ALTERNATIVE SUPERCONDUCTING MATERIALS FOR R.F CAVITY APPLICATIONS

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ABSTRACT

The improvement of sputter-coating techniques and the increased control of the surface coating processes by reactive diffusion have made possible the fabrication of high quality r.f. cavities for particle accelerators based on medium T_C compounds (NbTiN, Nb_3Sn) that have shown potential advantages over niobium for operation at 4.2K and therefore represent an interesting alternative to traditional Nb bulk or Nb coated cavities. In the present paper the basic criteria for selecting the materials are discussed. Results obtained in different Laboratories on medium T_C compounds both on small scale resonators and real cavities will be also presented and analysed . The perspectives for future work in the field will be also discussed .

INTRODUCTION

The idea of using superconducting compounds with T_C higher than niobium (MoRe, NbTa, NbN, Nb_3Sn) for the fabrication of high quality r.f. cavities for particle accelerators (or other applications) was already proposed in the mid seventies (see ,as an example,[1-3]). However the low quality of the superconducting surfaces produced fairly high losses that combined to quench problems related to the poor thermal conductivity of superconducting compounds, prevented any real success in applications. In the mid eighties the improvement of surface treatment and analysis techniques brought to more encouraging results using surface reaction techniques [4] . In the same years the CERN group set up a very innovative technique consisting in sputter-coating with a thin superconducting film a copper cavity [5-6] . In this way the possible choice of alternative superconductors was in principle much larger, since the thermal conduction was ensured by the copper substrate .

In the last ten years advanced research was carried out in this field with fairly encouraging results, though many problems remain to be solved in view of the use of superconucting compound cavities in particle accelerators.

In the present paper I will first describe the main selection criteria of superconducting compounds for r.f. applications. Tests made on both small scale samples and real cavities will be then presented together with data analysis and interpretation. The latest results obtained in the field and the future perspectives will be finally discussed.

SELECTION CRITERIA

In the theoretical description of the superconducting state (BCS theory) three main microscopic parameters need to be used :

$N(E_f)$: density of states at the Fermi energy
l_o : mean free path (due to impurity scattering)
$V_{e\text{-}e}$: effective (phonon mediated) electron-electron interaction

these represent respectively the effective number of free electrons, their scattering rate and their (phonon mediated) effective attraction.

These parameters can be written in terms of corresponding, directly measured, macroscopic parameters in the following way :

γ : Sommerfeld constant ($C_e = \gamma T$) $= \pi^2 K_b N(E_f)/3$
ρ_o : Residual resistivity (~ 1/RRR) $= [e^2 N(E_f)\, v_f /3]$
T_c : Critical temperature $= 1.14\, \Theta_d \exp[-1/V_{e\text{-}e} N(E_f)]$

(RRR is the residual resistivity ratio, Θ_d is the Debye temperature, v_f the Fermi velocity).

In the same frame, for a type II superconductor in the dirty limit, the relevant quantities for R.F. applications can be in turn expressed in terms of these macroscopic parameters as follows (CGS units, $T < T_c/2$) :

$$R_s(BCS) = A\, \rho_o^{1/2} \omega^2 \exp(-1.76\, \eta\, T_c/T)\{[\ln(.76\, \eta\, K_b T_c / 2 h \omega)/\sqrt{(3.52\, \eta\, T_c T)}]\} \qquad (1)$$

($A = 6*10^{-21}$, the term in {} is slowly temperature dependent , $\eta \geq 1$ is the strong-coupling correction)

$$\lambda = B\, [\rho_o/\eta T_c]^{-1} \qquad (B=10^{-2}) \qquad (2)$$

$$H_c = C\, \gamma^{1/2} \eta T_c ,\ H_{c1} = D \eta T_c / \rho_o = D\, B^2/\lambda^2 ,\ H_{sh} = 0.75 H_c \qquad (3)$$

($H_{c2} = E\, \gamma \rho_o \eta T_c$, $C = 2.4$, $D = 2*10^{-4}$, $E = 3*10^4$)

These approximate expressions clarify that for superconducting alloys and compounds, at a given operating temperature, the best r.f. performances (low R_s and λ, high relevant critical fields) are obtained for high T_c and low ρ_o materials .

