Effect of linearly polarized light on domain structure in a $Y_3Fe_{5-x}Si_xO_{12}$ plate

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The effect of linearly polarized monchromatic light on the local distribution of magnetization M in a $Y_3Fe_{5-x}Si_xO_{12}$ plate, cut in the (110) plane, is observed experimentally at temperature 77 K. Under the influence of the light, the maze-shaped domain structure (DS) of the Faraday type changes to a stripe DS of the Cotton type; that is, the magnetization vector of the domains changes from the direction perpendicular to the surface of the plate to the plane of the plate. The photoinduced direction the vector M is established along the axis of easy magnetization closest to the direction of the polarization vector of the illuminating beam E_s. The orientation of the vector E_s with respect to crystallographic axes also determines the efficiency (time) of the photoinduced reconstruction of M. It is shown that the Cotton DS can be changed repeatedly by purely optical means, in the absence of an external magnetic field. The effect of an external magnetic field on the photoinduced reconstruction of the DS is investigated.

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Polarization-dependent photoinduced magnetic effects (PIME) in $Y_3Fe_{5-x}Si_xO_{12}$ have been investigated in a number of papers (see, for example, Refs. 1 and 2). Linearly polarized light exerted an influence on such macroscopic characteristics of the specimen as a whole as the magnetic dichroism, the torque, the mechanical stress, and several others. The local action of light not on the whole specimen, but on individual parts of it, can be investigated by magneto-optical means. Such investigations of the effect of light on the domain structure of $Y_3Fe_{5-x}Si_xO_{12}$ and of $CdCr_2Se_4$ were made in Refs. 3 and 4 respectively. But the PIME investigated there were polarization-independent and showed up in the form of a stabilization of the motion (decrease of the the mobility) of individual domain walls and of the domain structure as a whole under the influence of unpolarized light. The effect of linearly polarized radiation on the local magnetic characteristics (magnetic structure) of the material, which showed up in a change of the domain structure and had a clearly expressed polarization-dependent character, is investigated for the first time, by a magneto-optical method, in the present paper.

EXPERIMENTAL METHOD

The specimen, in the form of a thin slice of monocrystalline yttrium-iron garnet, of composition $Y_3Fe_{4.96}Si_{0.04}O_{12}$, was cut in the (110) plane. From such a plate, a disk was prepared, of diameter 5 mm and thickness 0.6 mm, with polished surfaces.

The investigations were made with the setup of which a block diagram is shown in Fig. 1. The light source 1 was a laser, type LG-126, with radiation wavelength 1.15 μm and radiation power, in the continuous mode of generation, ~10 mW. For rotation of the plane of polarization of the laser radiation, a quarter-wave phase plate 2, with polarizer 3, was used, or else an apparatus of the Faraday type 12 with yttrium-iron garnet. The beam focussed by the collecting lens 4 fell on the specimen 5, located in the optical cryostat 6. Magnetic fields tangential and normal to the surface of the specimen could be produced in the specimen, at temperature 77 K, by the electromagnets 7 and 8. The electromagnet 7 for tangential magnetization of the specimen rotated with respect to the crystallographic axes located in the plane of the specimen. An image of the magnetic structure in the specimen was projected by a lens (objective) on the cathode of the image converter tube 11.

Two beams were used for the research: an illumination beam, which we shall denote by the index s, and a reading beam m. In general the beams s and m have different radiation wavelengths, different polarizations, and different intensities. The changes of magnetic characteristics produced by the reading beam m, depending on the particular features of the operating scheme of the apparatus, either were altogether absent, or were small and could be neglected.

For the case of normal incidence of the beam m on the plate, we shall use the terminology[5] in which the domains are called Cotton domains (because of the exis-

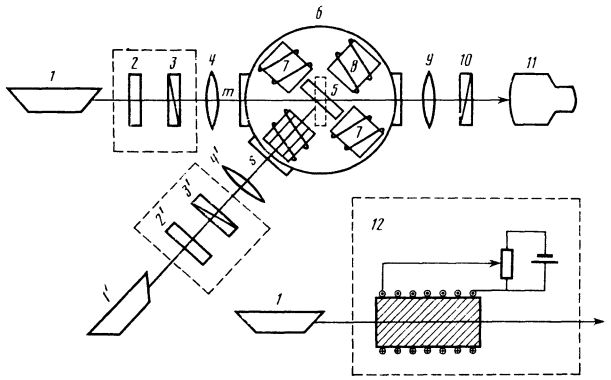

FIG. 1. Block diagram of the setup. 1) Light source (laser, type LG-126); 2) quarter-wave plate; 3) polarizer; 4) collecting lens (objective); 5) specimen; 6) optical cryostat; 7 and 8) electromagnets; 9) collecting lens (objective); 10) analyzer; 11) image converter tube; 12) apparatus of Faraday type for rotation of the plane of polarization; s) illumination beam; m) reading beam.

