DEPTH DISTRIBUTION OF LOSSES IN SUPERCONDUCTING NIOBIUM CAVITIES*

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Abstract

In order to improve performances of superconducting niobium cavities it is crucial to understand the structure of near-surface few tens of nanometers of the material. In particular, superconducting properties of niobium, which depend on the presence of impurities and lattice defects, may be non-uniform in the magnetic field penetration depth. In the first part of his contribution we report on "depth profiling" of the near-surface RF layer using hydrofluoric acid/water rinsing combination. Changes in the $Q_0(E_{acc})$ curve were investigated on electropolished, tumbled electropolished, and buffered chemical polished cavities as a function of number of HF rinsing cycles. A significant improvement in quality factors at all fields was obtained after a single HF rinse of the 120^{0}C baked cavity. In the second part of this paper we report a strong correlation between the medium and high field Q-slopes as discovered using detailed temperature mapping.

INTRODUCTION

RF currents flow in SRF niobium cavities only in the thin surface layer of a characteristic thickness of about 40 nanometers at 2 K. The structure of this layer determines fully the performance of such cavities. Mild baking at 120^{0}C, which is used to eliminate the high field Q-slope (HFQS), was shown to produce changes in niobium extending to a few hundred nanometers deep [1], out of which about 20 nanometers have the changes relevant (or high enough) to eliminate the HFQS [2, 3]. In the first part of this work we study changes in the full $Q_0(E_{acc})$ curve as the 120^{0}C baked cavity undergoes sequential material removal steps by HF rinsing alternating with water rinsing to re-oxidize fully the surface. The principle of the process is schematically depicted in Fig. 1.

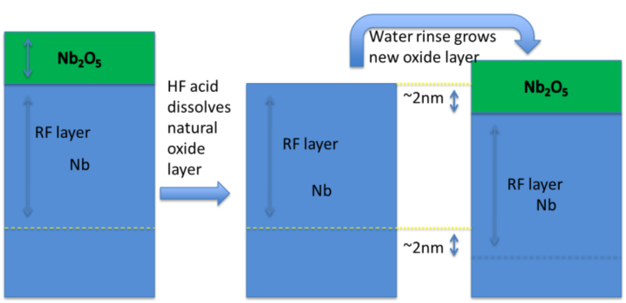

Figure 1: Schematic of the principle behind HF/water rinsing "nanoremoval".

During such process the cavity is first filled with the concentrated HF (48%). Natural niobium oxide Nb_2O_5 is dissolved almost immediately by the reaction with HF leaving bare niobium surface. After 5 minutes an HF acid is dumped and a cavity is filled and rinsed three times with ultrapure DI water. We assume that a new oxide of the same 4-5 nanometers thickness is formed in such a way. The thickness of niobium layer converted to oxide can be estimated based on the densities of Nb and Nb_2O_5 and we found it to be about 1.5-2 nm. Thus the net result of each HF/water cycle is a re-growing of the oxide and shifting of the RF layer about 1.5-2 nanometers deeper compared to before the cycle. Each of the cycles (or several cycles in some cases) is followed by HPR and RF testing of the cavity and thus we are able to evaluate the distribution of lossy layers inside the penetration depth.

In the other part we consider the connection between the medium and high field Q-slopes. We report our findings on the distribution of losses at medium and high fields using the temperature mapping system.

RESULTS

HF rinsing

We have used three different cavities for these studies with the processing histories before HF rinsing experiments summarized in Table 1.

Table 1: Cavity processing history.

Cavity	Material/prior history
TE1AES003	Fine grain, BCP 120 um
TE1ACC002	Fine grain, EP 120 um, tumbling to a mirror-smooth finish, 800^{0}C 3 hours vacuum degassing, 40 um EP
TE1ACC005	Fine grain, EP 120 um

BCP-treated cavity TE1AES003 had a high field Q-slope even after 120^{0}C 48 hours treatment, while the other two cavities had it removed and that was the starting state for the HF rinsing experiments.

RF test results after multiple successive rinses on each of the cavities are shown in Fig. 2-4.

One of the universal effects found on all three cavities was that a single HF rinse increased Q_0 at all fields due to the apparent decrease in the residual resistance. The "side" effect of a 120^{0}C bake is to decrease the BCS component of surface resistance by ~50% and to increase the residual component [1]. Hence the natural interpretation of our result is that HF rinse removes the

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layer responsible for the high residual losses after bake, which in turn indicates that either oxide itself or first ~2 nanometers under it are the source of such losses.

