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Abstract

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OBSERVATION OF THE DOMAIN STRUCTURE OF A FERROMAGNET BY MEANS OF PHOTOELECTRONS

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This paper describes an electron-optical method for displaying the domain structure of a ferromagnet by means of photoelectrons focused by magnetic optics. The advantage of this method is that it makes it possible to obtain a fully qualitative image, with high contrast, of the magnetic microfields of polycrystalline and single-crystal surfaces of ferromagnetic crystals. The present work is a further development of previous experiments carried out in our laboratory ($^{1-4}$) on the electron-optical visualization of magnetic microfields.

The main idea both of our preceding works ($^{1-4}$) and of the present investigation was the notion that it is possible to see domain fields directly if an electron beam is made to interact with a cathode electron lens, into the cathode plane of which the magnetic fields under study—the magnetic "microlenses" —have been introduced. These "microlenses" create chromatic and spherical aberration of the immersion optics, owing to which the "microlenses" are visualized on a fluorescent screen.

Thus, in our method the "defects" of the immersion optics caused by magnetic microfields at the cathode serve precisely for their display. We note two properties of the method we are developing: 1) it is possible to display the entire set of domains and their boundaries emerging at a flat surface; 2) it is possible to control the contrast and resolution of the electron-optical picture by changing the parameters characterizing the immersion optics and the properties of the electron beam.

A comparison with the electron-optical methods of visualization of magnetic microfields proposed by other authors was made by us earlier (^{1,2,3}).

The requirements imposed on an electron-optical system based on the use of a cathode lens reduce to the following: 1) high sensitivity to the magnetic

Fig. 2. 60×

Figure 1: Fig. 2. 60×

Fig. 3. 60×

Figure 2: Fig. 3. 60×

fields being visualized, providing the necessary contrast, and 2) high resolution with respect to the magnetic microstructure. The method based on the use of photoelectrons satisfies both these requirements better than the two other methods previously proposed by us (^{2,3}).

A simple setup was used for qualitative electron-optical visualization of the domain structure and other microfields of cobalt—a glass model of a photoelectron emission microscope with continuous pumping (Fig. 1). The source of photoelectrons in the microscope was an antimony-cesium cathode, the substrate of which was the ferromagnet under investigation—

Fig. 2. 60×

Fig. 3. 60×

ferromagnetic specimen. The locally distributed magnetic field of the substrate penetrates through the semiconductor photocathode and forms a picture of the magnetic field on the fluorescent screen. The focusing system is a short-focus shielded magnetic lens. The illumination source is an electric incandescent lamp. In the presence of a sufficiently thin sensitizing coating of the ferromagnet, a sufficiently deep modulation of the image by the local microfields of the domains is obtained. The voltage applied to the cathode-anode system (cathode—the specimen under investigation) was 6–8 kV. The magnetic field of the lens, both focusing and magnetizing the specimen, was 400–600 Oe. The vacuum in which the image was formed was of the order of $5 \cdot 10^{-7}$ mm Hg; it was produced by a rotary fore-vacuum pump and a -100 oil-vapor diffusion pump. Liquid nitrogen was used to freeze out oil vapors.

With the aid of this setup we obtained images of domains on the hexagonal surface of a cobalt single crystal, and also on the polished surface of polycrystalline cobalt. Figure 2a shows an image of the domain structure. The magnetic field of the focusing and magnetizing lens was applied perpendicular to the hexagonal surface of the cobalt single crystal (60×). Figure 2b gives a photoelectron image of the same region of the cobalt single crystal, but the direction of the magnetic field has been changed to the directly opposite one (60×). As can be seen from consideration of these two photographs (see the regions marked by arrows), when the sign of the direction of the magnetizing field is reversed, the sign of the contrast of the electron-optical image also changes. Figure 2c gives an image of domain figures of the same hexagonal surface of the cobalt single crystal, obtained by the powder-figure method ⁽⁵⁾.

Fig. 1. Device of the photoelectron microscope

Figure 3: Fig. 1. Device of the photoelectron microscope

Fig. 1. Device of the photoelectron microscope

Figure 3a shows a photograph of local magnetic microfields obtained in a photoelectron microscope on the polished surface of polycrystalline cobalt. The image obtained with the aid of ferromagnetic powder on polycrystalline cobalt is shown in Fig. 3b.

