BREAKDOWN PHENOMENA IN VACUUM

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Abstract

The surface phenomena of breakdown in a vacuum have been studied concerning two categories: breakdown on dielectric surfaces in an S-band(2856 MHz) rf field, and breakdown at the gap of metal electrodes in an impulse (60 x 700 μs) field. Multipactoring at an alumina rf window surface has been found to cause oxygen defects of the F-center, which induces surface melting. It is concluded that the durability of the alumina material depends on its micro-structure. Oxygen-free-copper having fewer micro-porosities shows a high breakdown field of about 200 MV/m (with a gap spacing of 0.5 mm), when *in-situ* sputter cleaning of the surface is applied prior to high-voltage conditioning. Trajectory simulation of field-emitted electrons in accelerating structures is also reported.

Introduction

The breakdown phenomena which take place in an ultra-high-vacuum have been experienced in various components of high-energy accelerators: electrode arcing in microwave-tubes, puncturing and cracking of rf windows, discharging in accelerating structures, and excessive heating of dummy loads.

Breakdown in a vacuum is mostly influenced by the material's condition at and/or adjacent to the surface. The contamination of such as hydrocarbon compounds and water molecules would be easily dissociated by an electron-stimulated desorption process. Microparticles of dielectrics as well as of metals would be desorbed under a high electric field. Volatile gas molecules absorbed in the bulk would be a source of both primary and secondary ions. Crystallographic defects in dielectrics should be charge-trapping sites. Not only field-electron emission, but all such kinds of surface processes are related to breakdown[1,2]. It is therefore essential to control the surface and bulk properties of the materials used for the high-power components.

In order to investigate the fundamental process of breakdown phenomena some experiments have been carried out at KEK. In this report the summarized results are described in two categories: breakdown at the gap of metal electrodes in an impulse field, and breakdown on dielectric surfaces in an S-band rf field.

Alumina dielectric material

Alumina ceramic is widely used as an insulator in vacuum devices, such as switching and microwave tubes. Since it has high stability against thermal treatment and a low outgassing rate, as well as high dielectric and mechanical strengths, it is a suitable material for insulators with good vacuum performance. However, the property of a ceramic having a high yield of secondary electron emission often induces breakdown phenomena under a high electric field. Especially in an rf field, once electrons impinge upon the alumina surface, the secondary emitted electrons are accelerated so as to impinge again onto the surface due to the alternating rf field; this causes a multiplication of secondary electrons.

This breakdown, generally known as multipactor, is one of the characteristic phenomena concerning rf windows. Window breakdown of the high-power klystrons used in accelerators has been not only a serious problem regarding operation, but has also been the key to future projects involving large accelerators which demand higher-power rf sources.

It is important to investigate the fundamental process of window breakdown and to develop an alumina material having durability under high-power operation. The experimental results concerning tests carried out in S-band(2856 MHz) pill-box-type windows used for pulsed high-power klystrons (3.5 μs, 30 MW) are described.

What is the breakdown induced by the multipactor effect?

It is often observed that breakdown accompanies rf reflection and pressure rise of the vacuum. Such a breakdown usually causes coloring, surface melting and puncturing of the alumina ceramic(Fig.1). As a pre-breakdown phenomenon, optical emission on the alumina is observed; especially when its intensity increases, surface melting takes place. A spectral analysis of the optical emission shows a structure with a broad band centered at about 300 nm and a line at 694 nm. Since the structure is identical to the luminescence spectra due to F^+-centers and the Cr impurity level(ruby color), respectively, the optical emission seems to be due to electron bombardment.[3]

The breakdown process which takes place under electron bombardment is possibly by a multipactor phenomenon. In order to estimate the behavior of multipactoring electrons, the trajectories and re-impinging energies of secondary emitted electrons in a pill-box rf field

