Field Emission Studies of Heat Treated and Chemically Treated Superconducting Cavities*

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ABSTRACT

With the newest heat treatment techniques, average surface electric fields of 50 MV/m with a maximum of 60 MV/m have been reached in 1.5 GHz single cell cavities. Using a high speed temperature mapping system, extensive studies have been carried out on the nature of emitters in RF cavities under various surface treatments. Results show that, like emitters studied with DC field, emissive areas are randomly distributed between 10^{-8} to 10^{-13} cm^2, and β values fall between 75 and 500. The density of emitters is about $0.2/cm^2$ at 40 MV/m with standard surface treatment, falling by a factor of 10 with heat treatment, which lowers β values. Clean air, water and methanol are proved not to be dominant sources of emitters which limit the performance of chemically treated cavities. Other than debris introduced by improper cleaning or assembly procedures, chemical residues or minute impurity inclusions remain important possibilities to be investigated. Condensed gases are shown to enhance emission from potential sites, and He processing is shown to be effective against the associated emission but its effectiveness decreases when higher initial fields are reached by techniques which provide cleaner surfaces.

BENEFITS OF HEAT TREATMENT

Encouraged by early results from DC field emission studies[1], there has been considerable exploration of the influence of high temperature annealing in the final stages of RF cavity preparation using 1-cell 1500 MHz cavities[2,3]. In 27 tests of fired cavities, the average accelerating field increased from 14 to 24 MV/m (assuming Epk/Eacc = 2). The most significant reduction in field emission is observed for heat treatments carried out at 1400-1500 C for periods between 4 - 8 hours. Fig. 1 shows that the average surface field reached in 6 separate heat treatments at 1500 C was 50 MV/m, with the record of 60 MV/m [3]. Lower temperature (1100-1350 C) treatments, not shown here, are also found useful in reducing field emission in RF cavities, but less substantially [3]. First results with temperatures > 1500 C indicate that new difficulties arise with thermal breakdown which are still under investigation. In the past, heat treatment up to 1800 C was used when cavities were limited not by field emission but by multipacting and thermal breakdown. Hence the fields reached with 1.5 GHz 1- cells were still low, Ep = 7 - 21 MV/m [4]

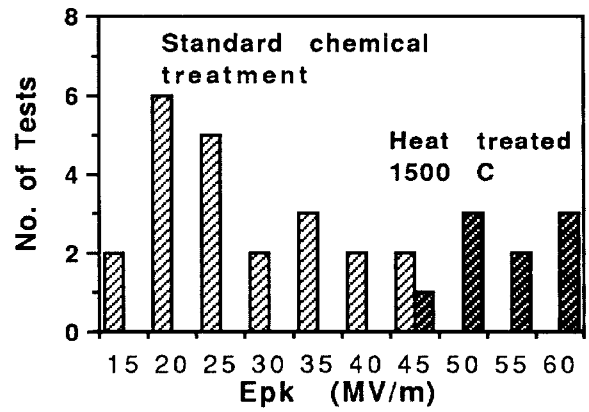

Fig. 1: Maximum field reached in chemically treated and heat treated (1500 C) cavities.

Past emission studies in RF cavities have been measurements of the current collected by an RF pick-up probe, or the X-ray intensity outside the cryostat, or increased cavity losses. These measurements integrate over the current from several active emitters. More detailed studies that localize individual emission sites and determine individual emitter Fowler- Nordheim (FN) properties are based on measurements of the cavity wall temperature increases caused by impinging electrons, i.e. temperature maps [5]. The maps can also be used to compile statistics on the numbers of emitters as a function of field level.

COMPARISON OF TEMPERATURE MAPS FROM CHEMICALLY TREATED AND HEAT TREATED CAVITIES

From a typical test on a chemically treated cavity, a selection of maps at 18 to 31 MV/m is shown in Fig. 2. At the lower fields, dominant emission sites processed quickly, whereas at the highest field, the emission was stable and the sites would not process with up to 50-100 watts of cw power. In contrast, heat treated cavities of Fig. 1 showed no significant emission up to 35 MV/m. Unfortunately, emitters are not completely eliminated. Fig. 3 shows the appearance of emitters on the surface of a heated cavity as the field level is raised above 35 MV/m to 51 MV/m.

