Structure of near-surface magnetic layer in iron borate

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Magnetic structure of inhomogeneously magnetized near-surface magnetic layer for non-basal faces of $FeBO_3$ single crystals has been calculated. That layer has macroscopic thickness and can be observed in easy-plane weak ferromagnets. The calculation is based on our theory of Iron Borate surface magnetism.

Произведен расчет магнитной структуры неоднородно намагниченного приповерхностного слоя для небазисных граней монокристаллов $FeBO_3$. Такой слой имеет макроскопическую толщину и может наблюдаться в легкоплоскостных слабых ферромагнетиках. Расчет основан на развитой нами теории поверхностного магнетизма бората железа.

Iron borate is a trigonal crystal described by D^6_{3d} spatial symmetry group. It is an antiferromagnet with weak ferromagnetism and magnetic anisotropy of easy-plane type [1]. Iron borate single crystals are traditionally grown from solution in melt. In this case, the samples are shaped as basal plates ($\perp C_3$) of a 50 to 100 μm thickness. To synthesize isometric crystals, we have developed and used the gas-transport growth method. The samples obtained were of different shapes and had mirror faces of the following types: $(10\bar{1}4)$, $(10\bar{2}0)$, $(10\bar{2}3)$, $(01\bar{1}2)$ and (0001).

The surface magnetism being a specific near-surface magnetic transition layer has been revealed and studied on non-basal natural faces of isometric $FeBO_3$ single crystals [2]. The near-surface transition layer arises due to exchange interaction and specific surface magnetic anisotropy, which pins the magnetic moments of surface ions in a certain direction in basal (easy) plane. This anisotropy is caused by change in the symmetry of magnetic ion environment at the crystal surface as compared to the volume [3]. The surface anisotropy and exchange interaction result in a gradual change in spin orientation from spin direction at the surface to its direction in volume. That rotation takes place in near-surface layer of macroscopic thickness, because of very small basal anisotropy in the sample bulk, the surface anisotropy existence and low demagnetization field proportional to weak ferromagnetic moment. In contrast to ordinary ferromagnet, the easy-plane weak ferromagnet is the case of favorable conditions for surface anisotropy observation.

Thus, a layer with inhomogeneous magnetization distribution of domain boundary type is formed in near-surface region of non-basal faces in iron borate single crystals. Let us calculate the magnetic structure of such near-surface layer.

Considering the magneto-dipole interaction of magnetic ions Fe^{3+} in near-surface region as a main mechanism of the surface anisotropy [2], we have obtained the expression for surface anisotropy energy σ. For the face $(10\bar{1}4)$, it is reduced to the form

$$\sigma = a_S \cdot \sin^2\varphi_0, \tag{1}$$

where a_S is the calculated magneto-dipole constant of the surface anisotropy; φ_0, the angle defining the spin direction on the surface (Fig. 1).

The magnetization distribution in the transition layer depends on external magnetic field. The layer structure can be determined basing on the expression for its energy, γ. For the face $(10\bar{1}4)$, γ has the form:

$$\gamma = \int_0^\infty \left[\frac{A}{2}\left(\frac{d\varphi}{dS}\right)^2 + MH(1 - \sin\varphi)\right] dS. \tag{2}$$

Here A is exchange parameter; M, spontaneous magnetization; H, magnetic field applied along hard axis ($H \| x$, Fig. 1), which orientation can be determined from the minimum condition for expression (1); S is the distance from the crystal surface into its depth; φ, the angle between magnetic field and the spin direction at the distance S from the surface.

Using functional (2) minimum condition, we have found the equilibrium value of the transition layer energy for arbitrary angle φ_0:

$$\gamma^{eq} = 4\sqrt{AMH}[1 - \cos(\pi/4 - \varphi_0/2)], \tag{3}$$

and got expression connecting spin orientation with its distance from the surface $(10\bar{1}4)$:

$$S, [\mu m] \cong \frac{1}{\sqrt{H}} \ln \frac{(1 + \cos\alpha)(1 - \cos\beta)}{(1 - \cos\alpha)(1 + \cos\beta)}. \tag{4}$$

were $\alpha = \pi/4 + \varphi/2$, $\beta = \pi/4 + \varphi_0/2$. The angle φ_0 is determined by the equation

$$\frac{\partial}{\partial\varphi_0}(\gamma^{eq} + \sigma) = 0. \tag{5}$$

Taking into account (1) and (3), the expression (5) can be reduced to the form

$$-2\sqrt{AMH}\sin\left(\frac{\pi}{4} - \frac{\varphi_0}{2}\right) + a_S \cdot \sin 2\varphi_0 = 0. \tag{6}$$

In fact, the equation (6) determines the curve of surface magnetization. The saturation field causing homogeneous magnetization distribution in near-surface region (erasing the transition layer) is found from this equation in the case $\varphi_0 = \pi/2$:

$$H_S = \frac{4}{AM} \cdot a_S^2. \tag{7}$$

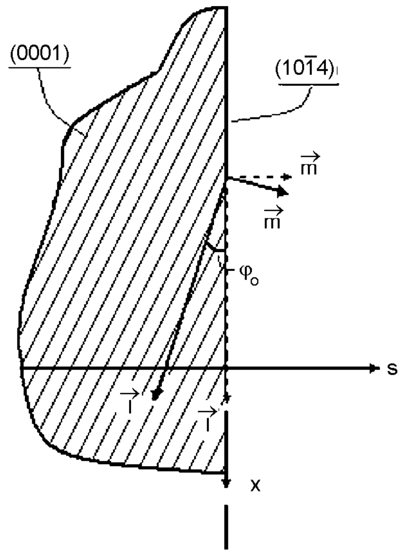

Fig. 1. Geometry of magnetization process.