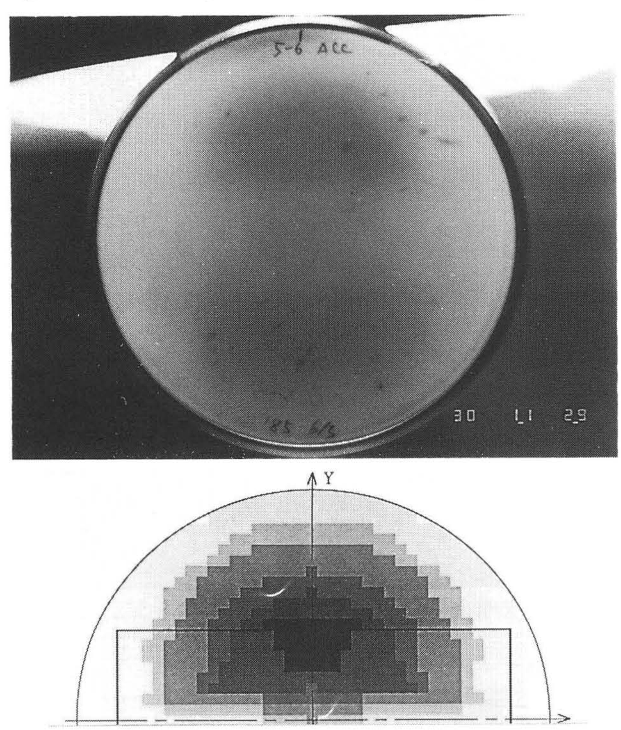

Fig. 1. Typically failed window with lighting from behind, and the simulated energy distribution of multipactor electrons. The alumina ceramic disk is 92 mm in diameter and 3.5 mm thick.

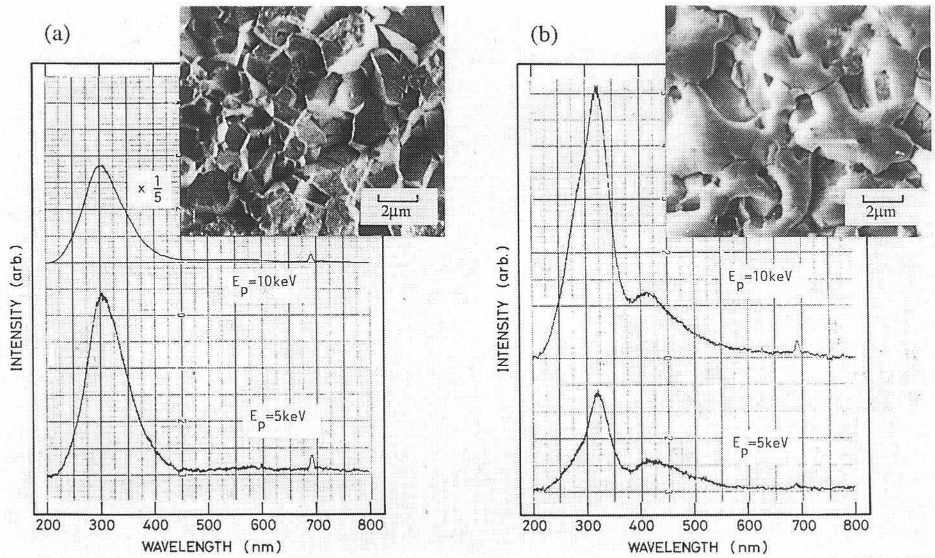

Fig.2. Cathodoluminescence spectra observed by e-beam(12 nA) irradiation using SEM; (a) unmelted and (b) melted alumina surfaces.

were simulated using a Monte-Carlo method[4]. Figure 1 shows the incident energy distribution weighted by the re-impinging rate. The pattern is very similar to that of the colored areas. It is thus ascertained that electron bombardment on the alumina surface occurs in a manner of multipactor breakdown, which causes coloring as well as luminescence.

