Study of superconducting films for accelerating cavity applications by a microstrip resonator technique

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Introduction

Niobium thin film sputter coated superconducting r.f. cavities, first developed at CERN in relation to the LEP accelerator [1,2], combining the superior superconductor surface properties with the optimal copper thermal conductivity, exhibited competitive performances in respect to bulk cavities in different contexts [3-5].

The sputter coating technique opens the possibility of using of a wide choice of alternative superconducting materials. To find possible "candidates" for this application, a first selection can be made on the basis of the knowledge of their d.c. superconducting properties, using the BCS theory of superconductivity. This approach gives a satisfactory prediction of the r.f. losses, i.e. of the surface impedance. However, the presence of residual losses, of different origin and often field dependent [6], makes impossibile to consistently predict the low temperature r.f. performances of superconducting materials.

Due to the inherent difficulties in realizing test measurements on large cavities of complex geometries, it is essential, in view of a development of the thin film coating technique in the direction of new materials, to have an efficient method to measure the high frequency properties of superconducting films on samples of small dimensions and in a more controlled enviroament. Using this approach, in fact, the effect of film properties (thickness, morphology, impurities, grain boundaries) and of temperature, frequency, and d.c. and r.f. field amplitude can be easily studied and possibly understood.

In this paper we present a useful method to measure the high frequency properties of superconducting films on small samples, and show the data recently obtained by this method on the temperature, frequency and power dependence of the surface impedance of (NbTi)N , a superconductor of high potential interest for r.f. cavity applications.

Experimental details

The measurements of the surface impedance of the superconducting films under investigation have been performed by using a microstrip ring resonator designed in our laboratory [7,8].

The resonator consists of a superconducting thin film , shaped by photolithography in form of a narrow ring (width w=100 μm), deposited on a thin (thickness d=130 μm) sapphire substrate . The substrate is placed on top of a ground-plane made of the same superconductor (or of a known superconductor) and acts as a low-loss dielectric layer. Two 50Ω symmetric microstrip launches are also deposited on the substrate to excite and pick-up the microwave signal from the resonator. The device is enclosed in a gold- plated copper package and standard 50Ω coaxial cables are used to connect the resonator to an HP 8022C network analyzer (0-20 GHz).

The film can also be deposited on a separate substrate and placed on top of the dielectric layer ("inverted" configuration).

The system temperature can be easily varied and controlled in the range 1.4—300K and a uniform d.c. field ($\lesssim$ 10mT) can be applied by means of a pair of Helmotz coils . The measurements can be performed under vacuum to avoid unwanted effects related to the changes of the liquid helium dielectric constant.

Given the narrow ring dimension , only the TM_{n10} modes can be excited in the resonator in the frequency range of interest and the resonance frequency is determined by the ring diameter D and by the order of the resonant mode n through the relation :

$$\nu_n = (nc/\pi D \sqrt{\varepsilon_{eff}})[1 + (\lambda_1 \coth t_1/\lambda_1 + \lambda_2 \coth t_2/\lambda_2)/d]^{-1/2} \qquad (1)$$

where λ_1 and λ_2 are the magnetic field penetration depths of the film and of the ground plane, t_1 and t_2 the respecrtive thicknesses, ε_{eff} is the effective dielectric constant of the device and c is the light velocity.

Since ring diameters up to 20mm can be used and $\varepsilon_{eff} \approx \varepsilon_r \approx 10$, measurements can be performed down to ~ 1.5 GHz , in the range of interest for r.f. accelerating cavity applications. In the following we will report on measurements performed on 10mm diameter rings with a fundamental resonant frequency $\nu_1 \approx 3$GHz .

The quality factor $Q_L = \nu_n/\Delta\nu_n$ of the resonant circuit is determined using the power trasmission method. The "intrinsic" quality factor of the ring resonator Q_i is related to Q_L by the relation : $Q_i = Q_L / (1 - R_v)$ with $R_v = 10^{-IL/20}$, where IL is the insertion loss measured in dB . The gaps between the resonator and the launchess are set to ≈ 1mm to achieve an "unloaded " situation, where $R_v << 1$ (IL > 20db) so that $Q_i = Q_L$.

