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GENERAL EXPERIMENTAL TECHNIQUES

Measuring and Visualizing Strong Magnetic Fields by Means of Indicators Based on Garnet Ferrite Films

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Abstract—A method for measuring by means of indicators based on garnet ferrite films the strong magnetic stray fields having intensities of 5–10 kOe that arise in systems of magnets with enormous magnetic anisotropy is described. The method is based on the phase transition from a strip domain structure into a uniformly magnetized state that takes place in garnet ferrite films in magnetic fields with intensities approaching the values of their anisotropy fields. It is shown that, by using indicators with various anisotropy field values, it is possible to obtain a fairly complete pattern of the stray fields localized in a narrow region over the magnets. The resolution limit in the localization region of a strong field is comparable to the width of the strip domains in the indicator and is 1–4 μm. The limiting value of the measured field intensity is equal to the anisotropy field of the indicator material.

It was shown in [1–5] that, by using various systems of permanent magnets, it is possible to generate strong magnetic fields whose induction can be several times higher than that of the material of the permanent magnets. Figure 1 shows one of these systems of magnets, while Figure 2 displays the calculated dependences of the vertical and horizontal components of the stray field induced over this system of magnets at $c >> a$. As can be seen from Figs. 2b and 2c, the stray fields can reach values of >20 kOe and are localized in the narrow region located near the OY axis and having the following dimensions: $-0.1a < x < 0.1a$ and $-0.1a < z < 0.1a$. In [4], the presence of strong fields in these systems was proven, and it was determined that the field's calculated dependencies were in conformity with those measured.

For these fields to exist, the material of the magnets must possess a powerful uniaxial anisotropy field ($H_k > 100$ kOe) and a high value of coercitive force ($H_c > 10$ kOe). Similar systems of magnets can be used to create the magnetic heads [6, 7] used for recording information on high-coercivity carriers; in various types of separators; to study the influence of strong, high-gradient magnetic fields on biological subjects; etc. Since the areas of application for these systems of magnets could be wider in the future, it is of practical importance that methods for measuring and controlling the intensities of these fields be found.

Since these strong fields are inhomogeneous and localized in the narrow region near the OY axis (see Fig. 2), either special micron-sized transducers or special magnetic materials are needed to measure them. In this work, we used indicators based on garnet ferrite films with a high field of uniaxial magnetic anisotropy, $H_k \approx 7$ kOe, to measure the strong magnetic fields over the system of magnets shown in Fig. 1. In order to grow the films, single-crystal gallium–gadolinium substrates with composition GdGa + CaMgZr and thickness $h = 480$ μm were used. The plane of the substrate was parallel to the crystallographic plane (111). The films were grown using liquid-phase technology. The thickness of the ferrite film of composition $(Y, Bi, Pr, Lu)_{3.0}(Fe, Ga)_{5.0}O_{12.0}$ was equal to 7 μm.

The axis of light magnetization was perpendicular to the plane of the ferrimagnetic layer. The saturation field of the ferrite film during magnetization in the normal direction was $H_s = 120$ Oe. When there was no external magnetic field, the domain structure of the films was labyrinthine with domain width $D \approx 5.0$ μm. The ferrimagnetic layers featured an enormous Faraday rotation equal to 2.1°/μm at room temperature. The films had a perfect crystalline structure, and, as a result, low (<0.1 Oe) coercitive force. The equilibrium laby-

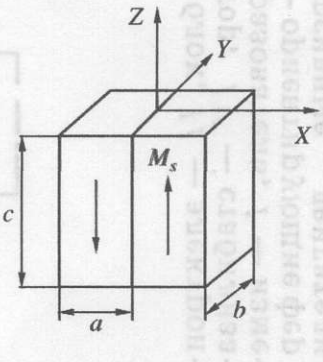

Fig. 1. System of magnets for a horizontal recording head.