The influence of the multipactor electron bombardment on alumina materials has been characterized by cathodoluminescence measurements; a ceramic disk is irradiated by an electron beam using a scanning-electron microscope[3]. The spectrum observed for a melted surface resulting from breakdown is shown in Fig.2 Another band at 410 nm appears in addition to the characteristic structure of the unmelted surface. This band can be identified as being luminescence due to anion defects of oxygen vacancies which cause coloring as F-centers.

These results indicate that the oxygen vacancies should generate conductive charges of free ions or electrons, thus inducing an increase in the loss tangent at the alumina surface, thus leading to surface melting.

Which material is more durable under rf operation?

The durability of alumina ceramic depends not only on its purity, but also the micro-structure[5], which is generally determined by the manufacturing process. In order to investigate the relation between the material properties and the durability, characterizations and high-power examinations have been carried out for several kinds of alumina materials.[6]

Their characteristic properties measured for the terms of secondary electron emission(SEE) yield (pulsed-beam method using SEM), loss tangent (cavity method), electrical resistivity (guard-ring method) and cathodoluminescence are listed in Table 1. UHA-99, which is pre-treated with highly pressurized forming before sintering, has a dense structure, showing higher values of specific gravity and resistivity. HA-997 is specially sintered in order to make the boundary additives crystallize, which contributes to a reduction of the loss tangent. Since XKP-999 is sintered without additives, it is liable to residual micro-porosities; the relatively high value of loss tangent is probably due to the porosity. Though sapphire(alumina single crystal) shows the best electrical properties, pre-existing F-centers have been found.

From the results of high-power examinations using a resonant ring, the following conclusions were obtained: (1)The multipactor effect takes place on all of the materials. (2)A high-purity alumina ceramic having crystallized sintering-additives and no micro-porosities is more durable, since F-centers are scarcely created in such a material, even though multipactoring occurs.(Table 1) (3)Pre-existing defects(F-centers) should be an origin of detrimental breakdown.

How can multipactoring be suppressed?

One of the most effective methods for avoiding

TABLE 1. Characterizatuion of alumina materials for rf window use.

aluimna marerial	purity (%)	specific gravity	ε	tan δ 10^{-5}	resistivity 10^{15} (Ω cm)	SEE @ 1 keV, @ 10 keV	sintering additives	CL spectra (before rf op.)	transmittable power (MW)	CL spectra (after rf op.)
UHA-99	99.0	3.90	9.81	9.4	>1000	6.0, 2.0	SiO_2, MgO, CaO	F^+, Cr^{3+}	>220	F^+, Cr^{3+} F
HA-997	99.7	3.91	9.95	4.2	6.7	5.2, 2.0	SiO_2, MgO	F^+, Cr^{3+}	>220	F^+, Cr^{3+}
XKP-999	99.9	3.91	9.67	13.3	3.3	6.7, 2.2	---	F^+, Cr^{3+}	144	F^+, Cr^{3+} F
sapphire	100	3.98	10.16	2.3	>1000	10.1, 3.7	---	F^+, F	75	F^+, F

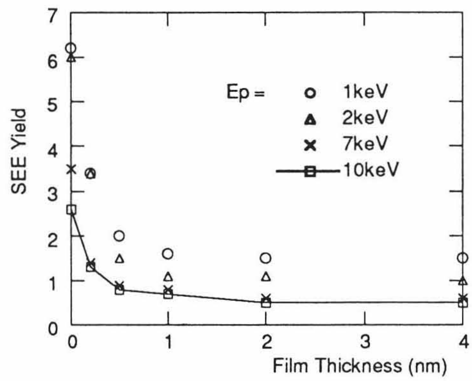

Fig. 3. SEE yields observed for TiN-coated alumina.

