F I Z I K A VOLUME 10 SUPPLEMENT 2, 1978
Proceedings of the VI Yugoslav Symposium of the Physics of Condensed Matter, Kruševac, September, 18-22, 1978

RADIOELECTRIC EFFECT IN THIN METALLIC FILMS

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1. In the field of an electromagnetic wave the electrons obtain a momentum in the direction of wave propagation. This gives rise to a flow of constant current or creates a constant voltage. Since the momentum of the electromagnetic wave is proportional to the square of its amplitude, we have to deal with nonlinear effect. This effect is known in the literature [1-3] as radioelectric or photoelectric effect.

In this paper we investigate the generation of constant voltage with an electromagnetic wave of frequency ω incident on a metallic film of thickness d which is much smaller than the mean free path ℓ of the conduction electrons. In the calculations we take into account the reflection properties of the film surfaces.

2. The electric field which acts on the electrons

$$\vec{E} = \vec{E}_1 + \vec{E}_2 \qquad /1/$$

is composed of one alternate component $\vec{E}_1$ of frequency ω and one constant field $\vec{E}_2$. The constant field is such that in a steady state the current in the direction of the electromagnetic wave is zero. We split the electron distribution function f in three parts

$$f = f_0 + f_1 + f_2 \qquad /2/$$

where f_0 is the equilibrium Fermi distribution function and f_1, f_2 are contributions to the distribution function from the fields $\vec{E}_1$, $\vec{E}_2$, respectively. We find f from the Boltzmann equation which we solve in τ - relaxation time approximation. We have

$$\frac{\partial \chi_1}{\partial z} + \frac{\nu + i\omega}{V_z}\chi_1 = \frac{eV_x}{V_z}E_{1x} \qquad /3/$$

$$\frac{\partial \chi_2}{\partial z} + \frac{1}{\tau V_z}\chi_2 = \phi(z) \qquad /4/$$

$$\phi(z) = eE_{2z} + \frac{e}{2V_z}\mathrm{Re}\left\{\left(E_{1x}^{*} - \frac{V_z H_{1y}^{*}}{c}\right)\frac{\partial \chi_1}{\partial P_x} + \frac{V_x H_{1y}^{*}}{c}\frac{\partial \chi_1}{\partial P_z}\right\} \qquad /5/$$

where the functions χ_1 and χ_2 are introduced with $f_1 = \chi_1 \frac{\partial f_0}{\partial \varepsilon}$,

$j_2 = \chi_2 \frac{\partial f_0}{\partial \varepsilon}$ and $\vec{V}$, $\vec{P}$, m^* , e , $\varepsilon(\vec{p})$ are respectively, velocity, momentum, effective mass, charge and energy of conduction electrons and c is the speed of light.

For simplicity we consider linearly polarized incident electromagnetic wave travelling along z -axis which is perpendicular to the film. In the film, the electromagnetic wave field has two components E_{1x} and H_{1y} . The time dependence is described with a factor $e^{i\omega t}$. We also assume that the wave vector coincides with an axis of high symmetry of the sample.

The boundary conditions on the distribution function are written down with the help of a phenomenological parameter q [4]

$$\chi^{+}_{1,2}(z=0) = q\chi^{-}_{1,2}(z=0) + \mu_{1,2} \qquad /6/$$

$$\chi^{-}_{1,2}(z=d) = q\chi^{+}_{1,2}(z=d) + \mu_{3,4}$$

where the constants $\mu_{1,2}$ and $\mu_{3,4}$ are to be found from the condition that the z -component of the current density is zero

$$j_{1,2z}(z=0) = j_{1,2z}(z=d) = 0 \qquad /7/$$

The fields E_{1x} and E_{2z} satisfy the equations of electrodynamics

$$\frac{d^2 E_{1x}}{dz^2} - i\frac{4\pi\omega}{c^2} j_{1x} = 0 \qquad /8/$$

and electrostatics

$$\frac{dj_{2z}}{dz} = 0 \quad , \quad E_{2z} = -\frac{d\varphi}{dz} \qquad /9/$$

where φ is the potential of E_{2z} .

