# Charging Characteristics of a Solid Insulator in Vacuum under ac Voltage Excitation

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## ABSTRACT

**We have investigated charging and flashover characteristics of a polymeric or glass insulator exposed to ac voltage in vacuum in order to develop compact and reliable high voltage VCBs (Vacuum Circuit Breakers). This paper focuses on charging characteristics of a cylindrical model insulator. The charging of an insulator is investigated using an electrostatic probe that measures the electric field near the triple junction on the grounded electrode. This method allows a time-resolved measurement of the charging process. The insulator was made of borosilicate, fused quartz or polymetyl methacrylate, and was in the shape of a right cylinder with 10 mm in thickness. It has been clarified that the charging is characterized by three sequential states; initiation, quasi-stable and stable states, and that the polarity of the charge is positive for these states irrespective of the voltage phase. The charging characteristics with ac voltage are compared to our previous results with dc voltage excitation. We find that the charge magnitude at the stable state coincides with that obtained by dc. The electric field on the grounded electrode, and therefore the charge magnitude, decreases with the surface roughness, and decreases as the insulation strength is increased. A computer simulation has been conducted to investigate the quasi-stable state, which clarifies that the transition in surface charge distribution being synchronous to the voltage phase is responsible for causing the quasi-stable state.**

Index Terms — **Surface charging, charge distribution, flashover, surface roughness, solid insulator, glasses, PMMA, vacuum.**

## 1 INTRODUCTION

**HIGH** voltage VCBs (Vacuum Circuit Breakers) capable of e.g. 140 kV rating voltage will be prominent alternatives of GCBs (Gas Circuit Breakers) in order to reduce $SF_6$ that has a high global warming potential [1]. The insulation design of the vacuum bottle made of glass or alumina ceramic is of importance for developing such VCBs with high reliability and compactness.

Theory or hypothesis of flashover mechanism in vacuum has been summarized in the literature [2, 3]. Based on our previous studies with pulsed and dc voltages it is believed that the charging of an insulator surface precedes flashover in vacuum [4, 5, 6]. The knowledge about surface charging under ac voltage excitation, however, is limited except for trapped charges assumed to be injected from the electrodes into the bulk of an alumina specimen [7].

We focus on charging characteristics on the surface of a cylindrical model insulator exposed to ac voltage. We investigate the characteristics by using an electrostatic probe which is embedded in the grounded plane electrode. The probe measures the electric field close to the triple junction and allowed a time-resolved measurement of the charging process [4, 5, 6]. The insulator examined is made of borosilicate or fused quartz. A polymeric insulator, polymetyl methacrylate, is also examined and compared to the results with glass insulators.

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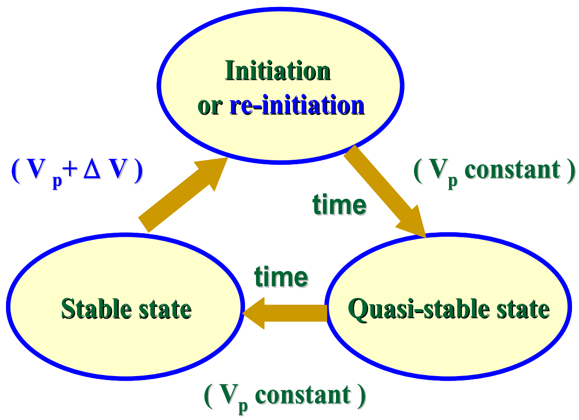
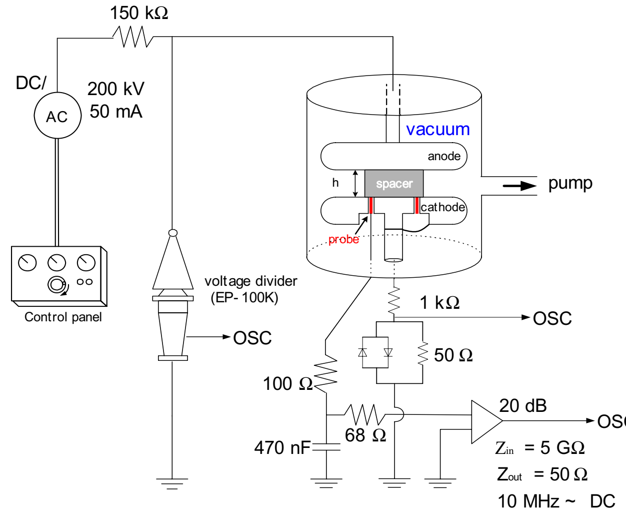