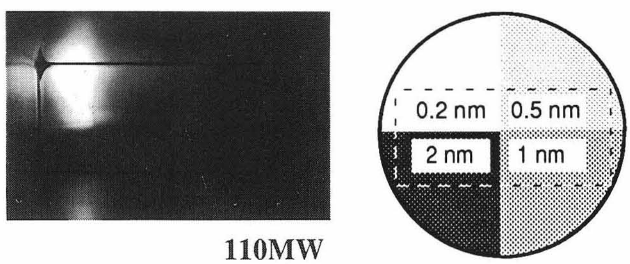

Fig. 4. Multipactor suppression by TiN coatings of 0.5 nm thick or more. Films of 0.2, 0.5, 1 and 2 nm thick are coated

detrimental breakdown is to suppress multipactoring as well as making a better choice of the dielectric materials. The surface coatings of some metal-compounds(such as TiN) having low SEE yields are applicable[7]. Although the films to be coated should be sufficiently thick so as to reduce SEE, they should be thin enough so as not to cause any excessive heating, since materials having low SEE yields are generally electrically conductive.

Figure 3 shows the thickness dependence of the SEE yields measured for magnetron-sputtered TiN films on alumina. A distinct decrease in the yields with thickness can be observed. When the incident energy is 10 keV (corresponding to the impinging energy of the multipactoring electron with an rf power of several tens MW), the SEE yield is reduced from 2 to less than unity as the thickness increases to a fraction of a nanometer. This indicates that a film that is 0.5 nm or more thick will suppress multipactoring. In fact, no luminescence has been seen on surfaces coated with films of 0.5 nm or more, as shown in Fig. 4.

In order to estimate excessive heating due to the films, measurements of the "effective loss tangent (tan δ')" have been carried out. Their results show that tan δ' increases almost exponentially with the film thickness, as shown in Fig. 5; a window with a 3 nm coat has a higher value than that of an uncoated one by 2 orders. A practical optimization of the thickness was achieved while also taking account of the high-power examination results[8]. The optimized region of our TiN film was concluded to be 0.5~1.5 nm.

Oxygen-free-copper material

Oxygen-free-copper (OFC) has excellent properties, such as high electrical- and thermal-conductivity and less degradation by hydrogen than that of other copper materials. It is mostly used for accelerating cavities, waveguides and high-power tubes. OFC for these devices is usually exposed to a "hot vacuum" with a high electric field and/or energetic particles. In order to avoid breakdown phenomena under such a condition it is important to control the material bulk properties as well as their surfaces. The desorption of hydrogen, oxygen and other volatile gases dissolved in the bulk should be enhanced by impinging particles, inducing breakdown and vacuum pressure rises.

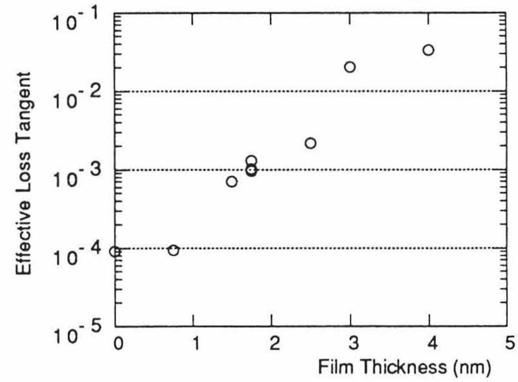

Fig. 5. Effective loss tangents measured for TiN-coated alumina disk. $E^2 \omega \varepsilon \tan\delta' dV = E^2 \omega \varepsilon \tan\delta \, dV(\text{alumina}) + E^2 \sigma \, dv(\text{film})$.

We characterized the fundamental properties of the OFC material concerning micro-porosities and gas contents.[9] The breakdown voltages of the OFC electrodes gap were also examined by applying an impulse field.[10]

What is the property of the OFC Class 1 material?

Because porosities cause blister development, degradation of workability and slow leakage, it is necessary to select an OFC material with a low porosity count in a micro-structure for accelerator vacuum devices. By using a comparison chart specified in ASTM-F-68, OFC materials are graded from Class 1 to Class 5 according to porosity.

