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# *CERTAIN SINGULARITIES OF CURRENT-VOLTAGE CHARACTERISTICS OF JOSEPHSON TUNNEL JUNCTIONS*

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The dV/dI characteristics of Josephson tunnel junctions are investigated for Sn-Sn, In-In, and Sn with In impurity. A complex dV/dI characteristic was observed for all junctions. This excludes the anisotropy of the energy gap as an explanation of this phenomenon. The observed singularities are attributed to the complex structure of the transition layer between superconducting films consisting of a number of microcontacts. The dependence of the intensity of the minima of the dV/dI characteristics on the magnetic field strength confirms that the minima are connected with the Josephson effect.

## 1. INTRODUCTION

It is known that the current-voltage characteristics of tunnel junctions between superconductors, in which the Josephson effect appears[1], reveal a number of singularities[2,3] in the voltage region $eV \lesssim \Delta$ ($\Delta$—half-width of energy gap). The frequency of the alternating Josephson current $\omega = 2eV/\hbar$, arising when a nonzero fixed bias is applied to the junction, does not exceed in this case the threshold frequency $\omega_g = 2\Delta/\hbar$. As a result, the power loss of the electromagnetic field excited by the alternating Josephson current is small. The tunnel current observed at $V \neq 0$ has, besides a component due to the tunnelling of the quasiparticles, also a dc component of the oscillating Josephson current; this component is due to the tunnelling of the Cooper pairs and is proportional to the absorption of the Josephson electromagnetic radiation in the junction[4]. Consequently, any resonance or threshold singularities in the absorption and (or) generation of the Josephson electromagnetic radiation lead to singularities on the current-voltage characteristics at the corresponding voltages. The singularities most thoroughly investigated experimentally are the so-called "steplike" singularities of the current-voltage characteristics, due to the generation of resonance type of oscillations of electromagnetic waves in the tunnel junction[3]. The theory of this phenomenon[5], based on the consideration of the properties of an ideal model of the tunnel junction in the form of two plane-parallel plates separated by a homogeneous dielectric layer, explains the observation results very well. There are, however, a number of singularities of the current-voltage characteristics and their derivatives, which have not yet been unambiguously interpreted theoretically. These include the spikes of the tunnel current at bias values approximately equal to the subharmonics of the superconducting energy gap $eV_n \approx 2\Delta/n$[2,6], as well as the fine structure of the dV/dI characteristics, which is retained in magnetic fields up to several dozen Oersted and more[4,7,8]. In the present paper we have investigated experimentally the properties of the "coarse" ($2\Delta/n$) and "fine" structures of the dV/dI characteristics of Josephson tunnel junctions. We investigated the changes of the characteristics resulting from aging of the samples at room temperature. We show that the observed singularities are connected with the complicated structure of the transition layer between the two superconductors, a layer that consists of a large number of microcontacts, and not with the anisotropy of the gap width.

## 2. EXPERIMENTAL PROCEDURE

The samples were prepared by sputtering thin films in high vacuum ($< 10^{-6}$ Torr) on a glass substrate cooled to 180–200°K. The dielectric layer 10–20 Å thick was produced by oxidizing the primary film at room temperature in oxygen or air for ~30 minutes at a pressure 0.5–1 Torr. The configuration of the tunnel structures, consisting of three junctions with different areas, is described in[3]. The two films of the tunnel junction were made of identical metals (Sn, In, or their alloys, and also Pb). The content of the In impurity in the Sn, in weight per cent, will henceforth be indicated in parentheses, for example, Sn-Sn (0.1% In) denotes that the tunnel junction is made of tin films with 0.1 wt.% In. The purity of the original metals was not worse than 99.999%. The film thicknesses were measured with a micro-interferometer accurate to ± 200 Å, and the smearing of the film edges was of the order of several dozen microns. After sputtering the secondary films, the samples were heated to room temperature and were mounted in a cryostat for 10–15 minutes. The entire system was then cooled to liquid nitrogen temperature, which was maintained during the entire storage time of the sample. During the storage at liquid-nitrogen temperature, the characteristics of the samples remained unchanged. To study the influence of the aging (annealing) processes, the samples were periodically heated to room temperature for a time ranging from 0.5 to 5 days.

