Triggers for RF Breakdown

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Abstract:
We outline a model of breakdown in RF cavities. In this model, the breakdown trigger is the injection of ions, atoms and clusters into cavities by either of two mechanisms. One mechanism is some combination of fracture and field evaporation of ions from solid surfaces caused by locally high electric fields. The second mechanism, driven by high local current densities, is localized Ohmic heating at grain boundaries and defects. Field evaporation and fracturing are similar processes, both driven by the high tensile stresses in the electric field that occur at local electric fields of ~10^{10} V/m, which have been measured in a number of experimental environments. We also outline how ions can be injected into cavities in the presence of large RF electric fields. The model can explain most of the behavior seen in a variety of cavities at different frequencies without assuming that melting or gas emission occurs at breakdown sites. This model may also be relevant to DC vacuum breakdown.

Introduction

Breakdown has been a problem in RF systems for as long as they have been built. During a breakdown event, much of the stored energy in the cavity suddenly hits the wall, usually in localized places, causing local melting and contamination of the surrounding surface. Because the phenomenon occurs so rapidly and randomly and a large number of mechanisms seem to be involved, there has been no agreement on the cause of this behavior[1 - 3].

Many studies have been done which used different materials, RF frequencies, temperature and vacuum conditions without producing unambiguous evidence that any these variables was directly involved in the triggering of these events. In addition, there seems to be conflicting data on whether this phenomenon was produced in regions of the cavity where the electric field was high or locations where the surface current density was high. Numerical modeling has been able to show that the existence of a local plasma in the cavity would explain the subsequent behavior during the discharge, but the nature of the "breakdown-trigger" was unknown. This breakdown trigger would be a source of ions or neutral gas injected into the cavity during high field operation[4].

We propose a model for the cause of breakdown in cavities. We will argue below that breakdown can be initiated by two mechanisms, 1) fracture/field evaporation of the interior wall caused by high electric fields, and 2) high local ohmic heating and surface potentials caused by high current densities. Field evaporation is an atomic scale fracture of a solid surface when the electric field tensile stress $\sigma = \varepsilon_0 E^2/2$ is greater than the atomic binding forces, comparable to the tensile strength of the material[5]. (The field always pulls on induced charges in the surface.) We also believe that enhancements in Ohmic heating and surface fields at grain boundaries and defects could cause perturbations sufficient to cause breakdown in high gradient, high frequency cavities.

This paper is intended as a general outline of relevant processes, and a more detailed study of these processes, both experimental and theoretical, is underway. We derive approximate relations, since the precise dimensions are not well known, however the conclusions are not sensitive to precise dimensions.

Surface parameters

While it is difficult to directly measure the parameters of breakdown sites in a cavity just before the cavity breaks down, we argue that indirect measurements of the sites are not only possible, but comparatively easy, using field emitted electrons. These measurements show materials under very high electric stress due to the way the local geometry produces induced charge on the surface.

We believe that electron field emission describes the local surface conditions at breakdown sites. Extensive measurements of an 805 MHz cavity in Lab G of Fermilab have shown that dark currents, produced by field emission at localized sites in the cavity, can be used to understand many aspects of the behavior of asperities within cavities, as shown in Fig. 1. This figure, from Ref. [5], compares the current vs field behavior of emitters in an RF cavity with theoretical predictions, graphically expressing the relevant parameters required to understand the process. Besides confirming the data follows the basic Fowler Nordheim (FN) current/field relations, the figure shows how the emitter sharpness, β_{FN}, and emitter area can be extracted from data by fitting the dark current vs. accelerating field behavior of a cavity to the FN predictions made at the dawn of quantum mechanics [6]. Other small corrections are due to the difference between RF and DC fields and the field

