VOLTAGE BREAKDOWN AND THE PROCESSING MECHANISM*

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Abstract

Although field emission and voltage breakdown are not current major limitations of superconducting RF cavities, field emission continues to degrade accelerator cavity performance; voltage breakdown, though undesirable in itself, often obliterates field emitters, improving cavity performance. With the eventual goal of finding surface treatments that will reduce electric-field-related problems and processing methods that will promote "therapeutic" breakdown with less power input, we have been studying the nature of the breakdown event itself in DC experiments and computer simulations, both of which lend themselves more easily to diagnostics than SRF experiments.

INTRODUCTION

A more detailed description of the apparatus and experiment, along with earlier results, can be found in reference [1]. Briefly, we caused voltage breakdown on sample cathodes by slowly increasing an applied DC voltage until breakdown occurred. The maximum voltage is 15kV; the distance between cathode and anode can be adjusted, but is usually around 150μm.

After breakdown, we find "starbursts" around the field-emitters that triggered the breakdown, so named because of the long streamers shooting out from the center (such a starburst is pictured at the top left of figure 1). During breakdown, ions from the plasma bombard the cathode and sputter away the surface in these starburst-shaped regions. Starbursts are apparent in an electron microscope because the sputtering action removes carbon contamination from the surface, which affects the secondary emission detected by the microscope. We have long since seen similar regions (shadows of intense plasma activity) without the characteristic starburst shape; we continue to call them starbursts, since they still have much in common with those that do have the elegant, long streamers, though perhaps "generalized starbursts" would be a better term.

NEW EXPERIMENTAL RESULT—OXIDE EFFECT

Here we describe the effect of a thick oxide layer on breakdown. Most of the cathodes pictured in this paper were (intentionally) contaminated with several small vanadium particles; we believe that particles triggered breakdown in these cases, and therefore the nature of the substrate (especially oxide thickness) had no noticeable affect on the breakdown voltage.

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The variation of surface damage with oxide thickness, originally found on niobium cathodes, turns out to be more generally applicable to copper and gold cathodes. Such general effects, which do not depend on detailed material properties, should be useful in modeling breakdown.

The effect of oxide thickness can be best described by pictures (all secondary emission images from a scanning electron microscope).

- Figure 1 shows a series of niobium cathodes with different oxide thicknesses, after being subjected to voltage breakdown.
- Figure 2 shows the similarity between copper and niobium with thick oxides, after breakdown.
- Figure 3 shows more pictures of heavily oxidized copper, after breakdown.
- Figure 4 shows a starburst on a gold surface (sputtered on niobium); gold has little oxide and (presumably) therefore the surface was heavily cratered.

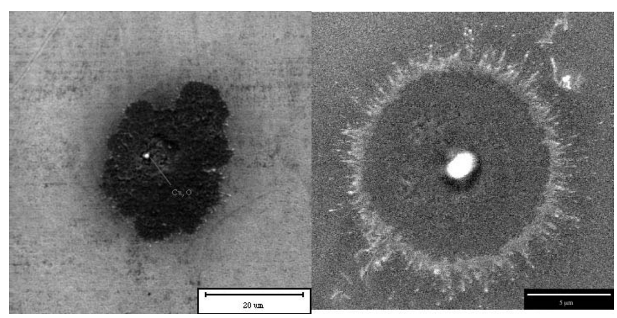

Figure 2: Typical starbursts on copper (left) and niobium (right) with thick oxides (The micron bar for the left picture is 20μm long, and that for the right picture is 5μm long.)

Voltage breakdown on niobium and copper cathodes with natural oxide thickness often creates small, deep craters, usually in the center of a starburst or breakdown region, but except for the craters there is little surface melting. Such craters are rarely seen, however, after breakdown on niobium and copper surfaces with very thick oxides. The thick oxide changes the nature of the surface damage: instead of discrete central cratering and long streamers, the result is a smaller "starburst," without streamers but with a fringe of once molten metal splashed like Edgerton's milk drop crown, and often a large blob of once-molten metal in the center and signs of melting all around. Tests on gold cathodes (1000Å gold sputtered on niobium) show starbursts with a great deal of cratering all over the starburst—this fits the pattern, since gold has very little oxide. Thicker

