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EFFECT OF ANISOTROPY ENERGY ON THE FORMATION OF NONCOLLINEAR MAGNETIC STRUCTURE IN HEXAGONAL FERRITE

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The effect of anisotropy energy on the formation of a noncollinear magnetic structure is investigated in the hexagonal ferrite $Ni_{0.4}Co_{1.6}BaFe_{16}O_{27}$ (type W) in the temperature range in which the anisotropy constant K_1 changes sign. The constant K_1 is found to depend on the value of the external field. The exchange-interaction parameter is calculated on the basis of the paraprocess susceptibility and of the critical field, and the value obtained is $\lambda = 0.8 \times 10^{23}$ G^2/erg.

THERE have recently appeared a number of papers in which are presented the results of investigation of noncollinear spin configurations in ferrite-garnets and in hexagonal ferrites of various types.[1-3] It is characteristic that for the majority of the hexagonal ferrites investigated, the appearance of a noncollinear spin structure is caused by various replacements of ions in the ferrites by nonmagnetic ions. Such a replacement leads to a change of the exchange bonds between ions, creating a reason for change of the magnetic structure of the ferrites.

Upon replacement of the Co^{2+} ions in ferrites of type W by any bivalent metal ion, a change in the form of anisotropy occurs. In the system of solid solutions $BaFe_{2-x}Co_xW$,[4] various forms of anisotropy are observed—with a cone, a plane, or an axis of easy magnetization—but, as neutronographic investigations have shown,[5] the spin ordering remains collinear.

It seemed to us of interest to investigate the effect of anisotropy energy on the formation of noncollinear magnetic structure. Therefore we chose as object of investigation the hexagonal ferrite $Ni_{0.4}Co_{1.6}BaFe_{16}O_{27}$, in which the value of the first anisotropy constant K_1 changes significantly with temperature.

The investigations showed that at various temperatures the ferrite investigated possesses a cone (below −53 °C), a plane (−53 to −13 °C), a cone (−13 to 127 °C), and an axis (127 °C and above) of easy magnetization. The investigations were made on monocrystalline specimens by the torque method. From an analysis of the torque curves in the temperature interval 90–140 °C, it follows that some crystals in this temperature range reveal a dependence of the aperture angle θ of the cone of easy magnetization on the value of the external magnetic field.

Figure 1 shows the dependence of the angle θ on the reciprocal of the field at various temperatures. The value of the aperture angle of the cone of easy magnetization in zero field can be found by extrapolation of the function $\theta(1/H)$ at each temperature point. The field leads to an increase of the aperture angle of the cone of easy magnetization, converting it to a plane of easy magnetization. From the curves shown, it is seen that the effect of the external magnetic field on the value of θ is most clearly expressed at temperature 125 °C.

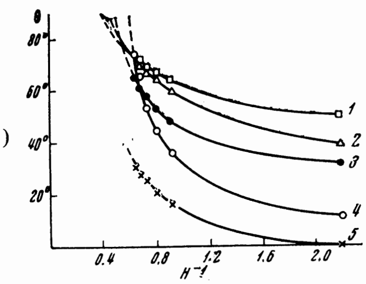


FIG. 1. Dependence of the aperture angle of the cone on the reciprocal of the field ((10⁴ Oe)⁻¹) at various temperatures: 1, 90°C; 2, 105°C; 3, 114°C; 4, 125°C; 5, 137°C.

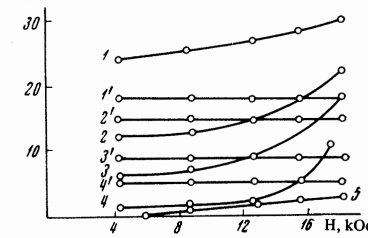


FIG. 2. Dependence of the anisotropy constants K_1 and K_2 on the external field for various temperatures: 1 and 1′, 90°C; 2 and 2′, 105°C; 3 and 3′, 114°C; 4 and 4′, 125°C; 5, 137°C (the primed numbers refer to K_2).

In order to determine which of the anisotropy constants—K_1 or K_2—is affected by the external field, these constants were calculated for a fixed value of H by the usual formulas for the torques in a hexagonal crystal. Graphs of the dependence of K_1 and K_2 on the value of the external magnetic field H at various temperatures are shown in Fig. 2. It is seen that the constant K_2, within the limits of experimental error, is independent of field over the whole temperature interval. The constant K_1 increases in magnitude under the influence of the field. In small fields, the dependence $K_1(H)$ is linear; with increase of the field, it becomes more complicated.

