Investigation of bridge junctions made of the high-temperature superconductor Nb_3Sn

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(Submitted 8 July 1977)
Zh. Eksp. Teor. Fiz. 74, 214–223 (January 1978)

The properties of Nb_3Sn bridge junctions produced by double scribing are investigated. The current-voltage characteristics and the temperature dependence of the critical current of such film bridges are measured, and current steps are obtained in centimeter and decimeter microwave fields. A model is proposed to describe the steplike character of the current-voltage characteristics of bridges of high-temperature superconducting alloys. It is shown that this model, which is based on the interaction between the alternating current due to the microwave field and the current due to the periodic motion of the Abrikosov vortices through the junction, agrees well with experiment.

PACS numbers: 85.25.+k, 74.50.+r

Objects having the properties of Josephson junctions are being extensively investigated of late.[1] These investigations are of interest because, on the one hand, such objects have already found practical applications that led to new developments in cryoelectronics and cryogenic metrology,[2] and on the other hand there are still unsolved problems connected with the determination of the mechanisms that govern the behavior and the limiting values of the parameters. Of particular interest is the study of the nonstationary properties of such systems as part of the general problem of nonequilibrium superconductivity. Among the objects with Josephson behavior, bridge-type superconducting junctions are outstanding for their reproducibility, stability, possibility of controlled variation of the parameters in a wide range, and many other properties. Bridges of high-temperature superconductors are attracting attention because of the exceptionally high critical parameters of the films and the possibility of developing quantum devices operating in hydrogen temperatures.[3-5]

However, when bridges of high-temperature superconducting alloys are developed, account must be taken of the small coherence length ξ of such materials. A typical value of ξ in such superconductors as Nb_3Sn is 100 Å,[6] so that as a rule bridges made of this material are wide ($a \gg \xi$, where a is the width of the bridge). The Josephson properties of such junctions are connected with periodic motion of Abrikosov vortices in the junction.[7,8] The study of the properties of bridge junctions made of high-temperature superconductors, of their vortex structure, and of the interaction of the vortices with microwave radiation is important for the understanding of the processes that take place in such junctions.

Some properties of Nb_3Sn junctions were investigated earlier.[3-5] In this paper we study the current-voltage characteristics (CVC) and the temperature dependence of the critical current of bridge junctions of Nb_3Sn, and the behavior of the bridges in a microwave field. A model is proposed to explain the appearance of steps on the CVC of such bridges when they are placed in a microwave field.

EXPERIMENT

The measurements were made on Nb_3Sn films obtained by simultaneous evaporation of the components from different evaporators in vacuum and by condensing the alloy on heated ruby substrates.[9] The Nb_3Sn films were produced in a vacuum $(5-7)\times 10^{-6}$ Torr, at substrate temperature ~900°C at the time of deposition, and at an alloy deposition rate 15 – 20 Å/sec. The remaining conditions were the same as in[3-5,9].

The deposited films were annealed in a vacuum of 2×10^{-6} Torr at 900–1000°C for 5–15 min. The junctions were made of films 0.3–0.7 μm thick. Prior to sputtering the alloy, a sublayer of pure niobium ~1000 Å thick was coated on the substrate; this coating contributed to formation of the alloy and served as a shunt in the electric measurements.

A number of control measurements were made on Nb films prepared by the method described in[10]. The conditions for the preparation of these films corresponded to the conditions of[4]. The film thicknesses were 0.3–0.7 μm. The thicknesses of the Nb and Nb_3Sn films were measured with an MII-4 interference microscope and with a profilograph-profilometer. Both methods gave identical results.

The superconducting-transition temperature was measured by a resistive method and amounted to 17.6–18 K for the investigated films. The width of the transition at 0.1–0.9 of the total transition was ~0.2 K.