This finding has important practical applications as it allows improving the Q_0 at all fields by 15-35% compared to the standard processing by applying an HF rinse.

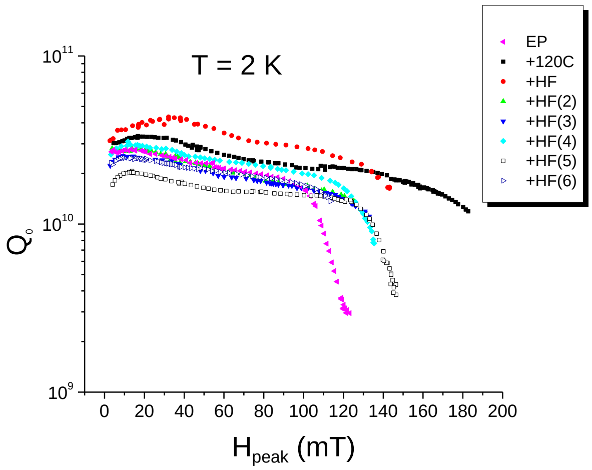

Figure 2: Results on TE1ACC002.

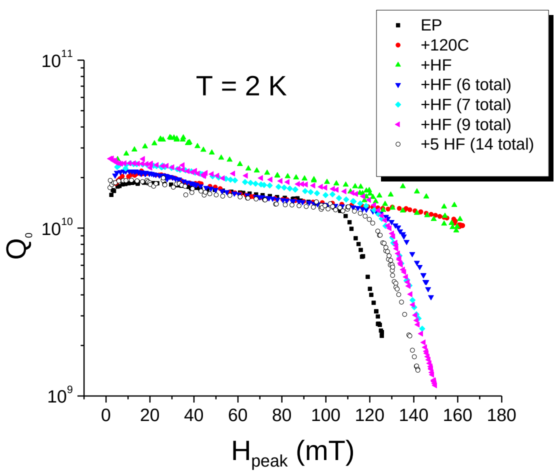

Figure 3: Results on TE1ACC005.

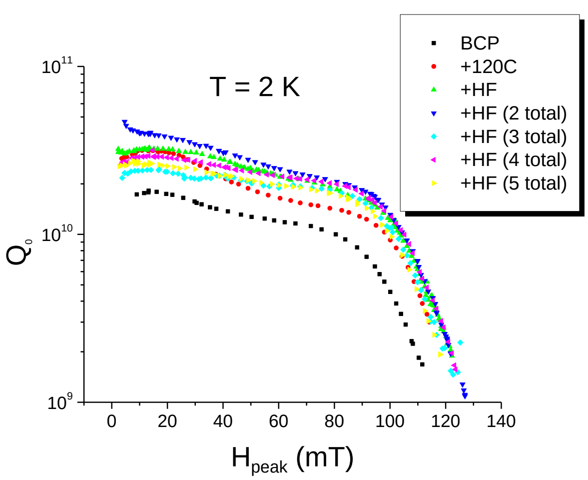

Figure 4: Results on TE1AES003.

The other significant result is a reappearance of the high field Q-slope in EP cavities after several HF rinses. In Fig. 3 the onset field of the HFQS is shifted to lower fields with each HF rinse cycle. Even after 14 HF rinse/water rinse cycles, which should remove about 21-28 nanometers of niobium, the HFQS is not back to the same onset field as before 120^0C baking, but remains at about 15 mT higher.

Further detailed analysis of low, medium, and high field Q-slope evolution with consecutive HF rinsing is being prepared for publication in a separate article.

Correlation between medium and high field Q-slopes

To our knowledge so far there was no reported connection between the medium and high field Q-slopes. To investigate this issue we have performed detailed analysis of temperature maps obtained during RF tests of cavities with the medium and high field Q-slopes. $Q_0(E_{acc})$ curve for one of the fine grain EP cavities we investigated is shown in Fig. 5 and corresponding temperature maps taken at E_{acc} = 16 MV/m in the medium field Q-slope range and at E_{acc} = 26 MV/m above the high field Q-slope onset are shown in Fig. 6a and Fig. 6b respectively. Similar results were obtained on another fine grain EP cavity. Two different things are apparent. First, the losses leading to the medium field Q-slope are concentrated in the high magnetic field region around cavity equator. Second, heating patterns are almost exactly the same in both temperature maps – hotter areas at medium fields are hotter at high fields. Therefore, a strong correlation between the medium and high field Q-slope is apparent. Similar results were obtained on a different fine grain cavity.