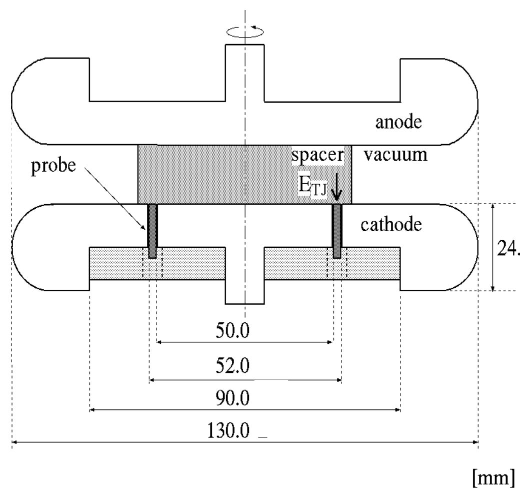

**Figure 1.** Charging process under ac voltage excitation in vacuum.

The observed results in the study can be summarized as follows: Irrespective of the material examined the charging process under ac excitation can be characterized by three sequential states as shown in Figure1. The charging initiates when the applied voltage peak has reached a starting voltage of several kilovolts. The charge, of which polarity is positive irrespective of the voltage phase, increases in amount over several cycles. After passing the period with the voltage kept constant, the charging reaches a quasi-stable state, where the probe signal consists of dc and periodical components. Within several minutes after the quasi-stable state has been established, the charging turns into a stable state, where the periodical component disappears and only the dc component remains. At this stage the charging activity is suspended until higher voltages are applied and charging re-initiates.

The new findings concerning charging characteristics with ac voltage mentioned above are presented in this paper. The quasi-stable state is discussed based on simulation results of surface charge distribution. Furthermore, an effective method to prevent surface charging and thereby to improve flashover strength is presented.




(a) Experimental setup




(b) Probe arrangement

**Figure 2.** Experimental setup and probe arrangement.

## 2 EXPERIMENTAL

Figure 2a shows the experimental setup used in this study. Since the setup except for the 60 Hz ac voltage source and experimental procedures are the same as that we have used for the study of charging phenomena under dc excitation [4, 5, 6], we briefly explain important items.

The test insulator was made of borosilicate (Pyrex®), fused quartz ($SiO_2$) or polymetyl methacrylate (PMMA), and was in the shape of a right cylinder with 54 mm diameter and 10 mm height. The surface of these insulators was polished by using buff to have an average roughness of sub microns, mirror finish. Insulators having larger roughness were also examined to investigate its influence on charging. That is, Pyrex® and $SiO_2$ insulators had an average roughness $R_a$ of 0.03, 0.75, 1.2, 2.6 and 3.0 µm (five classes), and PMMA 0.17, 0.34 and 3.0 µm (three classes). The details of the surface treatment have been written in our previous paper [6].

The probe is a ring shaped part isolated from a grounded electrode and is located coaxially with a cylindrical specimen as shown in Figure 2b. As the entire surface of the probe facing to the high voltage electrode is covered by the insulator, the probe hardly acquires true charge through vacuum or along the insulator surface. The probe signal and the applied voltage were measured simultaneously together with the current by using a 4 channel digital oscilloscope. The probe signal is converted into electric field strength $E_{TJ}$, which is the sum of the geometrical field component $E_g$ and the surface charge component $E_s$:

$$E_{TJ} = E_g + E_s \qquad (1)$$

The geometrical field can also be obtained from the oscillograph of applied voltage as

$$E_g = V_{ap} / d \qquad (2)$$

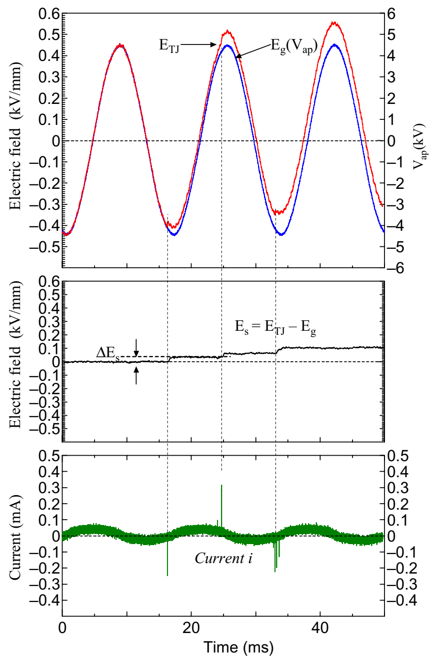



**Figure 3.** Wave forms of probe signal and current at the beginning of charging. Charging starts at negative phase in this example.

