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MAGNETIC ANISOTROPY AND MAGNETIZATION PROCESSES IN STRONTIUM-ZINC HEXAGONAL FERRITES

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Qualitative changes in the torque curves with increasing magnetic field and the presence of two minima in the magnetic anisotropy energy, i.e., the existence of two easy magnetization directions, are observed experimentally in single crystals of the hexagonal ferrites $Sr_2Zn_2Fe_{12}O_{22}$ and $Sr_3Zn_2Fe_{24}O_{41}$. A model of two magnetic sublattices with a weak exchange interaction between them is used to explain the experimental data.

SINGLE crystals of hexagonal zinc ferrites with **Y**, **Z**, and **X** structures with the barium ions completely replaced by strontium ions were grown by spontaneous crystallization from solution in an $NaFeO_2$ melt. An x-ray determination yielded the following values of the unit cell parameters: a = 5.87 Å for all types of crystals and c = 43.5 Å for the ferrite $Sr_2Zn_2Fe_{12}O_{22}$(Sr_2Zn_2**Y**), c = 52.3 Å for the ferrite $Sr_3Zn_2Fe_{24}O_{41}$(Sr_3Zn_2**Z**), and c = 84.0 Å for the ferrite $Sr_2Zn_2Fe_{28}O_{46}$(Sr_2Zn_2**X**).

Measurements of the magnetization curves of each of the indicated crystals were obtained with a vibrating-sample magnetometer in the 77–293°K temperature range in static magnetic fields up to 20 kOe and in pulsed magnetic fields up to 100 kOe. Figure 1 shows some of the results of these measurements for single crystals of Sr_2Zn_2**Y**. The curves for the Sr_3Zn_2**Z** single crystals are similar to the curves of Fig. 1. For a composition close to Sr_3Zn_2**Z** such curves are shown in[1]. At temperatures below 230°K one sees clearly in the Sr_2Zn_2**Y** (as well as in the Sr_3Zn_2**Z**) crystals the existence of a critical field which increases with increasing temperature. Above 230°K the magnetization increases smoothly with increasing magnetic field; however, the magnetization curve has a strong slope. The magnetization curves of Sr_2Zn_2**X** exhibit neither critical magnetic fields nor any other features. It should only be noted that they have an easy magnetization plane.

For the same samples for which we obtained the magnetization curves we also investigated the magnetic anisotropy by the torque method. Figures 2 and 3 show the torque curves for Sr_2Zn_2**Y** and Sr_3Zn_2**Z** curves respectively obtained in the plane perpendicular to the basal plane. We draw attention to the peculiarity of these planes: both the magnitude of the torque as well as the nature of the entire curve change with changing magnitude of the external magnetic field. It is seen from Fig. 2 that the anisotropy energy in Sr_2Zn_2**Y** crystals at 77°K in a magnetic field up to 7 kOe (curve 1 of Fig. 2) has only one minimum at $\vartheta = 90°$, i.e., the direction of easy magnetization (EM) lies in the basal plane. On increasing the field there appears another minimum in the magnetic anisotropy energy, i.e., another EM direction lying on the surface of a cone $0 < \vartheta < 90°$ (curves 2 and 3 of Fig. 2). On increasing the field fur-

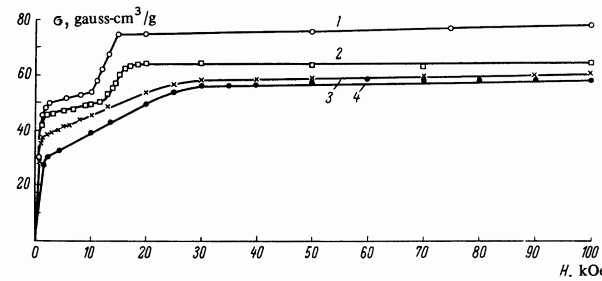

FIG. 1. Magnetization curves of a single crystal of $Sr_2Zn_2Fe_{12}O_{22}$ in the basal plane: 1 – T = 293°K, 2 – T = 230°K, 3 – T = 160°K, 4 – T = 77°K.