The volatile gas contents in the copper bulk have been investigated for the OFC Class 1 material manufactured by a vacuum degassing on an industrial scale. A gas chromatographic analysis of the hydrogen concentration showed a lower value of less than 0.3 ppm for Class 1 than for Class 4 of 0.8 ppm. A further investigation has been carried out by SIMS (secondary ion mass spectrometry) measurements. Figure 6 shows the negative secondary ion spectra observed for Class 1 and 4 samples, which were bombarded by an Ar-ion beam with an energy of 5 keV and a current density of 4×10^{-5} A/cm^2; obtaining the gas concentrations from the positive ion spectra is difficult, since the signals are low and noisy in the case of OFC with such a low gas content. It is found that the desorbed gases under ion

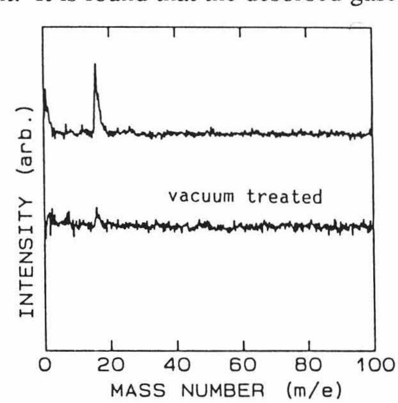

Fig. 6. Negative SIMS signals observed for a vacuum-treated(Class 1) and a normally manufactured(Class 4) OFC.

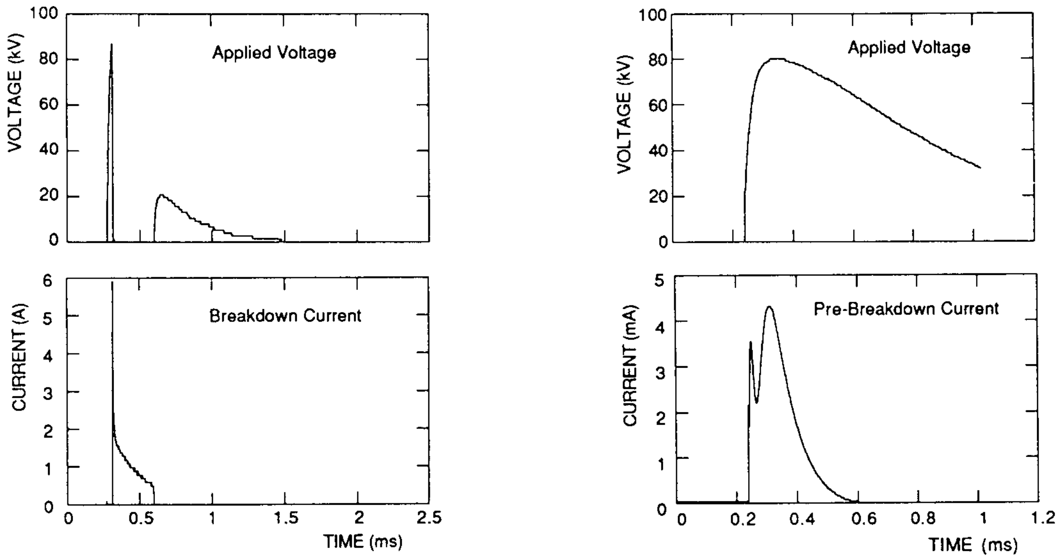

Fig.7. Waveforms of the applied voltage and breakdown current at the OFC electrodes gap; breakdown(left) and non-breakdown(right).

bombardment mainly comprise hydrogen and oxygen, and that their amount from Class 1 is much lower than that from Class 4 (by about 1/4). It is thus ascertained that a micro-structure with less porosity has lower contents of hydrogen and oxygen, resulting in a small desorption rate of the gases during ion bombarding.

How is the breakdown voltage of the OFC Class 1?

It is of interest to study the influence of such bulk-absorbed gases, as well as surface contamination, on the breakdown voltages. By applying an impulse field (60 x 700 μs) to a gap between electrodes, the breakdown field strengths (breakdown voltage / gap spacing) have been measured at a vacuum of ~10^{-10} Torr. The electrodes were of spherical shape 18 mm in radius and having a 3.5 mm initial gap spacing.

