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Tunneling $\alpha^2 F(\omega)$ from sputtered thin-film NbN

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High-quality NbN/oxide/Pb tunnel junctions on sputtered NbN have been fabricated. The $2\Delta/k_B T_c$ value is 4.25, showing this to be a strong-coupled superconductor. These junctions have satisfactory characteristics for taking derivative measurements. The data were reduced with the use of the modified McMillan-Rowell proximity-gap inversion analysis developed by Arnold and Wolf to generate $\alpha^2 F(\omega)$ and related microscopic parameters for the first time for a $B1$ compound. The spectra show two main peaks of comparable strength at about 13 and 47 meV (with a shoulder at about 40 meV). The electron-phonon coupling constant $\lambda = 1.46 \pm 0.10$, in reasonable agreement with the strong coupling seen in $2\Delta/k_B T_c$.

Although the $A15$ componds have held the record for high T_c for the last three decades, the $B1$ compounds, such as NbN and NbN_xC_{1-x}, have been of significant interest because of the combination of relatively high T_c (15–18 K) and superior mechanical properties. Thus it has held promise both as a system for potential applications and as a high-T_c system to increase the fundamental understanding of superconductivity. It is the latter issue that this paper addresses.

Tunneling is the most direct probe of superconductivity, but has been a difficult measurement to make. This is for two basic reasons. First, tunneling only probes about a coherence length into the material (< 50 Å in many of the high-T_c compounds). Thus the sample measured must be well made up to the surface. Second, there must be a good-quality insulating barrier to tunnel through. Unfortunately, many of the high-T_c compounds do not produce native oxide barriers of sufficient quality for good tunneling measurements. It has been through the development of artificial barriers that progress has been made in the $A15$ compounds, but for the $B1$ compounds and, in particular, NbN, while current-voltage (I-V) characteristics have been obtained (for example, van Dover and Bacon),[1] there have been no published reports of the electron-phonon spectral function $\alpha^2 F(\omega)$ being extracted from the tunneling data. In this work we used chemical annodization to produce the tunneling barrier, which allowed us to obtain $\alpha^2 F(\omega)$ for niobium nitride.

I. EXPERIMENTAL DETAILS

Early NbN work was done using bulk techniques by Ascherman, Frederick, Justi, and Kramer[2] and Gavaler, Janocho, and Jones,[3] and applied thin-film techniques, in particular sputtering, to prepare better-quality samples of NbN. Our samples were made by UHV rf sputtering[4] using a niobium target and an argon(75 mtorr)–nitrogen(10 mtorr) gas mixture. The pressure before addition of the Ar-N_2 mixture was 5×10^{-9} torr. The substrate table was heated to about 800 °C and about 2500 Å of material was deposited. Results of similarly prepared samples[5] indicate that in these nominally NbN samples there is typically a 2% level of carbon inclusion even in the absence of added carbon-containing gases. This is probably due to outgassing of the carbon heating strips. To the resolution of the Auger and x-ray measurements, the NbN_xC_{1-x} is at the stoichiometric concentration. A more complete description of the film preparation and properties can be found in Refs. 4–7.

The tunneling barrier was formed using chemical annodization,[8] where the sample is placed in a saturated solution of boric acid and water. An electric current is then passed through the solution to the sample causing the oxide ions in the solution to form an insulating barrier on the NbN. The resistance of the barrier can be chosen by monitoring the voltage across the sample and solution and stopping the annodization when a preset voltage is reached. One added advantage of the process is that any pinholes or weak spots in the oxide barrier draw increased annodizing current and are thus plugged up. The junction areas are then defined by photoresist and a Pb counterelectrode is then deposited.

The current-voltage characteristics of the NbN/oxide/Pb tunnel junction are shown in Fig. 1. Excess conductance below the sum gap was 5% of the above-gap conductance.