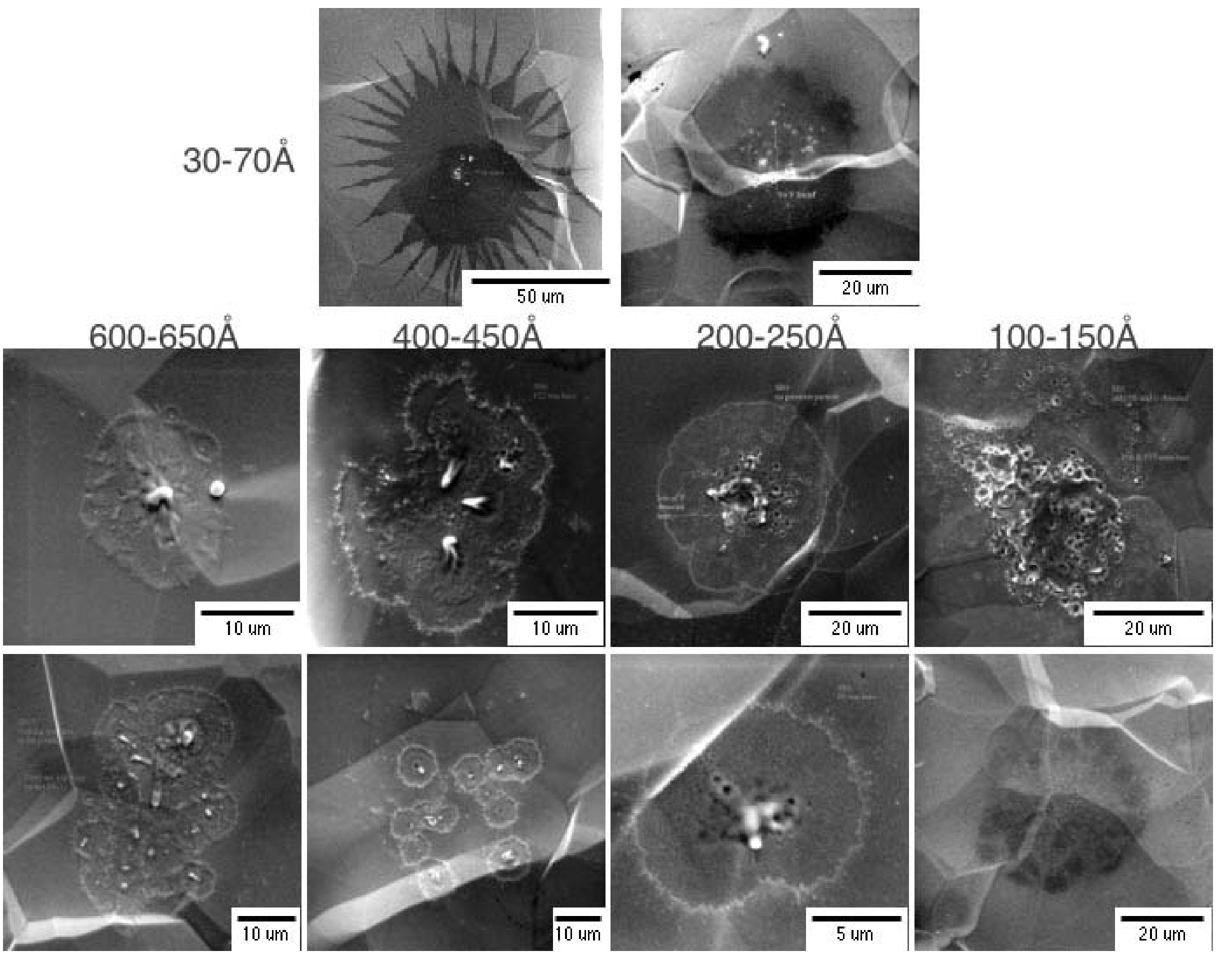

Figure 1: Starbursts (*i.e.*, regions of intense ion bombardment during breakdown) on niobium with varying oxide thickness. The natural oxide on niobium is usually about 30–60Å. The top left picture displays the characteristic pattern that suggested the name "starburst."

oxides seem to protect the surface against deep cratering (but maybe at the expense of general melting).

