Mechanism for instability and formation of an inhomogeneous state in a superconductor with intensive tunnel injection

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The spatial distribution of the two-gap inhomogeneous state of superconducting tin films was investigated experimentally using a number of detectors at injection voltage $V_i \simeq 2\Delta/e$. It was found that the initiation of the inhomogeneous state depended on how the current was fed into the generator. The spatial structure of the inhomogeneous state and the instability in the form of a negative voltage jump on the current-voltage characteristic of the generator, which leads to the inhomogeneous state, were found to be very sensitive to weak magnetic fields. The form of the current-voltage characteristic of low-resistance tunnel junctions for $V_i \simeq 2\Delta/e$ was very dependent on the dimensions of the junction and the transparency of the barrier. Instability was observed only for tunnel junctions whose dimensions exceeded the Josephson penetration depth of the magnetic field. The results are interpreted in terms of the presence in the junction of an inhomogeneous distribution of the constant component of the current, inherent in distributed Josephson junctions.

INTRODUCTION

The two-gap inhomogeneous state of a semiconductor with tunnel injection was first discovered in the case where the energy of the injected quasiparticles was $eV_i \gtrsim 2\Delta$ (Ref. 1). (V_i is the voltage across the generator and Δ is the energy gap of the superconductor). The transition to the inhomogeneous state occurred as a result of an instability on the current-voltage characteristic of the generator in the form of a negative voltage jump for $V_i \simeq 2\Delta/e$. Similar singularities were observed in Ref. 2. The experiments reported in Refs. 1 and 2 were carried out on Al-I-Al-I-Al (I being an insulator). On the other hand, the instability on the current-voltage characteristics was not observed in Ref. 3, in which a study was also made of the low-resistance tunnel junctions which, in contrast to Refs. 1 and 2, were based on tin. Since the instability was observed only for tunnel junctions based on Al, Gray and Willemsen[2] proposed that it was due to the characteristic structure of films of this material, namely the nonuniformity of their superconducting properties. According to these authors, tin films were more uniform, and this was responsible for the absence of instability in the case of the experiments reported in Ref. 3. Gray and Willemsen have also put forward the "load line" model based on the assumption that the films were nonuniform and the current-voltage characteristics of low-resistence tunnel junctions were highly nonlinear. After this, the attention of researchers turned to the case of high injection energies ($eV_i \gg 2\Delta$), for which the model proposed in Ref. 2 was not valid, but the transition of the superconductor to the inhomogeneous state was nevertheless observed.[4] The case $V_i \simeq 2\Delta/e$ was ignored. The Gray-Willemsen model[2] was not confirmed by direct experiment.

The fact that effects analogous to those described in Refs. 1 and 2 could be observed in tin films was demonstrated in Ref. 5. Other properties of the instability and of the nonuniform state that had not been known in the case of aluminium were also noted in Ref. 5.

In the present paper, we report new experimental facts that enable us to draw some conclusions about the mechanism of instability and formation of the nonuniform state in tin films at quasiparticle injection energies $eV_i \simeq 2\Delta$.

EXPERIMENT

We have carried out two groups of experiments in which we recorded the current-voltage characteristics of double tunnel junctions (Sn-I-Sn-I-Sn) and ordinary junctions (Sn-I-Sn) of different size and different barrier transparency. The double junctions with one generator and a number of detectors were used to investigate the spatial structure of the inhomogeneous state of tin films under quasiparticle injection in the "narrow source" regime ($eV_i \simeq 2\Delta$). Such studies were previously carried out exclusively with the "wide source" ($eV_i \gg 2\Delta$) (Ref. 6).