( Pyrex®, $R_a$ = 0.03 μm , $V_{ap}$ = 4.4 kV ) .

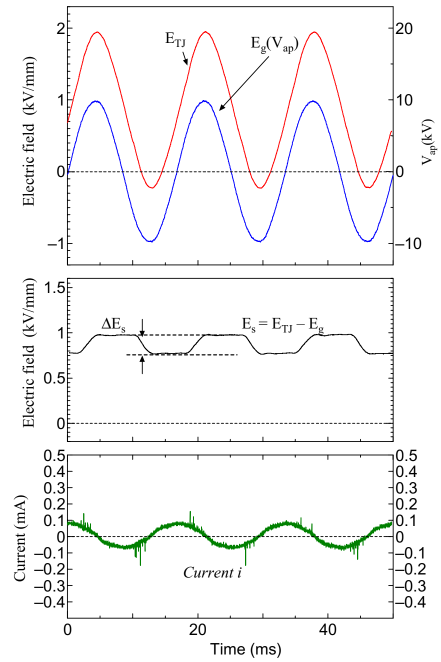



**Figure 4.** Wave forms of probe signal and current when the charging has reached at quasi-stable state.

( Pyrex®, $R_a$=0.03 μm, $V_{ap}$=10 kV )

where, $V_{ap}$ is the applied voltage and d (= 10 mm) the electrode separation. When we compare the oscillographs of probe signal and applied field obtained by equation (2) at a voltage low enough to suppress surface charging, e.g. $V_{ap}$ = 1 kV, there is a small difference in the magnitude. This difference has been calibrated by using a computer in this study.

## 3 CHARGING PROCESS

The glass and polymeric insulators having roughened surface (0.75 ≤ $R_a$ (μm) ≤ 2.6) show a similar charging process that consists of three different states: initiation, quasi-stable and stable states. The charging process of an insulator with optical grade surface finish ($R_a$ = 0.03 μm) consists of initiation and quasi-stable state. The stable state is hard to be achieved in this case.

The following describes above three states taking Pyrex® insulator as an example. It is worthy to note the polarity of surface charge is positive irrespective of the voltage phase (i.e. voltage polarity).

### 3.1 CHARGING PROCESS WITH SMOOTH SURFACE

#### 3.1.1 INITIATION

Figure 3 shows an example of simultaneous measurement of the probe signal $E_{TJ}$, applied voltage $V_{ap}$, and thus $E_g$, and current at $V_{ap}$ = 4.4 kV for the insulator with $R_a$ = 0.03 μm. At both positive and negative voltage phases, pulse currents are superimposed on the displacement current. The probe signal $E_{TJ}$ coincides completely with $E_g$ before the first current pulse flows. This means that $E_{TJ}$ does not include any surface charge component. $E_{TJ}$ shows a little distortion when the pulse current occurs. The first distortion exhibits the initiation of charging. $E_s$, which is obtained by subtracting the geometrical component $E_g$ from $E_{TJ}$, is shown in the same Figure. By comparing the current and $E_s$ waveforms, one notes that the polarity of surface charge is positive irrespective of the polarity of pulse current. This result indicates that the surface charge is always positive, and that the electric field at the grounded electrode increases stepwise over the voltage cycles. After passing several cycles the charging develops to a different situation as described below.