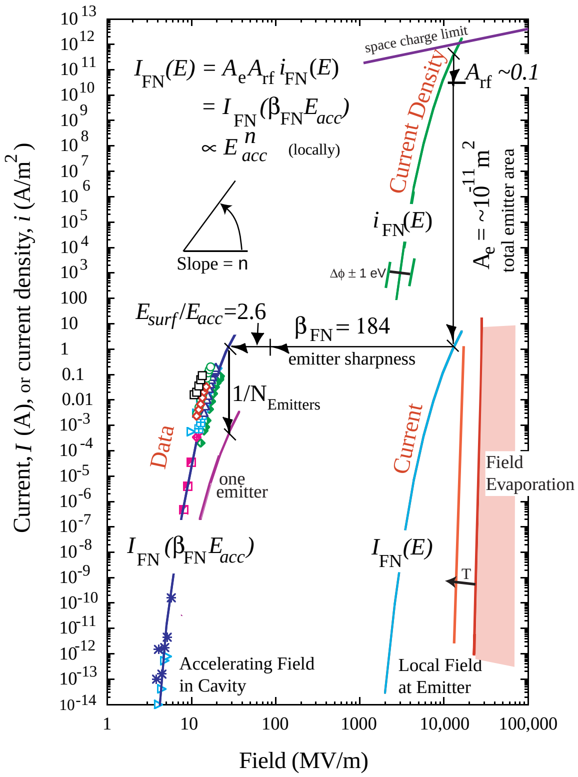

Figure 1. The environment around field emitters in an RF cavity, from Ref [5], showing the general parameters of field evaporation of copper ions. The fit compares experimental data on dark currents with the Fowler-Nordheim calculation of current density, $i_{FN}(E)$[6], and shows how the emitter area and sharpness terms are derived.

enhancements due to the shape of the cavity, E_{surf}/E_{acc}. Our primary conclusion from this argument is that the existence of dark currents requires local surface electric fields on the order of 5-10 GV/m, and the real geometrical field enhancements that produce them.

The nature of the field enhancement factor β_{FN} , defined as the maximum local electric field divided by the average surrounding surface field, E_{surf}, has been the subject of some disagreement. We assume, following Feynman, that for an equipotential surface of varying radius of curvature, the electric field would be proportional to $1/r$, where r is the local three dimensional radius of curvature[7]. Thus, while asperities with high electric enhancement factors could look like telephone poles, it may be more likely that they would be atomic scale corners of metallic grains that projected slightly above the surrounding surface. In fact, as we will show below, high field enhancements can also exist on perfectly smooth surfaces, driven by currents and defects below the surface.

Although electron emitters have been studied in detail, the breakdown process occurs fast enough so that it has been impossible to experimentally identify any specific characteristics of the pre-breakdown phase of these structures. Thus, it seems to be necessary to rely on models for guidance in describing many of the details of the breakdown event. One of the important parameters of field emission is the relation between the measured current and electric field. Since these go like $I \sim E^n$, where I is the current and E the electric field, a measurement of n is sufficient to determine the local value of the electric field at the emitter from the FN expression[5]. These indirect measurements of the electric field at emitter tips show that these fields are around 10 GV/m with high breakdown rates, but only about 5 GV/m for structures operating at low breakdown rates. This is in agreement with many measurements of DC and rf structures[8 - 10]. The tensile stress exerted by the field, which always pulls on the surface, can become comparable to the tensile strength of the material, see Fig. 2. When this happens, a fragment could be projected into the cavity and subsequently ionized by dark currents.

The environment measured at field emitters is consistent with solid materials operating very close to their mechanical limits. The ~10 GV/m fields and ~300 MPa stresses present at the majority of field emitters are not consistent with the existence of fluids, which would not survive. Likewise, weakly bound adsorbed gas would be field evaporated at lower fields and not present at the surface parameters we measure. While melted material and/or gasses may appear at some stage in the breakdown process, we argue that they are not an important component of the process.