In a double tunnel structure of the form Sn-I-Sn-I-Sn, the generator was a low-resistance tunnel junction of 0.78×0.15 mm. Five detectors of 0.1×0.17 mm were deposited on its upper electrode in steps of 0.04 mm. The detectors were at approximately 0.04 mm from the edges of the generator. The tunnel structures were prepared by thermal evaporation of Sn and oxidation of the resulting films. The films had roughly equal thickness (50–70 nm). Sapphire substrates were used to reduce heat losses, and measurements were performed in liquid helium at temperatures below T_λ. The specific tunnel resistance R_T of the generator was $3.4 \times 10^{-7} \Omega \cdot cm^2$ and the corresponding values for the detectors were in the range 1.4×10^{-4}–1.6×10^{-4} $\Omega \cdot cm^2$. Because of the considerable difference between the values of R_T of the generator and the detectors, the disturbance introduced by the detector current was small. For such low specific tunnel resistances (necessary to increase the injection intensity) and for dimensions of the order of 0.1 mm, the generators have the properties of a distributed Josephson junction, since the estimated Josephson penetration depth is $\lambda_J \simeq 0.02$ mm. The current can be supplied to the generator either by the asymmetric method (from one edge of the junction, Fig. 1) or by the symmetric method (from both edges simultaneously).

We recorded the current-voltage characteristics of the

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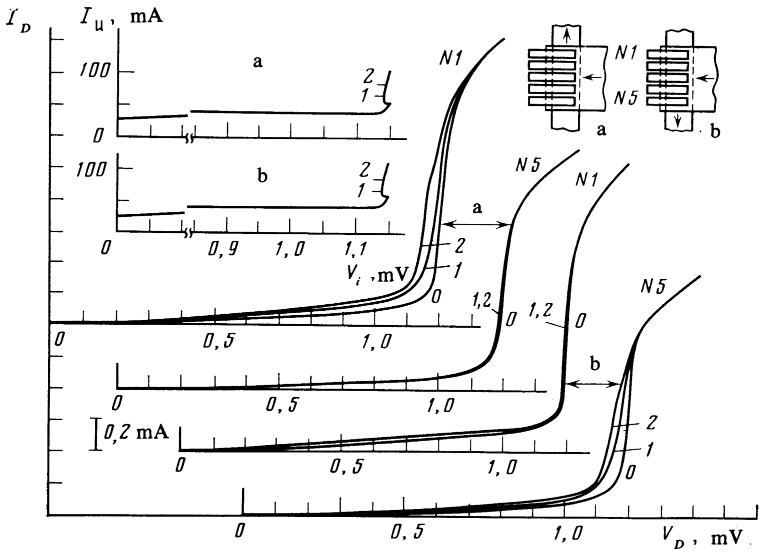

FIG. 1. Current-voltage characteristic of the generator of the two extreme detectors (Nos. 1 and 5) when the current is introduced through different edges of the generator (a and b) for $H=0$, $T=2.0$ K. Numbers indicated different injection levels and the corresponding detector characteristics.

generator and detectors for different injection levels and for different methods of supplying the current. The quasiparticle current-voltage characteristics and the variation of the *dc* Josephson current I_0 on the current-voltage characteristics of the generator in weak magnetic fields confirm the high tunnel quality of the junctions.

In the experiments with single-pair Sn-I-Sn junctions, we investigated how the characteristic depends on the dimensions of the junction and the transparency of the tunnel barrier. Tunnel junctions of 0.05×0.06, 0.12×0.6, and 0.7×0.7 mm were deposited on the substrate in a single vacuum cycle (we shall refer to them as small, intermediate, and large junctions, respectively). The deposition conditions were such as to produce junctions with equal specific tunnel resistances. The junction dimensions were held constant in the course of investigating the dependence of the current-voltage characteristic on R_T.

RESULTS AND DISCUSSION

Our investigation of the spatial structure of the inhomogeneous state that occurs for $V_i \simeq 2\Delta/e$, performed with the aid of a number of detectors, shows that the structure is very sensitive to the way the current is passed through the generator and to the weak external parallel magnetic field.