The intrinsic quality factor of the resonator can be expressed as :

$$Q_i^{-1} = Q_C^{-1} + Q_o^{-1} \tag{2}$$

where Q_C is determined by the conductive losses and Q_o describes the parasitic losses (dielectric losses, radiation losses, etc.) and it is essentially temperature independent.

If two identical superconductors are used for the ring and the ground plane, we have:

$$Q_C = \Gamma / R_S \tag{3}$$

where R_S is the surface resistance of the superconductor and Γ depends only on geometrical factors and can be easily calculated [9].

Since Q_0 is hard to evaluate , to determine the surface resistance of the superconductor under test by the measured quality factor Q_L, one can use eq.3 only if the condition $Q_i = Q_C$ is satisfied, i.e. if $Q_C << Q_O$. The dielectric losses of the sapphire are indeed very low ($Q_{dielectric} \approx 1/\tan\delta$ and $\tan\delta \leq 10^{-7}$ at liquid helium temperature). Radiative losses can be minimized using a narrow ring width and the same condition also maximizes conductive losses. We extimated [9] that for w= 100μm the condition $Q_C << Q_O$ should be indeed verified for all our measurements.

With this choice of the resonator parameters we get , from calculations [10], Γ=0.91Ω. The low Γ value implies low Q value but of course our goal is not to have low loss resonators but a good method to measure R_S. Moreover, is worth mentioning that, due to the resonator geometry, the Q is mainly determined by the surface resistance of the superconducting film used for the ring.

Results and Discussion

To test our system, we performed preliminary measurements of the surface impedance of Nb films ($t \gtrsim 1.5\mu m$) with a bulk Nb foil used as a ground plane [7]. The results for both the resistive and reactive components of the surface impedance showed a remarkable consistency with the BCS theory over the full temperature range, with a moderate strong coupling ratio ($2\Delta_0/KT_c \approx 3.7$), giving a convincing confirmation of the method. The residual surface resistance $R_0 \approx 1\mu\Omega$ was about 1/3 of the BCS component at 4.2K in the best films. This higher value in respect to the results obtained for the CERN Nb film cavities ($\approx$1/10 of the BCS value at 4.2K) should be related to the inferior properties of the first Nb layers at the sapphire interface.

As expected, the quality factor of the resonator at 4.2K showed a frequency dependence with a ν^{-1} behavior and a negligible dependence on the r.f. field amplitude.

The first innovative superconductor that we investigated with the technique described above is a niobium-titanium nitride compound, nominally $(Nb_{.8}Ti_{.2})N$. Sputtered films of this material, combining the high T_c and radiation hardness properties of NbN and