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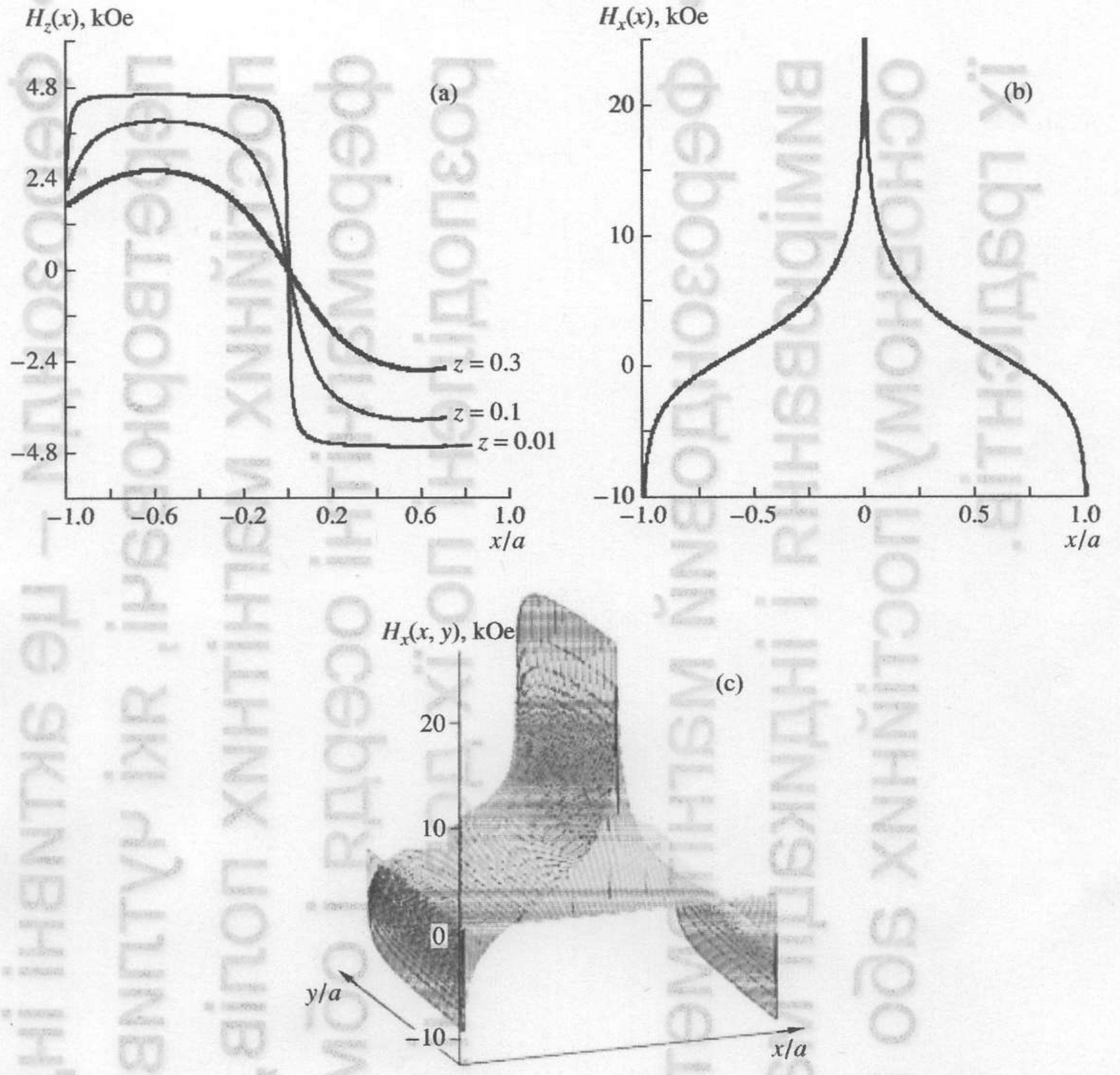

Fig. 2. Calculated dependencies of the (a) vertical $H_z(x)$ and (b) horizontal $H_x(x)$ components of the stray field at $z = 0$ on the ratio x/a, and (c) the horizontal components of the stray field $H_x(x, y)$ for points belonging to plane XOY ($-a < x < a$; $-b/2 < y < 0$) for the system of magnets shown in Fig. 1.

rinthine domain structure was formed in the layer of value H_c without application of the demagnetizing field.