Examples of the observed waveforms for the applied voltage and breakdown current are shown in Fig.7. When breakdown takes place, a current of the order of several A was observed with a gap-voltage drop. Since line spectra of Cu ions were observed during breakdown, the current comprised ions generated from evaporated metal of the electrodes, which is called arc current. It is considered that the breakdown was initiated by field-emitted electrons impinging to the anode, followed by arcing. In fact, a field-emitted current(several mA) can be seen as a pre-breakdown current in the case of non-breakdown, together with an induced current.

Figure 8 shows the dependence of the breakdown field strength on the number of breakdowns observed for pre-cleaned and as-received Class 1 electrodes; pre-cleaning of the electrode surface was carried out by *in-situ* sputtering using an Ar-ion beam(3 keV, ~10^{-5} A/cm^2). It was found that only when the electrodes were pre-cleaned the breakdown field strength increased with the number of breakdowns; this is called high-voltage(HV) conditioning effect.

A difference in the breakdown field strengths between Class 1 and 5 electrodes was observed(Fig.9) when the electrodes were pre-cleaned by *in-situ* sputtering. The breakdown field obtained for the Class 1 material was greater than 200 MV/m with a gap spacing of 0.5 mm. It was thus concluded that an OFC material having less micro-porosity and, consequently, a smaller amount of absorbed gases, shows better performance under high electric field. The chart of ASTM-F-68 grading OFCs according to micro-structure is useful to choose a copper material for accelerator use.

What is the HV conditioning effect?

The results described above confirm that the HV

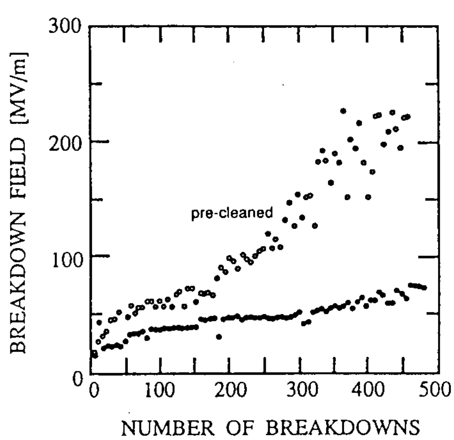

Fig. 8. Breakdown field strengths observed for pre-cleaned and as-received electrodes of OFC Class 1.

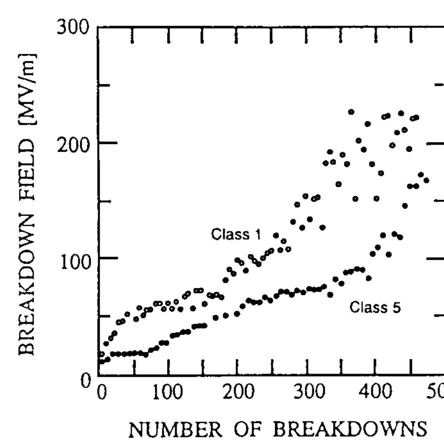

Fig. 9. Breakdown field strengths observed for OFC electrodes of Class 1 and 5. Both of the electrodes were pre-cleaned.