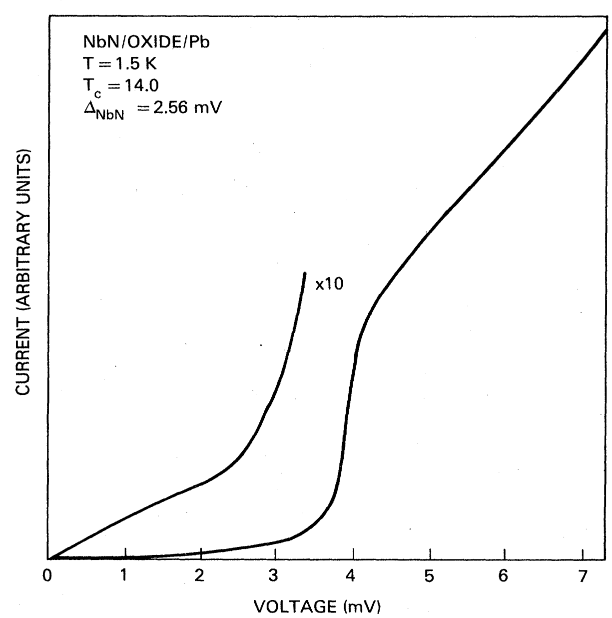

FIG. 1. The current-voltage characteristics for NbN/oxide/Pb. There was no evidence of a "knee-structure" characteristic of a proximity layer.

There was no evidence of a proximity knee structure in either the I-V curve or the derivative measurement through the gap. The differential conductance for this and another sample was measured in the superconducting state with the Pb electrode driven normal by an applied magnetic field (0.1 T), and then with the temperature elevated above T_c of the NbN so that both electrodes were normal. The reduced tunneling density of states was then input into the modified McMillan-Rowell (MMR) gap-inversion-analysis program (originally developed by McMillan and Rowell[9] and modified by Arnold,[10] Wolf, Zasadzinski, Osmun, and Arnold,[11] and Wolf *et al.*[12]).

II. EXPERIMENTAL RESULTS

The ratio $2\Delta/k_BT_c$, a measure of the coupling strength, for both samples was about 4.25 (well above the BCS limit of 3.51 for weak-coupled superconductors) indicating this is a strong-coupled superconductor. The gap (2.56 meV) was determined as the minimum in the derivative (dV/dI) through the gap region (then subtracting off the Pb gap). The T_c (14.0 K) was determined by gap opening (measuring dV/dI at zero bias as a function of temperature to see where the gap opens up). This agreed well with the separately measured resistive T_c.

Figure 2 shows the deviation from the BCS density of states, where the experimentally measured values are compared with those calculated by the MMR program from the generated $\alpha^2F(\omega)$. The agreement is by no means perfect, but it is typical of the agreement seen in the analysis of other high-T_c compounds. It is sufficiently good to proceed with the analysis of $\alpha^2F(\omega)$.

Figure 3 shows the $\alpha^2F(\omega)$ trace for one of the NbN samples. The other sample was also measured to obtain $\alpha^2F(\omega)$ and did produce the same general features, but the program did not completely converge to the experimental results and was not used in the quantitative analysis. In both samples there was no evidence of inelastic scattering in the tunneling barrier.

The spectra shows two main peaks of comparable size, one at 13 and the other at 47 meV (with a shoulder at about 40 meV). These features were common to both spectra and observable both from the first and second derivative data. A third sample (one with 10% carbon present) was also measured. It has a slight proximity knee in the I-V curve but nonetheless the $\alpha^2F(\omega)$ was obtained and it too showed the two main peaks in about the same positions. This sample also was not included in the quantitative analysis (due to the questions raised by the proximity knee). The high-energy peak is presumably due to the light nitrogen atoms in the compound contributing to a high-frequency mode. It may be the presence of this strong peak which helps give NbN its relatively high T_c.