This can be better seen in Fig. 1 . The R_s(BCS) v.s. T_c , ρ_o normogram is computed by expression (1) [7] . The data points represent typical values for different superconducting compounds. Based on Fig. 1 , the better results can be expected with

A15 compounds (Nb_3Sn, V_3Si). Nitrides (NbN, (NbTi)N) present an higher R_S (BCS) due to the higher value of ρ_O and transition metal alloys such as MoRe do not gain a lot in respect to Nb since T_C is only slightly higher.

Of course these ideas represent only a "first approximation" approach , since many other consideration come into play. First of all the surface for a real superconductor can differ significantly from the BCS prediction at low temperatures, due to the presence of additional losses caused by a number of possible sources (residual surface resistance) and this losses depend strongly on the degree of structural and morphological perfection of the surface . Moreover , depending on the specific preparation technique (sputtering or surface reaction) some materials can present additional problems. As an example A15 films need to be deposited on high temperatures (700-800°C) substrates , and this can be a serious problem in the sputter-coating technique , due to the possible interdiffusion with Cu .

On the basis of these considerations the first attempts to use alternative materials in the sputter-coating technique were addressed to NbN, due to the relatively high T_C even when deposited on relatively low temperature substrates (T_S = 200°C). However as clear from Fig. 1, the high resistivity due to intrinsic tendency to vacancies on the N sites and granularity, induces a quite high normal state resistivity and, in turn, an high value of the BCS surface resistance.

These problems could be partially overcome by the use of (NbTi)N alloys (close to 50% Ti percentage) [8] that present a lower normal state resistivity and the same T_C as NbN.

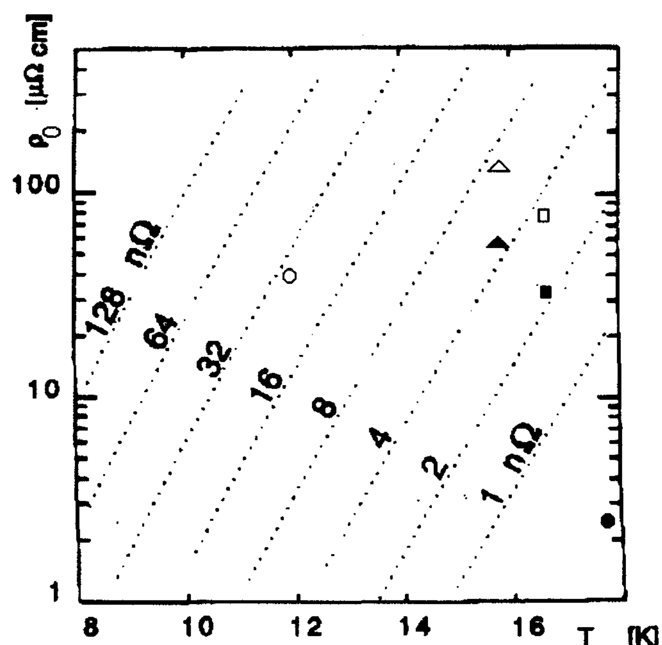

Fig. 1 Lines of equal R_{BCS} in the (ρ_0,Tc) plane at T=4.2 K and f= 0.5 GHz. (O)MoRe, (■)NbTiN, ((▲)NbTiN T_S=200°C), (□)NbN, ((Ω)NbN T_S=200°C), (●) Nb_3Sn; for Nb R_{BCS} =55nΩ.

The higher metallicity of (NbTi)N in respect to NbN turned out to give also a technical advantage in the sputtering process [9] and therefore most of the work done on real cavities with the sputtering technique has been carried out up to now with this material . In the surface reaction technique instead most of the work has been carried out on Nb_3Sn, mostly due to the availability of extremely well characterized Nb “substrates” (the standard high RRR Nb-bulk accelerating cavities) and the relatively easy Sn-vapour reaction technique [10].

RESULTS AND DISCUSSION

The r.f properties of innovative materials such as NbTiN and Nb_3Sn have been studied in the last decade using different techniques, namely microstrip techniques on small test samples deposited on shappire [11,12], endplate replacement cavity techniques [10, 13] or real cavity measurements [9,14] . The results and the indications obtained by the different methods are indeed very similar and consistent, so I will only present here those obtained in our Laboratory in Naples by the microstrip technique .