Figure 1 shows the current-voltage characteristics for the case where the current was introduced asymmetrically into the generator. The generator characteristic has a singularity in the form of a voltage jump, which has been related to the instability of the superconductor during tunnel injection.[1] When the generator current I_i is less than the instability current I_{ins}, whatever the method used to introduce it, the shape of the detector characteristic shows that there is a small uniform reduction in the energy gap which is the same for all detectors (for example, Fig. 1a shows the characteristic for detector No. 5). On the scale of the figure, this corresponds to the thickness of the line on the steep part of the characteristic.

For $I_i > I_{ins}$, the superconducting tin films undergo a transition to the nonuniform state, i.e., a region with reduced energy gap is found to appear. The position at which it actually appeared in our experiment was determined by the method used to supply the current to the generator, namely, it appeared at the particular edge of the generator to which the current was supplied, i.e., the nonuniform state was recorded on one of the detector edges, but was not present on the others. This is illustrated in Fig. 1 which shows the generator characteristic and the characteristics of the two extreme detectors (Nos. 1 and 5) to which the current supplied through different generator edges (a and b). When the current was supplied by the symmetric method, the nonuniform state appeared on both extreme detectors.

When the current was supplied asymmetrically (a) at right-angles to the generator length L, an external parallel magnetic field $H = 100$ G was applied to the system. This suppressed completely the instability on the generator characteristic, and a uniform reduction in the energy gap (Fig. 2), smaller than that in Fig. 1, was observed for all detectors. Figure 2 illustrates the situation where the magnetic field ensures that the generator characteristic no longer has a segment with a negative slope. In point of fact, the nonuniform state does not appear on the characteristics of the individual detectors even in lower fields in which the negative slope of the generator characteristic is still present. By recording the detector characteristics, we can follow how the reduced-gap region spreads over the entire length of the generator under the influence of the magnetic fields and, when its size becomes comparable with L, how the negative voltage jump on the generator characteristic is transformed into a segment with a negative slope. In this situation, the magnitude of Δ varies only slightly with position and can probably be regarded as approximately spatially uniform.

Let us consider our measurements in the absence of the magnetic field (Fig. 1). How the position of the reduced-gap region when the generator current I_{ins} is reached depends on the method used to supply the current to the generator shows that I_{ins} is nonuniformly distributed over the generator length. This nonuniform current distribution in the long Josephson junction is familiar in the stationary case[7] ($V_i = 0$). In

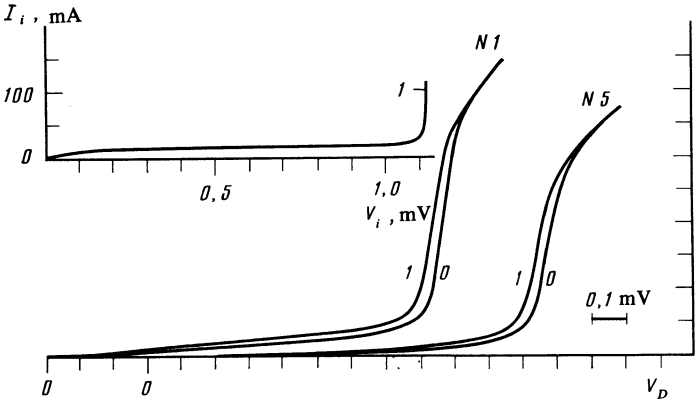

FIG. 2. Current-voltage characteristics of the generator and detectors in the magnetic field $H = 100$ G at $T = 2.0$ K. The current is supplied to the generator as in case *a* of Fig. 1.