Since the losses are highly correlated, their origin may be the same. A possible interpretation of these findings is being developed in a separate paper. In brief, we suggest that both medium and high field anomalous losses may be due to small hydrides formed around vacancy-hydrogen complexes in niobium upon cooldown to 2 K.

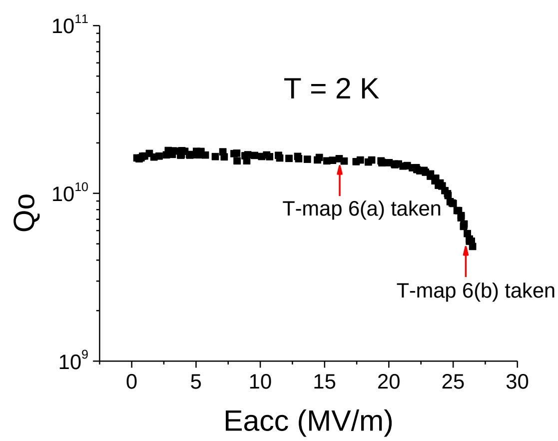

Figure 5: RF test results of the EP cavity. Field levels at which the temperature maps shown in Fig. 6 are taken are marked by arrows.

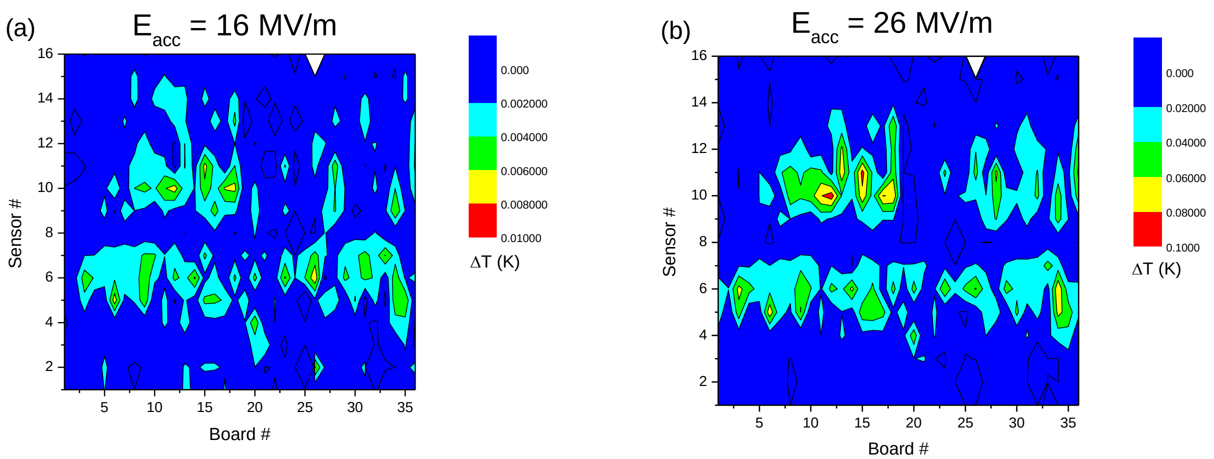

Figure 6: Temperature maps taken at (a) E_{acc} = 16 MV/m; (b) E_{acc} = 26 MV/m during the RF test shown in Fig. 5. Note a strong correlation between the heating patterns in the medium and high field Q-slope range.

Such complexes may form in niobium in excessive quantities in the presence of hydrogen – a so-called "superabundant vacancy" formation process. We suggest that the resulting hydrides nucleated around such complexes upon cool down are superconducting (but with altered properties) by proximity effect up to the critical field, which determines the high field Q-slope onset. The concentration of vacancy-hydrogen complexes drastically decreases by a 120^0C baking as we found out by positron annihilation [5], which may explain the removal of the high field Q-slope. Further details of this model will be reported elsewhere.

CONCLUSION

We performed multiple HF rinse cycles on several differently treated cavities to explore the distribution of lossy layers within the first several tens of nanometers. Consecutive HF cycles were found to gradually bring the high field Q-slope back in 120^0C baked cavities. We found that a single HF rinse restores the residual resistance increased by prior mild baking making the higher Q_0 possible by combination of baking/HF rinse. It was found that the high magnetic field region dominates the medium field Q-slope heating. MFQS heating patterns are found to be in strong correlation with the high field Q-slope ones in fine grain EP cavities. This hints towards the same underlying cause of these slopes.

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