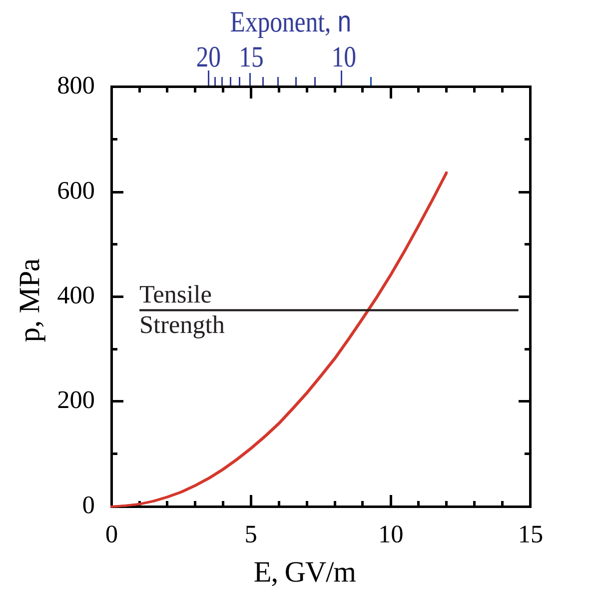

Figure 2. The relation between electric field and tensile stress for copper, compared to the measured values of n, defined by the relation between field emitted current and fields, $I \sim E^n$. From Ref[5].

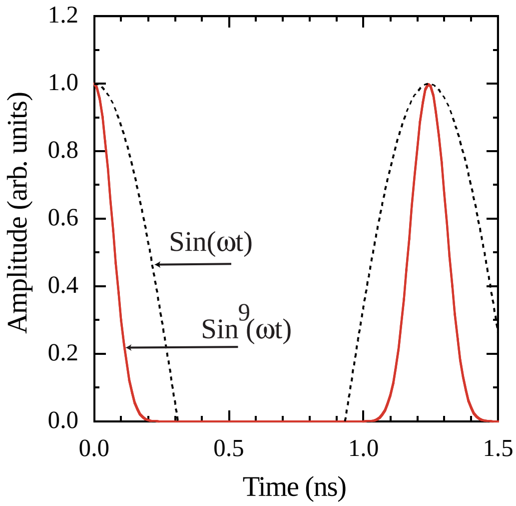

Figure 3, The intensity of field emitted currents in an 805 MHz RF system.

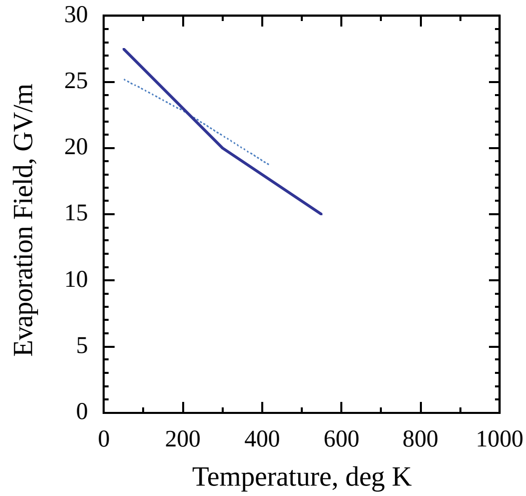

Figure 4. Measured values of the anomalous temperature dependence of the evaporation field, from Ref. [12].

There are a number of features of the dark current beams that effect breakdown. Since the electric field goes like $E \sim \sin(\omega t)$, the relation $I \sim E^n$, means that the dark current production goes like $I \sim \sin^n(\omega t)$. The result of this is that dark currents are only produced in a small fraction of the rf cycle. This is shown in Fig. 3, and limits the ionization that is required for the development of breakdown[5]. In addition to the time structure, there is a limit to the absolute current density emitted by the asperities imposed by beam loading, due to the Child-Langmuir limit[11]. This limit seems not to be reached for the typical emitters that contributed to the data shown in Fig. 1, but may be reached for small emitters.

Fracture / Field Evaporation

The removal of atoms, ions and fragments from solids using high fields is a complex process, but it has been well studied over the past 60 years using condensed matter surface techniques. These techniques, though relevant to breakdown triggers, have not generally been done in a parameter region particularly useful for understanding breakdown in RF cavities.

We have shown that electron field emission occurs at electric fields high enough to fracture materials. The study of high electric fields above surfaces has also shown that field evaporation, a process where atoms can be removed one by one, or as clusters, can occur at approximately the same gradients[12 - 14]. Since field evaporation can be more easily parameterized than fracture, it seems useful to look at models based on this process. Field evaporation occurs when metals are exposed to high surface fields, most commonly in field ion microscopes. While field ion microscopes produce images by ionizing gas atoms, field evaporation occurs in vacuum at somewhat higher fields, when atoms from a solid are directly removed from the material by the electric field stress.

