STUDIES OF HIGH-VOLTAGE BREAKDOWN SUPPRESSION RESULTING FROM E-BEAM MODIFICATION OF COPPER SURFACES *

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Abstract

Experimental studies of voltage breakdown suppression via electron beam surface melting of copper pieces have been performed at FM Technologies, Inc. The effects of different finishes and chemical etches were investigated. Both flat pieces and mock-ups of X-band cavity structures were tested. Observation of the treated surfaces indicate smoothing of both large (hundreds of microns) and small (micron) scale imperfections. Degassing effects are also evident. Results of visual observations and DC high-voltage breakdown measurements are presented.

1 BACKGROUND

The factor limiting accelerating gradients in RF cavities and particle sources is voltage breakdown. Recent work[1,2] using electron beams to flash melt metals has led to significant reduction in surface roughness. Other work has shown that electron beam surface modification can increase the voltage breakdown threshold in stainless steel[3].

2 EXPERIMENTAL APPARATUS

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2.1 General Layout

A schematic of a portion of the surface modification system is shown in Figure 1. The electron source is a field-emission gun using a carbon fiber cathode arrayed in a 2” diameter circle. A pulsed coil located coaxially with the cathode serves to both magnetize the beam and prevent breakdown within the gun. Two DC solenoids are used to transport the beam to the target chamber, located 70 cm from the cathode. The target chamber consists of a 6” CFF 6-way cross. The sample to be treated is mounted to a 36” travel linear/rotatable feedthrough. The feedthrough and target are isolated from ground so that the beam current on target can be measured using a Pearson coil. A 1” in-vacuum solenoid mounted on a linear feedthrough, located directly behind the target, provides the final focus. Typically, the pulsed filed at the location of the target reached about 2 kgauss. Another 6” CFF 6-way cross, attached to the target chamber is the Voltage Breakdown Test Chamber (VBTC). After irradiation, the sample can be moved from the target chamber to the VBTC without breaking vacuum. The target is placed between the high-voltage electrode, a 1 cm diameter polished stainless steel ball, and a micrometer-driven paddle beneath. Viewports on the sides and end of the chamber allow accurate placement of the target. When the test sample is in place, the paddle is raised until it contacts the back of the sample, and then gently pushes until the sample and ball just make contact, defined as the point at which electrical resistance reads less than 1 Gohm. The resolution of placement is 5 microns. The micrometer is than backed off to set the gap, typically 200 microns. At this point, the voltage across the gap is increased and the current is monitored by measuring the voltage across a 10 Mohm resistor.

*Research supported by the US DOE SBIR program.

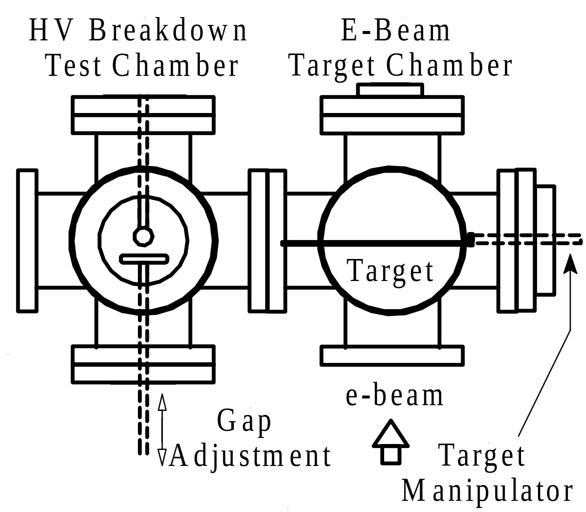

Figure 1: Schematic of the irradiation/ breakdown test apparatus.

2.2 Sample Preparation

Two geometries of samples were tested. The first samples consisted of 8” x 2” x 1/8” Hitachi C10100 class II OFE copper strips. The second geometry, modeling an X-band cavity nose, is shown in Figure 2. These were constructed of OFE copper rod. The surfaces were prepared to differing degrees. After cutting, the targets were washed thoroughly with water, then acetone. The surface was then sanded with 600 grit sand paper, then with 6 μm-, 3 μm-, and 1 μm-diamond paste. They were again cleaned with water and acetone. Then the targets were dipped in an acid bath consisting of phosphoric, nitric, and acetic acids. The target were then rinsed with de-ionized water and acetone and allowed to dry. Though care was taken, it is possible that dust contaminants could adhere to the surface between drying and installation into the system.

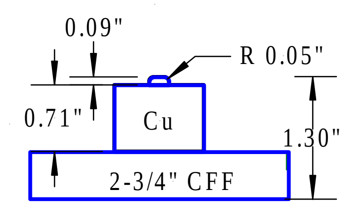

Figure 2. X-band nose model test sample.