The I-V and dV/dI characteristics were measured at a temperature of 1.4°K using the customary procedure[9]. A magnetic field ranging from zero to 100 Oe was applied parallel to one of the films. The amplitude of the low-frequency (29 Hz) alternating voltage, proportional to differential resistance of the junction –dV/dI, did not exceed 10 μV and decreased near the minima of dV/dI to several microvolts. Thus, the resolution of the

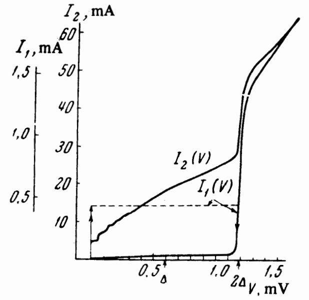

FIG. 1. Current-voltage characteristics of an Sn-Sn tunnel junction before and after annealing ($I_1(V)$ and $I_2(V)$, respectively), H = 0. The dashed line denotes the voltage jump occurring when superconductivity of the junction is destroyed.

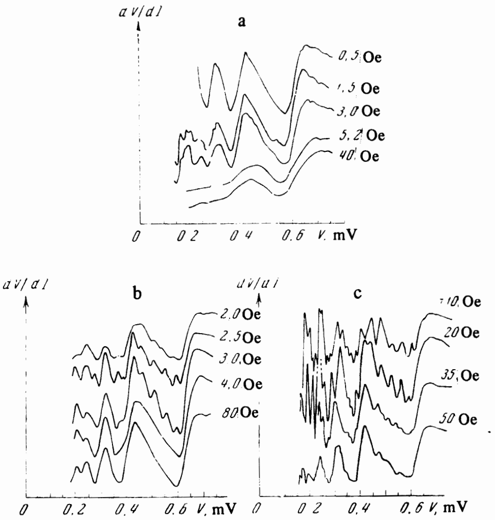

FIG. 2. Modification of dV/dI characteristics as a result of annealing: a) Sn-Sn, b and c) Sn-Sn (0.1% In) before and after annealing at room temperature for 14 hours. The location of the zero ordinates of the dV/dI curves is arbitrary for each curve and is not indicated in the figure.

system for the V axis was not worse than 10 $\mu$V. In most cases there was no hysteresis when the direction of the plotting of the I-V and dV/dI characteristics was reversed. The only junctions used in the measurements were those whose superconducting critical current decreased greatly (by a factor of more than several times) in fields on the order of several Oe.

## 3. CHANGE OF I-V AND dV/dI CHARACTERISTICS AS A RESULT OF ANNEALING OF THE SAMPLES AT ROOM TEMPERATURE

As a result of annealing of the tunnel samples at room temperature, an irreversible change takes place in the properties of the junctions and in the form of the I-V and dV/dI characteristics. The resistance of the tunnel junction decreases with aging. This decrease is logarithmic in the annealing (aging) time. The aging leads initially to a shift of the I-V characteristic parallel to itself into the region of large currents. The superconducting critical current (the Josephson current) then increases like $1/R_N$ in accordance with the theory[1] ($R_N$ is the resistance of the junction, determined from the slope of the asymptotic line for the I-V characteristics). With further annealing, however, the tunnel current increases at $eV < 2\Delta$ much more rapidly than the decrease in junction resistance. Figure 1 shows typical changes occurring in the I-V characteristic during the course of prolonged annealing. Although the true tunnel resistance of the junction decreased in this case by a factor of 16, as can be seen from the change of the current jump at $eV = 2\Delta$, the current through the junction increased at voltages $eV < 2\Delta$ by almost 500 times.