#### 3.1.2 QUASI-STABLE STATE

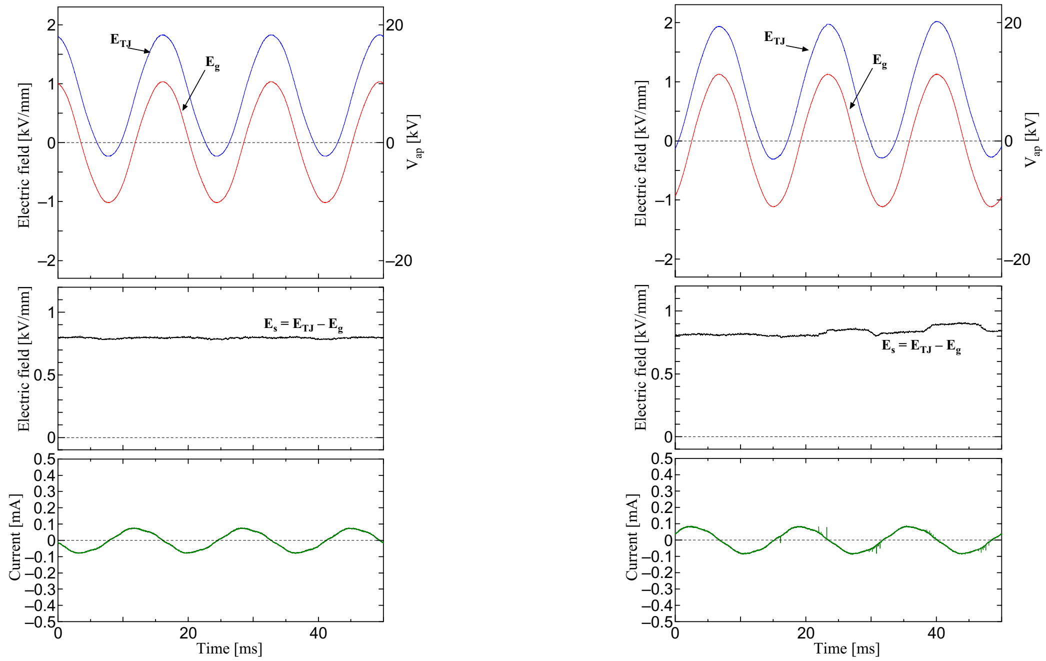
Figure 4 shows the probe signal and current observed at a higher voltage. It can be seen that several current pulses occur just before the peak of each half cycle. The probe signal $E_{TJ}$ and the applied field $E_g$ looks very similar. The surface charge component $E_s$, however, includes a dc component and a trapezoidal wave component that rises or falls by $\Delta E_s$ being synchronous to the current pulses.

This situation of the charging is called as the quasi-stable state in the paper. The origin of the trapezoidal component will be discussed in a later section. When the surface smoothness is fine the quasi-stable state continues. The magnitude of $E_{TJ}$ in this case is higher than those obtained for rough insulators as mentioned later in section 5.

### 3.2 CHARGING PROCESS WITH ROUGHENED SURFACE

#### 3.2.1 STABLE STATE

When roughened insulators are examined, the same charging process (initiation and quasi-stable state) as mentioned in the former section has been observed. For the roughened insulators, however, when the applied voltage is kept constant for more than a few minutes after the quasi-stable state has been established, the trapezoidal component mentioned above




(a) Stable state ($V_{ap}$=10 kV). (b) Re-initiation ($V_{ap}$=12 kV).

**Figure 5**. Different charging states for an insulator with comparatively rough surface. (Pyrex®, $R_a$=0.75 µm )

disappears and only the dc component remains. We call this situation as the stable state. Figure 5a shows the stable state when the insulator with $R_a$ = 0.75 µm is examined. In the stable state pulse currents no more occur as seen in the current waveform in the Figure 5a. Thus, the stable state is characterized as a situation where no charging activities take part.

At the stable state the dc electric field component, of which value depends on applied voltage height, can be almost equal to, or higher than, the applied one at near the triple junction on the grounded electrode.

The mechanism that restrains the insulator from charging activities and establishes the stable state for a roughened insulator is not clear at this moment. The stable state was achieved in the same manner when the PMMA insulator with $R_a$ = 0.17 µm was examined. Taking these results into consideration, we believe that the insignificant surface irregularity causes the transition from the quasi-stable state to the stable state.

### 3.2.2 FURTHER DEVELOPMENT (RE-INITIATION)

Higher voltages must be applied if one needs to observe further charging after the stable state has been reached. This situation is well established in Figure 5b, where the charging restarts in the same manner as described for the initiation process. Thus, the initiation, quasi-stable and stable states mentioned so far take part cyclically when the applied voltage increases stepwise. The cyclic charging process under ac voltage excitation has been shown schematically in Figure 1.

