Characterization of Microwave Properties of Superconducting NbTiN Films using TDS

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***Abstract*—In this work we perform comprehensive study of electrodynamic properties of superconducting films of NbTiN at frequencies up to 2.5 THz and in temperature range from 4 up to 15 K using commercial time-domain spectrometer TeraView TPS Spectra 3000. A set of NbTiN films with different content controlled by the pressure of nitrogen in magnetron chamber was fabricated. We found out that there is a trade-off between low normal-state resistivity, small London penetration depth and high critical temperature. By characterizing the films, the optimal manufacturing conditions were determined. Two models, with and without taking intragap states into account were used to describe experimental data and both show quantitative correspondence with the experiment.**

Keywords—thin films, superconducting materials, terahertz measurements

I. Introduction

Devices of superconducting electronics have been extensively used in fundamental research and number of practical applications. The devices based on superconductor-insulator-superconductor (SIS) tunnel junctions are the main element of receiving systems in terahertz (THz) range having the lowest noise temperature only few times higher than quantum limit. The operating frequency of the superconducting SIS-receivers is limited by the gap, being 750 GHz for Nb which is used in fabrication of the majority of superconducting devices nowadays. In order to expand the operating range to frequencies higher than 1 THz, other materials, e.g. Nb compounds, like NbN and NbTiN, with higher gap frequency should be used.

This work is dedicated to characterization of the parameters (normal state resistivity ρ_0, critical temperature T_c, London penetration depth λ_L) of superconducting NbTiN films fabricated at different technological conditions at frequencies close to 1 THz. The thicknesses of the films are around 330 nm, exceeding London penetration depth, which turned out to be more than 280 nm for all the samples.

II. Fabrication Processes

NbTiN films were sputtered on 535-µm-thick high-resistivity silicon substrates at room temperature using cluster magnetron system Kurt J. Lesker. The sputtering was performed from 3” NbTi (78 % of Nb and 22 % of Ti) target in mixture of nitrogen and argon. Power of magnetron was around 500 W. The pressure of nitrogen in magnetron chamber was varied from $0.35\cdot10^{-3}$ to $0.65\cdot10^{-3}$ mbar in order to investigate its impact on critical temperature of the film T_c and ρ_0 which is DC conductivity at normal state near T_c, and also determine the conditions at which the highest T_c and lowest ρ_0 are obtained. The DC-parameters measured by four-probe technique of all the samples are listed in Table I.

III. TDS-Measurements

The study of the samples at THz frequencies was performed using TDS-spectrometer TeraView TPS Spectra 3000. Transmission spectra of the superconducting films on substrates were measured for all the films in temperature range from 4 to 15 K. Conducting medium can be expressed in terms of complex permittivity $\varepsilon^* = \varepsilon' - 4\pi i\sigma_1/\omega$, where ε' is the real part of permittivity and σ_1 is the real part of conductivity. Measured spectra together with the fitting curves are shown in Fig. 1.

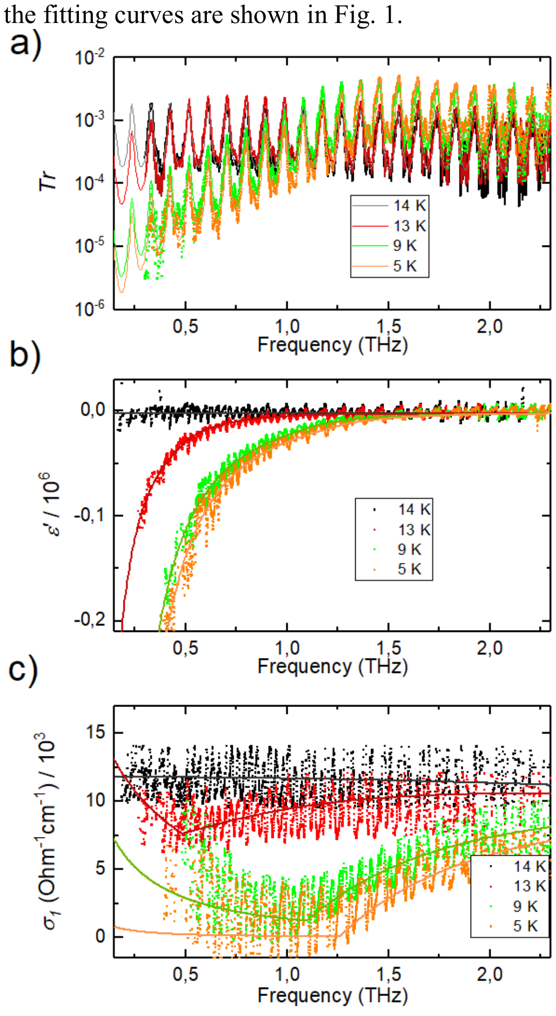

Fig. 1. Spectra of transmission coefficient (a), real part of permittivity (b) and conductivity (c) of superconducting NbTiN film (sample #5).

