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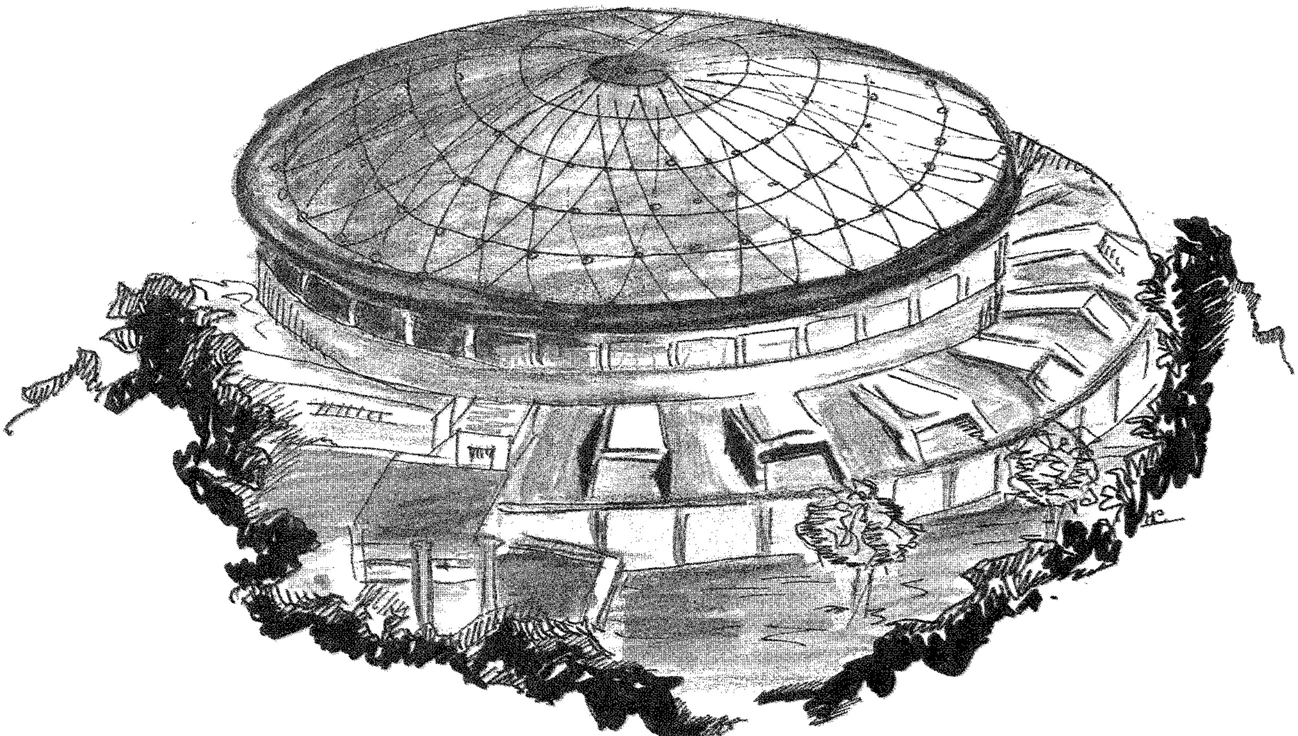

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DC FEATURES AND RF LOSSES OF Nb-BASED SUPERCONDUCTING THIN FILMS

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ABSTRACT

We have realized superconducting thin films of Nb, NbN, and NbZr, in view of their application to the superconducting accelerating cavities. The samples have been sputtered on different planar substrates, i.e. glass, sapphire, and Copper. The electrical and superconducting features of the films have been measured in the temperature range of 300 K ÷ 4.2 K and in the presence of a magnetic field up to 5 T. The expected RF properties are discussed. Measurements of the RF dissipation of Nb75Zr25 films sputtered on Copper substrates have been performed in a cylindrical TE011 cavity.

1. - INTRODUCTION

One of the most promising way to realize superconducting (SC) accelerating cavities able to get the features required by the ARES project[1] is to use a Copper cavity internally coated with a SC Nb film[2,3]. In this framework the study of superconducting materials which potentially may offer better characteristics than Nb is of great interest. The main characteristics of a SC accelerating cavity are the maxium accelerating electric field E_{acc} that can be attained and the corresponding low temperature dissipation, i. e. the surface resistance R_S.

