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ABSTRACT

The properties of a Josephson junction containing a proximity system are discussed. The value of the maximum dc Josephson current $I_M(T)$ depends strongly on the parameters of the proximity system. If N is a semiconducting film, the value of I_M may be affected by incident radiation. If N is a size-quantizing semimetal film, I_M becomes an oscillating function of the thickness L_N. The weak link can be formed by the inversion layer and I_M can be controlled by the applied field.

Introduction

The present paper is concerned with the properties of a Josephson junction containing a proximity system. One can study a number of such junctions, e.g., $S_\alpha - M_\beta - I - S_\gamma$, $S_\alpha - M_\beta - I - M_\gamma - S_\delta$, etc. (S is a superconductor, I an insulator, M is a normal metal, semimetal, semiconductor, or another superconductor, $T_C^\alpha \neq T_C^\beta$). Lately, such systems have attracted a lot of interest (see, e.g.[1])

The author has developed a method to study Josephson tunneling into a proximity system.[2] The approach is based on the method of thermodynamic Green's functions. The most interesting problem is connected with the analysis of the temperature dependence of the maximum dc Josephson current I_M, and its dependence upon the thickness L_β. It is interesting also to study the effect of magnetic field on the characteristics of the current.[3]

In this paper we focus mainly on the properties of N-S-I-S systems, where N is a thin normal film. These systems have not been studied before; as will be shown, one can noticeably affect the properties of the junction by changing the parameters of the N film.

Proximity system. Main equations

There are many papers concerned with proximity systems (see, e.g., the reviews in Refs. 1,2,4). A proximity system represents the simplest case of an inhomogeneous system. Moreover, the proximity effect allows to induce the superconducting state in a material which is by itself normal.

Many papers contain an analysis based on the method developed by the Orsay group (see, e.g., the reviews,[5,6]). This method uses the Ginsburg–Landau theory and is applicable only in the region $T \sim T_c$.

McMillan's tunneling model[7] represents another approach. This model gives a good description of experimental data (see, e.g.,[6,2]). It can be applied at any temperature and corresponds to the case of a not very clean contact. The limitation of McMillan's model is that the order parameter is assumed to be uniform in each of the films. (Note that this limitation can be eliminated; this problem will be discussed elsewhere). It requires that $L_N \ll \xi_N$ (ξ_N is the coherence length in the normal film, L_N is its thickness). It is important to note that decrease of T results in an increase of ξ_N[8], and the condition $L_N \ll \xi_N$ is satisfied better. This remark is important because we are mainly concerned with the low temperature region. If $T \sim T_c$, one can use the Ginsburg–Landau theory.

One can describe a proximity system with the use of thermodynamic Green's functions.[2,3] The main equations are:

$$\Delta_\alpha(\omega_n) = Z_\alpha^{-1} \pi T \sum_{\omega_{n'}} \int d\Omega \, g_\alpha(\Omega) \, D(\Omega, \omega_n - \omega_{n'}) \times K_\alpha^{-1} \Delta_\alpha(\omega_{n'}) + \Gamma^{\alpha\beta} K_\beta^{-1} \Delta_\beta(\omega_n) \quad (1)$$

$$\Delta_\beta(\omega_n) = Z_\beta^{-1} \pi T \sum_{\omega_{n'}} \int d\Omega \, g_\beta(\Omega) \, D(\Omega, \omega_n - \omega_{n'}) \, K_\beta^{-1} \Delta_\beta(\omega_{n'}) + Z_\beta^{-1} \Gamma^{\beta\alpha} K_\alpha^{-1} \Delta_\alpha(\omega_n) \quad (2)$$

