Superconducting energy gap of niobium nitride

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(Submitted 10 December 1980)


The superconducting energy gap $\Delta$ 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, $\Delta_x = 2.46$ meV and $\Delta_y/T_c = 3.53$, 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 expected in accord with the BCS theory, but the vanishing of the 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 $\Delta_x$. The ratio $\Delta_x/T_c$, for poor samples can therefore reach 6.

PACS numbers: 74.60. -w

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 $\Delta$. 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 $\Delta$ were made only on samples with substantially lower values of $T_c$.1-4

In the present study we measured, by the electron tunneling method, the superconducting energy gap $\Delta$ of niobium nitride films having a superconducting transition temperature $T_c = 16.15$ K and with high critical fields and current densities.1-3 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 mains, and vanishes only at $T = T_c$. 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.3 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 the sum of the superconducting gaps $\Delta_{NbN} + \Delta_{Pb}$ is constant. 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 $T > 11.1$ K. Singularities due to the gap difference $\Delta_{NbN} - \Delta_{Pb}$ 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 $T > 6.5$ K 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 3) revealed a new 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 0.8 mV. Figure 3 shows the CVC of...
Table I. The first column gives the value of $T$, the second $\alpha_{\text{max}}$, and the third and fourth $\Delta_{\text{max}}$ 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 $\Delta_{\text{max}}$ taken from the literature.\(^n\)

In the region $2>T>1.3$ K, the values of $\Delta_{\text{max}}$ and $\Delta_{\text{max}}$ were obtained from the sum $\Delta_{\text{max}}^2=\Delta_{\text{max}}^2$ and the difference $\Delta_{\text{max}}^2=\Delta_{\text{max}}^2$ 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.\(^t\)

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

The comparison of our results for $\Delta_0$ of niobium nitride with the results of others is shown in Table II. The first column lists the $T_0$ of the employed samples, the second $\Delta_0$, and the third the ratio $2\Delta_0/kT_0$. It is seen from Table II that the films investigated by us had the largest values of $\Delta_0$. The ratio $2\Delta_0/kT_0$ exceeded the theoretical ones substantially. It is seen also from Table II that the decrease of $T_0$ is faster than the decrease of $\Delta_0$. The reason for this is not yet clear.

The large ratio $2\Delta_0/kT_0$ 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. Vedeneev and K. V. Milkan for valuable advice on the performance of the experiment and N. V. Anshukova for measuring the $T_0$ of the films.

\(^n\)See as not to clutter up the figure, the CVC corresponding to $T>5.9$ K are not shown.

\(^t\)The results for $T=6.0$ pertain to junction 2 of sample No. 23.

Table II. Values of $\Delta_0$ and of the ratio $2\Delta_0/kT_0$ for niobium nitride, as obtained in various studies.

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
$T$, K & $\Delta_0$, meV & $2\Delta_0/kT_0$ & Reference \\
\hline
4.2 & 2.46$\pm$0.02 & 3.53$\pm$0.03 & 4 \footnote{Ref. 4} \\
4.5 & 2.28$\pm$0.02 & 3.53$\pm$0.03 & 5 \footnote{Ref. 5} \\
5.6 & 2.15$\pm$0.02 & 3.53$\pm$0.03 & 5 \\
6.5 & 2.06$\pm$0.02 & 3.53$\pm$0.03 & 5 \\
\hline
\end{tabular}
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Translated by J. G. Adzhikov