The bridges were produced on the Nb_3Sn films by the double-scribing method.[11] In this method a diamond cutter is used to scribe a notch on the polished ruby substrate. The depth and shape of the notch were determined by trial and error. After scribing the substrate, an Nb_3Sn film was sputtered on the substrate through a mask made of thin tantalum foil. The film was then cut with the diamond cutter again in a direction perpendicular to the notch. The pressure on the cutter was such that the film was cut through everywhere except on the depression of the substrate. This yielded bridges analogous in their configuration to variable-thickness

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bridges, of length 1–2 μm and several microns in width. The need for using ruby or sapphire as the substrates for the Nb_3Sn[9] poses additional difficulties in the bridge production, since these materials are almost as hard as diamond. The transverse cut needed to prepare the contact is made easier by the presence of the coating of niobium, which is softer than ruby.

The procedure for measuring the CVC of the junctions and of the temperature dependence of the critical current did not differ from that used in[3]. We note only that the junction voltage was measured with an F116/1 battery-powered microvoltmeter. In the study of the behavior of the bridges in a microwave field the frequencies used were 2 to 10 GHz. The experimental setup in the 3-cm band is described in[5]. The sample was placed in this case at the end of the waveguide transversely to the broad wall. At lower frequencies we used a scheme similar to that of Anderson and Dayem.[12] The sample was placed near a loop connected to a coaxial cable through which the microwave energy was fed to the cryostat.

The measurements were made in the temperature interval 13–20.3 K. The coolant was hydrogen. The temperature was determined from the vapor pressure with the aid of an Allen Bradley thermometer.

RESULTS AND DISCUSSION

1. The CVC of bridge junctions of Nb_3Sn films were measured for the first time in[3]. It was observed that they are described with good accuracy by the formula

$$I=(V/C+I_c^2)^{1/2}+V/R_s. \tag{1}$$

Here I is the current through the bridge, V is the voltage across it, I_c is the critical current of the bridge, R_s is the normal shunting resistance. It turned out that the parameter $C=r/I_c$ and the characteristic resistance r of the investigated bridges was ~$10^{-2}\Omega$.

The parabolic character of the CVC of wide bridges (1), obtained for Nb_3Sn films, was predicted theoretically.[7,8] Its cause is the proportionality of the number of vortices in the junction and their velocity of motion through the junction to the current flowing through the junction. The junction voltage V, whose value is determined by the number of Abrikosov vortices passing through the junction per unit time, is then a quadratic function of the current.

In the present study we investigated the CVC of Nb_3Sn junctions with a large set of parameters I_c, C, and R_s. It was found that all the CVC can be described with sufficient accuracy by relation (1). The parameters C were inversely proportional to the critical current I_c. The characteristic resistance r for various contacts ranged from 1.2×10^{-3} to $6\times10^{-2}\Omega$. The critical currents ranged from 60 μA to 3.5 mA. The expression (1) and the relation $C=r/I_c$ are thus valid for Nb_3Sn bridges with greatly differing parameters in a very wide range of critical currents.

We investigated the temperature dependence of the critical current $I_c(T)$ for four bridge junctions of Nb_3Sn with different characteristics. This dependence near T_c is shown in a logarithmic scale on Fig. 1. It is seen that for all bridges it can be described by the expression $I_c(T)\propto(T_c-T)^\alpha$. The exponent α ranges from 2 to 2.5. (The deviation of one point on the third curve from the top is probably due to an error in the determination of the critical temperature of the bridges.) The spacing between the curves of Fig. 1 is due to the different characteristics of the bridges, particularly their geometric dimensions.

For an ideal (tunnel) Josephson junction we have[13]

$$I(T)=\frac{\pi\Delta(T)}{2eR_n}\,\mathrm{th}\,\frac{\Delta(T)}{2k_BT} \tag{2}$$

where e is the electron charge, $\Delta(T)$ is the energy gap, and R_n is the resistance of the junction in the normal state. At a temperature close to critical we have $I_c(T)\propto(T_c-T)$. A similar linear dependence was observed in the experiments for narrow bridges with constrictions much narrower than the coherence length.[14,15]

The steep growth we observed in the critical currents of Nb_3Sn bridges with decreasing temperature can be explained on the basis of the vortex model proposed by Larkin and Ovchinnikov.[16] They have shown that if free-path or thickness inhomogeneities are present in the film and constrain the abrikosov-vertex lattice, then $I_c(T)\propto(T_c-T)^{5/2}$ In Nb_3Sn bridge junctions, for examples, the grain boundaries of the superconducting phase can serve as these inhomogeneities, which constrain the vortices produced when current is made to flow through the sample. The experimental results for Nb_3Sn agree well with the relation proposed in[16].