Here $\Delta_{\alpha(\beta)}(\omega_n)$ is the order parameter, $Z_{\alpha(\beta)}$ is the renormalization function, $K_{\alpha(\beta)} = [\omega_n^2 + \Delta_{\alpha(\beta)}^2]^{1/2}$. The first terms in Eqs. (1), and (2) describe the usual electron-phonon interaction. If the β film is a normal metal, one can keep only the second term in Eq. (2). The parameters $\Gamma^{\alpha\beta}$ and $\Gamma^{\beta\alpha}$ have been introduced by McMillan,[7] and are equal to:

$$\Gamma^{\alpha\beta} = \pi \tilde{T}^2 \nu_\beta SL_\beta; \; \Gamma^{\beta\alpha} = \pi \tilde{T}^2 \nu_\alpha SL_\alpha \tag{3}$$

where $\tilde{T}$ is the tunneling matrix element, $\nu_{\alpha(\beta)}$ is the density of states and S is the area of the contact. Hence $\Gamma^{\alpha\beta}/\Gamma^{\beta\alpha} = (\nu_\beta L_\beta)/(\nu_\alpha L_\alpha)$ and we have the single adjustable parameter $\Gamma^{\beta\alpha}$. Note also that $\Gamma^{\beta\alpha} \sim L_\beta^{-1}$. One can introduce the parameter $S_0 = \Gamma^{\beta\alpha}(L_\beta = L_0)$, where L_0 is a fixed thickness (we have chosen $L_0 = 100\text{Å}$).

Consider the Josephson junction $S_\alpha - N_\beta - I - S_\alpha$. The maximum dc Josephson current is equal to:[9]

$$I_M = \frac{\pi T}{eR} \sum_{\pi_n} \frac{\Delta_\beta(\omega_n)\; \Delta_\gamma(\omega_n)}{K_\beta\; K_\gamma}. \tag{4}$$

The thickness and temperature dependences of the Josephson current in the presence of the proximity system $S_\alpha - N_\beta$ have been evaluated by the author.[2] For example, the temperature dependence of I_M differs noticeably from the usual Ambegaokar-Baratoff expression[10] and the deviation increases with increasing thickness L_β (see fig. 1).

$\underline{N_\beta\text{-}S_\alpha\text{-}I\text{-}S_\alpha}$ system.

The system of interest (e.g., Cu-Pb-I-Pb) is characterized by a Josephson current between the two superconductors S_α, but the presence of the normal film leads, because of the proximity effect, to a change of the order parameter in its neighboring S_α film. In this way the normal film affect the Josephson current. As we shall see, the most interesting situation arises in the case of a semimetal β film.

The maximum dc Josephson current can be determined from Eq. (4):

$$I_M eR = \pi T \sum_{\pi_n} \tilde{\Delta}_\alpha(\omega_n)\, \Delta_\alpha(\omega_n)\, (\tilde{K}_\alpha\, K_\alpha)^{-1}, \tag{5}$$

where Δ_α is the order parameter of an isolated α film, $\tilde{\Delta}_\alpha$ is the order parameter of the α film in the presence of the β film, $\tilde{K}_\alpha = (\omega_n^2 + \tilde{\Delta}_\alpha^2(\omega_n))^{1/2}$.

Th order parameter $\tilde{\Delta}_\alpha(\omega_n)$ satisfies the equations (see Eqs. (1), (2)):

$$\begin{aligned}\tilde{\Delta}_\alpha(\omega_n) = \tilde{Z}_\omega^{-1}\, \pi T \sum_{\omega_{n'}} \int d\Omega\; g_\alpha(\Omega) \\ \times D(\omega_n - \tilde{\omega}_{n'}, \Omega)\, \tilde{K}_\alpha^{-1}\, \tilde{\Delta}_\alpha(\omega_{n'}) \\ + \tilde{Z}_\alpha^{-1}\, \Gamma^{\alpha\beta}\, K_\beta^{-1}\, \Delta_\beta(\omega_n)\end{aligned} \tag{6}$$

$$\Delta_\beta = Z_\beta^{-1}\, \Gamma^{\beta\alpha}\, \tilde{K}_\alpha^{-1}\, \tilde{\Delta}_\alpha \tag{7}$$

$\tilde{\Delta}_\alpha(\omega_n) = \Delta_\alpha(\omega_n)$ if $\Gamma^{\alpha\beta} = 0$. We put $g_\beta = 0$.

