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The search for new superconducting materials is of considerable interest. As is well-known, superconductivity in semiconductors is caused by intervalley interaction (M. Cohen; see Ref. [1]). Moreover, intervalley interaction may result in the appearance of a non-phonon mechanism.[2]

The present paper is concerned with a different type of superconductivity in semiconductors (SC) or semimetals (SM), namely, with induced superconductivity. If a SC (or SM) film is placed on a usual superconductor, there results a superconducting state of SC or SM because of the proximity effect. This proximity system is characterized by interesting features connected with the properties of SC and SM. We focus here on the analysis of the critical temperature T_c, magnetic screening and the Josephson effect.

<u>Critical Temperature</u>. Consider the system S_α - M_β containing two films, where S_α is superconductor, and M_β is a SC (or SM) film. Assume that $L_\alpha >> L_\beta$ (L_α, L_β are the film thicknesses), and $L_\beta << \xi_\beta$, where ξ_β is the coherence length; ξ_β increases with decreasing T.[3,4] Then one can use the McMillan tunneling model.[5] Our approach is based on the thermodynamic Green's function method; this method has been used in the theory of the proximity effect by the author.[4] One can write

$$\Delta_\alpha(\omega_n) = Z^{-1}\pi T \sum_{\omega_{n'}} \int d\Omega\; g_\alpha(\Omega)\; D(\Omega,\omega_n - \omega_{n'})\, \kappa_\alpha^{-1}(\omega_{n'})\; \Delta_\alpha(\omega_{n'}) + \Delta_{\alpha\beta}$$

$$\Delta_\beta(\omega_n) = \Delta_{\beta\alpha}(\omega_n) \qquad (1)$$

where Δ_α, Δ_β are the thermodynamic order parameters, $\omega_n = (2n + 1)\pi T$, $g_\alpha(\Omega)$ describes the electron-phonon interaction in α film, Ω is the phonon frequency, D is the phonon Green function, $\kappa_\alpha = (\omega_n^2 + \Delta_\alpha^2(\omega_n))^{1/2}$, Z_α is the renormalized function, and

$$\Delta_{\alpha\beta} = Z_\alpha^{-1}\Gamma^{\alpha\beta}\kappa_\beta^{-1}(\omega_n)\ \Delta_\beta(\omega_n) \quad ; \quad \Delta_{\beta\alpha} = Z_\beta^{-1}\Gamma^{\beta\alpha}\kappa_\alpha^{-1}(\omega_n)\ \Delta_\beta(\omega_n)$$

Here $\Gamma^{\alpha\beta} = \pi\tilde{T}^2\nu_\beta SL_\beta$; $\Gamma^{\beta\alpha} = \pi\tilde{T}^2\nu_\alpha SL_\alpha$ (ν_α, ν_β are the densities of the states, $\tilde{T}$ is the tunneling matrix element, and S is the area of the contact, see Ref. 5).

We consider the general case of strong electron-phonon coupling in the α film, e.g., S_α = Pb, NbN, etc. The weak coupling approximation has been used in Ref. [4]. Strong coupling effects can be considered on the basis of the theory.[6] In order to determine T_c, one should put $\Delta_\alpha = \Delta_\beta = 0$ in the expressions for $\kappa_{\alpha(\beta)}$ and Z. After a long calculation we arrive at the following expression

$$T_c = T_c^\alpha(u/T_c)^{-\rho} \quad . \tag{2}$$

Here T_c^α is the critical temperature of an isolated α film, $u = (2\gamma/\pi\sqrt{e})\langle\Omega\rangle$, if $L_\beta \lesssim 2\times10^2$Å, and ρ is equal to

$$\rho = (\nu_\beta L_\beta/\nu_\alpha L_\alpha) \tag{3}$$

If the β film is a degenerate SC with high electron concentration ($\mu - v \gg T$, v corresponds to the bottom of one conduction band), the density of states ν_β depends strongly upon n_e($\nu_\beta \sim n_e^{1/3}$), and hence T_c of the proximity system is a function of n_e in the SC film. One can see from Eqs. (2) and (3) that a decrease of n_e results in an increase of T_c. A change of n_e can be made by several methods (e.g., by radiation, see, e.g., Ref. [7]), and this dependence can be verified experimentally.

An interesting situation occurs if the β film is a thin SM size-quantizing film (e.g., Bi, Sb, InSb). If L_β is small enough (e.g., for Bi film $L_\beta \lesssim 2 \times 10^2$Å), then only the lowest transverse level is filled (see e.g., Ref. [4]). Then $\nu_\beta \sim m/L_\beta$ and T_c does not depend on L_β in this region. However, subsequent decrease of L_β might result in a so-called semimetal-semiconductor transition.[8] Decreasing the film thickness results in a removal of the overlap of the valence and conduction bands and in the appearance of an energy gap. Then n_e is exponentially small in the low temperature region. This transition will be accompanied by an increase at T_c and hence, this increase can be used in order to determine such a transition.

