Far-infrared Optical Conductivity of Nb Thin Films

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Abstract

Optical reflectance and transmittance spectra of Nb thin films deposited on Si substrates have been measured in the far-infrared region at temperatures above and below T_c. The results have been analyzed by using the R-T method (H. Shibata *et al.*, Jpn. J. Appl. Phys., **40** (2001) 3163.) to determine the temperature dependence of the optical conductivity spectra $\sigma_1(\omega)$. The results suggest that the size of the superconducting energy gap at 4.5 K is $\sim 10\ \mathrm{cm}^{-1}$.

Key words: Niobiumt; optical properties; far-infrared spectra

1. Introduction

Thin films of superconducting Nb are of great current interest for highly reliable Josephson device applications. Therefore, it is highly desirable to know precisely the fundamental electrical properties such as the optical conductivity spectra $\sigma_1(\omega)$ in both normal and superconducting states, particularly in the wave number ω region of $\sim 2\Delta(0)$, where $\Delta(0)$ is the size of the superconducting energy gap $\Delta(T)$ at temperature $T =$ 0 K. Since the values of $2\Delta(0)$ of high quality Nb is reported to be $\sim 24\ \mathrm{cm}^{-1}$, study of the optical properties in the far-infrared (FIR) region is necessary.

2. Experimental

Recently, a new method to characterize FIR optical properties of solids was developed, and was named as the R-T method [1]. In this paper, we have applied the R-T method for the study of the T dependence of $\sigma_1(\omega)$ of Nb thin films in the ω region of FIR.

Nb thin films were deposited by rf-magnetron sputtering onto Si substrates. T_c of the films was estimated to be ~ 7 K, which is somewhat lower than $T_c \sim 9.2$ K reported for high quality Nb. The thickness of the Si substrates and Nb layers was ~ 1.0 mm and ~ 30 nm, respectively. FIR optical reflectance spectra $R(\omega)$ and transmittance spectra $T(\omega)$ were measured using a BOMEM DA8 Fourier-transform interferometer with a Hg arc lamp source and a Si:B bolometer. The spectral resolution was $0.5\ \mathrm{cm}^{-1}$. The incident FIR radiation was nominally unpolarized, and was introduced normal to the film surface for the measurement.

3. Results and Discussion

$R(\omega)$ and $T(\omega)$ obtained at $T = 4.5$ and 10 K are shown in Figs. 1 and 2, where the solid and dotted curves were obtained at $T = 4.5$ K and 10 K, respectively. Since the Si substrate is highly transparent in this ω region, and since the Nb film is thin enough to transmit FIR radiation, the interference fringes due to multiple internal reflections within the Si substrate are clearly visible in both figures. $R(\omega)$ at $T = 10$ K exhibits no significant structure except for the interfer-

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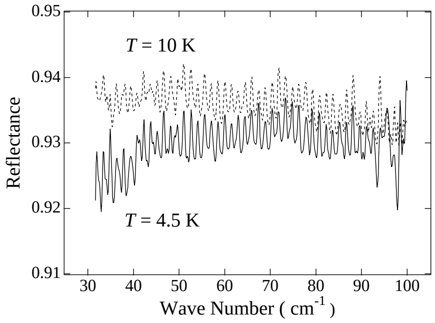

Fig. 1. Reflectance spectra observed at T = 4.5 and 10 K of Nb thin films deposited on Si substrates.

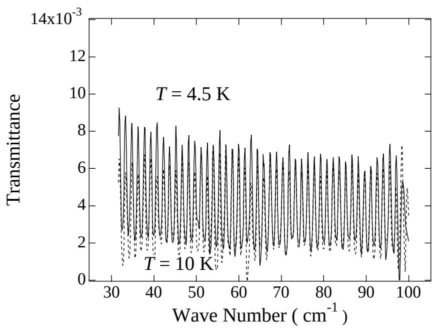

Fig. 2. Transmittance spectra observed at T = 4.5 and 10 K of Nb thin films deposited on Si substrates.