The renormalization functions are equal to:[2]

$$Z_\alpha = 1 + \lambda_\alpha + \Gamma^{\alpha\beta}/K_\beta \tag{8}$$

$$Z_\beta = 1 + \Gamma^{\beta\alpha}/K_\alpha$$

$$\lambda_\alpha = \int d\Omega\; g_\alpha(\Omega)/\Omega. \tag{9}$$

We assume that $\Gamma^{\beta\alpha} \ll \varepsilon_\alpha$ (ε_α is the energy gap in an isolated α film). This is a realistic assumption in the low temperature region for $\ell \sim 1$ ($\ell = L_\beta/L_0$). We assume also that $L_\beta \ll L_\alpha$ and, hence, $\Gamma^{\alpha\beta} \ll \varepsilon_\alpha$.

Based on Eqs. (6) - (9), we obtain:

$$\tilde{\Delta}_\alpha = \Delta_\alpha + \Delta_\alpha^1, \tag{10}$$

where

$$\Delta_\alpha^1 = -\Gamma^{\alpha\beta}\left[\omega_n^2 + (\Gamma^{\beta\alpha}\Delta_\alpha K_\alpha^{-1})^2\right]^{-1/2}\Delta_\alpha \tag{11}$$

Substituting (10) and (11) into Eq. (5), we arrive at the following expression:

$$I_M eR = (I_M eR)_0 + \Delta(I_M eR), \tag{12}$$

where $(I_M eR)_0$ is described by the usual expression,[10] and the additional term $\Delta(I_M eR)$ due to the proximity effect is equal to:

$$\Delta(I_M eR) = -\pi T\,\Gamma^{\alpha\beta}\sum_{\omega_n}\frac{\Delta_\alpha^4(\omega_n)}{K_\alpha^3\left[\omega_n^2 K_\alpha^2 + (\Gamma^{\beta\alpha}\Delta_\alpha)^2\right]^{1/2}} \tag{13}$$

In the low temperature region, one replaces summation by integration ($2\pi T\sum_{\omega_n} \to \int d\omega$); this is exact at $T = 0°$. Then we obtain

$$\Delta(I_M eR) = -\Gamma^{\alpha\beta}\int_0^\infty dx\,(x^2+1)^{-1/2}\left[x^2(x^2+1)+\lambda^2\right]^{-1/2}$$

$$+\,\Gamma^{\alpha\beta}\int_0^\infty dx\,(x^2+1)^{-3/2}\left[x^2(x^2+1)+\lambda^2\right]^{-1/2}; \quad \lambda = \Gamma^{\beta\alpha}/\Delta_\alpha \tag{14}$$

After a calculation, we arrive at the following expression:

$$\Delta(I_M eR) = -(\Gamma^{\alpha\beta}/\pi\varepsilon_\alpha)(I_M eR)_0, \tag{15}$$

or

$$\Delta(I_M eR) = (\nu_\beta L_\beta/\nu_\alpha L_\alpha)\pi\alpha t)^{-1}(I_M eR)_0, \tag{16}$$

where $t = \ell/S_0$ is the dimensionless quantity introduced in[2], $\alpha = \varepsilon_\alpha(o)/\pi T_c$, $\ell = L_\beta/L_0$, $L_0 = 10^2$Å and S_0 is the parameter of the theory (see above). Note that $\Delta(I_M eR)$ depends on the electron concentration ($\Gamma^{\alpha\beta} \sim n^{1/3}$, see[11]).

One can see directly from Eq. (16) that an increase of the thickness L_α results in a decrease of the correction $\Delta(I_M eR)$.

If the β film is a semiconductor, then the electron concentration can be changed by radiation.[1,12] According to Eq. (15), an increase of the electron concentration in the β film increases the Josephson current.

<u>Sm-S-I-S junction</u>

Let us consider the special case of the normal film being a size-quantizing semimetal film (e.g., Bi, Sb, etc.).

Size quantization, due to the finite thickness of the film, results in the electron energy $\varepsilon(\vec{\kappa}, n)$ being determined by the longitudinal two-dimensional crystal momentum $\vec{\kappa}$ and by the transverse quantum number "n".

The best conditions for size quantization are realized in a semimetal film[13] where low electron density and a small value of the transverse effective mass cause the de Broglie wavelength to greatly exceed the atomic distance; this makes surface scattering specular.

Otherwise, this scattering would result in broadening of the transverse levels and disappearance of size quantization.

