Photoeffect in a Josephson junction

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It is shown that when a tunnel junction consisting of two superconductors with different energy gaps is illuminated, an absolute resistance is produced and leads to generation of an alternating voltage on the junction.

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A number of experimental papers devoted to the influence of illumination on a superconductor have recently been published.[1–3] In[2,3] they investigated the current-voltage characteristics for the purpose of determining the energy gap Δ and the excitation relaxation times. In both papers the studies were made on tunnel junctions made of superconductors with equal gaps. In this paper we wish to call attention to the possibility of obtaining negative absolute resistance by illuminating a tunnel junction made of two different superconductors. Consider the structure shown in the figure. At equilibrium and at $V=0$ the quasiparticle fluxes from the first to the second superconductor and back, above and below the gap, are mutually balanced. At $V\neq 0$, as shown in the figure, the flux of quasiparticles from the second superconductor into the first is larger above the gap than the flux from the first to the second, and vice versa below the gap. Since the contributions of the quasiparticle fluxes above and below the gap are of opposite sign, resultant currents with opposite signs flow from the first superconductor to the second. If, on the other hand, the pumping causes the distribution function in the first superconductor to be much larger in the first superconductor than in the second, then application of the voltage will cause the current to flow in the other direction, since the quasiparticles above the gap, which tunnel from the first superconductor, fall into an energy region with a larger density of states than the quasiparticles under the gap. The flux of quasiparticles from the second superconductor to the first can be neglected at low voltages. Calculation shows that this is indeed the case.

We consider an illuminated tunnel junction. Assume that the light establishes in the superconductors a stationary distribution function $n_i=\exp[(\nu_i-\epsilon)/T]$. As shown in[4,5], this is possible if the recombination times of the excitations are much larger than their relaxation times. The chemical potentials ν_i are determined from the quasiparticle-number conservation equation and are equal to

$$\nu_i=(T/2)\ln\{1+(4\pi e^2/\omega c)I_0 D_i \tau_{Ri}\sqrt{2/\pi\Delta_i T}\,e^{\Delta_i/T}\}, \qquad (1)$$

where I_0 is the intensity of the light, while D_i, τ_{Ri}, and Δ_i are the diffusion coefficients, the recombination times at zero pumping, and the half-widths of the energy gaps in the superconductors. The expression for the quasiparticle current at $eV<\Delta_1-\Delta_2$ takes the form

$$I=(\Delta_1/eR)x_1\left\{\left(1-e^{(\nu_2-\nu_1-eV)/T}\right)(\Delta_1+eV)\Big/\sqrt{(\Delta_1+eV)^2-\Delta_2^2}\right.$$
$$\left.-\left(1-e^{(\nu_2-\nu_1+eV)/T}\right)(\Delta_1-eV)\Big/\sqrt{(\Delta_1-eV)^2-\Delta_2^2}\right\}, \qquad (2)$$

where R is the resistance of the tunnel junction in the normal state, and $x_1=\sqrt{(\pi/2)(T/\Delta_1)}\exp[(\nu_1-\Delta_1)/T]$ is the dimensionless concentration of the excitations in the first superconductor. It is seen from (2) that the quasiparticle current at low voltages becomes negative under the condition

$$e^{(\nu_1-\nu_2)/T}-1>(\Delta_1/T)[(\Delta_1^2/\Delta_2^2)-1]. \qquad (3)$$

At $eV>\nu_1-\nu_2$, as seen from (2), the quasiparticle current becomes positive.

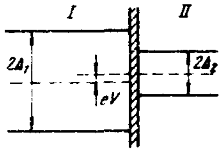
It follows from (1) and (3) that at sufficiently strong pumping, when $e^{\nu/T}\gg 1$, the temperature at which the conductivity vanishes is determined from the relation

$$(\tau_{R_1}/\tau_{R_2})(D_1/D_2)\,e^{(\Delta_1-\Delta_2)/T}=(\Delta_1/T)(\Delta_1/\Delta_2)^{3/2}$$
$$\times[(\Delta_1/\Delta_2)^2-1]. \qquad (4)$$

The corrections to the superfluid component of the current are proportional and are therefore small. The presence of a negative resistance to the quasiparticle current leads to generation of an alternating voltage on the open-circuited junction and an alternating current in the closed circuit. Recognizing that $(d\phi/dt)=(2e/\hbar)V$, we have for the open junction, from the condition that the total current be equal to zero

$$I_c\sin\phi+I\{(\hbar/2e)(d\phi/dt)\}+(C\hbar/2e)(d^2\phi/dt^2)=0, \qquad (5)$$

where C is the capacitance of the junction, ϕ is the phase discontinuity on the junction, and I_c is the critical current of the junction. Equation (5) has the same form as the equation for the Van der Pol generator and describes, at negative absolute resistance, the stationary



oscillations of the junction voltage and phase, the amplitude of which depends on pump intensity.

Assuming the negative conductivity to be small, we expand (2) up to terms of order V^3

$$I = -|\sigma| V[1 - \beta V^2], \tag{6}$$

where

$$|\sigma| = (2\Delta_1/R)\, x_1 \{\Delta_2^2/(\Delta_1^2 - \Delta_2^2) - (\Delta_1^2/T)\, e^{(\nu_2-\nu_1)/T}\}$$

is the absolute value of the conductivity at $V \to 0$, and β is the nonlinearity parameter.

Substituting (6) in (5), and solving the resultant equation in the case $\omega_0\tau \gg 1$, we obtain

$$\phi = (2/\sqrt{3})\,(\omega_0\sqrt{\tau\tau_{nl}})^{-1} \cos\omega_0 t. \tag{7}$$

In the opposite limiting case $\omega_0\tau \ll 1$, Eq. (5) describes nonlinear relaxation oscillations with a period $T = 1.614\,(\omega_0^2\tau)^{-1}$ and an amplitude $a = \frac{1}{2}\sqrt{\frac{3}{2}}\,(\omega_0^2\tau^{3/2}\tau_{n1}^{1/2})^{-1}$.[6]

We note in conclusion that the conditions for the onset of absolute negative resistance become weaker if only one large-gap superconductor is illuminated, as seen from (3). In addition, this property of the Josephson junction is not very sensitive to the actual form of the distribution function that is established following the illumination. Moreover, under certain conditions it is possible to obtain absolute negative resistance in a junction consisting of superconductors with equal gaps, for example in the case when $\omega - 2\Delta \ll \Delta$,[7] where ω is the frequency of the light.

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