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IV. Theoretical Models

We used the expressions from the paper by Zimmermann *et al*. [1] in order to fit our data. This model not only allows to calculate the complex conductivity of the superconductor, but also takes into account finite quasiparticle scattering time. The additional parameter, quasiparticle scattering rate γ, is reciprocal to scattering time τ: $\gamma = \hbar/\tau$. From fitting the experimental data, we obtain ρ_0, Δ and γ. Since the permittivity in superconducting state is many times higher than in normal state due to Cooper pairs, T_c is determined directly from Fig. 1 b as the lowest temperature where ε' takes finite value at zero frequency.

As is known, Nb compounds including NbTiN are superconductors with strong coupling. Related effects lead to that the ratio between the critical temperature and the gap at $T = 0$ $\Delta_0 = 1.76k_BT_c$ predicted by BCS-theory is no longer valid. The coefficient at k_BT_c determined from our measurements turned out to take values from 2 up to 2.2 for all the samples.

In recent papers on studying the properties of NbTiN films it was claimed that the density of states is also different from that predicted by BCS for whatever reasons [2]. Singularities in the density of states at the energies near the gap vanish and the gap frequency itself is slightly reduced. These effects can be treated by more complicated models, e.g. described in [3].

As can be seen from Fig. 1, theoretical curves calculated using the expressions from [1], where the BCS-like density of states is considered, are in good correspondence with the results of experiment in our work. Therefore, in order to understand the difference between the models we used both of them to process the data from [2], where the spectra of relative change in reflection coefficient upon transition from superconducting to normal state were measured. Multiple reflections were suppressed by adding additional silicon plates to substrate. Both models allow to obtain reasonable agreement with the experimental data (see Fig. 2). However, a small discrepancy between the curve corresponding to model [1] appears at frequencies near the gap which is around 1.1 THz. This discrepancy can be eliminated using model [3] by adjusting parameter Γ_s that corresponds to scattering rate on magnetic impurities, though the accuracy of the fit at frequencies higher than 1.3 THz becomes worse.

It still remains unclear if the discrepancy near the gap frequency is caused by intrinsic or extrinsic effects (such as surface roughness or contamination).

V. Conclusions

The resultant parameters of all the films are listed in Table I. It should be noted, that there is a trade-off between the lowest ρ_0, smallest London penetration depth at zero temperature λ_0 and highest gap and T_c. It was found out that ρ_0 monotonously grows with increasing the pressure of nitrogen in chamber; λ_0 has minimum near 4.5 mbar and T_c reaches its maximum at 5.5 mbar. Thus for particular purposes one should use the corresponding conditions.

Moreover, the values of the parameters, obtained from DC-measurements and using TDS differ by approximately 10 %, what is likely to be caused by the grain structure of the films. At temperatures close to T_c, there are areas in film both in superconducting and normal state. Direct current flows through superconducting pattern, which is not the case for

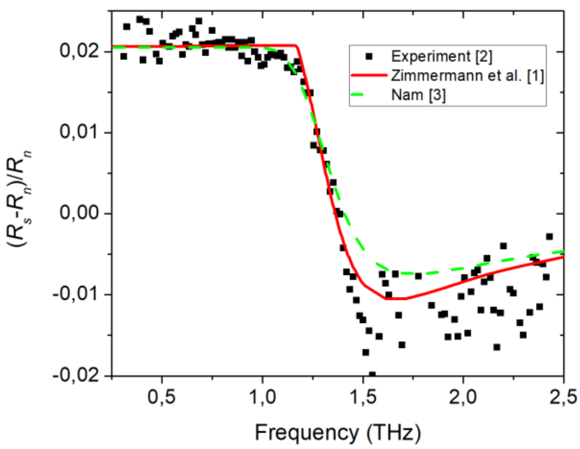

Fig. 2. Relative difference of reflection coefficients of NbTiN film in superconducting and normal states. Experimantal points were taken from [2]; solid and dashed curves represent the fits using expressions considering BCS-like and modified densities of states, respectively.

the current induced by the AC-radiation that flows through both the grains and the boundaries. Therefore, T_c of the films at high frequencies is determined by the transition temperature of the boundaries, which is lower. Therefore, the parameters obtained by TDS are those that should be used in design and modeling of superconducting devices.

TABLE I. Parameters of the Films

Sample no.	#1	#2	#3	#4	#5	#6
N_2 pressure, 10^{-2} mbar	6.5	5.9	5.3	4.7	4.1	3.5
Thickness, nm	333	332	328	339	338	325
$\rho_{0,\,DC}$, µΩ cm	127	114	104	98	93	92
$T_{c,\,DC}$, K	14.9	15.2	15.2	15.3	15.2	14.8
$\rho_{0,\,TDS}$, mΩ cm	110	105	95	91	89	85
$T_{c,\,TDS}$, K	14.1	14.4	14.6	14.4	13.9	13.8
$2\Delta_0$, meV	4.9	5.1	5.1	5.1	5.2	4.7
λ_0, nm	330	300	290	280	280	290

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