Solid State Communications, Vol 87, No 1, pp 17-21, 1993
Printed in Great Britain

0038-1098/93$6 00+ 00
Pergamon Press Ltd

DYNAMIC CONDUCTIVITY AND THE COHERENCE PEAK IN THE SUBMILLIMETER SPECTRA OF SUPERCONDUCTING NbN FILMS

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(Received 17 March 1993 by V M Agranovich)

A new technique is developed for measurement of electrodynamic parameters of superconducting films in the submillimeter wavelength range. In the frequency range 5-39 cm^{-1} at temperatures 5-300 K, the first detailed measurements of the temperature and frequency dependences of dynamic conductivity and dielectric permittivity of superconducting NbN films are performed. A coherence peak is discovered in the temperature dependence of dynamic conductivity of NbN films.

1. Niobium nitride is one of the most popular materials among conventional (low-temperature) superconductors from the viewpoint of applications in high-frequency electronic devices. This is connected with a relatively high critical temperature (13-18 K) and its mechanical and chemical stability. However there are actually no experimental data in literature on such important NbN characteristics as absorptivity and dielectric properties at frequencies close to and below the energy of the superconducting gap 2Δ, which lies in the submillimeter frequency range. At the same time the data obtained in this range by traditional techniques [1-4] are limited by difficulty of measuring absorption characteristics in the superconducting state.

The aim of the present work was to develop a technique, allowing reliable measurements of electrodynamic parameters of superconducting films at submillimeter waves and to perform with this technique systematic measurements of submillimeter spectra of dynamic conductivity and dielectric permittivity of superconducting NbN films

2 Samples under investigation were plane-parallel crystalline sapphire isotropic plates about 0 5 mm thick with NbN films of thickness 100-500 A deposited on one or both sides. Films were prepared by magnetron sputtering, their critical temperature was about 12 K and width of transition 0.3-0.5 K.

All measurements were performed on a laboratory submillimeter BWO-spectrometer "Epsilon" (BWO-backward-wave oscillator - a generator of the submillimeter radiation) described in detail in references[5,6]. Measured experimentally were the transmission coefficient T and phase shift φ of the submillimeter radiation passed through the sample. The electrodynamic parameters of the NbN films were calculated on the basis of the T and φ spectra using usual optical formulae for layered systems[7]. The dielectric properties of sapphire substrates were measured beforehand. The submillimeter (SBMM) measurements were done in the frequency range 5-39 cm^{-1} at temperatures 5-300 K.

3. We discuss first the experimental data obtained by a traditional measurement scheme, using a sample with a film only on one side Actually this system is an asymmetrical Fabry-Perot resonator, whose "mirrors" are represented by two faces of the substrate with and without the NbN film.

The submillimeter transmission spectra of the NbN film (115 A) on the sapphire substrate (0.43 mm) are shown in Fig.1a for temperatures above and below T_c Oscillations in the spectra come from interference of the SBMM radiation inside the substrate The distance bet-

