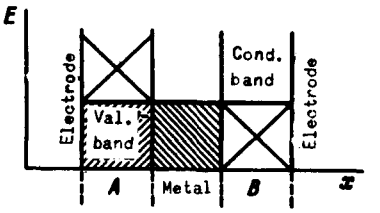
SUPERCONDUCTIVITY IN A NONEQUILIBRIUM SYSTEM

E. G. Batyev
Semiconductor Physics Institute, Siberian Division, USSR Academy of Sciences
Submitted 3 October 1966
ZhETF Pis'ma 5, No. 2, 45-48, 15 January 1967

As is well known, the gap in a superconductor decreases with increasing temperature because of the temperature smearing of the electron Fermi distribution. Let us assume that some means of reducing this smearing exist. Then superconductivity can appear at thermostat temperatures exceeding the temperature of the superconducting transition.

The effective "temperature" of a metal can be lowered by current flowing through a semiconductor - metal - semiconduct sandwich. The sandwich parameters are chosen such that when the current flows the electrons leaving the metal have a higher energy than those coming in. This is equivalent to stipulating the energy band scheme shown in the figure (the edges of the semiconductor bands are approximately at the level of the chemical potential μ of the metal). It is then possible to lower the effective "temperature" of the metal by producing a flow of electrons from A to B.



The required band arrangement can be obtained by satisfying certain conditions. Let us examine, for example, the metal-semiconductor junction B (the other junction can be considered similarly). It is obvious that the work function of the metal should be lower than the ionization energy of the electron from the bottom of the semiconductor conduction band. Then, when equilibrium is established, the electrons flow from the metal to the semiconductor, the band bends upward, and the edge of the band may be not too much higher than μ if the film is sufficiently thin.

The distance from the edge of the band to μ can be readily estimated for a film whose thickness is much larger than the electron wavelength. The electron density N is simply related with this quantity:

$$N \sim (m^* T)^{3/2} \exp\left(-\frac{E}{T}\right), \tag{1}$$

where E is the distance from the bottom of the band to μ, T the temperature, and m^* the effective mass. On the other hand, the film thickness L is larger than or of the order of the corresponding Debye radius L_D

$$L^2 \gtrsim L_D^2 \sim \frac{\epsilon T}{Ne^2}, \tag{2}$$

where ϵ is the dielectric constant and e is the charge. Comparing (1) and (2) we get

$$\exp\left(-\frac{E}{T}\right) \gtrsim \frac{\epsilon\left(\frac{T}{m^*}\right)^{1/2}}{e^2} \cdot \frac{1}{L^2(m^* T)}. \tag{3}$$

This reveals the connection between E and L. Relation (3) holds true if the density of the electrons going to the conduction band from the impurity levels is small compared with N.

We shall assume in the estimates that

$$\exp\left(-\frac{E}{T}\right) \sim \frac{\epsilon(T/m^*)^{1/2}}{e^2}. \tag{3a}$$

If $L > (m^*T)^{-1/2}$, then such a value of E can be obtained by applying a suitable voltage to the film (here $L_D^2(m^*T) \sim 1$). Further rise in voltage increases the effective "temperature." Indeed, when $(1/m^*L_D^2) \gtrsim E$, there are more electrons arriving from the left at a given level with energy $>\mu$ than leaving (see the figure). Thus, at some value of the current the thermostat temperature at which the Cooper instability sets in is maximal.

The current that can be produced in the semiconductor is of the order of

$$j \sim N\left(\frac{T}{m^*}\right)^{1/2} D, \tag{4}$$

where D is the coefficient of transition through the semiconductor - metal contact. Let us estimate the current needed to obtain strong nonequilibrium in the metal. It is required that the number of electrons of energy $> \mu$ be appreciably decreased within the energy relaxation time τ, i.e., the current produced should be

$$j \gtrsim \frac{T}{\mu} n \frac{l}{\tau}, \tag{5}$$

where l is the thickness of the metal film and n the electron density. From the condition $j' < j$ we obtain the limitation

$$\frac{l}{a} < \exp\left(-\frac{E}{T}\right) D \frac{m^*}{m}(T\tau), \tag{6}$$

where a is of the order of the interelectronic distances and m the mass of the electron in the metal.

