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Theory of photoinduced ballistic bulk current in metals

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It is shown that visible-light incident positioned perpendicularly on the surface of a normal metal and partly reflected at the surface can excite in the metal a dc *bulk* current if it is short circuited (for instance, by a superconductor). The current is calculated for a ballistic regime where the thickness of the metal sample is larger than the absorption length of the light but much smaller than the mean free path of the electrons. [S0163-1829(97)51240-9]

In former papers[1,2] it was shown that light incident perpendicularly on the surface of a normal metal could produce a bulk current if it was short circuited (for instance, by a superconductor). The current was calculated for the case where the thickness of the metal plate was considerably larger than the electron mean free path. The effect was confirmed experimentally by Laiho.[3]

The purpose of the present paper is to extend these considerations to the ballistic regime, where the thickness of the metal plate exceeds the dimension of the light absorption layer, but is much smaller than the electron mean free path. As regards the interaction of the conduction electrons with light, we assume that the light gives rise to interband transitions. Let the band structure have the form schematically depicted in Fig. 1. Under the influence of the light the electrons make transitions from the valence band into the conduction band. As we are not particularly interested in the threshold effects we will assume that the energy of the excited electrons is well above the Fermi level, in particular above the energy gap for quasiparticles in the superconductor.

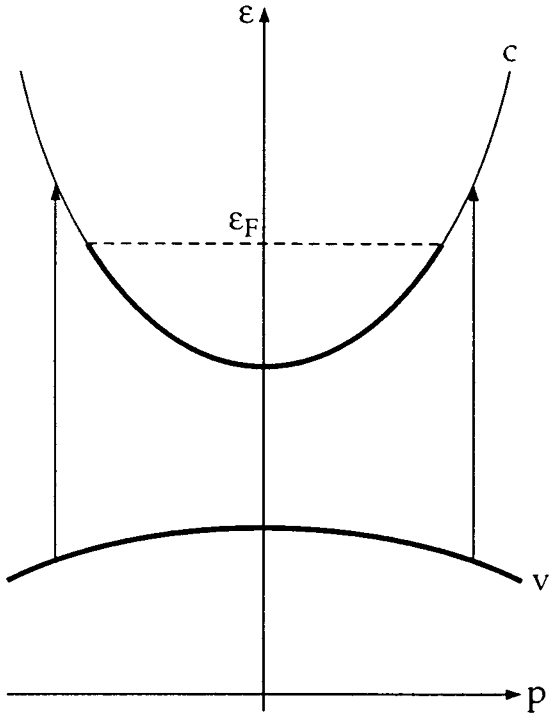

FIG. 1. The valence band v is filled with electrons. The conduction band c is filled up to the Fermi level. The electron transitions brought about by light are indicated by arrows. The arrows are vertical as we can neglect the small quasimomentum of light. The arrows connect an initial state in the valence band and an empty final state in the conduction band above the Fermi level.

We also assume that the normal metal plate is short circuited by a very thin transparent superconducting film deposited on the illuminated side and connected to a bulk superconductor attached to the other side of the plate (Fig. 2). We assume that the excited electrons moving towards the upper surface will all be reflected either by the interface with the

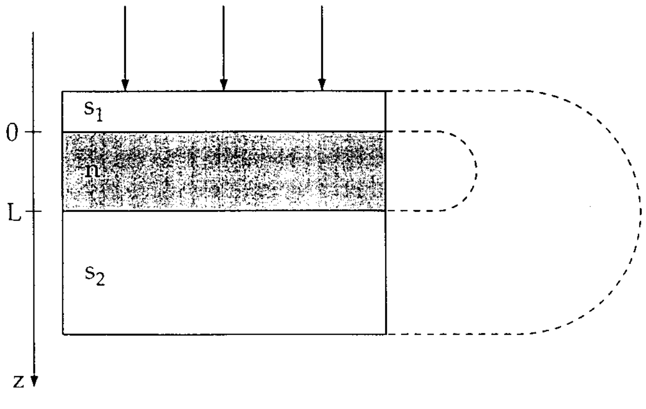

FIG. 2. The shaded region depicts a normal metal plate n of thickness L that is bigger than the light penetration depth and smaller than the electron mean free path. On its top a thin transparent superconducting layer s_1 is mounted. Below, a thick superconductor s_2 is attached. The broken lines symbolically indicate a superconducting lead between s_1 and s_2. The arrows indicate the light that illuminates the normal metal through the transparent superconductor s_1.

superconductor or by the outer surface of the superconducting film. Because of their high energy they will not form Cooper pairs in this thin layer, whose thickness (a few hundreds of Å) is much smaller than the ''charge imbalance decay length''[4] Λ (typically a few μm, see Ref. 4, p. 422) and will flow back into the normal metal. This results in total reflection of the excited electrons. On the other hand, at the lower surface of the normal metal the electrons will be partly reflected and partly transmitted. The transmitted electrons will carry quasiparticle currents into the bulk superconductor which decay into supercurrents over a distance Λ. The reflected electrons will go back to the upper surface and will be totally reflected back to the lower surface, where again part of them will be transmitted. So eventually all the excited electrons will flow into the bulk superconductor.