Significant changes occur in the shape of the I-V and dV/dI characteristics at biases $eV < \Delta$. The distinct periodic stepwise structure[3] vanishes and is replaced by spikes and smeared-out stepwise singularities on the I-V characteristics, manifest in the form of minima on the dV/dI characteristics; the positions of these minima on the V axis, generally speaking, do not coincide with the positions of the steps. Successive stages of the development of the complex structure of the dV/dI characteristics are shown in Fig. 2. Figure 2a shows the occurrence of broad minima located near voltages equal to subharmonics of the gap $eV_n = 2\Delta/n$. An appreciable dependence of the intensity of the minima on the weak magnetic fields is noticeable and disappears with further annealing (Figs. 2b and c). During the later stages of the annealing, a fine structure of the minima of the dV/dI characteristics, which depends strongly on the field (Fig. 2b) first appears, after which the intensity of the minima increases and the fine structure is observed up to fields of several dozen Oersted (Fig. 2c). At the same time, the dependence of the coarse structure ($2\Delta/n$-singularities) on the field in the interval 0—100 Oe disappears. The annealing time necessary to observe noticeable changes in the I-V and dV/dI characteristics fluctuates in a wide range, depending on the sample preparation conditions (from several hours to several days).

Summarizing briefly the changes occurring in the I-V and dV/dI characteristics during the aging process, we note the following.

1. Prior to the annealing, the critical Josephson current is close to the theoretical value[1] and experiences damped oscillations with increasing magnetic field, in agreement with the theory. This is evidence of a high homogeneity of the oxide layer between the films constituting the tunnel junction. The quasi-particle current is small when $eV < 2\Delta$, amounting, for example, for Sn at T = 1.5°K, to less than 1/100 of the tunnel current in the normal state. When $eV < 2\Delta$, the quasiparticle current decreases exponentially with decreasing temperature. The I-V and dV/dI characteristics have no singularities in strong magnetic fields (on the order of several dozen Oersted)[1)].

2. After the annealing, a number of deviations of the Josephson characteristics from the predictions of the theory are observed. The dependence of the critical current on the field is close to theoretical only for weak fields, but in strong fields (~ 10 Oe and more) the two differ greatly. The regular periodicity of the oscillations is lost, and the envelope of the maxima tends not to zero but to a certain finite value. At $eV < 2\Delta$ and $T \ll T_{cr}$, the current through the junction constitutes an appreciable fraction of the normal tunnel current and

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[1)] The ordinary steplike structure of the I-V characteristics, due to the generation of resonant types of oscillations, disappears completely in such fields

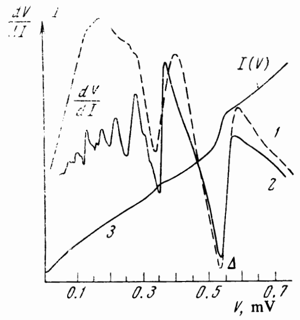

FIG. 3. I-V and dV/dI characteristics of an In-In tunnel junction at $eV \lesssim \Delta$. 1 - dV/dI characteristic prior to annealing, H = 26 Oe, 2 and 3 - dV/dI and I-V characteristics after annealing at room temperature for 14 hours, H = 60 Oe.

is independent of the temperature. The I-V characteristics have a number of singularities at $eV \lesssim \Delta$. These singularities are manifest on the dV/dI characteristics in the form of minima. There exist individual singularities that pertain only to a given junction and are not duplicated from sample to sample. However, the two groups of singularities connected with the changes produced in the junction by the annealing and shown in Fig. 2 do not depend on the concrete character of these changes, and are therefore reproduced in their main features in a large number of different tunnel junctions. We shall discuss in greater detail the properties of these groups of singularities, arbitrarily called the coarse (or $2\Delta/n$) and fine structures of the dV/dI characteristics.

