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FINE STRUCTURE OF CURRENT-VOLTAGE CHARACTERISTICS OF JOSEPHSON Sn—Pb *TUNNEL JUNCTIONS*

I. K. YANSON

Physico-technical Institute for Low Temperatures, Academy of Sciences, Ukrainian S.S.R.

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A study was made of the current-voltage characteristics, and of the first and second derivatives of these characteristics, of Josephson tunnel junctions made of thin tin and lead films. It was found that the constant component of the current was associated with the absorption of the Josephson electromagnetic radiation in the junction. The observed singularities were interpreted as threshold effects of the absorption of the radiation in anisotropic Sn and Pb.

CERTAIN singularities have been observed[1] in the current-voltage characteristics of Sn—Sn tunnel junctions; these singularities result in an additional current through the junction under a bias $eV \approx 2\Delta/n$, where n is an integer. Similar singularities have been observed also in the current-voltage characteristics of Pb—Pb[2, 3] and other junctions.[4] The present communication reports the preliminary results of an experimental investigation of the characteristics of Sn—Pb tunnel junctions. The method used to prepare these junctions and the configuration of the samples have been described in [1, 5]. The width of the films was $\lesssim 1$ mm and the thickness $\gtrsim 2000$ Å. The investigation was mainly concerned with low-resistance junctions ($\rho \ll 10^{-2}\ \Omega \cdot \text{mm}^2$), which clearly exhibited the Josephson effect. The constant Josephson current in fields of the order of 10 Oe decreased by a factor of several tens compared with the value in a zero magnetic field; consequently, the Sn oxide film was judged to be sufficiently uniform.

The current-voltage characteristic of Josephson Sn—Pb tunnel junctions in magnetic fields of the order of several tens of oersteds, applied parallel to the junction plane, was similar to the current-voltage characteristic of the one-particle tunnel current.[6] A region with a falling characteristic was observed between the voltages corresponding to $eV = \Delta_{\text{Pb}} - \Delta_{\text{Sn}} = 0.77$ meV and $V = \approx 1.2$ mV (Fig. 1). Therefore, we investigated the regions where $V < 0.77$ mV and $1.2 \text{ mV} < V < 1.97$ mV. The first region included singularities lying near Δ_{Sn} while the second region had singularities close to Δ_{Pb}. In addition to pronounced current surges at $eV = \Delta_{\text{Pb}}$, $eV = \Delta_{\text{Sn}}$, and at other values of V smaller than Δ_{Sn}/e, the constant component of the current depended strongly on the magnetic field.

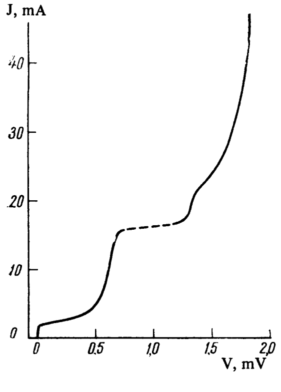

FIG. 1. Current-voltage characteristic of a Sn–Pb junction at T = 1.5°K, in H = 40 Oe. The sudden jump of the voltage is due to an instability of the working point in the falling part of the characteristic.

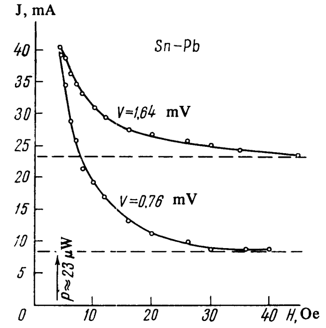

FIG. 2. Dependence of the constant component of the tunnel current on the magnetic field for two values of the voltage across the junction. T = 1.5°K. The electromagnetic power generated by the Josephson current in the junction was 23 μW for V = 0.76 mV and H = 4 Oe.

Figure 2 shows the dependence of the constant component of the current on the magnetic field intensity for two arbitrarily selected voltages across a junction. In sufficiently strong fields, the current approached asymptotically its value for the one-particle tunnel case. The additional current decreased proportionally to H^{-2}. This showed conclusively that the additional current was the constant component of the oscillatory Josephson current. The observed constant component of the current was proportional, on the one hand, to the amplitude of the Josephson current, and on the other, to the absorption in the system. However, the absorption was proportional to the one-particle current. Therefore, the characteristic of the constant component of the Josephson current reproduced the one-particle characteristic.

Another reason why the constant component of the current increased was the absorption of electromagnetic waves in the superconductors used for the tunnel junction. For $eV \geq \Delta$, these losses were due to the dissociation of Cooper pairs into two quasi-particles: they made an additional contribution to the absorption and caused an additional one-particle current to flow. The value of the latter depended on the ratio of the probability of the tunneling of an excited electron through a barrier and the probability of recombination with another electron to form a Cooper pair in the same superconductor, accompanied by the emission of a phonon.

