times. Thus, inasmuch as the frequency of the local oscillation of the U centers is LiF = 1015 cm^{-1}, our band at 2100 cm^{-1} must be ascribed to U_1 centers.

The authors are grateful to Academician E. L. Andronikashvili for stimulating interest in the work.

[1] Z. G. Akhvelidiani and N. G. Politov, Opt. spektrosk. 25, 163 (1968).
[2] R. Brout, Phys. Rev. 113, 43 (1959). A. Maradudin, Defects and Vibrational Spectrum of Crystals, (Russ. Transl.), M., 1968, p. 247.
[3] E. M. Voronkova, B. N. Grechushnikov, G. I. Distler, and I. P. Petrov, Opticheskie materialy dlya infrakrasnoi tekhniki (Optical Materials for Infrared Techniques), M., 1965, p. 82.
[4] A. Maradudin, op. ci.t. in [2], p. 319.
[5] H. Dotsch and W. Gebhardt, Ch. Martius. Solid State Comm., 3, 297 (1965).
[6] N. N. Kristovel', Trudy IFA AN ESSR 29, 3 (1964).
[7] B. Fritz, J. Phys. Chem. Solids, 23, 375 (1962).

SURFACE ELECTROMAGNETIC WAVES IN METALS IN A MAGNETIC FIELD

E. A. Kaner and N. M. Makarov
Institute of Radio Physics and Electronics, Ukrainian Academy of Sciences
Submitted 28 July 1969
ZhETF Pis. Red. 10, No. 6, 253 - 257 (1969)

In 1960, M. Khaikin observed an oscillatory dependence of the surface impedance of metals in weak magnetic fields (1 - 10 Oe) [1]. Subsequently Nee and Prange [2] explained this phenomenon as being the result of transitions under the influence of a high frequency field between discrete surface levels of electrons moving near the surface of the metal. Under the influence of the magnetic field, the electrons whose orbit centers are outside the metal, are reflected many times from the surface and drift along the surface. The motion of these electrons in a direction perpendicular to the interface is finite and periodic, and therefore can be quantized. Such quantum states have been named magnetic surface states. The impedance oscillations in a weak field actually represent cyclotron resonance on magnetic surface levels. The usual cyclotron resonance [3] due to transitions between Landau levels of volume electrons occurs in a strong magnetic field at frequencies that are multiples of the cyclotron frequency Ω. Since the frequency of transition between surface levels is larger by 2 - 3 orders of magnitude than the cyclotron frequency [2, 4], resonant Khaikin oscillations were observed in weak fields. It must be noted that this phenomenon, as any resonant effect, is a collective phenomenon.

On the other hand, it was established in recent years that collective oscillations -- weakly damped electromagnetic waves -- exist in the vicinity of resonant effects of various types. Examples are cyclotron waves [5, 6] near cyclotron resonances, spin waves in alkali metals near paramagnetic resonance [7, 8], quantum waves in the vicinity of giant quantum oscillations of Landau damping [9, 10], etc. Starting from this, it can be assumed that electronic waves should also exist near resonances on magnetic surface levels. Since the considered quantum states are localized near the surface of the metal, the waves corresponding to them should also be surface waves. We present in this paper the results of a theoretical investigation of this question, and show that such waves actually should exist in pure metals with sufficiently large electron mean free paths ℓ.

Assume that a metal is placed in a constant and homogeneous magnetic field $\vec{H}$ parallel to its surface. We direct the Oz axis along the vector $\vec{H}$ and the Ox along the inward normal to the interface. We seek a surface H-wave with polarization $E_x = E_z = 0$ and $E_y = E(x)\exp[ik_z z - i\omega t]$ when $x > 0$ and $E_y = E(0)\exp\{[k_z^2 - (\omega^2/c^2)]^{1/2} x + ik_z z - i\omega t\}$ in vacuum. To determine E(x) inside the metal, it is necessary to solve Maxwell's equation, which we write for the Fourier transform $\mathcal{E}(k) = 2\int_0^\infty E(x)\cos(kx)dx$:

$$(k^2 + k_z^2)\mathcal{E}(k) + 2E'(0) = 4\pi i\omega c^{-2} j(k, k_z). \tag{1}$$

The prime denotes here differentiation with respect to x, and $j(k, k_z)$ is the Fourier transform of the y component of the current density. From the condition for the continuity of the z component of the alternating magnetic field it follows that $E'(0) = [k_z^2 - (\omega^2/c^2)]^{1/2} \times E(0)$, where $E(0) = 1/\pi \int_0^\infty \mathcal{E}(k)\,dk$.