The electron-phonon coupling constant $\lambda = 1.46 \pm 0.10$, which is again characteristic of a strong-coupled superconductor. Also interesting (but probably unreliable) is the large value of $\mu^* = 0.33$. This leads to the relatively poor agreement between the measured T_c (14.0 K) and the calculated McMillan (9.3 K), an Allan and Dynes (7.3 K) T_c's. Unfortunately, μ^* is very sensitive to the choice of proximity parameters in the Arnold-Wolf program, and is thus diffi-

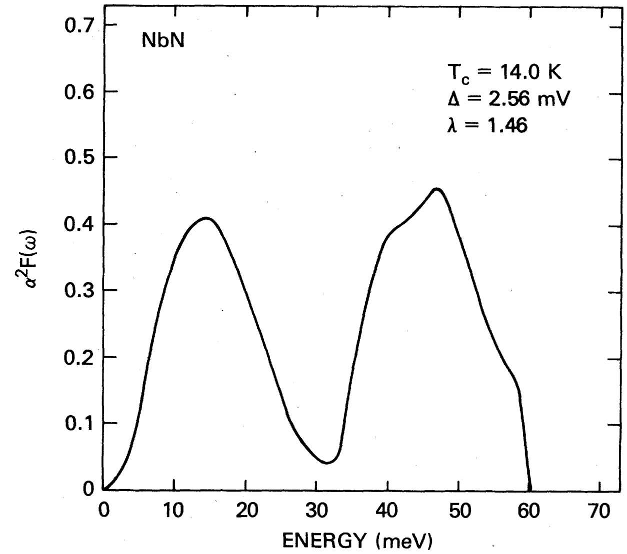

FIG. 3. Electron-phonon spectral function of $\alpha^2F(\omega)$ for NbN with $T_c = 14$ K.

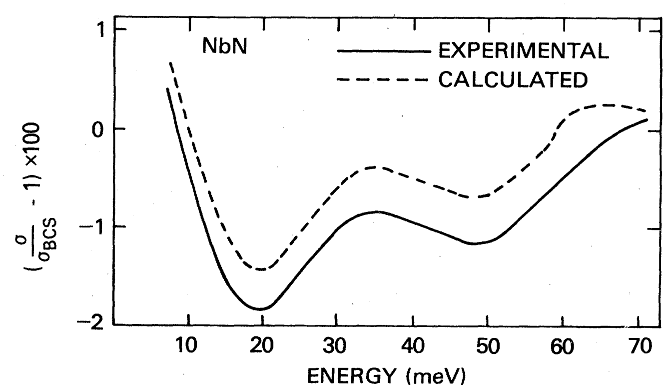

FIG. 2. Experimental vs calculated deviation from the BCS density of states for the NbN sample.

TABLE I. Microscopic parameters obtained from the $\alpha^2F(\omega)$ analysis.

Δ_{NbN}	2.56 mV
T_c (gap opening)	14.0 K
$2\Delta/k_BT_c$	4.25
L (excess conductance below sum gap in % of above-gap conductance)	5.0
Proximity parameters	
R	0.0090
d/L	0.095
λ	1.46 ±0.10
μ^*	0.33
$\langle\omega\rangle$	20.8
$\langle\omega^2\rangle$	673
ω_{log}	15.5
T_c (McMillan)	9.3 K
T_c (Allan and Dynes)	7.3 K

cult to determine accurately. Nonetheless, it is likely to be substantially greater than 0.11, which is more typical of other high-T_c superconductors. Due to the high-energy phonon peak, the different frequency averages are also higher than is typical for other high-T_c compounds. Table I gives a list of the microscopic parameters obtained from the $\alpha^2F(\omega)$ analysis.

III. CONCLUSIONS

NbN is shown here to be a strong-coupled superconductor as seen both by its large $2\Delta/k_BT_c$ (4.25) and $\lambda(1.46 \pm 0.10)$ values. The electron-phonon spectral function $\alpha^2F(\omega)$ shows two strong peaks at 13 and 47 meV. The high-energy peak contributes to high values of $\langle\omega\rangle$, $\langle\omega^2\rangle$, and $\omega_{\log}$. The additional strength from this peak may be partially responsible for the relatively high T_c of NbN. Two other samples (one NbN, the other $NbN_{0.9}C_{0.1}$) were also reduced to obtain $\alpha^2F(\omega)$, but in each case questions in the analysis restricted their usefulness to confirming qualitative features seen in the primary NbN sample.

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