Excitation of magnetized-plasma surface waves in nickel

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A change in the intensity of reflected light due to transverse magnetization of a nickel film (equatorial Kerr δ^e effect) in the energy range $1.5 < \hbar\omega < 3.2$ eV and at angles of incidence $15° < \varphi < 85°$ is measured under breakdown conditions of total internal reflection. The observed peaks on the curves $\delta^e(\varphi)$ are associated with excitations of two branches of magnetized-plasma surface waves (MPSW) on the nickel-air boundary. The dispersion relations for (MPSW) in the indicated frequency range are determined.

The method of breakdown of total internal reflection (BTIR) is widely used to excite nonradiative surface plasma waves (SPW) in metals and semiconductors.[1,2] Surface plasma waves become magnetized-plasma surface waves (MPSW) when a magnetic field is applied to the specimen; in addition, the dispersion relations change depending on the orientation of the magnetic field relative to the plane of incidence of light and the direction of propagation of SPW.[3] In particular, it is shown that in the case $\mathbf{H} \perp \mathbf{k}$ (the external magnetic field is perpendicular to the plane of incidence of light and the direction of propagation of MPSW) the dispersion curve $k(\omega)$ splits, forming high- and low-energy branches, depending on the sign (+ or −) of H. Surface plasma waves in semiconductors have been studied extensively theoretically[3,4] and have been observed experimentally.[4,5] For ferromagnetic metals, in which the appearance of MPSW must be a result of the presence of an internal molecular field, this problem has been studied very little. There are only two papers in which the dispersion for MPSW are presented and the observation of high-energy branch in nickel is reported.[6]

In this letter we present the results of magneto-optical measurements of the change in intensity of the reflected light under conditions of BTIR with transverse magnetization ($H \perp \mathbf{k}$) of the sample [equatorial Kerr effect (EKE)], which permitted determining the dispersion dependence $k(\omega)$ for two branches of MPSW in nickel and hence the magnitude of their splitting for different values of k. The data obtained are compared with magneto-optical measurements in the presence of longitudinal magnetization of the specimen ($H \| k$) [meridional intensity effect (MIE)].[7] The EKE and MIE are determined by the relation

$$\delta = \Delta R / R, \tag{1}$$

where ΔR is the change in the intensity of the reflected light due to magnetization of the sample, and R is the intensity of the reflected light at $H = 0$. The EKE was measured in the p component of the incident light (the vector $\mathbf{e}$ is oriented parallel to the plane of incidence of light), since for a gyroelectric medium this effect is two orders of magnitude higher than for the s component (the vector $\mathbf{e}$ is oriented perpendicular to the plane of incidence). The MIE is observed at angles of polarization of the incident light that differ from the p and s components.[7]

The measurements were performed according to the BTIR method in the geometry proposed by Kretschmann,[8] in which the sample, in a thin film, was deposited on the flat side of a glass semicylinder. The BTIR method can be summarized as follows. A nonuniform wave, which is generated as a result of the reflection of light from the prism-nickel boundary, penetrates into the film and excites a nonradiative SPW mode at the Ni-air boundary. The surface plasma waves are transverse TH electromagnetic waves[1,2] which propagate along the interface between two media and damp out on both sides of the interface. When the wave vector of SPW is equal to the wave vector of the optical wave that propagates parallel to the prism-nickel boundary, most of the energy of the incident light goes into the excitation of SPW and total internal reflection is disrupted.

Using the magneto-optical setup based on a DMR-4 monochromator and described in detail in Ref. 7, we investigated by the BTIR method the angular dependences of EKE in the energy range $1.5 < \hbar\omega < 3.2$ eV at the angles of incidence of light $15° < \varphi < 85°$. The MIE was measured with longitudinal magnetization. The samples consisted of nickel films obtained by vacuum deposition on the flat boundaries of semicylinders made of heavy flint (the index of refraction of flint is $N = 1.7$). The thickness of the film varied from 160 to 2000 Å.