3. The behavior of superconducting Nb_3Sn bridge junctions in a microwave field of frequency ~10 GHz was investigated in[5]. The CVC of the bridges revealed a steplike structure at voltages corresponding to the Josephson relation $2eV=n\hbar\omega$ (n is an integer). Figure 2 shows typical CVC of an Nb_3Sn bridge at various microwave power levels. The microwave frequency was 9.0 GHz and the sample temperature was 14.6 K. A steplike structure of CVC was obtained also at other frequencies down to 2 GHz.

The presence of a pronounced steplike structure on the CVC of bridges of Nb_3Sn attests to their Josephson properties. For junctions of the superconductor—constriction—superconductor type, however, the current of current steps is still not a sufficient criterion for the presence of the classical Josephson effect. Indeed,

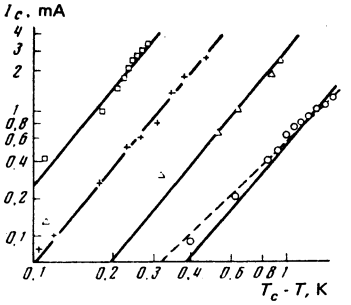

FIG. 1. Temperature dependence of the critical currents of four Nb_3Sn bridges. The solid and dashed curves correspond to $I_c\propto(T_c-T)^{2.5}$ and I_c $(T_c-T)^2$, respectively.

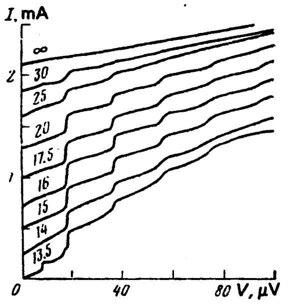

FIG. 2.

the CVC of Nb_3Sn junctions has an appreciable subharmonic structure.[5] The laws governing the variation of the critical current and of the sizes of the steps as functions of the microwave power in these junctions do not have the Bessel-function character predicted by the Josephson equation. All this indicates that there is no simple harmonic dependence of the critical current on the phase difference between the bulk superconductor "shores". To explain the properties of the investigated bridges and the character of their interaction with electromagnetic radiation we have used for the behavior of the junction the vortex model developed by Aslamazov and Larkin.[8]

4. The shape of the CVC of the bridge can be explained by using the following considerations.

Consider the total current through the junction at the instant of time t:

$$I(t)=I+I_\omega \sin \omega t, \tag{3}$$

where I is the direct current and I_ω is the amplitude of the alternating current of frequency ω. Expression (3) corresponds to the experimental situation when the system is equivalent to a current generator with respect to both the dc and the ac components. In our experiments the resistance of the bridge junctions was much lower than the output resistance either of the linear current sweep generator or of the waveguide.

We assume for simplicity that the CVC of a junction not acted upon by a microwave field is linear. It is then characterized by two parameters: the critical current I_c and the resistance R (the latter determines the slope of the CVC). If the period of the external electromagnetic radiation greatly exceeds the time of establishment of the superconductivity, then the average voltage developed across the junction under the influence of the microwave is given by

$$\bar{V}=\frac{R}{\pi}\int\limits_{x_0}^{\pi/2}(I+I_\omega \sin x-I_c)\,dx=\frac{RI_\omega}{\pi}\left[(1-i^2)^{1/2}-i\left(\frac{\pi}{2}-x_0\right)\right]. \tag{4}$$

Here $x=\omega t, x_0=\sin^{-1} i\tau$ ($\tau=x_0/\omega$ is the initial instant of appearance of voltage on the contact and occurs when the total current $I(t)$ exceeds the critical current I_c), ω is the frequency of the high-frequency field, and $i=(I_c-I)/\omega$. Expression (4) is valid at $|I_\omega|\leqslant I_c$ and $-1\leqslant i\leqslant 1$. In the case of a small total current $I+I_\omega<I_c$ (i.e., $i>1$) we have $\bar{V}=0$; for very large currents, when $I-I_\omega>I_c$, (i.e., $i<-1$), the average junction contact should be the same as for a non-irradiated sample.