Figure 3 shows a block diagram of the measuring facility, which was based on a ПТУ-29 television setup and a БИОЛАМ microscope and used for determining the stray field intensities of the magnet system in Fig. 1. The dimensions of the magnets, made in the form of a parallelepiped (see Fig. 1), were a = 1.8 mm, b = 2.0 mm, and c = 5.0 mm. The field indicator was a garnet ferrite film with a silver mirror coating. The in-plane dimensions of the indicator were 10 × 15 mm. This block diagram of the setup for the magnetooptical study of domain structures in magnetic material was first described in detail in [8]. In our experiments, the distance t between the magnets of the head and indicator in the circuit was regulated by means of a micrometer screw, or by using plates of various thicknesses.

In the setup (Fig. 3), the white light beam from illuminator *1* of the microscope is transformed by lens system *2*, passes through polarizer *3*, and is reflected by polarization mirror *4*. The beam then arrives at indicator *6*, set over the surface of test head *10*, through standard objective lens *5* of the БИОЛАМ microscope. The reflected beam, after passing twice through the substrate and indicator film, travels via semitransparent mirror *4* and analyzer *11*, and arrives at the recording device. The microscope's eyepiece (not shown in the figure) and digital camera *12* or video camera *13* with monitor *14* are used to record images in different experiments. Mirror *15* is used for switching the operating modes.

Indicator *6* is epitaxial garnet film *8*, grown on transparent single-crystal substrate *7*. The 0.2-μm-thick reflecting silver layer *9* is deposited on the film's surface by condensation in a vacuum. The magnetooptic contrast in this indicator increases by as much as 100% due to the double transmission of the beam through the garnet ferrite film.

In order to determine the intensity of the stray field component H_x over the gap between the magnets, the domain structure patterns of the indicator at various distances t from the head are used. The domain structure pattern comprises two regions of different contrast, separated by a transition zone in the form of strip (labyrinth) domains (Fig. 4). We call this zone the region of strip domain structure (SDS). It can be seen from Fig. 4 that, when distance t decreases, width D of this region over the gap between the magnets drops monotonously from 200 to 4 μm. Any further reduction in the distance leads to a narrowing of the remaining two domains, and at $t \approx 270$ μm, the remains of the strip domain structure at the center of the magnets disappear. There is no labyrinth domain structure at distance $t < 270$ μm, and the contrast between the two regions that earlier had opposite magnetization decreases.

It follows from the photos in Fig. 4 that a decrease in distance t between the head and indicator below certain value t_{crt} ($t < t_{crt}$) causes the labyrinth domain structure to disappear in the central part of the gap between the magnets, i.e., at the points with coordinates $M(0, y, t)$. The disappearance of the SDS at the boundary of the magnets at $t < 270$ μm indicates that, at these points, the stray field component H_x is equal to the value of the anisotropy field H_k of the indicator's garnet ferrite layer. The possible influence of the stray field component H_z on distance t_{crt} is small, since the field H_z at the boundary between the magnets is equal to zero and, at a distance from this boundary equal to the width of the strip domain (i.e., $x = \pm 2$ μm), is only several Oersted (see Fig. 2a). This value is much smaller than the saturation field $H_s = 120$ Oe of the indicator as it is being magnetized in the direction of the normal.

To determine distance t_{crt} exactly, we constructed the dependence of width D in the SDS region on distance t (Fig. 5). There is still a wedge-shaped SDS region (Fig. 6a) at distance t_{crt}, at the edges of the gap between the magnets. When t is reduced further, the wedge-shaped region shrinks (Fig. 6b). According to [5], this is due to the field component H_x being smaller at the edge of the gap between the magnets than at its center. In the part of the indicator located over the center of the magnet, strip domains are generated only at a large distance from the magnets, $z > 2a$, due to the larger field H_z (as compared to the indicator saturation field in the direction to the normal ($H_s = 120$ Oe)). This is also in conformity with the dependencies in Fig. 2b.

