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Article *in* physica status solidi (b) · November 1992

DOI: 10.1002/pssb.2221740123

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phys. stat. sol. (b) **174**, 235 (1992)

Subject classification: 74.20; 71.45

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Superconducting Gap Substructure in Bisoliton HTSC Theory

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The conditions and peculiarities of the realization of the superconducting gap substructure in a bisoliton superconductivity model are considered at temperatures much lower than the critical one in the case when the temperature dependence of the gap can be neglected.

В работе, при температурах значительно ниже критичезкой, когда зависимостью щели от температуры можно пренебречь, рассматриваются условия и особенности субструктуры сверхпроводящих щелей в бисолитонной модели сверхпроводимости.

1. Introduction

The superconducting band substructure revealed in a good deal of experiments [1, 2] in HTSC has not yet been explained unambiguously. It is apparent that comprehension of the reasons inducing the substructure is associated with the peculiarities of the superconductivity mechanism. As was noted in [3, 4], the multiband structure may arise in the bisoliton theory, and this is caused by the existence of a periodic structure of the bisoliton. The presence of such a structure resembles the charge density wave, but is distinct from the latter in that it is created by part of the current carriers only, which are situated near the Fermi surface. All these carriers form Cooper pairs and can migrate in the crystal generating thus the superconducting current. Here we consider the conditions and peculiarities of the realization of the energy substructure in the bisoliton superconductivity model at temperatures much lower than the critical one when the temperature dependence of the band can be neglected.

2. Conditions for the Bisoliton Stability

According to the bisoliton superconductivity model [5] in a quasi-one-dimensional system due to the interaction between the current carriers and the vibrations of lattice atoms the latter are displaced from their equilibrium positions forming periodically distributed deformation wells. This interaction leads to pairing between the Fermi particles (electrons or holes) and the opposite spins and momenta that differ by the magnitude $2\hbar k_F$ where k_F is the amount of the wave vector at the Fermi level. The latter is associated with the distance between the neighbouring wells by the condition

$$k_F L = 2\pi\nu\,, \tag{2.1}$$

where $\nu = 1, 2, 3, \ldots$. The number ν determines the relative part of carriers participating in the creation of the superconducting condensate. A bisoliton will be stable when the

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momenta of particles forming it, $\hbar k_1$, $\hbar k_2$ will satisfy the condition

$$\frac{\hbar\,|k_1 + k_2|}{2m} < c\,. \tag{2.2}$$

Here m is the particle mass and c the sound velocity. It follows from (2.2) that a particle on the Fermi surface ($k_i = k_F$) can make up a bisoliton with particles that differ in energy by ΔE taking values under the squared dispersion law

$$\omega(k_F) = ck_F\,,$$
$$\Delta E = \varepsilon(k_F) - \varepsilon(k_1) = \frac{\hbar^2}{2m}(k_1 + k_F)(k_1 - k_F) \leq \hbar\omega(k_F)\,. \tag{2.3}$$

Thus, the current carriers with energy in the interval $\Delta E = 2\hbar\omega(k_F)$ near the Fermi surface can be paired and, as a result, form the superconducting condensate. The carriers outside this interval lying deep in the Fermi sphere do not form bisolitons. Taking into account that the density of states near the Fermi energy equals

$$N(E_F) = \frac{m}{\pi\hbar^2 k_F}\,,$$

for the concentration of bisolitons L^{-1} we get

$$\frac{1}{L} \leq N(E_F)\,\Delta E = \frac{m}{2\hbar^2 k_F}\,\hbar\omega(k_F)\,. \tag{2.4}$$

Condition (2.4) with allowance for (2.1) takes the form

$$\nu \geq \frac{E_F}{\omega(k_F)} = \frac{\hbar k_F}{cm}\,. \tag{2.5}$$

The minimum value ν satisfying (2.5) corresponds to an extremely high density of the superconducting condensate. It should be noted that the requirement for quasi-one-dimensionality of a bisoliton theory is not restricted to the case of Fermi-type current carriers. This follows directly from the Cooper effect. In particular, the bisoliton theory is generalized to a two-dimensional system in [6].

