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ANISOTROPY OF MAGNETO-OPTICAL ORIENTATION EFFECT IN SINGLE CRYSTAL OF NICKEL

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Abstract. — It was been proved that besides with the isotropical magneto-optical Kerr effect (EKE) in the cubic single crystal Ni there is a strongly anisotropic magneto-optic orientation effect \( \delta_{\theta r} \) which is quadratic in magnetization. The dependence of \( \delta_{\theta r}(\omega) \) for the main crystallographical directions in the interval \( 0.17 < \omega < 3.25 \text{ eV} \) and the anisotropy of \( \delta_{\theta r} \) in the plane (110) at fixed \( \omega \) have been studied. The dependence of \( \delta_{\theta r}(\omega) \) is more complicated than for EKE, which is accounted for by the changing of the band structure of a ferromagnetic metal under the influence of the spin-orbit interaction due to the rotation of \( I \). On the basis of the above assumption the peculiarities of the curve \( \delta_{\theta r}(\omega) \) are related to the definite interband transitions according to the existing models of the electronic structure.

The investigation of the anisotropy and frequency dependence of magneto-optical orientation effect (MOE) [1, 2] consisting in even in magnetization change of intensity of p-wave of linearly polarized light is the most urgent task. The study of MOE anisotropy is important for the understanding of the nature of this magneto-optical phenomenon, while the knowledge of its frequency dependence will allow us to make the next step in ascertaining the structure of electronic energy spectrum of the ferromagnetic metals.

In this paper the investigation of MOE anisotropy of single crystals of ferromagnetic nickel is discussed. The measurements were carried out in the energy interval of light quanta from 0.17 to 3.25 eV on the magneto-optical setup described before [3]. The sample of the single crystal of nickel was cut out of a rod by the spark method in the plane (110) and had the form of a disc with the diameter of 10 mm and thickness 0.5 mm. The sample was subjected first, to mechanical and then to electrical polishing. The thickness of the removed layer was greater than 100 microns. The measurements of MOE and equatorical Kerr effect (EKE) were carried out simultaneously. The measurements of EKE, which is the odd function of magnetization, were carried out, as before, [4] by the commutation dynamic method with periodically changing magnetic field \( H = H_0 \sin \omega t \) (\( H_{\text{max}} = \pm 2 700 \text{ Oe} \)). EKE corresponding to the saturation magnetization is \( \delta = (\Delta R/R_0)_{H_z=H} \) (\( R_0 \) the intensity of light reflected by the ferromagnetic mirror in demagnetized state, \( \Delta R \) the change of reflected light intensity in result of magnetizing the sample). The change of the magnetic field from 0 to \( + H \) and from \( - H \) to 0 (\( |H| = 2 000 \text{ Oe} \)) causes the corresponding change in magnetization from \( I \) to \( I \) and from \( - I \) to \( - I \), which results in the effects \( \delta_a \) in the formed and \( \delta_b \) in the latter case.

The difference \( \frac{\delta_a - \delta_b}{2} \) defines the even in magnetization MOE \( \delta_{\theta r} \), while the sum \( \frac{\delta_a + \delta_b}{2} \) defines the odd EKE-\( \delta \).

Figure 1 represents the results of the measurements of the MOE frequency dependence \( \delta_{\theta r}(\omega) \) carried out on a single crystal of Ni being magnetized along different crystallographical directions \( [l, m, n] \). The positive sign of MOE corresponds to the increase of the reflected light intensity, while the sample is being magnetized. The values of the effect given in the picture are normalized according to [3] in order that the values of MOE should corresponds to the transition...
of the sample from the quite demagnetized state to that of magnetization saturation.

The curves of MOE dependence on the angle $\psi$ between the direction of magnetization field and the crystallographical axis [100], given in figure 2, display strong anisotropy of this effect where as EKE is quite isotropic within the limits of the error the measurement experiment.

The anisotropy of magneto-optical effects in ferromagnetic metals was discussed by Donovan and Medcalf [5]. Having made the calculation according to the scheme of Argyres [6], taking into account the terms of the second order in spin-orbit interaction, these authors showed that in cubic ferromagnetic metals, as well as in cubic semiconductors with anisotropic Fermi-surface, the phenomenon of anisotropy of magneto-optical effect is possible because of the effects of the second order. In paper [5] discussing the anisotropy of quadratic magneto-optical effects for Voigt configuration (E//I) in the plane (100), the observed MOE is shown to correspond to the Voigt configuration for the case of the crystallographical plane (110). Having made the calculations analogous to [5] for the plane (110), we obtain the angle dependence dielectric permeability tensor components $\varepsilon_{ij}^{(2)}$ quadratic in magnetization:

