Superconducting energy gap of niobium nitride

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The superconducting energy gap Δ was measured by the electron tunneling method in niobium nitride having a columnar structure and a superconducting transition temperature $T_c = 16.15$ K. The values obtained, $\Delta_0 = 2.46$ meV and $2\Delta_0/kT_c = 3.53$, are practically in agreement with the BCS theory. The temperature dependence of $\Delta(T)$ was measured in the temperature interval 2–6.5 K. It was found that the decrease of the gap with increasing temperature is faster than in accord with the BCS theory, but the vanishing of gap takes place at $T = T_c$. The results are compared with earlier data obtained using worse samples. It turned out that with deteriorating sample quality the value of T_c decreases more rapidly than Δ_0. The ratio $2\Delta_0/kT_c$ for poor samples can therefore reach 6.

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Niobium nitride is a superconductor with high critical superconducting parameters. It is of interest to study its electronic characteristics, particularly the value of the superconducting energy gap Δ. Methods have been recently developed permitting the preparation of niobium nitride with a superconducting transition temperature T_c of the order of 16 K and with high critical fields and current densities.[1-3] Up to now, however, the measurements of Δ were made only on samples with substantially lower values of T_c.[4,5]

In the present study we measured, by the electron tunneling method, the superconducting energy gap Δ of niobium nitride films having a superconducting transition temperature $T_c = 16.15$ K and a transition width $\Delta T_c = 0.3$ K. The films were prepared by reactive cathode sputtering. The temperature of the superconducting transition was measured by a resistive method with the aid of an Allen-Bradley carbon resistor calibrated against a TSG-1 germanium temperature and liquid-hydrogen temperature. The accuracy with which T_c was measured was 0.05 K.

Figure 1 shows the dependence of the resistance on the temperature T for one of the employed films. T_c was taken to be the temperature corresponding to the midpoint of the resistance jump, and ΔT_c was defined as the difference between the temperatures of the start and end of the superconducting transition.

The NbN-*I*-Pb tunnel junction was made up of freshly prepared NbN films 2000 Å thick, having a columnar structure (grain-growth direction perpendicular to the substrate surface). The substrates were polished quartz plates measuring 1 × 6 × 12 mm. The films were oxidized in air for 2.5–3 hours, after which the lead films were sputtered through a special mask. The area of the tunnel junction was about 0.1 mm² and the resistance 0.02–0.05 Ω. The overall view of the tunnel junction is shown in Fig. 2. Four tunnel junctions were prepared, using two NbN films (Nos. 22 and 23) with two junctions on each.

The current-voltage characteristics (CVC) and the derivatives dI/dV were obtained with electric circuits similar to those developed in Refs. 6 and 7, using an electronic slide-wire resistor.[8] An x–y recorder plotted the results.

Figure 3 shows the CVC, as a function of the temperature T, of one of the junctions. It is seen that when T is lower than the superconducting transition temperature of lead, an abrupt jump of the current I takes place and equal the sum of the superconducting gaps $\Delta_{\mathrm{NbN}} + \Delta_{\mathrm{Pb}}$. When T is lowered the jump shifts towards higher voltages. At $T > 7.2$ K the gap singularity of NbN remains, and vanishes only at $T \geqslant T_c$.[1)]

Singularities due to the gap difference $\Delta_{\mathrm{NbN}} - \Delta_{\mathrm{Pb}}$ are seen at temperatures 4.2, 5.6, 6.0, and 6.5 K. With decreasing T these singularities, as expected, shift towards lower V and decrease in magnitude. At $T = 2$ K is the singularity due to the gap difference is not detectable.

In addition to the indicated singularities, the curves of one of the junctions (sample 23, junction 2) revealed one more small singularity, that shifted rapidly towards lower values of V with increasing T. Thus, when T changed from 4.2 to 8 K, the position of the singularity shifted from 5.7 to 0.9 mV. Figure 3 shows the CVC of

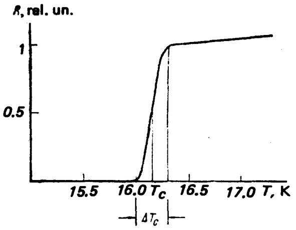

FIG. 1. Dependence of the resistance R on the temperature T.

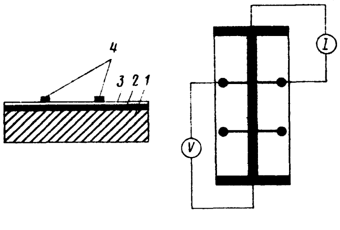

FIG. 2. NbN—I—Pb tunnel junction: 1) quartz substrate, 2) niobium nitride (NbN) film, 3) insulator (oxide of niobium nitride), 4) lead (Pb) film.