FOWLER NORDHEIM (FN) PROPERTIES OF EMITTERS

Using temperature maps and analysis methods described in [6], FN properties of emitters observed in chemically treated

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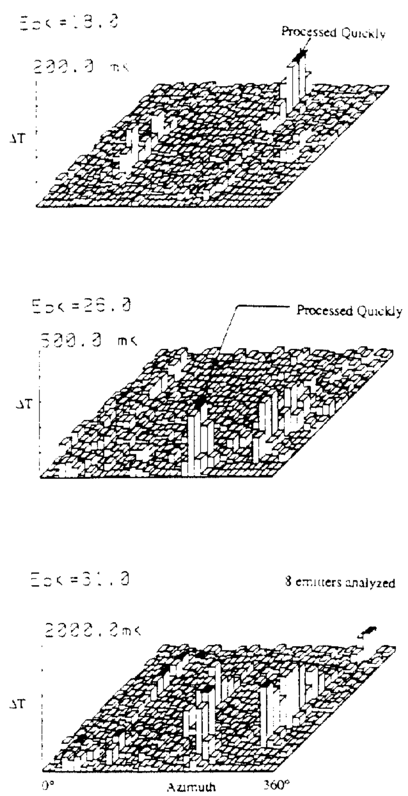

Fig. 2: Appearance of field emitters in a chemically treated cavity as the field level is raised from Epk = 18 to 31 MV/m

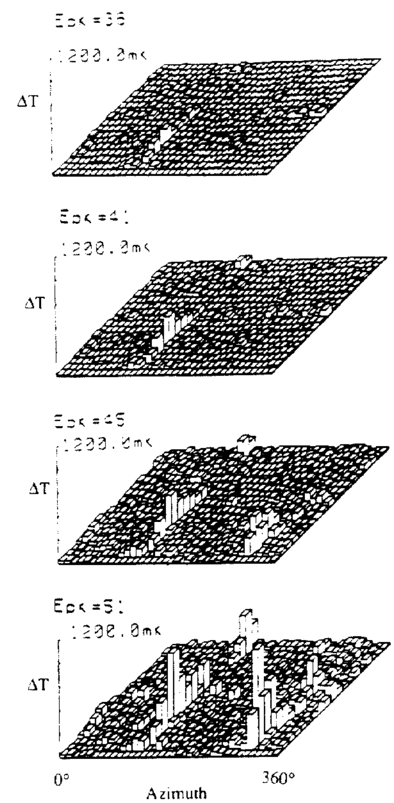

Fig. 3: Appearance of field emitters in a heat treated cavity as the field level is raised from Epk = 36 to 51 MV/m

cavities are shown in Fig.4. Typical β values are between 100 and 400, and emissive areas are between $10^{-5}$and 10^{-13} cm^2. In contrast, β-area distributions of emitters found in heat treated cavities are also shown in Fig. 4. Here we see that individual emitters found on a heat treated surface are weaker that those found on a chemically prepared surface. Most β values are less that 200. Note that in both chemically treated and heat treated cases, emitters which successfully RF processed showed significantly stronger emissive properties than the stable emitters. We suggest that the processability of emitters is related to the intensity of emission.

In other papers at this conference, we give results on microscopic examination of emission areas in Nb cavities. These studies imply that RF processing an emitter takes place by RF sparking, after which the site is destroyed and a micrscopic molten crater of Nb left behind[7,8].

DENSITY OF EMITTERS

The density of significant emitters in Nb cavities as a function of surface electric field is shown in Fig.5[6]. Here the effective cavity area is taken as that part of the surface on which the field maintains 80% of its peak value, typically 53 cm^2 for a 1.5 GHz, 1-cell cavity. For a Nb surface prepared by standard chemical and cleaning procedures, about 0.03

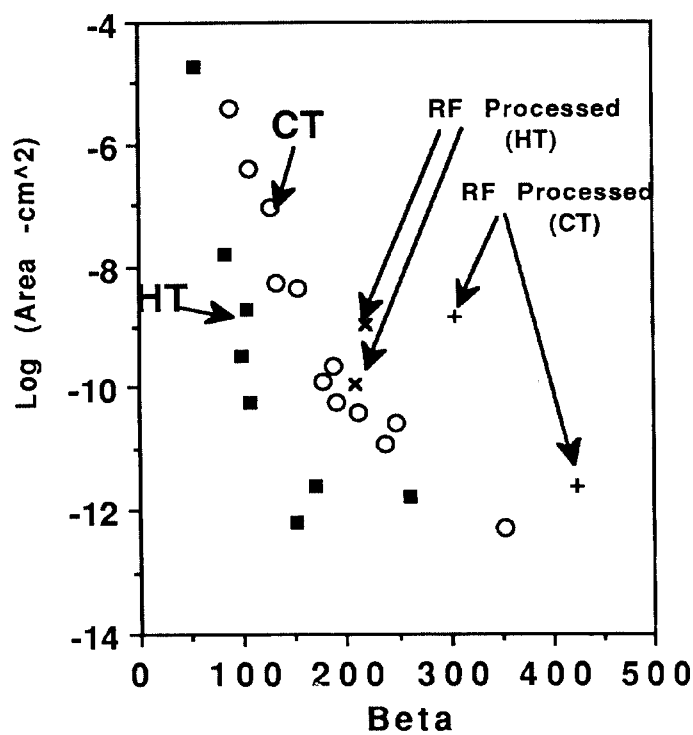

Fig. 4: Fowler Nordheim properties of emitters found in chemically treated (CT) and heat treated (HT) cavities