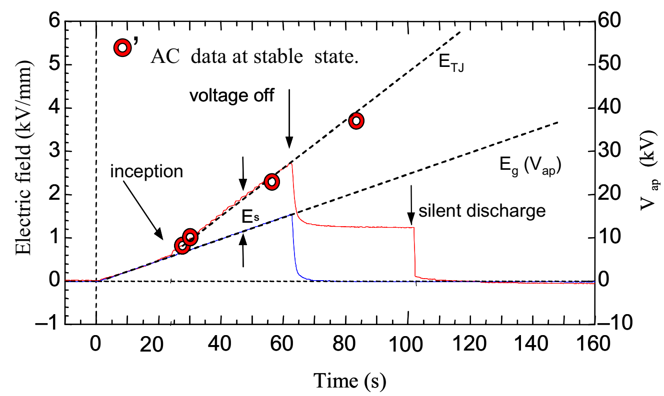



**Figure 6.** Typical charging process when an insulator is subjected to a ramped dc voltage. (PMMA, $R_a$ = 0.17 µm. The stable state is established at this roughness.)

## 4 MAGNITUDE OF CHARGES DUE TO ac AND dc VOLTAGES

The typical charging process when an insulator made of PMMA is subjected to a ramped dc voltage is shown in Figure 6, where the charging starts at about 5 kV and continues until the voltage is turned off at 16 kV (Refer to the literature [4, 5, 6] for more details.) When the applied voltage holds constant with the surface charge on the insulator, the electric field $E_{TJ}$ will keep constant and the charging activity is suspended. Further charging takes place only when a higher voltage is applied [4]. This is the same situation as mentioned earlier in the paper concerning the re-initiation under ac voltage excitation.

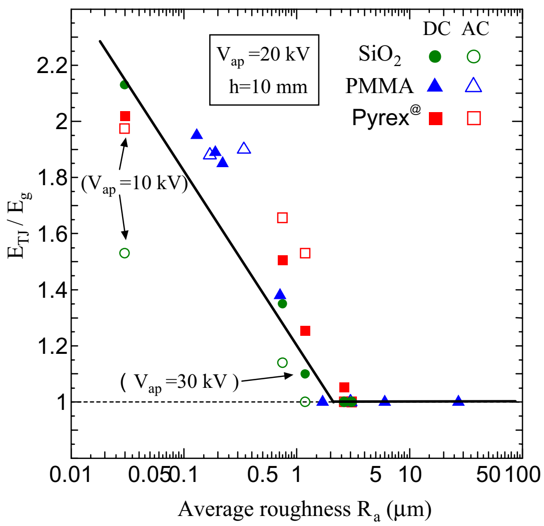



**Figure 7.** Relation of normalized charge magnitude with surface roughness.

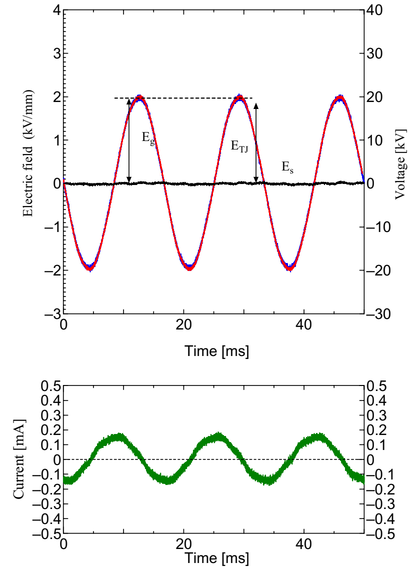



**Figure 8.** Wave forms of probe signal and current for a roughened insulator. Surface charge component of probe signal and current pulses disappear at this roughness. (Pyrex®, $R_a$ = 3 μm , $V_{ap}$ = 20 kV).

Under ac voltage excitation, the surface charge component $E_s$ at the stable state corresponds to that of the higher level at the quasi-stable state. The surface charge components for PMMA measured at the stable state for various applied peak voltages are plotted on the oscillograph in Figure 7. From the figure it is clear that the magnitude of charge due to ac voltage coincides with that of dc voltage, if the peak voltage is adopted for ac data. In the case when Pyrex® is examined, AC data are somewhat larger than DC data.

