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INFERROMAGNETIC METALS
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MAGNETO-OPTICAL ORIENTATION EFFECT INFERROMAGNETIC METALS

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Résumé. — Des essais ont été faits pour détecter optiquement l'influence de l'orientation du vecteur aimantation sur la structure électronique d'un métal ferromagnétique, effet qui semble résulter de l'interaction spin-orbite. Un nouvel effet magnéto-optique appelé effet d'orientation $\delta_{or}$ a été découvert dans l'effet Kerr en géométrie équatoriale. Contrairement aux effets magnéto-optiques ordinaires, cet effet est caractérisé par une variation particulière en fonction de la longueur d'onde de la lumière. Deux méthodes classiques de description de $\delta_{or}$ sont proposées consistant à introduire un terme supplémentaire d'anisotropie dans les composantes diagonales et non diagonales du tenseur de perméabilité diélectrique. Une méthode expérimentale est proposée permettant de vérifier la validité de l'un des modèles. Différentes possibilités d'utilisation de $\delta_{or}$ pour identifier les transitions entre bandes dans les métaux ou alliages ferromagnétiques sont envisagées.

Abstract. — An attempt was made to detect optically the influence of the orientation of magnetization vector on the electronic structure of a ferromagnetic metal which appears as a result of the spin-orbit interaction. A new magneto-optical effect named orientation effect $\delta_{or}$ was discovered at the geometry of the equatorial Kerr effect. In contrast to the usual magneto-optical effects it is characterized by the quadratic dependence on the magnetization, extremely great anisotropy and a peculiar dependence on the wavelength of the light. Two methods of classical description of $\delta_{or}$ by means of introducing an additional anisotropic term into the diagonal or non-diagonal component of the dielectrical permeability tensor are suggested. A method of experimental determination of the validity of one of these descriptions is given. Different possibilities of using $\delta_{or}$ for the identification of the interband transitions in ferromagnetic metals and alloys are considered.

It has been recently discovered that spin-orbit interaction in ferromagnetic metals results in an extremely interesting phenomenon. Investigating Fermi surfaces of ferromagnetic nickel Hodges et al. [1] have discovered a peculiar change in the form of the hole pockets at the X point and connected this with the fact that the spin-orbit splitting of the twice degenerated band $\Delta$ in the vicinity of the X point changes from zero to the maximum value of the order of 0.1 eV when the orientation of the magnetization vector I in the crystal changes (see also [2, 3]).

It is essential to point out here, that spin-orbit interaction must affect in the above sense, not only the energy levels of the Fermi surface but also the whole electron energy spectrum of the ferromagnetic metal, and this influence should be especially strong in those regions of Brillouin zone where the energy level degeneration is removed by the spin-orbit interaction. Hence, it is possible, in principle, to observe the indicated change of the electron structure of a ferromagnetic metal, following rotation of I, by an optical method at the frequencies of the interband transitions.

The localization of maximum changes of this kind in definite regions of the Brillouin zone gives us hope of a reliable identification of interband transitions are consequently quantitative determining band parameters of ferromagnetic metals and alloys. Paper [4] discusses the special experiment undertaken to discover the magneto-optical effect of change of electronic structure of a ferromagnetic metal following rotation of the magnetization vector. In [5] it was stated that this effect, called magneto-optical orientation effect (MOE), was proportional to the square of magnetization component normal to the plane of incidence of the light. In [6] a detailed study of anisotropy of orientation effect in single crystals of nickel and silicon iron is given, and it is shown that MOE cannot be reduced to the Voigt magneto-optic effect. Let us consider different types of orientation effect due to spin-orbit interaction, the possibilities of its application to the study of band structure and the phenomenological methods of defining the kind of the tensor of dielectrical permeability resulting in MOE.