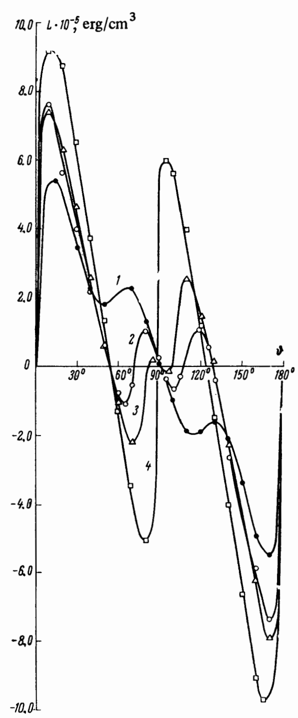

FIG. 2

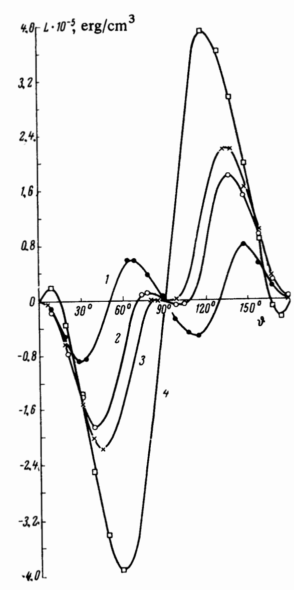

FIG. 3

FIG. 2. Torque curves of a single crystal of $Sr_2Zn_2Fe_{12}O_{22}$ in a plane perpendicular to the basal plane at T = 77°K: 1 – H = 7 kOe, 2 – H = 8 kOe, 3 – H = 9 kOe, 4 – H = 19.5 kOe.

FIG. 3. Torque curves of a single crystal of $Sr_3Zn_2Fe_{24}O_{41}$ in a plane perpendicular to the basal plane at T = 293°K: 1 – H = 5 kOe, 2 – H = 7 kOe, 3 – 8 kOe, 4 – H = 24.5 kOe.

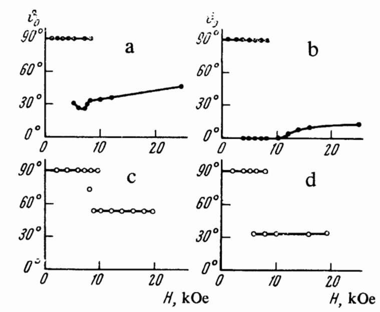

FIG. 4. Dependence of the vertex angle of the easy magnetization cone ϑ_0 on the magnitude of the magnetic field H for various single crystals at various temperatures: a – $Sr_2Zn_2Fe_{12}O_{22}$ at 293°K; b – the same at 77°K; c – $Sr_3Zn_2Fe_{24}O_{41}$ at 293°K, d – the same at 77°K.

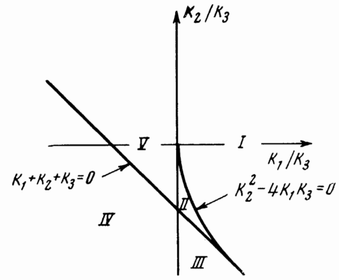

FIG. 5. The plane of the variables K_1/K_3 and K_2/K_3 of expression (1).

ther the minimum ϑ = 90° disappears (curve 4 of Fig. 2). It is seen from Fig. 3 that the Sr_3Zn_2Z crystals at 293°K in fields up to 8 kOe (curves 1–3) have both an axis (ϑ = 0) and a plane of EM (ϑ = 90°), and on increasing the field they have at first only an axis and then (in fields above 10 kOe) only a cone of EM (curve 4) which changes its vertex angle with changing magnitude of the magnetic field.