As far as the empty states (holes) in the valence band are concerned we assume that they have a much larger effective mass than the excited electrons in the conduction band. Furthermore, due to the recombination with the conduction electrons below the Fermi surface, the holes presumably have a relatively short lifetime. For these two reasons, we neglect their contribution to the current.

In order that this process be stationary the holes in the valence band should be continuously recombining with the electrons. Since the rate of recombination of the holes with the excited high-energy electrons is probably much smaller than with the electrons near the Fermi surface we assume that the electrons filling up the holes will be provided from the superconductor. And since the holes are created in the absorption layer, i.e., close to the illuminated surface of the metal, the electrons will flow in from the superconductor deposited on that side.

In accordance with the considerations above we make the following three assumptions: (i) The thickness L of the normal metal plate is small compared to the mean free path of the electrons l:

$$L \ll l. \tag{1}$$

(ii) L is somewhat larger than the absorption length δ of the light in the normal metal:

$$L \geqslant \delta, \tag{2}$$

so that practically all the light penetrating into the metal is absorbed. (iii) There will be no net flux of the excited electrons through the surface $z=0$ into the superconducting film. They will all flow into the bulk superconductor at $z=L$. Charge conservation will be maintained by a flux of electrons from the superconducting film through the surface $z=0$ into the normal metal at the Fermi level.

The number of electrons excited per unit time equals the number of photons absorbed per unit time. If all photons entering the metal are absorbed, i.e., if $L \gg \delta$, this number is $rS_zA/\hbar\omega$, where rS_z is the part of intensity S_z of the light wave that enters the normal metal, A is the area of the illuminated surface, and $\hbar\omega$ is the photon energy. Therefore, the total current of the excited electrons through the surface $z=L$ is

$$J = e\frac{rS_zA}{\hbar\omega}. \tag{3}$$

We can also start from the Boltzmann equation for the distribution function $f_p(z)$ of the excited electrons in the stationary state in the collisionless regime

$$v_z\frac{\partial f_{\mathbf{p}}(z)}{\partial z} = D_0 e^{-\kappa z}, \tag{4}$$

where v_z is the z component of the electron velocity, $\kappa = 1/\delta$, and D_0 can be obtained by calculating the probability for a transition from the valence band into the conduction band, e.g., based on Fermi's golden rule as was done in Ref. 2. The solution of Eq. (4) is

$$v_z f_{\mathbf{p}}(z) = D_0\kappa^{-1}(1-e^{-\kappa z}) + C, \tag{5}$$

where C is independent of z but may be a function of the electron quasimomentum $\mathbf{p}$. The current density is

$$\begin{aligned} j_z(z) &= e\int (dp) v_z f_{\mathbf{p}}(z) \\ &= e\kappa^{-1}(1-e^{-\kappa z})\int (dp)D_0 + e\int (dp)C. \end{aligned} \tag{6}$$

Here $(dp) = 2d^3p/(2\pi\hbar)^3$ (the factor 2 accounts for the two possible spin states). Since for the excited electrons $j_z(0)=0$ the last integral vanishes,

$$e\int (dp)C = 0, \tag{7}$$

and we have

$$j_z(L) = e\delta(1-e^{-L/\delta})\int (dp)D_0. \tag{8}$$

Since $\int (dp)D_0e^{-\kappa z}$ is the number of excited electrons per unit time and per unit volume,

$$A\int_0^L dz\int (dp)D_0e^{-\kappa z} = A\delta(1-e^{-L/\delta})\int (dp)D_0 = \dot{N} \tag{9}$$

is the total number $\dot{N}$ of electrons excited per unit time in the sample, and the current is

$$J = Aj_z(L) = e\dot{N}. \tag{10}$$

If $e^{-L/\delta} \ll 1$, $\dot{N} = rS_zA/\hbar\omega$, in agreement with Eq. (3).

The current density, Eq. (6), due to the excited electrons is z dependent; it varies from 0 at $z=0$ to the value given by Eq. (8) at $z=L$. In the stationary state it will be supplemented by a current of electrons near the Fermi surface entering the normal metal from the superconducting film at $z=0$ so that the total current density is independent of z and equals the value given by Eq. (8).

Now we are able to give an order-of-magnitude estimate of the current J. For a light intensity $S_z = 1$ W/cm^2 and $r=0.1$, an illuminated area of 0.1 cm^2 and a photon energy $\hbar\omega = 3$ eV, we obtain $J \approx 3$ mA. The effect is rather large, much larger than in the case $l \ll L$, where the current is diminished by a factor of l/L.[1,2]

Generally, 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 dispersion law and some other properties of these electrons. Second, this is a rather sensitive tool to investigate interaction of the electrons with light (it may prove to be more sensitive than the ordinary light absorption). Third, in this way one can learn a lot about the behavior of highly energetic conduction electrons in thin metal films. Fourth, if thesample were irradiated by circularly polarized light the excited electrons would be partially spin polarized. In magnetized materials one could therefore measure the spin dependence of the inelastic mean free path of the electrons.[5]

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[5] The authors are indebted to T. Greber and J. Osterwalder for drawing their attention to this interesting possibility.