## 4. PROPERTIES OF THE COARSE AND FINE STRUCTURES OF THE dV/dI CHARACTERISTICS

The coarse structure of the dV/dI characteristics has the following properties:

1. The form of the $2\Delta/n$ singularities on the I-V characteristics changes during the course of aging from steplike current spikes at $eV_n = 2\Delta/n$ to the resonant character of the maxima observed against the background of a monotonically increasing current component[2]. Figure 3 shows the corresponding change in the form of the dV/dI characteristics, which differs in having a sharp spike of the derivative at $eV_n = 2\Delta/n$. The location of the $2\Delta/n$ singularities on the V axis will be defined as the position of the inflection points corresponding to a positive slope of the dV/dI characteristics, ($d^2V/dI^2 > 0$).

2. The singularities are located near voltages that satisfy approximately the relation $eV_n \approx 2\Delta/n$. We were able to observe experimentally up to 12 singularities. The decrease of the product $nV_n$ with increasing number n (Fig. 4) is clearly observed and greatly exceeds the experimental error. The deviation of $nV_n$ from the expected value $2\Delta/e$ is most appreciable for those numbers n which correspond to minima with the lowest intensity. Since the intensity of the minima with large numbers n increases during the course of the aging, the plot of $nV_n(n)$ changes but the aforementioned tendency is retained. The temperature dependence of the positions of the singularities of the course structure is similar to the $\Delta(T)$ dependence. However, near $T_{cr}$ there is observed a small deviation of $nV_n(T) < 2\Delta(T)/e$, which increases with increasing number n.

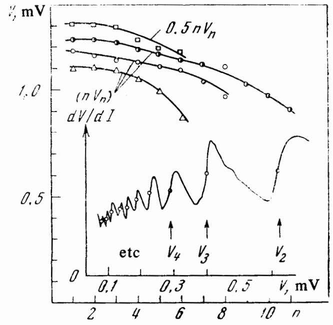

FIG. 4. Dependence of the position of the $2\Delta/n$ singularities on the V axis on the number n: □ - Pb-Pb; ○ - Sn-Sn; Δ - In-In; ◑ - Sn-Sn (0.1% In). In the insert are shown the $2\Delta/n$ singularities for the junction Sn-Sn (0.1% In), H = 65 Oe. The points on the curve designate the positions of the singularities.

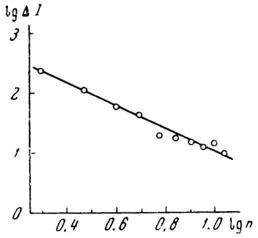

FIG. 5. Dependence of the heights ΔI of the current spikes on the I-V characteristic on the number n for an Sn-Sn (0.1% In) tunnel junction, plotted on a logarithmic scale, H = 65 Oe.

3. The height of the current spikes $\Delta I_n$ on the I-V characteristic decreases with increasing n approximately in accordance with a power law, $\Delta I \propto n^{-q}$, where $q \geq 2$. The exponent decreases with increasing annealing time. Figure 5 shows in a logarithmic scale a plot of ΔI against n, for the junction Sn-Sn (0.1% In), whose dV/dI characteristic is shown in the insert of Fig. 4. The quantity proportional to $\Delta I_n$ was chosen to be the ratio of the area bounded by the minimum of $2\Delta/n$ to the product of the derivative signal at the minimum by $\tilde{V}_0$, where $\tilde{V}_0$ is the value of the monotonic component of dV/dI at $eV_n = 2\Delta/n$. The slope of the straight line is close to two, yielding a dependence $\Delta I \propto n^{-2}$. For other junctions, a linear dependence of log ΔI on log n was also observed, with a proportionality coefficient ranging from −5 to −2. We note that the results differ from the empirical plots of ΔI against n given in[6,7]. Marcus[6] indicates a dependence in the form of a power function ($\Delta I \propto 2^{-n}$), while Rochlin and Douglas[7] speak of an exponential dependence of the intensity of the singularity on its number. We observe no difference between the functional ΔI(n) relations for even and odd series, all the points fitting satisfactorily a single curve (Fig. 5).