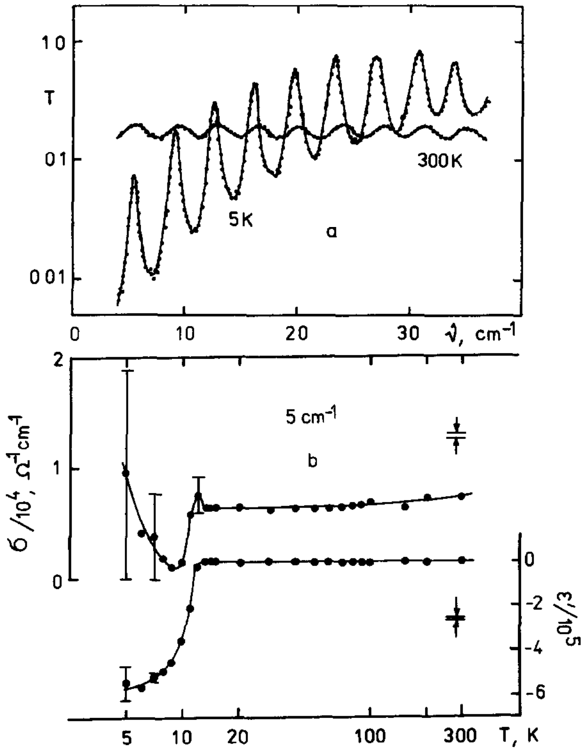

Fig.1a. Transmission coefficient spectra of an asymmetrical Fabry-Perot resonator, formed by a NbN film (115 Å) on a sapphire substrate (0.43 mm), measured at two temperatures above and below critical temperature.
Fig.1b. Temperature dependences of submillimeter dynamic conductivity and dielectric permittivity of NbN film at 5 cm^{-1}, calculated on the basis of the transmission spectra of Fig.1a. Solid lines are guides for eye.

ween maxima is determined mainly by the refraction index and thickness of the substrate, and their amplitude - by the NbN film transparency. In the normal state transmission spectra change only slightly when the temperature is lowered from 300 K down to T_c. Essential changes are seen in the spectra when the film becomes superconducting. at small frequencies transmission coefficient decreases by about an order of magnitude, while at higher frequencies it increases.

Fig.1,b shows temperature dependences of the dynamic conductivity σ and dielectric permittivity ε' of the NbN film, calculated for 5 cm^{-1} using the transmissivity spectra of Fig.1,a The lowering temperature in the normal phase leads to a small decrease in conductivity while dielectric permittivity remains virtually constant $\varepsilon' \approx 0$. In the superconducting state a sharp decrease of ε' (down to -10^6) is clearly observed. At the same time in spite of the fact that transmission spectra were measured with rather high accuracy, almost nothing can be said about the behaviour of dynamic conductivity in the superconducting state because of an increase of the error bars.

This situation is associated with the fact that in the superconducting state a decrease of absorptivity in the material takes place below the energy

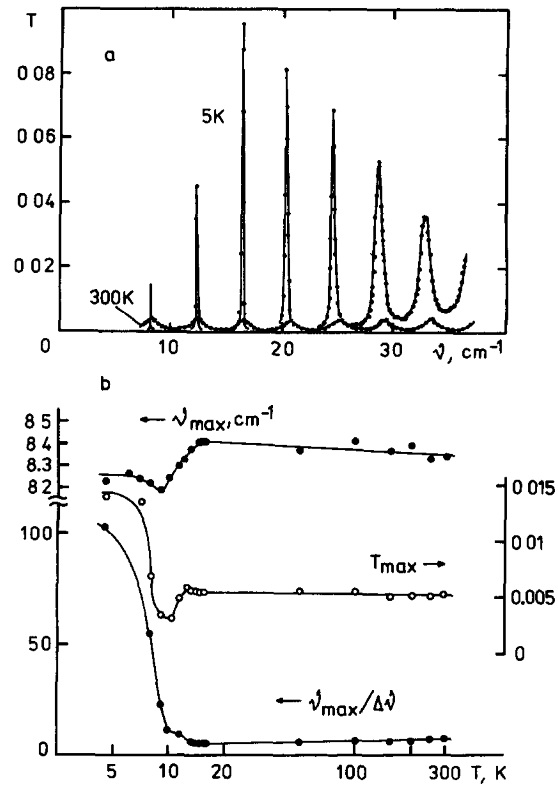

Fig.2a. Transmission coefficient spectra of a symmetrical Fabry-Perot resonator formed by two NbN films (540 Å) on a sapphire substrate (0.39 mm), measured at two temperatures above and below critical temperature
Fig.2b. Temperature dependences of parameters of interference maximum (frequency, amplitude, quality-factor) of Fabry-Perot resonator (see Fig.2a). Solid lines are guides for eye.

gap frequency[8,9]. In other words for $T<T_c$ the dynamic conductivity $\sigma=nk\nu$, the real part of the surface impedance $R_s=X_0n(n^2+k^2)^{-1}$, $X_0=376,7$ Ohm, and the refraction index n of the material should decrease. According to our analysis[10] in such a situation experimentally measured parameters T and φ become less sensitive to values characterizing radiation absorptivity, and this is the reason why error bars in determination of σ, R_s and n in the superconducting state grow up appreciably.