In Eq. (1) it is necessary to know the current density $j(k, k_z)$. For simplicity, we present the scheme and the result of the calculations for an idealized model of a metal, whose Fermi surface is a circular cylinder with axis parallel to the magnetic field. The generalization to the case of a complicated dispersion law, and also the derivation and a detailed discussion of the results, will be published in a more detailed communication. In the model under consideration, the current density $j(k)$ does not depend on k_z, since the electron velocity along $\vec{H}$ is equal to zero. We shall assume that the scattering of the resonant electrons by the surface of the metal is specular, since their glancing angle ϕ is small [4]. From physical considerations (which are confirmed by an exact calculation) it is quite obvious that only electrons glancing along the surface take part in the resonance, whereas the skin layer is formed by the volume (nonresonant) electrons. The current density is therefore represented in the form of a sum of two terms: $j(k) = j_0(k) + j_s(k)$. The first term describes the current of the volume electrons, and is independent of $\vec{H}$ in the considered weak-field case. This conclusion is valid if $(\delta R)^{1/2} \gg v/\omega$, where $(\delta R)^{1/2}$ is the characteristic path of the electron in the skin layer δ, R is the electron radius, v/ω is the effective free path in an alternating electromagnetic field, and v is the Fermi velocity. The current density of the glancing electrons j_s should be calculated with allowance for the quantization of the surface states. In the quasiclassical approximation, the final asymptotic expression for the current density is

$$j_0(k) = \frac{\omega_0^2 \mathcal{E}(k)}{2\pi k v}; \quad j_s(k) = i\frac{\omega_0^2}{\omega - \omega_{ns} + i\nu}\,\frac{\hbar}{\pi^2 p}\int_0^\infty dk'\mathcal{E}(k')\psi_{ns}(k)\psi_{ns}(k'), \tag{2}$$

$$\psi_{ns}(k) = \int_0^1 dx\cos(\pi s x)\cos[k\rho_n(1 - x^2)].$$

Here ω_0 is the plasma frequency, p is the Fermi momentum, ν is the electron collision frequency, $s = n' - n$ is the difference of the magnetic quantum numbers in the final (n') and initial (n) states, $\omega_{ns} = \pi s\Omega/\phi_n$ is the resonant frequency, $\phi_n = \{3\pi\hbar\Omega/mv^2\,[n - (1/4)]\}^{1/3}$ is the quantized value of the glancing angle, $\rho_n = (1/2)R\phi_n^2$ is the maximum distance of the n-th quantum trajectory from the surface of the metal, and m is the effective mass of the electron.

In the expression for $j_s(k)$ we retained only one resonant term. The ratio $|j_s/j_0|$ at the maximum is of the order of $\hbar k^2 v/p\nu$, and should be much larger than unity in order for a spectrum of surface waves to exist. Assuming that $k \sim 1/\delta$ and $\hbar/p \sim a$ (a is of the order of the electron wavelength, we write this inequality in the form

$$a\ell/\delta^2 >> 1, \qquad \ell = v/\nu.$$

Using (1) and (2), we can obtain and solve the dispersion equation for the surface electromagnetic waves. We write the solution of this equation in the long-wave limit, when the length of the surface wave is large compared with the skin-layer thickness $\delta = (c^2 v/2\omega\omega_0^2)^{1/3}$, and is small compared with the wavelength in vacuum, i.e., $\omega/c << k_z << 1/\delta$:

$$\omega = \omega_{ns}(1 - B\beta_{ns} + Ba_{ns}^2 k_z) - i\nu,$$

where

$$B = \hbar/\omega\delta^3 m, \quad a_{ns} = 2/\pi \int_0^\infty k\psi_{ns}(k)dk/(k^3 - i\delta^{-3}),$$

$$\beta_{ns} = 2/\pi \int_0^\infty k\psi_{ns}^2(k)dk/(k^3 - i\delta^{-3}).$$

The parameters α_{ns} and β_{ns} coincide in order of magnitude with the thickness of the skin layer (when $\rho_n \sim \delta$). Formula (4) determines the spectrum of the surface wave only at small values of k_z. The limiting frequency of the surface wave in this region of k_z differs from ω_{ns} by an amount $B\beta_{ns}\,\omega_{ns}$, which by virtue of the condition (3) is much larger than the damping of the wave ν. An analysis shows that the limiting frequency of the surface wave in the region $k_z\delta >> 1$ coincides with the transition frequency ω_{ns}. Thus, the spectrum of the surface waves is localized near the resonant frequencies ω_{ns} and has a relative width $B\beta_{ns} \sim \hbar/m\delta^2\omega$, which when $\delta \sim 10^{-5}$ cm and $\omega \sim 10^{11}$ sec^{-1} reaches about 10% of the resonant frequency itself. Of course, to observe surface waves it is necessary that the damping of the wave be small compared with the width of the spectrum - in accordance with the condition (3).