4. In spite of the fact that for annealed junctions the intensity of the minima of the coarse structure does not depend on the field in the investigated field integral, for weakly annealed junctions there was observed a significant dependence of the intensity of the minima on the field in a range of several Oersteds (Fig. 2a). This result apparently indicates that there is a connection between the coarse structure and the Josephson current, the magnitude of which depends strongly on weak magnetic fields.

The fine-structure minima arising during the annealing process become superimposed on the coarse structure of the dV/dI characteristics (Fig. 2a). We can point to the following features which are characteristic of the experimentally observed dV/dI characteristics.

A. The position of the minima on the V axis does not depend on the annealing time, the junction dimensions, and the constant magnetic field. As the characteristic point for the localization of the singularity on the V axis we chose in most cases (except those specially stipula-

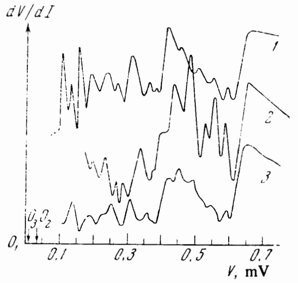

FIG. 6. dV/dI characteristics for tunnel junctions made of Sn-Sn with In impurity, H = 2.5 Oe. The scales of the abscissas for curves 2 and 3 are shifted relative to the scale for curve 1, which is indicated in the figure. The position of the zero ordinate is different and arbitrary for different dV/dI curves

| | Junction dimensions | % In | Film thickness, Å |
|---|---|---|---|
| 1 | 0.37×1.01 | 0.1 | 1700; 1500 |
| 2 | 0.21×0.34 | 0.4 | 1900; 2700 |
| 3 | 0.46×0.49 | 0.4 | 2500; 2700 |

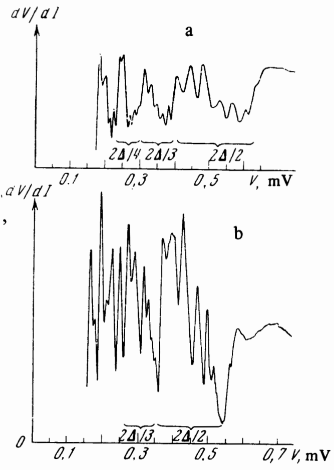

FIG. 8. Fine structure of the dV/dI characteristics of Josephson tunnel junctions: a)Sn-Sn (0.1% In), H = 12.5 Oe; b) In-In, H = 10 Oe, S = 0.37 x 1.01 mm.

ted) the value of the minimum of dV/dI. This choice was made exclusively for the sake of simplicity, and was not strictly justified, for as a rule it is impossible to determine from the I-V characteristics the form of the singularities of the fine structure. Figure 6 shows dV/dI characteristics of three Sn-Sn (with In impurity) tunnel junctions of different dimensions, different film thicknesses, and different In impurity contents. All three curves have the same abscissa scale, but the origins are shifted, as shown in the figure. The abscissa axis in Fig. 6 corresponds to curve 1. In spite of the greatly differing junction parameters, the groups of the minima of the fine structure, located inside the $2\Delta/2$-minima of the coarse structure, coincide in the main. The distance between the minima of the fine structure amounts to 30–50 $\mu$V, i.e., it has the same order of magnitude as the distance between the steps due to the generation of a resonance type of oscillation. The position of the minima does not depend on the magnetic field, as can be seen from Fig. 7.