The energy relaxation is due to phonon absorption. For τ in the metal we have (cf. e.g., [1]):

$$\tau = \frac{l}{\Lambda T}\left(\frac{\omega_0}{T}\right)^2, \tag{7}$$

where $\omega_0 = 2sp_0$ (s = speed of sound, p_0 = Fermi momentum), and Λ is a quantity that depends on the intensity of the electron-phonon interaction.

For an experimental verification of the effect, we can use a βSb - Zn - Ge sandwich

with zinc electrodes. The respective work functions are 4.08, 4.26, and 4.76 eV [2]. The forbidden-gap width is 0.11 eV in βSb [3] and 0.75 eV in Ge [4].

Let us estimate l with the aid of condition (6) for T = 1°K. For Ge we have $(m^*/m) \approx 0.2$ and $\epsilon = 16$ [4; also $\exp(-E/T) \sim 0.1$ (cf. (3a)), and $D \lesssim 0.1$, and $(T\tau)_{Zn} \approx 10^5$. Substituting these figures in (6) we get $l \lesssim 100$ Å.

Similar estimates for a degenerate semiconductor with low electron density leads to a weaker limitation on l. Unfortunately, the lack of data on the work functions does not enable us to pick the sandwich materials in this case.

The foregoing estimates are valid for sufficiently thick films, when quantization of the transverse electron motion can be disregarded. However, the results are qualitatively correct also for thin films, since the quantization effect is "smeared" in the metal by diffuse reflection from the film boundaries.

In conclusion, let us consider the instability of the system against formation of Cooper pairs. In the simplest case - for a homogeneous isotropic system with specified occupation numbers (only electrons having opposite momenta interact) - the problem is solved in exactly the same manner as in the equilibrium case, namely, by calculating the two-particle Green's function and determining the pole of its Fourier component. The imaginary part of the pole characterizes the degree of instability of the system against Cooper-pair production. The calculation method is that developed by Keldysh [5]. We present the final result:

$$-g\int_{-\omega_D}^{\omega_D} d\xi \frac{\xi[1-2f(\xi)]}{\xi^2+\Delta^2} = 1,$$

$$\int_{-\omega_D}^{\omega_D} d\xi [1-2f(\xi)] \frac{\Delta}{\xi^2+\Delta^2} = 0.$$

Here $f(\xi)$ is the electron distribution function, ξ the electron energy reckoned from χ, and 2χ and Δ are the real and imaginary parts of the pole, respectively. These equations yield χ and Δ. We note that they can always be solved for $g < 0$, if $f(\xi)$ experiences a jump satisfying the condition $f(\xi) > 1/2$ when $\xi < \xi_0$ and $f(\xi) < 1/2$ when $\xi > \xi_0$ (ξ_0 is the "coordinate" of the jump).

I am grateful to V. L. Pokrovskii, S. K. Savvinykh, A. V. Chaplik, and A. G. Shepelev for a discussion and valuable remarks.

[1] G. M. Eliashberg, JETP 39, 1437 (1960), Soviet Phys. JETP 12, 1000 (1961).

[2] B. M. Tsarev, Kontaktnaya raznost' potentsialov (Contact Potential Difference), Gostekhizdat, 1955, p. 166.

[3] Semiconductors, N. B. Henney, ed. (Russ. Transl.), IIL, 1962, p. 66.

[4] R. Smith, Semiconductors (Russ. Transl.) IIL, 1962.

[5] L. V. Keldysh, JETP 47, 1515 (1964), Soviet Phys. JETP 20, 1018 (1965).