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Control of Microscopic Superconducting Channel by the Proximity Effect

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SYNOPSIS

A possibility to control the microscopic superconducting channel based on the proximity effect is theoretically shown by a simple one-dimensional analysis of de Gennes' equation for the order parameter.

1. Introduction

Superconductors have many interesting and useful properties which are already utilized in macroscopic electrical apparatuses. In the microscopic scale, however, the analysis and application of superconductivity seem to be still in the stage of development. The function as a three terminal electronic device (transistor) based on superconductors has been confirmed only recently,[1] though one of such possibilities was pointed out long years ago.[2]

In these investigations, properties of the channel between the source and drain made of superconductors are changed by the gate electrode based on the proximity effect.[3] The channel is originally a normal conductor and the superconducting order parameter due to the effect, which is increased or decreased according to the carrier density in the channel, couples two superconducting electrodes, giving supercurrent between them.

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The purpose of this paper is to show a possibility to induce the transition of channel from the superconducting to the normal state by applying a voltage to an electrode corresponding the gate in a three terminal device. The channel itself is a superconductor and therefore other electrodes need not always to be superconductors when used in three terminal device. We also emphasize that the induced change is in the opposite direction compared with other proposals:

2. Structure

The main part of the structure of our system is schematically shown in Fig.1. On a semiconductor substrate of one type (n or p) (SC1), we have a thin layer of a semiconductor of the opposite type (p or n) (SC2), forming a pn junction at the interface. On the layer SC2, we place also a thin layer of superconductor (S). Typical thickness of SC2 and superconductor may be (0.5-1) micron.

The most important requirement is that the semiconductor SC2 and the superconductor S have a close coupling, i.e., the effect of the Schottky barrier between them is sufficiently small. One of such examples may be the combination of Pb alloy and p-type Si which has been used as the superconducting source or drain and the channel.[1] It may be also possible to use heavily doped thin layer to reduce the effect of Schottky barrier as in Ref.4 where superconducting channel is coupled to the superconducting source and drain.

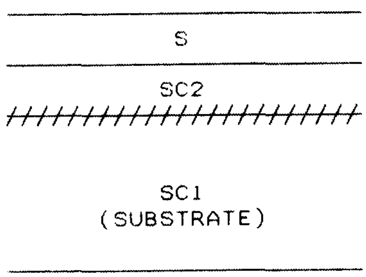

Fig.1. Schematic drawing of the structure. On the semiconductor substrate of one type (SC1), placed is a thin semiconductor of opposite type (SC2), forming a pn junction, and the superconducting channel (S) is coupled to SC2 by the proximity effect. The layer depleted of carriers is shown by shading.

When the above point is satisfied, we have a coupled thin layers of super and normal conductors. Since the superconducting order parameter is no longer confined within the layer of superconductor, the transition temperature becomes lower as the thickness of the normal part increases. We here note that the width of the depletion layer between the first and the second layers of semiconductors changes as much as (0.5-1) micron according to the electric potential applied to the substrate (SC2). As is shown below, the critical temperature of this system with similar thicknesses of the super and normal part is sensitive to the thickness of the normal part. We are thus able to control the state of superconducting layer through the width of the depletion layer.

The fabrication of such a structure may not be difficult; usual semiconductor device processes will be used to form the pn junction and the superconducting thin layer will be obtained by electron beam evaporation or other methods.

We expect that this structure works as the channel between the source and drain in the three terminal device, the substrate serving as the gate. The current between the source and drain is controlled by the state of the channel or the magnitude of the pair potential in the channel. One of the advantages of this structure is that the lateral separation between the source and the drain needs not to be as small as 0.2 micron as in superconducting transistor proposed hitherto, since the channel is originally superconducting and the effect of gate voltage is in the direction of reducing the pair potential.

3. Analysis of Transition Temperature

3.1 Formulation

The transition temperature of a bulk BCS superconductor T_c is given by

$$T_c = 1.14\Theta_D \exp(-1/V_S N_S). \qquad (1)$$

Here Θ_D, V_S and N_S are the Debye temperature, the attractive potential between electrons and the density of state on the Fermi surface, respectively. When a normal metal is coupled with this material, the pair potential spreads into the normal part by the proximity effect satisfying the boundary conditions specified by de Gennes.[5] Since we have weaker or no attractive interactions b between electrons in the normal part, the magnitude of the pair potential in the super part becomes small and the transition temperature is reduced by such spreading. A rough estimate of the critical temperature may be given by

$$T_c = 1.14\,\Theta_D \exp(-1/\langle VN \rangle), \tag{2}$$

where $\langle VN \rangle$ is the average of the product of the interaction potential V and the density of states N over the whole system. When the thicknesses of the super and the normal parts are d_S and d_N, respectively, we may estimate this average as $\langle VN \rangle = V_S N_S d_S/(d_S+d_N)$. We see thus that an increase of d_N drastically changes the critical temperature.