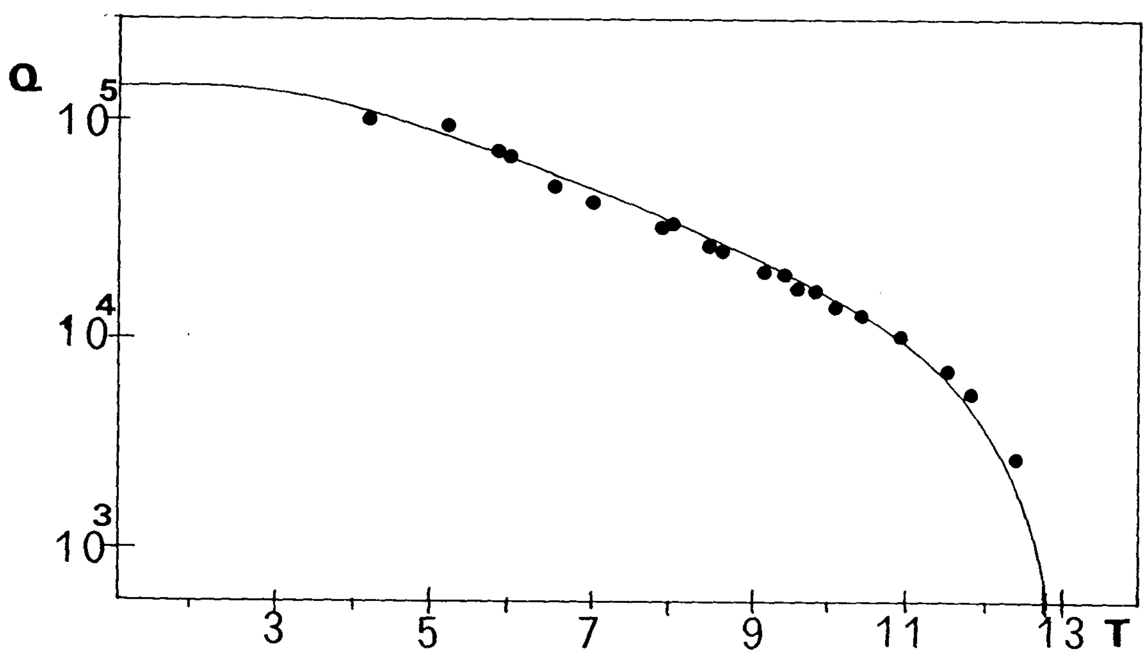

Fig.1 Temperature dependence of the quality factor for the $(Nb_{.8}Ti_{.2})N$ ring resonator. Q has to be multiplied by $2*10^4$ to be compared with 500 MHz CERN test cavities. The continous line is the BCS theoretical expression.

the good metallicity and excellent mechanical properties of TiN, were previously identified and discussed as potential candidates for r.f. cavities applications [11] and are presently tested at CERN in 500MHz prototype accelerating cavities for electrons [12].

In Fig. 1 the temperature dependence of the quality factor for one of our NbTiN resonators is reported. The ring was obtained by direct photolithography of a 1.5μm thick ($Nb_{.8}Ti_{.2}N$) film, obtained by triode magnetron sputtering on a dielectric sapphire substrate, whereas the ground plane was realized depositing the film on a Nb plate. It is important to observe that, due to the different Γ and ν_1 values, to compare our Q with those obtained at CERN with the 500MHz test cavities, the Q values have to be multiplied by a factor $\approx 2*10^4$.

The theoretical curve (continuous line) has been obtained by the expression :

$$R_s = R_{sBCS}(T) + R_0 \qquad (4)$$

where the BCS contribution in the local dirty limit has been computed using appropriate analytical approximations of the Mattis-Bardeen integrals [7] and a standard best-fit program, the measured low temperature resistivity ($\rho_n = 90\,\mu\Omega cm$) and the film thickness as input parameters. For the samples reported in the figure we obtained as a result of the fitting procedure,