The current (3) flowing through the contact has in the time intervals when it exceeds I_c a normal component

$$I_n=I+I_\omega \sin \omega t-I_c. \tag{5}$$

Expanding this periodic function in a Fourier series, we find that the amplitudes of the harmonics for the case $|i|<1$ are

$$I_k=\frac{I_\omega}{\pi}\left[\frac{\pi}{2}-x_0-i(1-i^2)^{1/2}\right],\quad k=1; \tag{6a}$$

$$I_k=\frac{2}{k(k^2-1)}\frac{I_\omega}{\pi}[i\cos kx_0-k(1-i^2)^{1/2}\sin kx_0],\quad \text{odd}\quad k; \tag{6b}$$

$$I_k=-\frac{2}{k(k^2-1)}\frac{I_\omega}{\pi}[i\sin kx_0+k(1-i^2)^{1/2}\cos kx_0],\quad \text{even}\quad k. \tag{6c}$$

For large currents ($i<-1$), in the linear approximation of the CVC, we have naturally $I_1=I_\omega$ and the other harmonics are equal to zero.

The interaction of a chain of vortices moving through the junction with the alternating field leads to the appearance of singularities on the CVC. The singularities, which take the form of current steps on the CVC, appear when the frequency of the external field is at resonance with the vortex-motion frequency. It is shown in [8] that this resonance takes place at a voltage

$$\bar{V}=\hbar\omega/2e. \tag{7}$$

The size of the current step is equal to double the amplitude of the alternating current. The physics of the phenomenon consists in the fact that the microwave field, which produces the alternating current in the junction, leads to a periodic variation of the normal component of the junction current. This in turn leads to synchronization of the motion of the vortex chain. This synchronization is possible with an alternating external current having a different phase at the instant of vortex formation. It is the possibility of varying the phase without changing the number of vortices flowing through the junction, and thus leaving the junction voltage unchanged, which produces on the CVC the current step having the dimensions indicated above.

In our case, the normal current of the bridge consists of a set of harmonic currents with frequencies that are multiples of the microwave-signal frequency. One should therefore observe on the CVC current steps equal to $2I_k$ at voltages $V_k=k\hbar\omega/2e$, where k is the number of the harmonic. Thus, the final form of the CVC is determined in this model by formula (4) with current steps occurring at voltages $\bar{V}=V_k$ and having amplitudes $2I_k$ given by (6).

Figure 3 shows the CVC calculated on the basis of this model. The parameters R and I_c of the curve without the microwave field (curve 1) correspond to the parameters of the experimental curve of Fig. 2. Curves 2–5 were obtained by successively increasing the amplitude of the alternating current I_ω. Comparison of Figs. 2 and 3 shows that the model agrees satisfactorily with the experiment.

5. The presented simple model can be easily im-

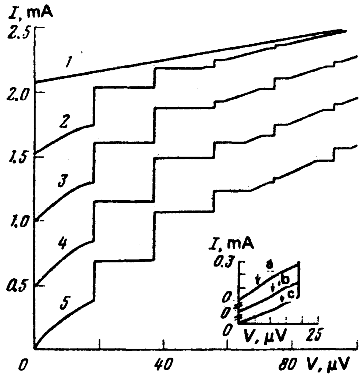

FIG. 3. Calculated CVC of bridge with parameters R and I_c corresponding to Fig. 3. Curve 1—without microwave field; curves 2—5 correspond to increasing power of the microwave field. The insert shows the initial sections of the CVC at $I_\omega > I_c$. The arrows mark the singularities (curves a, b, and c correspond to increasing microwave power).

proved. For example, it is possible to take into account the nonlinearity of the CVC. This alters somewhat formulas (4) and (6). However, in the investigated region of the currents and voltages, for CVC described by expression (1), the correction for the nonlinearity is not large.