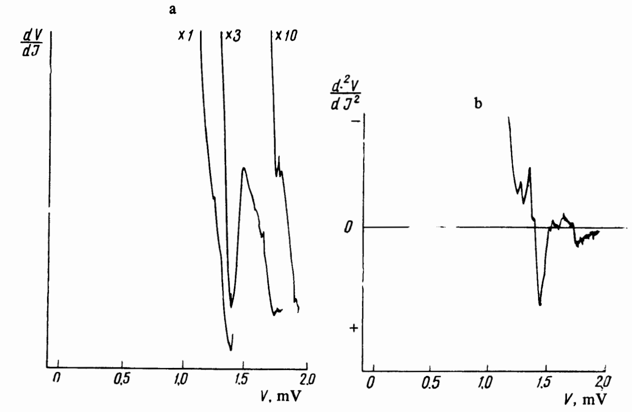

FIG. 3. a) dV/dJ characteristic near Δ_{Pb}. The factor shown alongside the overlapping parts of the curve represents different values of the modulating signal level; b) d^2V/dJ^2 characteristic near Δ_{Pb}. T = 1.43°K, H = 20 Oe.

Thus, the current-voltage characteristic could yield information on the lifetime of excitations in superconductors.

The experimentally observed complex structure of the dV/dJ characteristics in the energy range ≈ 0.1–0.2 meV near Δ_{Sn} and Δ_{Pb} was evidently due to threshold effects in the absorption of the electromagnetic radiation generated by the Josephson current.

We shall now consider the structure of the dV/dJ characteristic near Δ_{Pb}. Figure 3 shows the dV/dJ and d^2V/dJ^2 characteristics near Δ_{Pb} for one of the junctions. Table I lists the positions of the minima in the dV/dJ characteristics along the V axis for 12 different tunnel junctions. It is worth noting the presence of a minimum at $V = \overline{\Delta}_{Pb}/e = 1.38$ mV observed for almost all the junctions. The values V = 1.22 mV and V = 1.29 mV were found from the singularities in the d^2V/dJ^2 characteristics; in the dV/dJ characteristics these singularities were inflection points. Table I lists also the positions of the minima in the dV/dJ characteristics of Pb–Pb junctions, taken from a paper by Rochlin and Douglass,[3] for that range of voltages in which our results and theirs overlapped. The number of singularities in the characteristics of different junctions varied considerably, but the agreement between the positions of the singularities (for those junctions in which they were observed) was not too bad.

In addition to the singularities listed by Rochlin and Douglass,[3] we observed a series of minima at V = 1.6, 1.7, 1.75, and 1.85 mV, which lay about 0.3 mV higher than the series for Δ_{Pb} (cf. Fig. 3). Evidently, the fine structure of the dV/dJ characteristics near Δ_{Pb} was associated with the threshold properties of the absorption of electromagnetic energy in anisotropic Pb, because the thickness of Pb films was considerably greater than the coherence length ξ_0. The origin of the series of singularities at V = 1.6–1.85 mV was not clear.

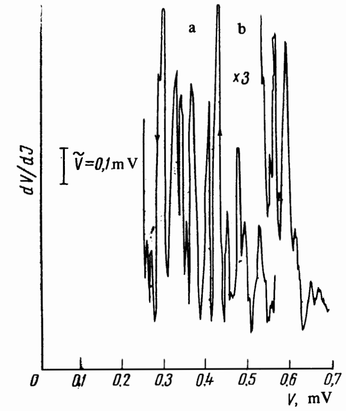

FIG. 4. dV/dJ characteristic near Δ_{Sn}. The factor alongside one of the curves indicates a different modulating signal level. T = 1.46°K, H = 42 Oe.

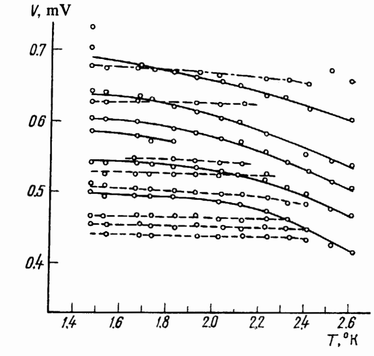

FIG. 5. Temperature dependence of the positions of minima in the dV/dJ characteristics on the V axis for junction No. 9.

We also observed a complex system of minima in the dV/dJ characteristics near Δ_{Sn}. Figure 4 shows the dV/dJ characteristic for one of the junctions, investigated in this range of voltages.

Table II lists the positions of the minima in the region of Δ_{Sn} for various junctions. The majority of the junctions had a minimum at $V = \overline{\Delta}_{Sn}/e = 0.595$ mV. The minima at other values of V were observed only in some samples. The difficulty was to distinguish the minima associated with Δ_{Sn} from the minima belonging to the $(\Delta_{Pb} + \Delta_{Sn})/(2n + 1)$ and Δ_{Pb}/n series (cf. [7]).