Two limits for E_{acc} in a SC cavity may theoretically be indicated: electron emission and the transition from the SC to the normal state induced by the magnetic component of the RF field.

Neglecting the unpredictable residual contributions to the surface resistance R_{res}, the lowest R_S value is limited by the BCS prediction. The BCS surface resistance R_{BCS} may be estimated, for type II superconductors in the "dirty" limit, evaluating the Mattis and Bardeen integrals[4] of the complex conducibility σ_1/σ_n and σ_2/σ_n, to be used into the relation[5]:

$$R_{BCS} = \frac{\sqrt{\mu_0 \omega \rho}}{2} \frac{\sigma_1 / \sigma_n}{(\sigma_2 / \sigma_n)^{3/2}}$$

On the basis of these considerations we report the superconducting properties of Nb, NbN, and $Nb_{75}Zr_{25}$ thin films in terms of their residual resistivity, critical temperatures T_c, and upper critical fields H_{c2}. Moreover for $Nb_{75}Zr_{25}$ thin films we have also measured the superconducting energy gap Δ and the surface resistance in a cylindrical TE_{011} cavity, in order to compare the experimental value to the theoretical BCS computation result.

2. - THIN FILMS CHARACTERIZATION

We have realized the SC films by using the Leybold L 560 thin film fabrication plant, equipped with a water cooled 3" diameter cathode. Our system allows for both RF and DC magnetron sputtering; only the latter has been used for Nb and NbN, while for $Nb_{75}Zr_{25}$ depositions both kind of sputtering have been used. The evacuation system consists of a fore-vacuum group (two stage 75 m^3/h rotary pump plus mechanical booster 500 l/s) and a 1000 l/s pumping speed turbo molecular pump. A final vacuum in the low range of 10^{-7} mbar is reached in a few hours. Many of the samples have been deposited through a steel mask, to obtain a linear strip of approximately 20 x 0.2 mm^2. All substrates have first been cleaned with alcohol, acetone, and an ultrasonic bath to achieve proper adherence. The Copper substrates, consisting of 2" diameter polished discs, have been coated with Nb and $Nb_{75}Zr_{25}$. The discs have been cleaned by using a mixture of sulfamic acid, followed by an ultrasonic bath. We were careful never to heat the substrates, although their temperature was not controlled. The film growth has been monitored by using the Inficon XTC quartz thickness monitor.

Nb samples were deposited in view of coatings of the Cu discs. A typical resistive behavior of Nb films obtained after long conditioning period (more than 20 samples deposited), is shown in Fig. 1. The adherence of the Nb films on Cu ($\approx$1 μm thick deposited at 13 Å/s in a 5 x 10^{-3} mbar of Ar atmosphere) was satisfactory also against thermal cycles. The measured residual resistivity ρ_n of the sample shown is less than 2 $\mu\Omega$ cm, and the $T_c \approx 9.3$ K. With a typical value $2\Delta/K_BT_c \approx 3.84$ for Nb, K_B being the Boltzmann constant, we compute using simple approximations[6], at a frequency f=500 MHz and T=4.2 K, a surface resistance: $R_{BCS} \approx 65$ nΩ.

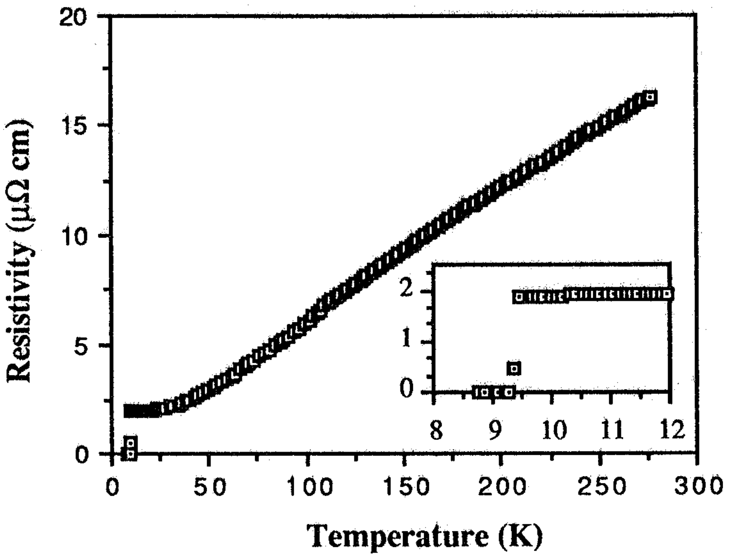

FIG. 1 - Typical resistive behavior of Nb films as a function of emperature. The transition region is shown in the inset.