Figure 1, reproduced from [7], gives the scheme of band structure of ferromagnetic nickel in the vicinity of the point L for two different orientations of I for the electron model with the reverse order of levels [8]. The first possibility for the appearance of MOE is the splitting of degenerated bands in the vicinity of certain lines or points of symmetry. In figure 1a, for example it is the region of strong splitting of the band $\Delta$ for transitions $\lambda_1 \downarrow \rightarrow \lambda_4 \downarrow$ in the interval from B to A. In the vicinity of the point of the intersection of the band $\Delta \downarrow$ with Fermi level (the edge A) and in the vicinity of the L point (the edge B) strong optical and magneto-optical orientation effects should be expected since here considerable changes of interband density of state take place. In the interval from B to A only parallel band shifting occurs, while the interband density does not change to the first approximation, and so, only magneto-optical effects of orient-

![Diagram of band structure near symmetry point L](http://dx.doi.org/10.1051/jphyscol:19711380)
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The third type effect when the turn of $I$ results in the appearance or disappearance of the hole pockets in the point $X$. In this case certain parts of the bands, in the vicinity of singularity, are excluded from the interband transitions, and therefore the change of the interband density and the appearance of strictly frequency localized orientation optical and magneto-optical effects are obvious. In order that MOE of the third type should appear, it is necessary that the singularity in the degeneration band should occur near the Fermi surface i.e. at the distance of the order of 0.1 eV. This situation is possible for the shown in figure 2 $X_5$ point in ferromagnetic nickel, the exchange splitting being $\Delta E_\text{d} \approx 0.3$ eV. This situation may be also obtained by means of changing some parameters such as temperature and alloy concentration. In all considered cases it should be born in mind that only one of the equivalent points of Brillouin zone was taken into consideration while it is necessary to find the averaged value of all the analogous in symmetry but not equivalent points, orientation being fixed. It is natural that the indicated inequality should lead to the characteristic fine structure peculiarity which may be used as an additional information for the identification of the interband transitions.

Let us consider now the possibility of phenomenological determining of the kind of the dielectric permeability tensor $\varepsilon$ resulting in MOE. It is clear from the symmetry considerations that MOE may be caused by the quadratic in magnetization additions in the diagonal and non-diagonal terms $\varepsilon$. To find out which of these additions play the main part is easier by measuring the dependence of MOE on the angle of light incidence. Let us consider separately the two cases of inserting quadratic in magnetization additions $q$ and $r$.

Case I: $\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon(1 - q)$, $\varepsilon_{zz} = \varepsilon = \varepsilon_1 - i\varepsilon_2$, $\varepsilon_{xy} = \varepsilon_{yx} = 0$ where $q = q_1 - iq_2$ is quadratic in magnetization addition, $q \ll 1$. From Maxwell equations for this case with the approximation $\varepsilon \ll 1$ and restricting to the linear terms for $q$ we find the following expression for the relative change of the intensity of $p$-component of reflected light $\delta'$:

$$\delta' = \frac{R - R_0}{R_0} = 2 \cos \varphi \frac{b(kq_2 - nq_1) - a(kq_1 + nq_2)}{a^2 + b^2}$$

where $n - ik = \sqrt{\varepsilon}$, $a = \cos^2 \varphi \varepsilon_2$, $b = \cos^2 \varphi \varepsilon_1 - 1$, and $\varphi$ the angle of light incidence.

Case II:

$$\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = \varepsilon, \varepsilon_{xy} = \varepsilon_{yx} = i\varepsilon r$$

where $r = r_1 - ir_2$ quadratic in magnetization addition, $r \ll 1$. Thus in the same way we receive the following expression for this case:

$$\delta'' = \frac{R - R_0}{R_0} = 2 \sin 2 \varphi \frac{b^2 r_2^2 - a^2 r_1^2}{a^4 + b^4}.$$

Comparing (2) and (3) we see that the diagonal addition $q$ retains its influence in the normal inci-
dence of light, while the contribution of the non-diagonal addition $r$ should vanish. It is interesting to measure the dependencies of MOE on $\phi$, the orientation of $I$ being along different axes of ferromagnetic crystal. In such measurements the main part for some axes may be played by diagonal additions $q$, while for the others additions $r$. Provided this qualitative characteristic of the kind of the tensor $\hat{\epsilon}$ is obtained, it is possible to calculate the corresponding orientation magneto-optical effects not only when the magnetization is equatorial but also for the case of polar and meridional magnetization of the ferromagnetic sample, as well as in the case of light passing through the sample with Faraday and Voigt geometry. Experimental detection and measurement of these orientation magneto-optical effects will make the quantitative determination of quadratic in $I$ components $q$ and $r$ possible.

References

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