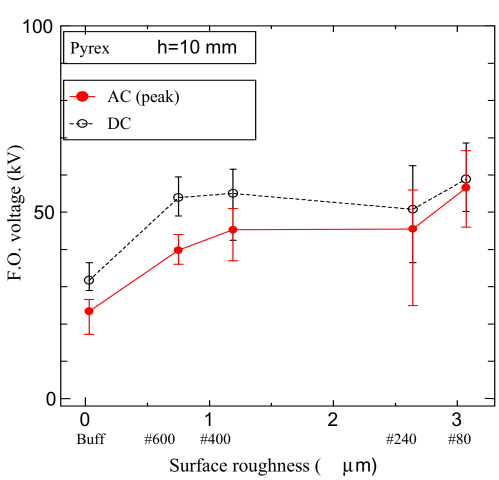
# 5 PREVENTING INSULATOR FROM CHARGING AND IMPROVING WITHSTAND VOLTAGE

## 5.1 EFFECT OF SURFACE ROUGHNESS ON CHARGING

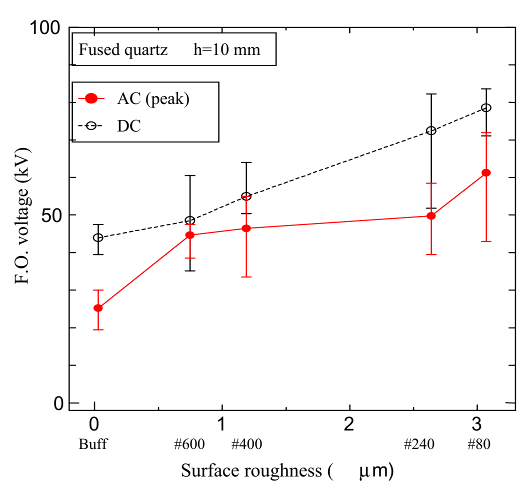
From our previous studies using dc voltage it has been found that the surface charging can be effectively suppressed by simply roughening the insulator surface [5, 6]. The method is applied for the present study with ac voltage.

Figure 7 shows the normalized electric field strength $E_{TJ}$ / $E_g$, thus the surface charge magnitude, as a function of the average surface roughness. For insulators with comparatively rough surface the normalized field was measured when the stable state was established. For the insulators with fine smoothness ($R_a$ = 0.03 μm) the higher level at the quasi-stable state was measured. These measurement were mainly conducted at 20 kV (ac peak). Figure 7 also includes data at 10 kV (ac peak) for $SiO_2$ and Pyrex insulators with $R_a$ = 0.03 μm, and 30 $kV_{dc}$ for $SiO_2$ with $R_a$ = 1.2 μm. The former voltage is to avoid flashovers that damage the probe circuit, and the latter is to facilitate charging.

From Figure 7 it can be seen the normalized field for ac voltage decrease linearly on a semi logarithmic scale, as it is in the case of dc experiment. It becomes unity at the roughness about 2-3 μm, meaning that surface acquires no charge. The surface charge component disappears at this roughness as shown in Figure 8. It needs a higher voltage to cause charging on roughened insulators. Roughening insulator is thus proved to be effective to prevent charging both for dc and ac voltages.




(a) Pyrex®.




(b) Fused quartz.

**Figure 9.** Flashover voltage as a function of surface roughness.

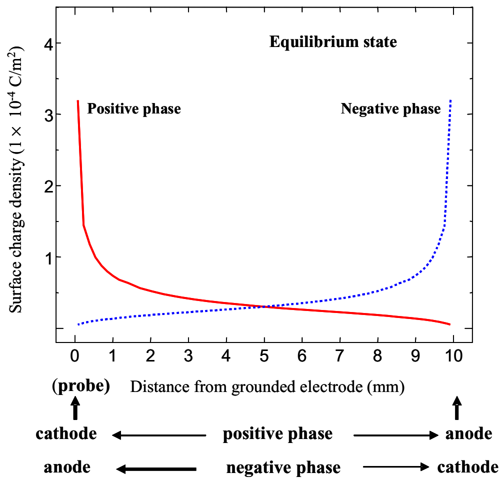



**Figure 10.** Calculated charge distributions for positive and negative polarities. Being the grounded electrode at 0 on the horizontal axis, it turns to cathode or anode depending on the voltage polarity.
(Pyrex®, $V_{ap} = \pm 10$ kV)

Charging takes place through the process in which electrons released from the triple junction, where the cathode, insulator and vacuum meet, propagate toward the anode causing secondary emission electron avalanches (SEEA) along the surface of an insulator [8, 9]. Thus, one might consider the secondary electron emission characteristic of an insulator will have a pronounced effect on the electrical field. It can be seen from Figure 7, however, that the difference in the probe signal is small among these three materials and that the surface roughness of an insulating spacer decisively affects on the charge magnitude. According to our simulation result, surface protrusions act as barriers against hopping electrons in the SEEA process [6].