We note, that this problem of measuring absorption of a superconductor is typical not only for the experimental geometry of the SBMM measurements under consideration (film on the substrate, see also[10]), but also for all standard methods of neighboring to submillimeter far-infrared and microwave ranges (see, for example,[2,11])

4. Our experience shows that the sensitivity of the SBMM measurements can be increased considerably by using a special sample represented by a dielectric substrate with two films on both sides. Such a system is essentially a symmetrical Fabry-Perot resonator Its advantages are due to much higher quality factor, or in other words, to a much higher effective number of reflections of the radiation inside the resonator. Similar systems based on high-T_c superconducting YBCO films have already been studied by FTIR spectroscopy as Fabry-Perot filters and laser resonators[12,13].

Fig.2 shows the SBMM transmissivity spectra of a symmetrical Fabry-Perot resonator formed by two NbN films (540 Å) on a sapphire substrate (0.39 mm) The spectra are shown for two temperatures, 300 K (normal state) and 5 K (superconducting state). As in the case of Fig.1,a, the main changes in the spectra are observed when the films become superconducting: a sharp growth of the amplitudes of interference maxima τ_{max} and their Q-factors are observed An increase in Q and τ_{max} shows that losses, A, of the resonator "mirrors" are reduced while their reflection coefficients, R, grow up. For maximum at 8 cm^{-1} and T=5 K, τ_{max} increases about three times and its Q-factor - more than by an order of magnitude (Fig.2b). It is interesting to note the non-monotone temperature behaviour of the interference maximum parameters in the vicinity of the critical temperature.

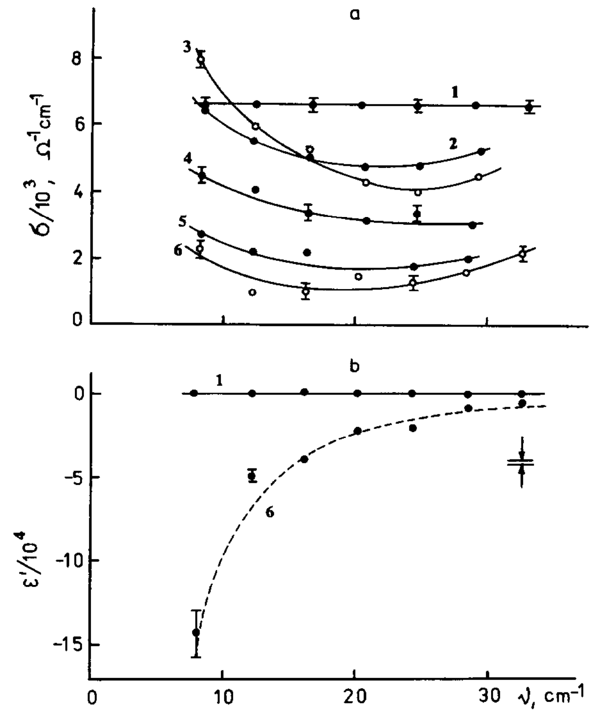

Fig.3. Frequency dependences of conductivity and dielectric permittivity of NbN film measured at different temperatures, K: 150-300 (1), 11 (2), 10 (3), 8 (4), 6 (5), 5 (6). Dashed line shows calculation according to the two-fluid model of superconductivity Solid lines are guides for eye.