Apparently the most convenient way of experimentally observing such surface electromagnetic waves in metals is to use their resonant excitation with the aid of surface hypersonic Rayleigh waves. The excitation will be most effective if the frequency and wave numbers of both surface oscillations coincide.

[1] M. S. Khaikin, Zh. Eksp. Teor. Fiz. 39, 212 (1960) and 55, 1696 (1968)[Sov. Phys.-JETP 12, 152 (1961) and 28, 892 (1969)].
[2] T. W. Nee and R. E. Prange, Phys. Lett. 25A, 582 (1967).
[3] M. Ya. Azbel' and E. A. Kaner, Zh. Eksp. Teor. Fiz. 30, 811 (1956) and 32, 896 (1957) [Sov. Phys.-JETP 3, 772 (1956) and 5, 730 (1957)].
[4] E. A. Kaner, N. M. Makarov, and I. M. Fuks, ibid. 55, 931 (1968) [28, 483 (1969)].
[5] E. A. Kaner and V. G. Skobov, Fiz. Tverd. Tela 6, 1104 (1964) [Sov. Phys.-Solid State 6, 851 (1964)].
[6] W. M. Walsh and P. M. Platzman, Phys. Rev. Lett. 15, 931 (1968).
[7] V. P. Silin, Zh. Eksp. Teor. Fiz. 35, 1243 (1958) [Sov. Phys.-JETP 8, 870 (1959)].
[8] S. Schultz and G. Dunifer, Phys. Rev. Lett. 18, 280 (1967); P. M. Platzman and P. A. Wolff, Phys. Rev. Lett. 18, 280 (1967).
[9] A. L. McWhorter and W. G. May, IBM, J. Res. Dev. 8, 285 (1964); O. V. Konstantinov and V. I. Perel', Zh. Eksp. Teor. Fiz. 53, 2034 (1967)[Sov. Phys.-JETP 26, 1151 (1968)].
[10] E. A. Kaner and V. G. Skobov, Fiz. Tekh. Poluprov. 1, 1367 (1967)[Sov. Phys.-Semicond.

1, 1138 (1968)]; Phys. Stat. Sol. 22, 333 (1967).

SECOND HARMONIC GENERATION IN BISMUTH IN THE MICROWAVE BAND

G. I. Leviev and E. G. Yashchin
Institute of Solid State Physics, USSR Academy of Sciences
Submitted 28 July 1969
ZhETF Pis. Red. 10, No. 6, 257 - 260 (20 September 1969)

A number of investigations (see, for example, [1] have been devoted to the reflection of light from the surface of a metal with emission of the second harmonic, excited by a current $\vec{j}$ which is nonlinearly (quadratically) connected with the fields $\vec{E}$ and $\vec{H}$ (for isotropic media with an inversion center)

$$j = \sigma E + \alpha [E H] + \beta E \operatorname{div} E . \quad (1)$$

It is shown in [1] that in the optical band both the conduction electrons and the bound electrons contribute to the nonlinear constants α and β. On the other hand, the nonlinear properties of metals have been traditionally investigated in galvanomagnetic experiments. The nonlinear connection between the current and sufficiently weak fields is usually written in the form [2]

$$E_i = \rho_{ij}\, i_j + \epsilon_{ijk}\, i_j R_{km} H_m + \rho_{ijmn} i_j H_m H_n \quad (2)$$

(here ϵ_{ijk} is a unit antisymmetrical tensor). The second term of (2) describes the Hall effect. In the case of alternating fields, second harmonic generation and the detection effect are connected with this term. The third term is connected with the magnetoresistance. It is of interest to investigate the nonlinear properties of a metal in the microwave band. Unlike the optical band, the principal role is played here by the free carriers, and furthermore the last term in (1) is negligible. Unlike the static case, temporal and spatial dispersion can play a role here.

We have investigated experimentally second-harmonic generation in bismuth in the microwave band. Bismuth was chosen because its carrier density is low; this leads to a larger Hall constant than in other metals and to a better penetration of the field into the metal.

The experiment was performed at room temperature. A bismuth single crystal grown by the method described in [3] was placed at the bottom of a two-mode copper resonator. The resonator was excited in the E_{010} mode by a powerful microwave generator (10 kW) at a frequency of 9200 MHz. The use of short pulses (10^{-6} sec) prevents heating of the sample. The resonator dimensions were chosen such that the H_{111} mode had the second-harmonic frequency, i.e., 18400 MHz. The bismuth crystal in the form of a disc (diameter 17.8 mm) with mirror-finished flat surfaces was secured to the resonator with a conducting adhesive.

Let us consider the nonlinear current given by (2):

$$j = [E \hat{\alpha} H]. \quad (3)$$

For bismuth, if X_1 and X_3 are the binary and trigonal axes, respectively,