### 5.2 FLASHOVER CHARACTERISTICS

It has been pointed out that roughening the surface of an insulator is effective to improve its insulation strength in vacuum for pulsed [10], dc [11] and ac [12] voltages. The reason of this effect has not been clear until we have quantitatively revealed that the roughening mitigates the charging [6]. The relation between surface charge magnitude and withstand ability has been discussed for dc voltage [6]. We have examined this effect again for ac voltage in this study.

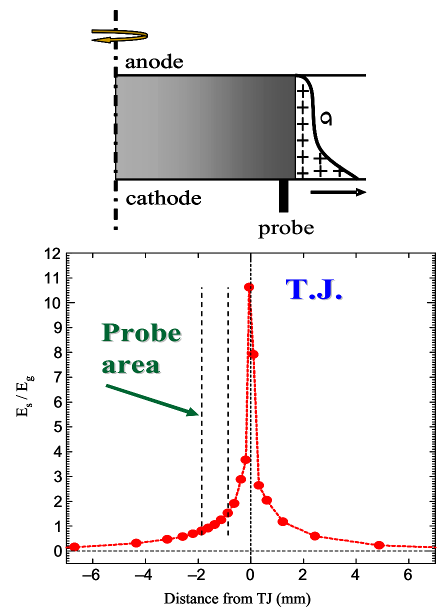
For each of the specimen we measured 30 flashover voltages. This test includes the neutralization [4] of residual surface charge by introducing small amount of air in the chamber after every 10 flashovers. We considered the first and second groups of the executions (20 flashovers) as conditioning process, and the voltages for last 10 flashovers were averaged. The results are shown in Figures 9a and 9b, respectively, for Pyrex® and $SiO_2$, where the average flashover voltages are summarized as a function of the roughness. The error bar for each datum indicates the lowest and highest flashover voltages in the 10 voltages. Although the average flashover voltages are somewhat lower than those of the dc, the increase in flashover voltage is distinct when the surface roughness is larger than about 1 μm, which is as same as the results with dc. PMMA specimens also showed similar results for dc and ac.

## 6 DISCUSSION

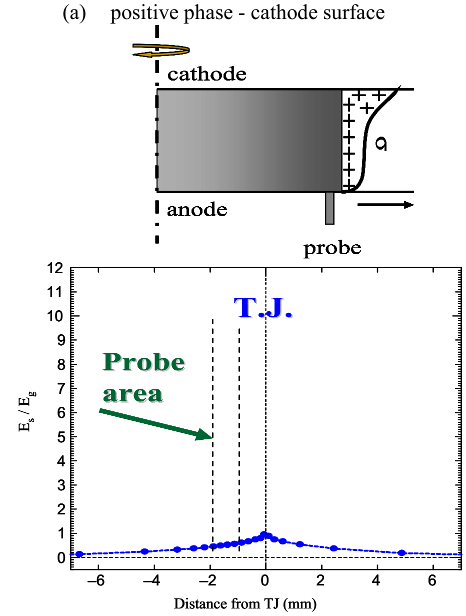
### 6.1 SURFACE CHARGE DISTRIBUTION

During the quasi-stable state, the charge component of probe signal changes by ΔE depending on the voltage polarity. Here we discuss the mechanism of this change.

We have calculated surface charge distributions at positive and negative peaks based on the SEEA mechanism [13], and the results are shown in Figure 10. The Pyrex® insulator with the same size used in the experiment was taken as an example. At the positive peak (+10 kV) the charge density becomes high as the position on the insulator surface gets closer to the grounded electrode, i.e. cathode. The distribution at the negative peak (-10 kV) is quite reverse.

