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THIN DIELECTRIC FILMS IN SUPERCONDUCTING CAVITIES*

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It was recently reported[1,2] that anodic oxidation of Nb cavities leads to an improvement by a factor of ~ 2 in both the superconducting Q and magnetic breakdown field, H_p'. Several years ago, coating the surface of superconducting cavities with a dielectric was proposed both to reduce field emission losses and to protect the cavity from deleterious effects of air exposure.[3] Experiments carried out[3] to determine the effect on field emission of dielectric films showed that Pb whiskers could grow through an Al_2O_3 overcoating and vitiate any reduction of the electric field by the dielectric.

We propose that rather than merely adding to the metal a dielectric layer which reduces the local electric field by a factor κ (the dielectric constant), anodization of niobium converts small conducting protrusions into dielectric material, thus vastly reducing or entirely eliminating their ability to enhance both electric and magnetic fields. This mechanism is especially important for the Martens et al.[1] cavity which was operated in the TE_{011} mode, with no electric field on the cavity surface. Our suggestion[4] has generated interest in the possibility that successive anodization and stripping of the oxide may be a partial substitute for the technique of high temperature firing of cavities to improve their Q and H_p'. This may allow the use of cheaper, lower temperature processing ovens. We feel that the presence of a dielectric such as Nb_2O_5 may ultimately lead to deleterious effects in a superconducting cavity.

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Since the reported work[1,2] made no mention of the loss tangent, $\tan\delta$, of Nb_2O_5, and it is not available in the published literature, we here make an upper limit calculation. The average dielectric power loss per unit volume is

$$\left\langle \frac{dP}{dV} \right\rangle = \frac{1}{2}\omega\kappa\epsilon_0 E_0^2 \tan\delta, \tag{1}$$

where ω is the angular frequency, κ is the dielectric constant, ϵ_0 is the vacuum permittivity, and E_0 is the peak electric field at the dielectric. Although the addition of Nb_2O_5 increased Q slightly, to put an upper limit on $\tan\delta$, we will assume that the dielectric loss dominates in the oxide-coated cavity.

$$Q \doteq \frac{2\pi\left[\frac{1}{4}\int_0^{V_c}\left(\mu_0 H_0^2 + \epsilon_0 E_0^2\right) dV\right]}{\frac{2\pi}{\omega}\int_0^{V_d}\frac{1}{2}\omega\kappa\epsilon_0 E_0^2 \tan\delta\, dV}, \tag{2}$$

where V_c and V_d are, respectively, the volume of the cavity and of the dielectric, μ_0 is the vacuum permeability, and H_0 is the peak magnetic field. Therefore, to a good approximation for TM cavities,

$$\kappa \tan\delta \sim \frac{1}{Q}\left(\frac{V_c}{V_d}\right). \tag{3}$$

Kneisel et al.[2] report $Q \sim 10^9$ (at an unspecified temperature, probably $\sim 2^\circ$ K) for their TM_{011} S-band cavity with $\frac{V_c}{V_d} \sim 10^5$. Therefore, from Eq. (3), $\kappa \tan\delta \sim 10^{-4}$. Extrapolating the data of Duffy et al.,[5] $\kappa \doteq 6$ at 2.6 GHz, assuming no resonance in this region. Therefore, for Nb_2O_5, $\tan\delta \sim 10^{-5}$ at 2.6 GHz and $T \sim 2^\circ$ K.

It should be borne in mind that Nb_2O_5 is an ionic dielectric.[6] Because of the distribution of relaxation times in such materials, there is no sound basis for extrapolation of the value of the loss tangent calculated above to considerably different frequencies or temperatures. For example, the loss tangent of another ionic dielectric, NaCl, has been measured[7] over the frequency range 40 to 1000 MHz. The loss tangent shows rapid variations with frequency and temperature. The 4.2° K tn δ values increase from 3.2×10^{-5} at 434 MHz to 9.7×10^{-5} at 996 MHz. The loss tangent at 996 MHz (9.7×10^{-5}) decreases to 5.3×10^{-5} at 2.2° K and further to 3.2×10^{-5} at 1.8° K. Such dramatic and rapid variations indicate that extreme caution should be used in extrapolating results obtained for Nb_2O_5 at 2.6 GHz and $\sim 2^{\circ}$ K to other frequencies and temperatures, particularly L-band ($\sim$ 1.3 GHz) at which a large machine is presently being constructed.

It has been established that irradiation of dielectrics[8] can increase the low temperature value of the loss tangent by a factor between 10 and 100. Oxide-coated cavities in an accelerator would certainly find themselves in a radiation environment. A reduction of Q by a factor of 10 during operation would probably not be acceptable. The dielectric with the lowest loss prior to irradiation may not be the most radiation resistant.

It is well known that color centers may be formed in dielectrics irradiated by photons of energy a few tens of eV and higher, as well as by particle bombardment. A color center is a lattice defect (binding a charged particle), which absorbs light. Therefore, (aside from radiation produced by beam missteering and accidents) field emitted electrons as well as the synchrotron radiation concomitant with necessary bending of the electron beam (as in a recirculator) will produce charge traps in many dielectrics. The interaction of the bound charge in these defects with the electric field will greatly increase the dielectric loss as has been observed for quartz.[8]

To minimize the effects of a large dielectric loss, one might be tempted to make the dielectric thinner. Aside from the problems of making a continuous dielectric film which is substantially thinner (30 Å rather than 300 Å), one encounters the Malter,[9] Stern, Gossling, and Fowler[10] effect. If the dielectric charges positively (due to a secondary electron emission coefficient greater than one, and/or positive ion impact), then for thin films, the electric field across the layer can produce copious electron emission from the substrate by a tunneling process.[11] This is an additional source of power loss. For thick films, the electric field usually does not build up to a high enough value for this to happen, but dielectric voltage breakdown or substantial conduction losses may occur.

The presence of the dielectric enhances the secondary electron emission yield over that of the metal, further increasing the likelihood of multipactoring and associated problems.

In addition to reducing field emission, a dielectric coating on a cathode may also increase the breakdown voltage.[3] Jedynak[12] has increased the breakdown voltage by almost a factor of 2 by using dielectric films thicker than 2000 Å on his cathodes. However, a dielectric coating on an anode can severely lower the breakdown voltage. For alternating radiofrequency fields, the net effect on breakdown voltage due to dielectric coatings is yet to be determined. If the coating is not self-healing, a breakdown which punctures the dielectric will generally cause subsequent breakdown at voltages lower than if the dielectric were not present at all.[12]

Stress induced, during thermal cycling, due to lattice mismatch between dielectric and substrate can enhance the probability of whisker growth. As was observed,[3] whiskers were capable of growing right through the dielectric.

Though the addition of a dielectric coating might possibly be advantageous, unless the above effects are understood and studied, any overall advantageous result may turn out to be serendipitous.

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