Field evaporation is characterized by a constant called the evaporation field E_e. Most field evaporation measurements have been made at low temperatures, which give better position resolution. The temperature dependence of the evaporation field is anomalous, and it has been shown experimentally that when the temperature increases, the evaporation field decreases, as shown in Fig. 4, where the evaporation field for copper is plotted against the temperature in ^{o}K[12]. As breakdown occurs at room temperatures or above, the temperature dependence becomes more important. The field evaporation rate, as shown in Fig. 1, goes like the electric field as E^{100}, so the process has a very sharp threshold above which very high fluxes of ions can move into the discharge.

While hard, pure metals behave well under high field conditions, it has been found experimentally that softer metals, less pure crystals, and structures with oxides and adsorbed gasses can behave badly under high fields [12 - 15]. When inserted in Field Ion Microscopes (FIM), these materials fracture at lower fields, flash at the phosphor, and can disappear before reaching fields useful for field evaporation studies. The effects of fatigue have also been seen, which degrade the high field performance of the surfaces. An example of fragments blown off of FIM samples is shown in Fig. 5 [15]. The y axis in this figure shows the voltage applied to the emitter tip for a constant evaporation rate, which is proportional to the three dimensional radius of the surface. The order of magnitude of the fragment sizes and the number of atoms involved is shown. Thus, the complexity in the field evaporation behavior as a result

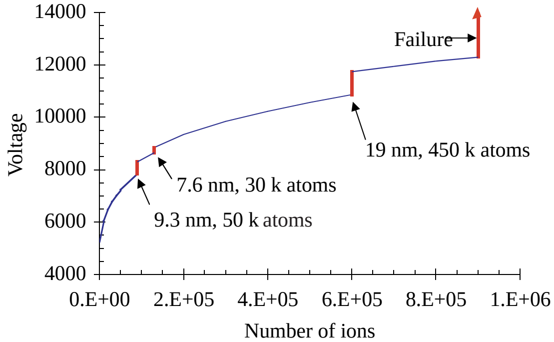

Figure 5. Abrupt discontinuities in the voltage vs. number of ions in a field evaporation system show evidence for large clusters produced at field ion microscope tips, from Ref. [15]. The approximate size of the fragments can be estimated from the size of the discontinuity and the densityof the material..

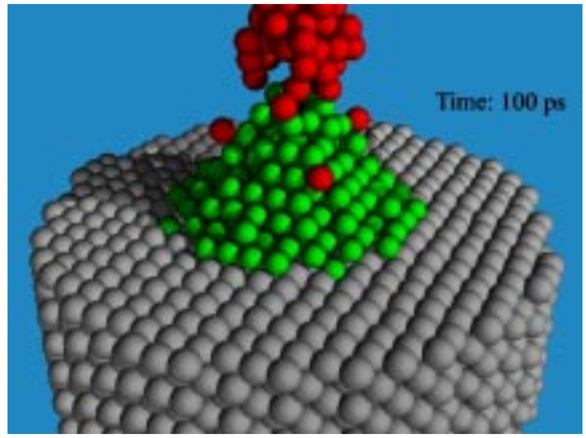

Figure 6. Numerical simulation of clusters evaporating from asperties in a field of ~10 GV/m. The red (dark) atoms are charged and the green (lighter) atoms are uncharged.

of imperfect structures depresses the field at which ions, atoms and clusters will be injected into the cavity. On the basis of field ion measurements, we assume that the fields involved in breakdown are perhaps a factor of three lower than those in idealized configurations used in field evaporation. Thus poor field ion probes are perhaps the best model for breakdown sites and worthy of study.

The behavior of highly ionized clusters is not well understood. Simulations show that clusters can be emitted from high field regions along with single ions. An example is shown in Fig. 6. This figure shows results from our Molecular Dynamics simulation of a nanoscale Cu tip evaporated in a strong local electric field, and a more detailed paper will be published separately. The stability of these clusters is not known since the electrostatic fields due to their highly charged state could break them up, in addition to the heat flux from field emitted electrons described below.