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tence of a transverse Cotton-Mouton effect) when the magnetization vector of the domains lies in the plane of the plate. When, however, the magnetization vector of the domains has an appreciable component normal to the plate surface (longitudinal component), and the Faraday effect dominates over the Cotton-Mouton-effect, we shall call the domain structure a Faraday structure.

Thus the principal features of the method used in our research consist of the following:

1) There is used for the first time, for investigation of polarization-dependent PIME, a magneto-optic method that makes it possible to investigate the effect of linearly polarized light on the domain structure of magnetically ordered substances. Other methods, used earlier, permitted investigation of the effect of polarized light on macroscopic parameters, characterizing the specimen as a whole.

2) Polarization-dependent PIME (incidentally so far observed only in YIG:Si, though it is natural to suppose that they exist also in other substances with photomagnetic properties, and primarily in $CdCr_2Se_4$ and $FeBO_3$) were investigated earlier at considerably lower specimen temperatures (4.2 K) than in our case (77K). This may suggest a higher sensitivity of the magneto-optic method.

3) The methods used earlier in principle do not permit investigations of polarization-dependent PIME without an external magnetic field; and the latter, as will be shown below, may exert a substantial influence on the magnitude and character of the effects under investigation. The magneto-optical method used in the present work eliminates the necessity for application of an external magnetic field, but at the same time it permits its use when that is necessary.

EXPERIMENTAL RESULTS

It was observed that the maze-shaped domain structure (DS) of the Faraday type, which existed in the disk under investigation both at 300 K and at 77 K, can be destroyed and changed to a stripe DS of the Cotton type under the influence of the linearly polarized monochromatic radiation of the illumination s. After the photoinduced formation of a Cotton DS, it can be changed, by new action of the beam s, to a Cotton DS with a different direction of the magnetization vector in the domains.

Angular variation

Figure 2 shows the angular variation, in the plane of the specimen, of the ferromagnetic-resonance field, which characterizes the magnetocrystalline anisotropy of cubic symmetry; the curve was taken for the disk under investigation at 300 K on a radiospectrometer. The form of the curve was no different when the temperature of the unilluminated specimen was 77 K. This indicates retention of the directions of crystallographic anisotropy and absence of an orientational phase transition,[6] the possibility of which in this material (yttrium-iron garnet doped with silicon) was suggested in

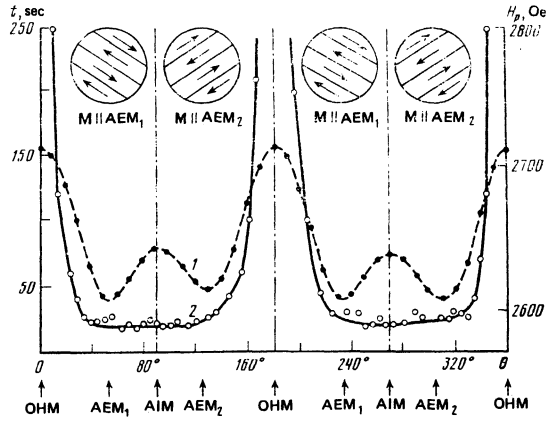

FIG. 2. Variation of ferromagnetic resonance field (1) and of time for photoinduced destruction of domain structure of the Faraday type (2), in a $Y_3Fe_{4.96}Si_{0.04}O_{12}$ plate in a (110) plane, with the angle between the axis of hard magnetization (AHM) and the direction of the external magnetic field (1) and between the AHM and the polarization vector of the preillumination beam (2).

Refs. 7 and 8. This result can be explained as a consequence of the fact that the orientational phase transition occurs in $Y_3Fe_{5-x}Si_xO_{12}$ for a relatively narrow range of concentrations of silicon (x),[7,8] which evidently does not include the value of x for our specimen.