To solve the equations /3/-/9/ we use the method proposed in [5] and

$$\ell \gg d(1+\omega^2\tau^2)^{1/2} \qquad /10/$$

thus, considering films of thickness much smaller than the mean free path of the electrons. The subsequent results are obtained for $\omega\tau \ll 1$.

Two limiting cases are considered: the case of diffuse /$q=0$/ and the case of specular /$q=1$/ scattering from the surfaces. The constant voltage between the boundaries $U = \varphi(d) - \varphi(0)$ is conveniently represented as a sum of three terms $U = U_1 + U_2 + U_3$ given below.

a/ Diffuse scattering $/q = 0/$

$$U_1^d \approx U_\infty \frac{\delta_0^2}{d^2} \frac{l}{d} \ln^{-1} \frac{l}{d} \qquad /11/$$

$$U_2^d \approx U_\infty \frac{l}{d} \ln^{-1} \frac{l}{d} \qquad /11/$$

$$U_3^d \approx U_\infty \frac{l^2}{d^2} \ln^{-1} \frac{l}{d} \qquad /11/$$

where $\delta_0 = \frac{c}{\omega_0}$, $\omega_0 = \sqrt{\frac{4\pi n e^2}{m^*}}$ is plasma frequency, $U_\infty = -\frac{4\pi e}{m^* \omega_0^2 c} J_0$ and J_0 is the momentum of the incident wave.

b/ Specular scattering $/ q = 1/$

$$U_1^e \approx U_\infty \frac{\delta_0^2}{l d} \ln \frac{6 l^2}{d^2} \qquad /12/$$

$$U_2^e \approx U_\infty \qquad /12/$$

$$U_3^e \approx - U_\infty \frac{l}{d} \qquad /12/$$

3. Because the surface impedance is small, $H_{1y} \approx 2E_i$ where E_i is the amplitude of the incident wave. This means that the alternate component of the current can be considered as given. Since the coefficients of specific conductivity in thin metallic films are different for $q = 0$ and $q = 1$, it follows that the corresponding fields also differ. The field is stronger when $q = 0$ which results in larger transfer of momentum from the wave to the electrons.

The contributions to the voltage /11/-/11'/ and /12/-/12'/ result from the x -component of the electromagnetic field force. This component is without influence on p_z, which allows to consider the problem formally, as one for a bulk sample but with a field E_{1x} as the one in the film. For $q = 1$ the conductivity in a film and in a bulk sample is the same and we can compare the results with those of Gurevich and Mezrin [1] where for the maximum voltage up to a factor of the order of unity, one obtains $U \approx U_\infty$ in agreement with /12'/. When $q = 0$ the voltage is larger, since the field which generates it is stronger.

The contributions of the electric field and the Lorentz force in the magnitude of the effect are different. The electric force dominates in very thin films: if $d \ll \delta_0$ when or if $d \ll \frac{\delta_0^2}{\ell}$ when $q = 1$. For films of larger thickness the Lorentz force becomes dominant.

The mechanism determined by the z -component of the Lorentz force gives a different contribution to the constant voltage. This force changes the P_z -component of the momentum, the full amount of change being dependent on the multiplicity of reflections from the boundaries as well as on the character of the reflections. The multiple reflections give rise to a factor $\frac{\ell}{d}$ in both cases $q = 0$ and $q = 1$. If the scattering is diffuse, this mechanism becomes most important when $d \gg \frac{\delta_0^2}{\ell}$. When the scattering is elastic it is predominant if $\ell \gg \delta_0 \gg d$.

The essential difference, dependent on the type of reflection is in the sign of the constant voltage. Since the voltage for $q = 1$ is $\frac{d}{\ell}$ times smaller than the voltage for $q = 0$, one can expect that even for small diffuseness, the sign of the voltage will be the same as of /11/.

4. We would like to thank Professor M.I.Kaganov for helpful discussions.

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