Unfortunately, a thick oxide does not endure as a protective coating, because all the oxide within a starburst region is removed (presumably by ion bombardment during the breakdown event), even when the oxide is 600Å thick.

COMPUTER SIMULATIONS

Recently we have begun to use a particle-in-cell code, OOPICpro [2], to simulate the initial stages of breakdown. Our results are in general agreement with those of Jens Knobloch using the program MASK [3], but with OOPICpro (and the advances in processing speed in the last several years) we have been able to simulate further into the discharge process.

The Code

OOPIC is open-source and free for research applications. Written in C++, the object-oriented code lends itself relatively easily to modification. For instance, OOPIC already had the ability to treat collisions (and ionization of a constant neutral gas) with Monte Carlo methods, but we added the ability to allow the neutral gas to evolve in time.

OOPIC is a 2-dimensional code, capable of x-y or z-r (cylindrical symmetry) geometries. OOPIC solves for the fields on a grid and calculates particle trajectories, including self-consistently the effects of charged particles on the fields.

Although OOPIC has a fully electrodynamic field solver, we chose to use the electrostatic solver only (with a time-dependent voltage, more AC than RF), neglecting the magnetic field and electrodynamic effects, so that we could isolate the effects of the electric field alone, before considering more complicated possibilities.

The Simulation

We simulate a 2D slice of a cylindrically symmetric region with a field emitter at on the axis at one end. We cannot at this point simulate an entire RF cavity, so we try to simulate a small section of a cavity around a field emitter—in this case 32μm in the z-direction and 8μm in the radial

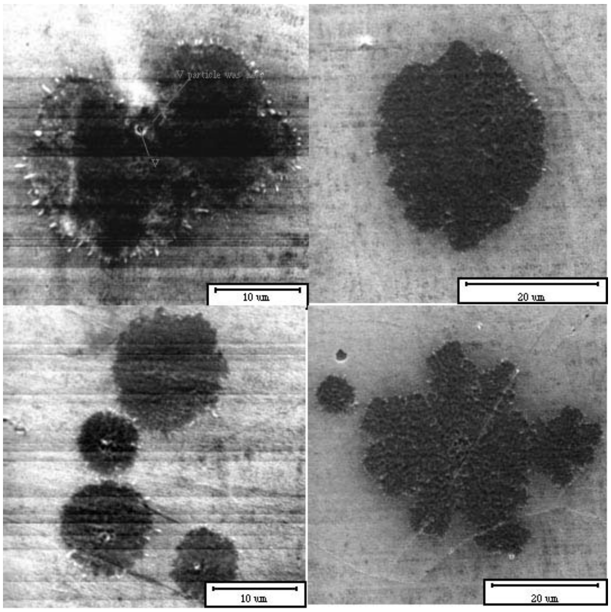

Figure 3: Starbursts on heavily oxidized copper (note similarity to starburst on heavily oxidized niobium)

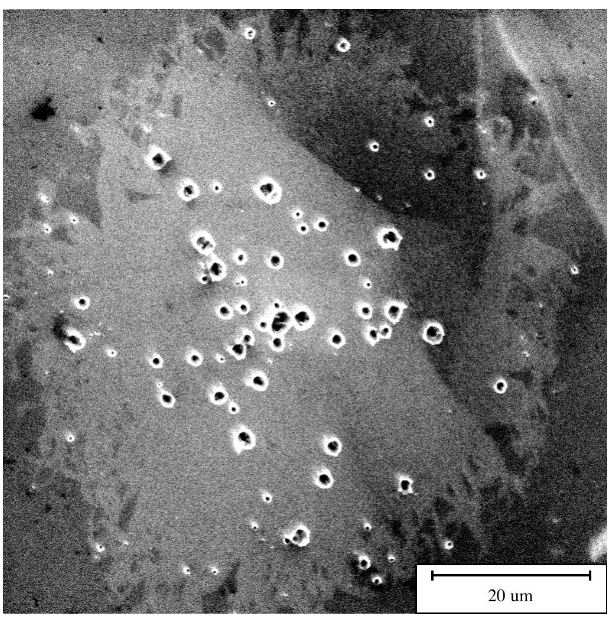

Figure 4: A typical starburst on gold (1000Å gold film sputtered on a niobium substrate) shows heavy cratering all over the starburst region; gold has a very thin oxide.

direction. At one end we put a field emitter on the cylindrical axis, and "evaporate" neutral vapor from the region around the field emitter as if it were very hot (~2000K). We then apply a voltage across the cylinder, either DC or time-dependent, and watch for an explosion of ions.