In Fig. 2 the quality factor Q of NbTiN and Nb_3Sn microstrip resonators (ring an meanderline respectively) is reported as a function of the r.f. field amplitude . The relatively low Q is linked to the low value of the "geometrical" parameter Γ appearing in the general relation $Q=\Gamma/R$ ($\Gamma= 1\Omega$ in our case) and to the high operating frequency (3.5GHz, the Q value has to be multiplied by $3*10^4$ to be compared to a standard 350MHz CERN-LEP cavity for particle accelerators).

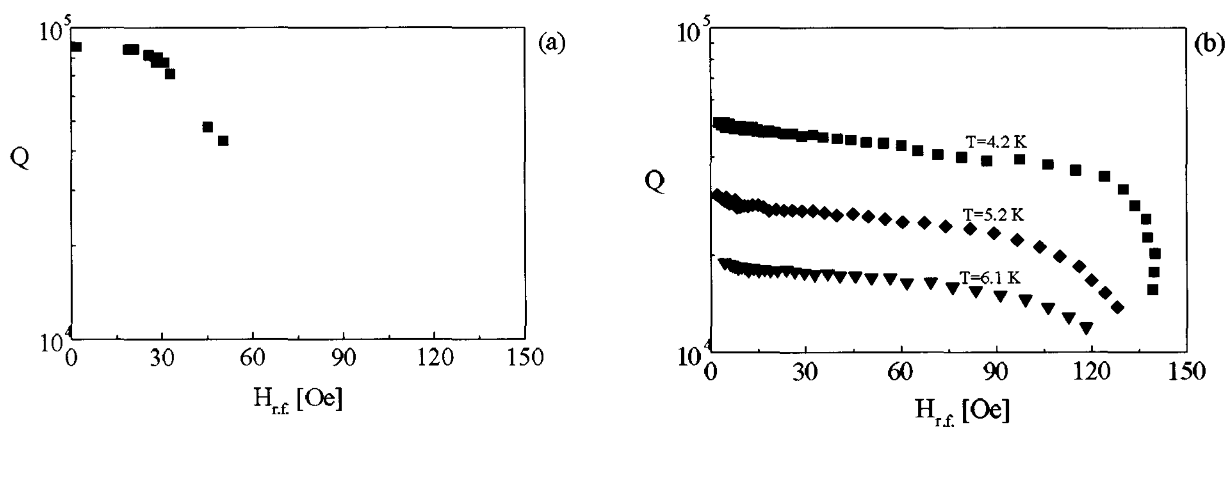

Fig. 2 Quality factor Q vs r.f. magnetic field Hr.f.: (a) for a (NbTi)N resonator at T=4.2 K and f=3.5 GHz; (b) for a Nb_3Sn at T=4.2 K, 5.2 K, 6.1 K and f=3.5 GHz.

In both cases a clear, strong, "slope" of the Q value with the applied r.f. field is observed (H_{rf} of 40 Oe is equivalent to an accelerating field of 1MV/m).

As mentioned above, similar results have been obtained by different techniques, though recently much better results in terms of "Q-slope" were obtained with surface reaction coated Nb_3Sn cavities [14]. In any case though, as predicted by the theory , the BCS surface resistance is much lower than for Nb and that the "residual" surface resistance is comparable to Nb, the "Q-slope" is markedly higher than for niobium so that the resonator performances become inferior to those of Nb resonators at high field.

To gain insight in the origin of the residual losses and the "Q-slope" a quite general model has been recently proposed [12]. It can in fact be shown that many types of losses (intrinsic effects predicted in the BCS framework, vortex penetration [15], weak link vortices [16,17], weakly coupled grains described by a non-linear Josephson inductance [18,19].) can be described using the simple equivalent circuit for a superconductor shown in Fig. 3. Here σ_1-iσ_2 represents the BCS conductance (weakly field-dependent) and α-iβ represents a conductance describing the losses due to "in series" weaker superconducting regions of various possible origins (including grain boundary weak-links, trapped flux, etc.).