High surface currents

In addition to electric field effects, it seems that breakdown can also occur in regions of the cavity where electric fields are small, if the local current densities are high. The currents flow parallel to the direction of the electric field, and carry the charges that produce the fields. The currents flow from one end of the cavity to the other whenever the fields reverse. These current densities are a function of the frequency, gradient and geometry of the cavity, can be as high as 10^8 A/cm^2 in some designs optimized for high electric fields. Breakdown under these conditions can be explained in terms of the interaction of the high current densities with grain boundaries and defects. There are many other physical processes at work in surfaces which we do not consider[16]

It has been shown that significant perturbations can develop at grain boundaries and defects when currents are passed through metals[16 - 19]. Measurements have been made with Scanning Tunneling Potentiometers (STP's) on thin films carrying high current densities (10^4 - 10^7 A/cm^2), as shown in Figs. 7a and b[17 - 18]. While the measured potentials are quite small, they change in distances comparable to a few atomic diameters, thus producing very large electric fields. When these

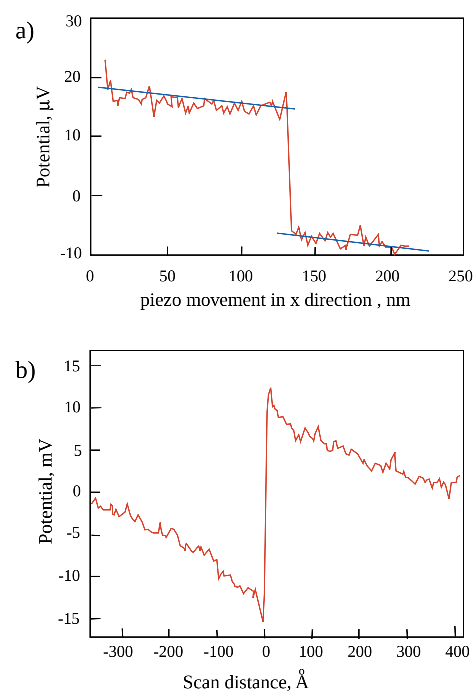

Figure 7a,b, Scanning Tunneling Potentiometer measurements (STP) of: a) grain boundaries and, b) defects, from Ref [17] and [18]. These data show that very high local electric fields can exist in current carrying structures.

measured potentials are scaled up to those produced by skin currents in high gradient rf cavities, the electric fields can be comparable to 1 GV/m. In addition to the electric fields at these defects, the Ohmic power levels should be many times the average power levels assumed in macroscopic calculations. The effect of these mechanisms would be to produce localized hot spots and electric field enhancements essentially equivalent to those produced by telephone pole (or any other) geometry field enhancements. We assume these could thus be potential field emission and breakdown sites.

It has been shown by Dolgashev, Tantawi and others, that high frequency cavities have increased failure rate when accelerating fields can produce surface skin effect heating greater than temperatures on the order of 100 ^{o}C [20]. Under these conditions, the local ohmic heating density would be *Ei*, where *E* is the local electric field in the metal and *i* is the local current density. As shown in Fig. 7, the electric potential at the grain boundaries, perhaps a few Angstroms wide, can be much higher when a metal is carrying current. The electric field at this point is enhanced by a factor of roughly Λ/w, where Λ is the mean free path for scattering in copper and *w* is the electrical width of the boundary. Assuming the mean free path for electrons in copper of 450 Angstroms[21], this local enhancement of the Ohmic heating power is of order 100. With this model, the grain boundaries would absorb ~100 times the average local power density. This would cause the local temperature to attempt to rise to 100 times the 100 ^{o}C that was calculated for the average surface, or 10,000 ^{o}C. This high heat deposition could cause local vaporization and injection of ions and atoms into the cavity volume. Fig. 8 shows an electron microscope image of a grain boundary after it was removed from a working cavity[22]. The result of high temperatures produced by enhanced local Ohmic heating would be distortions at grain boundaries like those seen in Fig. 8. While other effects may also be significant, grain boundaries are clearly associated with local perturbations. The effects caused by local defects should be comparable.

Ion trajectories

The trajectories of field evaporated ions in cavities are complex. Single ions are affected by the RF fields, ionized by field emitted electron beams, and the initial parameters of the emission site that produced them.

