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Existence of the proximity layer in Nb and NbN films leads to a peculiar dependence of the critical temperature upon the film thickness. Expressions describing $T_c$ for $S_a$-$S_b$ and $S_a$-$M_b$ proximity systems are obtained. The theory allows to explain the dependence $T_c(L)$ which has been observed experimentally. Measurements of $T_c$ can be used in order to determine the electronic density of states in the surface layer.

**Introduction**

Thin films of Nb and NbN are characterized by a specific behavior of $T_c$. A decrease of the thickness $L$ results in a decrease of $T_c$, and this decrease is described by an exponential dependence: $T_c = \exp(-a/L)$. This dependence has been observed in Ref. 1; similar behavior was observed also in Ref. 2. According to Refs. 1 and 2, this decrease of $T_c$ is due to the proximity effect, that is, to the existence of the surface layer, which is a normal metal or a superconductor with low $T_c$. This approach is supported by analysis of the Josephson current. According to Ref. 3, the behavior of the maximum d.c. Josephson current $I_{th}$ is affected by the existence of the proximity system in Nb film. An analysis of the structure of the surface of Nb films also leads to the necessity of taking the proximity effect into account.

In connection with the aforesaid, it is of interest to evaluate the critical temperature for the $S_a$-$M_b$ proximity system, where $S_a$ is a superconductor, and $M_b$ is a normal metal, or superconductor (we assume that $T_c < T_{c_b}$). This paper is concerned with this problem. An expression describing $T_c$ for $S_a$-$M_b$ ($M_b$ is a normal metal) has been obtained in the author's paper. In this paper the general case of an $S_a$-$S_b$ system will be considered. Moreover, the strong coupling effect will be taken into account, which is important, because both Nb and NbN films are superconductors with strong electron-phonon interaction (EPI). It will be shown also that measurements of $T_c$ allow to obtain information about properties of the proximity layers in Nb and NbN films.

**Critical Temperature**

Consider the proximity system $S_a$-$S_b$ ($T_{c_a} > T_{c_b}$; $T_{c_a}$ and $T_{c_b}$ are the critical temperatures of isolated films). Assume that $L_b \ll L_a$, where $L_a$ is the thickness of the $a$ film and $L_b$ is the coherence length. The proximity effect can be described on the basis of the McMillan tunneling model. In order to evaluate $T_c$, it is convenient to use the method of thermodynamic Green's functions. If $T = T_c$, the equations describing the thermodynamic order parameters $\Delta_a(w_n)$ and $\Delta_b(w_n)$ can be written in the form:

$$\Delta_a = \Delta_a^{ph} + i \Delta_a^{ab} |w_n| T_a / T_c$$

$$\Delta_b = \Delta_b^{ph} + i \Delta_b^{ab} |w_n| T_b / T_c$$

Here $\Delta_a^{ph}$ describe pairing due to the usual electron-phonon coupling, that is

$$\Delta_a^{ph} = Z_a^{-1} \sum \int d\Omega g_a(\Omega) x D_a(w_n)|/|w_n| T_c$$

where $D = <\Omega^2/(\Omega^2 + (w - w_n)^2)^2$ is the phonon Green's function, $g_a(\Omega)$ describe the electron-phonon interaction, $w_n = (2n + 1)\pi T$. According to Ref. 6, the parameters $\Gamma_a$ and $\Gamma_b$ are equal to

$$\Gamma_a = x^2 d_b; \quad \Gamma_b = x^2 d_a.$$ (3)

$T_c$ is the tunneling matrix element, and $d_a(w_n)$ is the densities of states, so that

$$d_a(w_n) = w_n S_a L_a.$$ (4)

$(\nu_0B_a)$ are the densities of states per unit volume, $S$ is the film area, and $L_a$ are the film thicknesses. The functions $Z_aZ_b$ in (1) - (3) are the renormalization parameters.

Assume that the $b$ film is a superconductor with weak EPI. Then one can put $D = D = \Omega^2/(\nu_0B_a + \Omega^2)$. In accordance with this, the solution of Eq. (2), one can determine $b$ and express $\Delta_b(w_n)$ in terms of $\Delta_a(w_n)$. We do not limit the strength of EPI in the $a$ film. Strong coupling effects can be treated on the basis of the theory. After some manipulations, we arrive at the equation allowing to evaluate $T_c$:
The critical temperature is described by Eq. (8) for the $S_a$--$N_b$ system and by Eq. (6) for the $S_b$--$S_b$ system. Consider the dependence of $T_c$ upon the thickness $L_a$. Equation (8) can be rewritten in the form

$$\ln(T_c/T_c^b) = -\frac{1}{L_a}$$

or

$$T_c = T_c^b \exp(-1/L_a),$$

where

$$L = (v_b/v_a)L_a \ln (\Gamma/L_a^b).$$

We consider the case of small $L_a$.

