed from a storage battery, is transformed into a parallel beam by means of a optical system, passes through a polarizer 3, is reflected from a ferromagnetic film 4, and enters the objective of microscope 6.

The analyzer 5 is best located ahead of the objective, so as to eliminate the influence of any internal stresses in the objective on the image of the domain structure. For an exact orientation of the film, the latter is mounted on a Fedorov stage 7 (Fig. 2), on which are placed the magnetization-reversal coils 8, fed with alternating current from transformer Tr or with direct current from battery B. The coils produce a field parallel to the plane of the film and to the plane of incidence of the light. When the Faraday effect is used, the illuminator together with the collimator are lowered in such a way that the beam strikes the mirror 9. The light reflected from the mirror passes through the film and the analyzer and enters the objective of the microscope. In this case the polarizer is located between the mirror and the film.

To obtain oscillograms of the hysteresis loops, a photomultiplier (FEU-19M) is attached to the microscope tube. The photomultiplier is placed in an iron screen 10 (see Fig. 2) to prevent induction from external magnetic fields, and is fed from a stabilized-voltage source UIP-1, the high-voltage leads of which are connected in series in such a way that the photomultiplier receives an adjustable voltage up to 1,000 V. The signal from the photomultiplier is fed to the vertical input of an oscilloscope of the S1-1 type. The signal to the horizontal input is from the non-inductive resistor R connected in series with the magnetization-reversing coils. To eliminate the phase shift, a phase shifter Ph is used. The magnetization of the film is reversed during the oscillography of the hysteresis loops by means of 50 Hz alternating current.

## OPERATING PROCEDURE

The films are usually magnetically anisotropic. Owing to the small thickness of the film, the magnetization vector lies as a rule in the film plane. In addition, there is in the plane of the film an easy-magnetization axis which coincides with the direction of the magnetic field applied during the process of film production. The straight line lying in the plane of the film and perpendicular to the easy-magnetization axis is called the difficult-magnetization axis. To observe the domain structure, the film is oriented

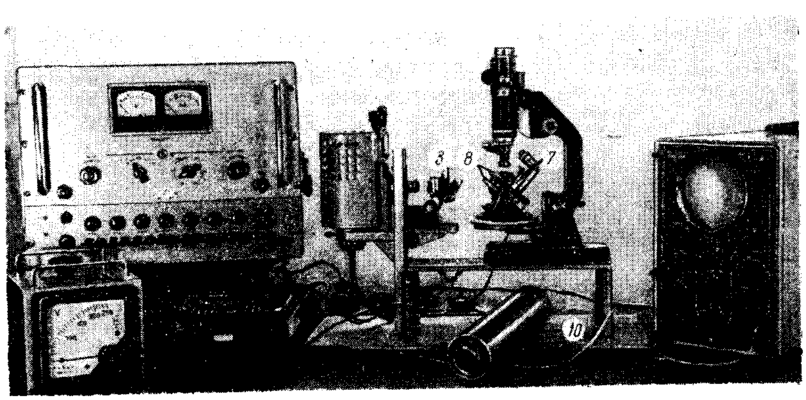


FIG. 2. Overall view of the setup.