Information on whether a given minimum belonged to a particular series could be obtained by investigating the temperature dependence of the positions of the minima. Figure 5 shows such dependences for one of the junctions; they were obtained by comparing the dV/dJ characteristics at intervals of T ≈ 0.1°K. We can see there a group of curves which are similar to the temperature dependence of the gap Δ_{Sn}, which follows from the BCS theory, while other curves are practically independent of temperature. The singularity corresponding to $(\Delta_{Pb} + \Delta_{Sn})/3$ depended weakly on temperature.

Table I. Experimental values of positions of group Δ_{Pb} singularities in dV/dJ characteristics of Sn–Pb Josephson tunnel junctions (T = 1.5°K; error in the determination of V, ≈ ± 1°)

Number of junction	Positions of singularities on V axis (in mV)				
1	1.23	1.29	1.34	1.375	1.48
2	1.22–1.28		1.35	1.385	
3				1.37	
4	1.22	1.29		1.38	
5			1.34		
6	1.22	1.28		1.38	
7	1.2	1.29		1.38	
8		1.29		1.38	
9	1.23	1.3		1.38	
10				1.38	1.39
11			1.34–1,38		
12				1.37	
Results of Rochlin and Douglass [3] *)	1.22 (±0.01)	1.31 (±0.01)	1.35 (±0.01)	1.38 (±0.05)	1.485 (±0.01)

*) The values V = 1.2 mV and V = 1.26 and 1.46 mV are omitted.

Table II. Experimental values of positions of group Δ_{Sn} singularities in dV/dJ characteristics of Sn−Pb Josephson tunnel junctions (T = 1.5°K; error in the determination of V, ≈ ± 1°)

Number of junction	Positions of singularities on V axis (in mV)								
1	0,696	0,65	0,63	0,59—0,57		0,54	0,525	0,51	0,463
2		0,65		0,585			0,53—0,515		0,462
3				0,592					
4				0,595					
5			0,635			0,54		0,51	
6				0,595		0,54		0,51	
7		0,645		0,595			0,53		
8		0,656	0,633	0,595—0,57		0,536		0,516	
9	0,693	0,645		0,603		0,54		0,51	
13				0,596	0,573		0,531	0,515	
In units of kT_c	4,05	3,8	3,7	3,48	3,35	3,15	3,11	3,0	2,72
Results of Zavaritskii, [8] kT_c *)		3,8—3,7			3,4		3,1—3,05		2,7

*) The value $kT_c = 3.55$ is omitted. The value $kT_c = 4.3$, reported in [8], was evidently masked in our experiments by a one-particle current surge near $\Delta_{Pb} - \Delta_{Sn}$.

The amplitude of this singularity was considerably less than the amplitudes of the singularities of the Δ_{Sn} group.

The structure of the characteristics below 0.43 mV was not considered because of its complexity. The results obtained should be treated with caution because of the presence of a large number of minima and a nonuniform variation of their depths with temperature in constant H. It should be mentioned that the positions of the minima on the V axis were independent of the magnetic field, while their intensities depended considerably on the field. In magnetic fields of ≈ 100 Oe, the fine structure of the minima disappeared and only one minimum at $V = \overline{\Delta}_{Sn}/e$ remained. No dependence of the positions of the minima on the thickness and width of the films was observed.

As already mentioned, the fine structure of the minima in the dV/dJ characteristics near Δ_{Sn} and Δ_{Pb} could be explained by threshold effects in the absorption of the Josephson electromagnetic radiation in the superconductors making up the tunnel junction (tin, lead). Since the average mean free path l in the investigated films was comparable with or greater than the coherence length, the surface $\Delta(\mathbf{k})$ was anisotropic. In this case, several absorption thresholds were possible, due to the multiply-connected nature of the Fermi surface and the different values of the gaps in different regions of the surface, or to sudden changes in the anisotropy of Δ of superconductors, first discovered by Zavaritskiĭ.[8] Depending on the relationship between l and ξ_0, we should observe more or less clear characteristics of the anisotropy of Δ. This would explain also why the number of observed minima was different for different samples. Moreover, the presence of regions with low values of l (for example the edges of a film) would ensure that the average value of the gap were observed.

Finally, we note that a Josephson tunnel junction is a form of spectroscope in which the functions of the radiation source and of the investigated sample are combined. The product of the constant components of the additional current and of the voltage gives the power emitted in the form of the radiation which is absorbed in the system. Such power may reach tens of microwatts (cf. Fig. 2) and the emission frequency may have any value up to $(\Delta_1 + \Delta_2)/\hbar$. This opens up new avenues in the spectroscopy of superconductors in the far infrared range.

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