Magnetooptical properties of weak ferromagnets

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It is shown that anomalously large magnetooptical effects in weak ferromagnets are due not to the absolute value of the resultant magnetic moment nor to its reorientation, but to the antiferromagnetism-vector reorientation that accompanies the magnetization reversal of the weak ferromagnet. Effects of the destruction of the surface magnetism of hematite by an external magnetic field were observed during the course of the experiment.

In one of the first investigations of the magnetooptical properties of weak ferromagnetic orthoferrites, attention was called to the unexpectedly large value of the polar Kerr effect. [1] The effect turned out to be approximately the same as in ferromagnetic iron garnets, although the spontaneous magnetization of the orthoferrites is approximately one-twentieth the spontaneous magnetization of yttrium iron garnet. This anomalous behavior of weak ferromagnets was most clearly pronounced in the investigation of hematite (α-Fe_2O_3). The equatorial Kerr effect in hematite, which was measured in[2], turned out to be the same as in ferrimagnetic dielectrics, although the spontaneous ferromagnetic moment of hematite is approximately one-thousandth the summary magnetization of its sublattices. In a discussion of[2], A. S. Borovik-Romanov and I. E. Dzyaloshinskiĭ advanced the hypothesis that the anomalously large magnetooptical effects in weak ferromagnets are due to reorientation of the antiferromagnetism vector **L** when the magnetization of the weak ferromagnet is reversed. The present investigation is devoted to an experimental verification of this hypothesis.

The idea of the experiment was to measure the magnetooptical effect in two cases in which the resultant magnetization is of the same magnitude, but in one case the antiferromagnetism vector changes its orientation upon reversal of the crystal magnetization, and in the other case it does not. The first case is realized upon reversal of the spontaneous ferromagnetic moment $\mathbf{m}_s$, and the second upon reversal of the moment $\mathbf{m}_H$ induced by an external field. Figure 1 shows diagrams that illustrate the foregoing. Figure 1a shows how the orientation of the sublattices changes when the hematite magnetization is reversed in the basal plane. The equatorial Kerr effect δ is then observed for light whose polarization plane is perpendicular to the vector $\mathbf{m}_s$. The plot of $\delta(H)$ corresponding to this case is shown in Fig. 2. It is shown in Fig. 1b that when the orientation of $\mathbf{m}_H$ is changed the orientation of the sublattices remains unchanged (we disregard here the influence of doubly-relativistic interactions, which can lead to rotation of the spin system and the basal plane[3]). We note that $\mathbf{m}_H$ can easily reach the values of $\mathbf{m}_s$, inasmuch as the Dzyaloshinskiĭ field for hematite is equal to 22 kOe. [4] Figure 1c shows a situation analogous to 1a for the nonbasal hematite plane (100). In this case one can observe not only the equatorial Kerr effect (the corresponding curve for $H \parallel [01\bar{1}]$ is shown in Fig. 2), but also the polar Kerr effect as a result of the normal magnetization component $\mathbf{m}_s^n$. Thus, the proposed experiment can be realized only, for example, by comparing the values of the polar Kerr effect in cases 1b and 1c, due respectively to the magnetic-moment components $\mathbf{m}_H^n$ and $\mathbf{m}_s^n$ normal to the surface. In case 1c, however, there is one complicating circumstance. The point is that, as shown in[2], surface magnetism is produced on the nonbasal faces of hematite, i. e., a macroscopic layer of the domain-wall type, in which, in particular, the normal magnetization component $\mathbf{m}_s^n$

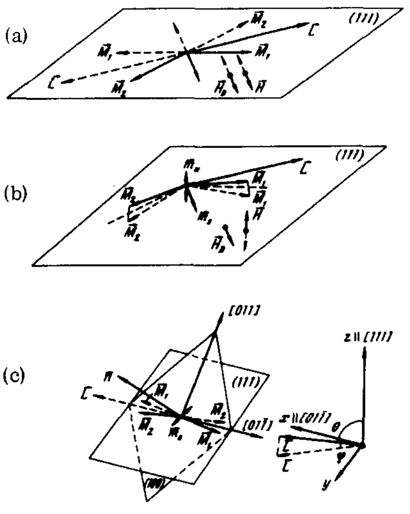

FIG. 1.

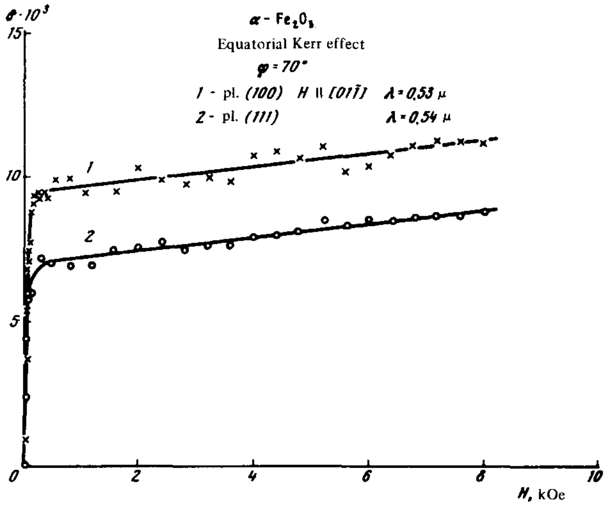

FIG. 2.

