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ON THE PHOTOMAGNETISM OF METALS. THEORY OF THE PHOTOINDUCED BULK CURRENT

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Photoinduced magnetic flux has been recently observed in normal metals illuminated by visible light falling obliquely on a metal surface. In the present paper we argue that a larger effect can be achieved for normal incidence of light partly reflected at a metal surface. The light excites within the metal a bulk current which can extend over a distance of the electron mean free path. For the case where the current is short-circuited by another conductor (preferably, a superconductor) we give estimates of the magnetic flux built up in such a loop.

In a recent paper [1] observation of the photomagnetism of metals was reported. In a double-connected metal sample illuminated in such a way that a circular d.c. *surface* current could be excited a build up of magnetic flux was observed. In a subsequent paper [2] dealing with a microscopic theory of the effect two contributions to the current were discussed. One of them is due to the quasimomentum transfer to the conduction electrons from the light partially reflected at the metal surface. Another is due to the anisotropy of the electron transitions with regard to the light polarisation direction, in combination with diffuse reflection of the electrons at the surface. Both contributions exist for the light falling obliquely on the metal surface.

The purpose of the present paper is to work out a theory of a photoinduced *bulk* current in metals. The current is excited by light incident normally on a metal surface. The light is partly reflected from the surface and partly absorbed due to the interaction with the conduction electrons.

There are two ways in which bulk current can be produced in a metal by incident electromagnetic radiation: interband and intraband transitions of the electrons. For visible light the first effect plays the dominant role, and in view of current experiments with visible light (see [1,3]) only interband transitions are considered in this paper*. As for the intraband transitions, we would like to mention that they were considered to calculate the voltage [5] (in semiconductors) and the bulk current (in metals) [6] produced by the radioelectric effect.

To be more specific, let us consider transitions from a full valence band into the empty states of the conduction band above the Fermi level. Let us assume that the average effective mass of the electrons in the conduction band is much smaller than that of the electrons in the valence band, so that most of the current is carried by the former. If the z-axis is perpendicular to the illuminated surface of the metal all the excited electrons fall into two groups: those with $v_z > 0$ and $v_z < 0$, where v_z is the z-component of the electron velocity. Both groups contribute to the electron current density, j_z, the first group directly, the second after a reflection from the surface. Taking these processes into account one can calculate the light-induced current density, $j_z^{(l)}(z)$.

There are two characteristic lengths that determine the spatial variation of this quantity, i.e. the light penetration depth, δ, and the electron mean free path, l.We will be particularly interested in the case $l \gg \delta$, wherethe effect under consideration is rather big. Then l is the characteristic length over which the current density, $j_z^{(l)}(z)$, falls off exponentially. The total current density,

$$j_z = j_z^{(l)}(z) + \sigma \mathcal{E}_z(z) = \text{const} , \tag{1}$$

where $\mathcal{E}_z$ is the d.c. electric field along the z direction which builds up in a stationary situation in order to guarantee charge conservation, and σ is the static electric conductivity. The actual value of the electric field is determined by the boundary conditions at the surfaces of the illuminated metal.

The simplest and most effective arrangement is achieved if the normal current excited by the light is short circuited by a superconducting loop. Then we have no voltage,

$$\int_0^L \mathcal{E}_z(z) dz = 0, \tag{2}$$

and the total current density determining the magnetic flux is obtained from Eq.(1) as

$$j_z = \frac{1}{L} \int_0^L j_z^{(l)}(z) dz. \tag{3}$$

Here we assume that the light falls perpendicularly on the metal surface, $z = 0$; $L > z > 0$ corresponds to the interior of the normal metal**.

Our main purpose is to give an order-of-magnitude estimate of the expected photomagnetic effect. The intensity of light will be measured by the time-averaged

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* In semiconductors a surface current due to the interband transitions and diffuse scattering of the electrons from the semiconductor's surface was observed and discussed theoretically in [4].

** The implication is that the superconductor is in good contact with the normal conductor. Such a contact can be easily achieved at the far (unilluminated) end of the normal conductor. One way to make a good contact at the illuminated end is to cover the surface of the normal metal with a superconducting gauze, the dimensions of a mesh being smaller than the electron mean free path. If the gauze is covered by a nontransparent substance only the normal metal will be illuminated.

Poynting vector in the ingoing wave, Q_z. For the Poynting vector of the reflected wave, Q'_z, we have

$$Q'_z = -(1-r)Q_z. \tag{4}$$

Then the absorbed energy flux is rQ_z, or the absorbed photon flux is, $rQ_z/\hbar\omega$, where ω is the frequency of light. Assuming that interband transitions of the electrons are mainly responsible for the absorption of the photons, the last ratio also gives the number of electrons excited per second within the volume that equals unit area times the penetration depth, δ.

Now, the excited electrons move away from the penetration layer, producing the current $j_z^{(l)}$, which falls off over the distance l, so that

$$j_z^{(l)}(z) = j_0 e^{-z/l}. \tag{6}$$

For j_0 one writes

$$\frac{j_0}{e} = \eta \frac{rQ_z}{\hbar\omega}\ , \tag{7}$$

where η is a numerical coefficient of the order of (but somewhat smaller than) unity. Its value can be calculated on the basis of a microscopic theory (that will be published elsewhere).

The total current, J, is

$$J = e\eta \frac{rQ_z}{\hbar\omega}\frac{l}{L}S^{(l)}\ , \tag{8}$$

where $S^{(l)}$ is the area of the illuminated part of the metal.

Now we are able to give an order-of-magnitude estimate of J. Assuming $\eta = 0.5$, $r = 0.1$, $l/L = 0.1$, $Q_z = 1\ W/cm^2$, $S^{(l)} = 0.1\ cm^2$, and $\omega = 3 \cdot 10^{15}\ s^{-1}$ we obtain $J \approx 0.3\ mA$.

The magnetic flux through the closed loop formed by a small normal-metal part and the superconducting short circuit is given by

$$\Phi = c^{-1}\mathcal{L}J\ , \tag{10}$$

where $\mathcal{L}$ is the selfinductance of the system. As a result, we get for the magnetic flux, measured in units of the magnetic flux quantum, $\Phi_0 = \pi c\hbar/e$,

$$\frac{\Phi}{\Phi_0} = \eta \frac{re^2}{\pi c^2\hbar^2}\frac{l}{L}\frac{Q_z S^{(l)}\mathcal{L}}{\omega}. \tag{11}$$

The order of magnitude of this ratio, assuming $\mathcal{L} = 5\ cm$, is $\Phi/\Phi_0 \approx 10^3$. This means that the expected effect is very large. It is interesting to compare it with the photoinduced surface current. Such a current in metals was observed in [1,3] and discussed theoretically in [1,2]. It is impossible to give here a detailed comparison. We will only indicate that the current considered in the present paper (and the magnetic flux associated with it) may be bigger than that considered in [1,3,2] typically by a factor 10 — 100.

The experimental investigation of this effect may be of considerable interest. First, under the illumination the electrons are highly excited above the Fermi level and in such a way one has a unique possibility to investigate the properties of these electrons and their relaxation. Second, together with the light absorption, this is a tool to investigate interaction of the electrons with light. Third, in this way one can learn a lot about the interaction of highly energetic conduction electrons with the metal surface.

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