Figs.3-6 show frequency and temperature dependences of the electrodynamic parameters of the NbN film, calculated on the basis of the transmission spectra of the symmetrical Fabry-Perot resonator. It is clearly seen from the figures that the use of symmetrical measurement scheme allows quite reliable determination (within ±20 % accuracy) of all electrodynamic parameters of NbN film including conductivity in superconducting state.

Temperature and frequency dependences of the SBMM parameters of NbN films obtained in the present work and earlier in[10] are qualitatively the same. Slight disagreement in the absolute values of σ is apparently due to different granularity of the films used in the studies.

In the normal phase the SBMM electrodynamic properties of NbN can be described within the framework of the Drude model of conductivity of free carriers[14] in the low-frequency limit $\nu \ll \gamma$ (γ - relaxation frequency of the carriers): at temperatures $T>T_c$ there is no dispersion in the SBMM spectra of conductivity and dielectric permittivity (spectra 1 in Fig 3) and $n=k=(\sigma/\nu)^{1/2}$ (Fig.4a). A slight decrease in conductivity at low temperatures may be caused by localization effects associated with the granular structure of the NbN films[2]

In the superconducting state the temperature and frequency behaviour of the NbN electrodynamic parameters is consistent with the concepts on optical properties of superconductors at low frequencies $\nu<2\Delta$, developed in the context of the BCS theory[8,9].

Monotone decrease of dynamic conductivity σ at relatively high frequencies (near 30 cm^{-1}) during the superconducting transition (Fig.3a and Fig.4b) corresponds to the opening of an energy gap in the excitations spectrum. At lower frequencies (about 8 cm^{-1}) the dependence appears to be more complicated while going down below the critical temperature the conductivity first grows up and then goes down. Such kind of the temperature behaviour of dynamic conductivity is known as a coherence peak. The presence of this coherence peak in the NbN film suggests that the ground state in the material is of a singlet origin[8]. It is interesting to note that the peak structure in the $\sigma(T)$ dependence corresponds to the non-monotone temperature behaviour of the refractive n and extinction k indexes (Fig.4,a) and to the maxima in the temperature dependences of the real and imaginary parts of surface impedance (Fig 5).

In the superconducting state the NbN dielectric permittivity ε' decreases from zero down to values of about -10^5 (at 8 cm^{-1}, Fig.4c). Frequency dependence of ε' in the superconducting state is described by a London-type expression (dashed line in Fig.3,b)

$$\varepsilon'=-c^2(4\pi^2\nu^2\lambda_L{}^2)^{-1} \quad (1),$$

with λ_L the London penetration depth.

Fig 6 shows frequency and temperature dependences of the penetration depth $\lambda=(2\pi k\nu)^{-1}$, calculated on the basis of experimental data. At room temperature the penetration depth behaves like $\nu^{-1/2}$, which is in accordance with the Drude conductivity model. In the superconduc-

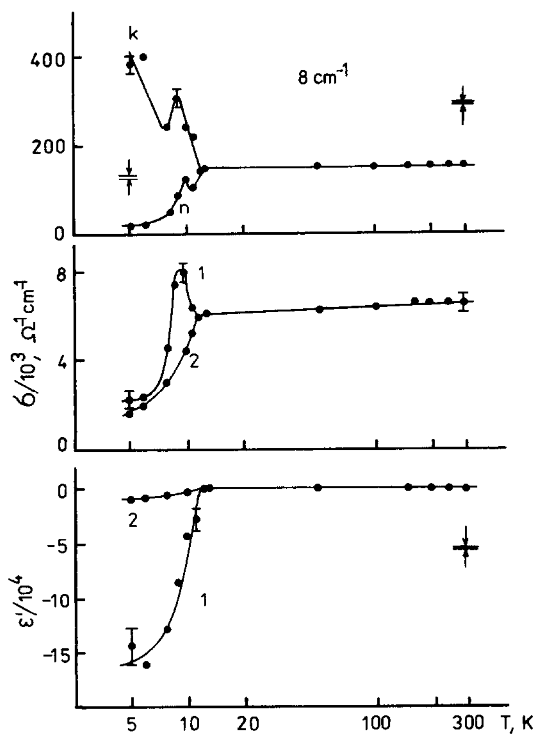

Fig.4. Temperature dependences of the submillimeter optical parameters of NbN film, calculated for two frequencies, 8 cm^{-1} (1) and 29 cm^{-1} (2) Solid lines are guides for eye