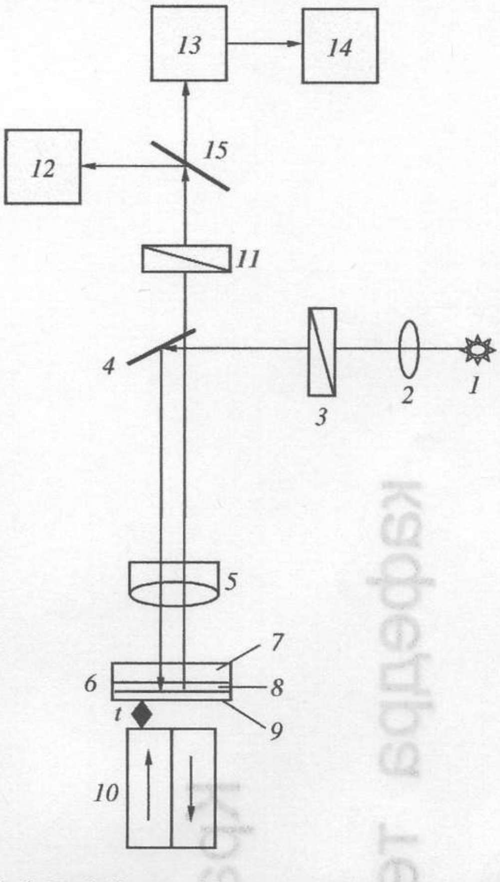

Fig. 3. Block diagram of the magnetooptical setup for measuring the stray fields over the head: (*1*) microscope light; (*2*) lens system; (*3*) polarizer; (*4*) polarization mirror; (*5*) БИОЛАМ microscope's standard objective lens; (*6*) indicator; (*8*) epitaxial garnet film; (*7*) transparent single-crystal substrate; (*9*) reflecting silver layer; (*10*) head being tested; (*11*) analyzer; (*12*) digital camera; (*13*) video camera; (*14*) monitor; (*15*) mirror.

We note that the contrast in Fig. 4e is attributable to certain features of the magnetization distribution in the part of the indicator over the magnets' boundary. In this region, the variation of field components H_x and H_z indicates (in accordance with Figs. 2a and 2b) that the magnetization distribution in the transition layer is similar to that in the Néel domain wall [9]. On the side opposite the boundary of the magnets, the magnetization component M_z changes sign, and, hence, the contrast shows up in the magnetooptic photos. If the distance from the magnets to the indicator is not too great ($t < 100$ μm), the contrast virtually disappears, due to the increase in the field component H_x. The contrast on the boundary between the magnets can also be reduced (or strengthened) by switching on external field $\pm H_x$.

Thus, according to our data, there is a critical distance t_{crt} from the indicator to the magnets, at which a transition from the strip domain structure to the uniformly magnetized state arises in the indicator at the