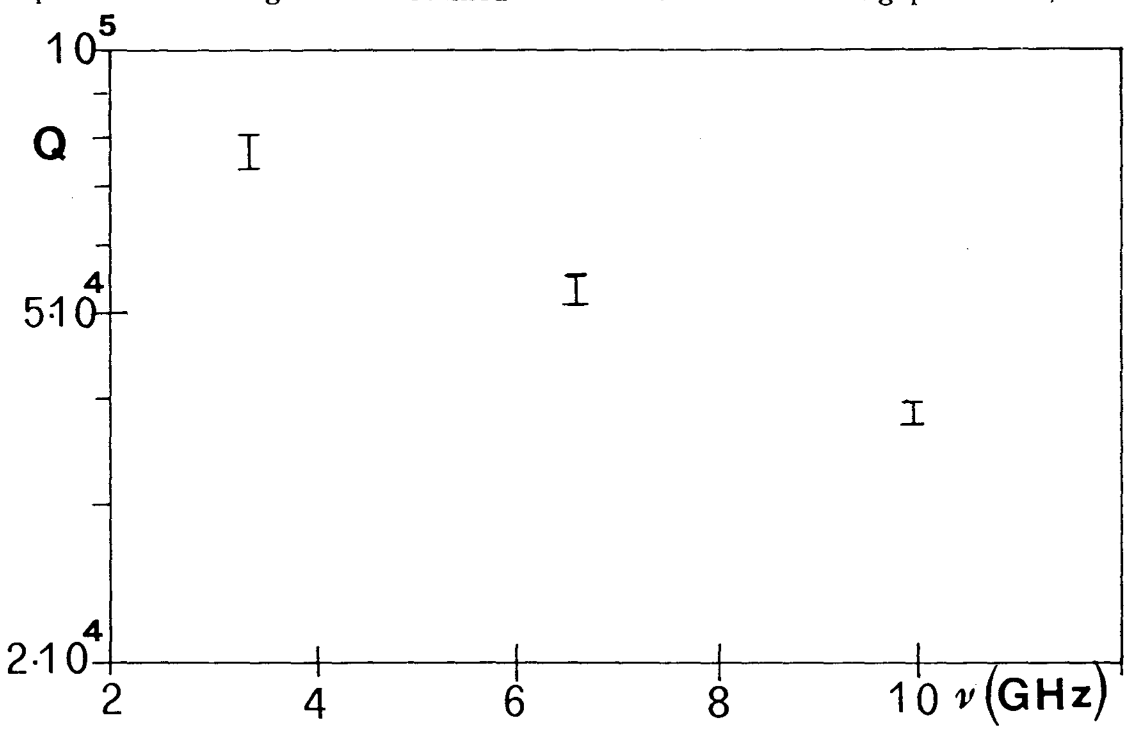

Fig. 2 Frequency dependence of the quality factor for ($Nb_{.8}Ti_{.2}$)N ring resonator, obtained using the first three resonant modes of the resonator.

T_C= 13.1K, Δ_0= 2.0 meV and R_0 =6.0 $\mu\Omega$.

It is important to observe that, in contrast with the results obtained by Oates et al. with a similar method ($2\Delta_0/K_bT_C$ = 4.75 $\pm$ 0.25) [13], our value of $2\Delta_0/KT_C$ = 3.6 is very close to the BCS weak-coupling prediction, in agreement with the results obtained by tunneling methods on NbN films with T_C in the same range [14]. For the sample reported in the figure, and for all our best samples the values of Q (4.2K) result to be comparable to those obtained with Nb.

The frequency dependence of the quality factor at T=4.2K, obtained analysing the second and third order ring resonances, is reported in Fig.2 for the same sample. The behavior corresponds to $Q \sim \nu^{-.7}$. Since for (NbTi)N the quality factor at 4.2K is mainly determined by the residual surface resistance, our result implies $R_0 \sim \nu^{1.7}$, in agreement with those models predicting a quadratic frequency dependence for the residual losses [6].

In Fig.3 the dependence of the quality factor at T= 4.2K on the r.f. field amplitude is reported for the same sample. A decrease of Q by a factor two is observed for a r.f. field amplitude $B_{rf} \approx$ 5mT (a dependence of this order of magnitude is also found for NbN [15]). It is worth to observe that an r.f. field amplitude of 5mT would correspond to an accelerating field