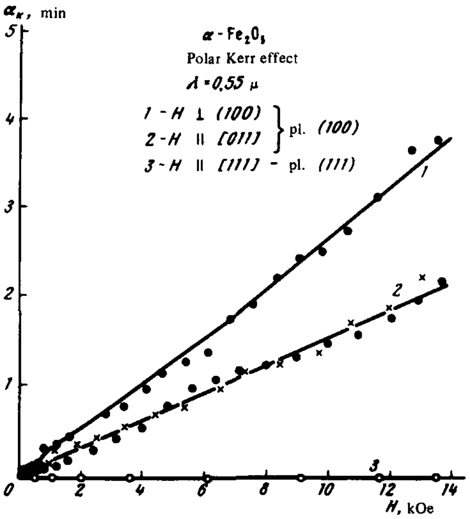

FIG. 3

vanishes on approaching the surface. We have therefore calculated the critical field capable of destroying the surface magnetism on a nonbasal face of hematite and of bringing $\mathbf{m}_s^n$ to the surface. Estimates have shown that the decisive role in securing of $\mathbf{m}_s$ on the surface of hematite is played by magnetic-dipole interaction. The energy of the magnetic anisotropy in the volume of the hematite crystal consists of two components that are opposite in sign and almost equal in magnitude, [5] namely the energies of the magnetic-dipole interaction and of the single-ion crystal anisotropy. It is natural to assume that in contrast to the magnetic-dipole anisotropy, the single-ion anisotropy changes much less on the surface than in the volume. Under this assumption, we calculated the surface-anisotropy energy for the faces (100) and (111) of hematite in two cases, when the last atomic plane of the Fe^{3+} consists of ions of type 1 or 2. [3] We present below expressions for the densities of the indicated energies (in erg/cm^2)

$$\sigma^1_{(100)} = -0.1\sin^2\theta\cos^2\phi + 0.1\sin^2\theta\sin^2\phi - 0.01\cos^2\theta - 0.25\sin\theta \times \cos\theta\sin\phi$$

$$\sigma^2_{(100)} = 0.24\sin^2\theta\cos^2\phi - 0{,}03\sin^2\theta\sin^2\phi - 0.21\cos^2\theta + 0{,}04\sin\theta \times \cos\theta\sin\phi$$

$$\sigma^1_{(111)} = 0.24\cos^2\theta$$

$$\sigma^2_{(111)} = -0.24\cos^2\theta$$

θ and ϕ are the spherical angles of the vector L (Fig. 1c). On most of the investigated nonbasal faces of hematite there is observed a surface magnetism attributed to allowance for the energy $\sigma^2_{(100)}$. We can draw from this the interesting opposite conclusion, that the natural growth of faces of the (100) type terminates as a rule, in an atomic plane consisting of Fe^{3+} ions of type 2. Calculation has shown that when $\sigma^2_{(100)}$ is taken into account the width of the surface magnetic layer in a field $H = 1$ kOe is approximately 0.4 μ, and this layer is annihilated by decreasing its width and by rotation of the vector L in a field $H \parallel y$ (Fig. 1c) on the order of 20 kOe. Indeed, measurement of the polar Kerr effect on nonbasal faces of several crystals1) has revealed a power-law growth of the polar effect with increasing field perpendicular to the sample surface (Fig. 3), a fact that can be interpreted as the result of the erasure of the surface magnetism. From the form of the $\alpha_K(H)$ curve it is seen that a field of 13.5 kOe has not yet destroyed the surface magnetism completely. We note that the process of magnetization of a hematite single crystal in the absence of the influence of surface magnetism terminates in fields ~200 Oe (see Fig. 2). The result is confirmed also by the presence of the polar effect when a field is applied in the plane of the sample along the [011] axis. The points of curve 1, when recalculated to the equivalent value of $\mathbf{m}_s^n$, then fit well the curve 2 (crosses in Fig. 3). At the same time, the polar effect on the basal plane in normal fields up to 13.5 kOe (at $m_H^n \approx m_s^n$ on the nonbasal plane) turned out to be practically equal to zero (curve 3 of Fig. 3). This result, in our opinion, proves unambiguously that the anomalously large magnetooptical effects in weak ferromagnets are determined not by the absolute value of m and by its reorientation, but by the reorientation, which accompanies the magnetization reversal of $\mathbf{m}_s$, of the entire spin system of the weak ferromagnets, including its antiferromagnetism vector L. The foregoing must not be understood in the sense that the weak-ferromagnet vector L is analogous in its magnetooptical properties to the vector I of a ferromagnet or a ferrimagnet. For example, the presence of a normal component of L on the surface does not give rise to the appearance of the polar Kerr effect. Moreover, even a reorientation of the vector L in the antiferromagnet may not be accompanied by large odd magnetooptical effects. The point is, apparently, that the same microscopic mechanisms that lead to the appearance of the Dzyaloshinskiĭ field and eventually to $\mathbf{m}_s$ of the weak ferromagnet lead also to the appearance of anomalously large nondiagonal components of the dielectric tensor, which reverse sign when the vectors $\mathbf{m}_s$, L, and $\mathbf{H}_D$ are reoriented, and by the same token give rise in weak ferromagnets to large magnetooptical effects that are linear in $\mathbf{m}_s$. It is therefore possible that when a quantitative theory of magnetooptical effects in weak ferromagnets is developed it will be found that a relation exists between the hypothesis of Borovik-Romanov and Dzyaloshinskiĭ, which has been confirmed by the present study, and the hypothesis of Kohn and co-workers[1] concerning the role of anisotropic quenching of the orbital angular momentum in magnetooptical phenomena.

1)In some cases a more complicated picture was observed, due to the singularities of the surface magnetism, and worthy of a special discussion.

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