While neutral atoms, fragments and clusters fractured or evaporated off the surface will all fly ballistically into the cavity, the fate of ions injected into the cavity volume is somewhat more complex. The ions will be affected by the high RF fields which strongly affect their motion. If the ions are emitted from a protrusion with an enhancement factor β, they will experience a much higher field in the

Figure 8. Damage at grain boundaries due to high field operation in an RF cavity, from Ref [22].

first part of their trajectory, and this high field will persist for a distance roughly equal to the dimensions of the emitter, *d*. The energy transmitted to the ions in the first part of the trajectory will thus be $\beta E_{surf} d$, where E_{surf} is the average surface field. Since we know from field emitted electron data, (Fig. 1), that βE_{surf} is roughly 10 GV/m, and *d* is about 0.1 μm, $\beta E_{surf} d \sim 1$ *kV*, we can estimate that the initial velocity of the ion is equal to $v = (2\beta Ed/M)^{1/2}$, where *M* is the mass of the copper ion. This velocity is of the order 10^4 m/s. We have studied the behavior of ions emitted into RF fields with various RF phases and initial velocities, as shown in Fig. 9. While the exact phase at which the ion is emitted makes some difference and the velocity of the ion makes a considerable difference, the general behavior of the ion motion is similar to that shown. The trajectories follow a sinusoidal oscillation around the initial drift velocity *v*. For single metallic ions and realistic enhancement factors, the initial drift velocity dominates the RF motion and the ions can move across the cavity with little subsequent interaction.

The behavior of clusters and fragments is particularly interesting. Very large clusters, (Fig. 5), and also small ones with 2-50 atoms[23], have been seen in atom probe field ion microscopes, but the detectors are not particularly sensitive to intermediate sizes and these have not been commonly detected. Large clusters would move comparatively slowly, since their charge to mass ratio would be expected to be much lower than that of ions. Thus they would stay in range of the initial emitter

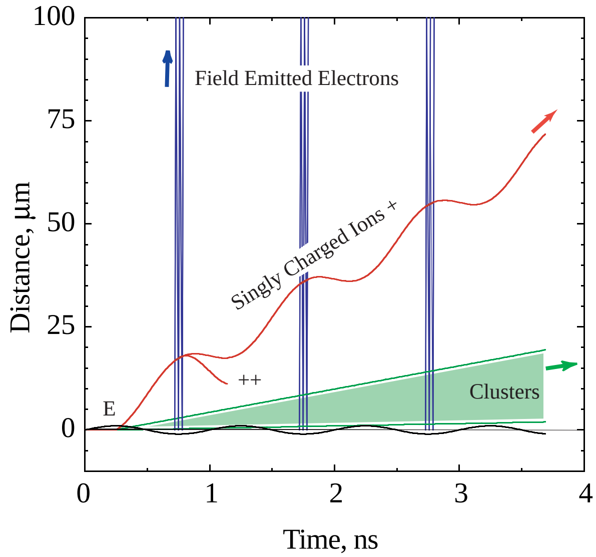

Figure 9. Behavior of ions emitted from asperities in an electric field of 50 MV/m. The initial ion velocity comes from the local field of 10 GV/m operating over dimensions of 0.1 μm. Field emitted electron beams are produced when the electric field reverses, and these electron beams can further ionize the ions near the emitter.

for a long time and be a potential source of backbombarding ions. The charge state of clusters is difficult to estimate and may be rapidly changing due to absorbed and emitted electron fluxes, but the dynamics of cluster sizes of 1000 atoms, with charge between 1 and 100 electrons is shown in Fig. 9.

Clusters are not tightly bound and will probably be highly charged, thus may be vulnerable to "Coulomb explosions"[23]. These explosions will blow up the clusters and send large quantities of atoms, ions and clusters in all directions. Backbombardment of the surface could then occur efficiently coupling field energy into surface heat. While ionization may occur due to electron collisions, the balance between the absorption and field emission of electrons from the sharp corners of the cluster and the wall may be the dominant mechanism for ionization.

If ions are further ionized by the field emitted electrons, they can impact the surface of the cavity if the secondary ionization does not occur not too far away. If ions hit the surface they will have energies of less than 1 keV, which may produce further neutrals and ions entering the vacuum, as well as heating up the surface.