the time-dependent case, for values of V_i not too close to zero, the junction contains a large number of vortices, so that the time-averaged current distribution should be uniform.[8] This is indicated by the uniform reduction in the energy gap that can be seen on the detector characteristics for $V_i < 2\Delta/e$. Nevertheless, since the variation in the distribution of I_i is definitely present for $V_i \simeq 2\Delta/e$, it may be considered that it was also present for $V_i < 2\Delta/e$, but was too small to be observed on the detector characteristics. A special experiment was performed to verify this. A bias voltage of magnitude somewhat lower than the value for which the instability occurred was applied to the generator. A constant bias current was simultaneously introduced into one of the extreme detectors, with the voltage $V_d \simeq 2\Delta/e$ across it. We measured V_d with the current introduced through different edges of the generator. The geometry of the tunnel structure was modified somewhat in order to ensure that the two extreme detectors completely covered the edges of the generator, but there was no direct contact between the upper and lower films of the structure. It was found that, for the low-resistance generator ($R_T \sim 10^{-7} \Omega \cdot \mathrm{cm}^2$), there was a difference of a few microvolts between the values of V_d when the current was supplied to the generator through different edges. Experiment may thus be indicating that a slight variation in the current distribution is present even for $V_i < 2\Delta/e$. We note that the question of the current distribution in long Josephson junctions in the nonstationary state has received practically no attention.[1)]

As far as the suppression of the energy gap for $V_i < 2\Delta/e$ is concerned, this may be due, on the one hand, to a current of thermally excited quasiparticles[2] and, on the other, to the absorption in the superconducting films of Josephson radiation with energy in excess of 2Δ. It may therefore be considered that the injection of quasiparticles for $V_i \gtrsim 2\Delta/e$ amplifies existing variation in the current distribution and thus leads to the nonuniform state observed on the detector characteristics. However, the experimental results shown in Fig. 1 do not in themselves exclude the possibility that the instability and formation of the nonuniform state[2] are related to the nonuniformity of the film material. Actually, it may be considered that, when the nonuniform current distribution is present, the inhomogeneous state will only be produced by the film irregularities present at the point of current concentration, which would explain the dependence on the method used to supply the current. The variation in the current distribution would then be irrelevant for the appearance of the instability and of the nonuniform state, so that one would not expect a substantial dependence of the instability pattern on the size of the junction. On the contrary, if the instability and the formation of the nonuniform state are determined by an internal current variation in the distributed junction, the situation should be very sensitive to the ratio of the junction dimensions to the Josephson depth λ_J. In particular, for dimensions approaching λ_J, one would expect that quasiparticle injection would not give rise ot the formation of the nonuniform state.

To elucidate this point, we have carried out experiments with Sn-I-Sn tunnel junctions. We investigated the dependence of the type of instability on the dimensions of the junction and its transparency. Figure 3 (curves 1–3) shows current–voltage characteristics for tunnel junctions with areas respectively equal to 0.05×0.06, 0.12×0.6, and 0.7×0.7 mm, and values of R_T approximately equal to the specific tunnel resistance of the generator of Fig. 1, 2. It is clear that the current-voltage characteristic of the small junction has a negative slope for a considerable range of currents, whereas the characteristic for the medium-size junction exhibits an instability. The characteristic of the large junction (curve 3) shows practically no evidence of a region with a negative

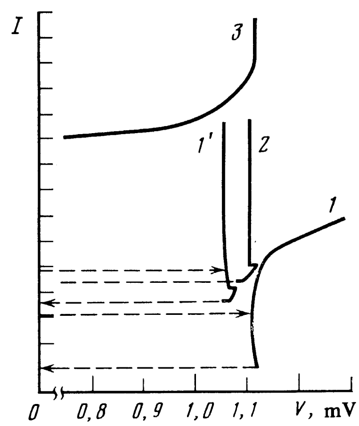

FIG. 3. Current-voltage characteristics of small (1), intermediate (2), and large (3) junctions with the same barrier transparency. When the barrier transparency is increased, the characteristic of the small junction takes the shape shown by 1′. The scale along the I axis is: for curves 1, 1′—2.5 mA/div; ;2—20 mA/div; 3—100 mA/div. Curves 1–3 were recorded at $T = 1.85$ K and curve 1′ at 2.0 K.

slope or of a votage jump. Figure 3 also shows the characteristic of a junction with the same small dimensions but specific tunnel resistance reduced by a substantial factor (curve 1′). As can be seen, the reduction in R_T has resulted in the suppression of instability (voltage jump).