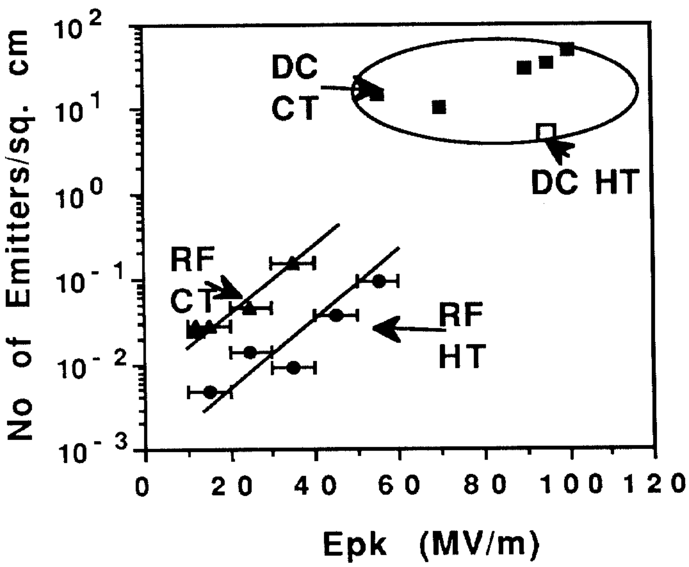

Fig. 5: Emitter density observed in chemically treated(CT) and heat treated(HT) cavities compared with DCemitter densities[1]

emitters/cm^2 is typical between 10 - 20 MV/m, increasing exponentially with field level. Typical emitter densities encountered with (higher) DC surface electric fields on Nb are also given[1]. The rapid increase of density makes understandable the difficulties in reaching high fields. A careful count of emitters vs. field level shows a factor of 10 reduction in emitter density after heat treatment. Thus we see from Figs. 4 & 5 that heat treatment reduces both the density and the emissivity of sites.

HE PROCESSING

It is well known that He processing plays a role in reducing FE, and therefore raises Epk . In particular our results show that the effectiveness of He processing depends on the field level. Fig.6 shows the benefit derived from He processing in 15 tests with chemically treated and heat treated cavities. At 20 MV/m, gains between 20 - 40 % are possible. These reduce to 10% at 30 MV/m and to below 5% at 50 MV/m. We have also established that at least part of benefits of He processing are derived from removal of gas condensates, i.e. emitters activated by condensed gas have been extinguished by He processing [9].

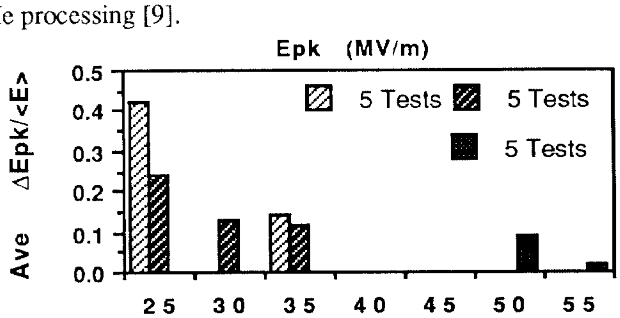

Fig. 6: Benefits of He processing at various field levels

SUMMARY OF OTHER STUDIES

In an attempt to search for the chief source of emitters that contaminate RF cavities, exposure tests were carried out on cavities which reached high electric fields (30 - 50 MV/m) by heat treatment and processing, and which were well characterized before exposure [10]. It was found that short exposure to dust-free (class 100) air, or high purity methanol does not destroy the surface with an abundance of new emitters, showing that these agents, which are routinely used in RF surface preparation, are not the main source. Exposure to clean water (18 MΩ,0.2 μm filters) showed significant increase in emission. However He processing was completely successful in restoring the baseline performance. Therefore we suspect that water is a potential but not a severe contributor. Chemical etching of cavities that previously reached high fields (by heat treatment and processing) showed substantial increase in emission, which could not be recovered by He processing. Indeed the performance benefit derived from heat treatment was reversed to the degree that the cavities could not be distinguished from those which had received only chemical treatment. These results suggest two possible sources for the major emission sources in chemically treated cavities: (a) chemical agents and (b) impurity inclusions in the raw material Nb that become exposed upon re-etching.

Strong evidence has accumulated to show that condensed gases do play a role, although gas layers may be just one of many contributing factors to field emission [9]. Deliberate condensation of oxygen gas onto a cold cavity was observed with temperature maps to activate a site. This site could subsequently be de-activated by cycling to room temperature. The same site was re-activated by re-condensing oxygen. He processing was sucessful in removing this site.

CONCLUSIONS

Studies of emitters from temperature maps show that the FN properties and densities of emitters found in Nb cavities are similar to those found in DC studies. Heat treatment is found to reduce the number density of emitters as well as the emissivity of individual sites. Consequently it allows higher fields to be reached in Nb cavities.

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