# Photothermomagnetic effect in a semimetal upon excitation of weakly damped waves

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(Submitted 18 October 1972)

Zh. Eksp. Teor. Fiz. **64**, 1071-1073 (March 1973).

It is shown that the photothermomagnetic emf in a semimetal in which weakly damped monochromatic UHF waves have been excited oscillates on when the magnetic field is varied, owing to interference in the sample. At a certain field strength, the oscillating emf passes through zero and reverses sign, which now corresponds to greater heating of the real (non-irradiated) surface of the sample as compared to the heating of the irradiated surface. The mean value about which the emf oscillates decreases as the field strength increases and also reverses sign. With decrease of sample thickness, the oscillation amplitude and the negative emf values attained both increase. The theory can explain the results of the experiments of Khaĭkin and Yakubovskiĭ.[1]

If a conductor located in a magnetic field absorbs UHF radiation and a gradient develops in the temperature of its electrons or its electrons and phonons in a direction normal to the field, then a photo-emf appears in the conductor, similar to the transverse Nernst-Ettingshausen thermomagnetic emf. The constant electric field (in an open circuited sample) is proportional to the temperature difference between the irradiated and opposite faces of the sample:

$$E_y = -\alpha_{yx}[T(0) - T(l_x)]/l_x. \tag{1}$$

In the derivation of (1) it is assumed that the temperature depends only on the x coordinate in the direction of incidence of the radiation (here $E_y$ does not depend on x), the magnetic field is parallel to the Oz axis, and $l_x$ is the thickness of the sample. Usually it is assumed that $T(0) > T(l_x)$ and the sign of the effect is determined only by the sign of $\alpha_{yx}$. Thus we actually have a situation in which the radiation is strongly damped in the sample. It is shown below that if weakly damped monochromatic waves are excited in a semiconductor, the difference in the temperatures of the surfaces of the sample, and hence the photothermomagnetic emf, is opposite in sign to the difference for strong damping of the wave (the sign of $\alpha_{yx}$ is assumed to be unchanged). For definiteness, we consider magnetoplasma (MP) waves in Bi. In the experiments of Khaĭkin and co-workers,[1,2] it has been established that in weak magnetic fields, when the MP waves are not excited, the observed photo-emf is thermomagnetic. On the other hand when weakly damped MP waves are excited in Bi, the photo-emf oscillates and reverses sign. The mechanism of the photo-emf sign reversal was not determined in[1,2]. It was assumed in[3,4] that this effect is connected with the generation of the UHF Hall emf (the "lightelectric emf").

We consider the case in which the temperatures of the electrons and phonons are identical at each point (in the other extreme case, when only the electron temperature increases, the results are qualitatively the same). The heat flux density is equal to

$$w_x = \Pi_{xy} j_y - \varkappa_{xx} dT/dx. \tag{2}$$

Integrating (2) over the cross section at zero total transverse current we obtain

$$\varkappa_{xx}[T(0) - T(l_x)] = \frac{l_x}{2}\left[w_x(0) + w_x(l_x) + \int_0^{l_x} dx\left(1 - 2\frac{x}{l_x}\right)\frac{\partial w_x}{\partial x}\right]. \tag{3}$$

The source in the heat conduction equation is equal to the power $U(x)$ of the UHF field absorbed per unit volume. On the boundaries of the sample,

$$w_x(l_x) = \gamma\delta T(l_x), \quad w_x(0) = -\gamma\delta T(0), \tag{4}$$

where $\delta T = T = T_0$, $T_0$ is the temperature of the thermostat and $\gamma$ is a constant. From (3) and (4) we find $T(0) = T(l_x)$; we substitute in (1) and get

$$E_y = -\frac{W}{S}\frac{\alpha_{yx}}{2\varkappa_{xx} + \gamma l_x}F.$$

Here

$$W/S = \int_0^{l_x} dx\, U(x)$$

is the power absorbed in the sample per a unit surface area:

$$F = \int_0^{l} dx\left(1 - 2\frac{x}{l_x}\right)U(x) \Big/ \int_0^{l} dx\, U(x).$$

When the spatial dispersion is unimportant we have $U(x) \propto |\mathbf{E}(x)|^2$, where $\mathbf{E}$ is the amplitude of the UHF field, which is proportional to

$$E(x) \propto [(N+1)\exp\{ik(x - l_x)\} + (N-1)\exp\{ik(l_x - x)\}],$$

$k = N\omega/c$, and $N$ is the complex index of refraction. From the very definition of $F$ we can see that if the damping over the thickness of the sample is strong ($\delta = (2k'')^{-1} \ll l_x$), then $F \approx 1$ and the effect has the "usual" sign.