In the structure shown in Fig.1, the layer SC2 works as the normal part and its thickness is changed by the increase or decrease of the depletion layer of the pn junction between the layers SC1 and SC2. The thickness of controllable superconducting layer is of the comparable order of the maximum width of the depletion layer.

More precise analyses may be made on the basis of de Gennes' treatment of the Gorkov equation for the pair potential $\Delta(\mathbf{r})$ near the critical point[3]

$$\Delta(\mathbf{r}) = V(\mathbf{r})\, k_B T \sum_{\omega} \int Q(\mathbf{r}, \mathbf{r}'; \omega)\, \Delta(\mathbf{r}')\, d\mathbf{r}'. \tag{3}$$

Here the kernel $Q(\mathbf{r}, \mathbf{r}'; \omega)$ is determined by the Green function for normal electrons on the Fermi surface. In the dirty limit, the electrons follow the diffusion equation with the diffusion coefficient $D(\mathbf{r})$ and the kernel is given by

$$Q(\mathbf{r}, \mathbf{r}'; \omega) = \int_0^\infty dt\; g(\mathbf{r}, \mathbf{r}'; t) \exp(-2|\omega| t), \tag{4}$$

$$g(\mathbf{r}, \mathbf{r}'; t=0) = N(\mathbf{r})\, \delta(\mathbf{r}-\mathbf{r}'), \tag{5}$$

$$\frac{\partial}{\partial t} \frac{g(\mathbf{r}, \mathbf{r}'; t)}{N(\mathbf{r}) N(\mathbf{r}')} = -\frac{1}{N(\mathbf{r})} \nabla \cdot N(\mathbf{r}) D(\mathbf{r}) \nabla \frac{g(\mathbf{r}, \mathbf{r}'; t)}{N(\mathbf{r}) N(\mathbf{r}')}. \tag{6}$$

The boundary conditions for $g(\mathbf{r}, \mathbf{r}'; t)$ has been given by de Gennes. The critical temperature is determined by the condition that (3) has a nontrivial solution for the pair potential.

We solve the above equation by expanding the solution in terms of the eigenfunctions φ_n of the diffusion operator

$$\left[-\frac{\hbar}{N(\mathbf{r})}\nabla\cdot N(\mathbf{r})D(\mathbf{r})\nabla-\varepsilon_n\right]\varphi_n(\mathbf{r})=0 \tag{7}$$

as

$$\frac{\Delta(\mathbf{r})}{N(\mathbf{r})V(\mathbf{r})}=\sum_n a_n\varphi_n(\mathbf{r}) \tag{8}$$

with the boundary conditions that

$$\varphi_n(\mathbf{r}), \qquad N(\mathbf{r})D(\mathbf{r})\nabla\varphi_n(\mathbf{r}) \tag{9}$$

are continuous at interfaces and the latter vanishes at the surface. Eq.(3) thus reduces to

$$\sum_n C_{nn'}a_{n'}=0, \tag{10}$$

where

$$C_{nn'}=\delta_{nn'}-A_n\int d\mathbf{r}N(\mathbf{r})\varphi_n(\mathbf{r})V(\mathbf{r})N(\mathbf{r})\varphi_{n'}(\mathbf{r})\Big/\left[\int d\mathbf{r}N(\mathbf{r})\varphi_n^2(\mathbf{r})\int d\mathbf{r}'N(\mathbf{r}')\varphi_{n'}^2(\mathbf{r}')\right]^{1/2}, \tag{11}$$

$$A_n=\ln(1.14\hbar\omega_D/k_BT)+\psi(\tfrac{1}{2})-\psi\left(\tfrac{1}{2}+\frac{\varepsilon_n}{4\pi k_BT}\right), \tag{12}$$

$\psi(x)$ being the digamma function. The critical temperature is determined by

$$\det(C_{nn'})=0. \tag{13}$$

The eigenfunctions of some operator related to de Gennes' equation for the integral kernel has been first used by Takahashi and Tachiki[5] to solve eq.(3). The formulation described above which is different from theirs seems to be more useful at least in that the boundary conditions at the interfaces are not necessary to be considered explicitly except for those at outermost boundaries.