2.3 Irradiation and Breakdown Test Procedure

Upon finishing preparation of a test sample, it was installed in the system. The sample was then moved into the target chamber. The in-vacuum solenoid was placed directly behind the target and a single shot was taken, resulting in a melted spot approximately 1.5-2.0 cm in diameter, depending on the focusing. The sample was then moved so as to irradiate a new location, typically 1" from the previous shot. To perform a breakdown test, the sample was moved into the VBTC. It was straight-forward to place the target within 1 mm of the desired location, allowing multiple measurements within the same irradiated region. After setting the gap, the voltage on the ball would be raised, up to a maximum of 30 kV. The current between the ball and sample was recorded until breakdown occurred, which was indicated by a sudden rise in current to the value established by the limiting resistor.

The X-band nose models were mounted inside an in-vacuum solenoid in order to achieve adequate beam focusing on target. Because of this, the test piece had to be removed from vacuum and mounted in the breakdown test chamber. This limited the number of measurements on this type of sample.

3 EXPERIMENTAL RESULTS

3.1 Flat Target Results

Two flat targets were irradiated with varying degrees of intensity in 26 different locations. Each irradiated spot is approximately 1.5-2.0 cm in diameter. This allowed multiple measurements within the same spot, though generally the measurements were greater than 5 mm apart. During irradiations and measurements on the first target, it was noticed that the surface was not being melted uniformly. At some points under strong focusing, surface ablation occurred, creating ~1 mm diameter indentations. Furthermore, it was noticed that, excluding the ablated areas, there was still variation of the surface as evidenced by differing reflectivity. Breakdown measurements on the first target were done without regard to these different finishes, though the location of each measurement was carefully noted. In fact, after breakdown, a small mark would sometimes appear at the test point. This proved important in locating test points precisely.

On the two flat targets, a total of 42 breakdown measurements were done, of which 16 were done on non-irradiated surfaces and 26 on irradiated surfaces. Of the irradiated surface field-emission measurements, 10 were done on smooth (high reflectivity) surfaces, 7 on rough (low reflectivity) surfaces, and 9 on surfaces that were not able to be categorized because of ambiguity in location or finish. The average breakdown of the non-irradiated surfaces was found to be 58 MV/m with standard deviation of 31 MV/m. The averages of the smooth, rough, and undetermined surfaces were 109, 49, and 64 MV/m, respectively, with standard deviations of 18, 13, and 24 MV/m, also respectively.

One potential mechanism for reduction in field-emitted current desorption of adhering gas molecules on the surface. Figure 3 shows a plot of first observable field-emitted current (~10 pA) vs applied E-field. The average onset value of dark current for non-irradiated surfaces is 20 MV/m and 31 MV/m for irradiated surfaces.

Microscope photographs comparing smooth and rough finishes are shown in Figure 3.

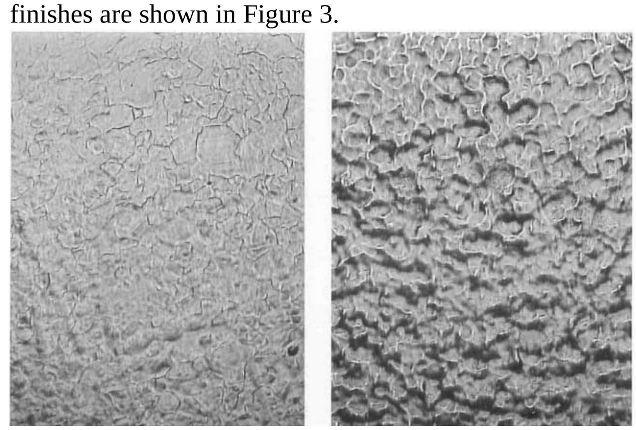

Figure 3. Examples of an optimally treated surface (left) and an over-exposed surface (right). Each picture portrays an area of 0.37 mm x 0.48 mm.

3.2 X-Band Nose Results

Several X-band nose mock-ups were irradiated and tested for DC breakdown. Because of the necessity of moving the test piece from the target chamber to the breakdown test chamber manually (i.e. removing it from vacuum and placing it in the next chamber), only a few of this target type were breakdown tested. However, because of their small size, magnified photographs before and after irradiation could be taken much more easily than for flat targets. Of the three that were measured, the average breakdown threshold was a disappointing 50 MV/m. On the other hand, there was no measurable dark current until just prior to breakdown. Pictures under high magnification showing a surface before and after irradiation are shown in Figure 4. Overall smoothing of the area is evident in protrusions and rough areas. Scratches are also reduced in extent, in some cases virtually disappearing. Grain boundaries generally remain intact, though they can be somewhat smoothed. Some cratering resulting from the irradiation is visible.