It should be mentioned that at the field at which the transition from a cone of easy magnetization to a plane of easy magnetization is completed, $|K_1| = 2K_2$ (curve 4), as is to be expected from the limiting condition for existence of a plane of easy magnetization. The field necessary for a transition from a cone to a plane of easy magnetization—the critical field—can be obtained by ex-

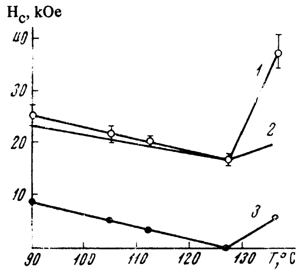
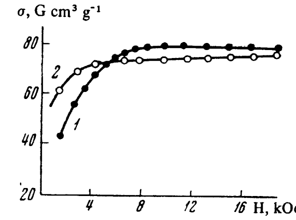


FIG. 3. Dependence of the critical field (curves 1 and 2) and of the anisotropy field (curve 3) on temperature (curve 2 calculated by formula (4)).

FIG. 4. Dependence of the specific magnetization on the field at 20°C (curve 1) and at 124°C (curve 2).



trapolation of the curves $\theta(1/H)$ to cone aperture angle $\theta = 90°$ or by extrapolation of the curves $K_1(H)$ to the values $|K_1| = 2K_2$.

Figure 3 shows the dependence of the critical field on temperature. It is seen that the critical field is minimum at 127°C and increases sharply on both sides of this temperature. It is interesting to compare this dependence with the temperature dependence of the anisotropy field $H_a^{(1)} = 2K_1/I_S$, where K_1 is the value of the anisotropy constant in zero external field (Fig. 3, curve 3). At 127° C the field $H_a^{(1)} = 0$, and H_c is minimum. This indicates a definite connection between the first anisotropy constant and the critical field.

The field dependence of the anisotropy constant can be explained by the presence of a noncollinear magnetic structure in the ferrite in the temperature range investigated. For a noncollinear structure, following Sannikov and Perekalina,[1] one can exhibit the first term of the expansion of the anisotropy energy $E_a = K_1 \sin^2\theta$ in the form

$$E_a = \tfrac{1}{2}k\cos^2\psi_1 + \tfrac{1}{2}k'\cos^2\psi_2 + k''\cos\psi_1\cos\psi_2 + k'''\sin\psi_1\sin\psi_2\cos(\varphi_1 - \varphi_2), \quad (1)$$

where k, k′, k″, and k‴ are the anisotropy constants in the first approximation of perturbation theory; ψ_1 and ψ_2 are the angles between the magnetic moments of the sublattices, M_1 and M_2, and the axis c; and φ_1 and φ_2 are the azimuthal angles of the magnetic moments of the sublattices in the basal plane. The anisotropy constant K_1 depends on the value of the field because with change of field, the angles ψ_1 and ψ_2 change. Since only the angles ψ_1 and ψ_2 change, whereas the magnitudes of the magnetic moments M_1 and M_2 of the sublattices are considered constant, it is necessary that the exchange interaction between sublattices should be smaller than the exchange interaction within each sublattice. Ermolaev and Kaganov[6] showed that when the exchange interaction is weak, it may depend on the value of the external magnetic field. In consequence of this, there is a change of the magnetic structure in an external magnetic field, which also leads to a change of the angles ψ_1 and ψ_2.

It is interesting to note that on the magnetization curves in the basal plane of a $Ni_{0.4}Co_{1.6}BaW$ crystal in the temperature interval 90–140°C, saturation is not attained in fields up to 20 kOe, although the anisotropy field at these temperatures is $H_a^{(1)} \sim 10^3$ Oe.

Figure 4 shows the basic magnetization curves in the basal plane for the monocrystal investigated, at 20 and at 124° C. At 20° C, the ferrite is magnetized to saturation in fields $H > 10$ kOe. At 124° C, a linear section is observed on the magnetization curve, with slope $d\sigma/dH = 4 \times 10^{-4}$ G cm³/Oe g; this may be evidence of a change of orientation of the magnetic moments of the sublattices in this field interval.

Thus in the hexagonal ferrite $Ni_{0.4}Co_{1.6}BaW$ in the temperature interval 90–127° C, where the first anisotropy constant is small, an effect of the external field on the magnetic structure of the ferrite is observed. This means that in the temperature interval considered, there is a noncollinear spin ordering in the ferrite.