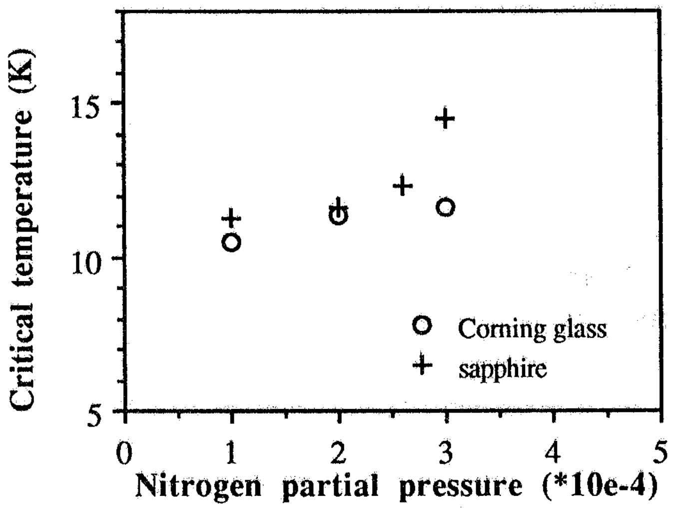

FIG. 2 - Critical temperature of NbN films deposited at 10.5 Å/s as a function of the Nitrogen pressure.

Because higher accelerating fields may be expected for materials having higher critical fields, we also tried to realize high T_c NbN films by reactive sputtering, without heating the substrate. The NbN samples have been realized at a Nitrogen partial pressure ranging from 1÷3.6 x 10^{-4} mbar. The Ar pressure was always set at 5 x 10^{-3} mbar. The deposition rate has been fixed at 10.5 Å/s for all samples, by means of an automatic feedback on the sputtering power. In Fig. 2 the NbN critical temperatures as a function of the Nitrogen pressure, on different substrates, are reported. The measured residual resistivity is about 200 μΩ cm, and the residual resistivity ratio RRR<1. The R_{BCS} computation gives, for a NbN sample with $T_c \approx 12$ K, $R_{BCS} \approx 62$ nΩ. This value does not seem worse than that of Nb, but it does not take into account the high R_{res} usually found[7,8] in NbN and accounted because of its granular nature. In fact granularity seems to play an important role in determining high values of R_{res}[9].

The $Nb_{75}Zr_{25}$ films have been realized either by DC or by RF magnetron sputtering from a cathode of the alloy, realized by arc melting, and kept at room temperature. Several kinds of substrates, such as Corning glass, sapphire, and Copper, have been used, all allowed only to warm up naturally. The films have been deposited both without and through metallic masks; their thickness ranged from 5 ÷ 10 kÅ, while the deposition rates have been changed, by either varying the power or the Ar pressure, in the range 6÷22 Å/s. Fig. 3 shows the measured critical temperature of some of the samples deposited both with RF and with DC magnetron sputtering, as a function of the deposition rate. We have not observed any significant variation of the resistive T_c for deposition rates higher than 15 Å/s. The residual resistances of the films were in the range of 30÷32 $\mu\Omega$ cm, and the RRR's≈1.5.

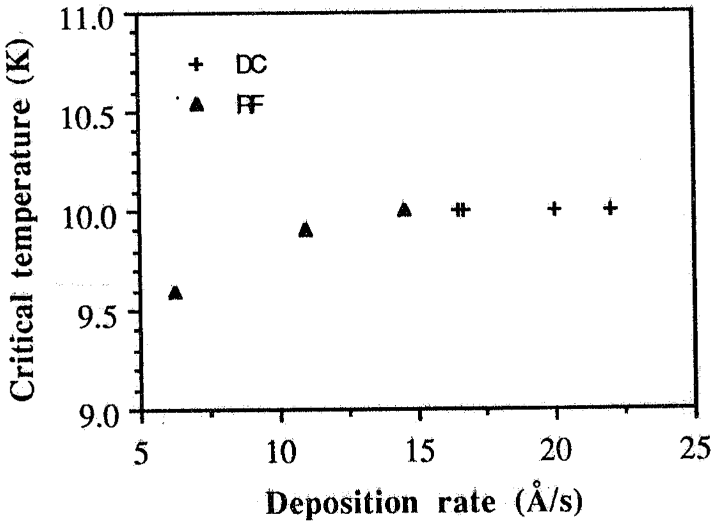

FIG. 3 - Critical temperature as a function of the deposition rate for $Nb_{75}Zr_{25}$ superconducting films.