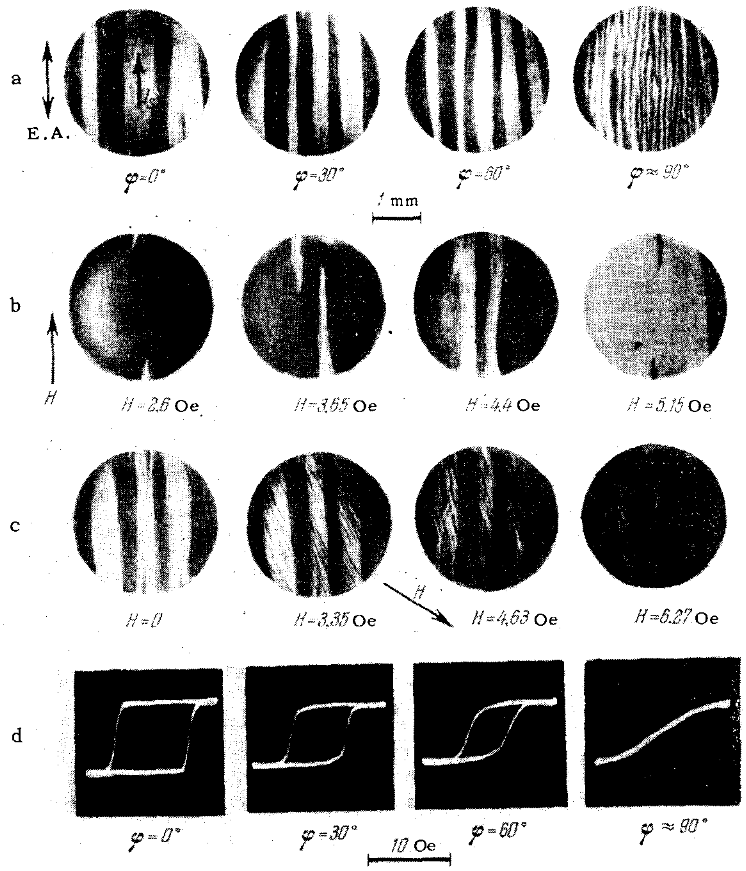


FIG. 3. Domain structure and hysteresis loops of a permalloy film 1200 Å thick, obtained with the aid of the Kerr effect.

in such a way that the easy-magnetization axis is parallel to the plane of incidence of the light. The film is broken up into domains by demagnetizing it with an alternating magnetic field whose amplitude decreases gradually to zero. The analyzer and the polarizer are then set for maximum darkening of the field of view, and the analyzer is rotated to a position in which the maximum contrast between the neighboring domains is observed. The hysteresis loop oscillograms are obtained at the same position of the polarizer and analyzer as used in the observation of the domain structure. Sometimes a phase shift in the horizontal direction is possible. This is manifest in the fact that when the current in the coils is increased, the increase in the "whiskers" of the hysteresis loop is accompanied by a change in its width. The phase shifter should be adjusted in such a way that the width of the loop remains constant when the current in the coils is varied.

The presence of uniaxial anisotropy in the plane of the film leads to differences in the character of the process of magnetization reversal at different angles to the easy-magnetization axis (E.A. in Fig. 3a). By way of an example, Fig. 3a shows the domain structures produced in a film demagnetized at different angles to the easy axis. With increasing angle, the domain structure assumes the form of narrower strips.

Figure 3b shows the reversal of magnetization of the film along the easy axis. When a magnetic field of opposite direction is applied to a previously magnetized film, wedge-like domains are produced on the edges of the films. The direction of the magnetization vectors in these domains coincide with the direction of the magnetization-reversing field. An increase in the magnetic field is accompanied by an increase in the size of the produced domains by displacement of the boundaries. The film magnetization is completely reversed in a field exceeding 5.15 Oe.

Figure 3c shows the magnetization of a film from a demagnetized state at an angle to the easy axis. In this case, besides the boundary-displacement processes, there occur also magnetization-rotation processes. When observed visually, this is revealed by the change in the contrast between the neighboring domains.

The presence of magnetic anisotropy in the films is well demonstrated by the form of the hyteresis loops (Fig. 3d), obtained when the film magnetization is reversed at different angles to the easy axis. With increasing angle, the rectangularity of the loops decreases, and their slope increases. The hysteresis loop obtained at 90° to the easy axis has practically no hysteresis.

Hysteresis loops obtained in the easy and difficult directions make it possible to determine such magnetic characteristics as the coercive force $H_c$ and the anisotropy field $H_k$. For example, the coercive force can be determined from the hysteresis loop in the easy direction by using the formula $H_c = Ci\sqrt{2d}/L$, where C is the constant of the magnetization-reversing coils, i the effective value of the current in the coils, L the magnitude of speed, and d the width of the hysteresis loop.

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