Clearly this model is not intended to simulate every aspect of a real breakdown event; rather, its purpose is to identify the most important mechanisms to be put into a model for breakdown. We find that breakdown can occur with: enhanced field emission, evaporation around the emitter, ionization, and electrostatic forces. The weak point is the lack of a good explanation for the production of neutral vapor, or at least evidence that field emitters approach very high temperatures or measurements of evaporation before breakdown events.

If the field emission current is high enough and enough neutral gas is injected, the following steps lead to a discharge current that would cause breakdown:

1. When the electric field is high enough, electrons are emitted from the field emitter.

2. Neutral vapor spews from around emitter.

3. Once the neutral vapor gets far enough away from the wall so that electrons will have gained enough energy to ionize (about 20eV), emitted electrons can collide with neutral atoms and produce (positive) ions.

4. Because the ions are much heavier than the electrons, they remain closer to the emitter, while the electrons travel far away, leaving a growing cloud of positive charge near the field emitter, increasing the electric field at the emitter and hence increasing the emission current.

5. The positive feedback between field emission and the growth of the ion cloud quickly (in hundreds of picoseconds) raises the current from field emission levels of tens of microamps to several amps, which will cause voltage breakdown.

The amount of neutral gas must be very high in the local region around the field emitter; in our simulations, we see maximum number densities as high as $10^{25}\mathrm{m}^{-3}$—of course this is in a very small volume.

Whether the applied field is DC or RF, the process looks quite similar, expect that with the oscillating field electrons are emitted (hence ions are created) only during the fraction of the RF period when the field is near its peak; for the rest of the period, the ions dissipate, due to their own mutual repulsion and the field. When the ions are heavy and the frequency high, the ions stay close to the field emitter; however, when the ions are light and the frequency lower, the ions may travel so far that they do not increase the field emission current during the next period. On the other hand, if the frequency is low enough, then in a single period the field is near its peak for a longer time than at higher frequencies—if that time is long enough to ignite the discharge, it doesn't matter how long the rest of the period is. In other words, when the RF period is much longer than the ignition time, the situation approaches the DC limit.

Once in the breakdown regime, with high currents, the ion cloud dominates the electric field, and the behavior afterwards is DC, with the externally applied field having relatively little effect. In this light it is not surprising that DC and RF breakdown can leave such similar features on the surface.

SUMMARY

We present pictures of cathode surfaces after DC voltage breakdown for cathodes with different oxide thicknesses, showing that thicker oxides inhibit deep, isolated craters, but perhaps lead to melting over a wider area. Most important, the effect of oxide thickness seems to be consistent across different materials, a general result that may help formulate more detailed models of voltage breakdown.

We also describe preliminary results from an attempt to simulate the initiation of breakdown, from microamps of field emission to many amps of discharge current. Given experimentally-seen field emission currents, a burst of gas at the field emitter will result in a large growth of current that would cause voltage breakdown. The growth of an ion cloud very near the field emitter seems to be important for the current growth; once this ion cloud becomes large enough, both DC and RF simulations become very similar, since the field of the ions dominates the externally-applied field.

REFERENCES

[1] G. R. Werner, *et. al.*, “Voltage Breakdown on Niobium and Copper Surfaces,” 10^{th} Workshop on RF Superconductivity, 2001, Tsukuba, Japan, p. 68.

[2] J. P. Verboncoeur, *et. al.*, “An object-oriented electromagnetic PIC code,” Computer Physics Communications **87**:199-211 (1995). OOPICpro is now maintained by TechX corporation, www.txcorp.com.

[3] Jens Knobloch, dissertation, “Advanced Thermometry Studies of Superconducting RF Cavities,” Cornell University, 1997 (chapter 6).