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DETERMINATION OF ANISOTROPY FIELDS OF POLYCRYSTALLINE AND POWDER FERRIMAGNETICS WITH HEXAGONAL CRYSTAL STRUCTURES BY THE FERROMAGNETIC RESONANCE METHODS

Values of magnetocrystalline anisotropy fields of hexaferrite powders with different types of magnetocrystalline anisotropy are determined by investigation of frequency dependencies of parameters of ferromagnetic resonance lines.

Keywords: *ferromagnetic resonance, hexaferrites, the magnetocrystalline anisotropy.*

Method for determination of anisotropy fields of single-crystal uniaxial ferrimagnets with hexagonal crystal structure from experiments on ferromagnetic resonance (FMR), based on the use of the formula for the resonance frequency (ω_0) of uniform precession of the magnetization [1,2]:

$$\omega_0 = \frac{\gamma}{M_0 \sin\theta_0}\left(U_{\theta\theta}U_{\varphi\varphi} - U_{\theta\varphi}^2\right)^{\frac{1}{2}}. \qquad (1)$$

Here γ – gyromagnetic ratio, M_0 – saturation magnetization, $U_{\theta\theta}$, $U_{\varphi\varphi}$, $U_{\theta\varphi}$ – second derivatives of the magnetic part of the free energy of the sample: $U=U_{Zee} + U_M + U_a$. $U_{Zee} = -\vec{M} * \vec{H}_0$ – Zeeman energy, $U_M = (1/2)\vec{M}\overleftrightarrow{N}\vec{M}$ – demagnetizing energy and $U_a = k_1 sin^2\theta + k_2 sin^4\theta + k_3 sin^6\theta$ – magnetocrystalline anisotropy energy. k_i – anisotropy constants. The orientation of the vectors $\vec{M}$ and $\vec{H}_0$ in a spherical coordinate system with axis z is directed along the hexagonal c-axis, defined by angles θ, φ and Θ, Φ, respectively. Note for an arbitrary orientation of the magnetizing field $\vec{H}_0$ relative to the crystallographic axes of the sample that before applying the formula (1) is necessary to solve the problem of the equilibrium orientation of the magnetization vector - to find the equilibrium angles θ_0,φ_0. In the case of magnetic uniaxial crystal, energy depends only on the angle θ and the equilibrium condition can be written: $U'_\theta(\theta_0, \Theta) = 0$. This equation is transcendental, and its solution in the general case is possible only by numerical methods. The problem is greatly simplified if the magnetizing field is applied along a stationary directions (SD) of magnetization. For a sample magnetized to saturation, in this case, the equilibrium angle $\theta_0 = \Theta$. The only SD of uniaxial crystals with $|k_1| >> |k_2| + |k_3|$ is the direction along the hexagonal axis $\theta_0 = \Theta = 0$ and in the basal plane $\theta_0 = \Theta = \pi/2$. The resonance frequencies for these directions can be written:

$$\omega_\parallel = \gamma_\parallel\left[H + H_{a1}\right],\ \omega_\perp = \gamma_\perp\left[H\left(H - H_\theta\right)\right]^{1/2}. \qquad (2)$$

Here H_{a1} – anisotropy field along the hexagonal axis, $H_\theta = H_{a1} + H_{a2} + H_{a3}$ – anisotropy field in the basal plane, $H_{ai} = 2ik_i / M_0$. Thus, to determine the gyromagnetic ratio and the anisotropy fields from the FMR experiments on single-crystals you have to orient the sample along the directions $\theta_0 = \Theta = 0$ and $\theta_0 = \Theta = \pi/2$, determine the frequency dependence of the resonance fields and process these dependencies by formulas (2) to estimate unknown parameters: $\gamma_\parallel, \gamma_\perp$ and the anisotropy fields H_{a1}, H_θ.

Note that although the polycrystalline and powder materials macroscopically isotropic, the presence of the magnetic anisotropy of individual grains is shown in the FMR resonance curves in the form of features - maxima or steps. Especially simple to analyze the FMR in such inhomogeneous materials with the independent grains approximation, which is well satisfied for the hexaferrite powder with a large value of the magnetocrystalline anisotropy [3]. On the FMR curves of the magnetic uniaxial materials there are two features:

- low-field feature, corresponding to the resonance of the crystallites for which the direction of the magnetizing field (H) is close to the directions of easy magnetization. For $k_1>0$ resonance field of this feature is defined by (2) for $\omega_\parallel$, for $k_1<0$ – $\omega_\perp$;

- high-field feature corresponds to the resonance of the crystallites in which the magnetizing field is oriented near the hard magnetization directions of the grains. For $k_1>0$ the resonance field is given by (2) for $\omega_\perp$, for $k_1<0$ – $\omega_\parallel$.

Note that the values of the resonance fields (or frequencies) of the powder (polycrystalline) sample features - maxima and steps, which available on the FMR curves, will coincide with those calculated by the formulas (2) only in the case of negligible dissipation in a individual single-crystal grains [1]. The calculations show that in the presence of dissipation, the resonant field, given by the formulas (2) are close to the fields corresponding to the maxima of the derivatives of the resonance curves.

So, analysis of the experimental FMR spectra is conducted in two stages. In the first stage being built frequency dependence of magnetizing fields corresponding to the maxima of the derivatives. Processing of these relationships by least squares method according to the formulas (2) is determine $\gamma_\parallel, \gamma_\perp$, and approximate values of the anisotropy fields H_{a1}, H_θ. Next, through a detailed comparison of the calculated and experimental forms of the FMR curves is carried out refining of the values of the anisotropy fields.

This methodology was applied to analyze the magnetocrystalline anisotropy of hexagonal ferrimagnetic powders with the easy magnetization axis and the easy magnetization plane of (EMA and EMP). FMR curves were investigated in the frequency range 26 - 53 GHz.

Materials with EMA were synthesized by method of self-propagating high temperature synthesis (SHS):

- nanocrystals of barium hexaferrite $BaFe_{12}O_{19}$ –(BaM). The average particle size – 60÷90 nm, content of the main phase 98 %. The measured value of the anisotropy field H_{a1} =14,0 ± 0,2 kOe is less than the H_{a1} of the bulk material at 3 kOe [2];
- single-domain hexaferrite powders of $Sr(Co_xTi_x)Fe_{12-2x}O_{19}$ –(SrCoTiM) ($0 \le x \le 1{,}0$). The content of the M-phase is more than 90 %. The average particle size ≥ 1 μm. The values of anisotropy fields for this powders placed in the table below:

Anisotropy field of hexaferrite powders system $Sr(Co_xTi_x)Fe_{12-2x}O_{19}$.

x	0,0	0,5	0,6	0,7	0,8	0,9	1,0
H_{a1}, kOe	16,4	15,2	13,5	12,3	10,5	9,7	8,4
$H_{a2} + H_{a3}$, kOe	–	–	–	–	0	–1,2	–2,4

Hexaferrite EMP powders synthesized by ceramic technology with following grinding in a ball mill:

- $BaCo_1Zn_1Fe_{16}O_{27}$ – (CoZnW), the size of the powder particles 37–400 μm. The content of W-phase ≈ 85 %. The measured value of the anisotropy field H_θ = -8,2 ± 0,2 kOe.
- $Ba_3Co_{2,4}Ti_{0,4}Fe_{23,2}O_{41}$ – (CoTiZ), the size of the powder particles 100–125 μm. The content of Z-phase ≈ 90 %. The measured value of the anisotropy field H_θ = -14,3 ± 0,2 kOe.

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