In the presence of size quantization, we have a set of two-dimensional subbands instead of a Fermi surface. If the condition n $L^3 < a^3(\tilde{m}/m_{\perp})$ is satisfied,[4] then only the lowest subband is filled ($m_{\perp}$ is the transverse electron mass, $\tilde{m} = (m_1 m_2)^{1/2}$, m_1 and m_2 are the longitudinal masses, a = 1.7, n is the electron concentration). For example, for Bi films this condition is satisfied up to $L = 2 \times 10^2$Å. Then we deal with an interesting physical system: the film, which remains a three-dimensional system in coordinate space ($L \gg a$, a is the atomic distance), becomes a two-dimensional system in momentum space. Increasing the thickness decreases the spacing between the transverse levels and, as a result, the next subband begins to be filled. Hence, an increase in thickness is accompanied by oscillations of the density of states.

Size quantization has been observed experimentally in films of Bi, Sb, InSb.[14] Observation of size quantization in thin metallic films is also possible, but the sensitivity of the effect to the quality of the film makes this observation more complicated. In connection with this, I would like to mention the very interesting paper[15] describing an observation of size quantization in thin Sn films. The authors[15] have observed oscillations of the critical temperature due to size quantization. So, the density of states in a size-quantizing film is an oscillating function of the film thickness. The properties of the proximity system S_α-N_β depend on the density of states in the β film. As a result, the critical temperature and the penetration depth oscillate as functions of L_β (see Refs. 3,4).

According to Eqs. (12) and (16), the Josephson current contains an additional term which is proportional to the density of states in the β film: $\Delta(I_M eR) \sim \nu_\beta$. Therefore, if the β film is size-quantizing, the quantity I_M will oscillate as a function of the thickness L_β. It would be interesting to verify this conclusion experimentally.

The Josephson current in the Sm-S proximity system can be also affected by the structural transition occurring in size-quantizing Bi films. This structural transition has been studied by the author in ref. 16. If the thickness of the Bi film is such that only the lowest subband is filled ($L_\beta \lesssim 2 \times 10^2$ Å), then we have a Fermi curve $\varepsilon(\vec{\kappa}) = \varepsilon_F$ instead of a Fermi surface. This Fermi curve is anisotropic and represents a very stretched ellipse (for a more detailed discussion see Ref. 16). Such anisotropy implies the presence of intervals with electron degeneracy along the Fermi curve (nesting states). These states comprise a greater part of the curve (~90%). This results in phonon instability and in a structural transition accompanied by the appearance of specific charge density waves. This transition occurs at low temperatures at $T = T_p$ ($T_p \simeq 5^\circ$K) and is characterized by an energy gap along the linear segments of the Fermi curve. As a result, one can observe an effective decrease of the electron concentration.

Consider the proximity system containing a size-quantizing Bi film Decreasing the temperature below T_p results in a decrease of the electron concentration and hence in a decrease of $\Gamma^{\alpha\beta}$ (see above). If

$T_p < T_c$ and the proximity system is the part of a Josephson junction, then in the region $T < T_p$ there is an additional increase of I_M caused by the structural transition in the Bi film. This increase can be observed experimentally.

Two-Dimensional Electron Systems and the Josephson Effect

In this section we consider a Josephson junction containing two proximity systems: S_α-M_β-I-M_β-S_α. The general analysis has been carried out by the author.[2] Here we focus on the case when M is a size-quantizing film, e.g., a Bi film. The superconducting state in the M film is induced by the proximity effect, and the Josephson current occurs between two-dimensional systems (for simplicity we consider the case of two similar proximity systems). The maximum dc Josephson current is equal to:

$$I_M = \frac{1}{eR}\sum_{\omega_n} \frac{\Delta_\beta^2(\omega_n)}{\omega_n^2 + \Delta_\beta^2(\omega_n)} \quad , \tag{17}$$

where

$$\Delta_\beta(\omega_n) = (\Gamma/[\Gamma + K])\,\Delta_\alpha \quad , \tag{18}$$

or (see Ref. 2)

$$\Delta_\beta(\omega_n) = [1 + \alpha t\sqrt{x_n^2 + 1}\,]^{-1}\Delta_\alpha \tag{19}$$