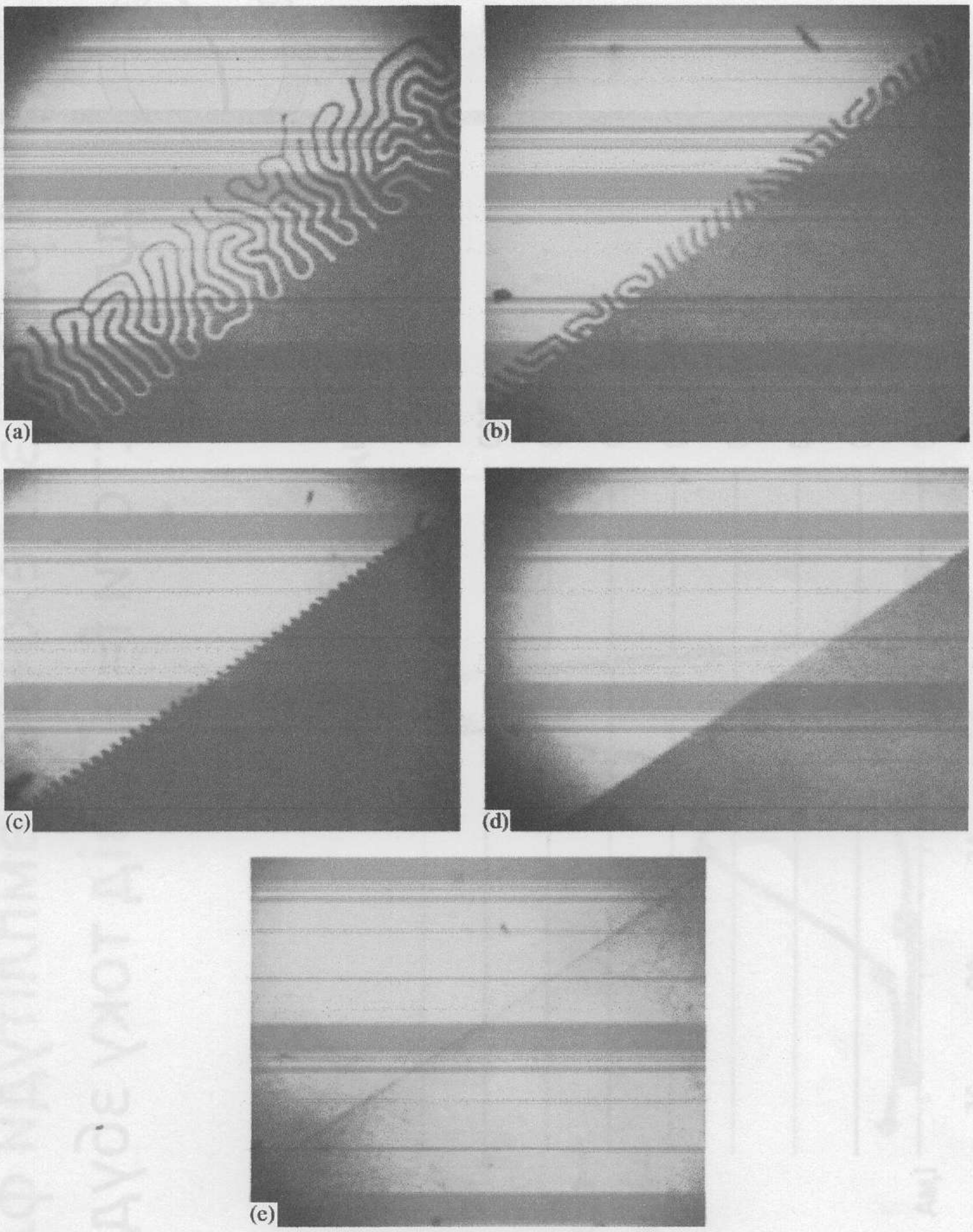

Fig. 4. Domain structure formed in the indicator at various distances t from its plane to the magnets: (a) 750; (b) 400; (c) 300; (d) 280; and (e) 200 μm.

boundary between the magnets. In our indicator, the transition to the single-domain state took place when a uniform magnetic field equal to the field of the indicator material's uniaxial magnetic anisotropy ($H_k \approx H_x \approx$ 7 kOe) was switched on. It follows that, by using value of the distance t_{crt}, it is possible to determine the intensity of the horizontal component of the stray field H_x at a distance from the magnets $z = t_{crt}$.

The accuracy of this estimate can be verified by comparing the measured value H_k = 7 kOe with the value H_x calculated by the approximate formula [4, 5]

$$H_x \approx 4M_s \ln(a/t_{crt}). \quad (1)$$

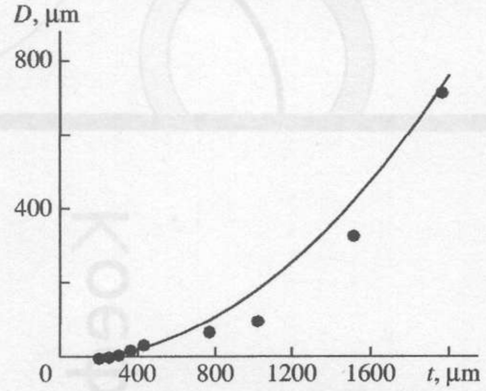

Fig. 5. Change in width D of the region with the labyrinth domain structure at various distances t between the head and indicator (points).

Considering that the saturation magnetization in these magnets $M_s \approx 900$ G and $a = 1.8$ mm, we obtain $H_x = 6.5$ kOe. This is very close to the measured field value $H_k = 7$ kOe.

The accuracy of measuring field H_x from the critical thickness value t_{crt} is 5–10%. The same accuracy of field measurements in a system of magnets with size $a = 40$ mm was achieved by means of magnetoresistive transducers based on Ag–Co granulated films [4].

The advantage of our method is also that it allows the field over the magnets to be visualized. This can be seen from Fig. 6, which graphically displays the inhomogeneity of the field H_x near the gap at the edges of the magnet at various distances t. Other magnetic irregularities can be revealed in a similar way.