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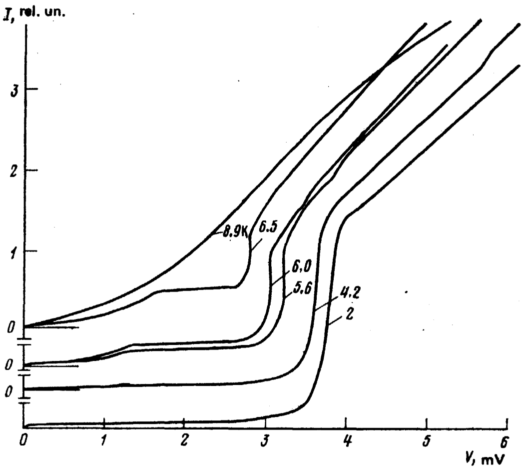

FIG. 3. Temperature dependence of the CVC of one of the tunnel junctions.

this junction. Additional investigations are needed to ascertain the origin of this singularity.

The gap singularities were used to determine the superconducting gap of niobium nitride (Δ_{NbN}) and its dependence on the temperature. The results are given in Table I. The first column gives the value of T, the second Δ_{NbN}, and the third and fourth Δ_{Pb} in accordance with our measurements and with the published data. At $T=2$, as indicated above, the singularity connected with the gap difference is hardly discernible. We used therefore the values of Δ_{Pb} taken from the literature.[9,10]

In the region $2<T<7.2$ K, the values of Δ_{NbN} and Δ_{Pb} were obtained from the sum $\Delta_{\text{NbN}}+\Delta_{\text{Pb}}$ and the difference $\Delta_{\text{NbN}}-\Delta_{\text{Pb}}$ of the gaps.

The CVC and the derivatives dI/dV were recorded at $T=2$ and 4.2 for all four junctions, at $T=5.6$ and 6.5 K for three junctions, and at $T=6.0$ K for one junction.[2] At $T=2$ K the results obtained for all the junctions differed by less than 0.01. To estimate the error in this case we used the accuracy of the instrument. In the remaining cases, when several junctions were used, the error was estimated from the scatter of the results for the different junctions.

It is seen from Table I that niobium nitride has a gap $\Delta\ (T=2)=2.46$ meV. Inasmuch as for superconductors with high $T_c=16$ K the difference between Δ_0 and $\Delta\ (T=2)$ is much less than the indicated measurement error, it can be assumed that $\Delta_0=2.46\pm0.02$ meV. Here $\Delta_0=\Delta(T=0)$. The $\Delta(T)$ dependence is clearly seen. With increasing temperature, the gap decreases more rapidly than would follow from the BCS theory.

TABLE I. Temperature dependence of the superconducting energy gap Δ of niobium nitride.

T, K	Δ_{NbN}, meV	Δ_{Pb}, meV		$\Delta(T)/\Delta_0$	
		Present work	data of Refs. 9 and 10	Present work	from BCS theory
2.0	2.46±0.02	–	1.34 [9]	1	1
4.2	2.42±0.03	1.25±0.03	1.25 [10]	0.983±0.012	0.999
5.6	2.28±0.05	1.00±0.03	–	0.926±0.021	0.993
6.0	2.19	0.89	–	0.890	0.990
6.5	2.19±0.05	0.62±0.03	–	0.890±0.020	0.983

TABLE II. Values of Δ_0 and of the ratio $2\Delta_0/kT_c$ for niobium nitride, as obtained in various studies.

T_c, K	Δ_0, meV	$2\Delta_0/kT_c$	Reference
16.15	2.46±0.02	3.53±0.03	Present work
12.8	2.25±0.03	4.08±0.03	[4]
11.9	2.08±0.03	4.05±0.05	[4]
7.5	2.0	~6	[5]

The comparison of our results for Δ_0 of niobium nitride with the results of others is shown in Table II. The first column lists the T_c of the employed samples, the second Δ_0, and the third the ratio $2\Delta_0/kT_c$. It is seen from Table II that the films investigated by us had the largest values of Δ_0. The ratio $2\Delta_0/kT_c=3.53$ and agrees in practice with the BCS theory. The samples used in Refs. 4 and 5 had lower values of Δ_0 and their ratios $2\Delta_0/kT_c$ exceeded the theoretical ones substantially. It is seen also from Table II that the decrease of T_c is faster than the decrease of Δ_0. The reason for this is not yet clear.

The large ratio $2\Delta_0/kT_c$ obtained in Ref. 4 was regarded by the authors of that paper as proof that niobium nitride is a tight-binding superconductor. Our present results show that there are no grounds as yet for this assumption. Whether the binding is tight or not can be concluded only after the electron-phonon interaction constant is measured.

In conclusion, we thank S. I. Vedneev and K. V. Mitsen for valuable advice on the performance of the experiment and N. V. Anshukova for measuring the T_c of the films.

[1] So as not to clutter up the figure, the CVC corresponding to $T>8.9$ K are not shown.

[2] The results for $T=6.0$ pertain to junction 2 of sample No. 23.

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