Here $\Gamma \equiv \Gamma^{\beta\alpha}$; $K = \sqrt{\omega_n^2 + \Delta_\alpha^2}$, $x_n = \omega_n/\varepsilon_\alpha$, $\alpha = E_\alpha/\pi T_c$, $t = \ell/S_0$, $\ell = L_\beta/L_0$ ($L_0 = 10^2$Å), $S_0 = \Gamma\ell$. For a usual non-quantizing clean β film, S_0 does not depend on L_β (see Ref. 2). The dependence of $I_M eR$ on the parameter t is presented in fig. 2. Usually $t \sim L_\beta$, and the curve in fig. 2 directly represents the dependence $I_M eR(L_\beta)$ (the parameter S_0 can be determined by an independent single measurement).

The situation differs noticeably if β is a size-quantizing film. Then $\Gamma \sim p_z/L \sim \ell^2$, so that $t \sim L_\beta^2$, and therefore size quantization leads to a steaper thickness dependence of $I_M eR(L_\beta)$. In addition, the normal resistance of the barrier R and, consequently, I_M oscillate with increasing thickness L_β.

If the β film is made from Bi, then one can observe a low-temperature structural transition at $T = T_p$ (see Ref. 16) due to the strong anisotropy of the Fermi curve and the appearance of charge density waves. If $T_p < T_c$ (e.g., for a Nb-Bi system), then one can observe a strong temperature dependence of n_e, where n_e is the electron concentration. The problem of the temperature dependence of I_M will be considered in detail elsewhere.

Proximity Effect and Inversion Layers

A supercurrent in the native inversion layer on InAs has been observed[17]. A remarkable achievement of the authors [7] is that the Josephson current was controlled by electric field (see fig. 3). A weak link has been formed by the inversion layer (for a detailed analysis of the properties of inversion layers, see the review[18]).

Consider the system S_α-M_β-S_α (M_β contains the inversion layer). We use the tunneling model. According to the tunneling Hamiltonian formalism, one can introduce the complete sets $\{\psi_\alpha\}$, $\{\psi_\beta\}$, and, hence, the Green's function $G_\beta(x,x')$. This function can be written in the form (we assume that only the lowest subband is filled):

$$G_\beta(\vec{r},\vec{r}\,'; \omega_n) = \psi_1(z)\psi_1(z')\ G_\beta(\vec{\rho},\vec{\rho}\,'; \omega_n)$$

where $\vec{\rho} = \{x,y\}$, $\vec{\rho}\,' = \{x',y'\}$. The function $G_\beta\ (\vec{\rho},\vec{\rho}\,'; \omega_n)$ satisfies the diagrammatic equation (see Fig. 4).

$$(20)$$

Here $G_{0\beta}$ is the Green's function of normal two-dimensional electron gas,

$$\tilde{\Delta} = |\tilde{T}|^2 F^{\alpha}_{1(2)} = |\tilde{T}|^2 \Delta_\alpha (\omega_n^2 + \Delta_\alpha^2)^{-1/2} e^{i\phi_{1(2)}} \nu_\alpha SL_\alpha,$$

($F_1^\alpha = F^\alpha(0,0)$ is the abnormal Green's function in the superconductor; ϕ_1, ϕ_2 are the phases in the superconductors). The current is equal to:

$$\tilde{j}_x(\vec{\rho}) = \frac{ie}{m} T \sum_{\omega_n} [(\partial/\partial x) - (\partial/\partial x')] \tilde{G}_\beta (\vec{\rho},\vec{\rho}\,',\omega_n)\Big|_{\vec{\rho}=\vec{\rho}\,'} \qquad (21)$$

Based on Eqs. (20) and (21), one can arrive, after some manipulations, at the following expression (we consider the case of a clean normal metal):

$$j_{x,max} \simeq \frac{e}{m} |\tilde{T}|^4 \sum_{n\geq 0} \frac{\Delta_\alpha^2}{(2n+1)^2((\pi T)^2 + \Delta_\alpha^2)} e^{-\frac{(2n+1)\pi T}{V_F} L} \times K(\vec{\rho},\omega_n), \qquad (22)$$

where $K(\vec{\rho},\omega_n)$ can be determined from Eq. (20).