Using (7), equation (6) can be written in another form:

$$-\sqrt{H}\sin\left(\frac{\pi}{4} - \frac{\varphi_0}{2}\right) + \frac{\sqrt{H_S}}{4}\sin 2\varphi_0 = 0. \tag{8}$$

Our calculations based on the formula (7) give H_S = 750 Oe at room temperature. In experiment, the saturation field H_S, which is actually field of surface atomic layer magnetizing, can be determined by means of magneto-optical reflecting Kerr effects. Since the depth of reflected beam formation is very small (~0.01 μm), the Kerr effects enable to measure magnetization of very thin surface layer (much thinner that said transition magnetic layer).

Using the equatorial Kerr effect, we have found experimental value of saturation field for the face $(10\bar{1}4)$ at room temperature: $H_S \approx 1000$ Oe. The symmetry of measured surface anisotropy was in coincidence with the theory.

We have studied the magnetization distribution in the transition layer by constructing curves $\varphi(S)$ on the basis of (4), (8), and experimental value of the field H_S for different values of magnetic field H (Fig. 2).

In experiment, the structure of near-surface magnetic layer can be studied by measuring magnetization curves of near-surface layers of different depths. In principle, magneto-optical reflecting effects can be used for this purpose, since the effect formation depth can be controlled within certain limits by changing the light wavelength [4]. In our case, however, this method is ineffective, because of too small

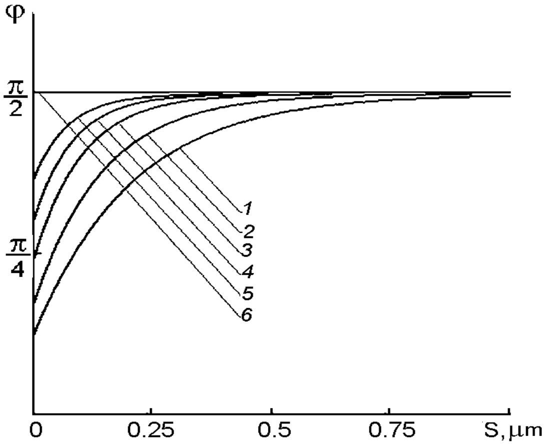

Fig. 2. Spin directions in transition layer in magnetic field: H (Oe): 100 (*1*), 200 (*2*), 400 (*3*), 600 (*4*), 800 (*5*), 1000 (*6*).

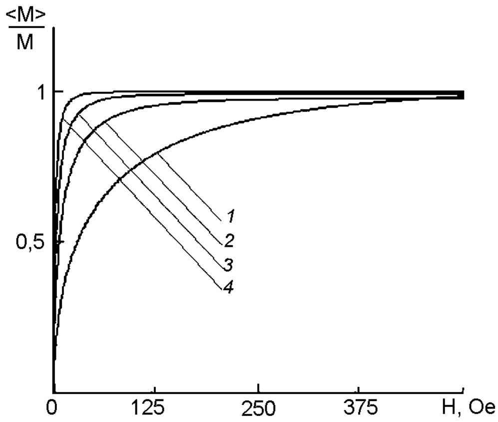

Fig. 3. Magnetization curves for near-surface magnetic layers of different depth S (μm): 0.1 (*1*), 0.3 (*2*), 0.5 (*3*), 0.8 (*4*).

depth of magneto-optical signal formation. To investigate the magnetic structure of iron borate transition layer, the use of magnetic Moessbauer effect registration method seems to be of interest that enables to measure the average magnetization of the near-surface magnetic layer determined by depth of radiation penetration into the crystal. Detuning from resonance and changing the γ-quantum energy, the penetration depth can be varied [5]. Using for this purpose a high-power synchrotron radiation instead of "classic" radioactive Moessbauer source, seems to be the most promising trend [6]. In this case, we could experiment with samples $FeBO_3$ containing the Messbauer isotope ^{57}Fe in natural concentration (~2 %).

Let us calculate average magnetizations of the layers expected in experiment. The average magnetization of the layer is determined as:

$$\langle M(H)\rangle = \frac{1}{S_l}\int_0^{S_l} \rho(S)\cdot M_H(S)\cdot dS = \frac{1}{S_l}\int_0^{S_l} \rho(S) M\cos(\pi/2-\varphi)dS. \quad (9)$$

Here S_l is the thickness of probed layer; $M_H(S)$, magnetization in the depth S; $\rho(S)$, weighting factor considering Messbauer radiation damping in the crystal. Fig. 3 presents curves $M(H)$ calculated according to (9) and taking into account (4), (8) and experimental value of saturation field H_S = 1000 Oe. In (9), we have assumed $\rho = 1$ for simplicity sake.

Thus, we have calculated the transition magnetic layer structure in iron borate. The dependence of the structure on applied magnetic field has been determined. Experimental possibilities of investigation of this structure have been discussed as well.

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Структура приповерхневого магнітного шару у бораті заліза

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Виконано розрахунок магнітної структури неоднорідно намагніченого приповерхневого шару для небазисних граней монокристала $FeBO_3$. Такий шар має макроскопічну товщину і може спостерігатися у легкоплощинних слабких феромагнетиках. Розрахунок базується на розвинутій нами теорії поверхневого магнетизму борату заліза.