According to the conclusions of[8], the steps should be parabolic in shape, i.e., the CVC should satisfy near the steps the relation

$$\bar{V}=k\frac{\hbar\omega}{2e}+\frac{d\bar{V}}{dI}\left((I-I_{0k})^2-I_k^2\right)^{1/2}. \quad (8)$$

Here $d\bar{V}/dI$ is the differential resistance calculated from (4), and I_{0k} is the current corresponding to the center of the k-th step. Allowance for this circumstance leads to the experimentally observed smoother voltage dependence of the current in the regions between the steps.

It is easy to estimate from (6) the maximum number k of steps that can be observed on the CVC:

$$k\sim(2I_\omega/\pi I_k)^{1/2}. \quad (9)$$

Assume that the minimal height of the step discernible on the CVC is $2I_k \sim 1$ μA. Then, assuming $I_\omega \sim 1$ mA, we get $k \approx 30$. For real CVC, the number of steps is frequently limited by the relation

$$k \leqslant (2eR/\hbar\omega)I_\omega, \quad (10)$$

i.e., by the condition that there be no additional harmonics in the normal current of the bridge. For the case of Fig. 2 at $I_\omega \approx 1$ mA, this limiting value corresponds to ~12 steps.

The foregoing estimates are valid without allowance for the noise in the bridge junctions. The presence of internal noise in the junction also decreases the observed number of steps. This noise leads to absence of a vertical section on the steps, starting with a definite value of k. The cause of the noise lies in the stopping of the Abrikosov vortices by various inhomogeneities in the film, and this disturbs the periodicity of their motion.

6. The vortex model offers an explanation of an interesting phenomenon observed in bridge junctions made of high-temperature alloys,[5,17] wherein a rather sharp increase of the current is observed at a certain voltage (that depends on the microwave power level), and the CVC acquires a kink (Fig. 2). At lower voltages the current is either practically zero, as in[17], or of the order of the current flowing through the bridge in the normal state at the same voltage, as in our case. The effect is observed at high microwave powers, when the critical current is fully suppressed.

The insert of Fig. 3 shows the initial sections of the CVC calculated for the case $I_\omega > I_c$. The formulas used in the calculations are similar to (4) and (6), with account taken of two spikes of the normal current during the period of the microwave field. Curves a–c on Fig. 3 correspond to an increase in the alternating current. The positions of the singularity (marked by arrows) are determined by the condition that the equality $I+I_\omega=I_c$ is attained for one of the current directions.

In the experiment, this singularity can become more strongly pronounced because of the nonlinearity of the real CVC and of the dependence of the critical current on the direction. The last dependence can explain the detection effect observed in[17] in Nb_3Ge junctions.

7. The dependence of the critical current I_c and of the amplitudes of the first steps on the microwave power P was investigated for a number of Nb_3Sn bridges. Figure 4 shows for one of the bridges plots of I_c and of the amplitude of the first step I_1 on $\sqrt{P}$. The $I_c(\sqrt{P})$ plot is nearly linear. The amplitude of the first step increases with increasing $\sqrt{P}$ and then goes through a smooth maximum. No decrease of I_1 to zero was observed even after the entire pattern disappeared at large power. Analogous plots against P were obtained for the amplitudes of the second and third steps.

The character of the obtained relations differs from the picture observed for bridges with constriction dimensions $a \ll \xi$.[15] Nb_3Sn bridges are characterized by the absence of oscillations of I_c and of the step amplitudes as functions of the electromagnetic-radiation power, although such oscillations were predicted by the resistive model.[18] The observed dependence of I_c on the microwave power in the case of Nb_3Sn bridges can be explained in the following manner. The current at which the voltage on the junction appears and which is by definition the critical current of the bridge in a