3. Superconducting Gaps

When the superconducting state at the Fermi level is formed in a bisoliton model [3, 4] an energy gap with the state density equal to zero arises. The gap value [2] is described by

$$\Delta = \frac{4E_F}{\lambda}\sinh^{-1}(1/\lambda)\,; \qquad \lambda = N(E_F)\,G\,, \tag{3.1}$$

$G = \sigma^2/\varkappa$ is the parameter characterizing the electron–phonon interaction, σ is the deformation potential, $\varkappa$ the elasticity coefficient. In soliton theory G determines the nonlinearity of the system. The energy spectrum of particles is divided into two bands,

$$E_{1,2}(k) = \frac{\varepsilon(k) - \varepsilon(k - 2k_F) - 2E_F}{2} \pm \sqrt{\left(\frac{\varepsilon(k) + \varepsilon(k - 2k_F)}{2}\right)^2 + \Delta^2}\,. \tag{3.2}$$

The upper band is empty, the lower one is occupied by electrons.

As is shown in [3] in a quasi one-dimensional system, Δ as a function of the wave vector k_F is of nonmonotonous character taking the maximum value at $k_F = mG/8\pi\hbar^2$, i.e., when $\lambda = 0.5$.

Depending on the ratio between E_F and $\hbar\omega(k_F)$ and also the value of ν the bisoliton superconductivity model is conveniently divided into three cases.

1. $E_F \gg \hbar\omega(k_F)$, $\lambda \ll 1$. These conditions are typical for metal systems. The expressions for the energy spectrum and the band value take the form

$$E_{1,2}(k) = \pm\sqrt{[\varepsilon(k) - E_F]^2 + \Delta^2}\,, \tag{3.3}$$

$$\Delta = 8\hbar\omega(k_F)\, e^{-1/\lambda}\,, \tag{3.4}$$

where the values E_F and $\hbar\omega(k_F)$ are typical for metals, $\nu > 100$. Equations (3.3) and (3.4) are analogous to the corresponding energy and band values in the BCS theory. It should be noted in this case for Δ the isotopic effect holds as in BCS theory.

2. For $E_F > \hbar\omega(k_F)$, $\nu > 1$. This case is typical for ceramic oxides. Indeed, at $k_F \approx 10^7\ \text{cm}^{-1}$, $c \approx 10^5$ cm/s, $m \approx 10m_e$ we get $\nu = 5$.

Comparing the bisoliton theory with experiment [3, 4] leads to values ν for ceramic oxides lying within the range $1 < \nu < 10$.

3. For $E_F < \hbar\omega(k_F)$, $\nu = 1$. This case has been called the charge density wave [7]. Although formally the conditions for the existence of superconductivity are satisfied [8], the dissipativeless transfer is improbable here because of pinning. The pinning probability of the bisoliton condensate is much less at $\nu > 1$. But, in this case, with increasing ν the energy gain of the system under the formation of the superconducting condensate decreases, which naturally leads to a decreasing transition temperature.

Thus, according to (3.1), the change in the concentration of carriers in the system or the parameters characterizing the system can result, along with a continuous variation of the superconducting band value, to its jump-like change by the condition (2.5). The number ν then undergoes a change, too. These peculiarities should be manifest in experiments studying the current in metal–dielectric–superconductor systems.

4. Current–Voltage Characteristics

We consider a system composed of a metal in the normal state, a dielectric barrier, and a superconductor, as is shown in Fig. 1. When there is contact between the metal needle and the superconductor surface, the latter in the near-surface region can be characterized by different concentration values of carriers and parameters ν in each of the regions S_i. With changing concentration the gap value undergoes a constant change. The ν variation leads, by (3.1), to a jump-like change of the gap.