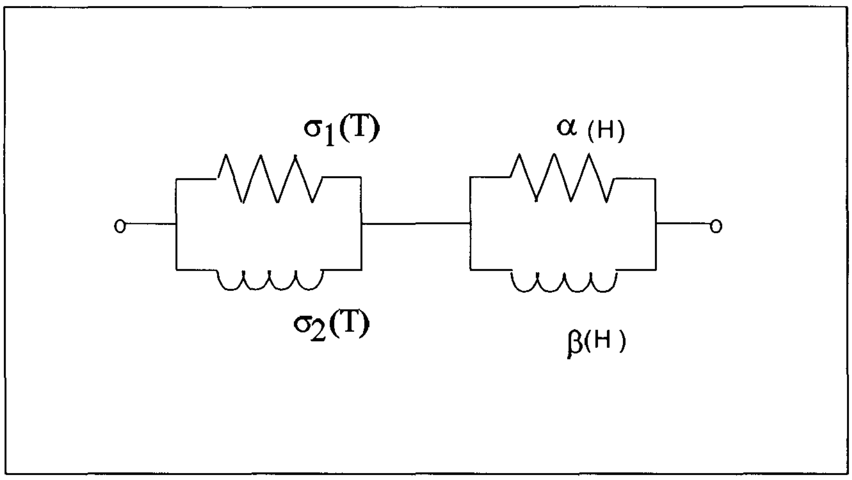

Fig. 3 Equivalent circuit describing the surface impedance of a real superconductor.

Assuming $\sigma_1 << \sigma_2$ and $\alpha << \beta$ we are led to the following general expressions :

$$R_S = \frac{1}{2\lambda}\left[\frac{\sigma_1}{\sigma}\left(1+\frac{\alpha^2}{\beta^2}\right)+\frac{\alpha}{\beta^2}\right] \qquad (4)$$

$$X_S = \mu\omega\lambda \qquad (5)$$

$$\lambda^2 = \left[\frac{1}{\mu\omega}\left(\frac{1}{\sigma_2}+\frac{1}{\beta}\right)\right] \qquad (6)$$

We note that, due to the inductive character of the related circuit element , it is

$\beta \propto 1/f$ whereas α is frequency independent. Furthermore, α and β can be assumed temperature independent (at least for $T \leq Tc/2$) and field dependent ($\alpha = \alpha(H)$, $\beta = \beta(H)$). With these hypothesis, from eq. 6a, since σ_1 goes exponentially to zero with temperature, and σ_2 is temperature independent for $T \leq Tc/2$, we can identify the "residual" term being:

$$R_0 = \frac{1}{2\lambda}\frac{\alpha}{\beta^2} \qquad (7)$$

It is worth observing that with this model the phenomenological expression $R_S=R_O+R_{BCS}$ breaks down and we should write instead :

$$R_S= R_O(H) +\text{"}R_{BCS}(T)\text{"}f(H) \qquad (8)$$

with:

$$R_{BCS} = \frac{1}{2\lambda}\frac{\sigma_1}{\sigma_2^2}$$

$$f(H) = 1+ \alpha^2(H)/\beta^2(H)$$

The peculiarity of eqs. (4)-(7) is to present general properties well describing many of the observed features of the data found with innovative materials. In particular the data found for NbTiN can be well interpreted assuming for α and β the expressions that can be obtained in the coupled grains model and for Nb_3Sn with the expressions of the Halbritter/Portis type models for flux penetration at grain boundaries [16,17]. This is also confirmed by the observed "r" values (r= ΔR (H)/ΔX (H)[20]) being r= 10^{-2} in the first case and r = 0.5 in the second one [21] .

As a matter of fact, though different mechanisms seem to be responsible of the losses in different materials, in all cases the improvement of surface structural and morfological properties would lead to a significant loss reduction.

CONCLUSIONS

Innovative materials for accelerating cavity applications have been widely studied in the past, but a much bigger effort should be now necessary to improve the sputter-coating techniques and/or the surface reaction techniques to achieve materials with a sufficient degree of surface perfection to limit spurious losses (that have been proved to be due to defects, grain boundary weak-links etc.) and avoid the "Q-slope" problem. Encouraging results were obtained with NbTiN coatings [9] and recently very promising results have been obtained with Nb_3Sn [14]. In the light of these achievements and of the continuous progress in the surface coating and surface characterisation techniques, it is worth to invest further efforts in the development of innovative materials and techniques for a new generation of high performance accelerating cavities.

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