In Fig. 4 we present a graph of the dependence of the vertex angle of the EM cone ϑ_0 on the magnitude of the magnetic field for Sr_2Zn_2Y and Sr_3Zn_2Z crystals. The case $\vartheta_0 = 0$ corresponds to the EM axis and $\vartheta_0 = 90°$ to the EM plane.

The simultaneous existence of the plane and cone of easy magnetization has previously been observed in hexagonal ferrites close in composition to Sr_2Zn_2Y.[2,3] The simultaneous existence of an EM axis and plane in hexagonal crystals is apparently observed for the first time.

Let us proceed to a discussion of the obtained results. First we shall briefly explain the simultaneous existence of two EM directions. The magnetic anisotropy energy E_K of a hexagonal crystal in the plane perpendicular to the basal plane can be represented in the form

$$E_K = \frac{K_1}{2}\sin^2\vartheta + \frac{K_2}{4}\sin^4\vartheta + \frac{K_3}{6}\sin^6\vartheta + \dots, \qquad (1)$$

where ϑ is the angle between the magnetization vector and the hexagonal axis of the crystal. An investigation of expression (1) for a minimum leads to the results shown in Fig. 5. The EM ($\vartheta_0 = 0$) axis exists in regions I, II, and III, the EM plane (ϑ = 90°) exists in regions III and IV, and the EM cone $[\sin^2\vartheta_0 = (-K_2 \pm (K_2^2 - 4K_1K_3)^{1/2})/2K_3]$ exists in regions II and V. Thus in region II the EM axis and cone exist simultaneously, and in region III the EM axis and plane exist simultaneously.

If one takes account in expression (1) of only two terms, then region II in Fig. 5 disappears. Accordingly, if the following terms in expansion (1) are taken into account there appears a region of simultaneous existence of the EM plane and cone.

We note that the observation of the simultaneous existence of two directions of easy magnetization in the ferrites under consideration indicates thus the weak convergence of the series (1) and the necessity of taking into account several of its terms.

The existence of critical fields in ferrites of the group under consideration was explained in[1] on the basis of a model of two magnetic sublattices with a weak exchange interaction between them. We make use of the same model to explain the dependence of the torque curves on the magnitude of the magnetic field (Figs. 2 and 3). The magnetic anisotropy energy of a hexagonal ferrite can be represented in the first approximation of perturbation theory in the form[1]

$$E_K = {}^1/_2K\sin^2\psi + {}^1/_2K'\sin^2\psi' + K''\cos\psi\cos\psi' + K'''\sin\psi\sin\psi', \qquad (2)$$

where ψ and ψ' are the angles between the magnetic vectors of the sublattices M and M′ and the principal symmetry axis of the crystal. The anisotropy constants in expression (2) are constant quantities, i.e., they depend only on the temperatures and do not depend on the magnetic field intensity H. It is, however, commonly accepted that the magnetic anisotropy energy is described in the same approximation differently, namely in the form of the first term of the series (1). Here the coefficient K_1 will no longer be a constant but will be a function of H. In fact, with the aid of the obvious relation

$$\mathrm{tg}\,\vartheta = (M\sin\psi + M'\sin\psi')\,/\,(M\cos\psi + M'\cos\psi')$$

one can compare expression (2) with the first term of the series (1). Now K_1 will be determined not only by the constants K, K′, K″, and K‴, M, and M′ but also by the angles ψ and ψ'. Since the orientation of the vectors M and M′ changes in the process of magnetization, ψ and ψ' and consequently also K_1 depend on H. The specific dependence differs for the various particular solutions ψ(H) and ψ'(H) (see[1]). Account of the following approximations in expression (2) will only complicate the dependence of K_1, K_2, etc. on H. In the processing of experimental data one employs mostly the simple expression (1) appropriate, strictly speaking, only when the mutual orientation of the sublattices does not change. It is, therefore, on the whole not surprising that the torques L turn out to depend on the magnetic field intensity H.

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