This figure shows the positions of the minima of the fine structure for different magnetic fields for the junctions 2 and 3 of Fig. 6. The diagrams were plotted in a manner to permit convenient comparison of the systems of minima of both junctions. In spite of the fact that the dimensions of the junctions differ by more than a factor of 2 in the direction perpendicular to **H**, the systems of the minima of the fine structure in fields exceeding 5 Oe are approximately the same. It is significant that the distance between the minima of the fine structure does not change in inverse proportion to the junction width, as is the case for the stepwise structure. It is possible that a certain degree of complexity of the fine structure in weak fields (0–5 Oe) is connected with the excitation of certain steps.

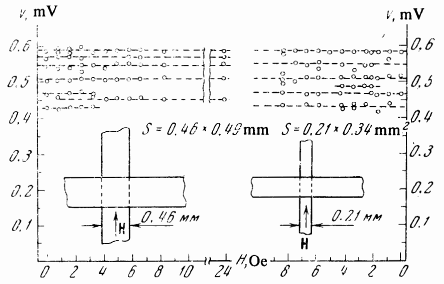

FIG. 7. Positions of the minima of the dV/dI characteristics on the V axis vs. the magnetic field H for junctions 2 and 3 in accordance with Fig. 6. The data are presented only for the $2\Delta/2$ series. In the insert are shown the configurations of the tunnel junctions and the direction of the magnetic field.

B. The fine structure of the dV/dI characteristics does not depend on the small amounts of impurities, eliminating the anisotropy of the energy gap as an explanation of this phenomenon. The properties of the fine structure of the dV/dI characteristics of Sn-Sn tunnel junctions containing several tenths of a percent of In impurity by weight, do not differ from the fine structure of junctions of pure Sn. The energy gap in Sn increases upon addition of In, leading to a shift of the $2\Delta/n$ singularities towards larger V. The obtained alloy films had a highly perfect structure and homogeneity, as indicated by an electron-diffraction investigation of the structure2), and also by the presence of a sharp increase of the current near $eV = 2\Delta$ on the single-particle tunnel characteristic. Films of Sn containing several percent of In were characterized by a smeared-out increase of the current on the single-particle tunnel characteristic at $eV = 2\Delta$, indicating an essential inhomogeneity in the superconducting properties of the obtained alloys. It should be noted that according to[10] an admixture of In in single-crystal Sn, amounting to several tenths of a per cent, eliminates completely the anisotropic character of the dependence of the gap $\Delta$ on the wave vector of the electrons **k**. Thus, the explanation[4,7,8,11] whereby the anisotropy of the gap is the mechanism responsible for the occurrence of the fine structure is not verified by experiment.

C. The distance between the minima of the fine structure within different $2\Delta/n$ series decreases with increasing number n. This property is quite important, since it excludes the usual steplike structure as being responsible for the occurrence of the fine structure of the dV/dI characteristics. Figure 8 shows the dV/dI characteristics, which illustrate clearly the decrease of the distance between the minima of the fine structure with increasing number n. It should be noted that the resolution of the individual fine-structure line in series

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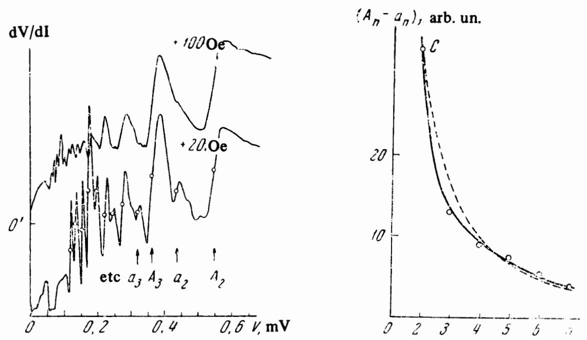
2) Layers of Sn with In impurity had a more perfect texture ([001] axis in the substrate plane) than layers of pure Sn obtained under analogous conditions.



a b

FIG. 9. Dependence of the distance between the singularities of the fine structure on the number n. a - dV/dI characteristic of Sn-Sn tunnel junction, containing two series of 2Δ/n singularities, $A_n$ and $a_n$. The points on the curve designate the positions of the singularities; b - difference ($A_n$ - $a_n$) as a function of the number n. The dashed curve is proportional to ln(n + 1), C - congruence point.

with sufficiently large numbers n is made difficult by the limiting resolving power of the measuring system.