The results of these experiments can be explained as follows. The absence of instability in a small junction is in total agreement with the results reported in Ref. 3 and is consistent with the uniform change in the energy gap under the influence of quasiparticle injection.[10] In other words, the characteristic size of the variation is comparable with the size of the junction itself. The essential difference between the characteristic of the intermediate-size junction and the last case is probably due to the fact that the scale of the variation is now much smaller than the area of the entire junction, and another condition (as well as the presence of a segment with negative slope for small junctions) is satisfied in order to give rise to switching over the load line.[2] The absence of a segment with negative differential resistance on the characteristics of large tunnel junctions can be explained in terms of the model put forward in Ref. 2 by saying that the scale of the variation becomes very small in comparison with the size of the junction, so that the load line becomes too steep.

The appearance of the instability on the current-voltage characteristic of the small junction as the barrier transparency is increased may be an indication that the current distribution in the tin tunnel junction has become highly nonuniform due to the reduction in the scale of the variation. Since, in the present case, this size depends on the transparency of the barrier, it cannot be determined by some characteristic length of the superconductor (for example, the quasiparticle diffusion length) and must depend only on the Josephson depth λ_J which, in turn, depends only on R_T and the injection level.

Thus, the model put forward in Ref. 2 provides a good explanation of the experimentally observed dependence of the size of the negative-voltage jump on the specific tunnel resistance and junction size, which passes through a maximum as these quantities are varied. Other interpretations of instability and formation of the nonuniform state are given in Refs. 10–13. The models proposed in Refs. 11–13 require the presence of a critical quasiparticle density in the superconductor, and are therefore definitely unsuitable for explaining our experimental data. The only rigorous theory of instability and formation of the nonuniform state of a semiconductor for a narrow quasi-particle source is the theory put forward by Elesin.[10] However, this theory does not describe the following experimental facts: the high sensitivity of the instability (both the current $I_{\rm ins}$ and the negative voltage jump) and the spatial structure of the nonuniform state to weak magnetic fields, which have an appreciable influence only on the Josephson effect; the reduction in the characteristic scale of the variation as barrier transparency increases; and the dependence of the negative voltage jump on the junction size, including, in particular, the absence of the jump on the characteristics of large junctions. It may therefore be considered that, in our experiments, the switching mechanism described in Ref. 2 was more likely, but the mechanism responsible for the formation of the nonuniform state was determined not by the inhomogeneity of the superconducting films but the inhomogeneity in the current distribution in the low resistance tunnel junction, which is due to its Josephson properties. The application of a weak magnetic field results in the suppression of the Josephson effect and to an increase in the degree of homogeneity of the system.

Characteristics analogous to those shown in Fig. 3 (curves 1–3) have been observed separately in different experiments,[1–3] but it was not clear why they had such different shapes for $V_i \simeq 2\Delta/e$. It follows from these experiments that the shape of the quasiparticle current-voltage characteristics of low-resistance tunnel junctions for $V_i \simeq 2\Delta/e$ may be determined, to a considerable extent, by the ratio of the junction size to the depth λ_J.

It is interesting to note the influence of high-frequency electromagnetic induction on the spatial structure of the inhomogeneous state for $V_i \simeq 2\Delta/e$, which turns out to be just as sensitive to the induction as the *dc* Josephson current for $V_i = 0$. It was found that, under the influence of this effect, the reduced-gap region remained, but could shift as a whole along the generator. This is detected simply as an instantaneous "switching" of the singularity on the detector characteristic, due to the inhomogeneous state, from one detector to another (for example, from No. 1 to 5, see Fig. 1). The fact that the position of the reduced-gap region can be controlled in this way was not previously known.

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[1)]A recent paper,[9] published after the first draft of the present paper was sent to the Editorial Board, reports similar results obtained by different methods.

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