The investigations of the effect of light showed that in photoinduced destruction of the Faraday DS, the magnetization **M** of the irradiated sections changes its direction, under the influence of the illumination beam, from the direction perpendicular to the plane of the disk to a direction lying in the plane of the disk, and aligns itself with one of the two axes of easy magnetization (AEM), namely the one with which the polarization vector $\mathbf{E}_s$ of the illumination beam makes the smaller angle.

The efficiency (time) of the photoinduced destruction of the DS of Faraday type depends on the angle between the polarization vector $\mathbf{E}_s$ and the crystallographic axes. This dependence is shown in Fig. 2. It follows from this dependence that the Faraday DS is destroyed fastest (most efficiently) if the vector $\mathbf{E}_s$ lies in the angular sectors from 40 to 140° and from 220 to 320°. When $\mathbf{E}_s$ is oriented along an axis of hard magnetization (AHM), destruction of the Faraday DS does not occur. The insets in Fig. 2 show the direction of the photoinduced domains after destruction of the Faraday DS. When the vector $\mathbf{E}_s$ is directed along an axis of intermediate magnetization (AIM), the Faraday domains are replaced by randomly located Cotton domains with different directions of magnetization (along AEM_1 and AEM_2); this can be explained as the result of the equally probable occurrence of the two states that are possible for this case.

Thus it is possible to annihilate the Faraday DS over the whole area of the specimen and to produce in it a Cotton stripe DS. The directions of magnetization **M** in adjacent Cotton domains are at 180°. The antiparallel arrangement of the magnetization vector (for example, along AEM_1) was observed experimentally on the screen of the image converter tube with a special tilted ar-

rangement of the plate with respect to the direction of propagation of the beam m. Here the Cotton 180-degree domains were made visible by the appearance of a Faraday component of the magnetization.

If we change the direction of the vector $\mathbf{E}_s$ and direct it along AEM_2, then against the background of the section with $\mathbf{M} \| AEM_1$ we can produce a photoinduced rotation of the vector $\mathbf{M}$ to the direction AEM_2. By changing the direction of the vector $\mathbf{E}_s$ still again, we can produce new changes, etc. The variation of the efficiency (time) of such changes with the angle θ between the polarization vector $\mathbf{E}_s$ and the AHM is shown in Fig. 3. The insets to this figure represent a region with a direction of the vector of photoinduced magnetization $\mathbf{M}_1$, against the background of which are produced photoinduced changes with a new direction of magnetization $\mathbf{M}_2$.

We point out that in contrast to the case when the Faraday DS was destroyed by the light (Fig. 2), the photoinduced changes of the Cotton DS (Fig. 3) occur in sectors located between an AHM and an AIM, and not in sectors between AHM as in the first case.

After shutting off of the illumination beam, the photoinduced changes of direction of $\mathbf{M}$ (both in the case of destruction of the Faraday DS and in photoinduced changes of the Cotton DS) persist.

Action of an external magnetic field

As was indicated above, the magneto-optical method applied in the present research makes it possible to investigate polarization-dependent PIME in the absence of an external magnetic field. But it is of interest to investigate the influence on the observed effects of an external magnetic field for the cases of normal and of tangential magnetization of the specimen.

In the absence of the illumination beam s (only the reading beam m acts), the effect of an external magnetic field manifests itself in a change of the type and dimensions of the DS, having no peculiarities as compared with the results described in papers on investigation of the effect of a magnetic field on the DS in cubic crystals.[5,9]

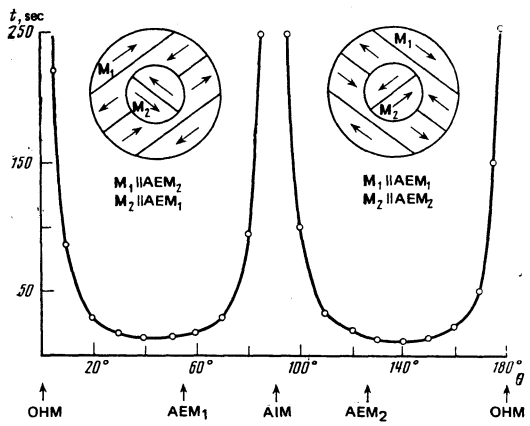

FIG. 3. Variation of the time for photoinduced change of the magnetization vector in the plane of a $Y_3Fe_{4.96}Si_{0.04}O_{12}$ plate with the angle between the axis of hard magnetization and the polarization vector of the preillumination beam.