Here $\vec{\rho}_0 = \{0, y_1\}$, $\vec{\rho}_L = \{L, y_2\}$.

We should compare the coherence length $\xi_N = V_F/T$ and L. For a two-dimensional system, $V_F = (2\pi^2 nL_\beta)^{1/2}/m$, where n is the electron concentration. If $nL_\beta = 5 \times 10^{11} cm^{-1}$ (see [17]), we obtain $\xi_N \simeq 1.3 \times 10^3/T$ Å. If, for instance, $T = 3°K$ (for the system studied in [17], $T_c = 6°K$), we obtain $\xi_N = 5 \times 10^2$ Å. Since $L = 0.2 - 0.5\mu m$, the inequality $\xi_N << L$ holds if $T \geq 0.5\ T_c$. In this case one should keep only the term n = 0 in Eq. (22). As a result, the thickness and temperature dependences of j_{xm} are described by the expression

$$j_{xm} \sim \Delta_\alpha^2 [(\pi T)^2 + \Delta_\alpha^2]^{-1} \exp(-2TL/V_F). \qquad (23)$$

This expression is not valid in the low temperature region $T \to 0$. This case will be considered elsewhere.

The value of j_{xm} can be controlled by electric field[17]. The presence of electric field leads to a change of the electron concentration and, therefore, to a change of V_F (see Eq. (23)). The increase of the electron concentration results in an increase of the current.

Conclusion

The thermodynamic Green's function method allows to carry out a detailed analysis of the properties of a Josephson junction with a proximity system. We focus on the system N-S-I-S containing a superconducting film backed by a normal one. Another important example is the S-N-I-N-S system. The most interesting case is that of a size-quantizing semimetal N film. Then the Josephson current oscillates with changing thickness of the normal film. The structural transition occurring in thin Bi films may also affect the value of I_M. Hence, varying the temperature and the parameters of the normal film allows to change the properties of the Josephson junction in the desired direction.

The weak link can be formed by the inversion layer (see Ref. 17). The critical current depends strongly on the temperature and the length of the link. The applied voltage affects the electron concentration and, consequently, the value of I_M.

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Figure Caption

Fig. 1. Temperature dependence of I_M (S_α-M_β-I-S_α junction) for (1) L_β = 100Å, (2) L_β = 500Å (S_0 = 1.8); the curve AB corresponds to S_α-I-S_α contact.

Fig. 2. Thickness dependence of $I_M e R$ (S_α-M_β-I-M_β-S_α system).

Fig. 3. Junction structure (Ref. 17).

Fig. 4. a) S_α-M_β-S_α system; b) Temperature Green's function.