Thus, we see that with the aid of photoelectron emission it is possible to obtain electron-optical images of local magnetic microfields distributed in the plane of the object, which in their quality are comparable with powder figures and are considerably better than those obtained by us earlier (2,3).

Let us compare the state and prospects of two previously proposed methods for visualizing magnetic microfields (2,3) with the method of the present work.

The images obtained with the aid of a secondary-emission microscope (2) agree rather well with the picture obtained by the powder method, but in resolution of details they are inferior to the latter. With the aid of the secondary-emission method it has not yet been possible to obtain a sufficiently contrasted electron-optical image of the fine structure of domain figures. In our opinion, the reason for this is the use of secondary electrons having relatively large initial velocities (of the order of 5-10 eV), which leads to geometrical and chromatic aberrations characteristic-

to an immersion objective, the more significant the higher the initial velocities of the electrons [6]. In addition, alignment errors lead to first-order aberrations. These circumstances determined the relatively weak contrast and the not entirely sufficient resolution of the electron-optical image. An important feature of the secondary-emission method is that the surface does not need to be sensitized, a sufficiently large emission can be produced, and the aberrations indicated above can subsequently be significantly reduced.

The application of an electron mirror [3] to the problem of visualizing magnetic microfields made it possible at once to obtain images with a contrast considerably exceeding the effect achieved with the aid of secondary electrons, and with a relatively large useful magnification of 200×. The use in this case of electrons that are stopped at the surface of the ferromagnetic specimen under investigation considerably increased both the resolving power of the optical system and the contrast of the image. But the image obtained with the aid of an electron mirror has the feature that reflection of the electrons occurs from a concave surface that does not coincide with the plane of the specimen, which leads to distortion of the picture. Distortion of the electron-optical image complicates interpretation of the image obtained and thereby, to a certain extent, limits the possibilities of applying the mirror method. The mechanism of formation of the electron image of magnetic inhomogeneities in an electron mirror is considered in paper [3].

The contrast of the electron-optical image obtained with photoelectrons by the method described above is not inferior to that achieved with the aid of an electron mirror. The image, as comparison with powder figures shows, is free of distortions. In this case the significant contrast and good resolution are due to a number of circumstances: 1) in the photoeffect slow electrons are used, with velocities approximately an order of magnitude smaller than in the case of imaging with secondary electrons [2]; 2) oblique electron beams are absent. The contrast of the picture must depend both on the electron trajectories "external" with respect to the specimen and on the work function of the photoelectrons, modulated by the magnetic field [7].

The effectiveness of the twisting, near the cathode surface, of the electron trajectories emerging into the vacuum is known to determine the contrast of the picture [2,4]. At the same time, theory [8] leads to a dependence of the electron work function on H, which has recently been studied at different temperatures and for field emission [9].

A photocathode imaging the magnetic microstructure must be sufficiently effective: 1) in terms of the magnitude of the electron emission, ensuring the necessary brightness of the screen; 2) with respect to the uniformity of the emission; and 3) small in thickness, so that the magnetic field of the ferromagnetic substrate penetrates appreciably into the vacuum.

The uniformity of photoemission is associated with the roughness of the cathode. As recent observations have shown [10], the roughness of an antimony-cesium cathode can be made sufficiently small, not impairing the uniformity necessary for imaging the magnetic microstructure.

Electron-optical methods of visualizing magnetic fields [1–4] give brighter and more contrasty images than the magneto-optical method using the Kerr effect, where visual observation is difficult [11] and photography is carried out with a considerable exposure time.

Significant successes have recently been achieved in the study of domains of ferromagnets as a result of the application of the powder method [12]. At the same time, it should be remembered that the inertia of the powder particles and their dimensions when observed with an optical microscope impose

a definite limit to further penetration into the microworld of domain structures by means of the powder method. Therefore, the development of electron-optical methods is also quite expedient, in view of the need for a detailed study of the structure of domain microfields.

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Note: Figure translations are in progress. See original paper for figures.