For MP waves, $N' \gg 1$ (of the order of $10^2$ and larger) and $N''/N' \approx (2\omega\tau)^{-1} \ll 1$ ($\tau$ is the relaxation time). With account of this,

$$F = \left[f\left(\frac{l_x}{\delta}\right) + \frac{\sin\varphi}{\varphi} - 2\frac{1-\cos\varphi}{\varphi^2}\right]\left[\frac{\operatorname{sh}(l_x/\delta)}{l_x/\delta} + \frac{\sin\varphi}{\varphi}\right]^{-1},$$

where $\varphi = 2N'\omega l_x/c$,

$$f(z) = \frac{1}{z}\left[\operatorname{sh} z - 2\frac{\operatorname{ch} z - 1}{z} + \frac{2}{N'}\left(\operatorname{ch} z + 1 - 2\frac{\operatorname{sh} z}{z}\right)\right].$$

We analyze the dependence of $F$ on the magnetic field, bearing in mind that $N' \propto H^{-1}$, and consequently, $\varphi \propto H^{-1}$ and also $l_x/\delta \approx \varphi/2\omega\tau$. In the weakest magnetic field in which MP waves begin to be excited, the quantities $\varphi$ and $l_x/\delta$ are large and $F$ executes small and frequent oscillations (of period $\Delta H \propto H^2$) about $F \approx 1$. With increasing field and decreasing $\varphi$, the damping over the thickness of the sample becomes small ($l_x \ll \delta$) and then

$$f\left(\frac{l_x}{\delta}\right) = \frac{1}{3}\left[\frac{1}{4}\left(\frac{l_x}{\delta}\right)^2 + \frac{1}{N'}\frac{l_x}{\delta}\right] = \frac{1}{6}\left[\frac{1}{8}\left(\frac{\varphi}{\omega\tau}\right)^2 + \frac{1}{N'}\frac{\varphi}{\omega\tau}\right]$$

  

This means that the average value of F, about which the oscillations take place, decreases, while the swing of the oscillations of F increases, since it is proportional to $\varphi^{-1}$. In a magnetic field such that $\varphi^{-1} > f(\varphi/2\omega\tau)$, the function F at the minima takes on negative values. Finally, in an even stronger magnetic field, when $f(\varphi/2\omega\tau) < (5/2)\varphi^2$, the very mean value about which the oscillations take place becomes negative and equal to $-(5/2)\varphi^2$. However, in the oscillation region $(\varphi > 2\pi_0)$ the amplitude of the oscillations is larger than the mean value, so that the function F also takes on positive values. The smallest value $F \approx 0.4$ is obtained at $\varphi \approx \pi$. As $\varphi \to 0$, the function $F \to 0$.

With decrease in the thickness of the sample, the amplitude of the oscillations and the absolute value of the negative emf attained should increase (for the same range of magnetic field) because of the decrease in $\varphi$.

The described picture of the variation of the photothermomagnetic emf with the magnetic field and with the sample thickness is in excellent agreement with that observed experimentally.[1] This provides a basis for supposing that the photoemf observed experimentally[1,2] in the region of excitation of weakly damped waves is a photothermomagnetic emf, just as in weak magnetic fields, when these waves are not excited.

A similar phenomenon of oscillations and sign reversal of the emf should also take place for the photogalvanomagnetic effect, if it is excited by monochromatic weakly-damped waves. It should be emphasized that the considered interference oscillations of the photo-emf differ from the well-known interference oscillations of optical transmission and reflection in that they are accompanied by a reversal of the sign of the effect.


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[2] M. S. Khaĭkin and S. G. Semenchinskiĭ, ZhETF Pis. Red. 15, 81 (1972) [JETP Lett. 15, 55 (1972)].
[3] L. É. Gurevich and O. A. Mezrin, Zh. Eksp. Teor. Fiz. 62, 2255 (1972) [Soviet Phys.-JETP 35, 1180 (1972)].
[4] L. É. Gurevich and O. A. Mezrin, ZhETF Pis. Red. 14, 562 (1971) [JETP Lett. 14, 387 (1971)].



Translated by R. T. Beyer
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