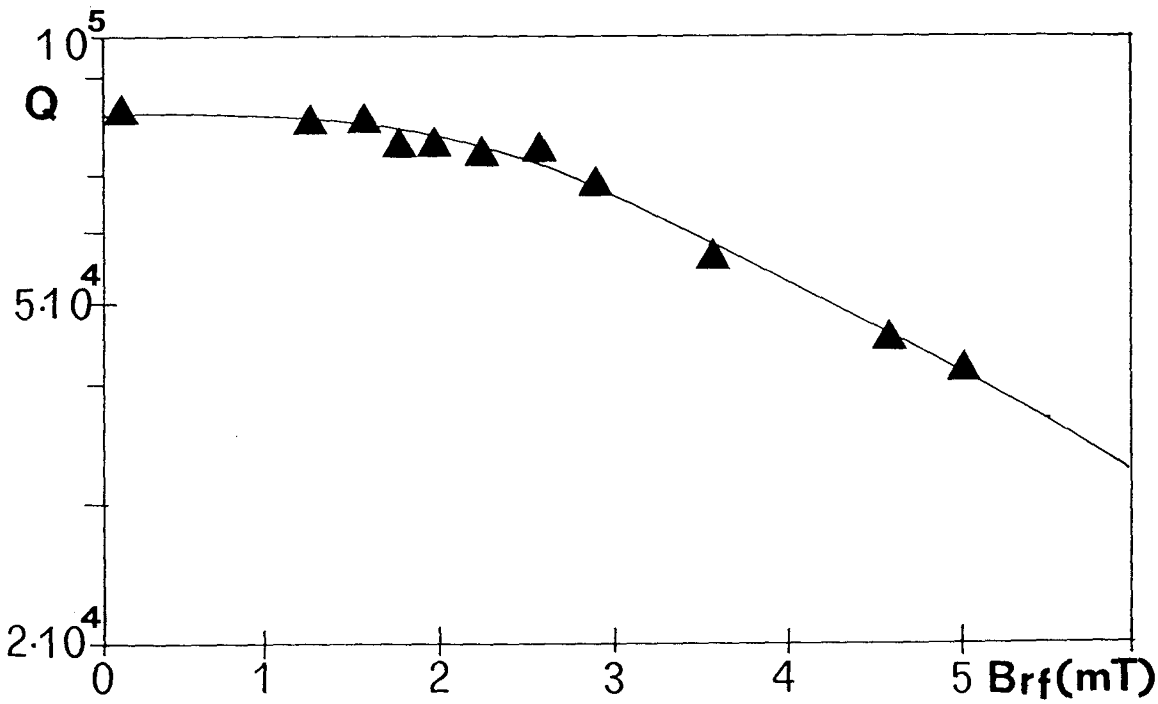

Fig. 3 Dependence of the quality factor for $(Nb_{.8}Ti_{.2})N$ ring resonator on the rf field amplitude. B_{rf}=5mT corresponds to $E_{acc} \sim$ 1MV/m in a 500 MHz CERN test cavity. The continous line is a guide to the eyes.

of about 1MV/m in a 500MHz CERN accelerating cavity, and that a decrease of a factor two in the quality factor for cavities coated with comparable quality (NbTi)N films, at the same field, has been also observed in ref. [12].

Finally, in Fig. 4 the temperature dependence of the frequency shift $\Delta\nu_1 = \nu_1(0) - \nu_1(T)$, proportional to the variation of the magnetic field penetration depth $\Delta\lambda = \lambda(T) - \lambda(0)$, is reported (equation 1) for one of our $(Nb_{.8}Ti_{.2})N$ films. Given the high Q values, the frequency shift can be easily measured with less than 1KHz accuracy, corresponding to a sensitivity less than 1Å in penetration depth changes. The theoretical curve is again obtained using the BCS theory in the local dirty limit, where as input parameters we used T_c=13.1 K, Δ_o= 2 meV as obtained from the $R_s(T)$ dependence.
The fit yields to λ_o = 5300 Å and ε_{eff}=8.3.