The magnetic behavior of $Nb_{75}Zr_{25}$ films has also been analysed. Fig. 4 shows the measured $H_{c2}(t)$ behavior, $t=T/T_c$, being the reduced temperature, and $T_c=10.14$ K. The magnetic field is parallel to the surface and perpendicular to the bias current. By using the relation[10] $H_{c2}(0) \approx 0.7\,[dH_{c2}(T)/dT]_{T=T_c}$ a value of $H_{c2}(0)=11$ Tesla has been estimated. From the Gor'kov formula[11] $H_{c2}(0) = 1.77\,\kappa_1\,H_c(0)$, where $H_c(0)$ is the thermodynamic field, and from previously reported data[12] on κ_1, one computes $H_c(0) \approx 2800$ Gauss, somewhat higher than the value for Nb. Because the upper limit of the corresponding electric accelerating field that can be attained in the cavity is related to the superheating field[6] $H_{sh} \approx 0.75\,H_c$, we expect that, from this point of view, the $Nb_{75}Zr_{25}$ alloy is not worse than Nb.

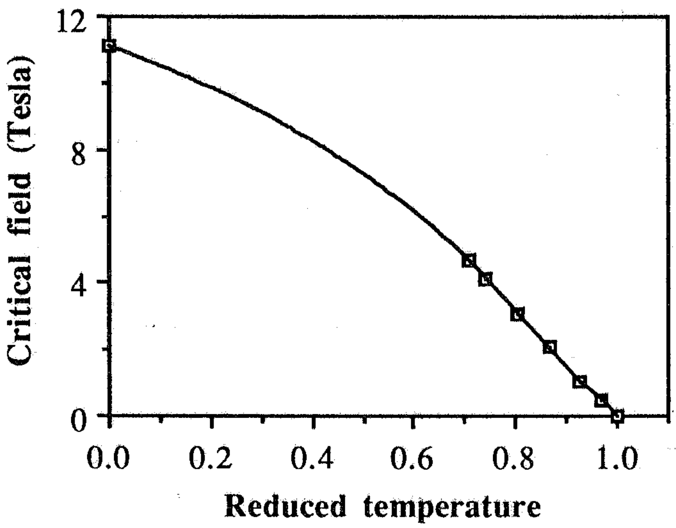

FIG. 4 - Measured upper critical field of $Nb_{75}Zr_{25}$ superconducting films. The value $H_{c2}(0)$ is computed by theory.

To obtain a more accurate estimate of R_{BCS} we measured the value of the superconducting energy gap Δ by means of a $Nb_{75}Zr_{25}/Nb_{75}Zr_{25}$ tunnel junction. Fig. 5 shows the dV/dI - V characteristic of a tunnel junction at 4.2 K, recorded by using an a.c. bridge. From the measured $\Delta(4.2)$ value and using the normalized BCS curve[13] of $\Delta(t)$, we extrapolate a value of $\Delta(0)=1.63$ meV; the ratio $2\Delta(0)/K_BT_c$ is thus ≈ 3.8. The estimation of R_{BCS} for our samples is about 82 nΩ at 4.2 K and 500 MHz.

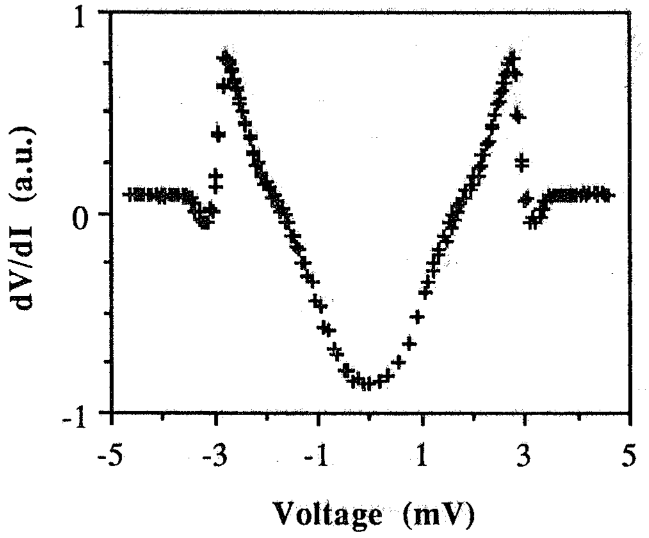

FIG. 5 - Dynamical resistance vs. sample voltage for a $Nb_{75}Zr_{25}$ / $Nb_{75}Zr_{25}$ tunnel junction.