Figure 1 shows the angular dependences of EKE $\delta^e(\varphi)$ for a Ni film 160 Å thick. Curves 1–4 correspond to incident light energies $t = 2000$ Å and 1.5 eV. For comparison, the dependence of EKE for a Ni film $t = 2000$ Å thick with $\hbar\omega = 3.2$ eV is presented (curve 5). This figure also shows the typical angular dependence of the ratio of the coefficients of reflection of the p and s components $(R_p/R_s)(\varphi)$ (curve 6) for a thin film ($\hbar\omega = 3.2$ eV), which qualitatively reflects the behavior of the curve $R_p(\varphi)$. The analogous curve for $t = 2000$ Å has a form characteristic of the angular dependence of the coefficient of reflection of two media (flint–nickel) with a nonzero absorption coefficient. For a thin film the reflection coefficient is written in the form

$$R = (r_1 + r_2 e^{-i2\Delta}) / (1 + r_1 r_2 e^{-i2\Delta}), \tag{2}$$

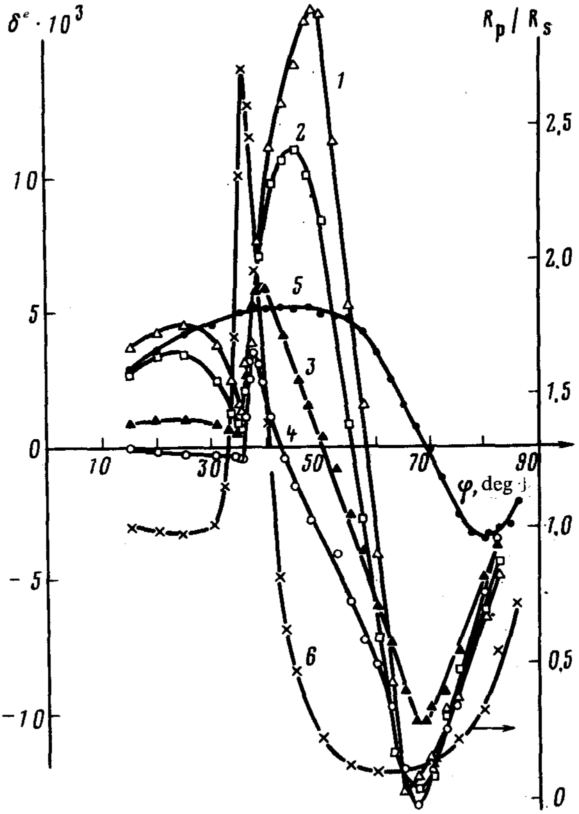

FIG. 1. Angular dependence $\delta^e(\varphi)$. Curves 1–4 correspond to a thickness of $t = 160$ Å and $\hbar\omega = 3.2, 2.75, 2.0$, and 1.5 eV, respectively, for curve 5 $t = 2000$ Å, $\hbar\omega = 3.2$ eV; b) angular dependence $R_p/R_s(\varphi)$ for a film $t = 160$Å, $\hbar\omega = 3.2$ eV.

where r_1 and r_2 are respectively the coefficients of reflection at the flint–nickel and nickel–air boundaries, $\Delta = 2\pi nt \cos\phi / \lambda_0$ is the phase factor proportional to the thickness of the film, n is the complex index of refraction of the film, ϕ is the angle of refraction, and λ_0 is the wavelength of light in a vacuum. The sharp increase in R_p/R_s at $\varphi = 36°$ (curve 6) corresponds to total internal reflection of the p component of the incident light at the Ni–air boundary ($\varphi_{\kappa p} = \arcsin 1/N$), while the deep minimum in R_p/R_s near $\varphi = 55$–$65°$, according to Refs. 1 and 8, indicates breakdown of total internal reflection due to excitation of SPW at the Ni–air boundary. The wave vector of SPW is determined by the relation

$$k = \frac{\omega}{c} N \sin\varphi , \tag{3}$$

where φ is the angle at which R_p assumes its minimum value.

In the presence of an external magnetic field surface plasma waves become surface magnetized-plasma waves. The excitation of MPSW is manifested as a sharp increase in the magnetic reflection δ. Comparison of $R_p/R_s(\varphi)$ and $\delta^e(\varphi)$ in Fig. 1

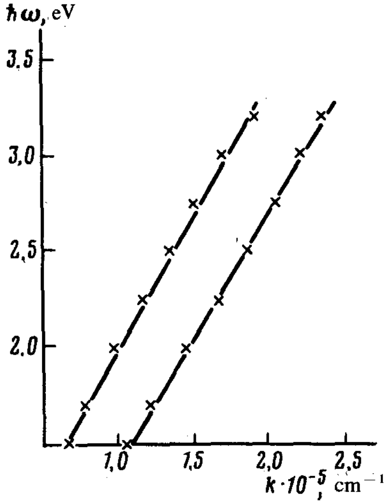

FIG. 2. Dispersion curves $k(\omega)$ of MPSW in a transverse magnetic field.