Though the fitting appears to be fairly good, there is a quite large discrepancy between the fitting value of $\lambda(0)$ and the value that can be

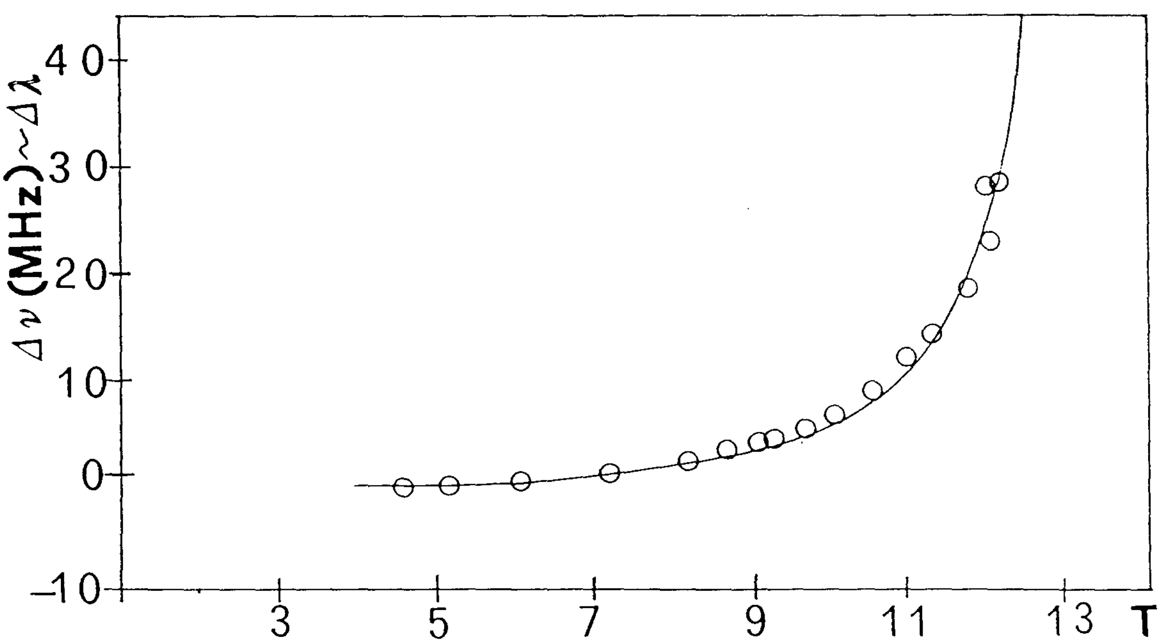

Fig. 4 Temperature dependence of the frequency shift $\Delta\nu_1 = \nu_1(0) - \nu_1(T)$, proportional to the variation of the magnetic field penetration depth $\Delta\lambda = \lambda(T) - \lambda(0)$. The continous line is the BCS theoretical expression.

calculated directly through the BCS theory ($\lambda(0) = 2800$ Å) This discrepancy, more relevant for samples with higher values of R_0, can be understood by a simple model that can be shown to hold for granular superconductors, explaining also the Q degradation with field amplitude observed for the same samples.

Indeed, all these effects have been often observed for high T_C ceramic superconductors and have been accounted for by Hilton et al. [16] in terms of the occurrence of weak Josephson coupling at grain boundaries or twinning domains in the material. More recently, Attanasio et al. [17] have extended the same model including the dependence on the r.f. field amplitude and pointed out that, by this approach, the losses in conventional superconductors with a strong policrystalline nature, as those belonging to the NbN family, can be also described. The application of the model to our (NbTi)N films gives in fact consistent results [7].

In conclusion we developed a method to measure the surface impedance of superconducting films based on a ring microstrip technique allowing measurements of the surface resistance and of the magnetic field penetration depth of the material under test. The achieved resolution is around $10^{-7}\,\Omega$ for R_S and better than 1Å for λ varia tions. The method has been used to determine the surface resistance of NbTiN sputterd films as a function of temperature, frequency and amplitude of the r.f. field, and the magnetic field penetration depth. The behavior of the films can be well described by a simple model of grain boundary losses.

The overall results indicate that this technique can indeed furnish rapid and consistent informations on the r.f. characteristics of innovative materials in the perspective of improving the performances of future generation of superconducting accelerating cavities.

Due to its versatility and sensitivity, we are also presently using the same technique to investigate the r.f. properties of high Tc ceramic superconductors [18].

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