Double stimulation of critical current in pure SNINS systems

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It is shown that under the action of a microwave field, a sharp increase in the critical current of pure SNINS junctions is possible. This is a direct result of two circumstances: the nonequilibrium nature of the electron distribution function in the junction and the presence of resonant singularities (logarithmic peaks) of the Josephson current (Ref. 1).

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The microscopic theory of the nonstationary Josephson effect in SNINS junctions (i.e., superconductor–normal metal–superconductor junctions with an insulating layer in the normal metal) with arbitrary voltage variation on the junction was constructed in Ref. 1. In particular, it was shown that the amplitude of the pair current in the presence of a voltage has a power-law dependence on the thickness of the layer of normal metal d even at temperatures $T \gg v_F/d$, although the steady-state current in SNS systems at such temperatures is exponentially small $j \sim \exp\{-2\pi T d/v_F\}$ (see, for example, Ref. 2). This effect is related to the nonequilibrium nature of the quasiparticle distribution in the N layer, which arises with the passage of electrons that tunnel through the insulating layer with a potential difference across the junction. However, the difference in the phases of the order parameters of the superconducting boundaries in this case oscillates in time, so that the time average of the pair current is equal to zero.

However, a slightly different situation can be examined. Suppose a steady-state current pass through the SNINS junction, so that the superconducting phase difference has the value φ_0, which is independent of time. Let us place such a junction in a microwave field and assume that an additional phase difference $\varphi_1(t)$ appears on the junction:

$$\varphi(t) = \varphi_0 + \varphi_1(t), \quad \varphi_1(t) = 2e\int^t V(t')\,dt', \quad V(t) = V_0 \cos\omega_0 t. \tag{1}$$

In this case, the tunneling current will have the form

$$j(t) = \mathrm{Im} \sum_{n,k} J_n\left(\frac{eV_0}{\omega_0}\right) e^{ik\omega_0 t}\left\{J_{k+n}\left(\frac{eV_0}{\omega_0}\right) j_q(n\omega_0) + e^{i\varphi_0} J_{k-n}\left(\frac{eV_0}{\omega_0}\right) j_p(n\omega_0)\right\} \tag{2}$$

Here J_n is an nth order Bessel function, and the currents j_p and j_q were calculated in Ref. 1. Averaging (2) over time, we obtain

$$j = \mathrm{Im}\, e^{i\varphi_0}\left\{J_0^2\left(\frac{eV_0}{\omega_0}\right) j_p(0) + 2\sum_{n=1}^{\infty} (-1)^n J_n^2\left(\frac{eV_0}{\omega_0}\right) j_p(n\omega_0)\right\} \tag{3}$$

We shall examine the case $eV_0 \ll \omega_0$ [i.e., $\varphi_1(t) \ll 1$]. Thus, from (3) we find

$$j = \left\{ j^r_1(0) - \frac{e^2 V_0^2}{2\omega_0^2} [j^r_1(0) + j^r_1(\omega_0) + j^a_1(\omega_0)] \right\} \sin\varphi_0 - \frac{e^2 V_0^2}{2\omega_0^2} j_2 \cos\varphi_0 , \tag{4}$$

where $j_1^r + j_1^a = Imj_p$, and $j_2 = Rej_p$. For $T \gg v_F/d$, the current j_i^r is exponentially small, while the currents j_1^a and j_2 are not that small.[1] Thus, the presence of an alternating electromagnetic field amplifies the superconducting properties of SNS junctions.

This effect is essentially analogous to the well-known phenomenon of stimulation of superconductivity by a microwave field.[3] Indeed, the quantity $\Delta_N \sim v_F/d$ plays the role of a gap in the spectrum of quasiparticle excitations of SNS systems. For $\omega_0 \gtrsim \Delta_N$, nonequilibrium quasiparticles with energies of the order of (or higher than) the inverse flight time through the junction v_F/d, which for $T \gg v_F/d$ give the main contribution to the current, will appear in the N layer. Only the magnitude of the current, and not the effect itself, depends on the positioning of the insulating layer in the N layer (and, generally, on its presence or absence). An analogous phenomenon occurs in superconducting bridge structures.[4] We note also that there are experimental indications of the amplification of the critical current in SNS junctions with a short mean free path in a microwave field.[1),5]

In SNINS systems, there is also an additional amplification of the critical current, which is related to the presence of logarithmic peaks in the dependence $j_1^a(\omega_0)$[1]. Under the conditions $v_F/d \ll T$, $\omega_0 \ll \Delta$, and $d \gg \xi_0$ (Δ is the modulus of the order parameter of the superconductors and ξ_0 is the coherence length), the expression for j_1^a has an especially simple form[1]

$$j^a_1(\omega_0) = \eta \frac{v_F}{eRd} \ln \left| \frac{1 + \cos(\omega_0 d / v_F)}{1 - \cos(\omega_0 d / v_F)} \right| , \quad \eta = \begin{cases} 1, & \omega_0 \gg T, \\ \omega_0/T, & \omega_0 \ll T \end{cases} \tag{5}$$

(R is the resistance of the insulating layer), while $j_2(\omega_0) = 0$. In this case, the critical current density in the junction is

$$j_c = \frac{e^2 V_0^2}{2\omega_0^2} | j^a_1(\omega_0) | . \tag{6}$$

The difference in the expressions (5) for values $\omega_{0n} = \pi v_F n/d$ are explained by the resonant absorption of photons by electrons which tunnel through the insulating layer between two systems of Andreev levels.[1] Thus, in order for this mechanism of stimulation of the critical current to appear, a discrete spectrum of excitations on both sides of the insulator, which is specific to SNINS systems, must be present. The differences in expressions (5) are evidently of a formal nature, since the Andreev levels always have a finite width due to electron scattering by impurities, inhomogeneities of the NS boundaries, as well as inelastic relaxation processes. Near the frequencies ω_{0n}, we have with logarithmic accuracy,

$$j_c = \eta \frac{v_F e V_0^2}{R d \omega_0^2} \ln \frac{v_F}{\gamma_N d} \tag{7}$$

Here γ_N is the characteristic broadening of the levels in the discrete spectrum of the normal metal.

Thus, in a microwave field, the critical current can be stimulated in pure SNINS systems as a direct result of two effects. Irradiation of the junction leads to the formation of nonequilibrium electrons in the N layer, which pass freely through the junction, and, in addition, to resonant (with fixed frequencies) hopping of tunneling electrons from one energy level to another. As a result, the critical current, even at low irradiation power, can have an appreciable magnitude, varying inversely proportional to the thickness of the N layer (7) (rather than exponentially, as in the equilibrium case). The results obtained are valid when[1]

$$\nu_T \ll 1/\tau_{\epsilon N} \ll v_F/d, \tag{8}$$

which allows speaking about the presence of a discrete spectrum as well as calculating the current using perturbation theory with respect to the parameter $8\pi^2/e^2p^2{}_FR \ll 1$ (ν_T is the characteristic hopping frequency of electrons through the barrier, and $\tau_{\epsilon N}$ is the energy relaxation time of quasiparticles in the N layer).

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[1)] We also learned about the work in Ref. 6, wherein the effect of stimulation of a supercurrent in dirty SNS bridges with low intensities of microwave irradiation is studied. The critical current under these conditions also depends exponentially on the thickness of the N layer ($I_c \sim d^{-4}$).

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