ence fringes. On the other hand, $R(\omega)$ at $T = 4.5$ K decreases with decreasing ω at ω below ~ 70 cm^{-1}. The same temperature dependence of $R(\omega)$ below T_c has been observed in conventional BCS-type superconductors such as $NbN_{1-x}C_x$, where $R(\omega)$ was suppressed at around $\omega = 2\Delta(0) \sim 6\Delta(0)$ of $NbN_{1-x}C_x$ [2]. The emergence of such reflectance edge was attributed to the evolution of superconducting energy gap [2]. Therefore, the results in Fig. 1 suggest that the sample is in the superconducting state at $T = 4.5$ K. $T(\omega)$ at $T = 10$ K exhibits no significant structure except for the interference fringes. However, $T(\omega)$ at $T = 4.5$ K increases with decreasing ω at low ω region, which is related to the evolution of the reflectance edge in $R(\omega)$; $T(\omega)$ increases near the ω region in which $R(\omega)$ decreases.

The $\sigma_1(\omega)$ spectrum for Nb were calculated by the R-T method using the experimental results shown in Figs. 1 and 2, and converted to the relative conductivity ratio $\sigma_{1s}(\omega)/\sigma_{1n}(\omega)$ where $\sigma_{1s}(\omega)$ and $\sigma_{1n}(\omega)$ are $\sigma_1(\omega)$ at T = 4.5 K and 10 K respectively. The results are shown in Fig. 3. The value of $\sigma_{1s}(\omega)/\sigma_{1n}(\omega)$ in Fig. 3 was found to be decreased with decreasing ω at low ω region. This suppression of the spectral weight of $\sigma_1(\omega)$ below T_c at low ω region is a consequence of the evolution of the superconducting energy gap, and suggests that the sample is in the superconducting state at $T = 4.5$ K. The ω dependence of $\sigma_{1s}(\omega)/\sigma_{1n}(\omega)$ was theoretically

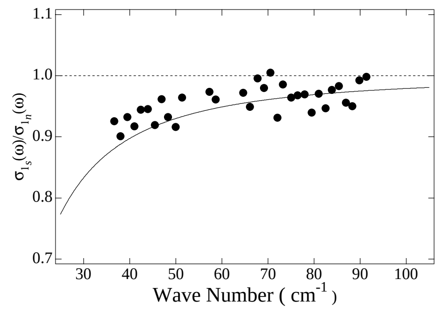

Fig. 3. The relative conductivity ratio $\sigma_{1s}(\omega)/\sigma_{1n}(\omega)$ observed in Nb thin films deposited on Si substrates (solid circles). The solid curve shows the results of the calculations by the M-B theory.

given by the Mattis-Bardeen (M-B) theory for dirty-limit BCS-type superconductors, where $\sigma_{1s}(\omega)$is the $\sigma_1(\omega)$ at $T = 0$ K [3]. Although the $\sigma_{1s}(\omega)$ shown in Fig. 3 were those obtained at $T = 4.5$ K, we tentatively apply the M-B theory to analyze them. The results of the calculation using the M-B theory are shown as solid curves in Figs. 3. In order to obtain the excellent agreement between the M-B theory and experimental results, we assumed the value of $2\Delta(0)$ to be 10 cm^{-1}, which is significantly smaller than the value of $2\Delta(0)$ ~ 24 cm^{-1} reported for high quality Nb. We suppose that it is mainly because the quality of the Nb studied in this work was not sufficiently high, which results in relatively low value of T_c and $2\Delta(T)$ at $T = 4.5$ K.

4. Conclusion

We have measured the $R(\omega)$ and $T(\omega)$ of Nb thin films deposited on Si substrates in the FIR region at $T = 4.5$ K and 10 K. The results have been analyzed by using the R-T method to obtain the $\sigma_{1s}(\omega)/\sigma_{1n}(\omega)$ spectra. The value of $2\Delta(T)$ at $T = 4.5$ K was estimated to be ~ 10 cm^{-1}, which is significantly smaller than the value of $2\Delta(0) \sim 24$ cm^{-1} reported for high quality Nb. We suppose that it is mainly because the quality of the Nb studied in this work was not sufficiently high, which results in relatively low value of $2\Delta(4.5)$.

References

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