3.2 Example

Now we calculate the transition temperature for a one-dimensional structure composed of uniform super and normal conductors of thicknesses d_S and d_N, respectively, on the basis of the equations given above. This is a simplified model of the system of S and SC2 described in Section 2.

As typical values of parameters, we take $V_S N_S=1/3$, $\Theta_D=10^2$K, $T_C=1.14\Theta_D \exp(-3)=5.7$K for bulk superconductor and assume $V_N=0$ for normal part. We also assume that $D_S=D_N$ and $N_S=N_N$ for simplicity.

The result depends on the parameter

$$\eta = 2\pi\left(\frac{\xi}{d}\right)^2, \tag{14}$$

where ξ is the coherence length in the normal state and $d=d_S+d_N$. We expect that this parameter is smaller than unity for our system where d is of the order of microns but, at the same time, is not very small.

Typical behavior of the pair potential at the critical point is shown in Fig.2 where $d_S/d=0.7$ and $\eta=0.05$. We see the spreading of the order parameter to the normal part on the left hand side.

Fig.3 shows the dependency of the critical temperature on the ratio d_S/d for several values of η. We note that, irrespective of the value of η, there exists a range of the values of d_S/d where the critical temperature rapidly changes. Our proposal is to use this domain to control the property of the channel.

In this analysis, some parameters are rather arbitrary chosen and physical conditions are oversimplified. Main features of the results are not, however, critically dependent on these selection of values.

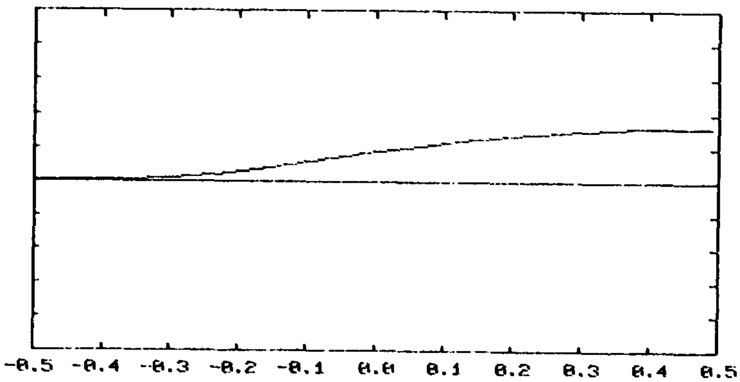

Fig.2. Pair potential at the critical temperature for $d_S/d=0.7$ and $\eta=0.05$.

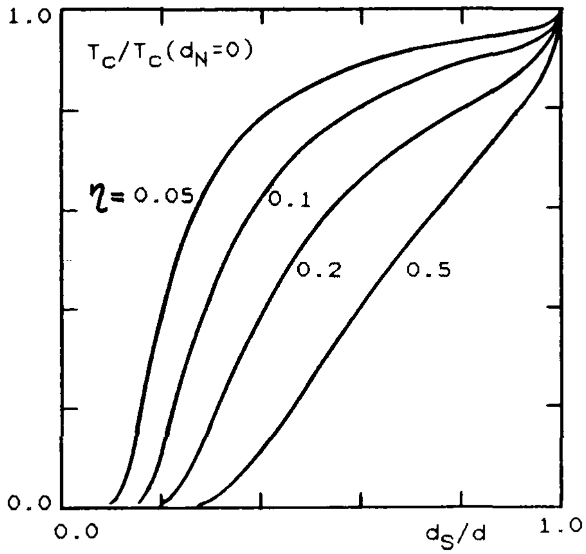

Fig.3. Critical temperature of the superconductor coupled with the normal conductor by the proximity effect.

4. Concluding Remarks

A possibility to control the superconducting channel by the proximity effect is proposed by a simplified analysis of one-dimensional case. Some advantages of this method in application to three terminal devices are also briefly discussed. As for the parameter and structure dependencies of the results and three terminal functions, more detailed and extended analyses will be necessary. They are now in progress and will be reported elewhere.

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