Thus, our measurements of the field component intensity H_x at point M with coordinates $x \approx 0$, $y = 0$, and $z \approx t_{\text{crt}}$ prove that strong fields exist over the system of magnets shown in Fig. 1 and are localized in a narrow region near the boundary of the magnets (the OY axis). In order to obtain other experimental points of dependence $H_x(z)$, a set of indicators with different values of the uniaxial anisotropy field must be used. Garnet ferrite films with fields of uniaxial magnetic anisotropy and H_k of up to 15 kOe are now being manufactured. By consistently using indicators with different values of H_k, it is possible to construct dependence $H_x(z)$.

As can be seen, it is possible to measure only one field value by using one transducer. Nevertheless, it is possible to expand the range of measured fields by using even one transducer if an additional magnetic field with known intensity H_x is switched on. By changing the value and direction of additional magnetic field H_x, it is possible to obtain a complete pattern of the stray fields over a system of magnets. We have done work along these lines: the additional field $H_x \approx \pm 4$ kOe was created using a pair of permanent magnets. However, since our indicators were easily magnetized by the vertical field component $H_z = 120$ Oe, it was difficult to place the magnets so that the field H_x was strictly horizontal and component $H_z = 0$. Deviating field H_x by 1°–2° resulted in the disappearance of the strip domains over the surface of the indicator. To implement this measurement scheme, it is necessary to have either special sources of the permanent field or indicators with high saturation fields H_s (i.e., with large induction B_s).

Note that, when estimating the field intensity H_x by formula (1), we ignored the possible influence of the inhomogeneous distribution of the magnetization in the indicator, caused by effect of the stray fields from mag-

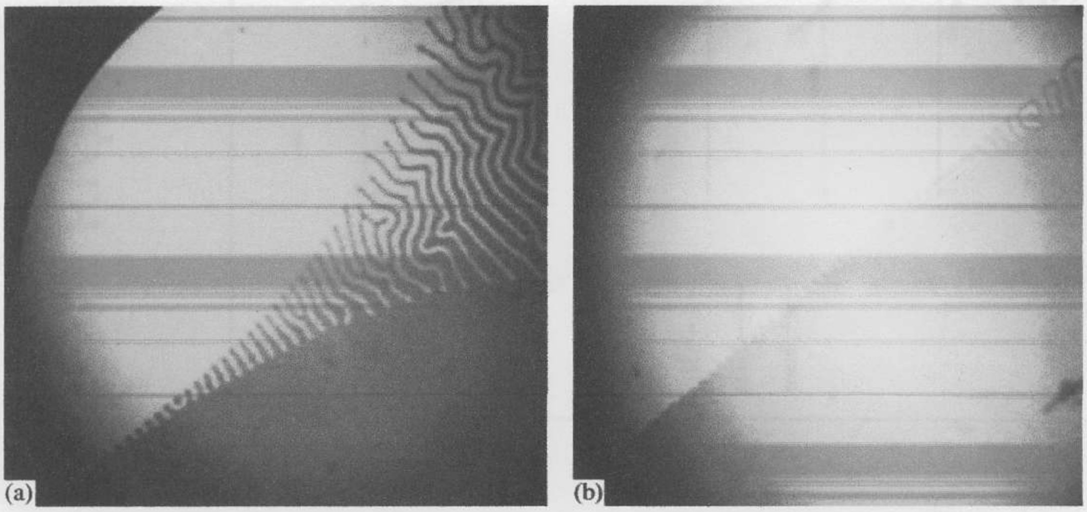

Fig. 6. Wedge-shaped regions with the strip domains at the edge of the magnet (Fig. 1) near the points with coordinates $M(0, \pm b/2)$ at a distance of the indicator from the substrate of (a) 280 μm; and (b) 250 μm.

nets (see Fig. 2). Due to the exchange interaction and anisotropy, the influence of the inhomogeneous distribution of the magnetization should become apparent when the dimension a of the magnets is small (approaching the width of the strip domains). This must be considered independently.

It should be noted that, due to its simplicity, our method for determining the intensity of magnetic fields can be used for the rapid testing of not only magnetic heads but of other magnetic field sources as well.

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