Screening. As is known, superconductors are characterized by anomalous diamagnetism (Meissner effect). In connection with this, it is of interest to study the behavior of a SC (SM) in an external field. The current density can be written in the form: $\vec{j} = 2\ (ie/2m)\ (\nabla_{\vec{r}'} - \Delta_{\vec{r}})\ G(x,x') - (e^2\vec{A}/m)\ G(x,x')\ |\vec{r}' \to \vec{r}\ ,\ \tau' \to \tau + 0$, where G(x,x') is the thermodynamic Green's function and $x = \{\vec{r},\tau\}$, τ is the imaginary time. The electron-phonon interaction can be included directly in the equation for $G(x,x')$ and it allows to take into account the strong coupling effect.[9] We focus on the low temperature region, where non-locality plays an important role. As a result, the penetration depth (we restrict ourselves to the case of specular reflection) can be evaluated from the equation

$$\lambda = \int_0^\infty dq[q^2 + \kappa(q)]^{-1} \quad , \tag{4}$$

where $\kappa(q) = (3\pi^2/v_F^\beta q) \sum_{\omega_n>0} \Delta_\beta^2(\omega_n)[\omega_n^2 + \Delta^2(\omega_n)]^{-1}$.

The order parameter $\Delta_\beta(\omega_n)$ can be obtained from Eq. (1). We assume that $\lambda > L_\beta$. Finally we arrive at the following expression describing the temperature dependence of the penetration depth:

$$\lambda(T)/\lambda(0) = [\phi(0)/\phi(T)]^{1/3} \tag{5}$$

where

$$\phi(T) = \pi T \sum_n f_\alpha^2 \left\{ X_n^2[1 + (\epsilon_\alpha/\pi T_c^\alpha)t\sqrt{X_n + f_\alpha^2}]^2 + f_\alpha^2 \right\}^{-1} \quad ;$$

Here $X_n = (2n + 1)\pi T/\epsilon_\alpha(0)$, $f_\alpha = \Delta_\alpha(X_n\epsilon_\alpha)/\epsilon_\alpha$, ϵ_α is the energy gap in the film. If is a strong coupled superconductor, then[6] $\epsilon_\alpha(0) = 1.76\, T_c[1 + 5.3(T_c^\alpha/\Omega)^2 \ln(\Omega/T_c)]$, Ω is a characteristic phonon frequency; e.g., $\Omega_{Pb} = 4.5$ meV. The parameter t has been introduced in Ref. [4] and depends on the thickness of SC film ($t \sim L_\beta$), the quality of the proximity contact and the electron concentration. It is essential that $t \sim n_e^{-1/3}$. Hence the increase of the electron concentration in SC film results in an decrease of t, and, as a result, the temperature dependence $\lambda(T)$ becomes less slanting (see Fig. 1). One can show that the increase of n_e at fixed T and L_β leads to a decrease of the absolute value of the penetration depth. As is known, the dependence $\lambda(T)$ for one usual superconductors is very weak in one region $T \ll T_c$. The situation becomes entirely different for the case of the induced superconductivity.

Josephson effect. Consider a Josephson junction $S_\alpha - M_\beta - I - S_\gamma$, where M_β is a SC or SM film. In this case the Josephson contact occurs between the superconductor S_γ and the film M_β, which is characterized by the induced superconductivity. The maximum Josephson current can be evaluated[4] with the use of the expression $I_M = (T/\pi eR) \sum_n \int d\xi_\beta d\xi_\beta F_\beta^+ F_\gamma$, where F_β, F_γ are the anomalous thermodynamic Green's functions, R is the normal resistance, $\xi_{\beta(\gamma)}$ is the electron's energy referred to the Fermi level. It turns out that I_M depends on n_e. It is interesting to note that, contrary to the behavior of $\lambda(T)$ (see above), I_M decreases with an increase of n_e. The value n_e can be affected by the radiation

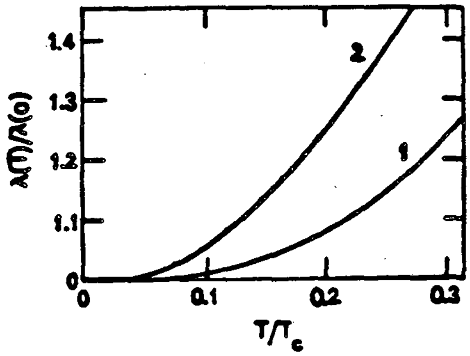

Figure 1. Temperature dependence of for S_α - SC(SM) systems: (1) t = 5, (2) t = 10. When n_e increases by an order of magnitude, the dependence $\lambda(T)$ changes from curve (1) to curve (2).

(see, e.g., Ref. [7]). If M_β is a size-quantizing SM film, I_M becomes an oscillating function of L_β.

It is worth noticing that the problem of magnetic screening (see above) is directly related to the problem of the behavior of a Josephson junction in a magnetic field. The period of oscillations of the current is related to the penetration depth.

Hence, the SC and SM films with the induced superconductivity are characterized by the peculiar behavior of T_c, screening and the Josephson current. These properties allow to change their behavior in the desired direction.

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