As is suggested in [9] and used in [10] the common current in such a system can be represented as a sum of the tunneling currents from each superconductor region to the metal contact. Thus, the total current that runs through the system shown in Fig. 1, is determined by

$$I = \sum_i I_i\,, \tag{4.1}$$

where

$$I_i = I_{0i}\int dE\,\frac{|E|}{\sqrt{E^2 - \Delta^2}}\,[f(E - V) - f(E)] + \alpha V\,, \tag{4.2}$$

$$I_{0i} = \frac{e}{2\pi\hbar}\,\varrho_i k_F\,,$$

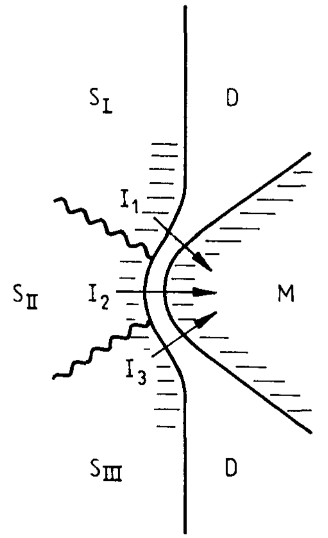

Fig. 1. The metal(M)–dielectric(D)–superconductor(S) structure

ϱ_i is the carrier concentration in the i-th region of the superconductor characterized by Δ_i, the value of the superconducting gap. f is the Fermi distribution function for current carriers, α the conductivity caused by the Josephson component [11]. The dependence of the conductivity $\sigma = \mathrm{d}I/\mathrm{d}V$ on the magnitude of the applied potential for the case of an inhomogeneous superconductor composed of two regions with $\Delta_2/\Delta_3 = 3/2$ at $k_B T_c/\Delta = 0.1$ and $I_{02}/I_{03} = 0.75$ is shown in Fig. 2. Current–voltage dependences of this type are observed for many HTSC [1, 2]. It should be noted that the values for the quantity Δ obtained experimentally are well described by the function $\Delta_n = \Delta_0/n$ established empirically, where n are integers. Thus dependence directly follows from (3.1).

5. Conclusion

Thus, in the metal–dielectric–superconductor system, when the latter has an inhomogeneous structure, peculiarities can arise near the surface in the current–voltage dependences. These indicate the existence of superconducting regions with the different gap values. The value of the gap magnitudes is well described empirically by the law with n lying within the range

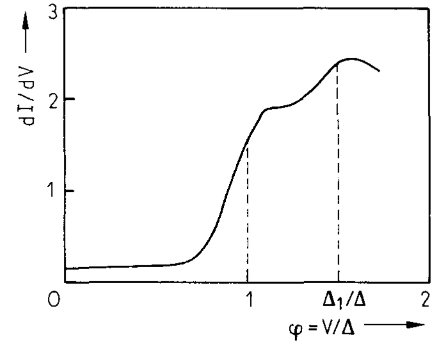

Fig. 2. The conductivity dependence $\sigma = \mathrm{d}I/\mathrm{d}V$ on the external potential for the inhomogeneous superconductor with $\Delta_2/\Delta_3 = 3/2$

$1 < n < 10$. It should be noted that these peculiarities in current–voltage characteristics cannot be explained by a simple change in the carrier concentration since in this case the gap magnitude variation would not be discrete. The multigap structure leads, naturally, to a large range in the ratio $2\Delta/k_B T_c = p$. If the critical temperature in the superconductor volume is due to the presence of the gap Δ^* with the number $\nu = \nu^*$, then for the remaining gaps from (3.1) we get the relation $p = p^* \nu^*/\nu$ where $p^* = 2\Delta^*/k_B T_c$. Depending on the ratio ν^*/ν gaps with p larger or smaller than p^* will be observed.

Thus, the multigap energy structure and the large range in the p ratio observed in experiments, can be naturally explained in the bisoliton superconductivity model.

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(Received July 2, 1992)