Ions and neutral atoms emitted from Ohmic "hot spots" would also be produced from surfaces. They would, however, be emitted at thermal velocities in comparatively low electric field regions of the cavity so their transport into the cavity volume would go more slowly than ions emitted from field emitters.

It has been shown by a number of authors that the presence of a significant density of ions in an rf cavity along with the field emitted electrons will eventually heat the walls and cause a thermal avalanche, followed by an electrical avalanche which would result in absorption of all the RF energy in the structure[3 - 4][20].

Ionization and heating

While the ohmic heating power at field emission sites is well understood, much higher power levels can be coupled to solid materials by electrons accelerated in the local fields of these emitters when the electrons hit solid materials. The 10^{10} GV/m local electric fields at emitters couple power into surfaces very efficiently.

The atoms, ions, fragments and clusters that are injected in to the cavity coexist with intense beams of field emitted electrons. These electron beams increase in energy as they travel from the emission point, with an energy on the order of $U_{\mathrm{electron}} \sim \beta E_{\mathrm{surf}} d + E_{\mathrm{surf}} z \sim 1000{+}50z$, where d and z are the dimensions of the emitter and the distance from the surface measured in μm, and assuming $d \sim 0.1$ μm.

The deposited power density in the field emitted electron beams can be huge. The range of keV electrons is short, on the order of 1 nm for 1 keV electrons[24], so each electron deposits roughly 10^{10} eV/cm. The electron densities depend on the geometry of the field emitter, but field emitted currents of μA to mA have been measured (Fig. 1), and we assume that at a few microns from the emitter would have dimensions comparable to their distance from the emitter. The total absorbed power in the top nm of a 5 μm by 5 μm fragment, 5 μm from the emitter would be roughly $P_W = IU_{\mathrm{electron}}/V$, where V is the volume that absorbs the energy, which would be on the order of (1 mA)(1 kV)/(25×10^{-8} cm^2)(1×10^{-7} cm) = 4×10^{13} W/cm^3. The rate of heating of copper at this power level would be $dT/dt = P_W/4c\rho$, where c and ρ are the specific heat of copper (~0.1 cal/g deg) and its density (~10 g/cm^3) and the 4 converts units, so the temperature could rise at the rate of approximately 10^{13} ^{O}C/sec. If this process occurs near, that is, within a few microns, of the wall, backbombardment and avalanches are much more likely.

As heavy atoms, ions, fragments and clusters move further from the surface their higher energy, longer range and lower ionization cross section makes further ionization occur at a lower rate, thus most ionization is expected to occur quite near the emitter. The natural divergence of the field emitted electrons, perhaps increased by the space charge forces at high current densities, will also decrease the ionization effects at larger distances form the emitter.

Required R & D

At present there is very little data on either field evaporation of clusters and fragments, or fields produced by high current densities in solids. Since these phenomena seem to explain the behavior of cavities under breakdown, it seems essential that we understand them and are able to minimize their effects. In addition it is essential to understand how the parameters of the discharge evolve, and this will require modeling. It is important to understand how imperfect surfaces can perform under high voltage and high temperature conditions, and there seems to be very little information on this behavior in the literature. There is also very little information on the behavior of grain boundaries and defects under high current conditions. An overall model of the initiation of breakdown is essential. A wide variety of coatings and surface modifications are possible, such as chemical and electropolishing, and Gas Cluster Ion Beam, (GCIB)[25], smoothing, and these should be systematically tested.

Conclusions

We have shown how high fields and high surface current densities could inject large quantities of ions and neutral atoms into cavities to initiate breakdown. While simple ions might move through the cavity without further interaction, clusters and fragments would move slowly and remain in beams of field emitted electrons. We have also shown how field emitted electrons can deposit enormous power densities into atoms, clusters and fragments near the emitters and produce a thermal avalanche. We have also shown how breakdown due to melting and/or adsorbed gas seems inconsistent with experimental data, since neither would be stable in 10 GV/m fields. These mechanisms are not particularly well understood for the surface conditions that would cause breakdown. There is a need for more data to describe in detail how these mechanisms work and to optimize the construction of these devices.

Acknowledgements

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