Figure 9 shows the dV/dI characteristics of an Sn-Sn tunnel junction for two values of the magnetic field. In a 20 Oe field, the fine structure consists of one minimum, the repetition of which can be readily recognized in various 2Δ/n series. Let us trace the position of this singularity on the V axis. In the present case, the characteristic point of the singularity was chosen to be the inflection point, just as for the coarse 2Δ/n structure. The distance between the position of $a_n$ and the corresponding singularity of the coarse structure $A_n$ varies approximately like 1/n(n + 1), a fact reflected in Fig. 9b. The quantity 1/n(n + 1) is proportional to the difference between the two neighboring 2Δ/n singularities:

$$\frac{2\Delta}{n} - \frac{2\Delta}{n+1} = \frac{2\Delta}{n(n+1)}. \quad (1)$$

Thus, the voltage interval within the corresponding 2Δ/n series decreases like ~ 1/n(n + 1), and the number of the minima of the fine structure remains apparently constant. This conclusion follows from an observation of a large number of dV/dI characteristics for different junctions, including those shown in Fig. 8.

D. The intensity of the minima depends strongly on the magnetic field and is maximal when the phase velocities of the Josephson-current density wave and the electromagnetic wave in the junction are equal. For the minima of the 2Δ/2 series (V ~ 0.5—0.6 mV), the corresponding magnetic field, which controls the phase velocity of the current-density wave, is 2—3 Oe (see Fig. 2b). Similar values of the field correspond to the maximum intensity of the stepwise structure in the indicated voltage interval[3]. Appreciable differences between the field dependences of the intensity of the minima of the fine structure and of the heights of the steps occur during the course of aging of the tunnel junctions. Annealing causes the decrease of the intensity of the minima of the fine structure with increasing field to become less rapid (Fig. 2c). Moreover, as noted in[11], the decrease of the intensity of the minima of the fine structure with increasing field differs qualitatively from the dependence of the height of the steps on the field. A stepwise structure is characterized by a direct proportionality between the voltage of the step and the field in which the height is maximal[3]. The minima of the fine structure corresponding to large voltages, to the contrary, vanish in weaker magnetic fields.

E. The temperature dependence of the positions of the minima is close to the temperature dependence of the gap Δ(T), which differs from the temperature dependence of the frequency of electromagnetic resonances. However, the temperature dependence of the positions of the minima in the temperature interval of greatest interest, near $T_{cr}$, cannot be traced, since the intensity of the minima decreases rapidly with increasing temperature, and the minima become smeared out in the V scale.

## 5. DISCUSSION OF RESULTS

Let us consider different possible explanations for the mechanisms giving rise to the complex structure of the I-V and dV/dI characteristics. If we attempt to attribute the observed singularities to multiparticle tunnelling[12,13], then we must assume that the penetrability of the barrier is close to unity. The multiparticle tunnel current should not depend on the magnetic field in the region of weak fields, in contradiction to the observed characteristics. A more likely explanation of the dependence of the intensity of the minima on the field involves the Josephson electromagnetic radiation[11,14]. However, all the possible absorption mechanisms of the Josephson radiation in the junction yield, generally speaking, different ΔI(n) dependences for the even 2Δ/2n and odd 2Δ/(2n + 1) series of the coarse-structure minima, whereas the experimental ΔI(n) is a single curve for all the numbers n (Fig. 5).