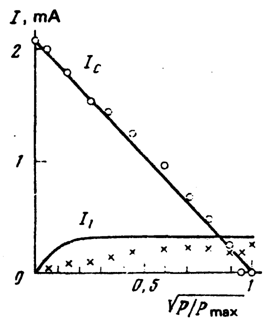

FIG. 4. Dependence of the critical current I_c (circles) and of the amplitude of the first step I_1 (crosses) on $\sqrt{P}$. P_{max} is the maximum value of the microwave power. The solid lines were calulated on the basis of the vortex model.

microwave field, is equal according to our model to $I = I_c - I_\omega$. Here I_c is the critical current in the absence of microwave radiation. Since the amplitude of the alternating current, determines by the microwave field, is $I_\omega \propto \sqrt{P}$, the dependence of the critical current on $\sqrt{P}$ should be linear. This agrees well with experiment.

The dependence of the steps on the microwave power (i.e., on I_ω) can also be calculated from formulas (4), (6), and (7). For the first step the function $I_1(\sqrt{P})$ is shown by the solid line of Fig. 4. A qualitative agreement is observed between theory and experiment.

8. For the study of the properties of Nb_3Sn at various microwave frequencies, we measured the CVC at frequencies up to 2 GHz. These experiments have also made it possible to verify some of the conclusions of the model. Figure 5 shows a typical CVC of an Nb_3Sn junction, measured at $\omega/2\pi = 2.45$ GHz. The presence of distinct steps at frequencies up to 2 GHz is evidence that the limit of the noise-induced blurring in our bridges does not exceed 1–2 GHz.

Low-frequency measurements have also confirmed the conclusion, deduced from the model, that the number of steps on the CVC is limited [formula (10)]. According to the model, a decrease of ω should lead to an increase of the number of steps. For the junction whose CVC is shown in Fig. 5, several steps were observed at $\omega/2\pi = 2.45$ GHz, but in the 3-cm radiation field only one step was observed at $V \approx 20$ μV.

9. A peculiarity of Nb_3Sn bridges is the dependence of their properties on the direction of the working current. An example of such a dependence is the hysteresis in the CVC shown in Fig. 6 for two microwave power levels. As seen from the figure, the critical current and the size and shape of the steps depend somewhat on the direction of the direct current. The hysteresis increases with decreasing temperature.

This phenomenon seems to be due to the large inertial of the Abrikosov-vortex motion.

Investigations performed in the present study and in the preceding ones[3-5] on Nb_3Sn bridge junctions show that their properties are adequately described by the vortex model. Since this bridges are in all cases broad and long ($\xi \ll a$ and $\xi \ll L$, where L is the length of the bridge), Abrikosov vortices are produced in them. The CVC of the junctions and other properties are influenced by fact that these vortices interact not only with the microwave field but also with the shores of the junction

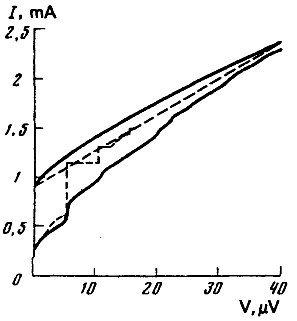

FIG. 5. CVC of an Nb_3Sn junction (solid curves) without a microwave field (upper curve) and in a 2.45-Hz microwave field. Temperature 14.2 K. The dashed lines indicate the CVC calculated on the basis of the vortex model.

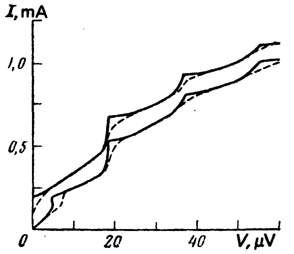

FIG. 6. Hysteresis of the CVC of Sb_3Sn bridges at two microwave power levels. Solid curve — increasing stationary current through the bridge, dashed — decreasing current.

and with inhomogeneties of the bridge. In particular, the formation of the aforementioned vortex chains is due to their strong repulsion from the shores of the junction.[7,8] The latter is due to the considerable depth of penetration of the magnetic field into the film, a depth comparable with the distance between the shores.