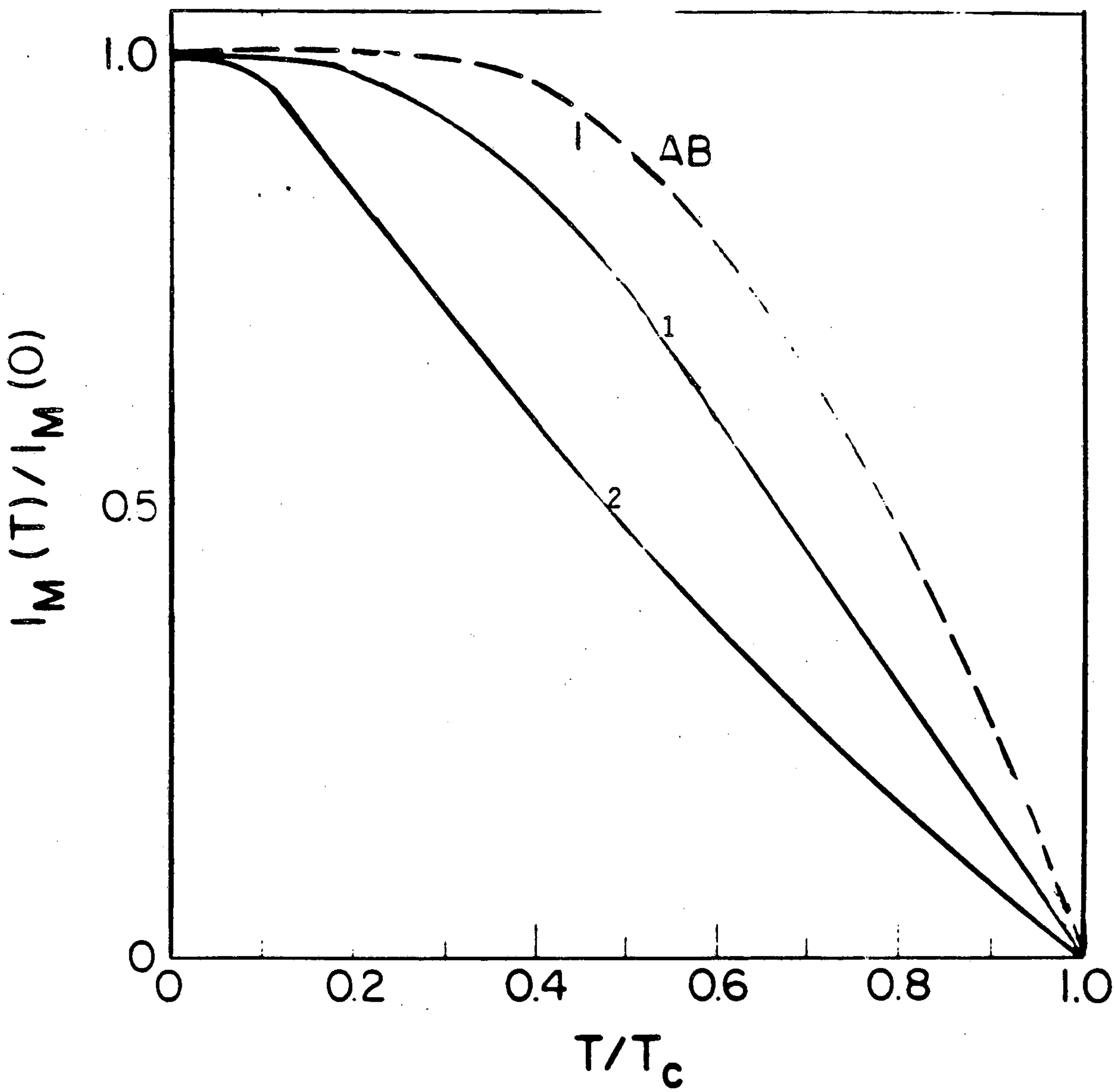

Fig. 1

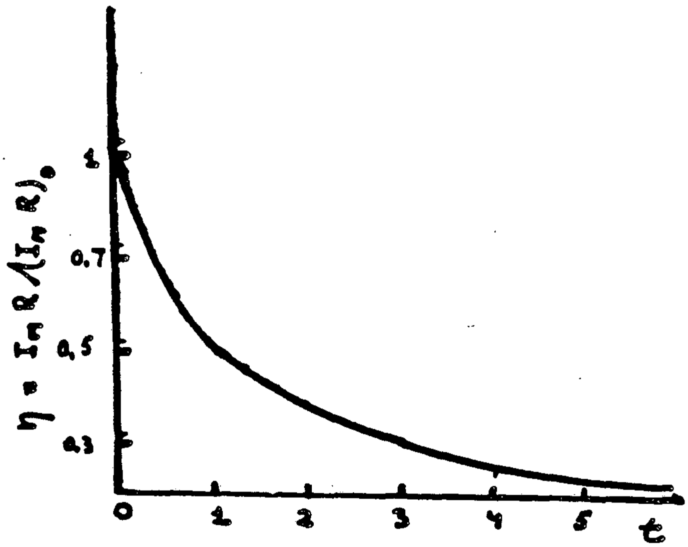

Fig. 2

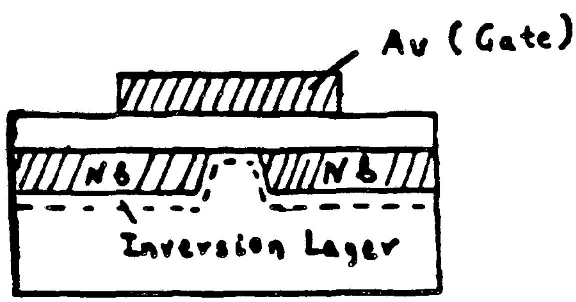

Fig. 3

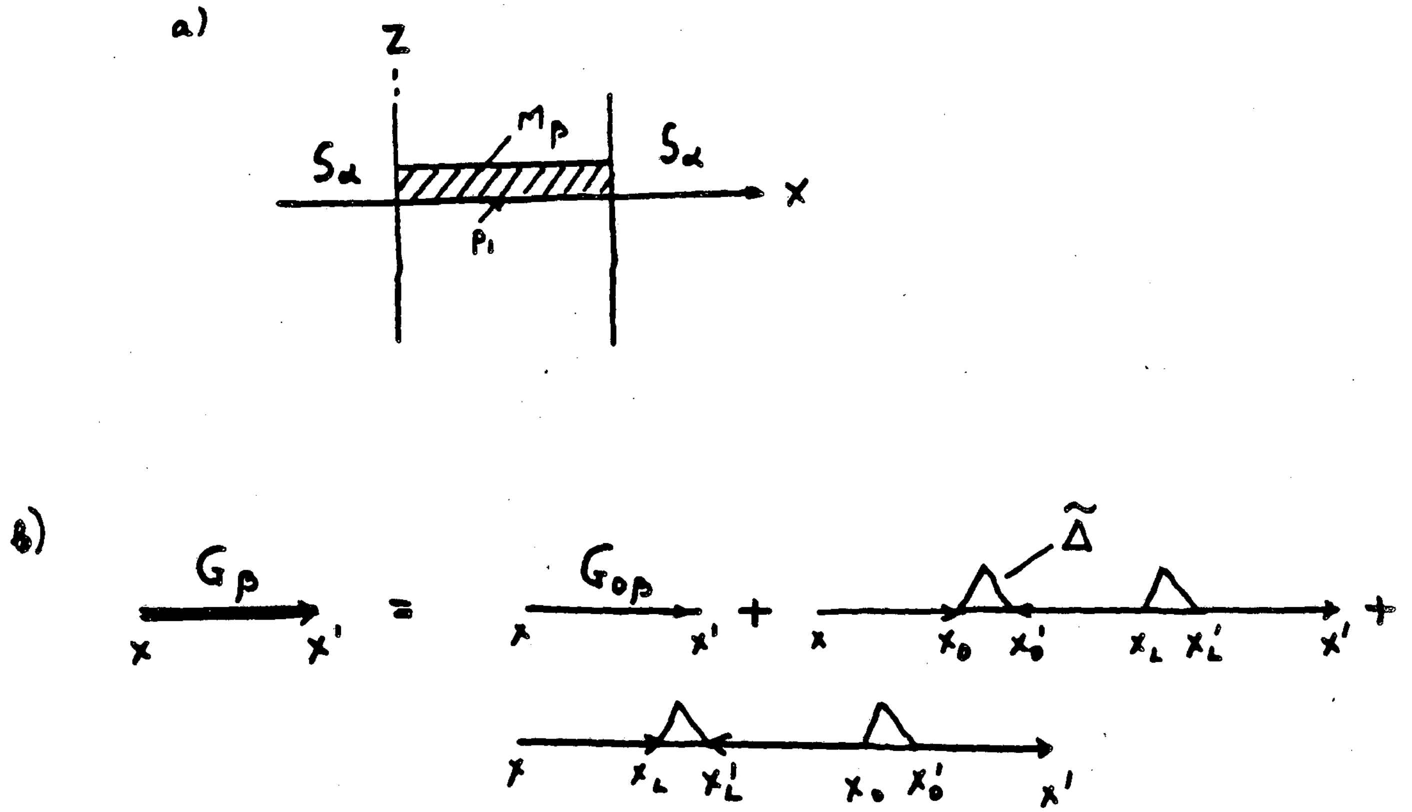
a)
Z
M_β
S_α
S_α
x
p_1
b)
G_β
x
x'
=
$G_{0\beta}$
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Fig. 4

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