The dependence (9) has been observed experimentally in Refs. 1 and 2 (see above). Hence, the analysis based on the theory of the proximity effect allows to describe the dependence $T_c$ ($L_a$). Note that the dependence

$$\ln(T_c/T_c^b) = -\frac{1}{L_a}$$

can be also obtained for the $S_a$--$S_b$ system (if $L_b \gg L_a$). Indeed, one can usually neglect unity in the denominator in Eq. (7). Then $F = 1 - L_a^{-1}$.

Based on Eq. (7), one can obtain the dependence $T_c(L_b)$ for the $S_a$--$S_b$ system. Then $n = L_a^{-1}[1- (L_a/2L_0)]$. If $L_b \gg L_a$, the function $\ln(T_c/T_c^b)$ is proportional to $L_a^{-1}$ with high accuracy. If $L_b$ is small ($L_b \ll L_a$), there is a deviation from linear dependence; this deviation has been observed experimentally in Ref. 2.

Measurements of $T_c$ allow to obtain information about the properties of the surface proximity layer. Namely, based on Eqs. (6), (7), or (8), one can evaluate the electronic density of states in the surface region. Consider, for example, a Nb film. In this case $T_a = 9.2^\circ$, $T_b = T_c = 1.4^\circ$ (see, e.g., Ref. 2). The thickness $L_b$ is small ($=30\AA$) and hence $U_b = U_e = 110^\circ$. If $L_b = 2.10\AA$, the critical temperature is equal to $T_c = 8^\circ$. Based on Eqs. (6) and (7), one can obtain the following ratio of the densities of states: $d_g/d_a = (v_b/v_a)(L_b/L_a) = 0.14$. The density of states (per unit volume) in the surface layer is smaller than in bulk, i.e., $v_b/v_a = 0.8$.

Consider a NbN film. Assume that the $a$-layer is a normal metal. Then we can use Eq. (8). In this case $T_c = 15.5^\circ$, $T_b = 66.9^\circ$, $T_c(L) = 2.10^2\AA = 13.5^\circ$. Based on Eq. (8), we obtain $(d_g/d_a) = (v_b/v_a)(L_b/L_a) = 0.09$.

Discussion

The critical temperature is described by Eq. (8) for the $S_a$--$N_b$ system and by Eq. (6) for the $S_b$--$S_b$ system. Consider the dependence of $T_c$ upon the thickness $L_a$.

Equation (8) can be rewritten in the form

$$\ln(T_c/T_c^b) = -\frac{1}{L_a}$$

or

$$T_c = T_c^b \exp(-1/L_a),$$

where

$$L = (v_b/v_a)L_a \ln (\Gamma/L_a^b).$$

We consider the case of small $L_a$.

The dependence (9) has been observed experimentally in Refs. 1 and 2 (see above). Hence, the analysis based on the theory of the proximity effect allows to describe the dependence $T_c$ ($L_a$). Note that the dependence

$$\ln(T_c/T_c^b) = -\frac{1}{L_a}$$

can be also obtained for the $S_a$--$S_b$ system (if $L_b \gg L_a$). Indeed, one can usually neglect unity in the denominator in Eq. (7). Then $F = 1 - L_a^{-1}$.

In the case $<\partial> = \Gamma$ in a weak coupling approximation Eq. (6) corresponds to the Cooper limit (one should also assume that $\langle\delta\rangle = \langle\delta\rangle^b$; see Ref. 10).

According to Eqs. (6), (8), $T_c$ depends upon $v_b$.

$\nu_b$ is a function of the electron concentration and, hence, $T_c$ can be affected by radiation (if a film is a semiconductor, see Ref. 11). Note also that the dependence $T_c(L Ge)$ observed in Ref. 12 for Nb-Ge multilayers, can be connected with the influence of Ge films, because of the proximity effects (cf. Ref. 13, see also Ref. 5). The authors also observed the dependence $T_c(L NO)$ for a single Nb film (see also Ref. 14). Note also that if a film is a size-quantizing film, it results in a non-monotonic behavior of $T_c(L_b)$ (see Ref. 5).

Summary

Equation (6) is a general expression describing $T_c$ for the proximity system $S_a$--$S_b$ containing two superconducting films. Equation (8) is valid for the $S_a$--$N_b$ system. These equations allow to explain the dependence of $T_c$ upon the film thickness which has been ob-
served experimentally. Moreover, measurements of $T_c$ can be used in order to determine the electronic density of states in surface layers of such films as Nb, NbN, etc.

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