It was shown above that the anisotropy of the energy gap can likewise not be used to explain the fine structure of the dV/dI characteristics. As to the stepwise structure of the current-voltage characteristics, a direct comparison of the period of the steps with the distance between the minima of the fine structure is difficult, since the conditions for the establishment of a high-Q electromagnetic resonance in the tunnel junction during the course of annealing are violated, especially at short wavelengths (near the threshold frequencies). In many cases, however, it is possible to set in correspondence the period of the steps on the I-V characteristics prior to annealing with the distance between the minima of the fine structure observed after annealing. Thus, for example, for the In-In junction whose dV/dI characteristic is shown in Fig. 8b, the ΔV of the steps amounted to 34 μV, and the distances between the minima of the fine structure amounted to 34, 23, 35, 45, and 33 μV in the 2Δ/2 series, and to 10, 11, 15, 18, and 28 μV in the 2Δ/3 series. The approximate agreement between ΔV and the distances between the minima in the 2Δ/2 series is not always observed, as can be seen already from an examination of Fig. 7. For a junction with the width (⊥H) w = 0.46 mm, we have ΔV = 30—40 μV, whereas for the junction with w = 0.21 mm it equals ΔV = 60—80 μV. In addition, the period of the stepwise structure, as shown by experiment, depends very little on V, in contradiction to the sharp changes of the distance between the minima of the fine structure when crossing the boundaries of the 2Δ/n series.

Nonetheless, the obtained results do not suffice to exclude the possible influence of the electromagnetic resonances in the junction on the properties of the fine structure of the dV/dI characteristics of the annealed samples, since the structure of the transition layer between the superconducting films obviously experiences appreciable changes during the annealing process, and the behavior of the electromagnetic resonances under these conditions has not been investigated. Changes in the structure of the transition layer are manifest apparently in the occurrence of a homogeneous structure of microscopic metallic bridges passing through the oxide layer. Such a system of microcontacts should exhibit all the properties of a Josephson junction, so long as the wavelength of the Josephson current density

$$\lambda = \Phi_0 / dH \qquad (2)$$

($\Phi_0$—quantum of the magnetic flux, equal to $2.07 \times 10^{-7}$ G-cm$^2$, $d \approx 2\lambda_L$) exceeds the average distance L between microcontacts. From the $I_{cr}(H)$ dependence for the tunnel junction it is possible to obtain an upper limit for L, corresponding to that value of the field $H_{lim}$, above which the regular periodic and damped $I_{cr}(H)$ dependence is violated:

$$L[\mathrm{cm}] \leqslant \frac{2}{10^2 H_{\mathrm{lim}}[\mathrm{Oe}]} = \lambda_{\mathrm{lim}}[\mathrm{cm}]. \qquad (3)$$

Inasmuch as the number of microcontacts is $N \approx S/L^2$, where S is the area of the junction, it follows that by using the formula for the resistance of a single microcontact[15] $R \cong \rho l/D^2$, where $\rho l$ = const for a given metal ($\sim 2 \times 10^{-11}$ ohm-cm$^2$ for Sn), D is the diameter of the junction, and the total resistance of the junction $R_0$ is known, it is possible to obtain, assuming all the microcontacts to be identical, an estimate for the diameter D of a single microcontact:

$$D \leqslant \lambda_{\mathrm{lim}} \sqrt{\rho l / R_0 S}. \qquad (4)$$

For typical values $H_{lim}$ = 4–5 Oe, $\lambda_{lim} \cong 4 \times 10^{-3}$ cm, $R_0$ = 0.38 ohm, and $S = 4 \times 10^{-3}$ cm$^2$, we obtain the reasonable estimate $D \lesssim 32$ Å, i.e., the diameter of the "aperture" in the oxide layer has approximately the same magnitude as the thickness of the oxide layer. The appearance of a voltage across the tunnel junction when current flows to the latter obviously denotes that the current density near each microcontact exceeds the critical value and the superconductivity is destroyed. The properties of such a system have not yet been investigated theoretically, and it is possible that they are responsible for the observed singularities in the I-V and dV/dI characteristics of annealed Josephson tunnel junctions.

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