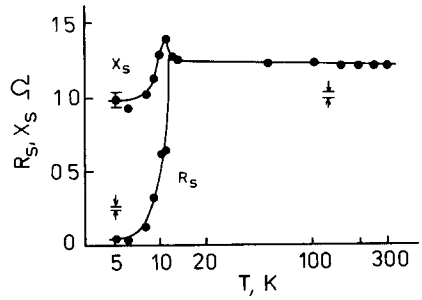

Fig.5. Temperature dependences of real and imaginary parts of surface impedance of NbN film at 8 cm^{-1}. Solid lines are guides for eye.

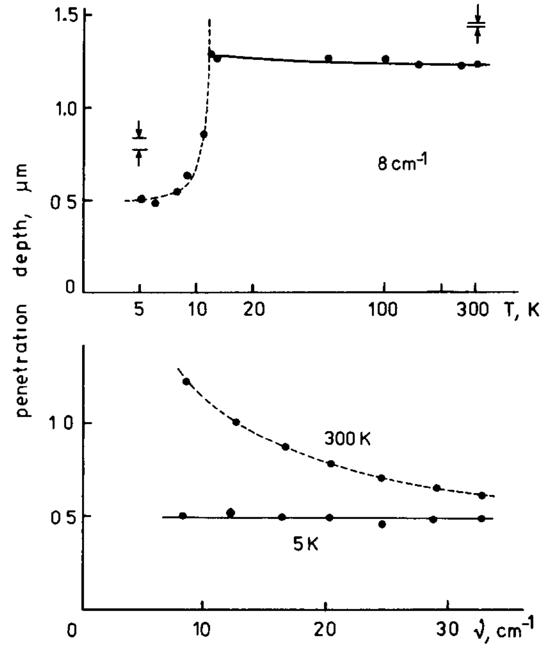

Fig.6 Temperature and frequency (for two temperatures above and below T_c) dependences of the submillimeter radiation penetration depth for NbN film Dashed lines show calculations according to the two-fluid superconductivity model (upper part) and Drude conductivity model (lower part). Solid lines are guides for eye

ting state λ becomes smaller and frequency independent in agreement with the model representations[8,9] A sharply decreasing penetration depth in the superconducting phase can well be described by a two-fluid model expression[9]

$$\lambda(T)=\lambda(0)[1-(T/T_c)^4]^{-\frac{1}{2}} \qquad (2).$$

Using (1) and (2) we determine the values of the London penetration depth λ_L=0 5 μm and plasma frequency $\nu_p=c/\lambda_L$= 3200 cm^{-1}, which are in good agreement with literature data[1-4]

5 In conclusion, we have developed a new technique, allowing precise measurement of the electrodynamic characteristics of superconducting films in the submillimeter and far-infrared frequency ranges. The technique employs a symmetrical Fabry-Perot resonator formed by two superconducting thin films on a transparent dielectric substrate. Using this technique detailed measurements of electrodynamic parameters of NbN superconducting films are performed for the first time in the frequency range 5-39 cm^{-1} at temperatures 5-300 K. A coherence peak is discovered for the first time in the temperature dependence of the NbN dynamic conductivity, which suggests a singlet origin of the ground state in the material. It is shown that the temperature and frequency behaviour of the submillimeter electrodynamic characteristics of NbN films is in accordance with the BCS-based concepts of optical properties of conventional (low-temperature) superconductors at frequencies below the superconducting energy gap

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