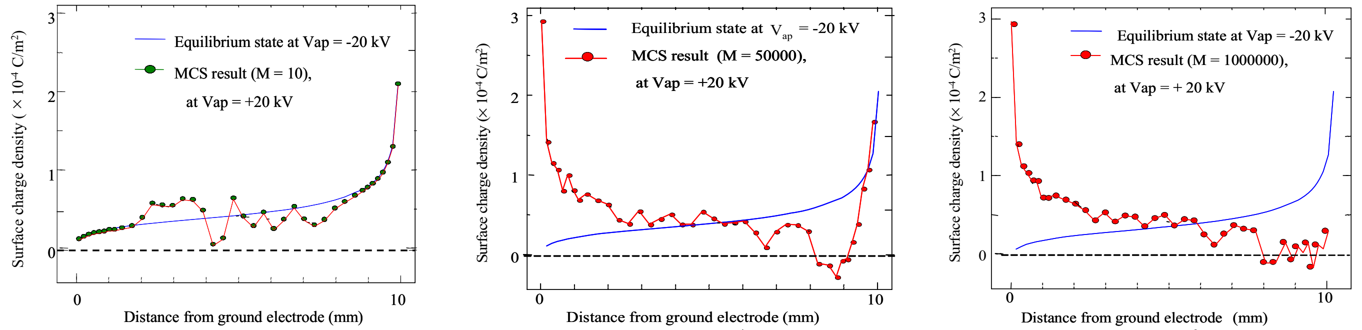



(a) positive phase - cathode surface




(b) negative phase - anode surface

**Figure 11.** Calculated and normalized electric field distributions, surface charge components, on the grounded electrode. Triple junction is at 0 and probe covers from -1 to -2 mm on the horizontal axis. (Pyrex®)




(a) M =10 (b) M = $5\times10^4$ (c) M = $10^6$

**Figure 12.** Transition of charge distribution from negative to positive phase (PMMA).

Calculated and normalized electric field distributions on the grounded electrode are shown in Figures 11a and 11b, respectively for positive and negative peaks. Note that the applied electric fields are removed in theses Figures. It can be seen the field strength is higher at positive peak. Since the probe is embedded in the grounded electrode, it acquires a larger induction charge when the voltage is positive.

We measured the normalized surface charge fields $E_s$ / $E_g$ from the probe signal at ± 10 kV (Figure 4) and compared to the calculated ones. At the positive peak, the normalized fields are 0.95 and 1.01, respectively, for measured and calculated results. They are 0.75 (measured) and 0.51 (calculated), respectively, for the negative peak. The same measurement and calculation were conducted for PMMA at ±20 kV, and they were 0.69 (measured) and 0.64 (calculated) at the positive peak, and 0.47 (measured) and 0.51 (calculated) at the negative peak. As the calculated fields are much the same as measured ones, we believe that the transition of surface charge distribution due to the polarity change is responsible for causing the quasi-stable state.

### 6.2 TRANSITION

The calculated charge distributions shown in Figure 10 are at the equilibrium states of charging for positive and negative voltage peaks, where the number of secondary electrons released from a point everywhere on the insulator surface equals to the incident electrons [8, 9, 13]. This situation is established when the incident electrons have an energy at which the secondary electron yield is unity.

The transition in charge distribution due to the change in voltage polarity can be pursued by simulating trajectories of electrons in vacuum. We have conducted the simulation by using a Monte Carlo method [13]. Figure 12 shows how the transition progresses. In this example we assume that the equilibrium state has been reached at the negative peak, and then the voltage turns suddenly to the positive peak value. In Figure 12a a bunch of electrons is released ten times from the cathode (grounded electrode) and they cause SEEA along the charged surface. It can be seen the SEEA brings a little distortion in the midst of the surface. As the number of electron release M increases the distortion becomes large (See Figures 12b and 12c). A charge distribution much closer to the equilibrium state at positive peak is achieved in Figure 12c. The complete equilibrium state will be realized with much larger M. Thus we recognize the SEEA mechanism plays decisive role when the charging of an insulator occurs in vacuum even in the case that AC voltage is applied.

## 7 CONCLUSION

The charging phenomena of an insulator subjected to ac voltage in vacuum can be characterized by three different states. They are initiation, quasi-stable and stable states. Acquired charge on the insulator is positive in all of the three states. In the first state, positive charge accumulates irrespective of the voltage phase. In the second state, the charge changes its distribution depending on the voltage polarity. The last state is characterized as a situation where no charging activities take part. The mechanism that restrains the insulator from charging activities is not clear at this moment and needs further studies. For an insulator with fine surface smoothness the stable state is hard to be established and the quasi-stable state is maintained.

Charging simulation has revealed that the transition in charge distribution due to the change in voltage polarity is responsible for causing quasi-stable state, and that the secondary emission electron avalanche mechanism plays decisive role in the transition. Roughening the insulator surface has been proved effective to prevent insulators from charging, and thus to improve withstand ability. These results are identical with the results obtained earlier with dc voltage application.

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