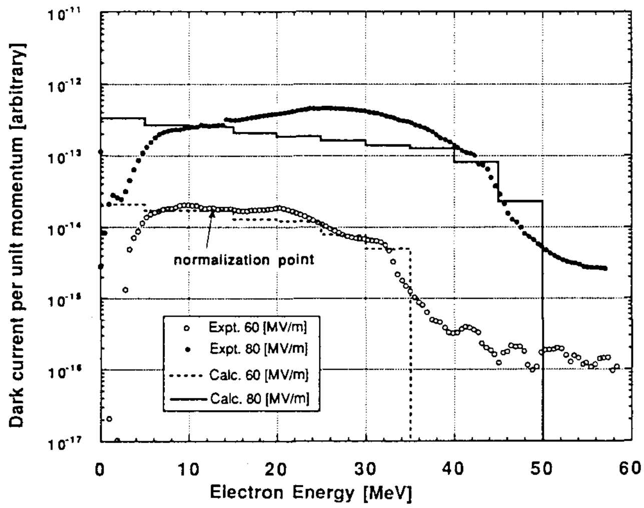

Fig. 10. Calculated and experimental energy spectra of field-emitted electrons in a 0.6 m long S-band accelerating structure.

conditioning without pre-cleaning is not always effective to increase the breakdown field. This implies that removing the initial surface contamination by high-energy particles during breakdown causes only little improvement in the hold-off voltage. In fact, it was observed that the effect of *in-situ* sputter cleaning is reduced when the Ar^+ beam energy and flux density are too high.

After HV conditioning the anode surface was found to be melted; on the cathode surface a lathe trace still remained (unmelted). [This indicates that a conditioning is not always surface-smoothing.] The high-energy consumption during repetitive breakdown is therefore considered to melt the anode surface and to promote outgassing from both the surface and bulk. These conditioning effects should persist as a "memory effect". Indeed, it was observed that a reduction in the breakdown field strength due to re-adsorption of gases during atmospheric exposure can be easily recovered.

How do field-emitted electrons behave in an rf field?

It is important to evaluate the dark (pre-breakdown) currents generated at the material surfaces in a practical structure for rf use.

One successful simulation technique for the dark current in a high-gradient disk-loaded structure of S-band(2856 MHz) was recently carried out by the KEK JLC-group.[11,12] A traveling-wave field in the structure was obtained by making a linear-combination(in the time-domain) of the symmetric and anti-symmetric standing-wave modes; the fields of these modes were calculated using the MAFIA code. [This method is also available for simulating the trajectory of secondary emitted electrons in the rf window, as mentioned before.]

Figure 10 shows the energy spectra calculated for electrons emitted from the downstream sides of all the disks when the accelerating field-strength is 60 and 80 MV/m, respectively. The emission timing with respect to the rf phase was taken at every 10 degrees. The normalization and ratio of the dark currents at these fields were determined experimentally. From the results it is confirmed that the dark currents generated under rf operation are due to the field-emitted electrons at the disk surface. In order to develop a high-gradient accelerator it is thus essential to suppress field emission by surface modification as well as cleaning.

Summary

The surface phenomena of breakdown in a vacuum have been studied: breakdown of the alumina rf window for S-band(2856 MHz) high-power use, and breakdown at the gap of oxygen-free-copper(OFC) electrodes in an impulse (60 x 700 μs) field.

It was found that the dielectric breakdown of alumina rf windows is caused by a multipactor effect. The impinging electrons during multipactoring create oxygen defects of the F-centers in alumina, which induces a detrimental breakdown leading to surface melting. From the high-power examination using a resonant ring, a high-purity alumina ceramic having crystallized sintering-additives and no micro-porosities is concluded to be more durable. A TiN-film thickness for multipactor suppression should be optimized so as not to cause any excessive heating.

An *in-situ* sputter cleaning of the OFC electrode surfaces using an Ar-ion beam was found to be an effective way to increase the breakdown voltage when it is applied prior to high-voltage conditioning. The influence of the gas contents on the breakdown voltages was investigated. OFC class-1 (ASTM-F-68), which has fewer micro-porosities and, consequently, less absorbed hydrogen and oxygen, shows a higher breakdown field strength of about 200 MV/m (with a gap spacing of 0.5 mm). The trajectory simulation of the field-emitted electrons can explain the energy spectra of the dark-current measured for the high-gradient experiments.

In order to develop accelerator components for higher power use, further investigations involving 1)charging phenomena in dielectrics[13] and 2)field-emission process at metal surfaces should be carried out from the view point of the material micro-structure.

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