At less magnification the cratering phenomenon becomes more evident. Figure 5 shows before and after photographs of the same copper surface as shown in Figure 4 except at lower magnification. Craters resulting from the e-beam irradiation have been produced and almost exclusively follow grain boundaries. This most likely results from pockets of trapped gas that erupt when the surface melts. A similar structure has appeared in RF cavities test fixtures as a result of breakdown [4]. It is interesting to note that the flat targets did not show this tendency for grain boundary cratering, suggesting that it is dependendt on the manufacturing process of the metal. In future work, the electron beam will be used to degas the target for varying periods of time, to check if this can reduce the cratering.

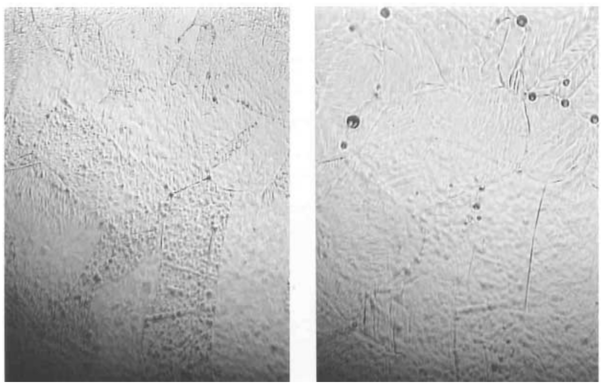

Figure 4. Before (left) and after (right) irradiation photos. of a copper surface. Each picture depicts an area 0.22 mm x 0.29 mm.

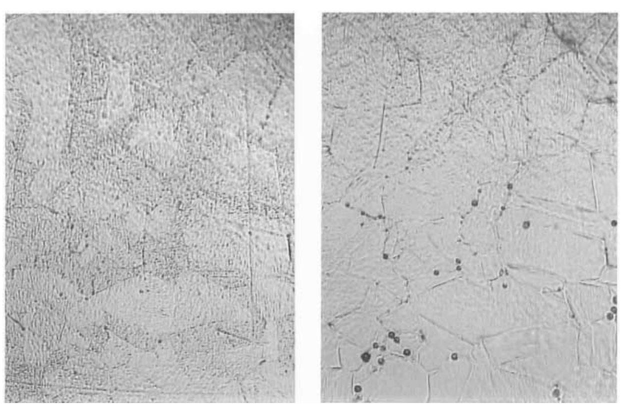

Figure 5. Before (left) and after (right) irradiation photos of a copper surface. Each picture depicts an area 0.22 mm x 0.29 mm.

4 FUTURE WORK

Several issues have not been addressed in this research. First, the targets were not baked prior to breakdown irradiation. High temperature bakeout has been shown to reduce grain boundary cratering. It is possible that the improvement in field emission resulting from electron beam irradiation arises from degassing and cleaning of the surface, which could be alternately achieved with baking and other processing. Even if this is the case, processing time could be significantly reduced (e.g. from days to hours) using e-beam irradiation.

Both of these issues will be addressed in the next upgrade of the surface modification system.

5 CONCLUSION

Electron beam surface melting of OFE copper has been shown to increase average voltage breakdown threshold by 90%. Dark current onset threshold has been increased by 55% while dark current magnitude has dropped by three orders of magnitude. While some issues remain, it appears that electron beam surface modification has potential to increase operating gradients of high field components while reducing dark current, and processing time.

6 ACKNOWLEDGEMENTS

The authors would like to thank R. Purdy for help with construction of the targets and vacuum system components. Thanks also goes to D. Sprehn and L. Laurent of SLAC for insights into breakdown mechanisms and sample preparation.

7 REFERENCES

1] G. Muller, G. Schumacher, D. Strauss, V. Engelko, A. Andreev, and V. Kavaljov, Proc. Of the 11^{th} International Conf. On High Power Part. Beams, Prague, Czech Rep., June 10-14, 1996, 809, Inst. Plasma Phys., Czech Acad. Sci., Czech Rep.(1996).

[2] J. Singh, A. K. Kurvilla, G. Jerman, and B. Phat, Proc. Of the 2^{nd} International Conf. On Beam Proc. Of Adv. Mat., Cleveland, OH, Oct. 30-Nov. 2, 1995, ASM International (1996).

[3] D. I. Proskurovsky, V.P. Rothstein and G. E. Ozur, Proc of the 11^{th} International Conf. On High Power Part. Beams, Prague, Czech Rep., June 10-14, 1996, 259, Inst. Plasma Phys., Czech Acad. Sci., Czech Rep.(1996).

[4] L. Laurent, G. Caryotakis, G. Scheitrum, D. Sprehn, and N.C. Luhmann, Jr., *Pulsed RF Breakdown Studies*, SLAC-PUB-8409, March 2000, presented at SPIE Microwave Intense Pulsed VII, Orlando, Florida, April 24-26, 2000.