shows that the decrease in EKE at $\varphi = 36°$ is due to the increase in R_p at this angle. For a Ni film with $t = 160$ Å, a sharp increase in δ^e (by a factor of 3–5), observed on both sides of the minimum on the curve $(R_p/R_s)(\varphi)$ in the region $\varphi = 37–50°$ and $\varphi = 60–70°$, was observed. Since in the case $H \perp \mathbf{k}$ $k(\omega)$ splits into two branches, which are symmetrical relative to $k(\omega)$ at $H = 0$, for a fixed value of $\hbar\omega$ the wave vector of the MPSW, which belongs to each of the branches, can be reached by changing the angle of incidence of the light. For this reason, the observed increase in δ^e for a film with $t = 160$ Å can be attributed to the resonance response of the system due to the excitation of MPSW. The fact that the indicated maximum values of EKE have different signs requires a special theoretical analysis, which has not been performed for ferromagnets. However, if we consider the analogy of semiconductors,[4] the change in sign of δ in this case is physically understandable. Since both branches of MPSW correspond to the symmetrical splitting of the starting curve of the coefficient of reflection with a minimum at the frequency of excitation of SPW ω_0, magnetic reflection at this frequency must be zero, while the two peaks corresponding to the frequencies of excitation of MPSW must have different signs (shifted in phase by 180°).

Figure 2 shows the dispersion relations $k(\omega)$ for two branches of MPSW. The curves $k(\omega)$ were calculated using Eq. (3), into which the values of the angle φ corresponding to two maximum values of EKE with fixed value of $\hbar\omega$ were substituted. It is evident that for both branches the wave vector of the MPSW depends linearly on $\hbar\omega$; the splitting $\Delta(\hbar\omega)$ due to the application of a transverse field to the sample is 0.6 eV.

The results of measurements of MIE are shown in Fig. 3. The angle of polarization of the incident light is 45°. Curves 1–4 correspond to a film with a thickness of $t = 160$ Å; curve 5 corresponds to a film with $t = 2000$ Å at $\hbar\omega = 3.2$ eV. It is evident that with longitudinal magnetization of the sample, in the region of the minimum in R_p/R_s, the MIE has only one peak in the region $\varphi = 65–70°$. The increase in δ^{MI} in a thin film (see curves 1 and 5) apparently indicates that the MPSW are excited. This result qualitatively corresponds to the theoretical conclusion obtained for the Drude

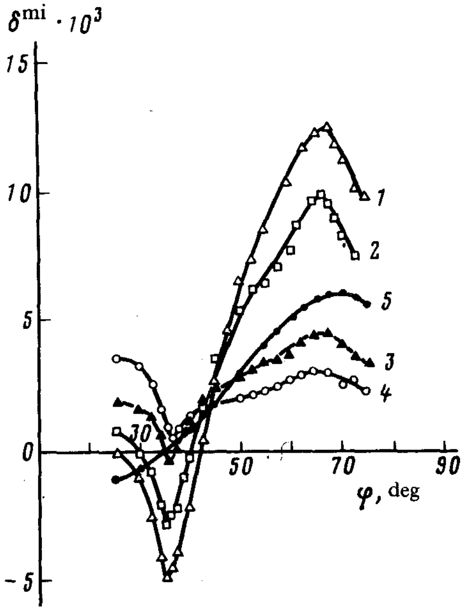

FIG. 3. Angular dependence $\delta^{MI}(\varphi)$. Curves 1–4 correspond to $t = 160$ Å and $\hbar\omega = 3.2$, 2.75, 2.0 and 1.5 eV, respectively; 5) $t = 2000$ Å, $\hbar\omega = 3.2$ eV.

model, according to which only a single branch of MPSW should be observed for longitudinal magnetization. We note that the dispersion curve $k(\omega)$, determined from the peaks in δ^{MI} in Fig. 3, essentially coincides with the low-energy branch in Fig. 2. This fact and the fact that with the extrapolation to $\omega\to 0$ only the low-energy branch of the two MPSW branches passes through the origin require further theoretical study.

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