But a magnetic field exerts a substantial influence on the photoinduced change of DS. An external magnetic field applied tangentially to the surface of the specimen and parallel to the polarization vector $\mathbf{E}_s$ decreases the time of the photoinduced change of DS approximately by an order of magnitude.

DISCUSSION OF RESULTS

The observed effect of linearly polarized light on the magnetization distribution and domain structure in an orientated plate of yttrium-iron garnet with silicon impurity cannot be attributed to the thermal action of the light beam. The electromagnetic (nonthermal) nature of the observed phenomena is indicated by their strong dependence on the orientation of the polarization vector of the beam s with respect to the crystallographic axes of the specimen.

The domain structure of a crystal with spontaneous magnetization, as is well known, is determined by the crystal and, in particular, depends on the magnetic anisotropy energy. In the absence of an external magnetic field, yttrium-iron garnet possesses magnetic anisotropy of cubic symmetry, which characterized also the $Y_3Fe_{5-x}Si_xO_{12}$ crystal investigated by us (Fig. 2) before illumination. At the same time it is known that in certain cases the magnetic anisotropy of a given crystal can be effectively changed, for example by thermomagnetic treatment.[7] As a result of such treatment, which consists in cooling of a specimen specially magnetized along certain crystallographic axes, there is finally induced a strong uniaxial magnetic anisotropy. To explain it, a theory was proposed in Ref. 10 and developed in Refs. 11 and 12, based on a model of orientationally nonequivalent sites. This model can also be used as the basis for an explanation of polarization-dependent PIME.

Briefly, the essence of this model is that the strongly anisotropic Fe^{2+} ions,[1)] on whose presence and position the magnetic anisotropy of the crystal to a large degree depends, may be located on sites of four types, differing in that the local axes of symmetry of these sites are oriented along one of four ⟨111⟩ directions. At low temperatures, when thermally activated transitions $Fe^{2+} \rightleftharpoons Fe^{3+}$ are impossible, it is possible to make one of the ⟨111⟩ directions a preferred one (to increase or decrease the occupancy of one type of sites at the expense of the other three), and thus to produce in a cubic crystal an induced uniaxial magnetic anisotropy.

In the case of magnetic annealing, the magnitude and direction of the uniaxial magnetic anisotropy are determined by the external magnetic field. In the case of our experiments, when the external magnetic field is absent, the selected character of one of the four directions results from the fact that the probability of optical removal of an electron from an Fe^{2+} ion depends on the polarization $\mathbf{E}_s$ of the preillumination beam and therefore is different for sites with different directions of the axes of trigonal symmetry. Thus the probability of optical removal of an electron from an Fe^{2+} ion is

greatest for a site whose trigonal axis of symmetry is perpendicular to the vector $\mathbf{E}_s$ and is least when the axis of symmetry is parallel to $\mathbf{E}_s$.[2] In our case, the angle between the directions of easy magnetization (AEM_1 and AEM_2) is $\approx 70°$, and the efficiency of the action of polarized light is not optimal for the orientation $\mathbf{E}_s \| AEM$. (A difference of the angle between AEM_1 and AEM_2 from 90° is necessary for efficient reading.) Therefore the minimum time of photoinduced reconstruction of the DS is observed for the case when the vector $\mathbf{E}_s$ is not parallel to AEM (Fig. 3).

We thank the participants in the seminar of K. P. Belov for useful discussion of the results of this paper.

[1)] Fe^{2+} ions originate as a result of partial replacement of iron ions contained in stoichiometric $Y_3Fe_5O_{12}$ in a trivalent state by tetravalent silicon ions: $Fe^{3+} + Fe^{3+} \rightarrow Si^{4+} + Fe^{2+}$. The contribution of Fe^{2+} ions (as also of Co^{2+} ions) to the magnetic anisotropy of a crystal is extremely large.[13] Furthermore, the presence of iron ions of different valences creates a possibility of electronic processes of the valence-exchange type, $Fe^{2+} \rightleftarrows Fe^{3+}$.

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