3. - RF MEASUREMENTS

The measurement of the RF properties of the $Nb_{75}Zr_{25}$ film was performed at a frequency of 7850 MHz, in the temperature range 4.2÷1.8 K. The Cu disc coated with the superconducting film was used as the bottom flange of a Nb cylindrical cavity operating in the TE_{011} mode, in order to have a current free joint and thus the possibility to seal the cavity with a lead O-ring.

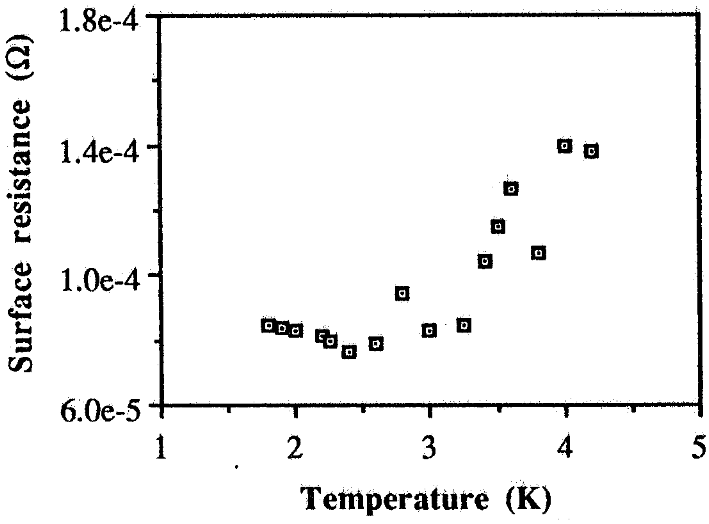

FIG. 6 - Surface resistance of $Nb_{75}Zr_{25}$ film at a frequency of 7850 MHz as a function of the temperature.

We measured the unloaded quality factor Q_0 of the composite cavity as a function of the bath temperature. The cavity RF power losses of can be written as

$$P_{tot} = P_{Nb} + P_x$$

P_x being the losses related to the unknown material (in our case the $Nb_{75}Zr_{25}$ film). We can readily write the surface resistance of the sample, R_{Sx}, as:

$$R_{Sx} = (1/Q_0 - R_{SNb}/\Gamma_{Nb})\,\Gamma_{Nb75Zr25} \qquad (1)$$

where R_{SNb} is the surface resistance of the Nb cavity, $\Gamma_{Nb} = 856\ \Omega$ and $\Gamma_{Nb75Zr25} = 10700\ \Omega$ respectively are the magnetic geometric factors of the Nb and $Nb_{75}Zr_{25}$ parts, and Q_0 is the measured quality factor of the complete cavity. The gammas are in our case easily computed either analitically, the field distribution into the cavity being espressed in the form of Bessel functions, or numerically with a computer code (e.g. OSCAR2D, SUPERFISH, etc). The surface resistance of the $Nb_{75}Zr_{25}$ film, computed from eq. 1, as a function of the temperature is shown in Fig. 6. The sample showed a R_{res}≈80 μΩ below about 2.5 K. The measured $R_S(4.2)$≈138 μΩ, leads to a R_{BCS} of 58 μΩ at 4.2 K and 7.85 GHz.

This result does not match the value $R_{BCS} \approx 22\ \mu\Omega$ that is expected from theoretical considerations on a $Nb_{75}Zr_{25}$ material having $\rho_n \approx 30\ \mu\Omega$ cm and $T_c=10.14$ K.

4. - CONCLUSION

The study of superconducting materials suitable for coating of Cu accelerating cavities, with improved performance with respect to pure Nb, is in progress. As already observed in high T_c NbN, films either granularity or the difficulties in getting the right phase on an unheated substrate do not make the use of this compound easy. The study of metallic alloys, such as NbZr, may help to overcome granularity problems while offering higher T_c and critical fields than Nb. However the very first results indicate again the presence of high R_{res}. Further measurements and analysis of the SC film properties on the Cu substrate are needed to explain this result.

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