In order to discuss the values that we have obtained for the critical fields that break down the noncollinear ordering, we shall apply the method of Clark and Callen.[7]

The expression for the free energy of a two-sublattice noncollinear model can be exhibited, in first approximation, as the sum of the energy of exchange interaction between sublattices, the energy of interaction of the magnetic moments of the sublattices with the field, and the anisotropy energy:

$$F = -M_1H\cos\psi_1 - M_2H\cos\psi_2 - M_1H_a^{(1)}\cos^2\psi_1 - M_2H_a^{(2)}\cos^2\psi_2 - \lambda M_1M_2\cos(\psi_1-\psi_2), \quad (2)$$

where M_1, M_2, $H_a^{(1)}$, and $H_a^{(2)}$ are the magnetic moments and the anisotropy fields of the sublattices; ψ_1 and ψ_2 are the angles between the magnetic moments of the sublattices and the axis c; and λ is the exchange-interaction parameter. By minimizing the free energy with respect to the angles ψ_1 and ψ_2, we get equations that determine the ψ_1 and ψ_2 that correspond to a minimum of the free energy of the crystal. By setting $\psi_1 = 0$ and $\psi_2 = \pi$ and neglecting small terms, we obtain equations for the limiting field for the collinear and noncollinear phases for the two cases:

$$M_1 = M_2, \quad H_{c_1} = \sqrt{2\lambda|K_1|}, \quad K_1 = H_a^{(1)}M_1 + H_a^{(2)}M_2; \quad (3a)$$

$$K_1 = 0, \quad H_{c_2} = \lambda(M_1 - M_2). \quad (3b)$$

In the general case, the critical field that breaks down the noncollinear magnetic structure can be expressed in the form

$$H_c = \lambda(M_1 - M_2) + \sqrt{2\lambda|K_1|}. \quad (4)$$

The temperature dependence of the critical field, calculated by formula (4), is shown in Fig. 3 (curve 3). There is good agreement of the experimental and calculated values of the critical fields. To speak of values of H_c for $T < 90°$ C makes no sense, since there the noncollinear phase is absent.

It is of considerable interest to estimate the parameter λ of exchange interaction between sublattices. From formula (3) with $T = 127°$ C, we get $\lambda = 0.8 \times 10^{23}$ G²/erg. This value can be verified by calculating with the well-known formula,[8] the susceptibility of a ferromagnet with a noncollinear spin structure in a field interval in which deformation of this structure is occurring:

$$\chi = \left\{ \frac{32H_c}{7.76\mu_s} [1 + 2\cos\alpha(1 + \cos\alpha)] \right\}^{-1}; \tag{5}$$

Here μ_S is the magnetic moment of a molecule of the ferrite. The helicoid angle α is found from the formula

$$H_c = 7.76\mu_s J_2 \sin^4(\alpha/2), \tag{6}$$

with $J_2 = \lambda$. We do the calculation for $T = 127°C$.

The value obtained in this calculation, $\chi = 3.2 \times 10^{-3}$ G/Oe, agrees with the experimental value for this temperature, $\chi = 2.1 \times 10^{-3}$ G/Oe. The good agreement between the values quoted shows that the parameter of exchange interaction between sublattices is $\lambda = 0.8 \times 10^{23}$ G^2/erg; that is, the assumption of a small value of the exchange interaction for the noncollinear magnetic structure is correct.

[1] D. G. Sannikov and T. M. Perekalina, Zh. Eksp. Teor. Fiz. **56**, 730 (1969) [Sov. Phys.-JETP **29**, 396 (1969)].

[2] K. P. Belov, L. A. Chernikova, E. V. Talalaeva, R. Z. Levitin, T. V. Kudryavtseva, S. Amadesi, and V. I. Ivanovskiĭ, Zh. Eksp. Teor. Fiz. **58**, 1923 (1970) [Sov. Phys.-JETP **31**, 1035 (1970)].

[3] A. D. Shchurova, T. M. Perekalina, and S. S. Fonton, Zh. Eksp. Teor. Fiz. **58**, 1571 (1970) [Sov. Phys.-JETP **31**, 840 (1970)].

[4] T. M. Perekalina and A. V. Zalesskiĭ, Zh. Eksp. Teor. Fiz. **46**, 1985 (1964) [Sov. Phys.-JETP **19**, 1337 (1964)].

[5] I. I. Yamzin, R. A. Sizov, I. S. Zheludev, T. M. Perekalina, and A. V. Zalesskiĭ, Zh. Eksp. Teor. Fiz. **50**, 595 (1966) [Sov. Phys.-JETP **23**, 395 (1966)].

[6] A. M. Ermolaev and M. I. Kaganov, Fiz. metallov i metallovedenie **29**, 897 (1970).

[7] A. E. Clark and E. Callen, J. Appl. Phys. **39**, 5972 (1968).

[8] K. P. Belov, M. A. Belyanchikova, R. Z. Levitin, and S. A. Nikitin, Redkozemel'nye ferromagnetiki i antiferromagnetiki (Rare-earth Ferromagnets and Antiferromagnets), Nauka, 1965.

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