The results attest to the possibility of using films of the high-temperature superconductor Nb_3Sn to produce devices for cryoelectronics and cryogenic metrology. It is important here that quantum interferometers and other devices made of Nb_3Sn are capable of operating at liquid-hydrogen temperatures,[3] a region in which ordinary superconductor devices cannot be used. The results show, however, that the existing Nb_3Sn bridges have large internal noise in comparison, for example, with bridges of the S–N–S type.[19]

It is of interest to extend the research on bridge junctions to include other materials with A-15 lattices. Such investigations will make it possible to identify the character of the inhomogeneities that determine the pinning of the vortices, as well as the nature of the pinning forces in high-temperature superconductors. These investigations make it possible to determine the different physical parameters connected with the motion and interaction of the vortices, such as the time of motion through the junction, the viscosity coefficient, and some others.[3,7,8]

In conclusion, we thank I. S. Levchenko and L. I. Makhashvili for preparing the Nb_3Sn films, G. F. Zharkov for a discussion of the results, and B. G. Zhurkin and V. I. Novikov for useful advice on measurements in the microwave band.

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Translated by J. G. Adashko

Nonequilibrium phenomena in superconductor junctions

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(Submitted 12 July 1977)
Zh. Eksp. Teor. Fiz. **74**, 224–235 (January 1978)

The derivation is considered of a kinetic equation that describes the asymmetry of the electronlike and holelike excitations in a superconductor having a large concentration of nonmagnetic impurities. Besides the electron-phonon interaction, the alternating field is considered as a source of additional relaxation of the electron-hole unbalance. The dependence of the shift of the chemical potential and of the energy gap on the temperature and on the injection voltage is obtained at temperatures that are low compared with the critical value.

PACS numbers: 74.50.+r

1. INTRODUCTION

A tunnel current through a junction of a superconductor and another metal has been demonstrated experimentally and theoretically[1-4] to be able to produce an equilibrium state in the junction. The particles injected into the superconductors relax in energy on the phonons, and the result is a difference between the populations of the electron and hole branches, leading in turn to a shift of the chemical potential. Whereas in a normal metal the mixing of the branches is due to spatial diffusion, a distinct mechanism of homogeneous mixing is possible in a superconductor.[4] Spatially homogeneous situations can therefore arise in flat junctions of sufficient length. Because of the electron-phonon interaction, the excess particles produce a current whose divergence in the film differs from zero, and by the same token the pattern is homogeneous in the coordinate only over very large distances.

We shall deal hereafter with the experimental situation shown in Fig. 1.[2] The particles injected into the superconductor alter both the size of the gap and the chemical potential. For this reason, to prevent tunnel current from flowing between the superconductor and the probe N_p, it is necessary to apply to the latter some compensating voltage U. We obtain here the dependence of the compensating voltage and of the energy gap on the injecting voltage V and on the temperature if the latter is small compared with the critical temperature. A similar problem was investigated by Volkov and Zaĭtsev.[5]

In the limit of large impurity concentration, the quantity $\xi = v(p - p_0)$ is a poor quantum number, so that the kinetic equation of Aronov and Gurevich,[6] for example, cannot be directly employed here. On the other hand, to calculate the collision integral and the term with the field pumping it is more convenient to use directly the kinetic-equation approximation rather than a more general approach.[7-9] For this reason we start out with Green's functions that are integrated with respect to ξ and depend on the energy variable ϵ. In these terms, we introduce a particle distribution function n_ϵ, in contrast to the quasiparticle function used in [6].

2. DERIVATION OF THE KINETIC EQUATION

We derive below a kinetic equation for a superconductor with impurities in the presence of field pumping in the asymmetrical case $n_\epsilon \pm 1 - n_{-\epsilon}$, i.e., when a shift of the chemical potential appears. In the case symmetrical in the electrons and holes, an analogous equation was derived by Éliashberg.[10] Here, however, we use Keldysh's technique,[11] in which the equations are more compact.

We write down, by way of example, one of the functions G prior to integration with respect to ξ:

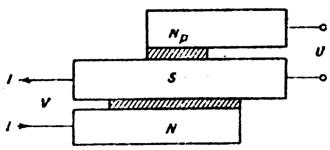

FIG. 1.