$$
\varepsilon_{xy}^{(2)} = \varepsilon_{yx}^{(2)} = \frac{1}{2} \sin 2 \psi \sin \phi (\cos 2 \psi + \cos^2 \psi) \varepsilon^{(2)}
$$

$$
\varepsilon_{xx}^{(2)} = \sin^2 \psi (1 + \cos^2 \psi) \varepsilon^{(2)}
$$

$$
\varepsilon_{yy}^{(2)} = \sin^2 \psi (\cos^2 \phi + 3 \cos^2 \psi \sin^2 \phi) \varepsilon^{(2)}
$$

where $\psi$ the angle between the direction of the magnetic field $H$ and the axis [001]; $\phi$ the angle of light incidence. It follows, from the received expressions, that when $\psi = 0$ i. e. for the case when the crystal is magnetized along the x axes [001], all $\varepsilon_{ij}^{(2)}$ components become zero, and consequently, the linear double refracting in Voigt configuration is absent. This conclusion is quite contradictory to the above experimental results, as well as the analogous measurements on the single crystal of silicon iron [3] and consequently, the observed even in magnetization change of reflected light intensity (MOE), comparable in magnitude with the usual EKE, is not reduced to the Voigt effect in cubic crystals obtained by the calculations taking into account the terms of the second order in spin-orbit interaction [5].

Besides strong anisotropy the orientation effect differs from the equatorial effect by a peculiar dependence on the wavelength which is evidently, connected with the orientation effect «localization» in the vicinity of those points and lines of Brillouin zone where the energy band degeneration is removed by the spin-orbit interaction. In this respect the obtained experimental results are in qualitative agreement with the electron structure model of Ni with the reverse order of levels [4, 7]. In papers Falicov and Ruvalds [8] and Zornberg [9] a detailed analysis of the problem of spin-orbit removing degeneration occurring at the intersection of oppositely directed band spins is given. Figure 1 in paper [2] reproduced the scheme of such removing of band degeneration $L_{132} \uparrow$ and $L_{132} \downarrow$ due to the change of magnetization vector orientation $I$.

Let us consider the following identification of the peculiarities of $\delta_{ob}$ curves with the interband transitions B, E, F and G. The broad maximum on the curves $\delta_{ob}^{[100]}$ and $\delta_{ob}^{[110]}$ in the region of 0.7-0.9 eV (Fig. 1) may be connected with the transition F, while the maximum $\delta_{ob}^{[111]}$ in the interval of 0.9-1.2 eV with the transition E (MOE of the second type [2]). Using the additional data on these maxima, obtained from
the low temperature measurements [3] receive that \( h\omega_{p} = 0.76\) eV and \( h\omega_{e} = 1.1\) eV. The maxima in the region \( h\omega \approx 0.3\) eV on the curves \( \delta_{\nu} \) may be connected with the transitions B and G. To eliminate ambiguity, let us assume \( h\omega_{p} = 0.35\) eV (maximum on the curve \( \delta_{[111]}^{[001]} \)) and \( h\omega_{e} = 0.3\) eV (maxima on the curves \( \delta_{[100]}^{[111]} \) and \( \delta_{[110]}^{[111]} \)). The transitions C and D should be less influenced by the spin-orbit interaction, though it is possible, that the low energy maximum on the curve \( \delta_{[111]}^{[111]} \) is due to C transitions i.e. \( h\omega_{e} = 0.2\) eV. Applying the set VII of band parameters from [9], obtain the following values for the above interband transitions: \( h\omega_{p} \approx 0.4\) eV, \( h\omega_{e} \approx 0.25\) eV, \( h\omega_{F} \approx 0.7\) eV, \( h\omega_{E} \approx 1.0\) eV.

Figure 3 shows the results of MOE frequency dependence measurements for three main crystallographical directions in the visible region of the spectrum (2.0-3.25 eV) where, according to the magneto-optical observations [4] the anomaly connected with the interband transitions \( X_{5} \rightarrow X_{4} \) in the vicinity of point X occurs. The measurements of the EKE in this energy interval have shown that, within the exactness of the measurements, this effect is isotropic (one curve \( \delta_{\nu}(\omega) \) for the axis [111] is given in the figure 3 for the sake of illustration), while MOE in contrast to EKE displays strong anisotropy. It is most probable, that such a behavior of MOE in the vicinity of point \( X_{5} \) is connected with the anisotropic spin-orbit splitting of \( X_{5} \) band due to the magnetization vector rotation.

It is also worthwhile to note, that the above identification of the transition \( X_{5} \rightarrow X_{4} \) (\( h\omega = 2.4\) eV) is in a considerably better agreement with band calculations according to the model with the reverse order of levels in point L [7, 9].

References