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Long Time Range Breakdown Caused by Penetration of Positive Charges Packet in Low Density Polyethylene Sheets

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Abstract: This paper presents an experimental study on long time range breakdown of Low Density Polyethylene (LDPE) under very high dc applied fields (E_{mean}) of 2.0 MV/cm or 3.0 MV/cm. Breakdown time lag and space charge distribution are simultaneously measured for a 200-μm-thick LDPE sheet with positive-semicon and negative-evaporated Al electrodes. A voltage is applied to the sheet until the dc breakdown occurs. 20 samples are tested for both the applied voltages. It should be remarked that 50 % survivor probability T_{50} , corresponding to time in which breakdown occurs for 10 samples out of 20, is 70 min for 40 kV, whereas it is 90 min for 60 kV. Results of the space charge measurement by pulsed electro acoustic (PEA) method indicates that a large number of positive charges are injected from the semicon-anode and they are accumulated in the bulk of LDPE, so that field distribution in LDPE is strongly distorted. The maximum field strength $E_{max}(t)$ in LDPE after the space charge penetration for 60 kV becomes higher than that for 40 kV. However, the distortion ratio $E_{max}(t)$ / E_{mean} under 40 kV is higher than that under 60 kV. This is because the positive charges packet produced by 40 kV penetrates into deeper area of the bulk as compared with that by 60 kV.

Keywords: Space charge, pulsed electro acoustic method, low density polyethylene, breakdown time lag

1. Introduction

Nowadays, most of oil-filled (OF) cables have been replaced by polymer insulated cables namely cross-linked polyethylene (XLPE) cable. XLPE cables has high temperature resistant and tensile strength. The main tenant cost of this cable is also lower than OF cable because it is more durable thus reducing the probability of breakdown. However, under long time dc voltage application, cable deterioration due to space charges penetration into the bulk of the insulation is a well-known phenomenon among the researchers in this field [1]. In this study, pulsed electro acoustic (PEA) method is utilized [2]-[4]. In this kind of study, usually low density polyethylene (LDPE) is used instead of XLPE. This is due to the additive content in XLPE such as cross-linking by-product and antioxidants that will affect space charges behavior. LDPE is considered ‘cleaner’ from additive than XLPE.

It is already understood that under positive polarity high voltage application, positive space charges penetrate from high voltage (semicon rubber) electrode and propagates towards ground electrode [5]-[14]. The penetration of space charge into the bulk of insulating material will disturb local electric field. Moreover, space charge penetration depth becomes shallower with the increase of mean applied electric field [3]. However, relationship between space charge and breakdown is not clearly understood.

In order to extend knowledge on this phenomenon further, in this study, the influence of mean applied field (which is set at 2.0 MV/cm or 3.0 MV/cm) on the breakdown time lag (time from the beginning of voltage application until breakdown occurs) is investigated. From

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breakdown time lag measurement, a statistical data of breakdown occasion can be obtained. Usually, one expect that breakdown occur earlier in sample under high mean applied field than that under lower one. In the other words, breakdown time lag decrease with increasing the mean applied field. However the obtained data shows the contrary. In other words, breakdown is easier to occur under 2.0 MV/cm than 3.0 MV/cm. This phenomenon is very interesting and the process behind it should be profoundly investigated. In this paper, space charges behavior under 2 different mean applied field is discussed.

2. Experimental Methods

Figure 1 shows the cross-section of the sample and the experimental arrangement diagram. Semicon rubber and evaporated aluminium layer are used as high voltage and ground electrode respectively. By using semicon rubber as high voltage electrode, under positive polarity voltage application, positive space charge can easily penetrate into bulk of the sample. This is because the barrier height at the interface between semicon electrode and insulator is much lower than that between Al electrode and LDPE [16] Sample is made of LDPE. LDPE pellet Grade G201 (Sumitomo chemical Inc.) is mixed by a mixing-roll machine in order to create LDPE sheet. Then, it is hot-pressed to reduce thickness of the film centre to 200 µm. Normally, film-type sample is used. In this study, recessed-type sample is used to avoid breakdown that caused by the edge of effect (refer figure 1). The fabrication of curvature-edge in the sample instead of sharp-edge reduces the probability of breakdown at semiconductor edge. The semicon rubber sheet will be bent thus increases the distance to ground electrode as shown in figure 1. Silicone oil is used to fill the vessel in order to avoid surface discharge during high voltage application.

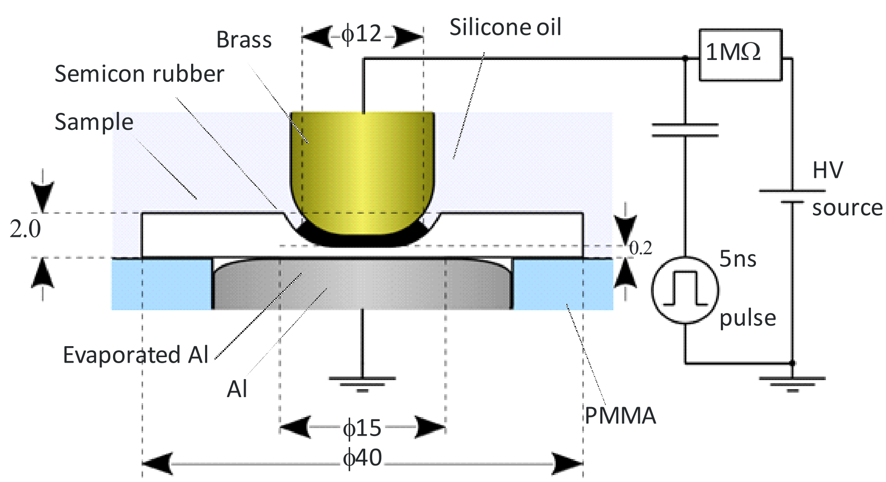
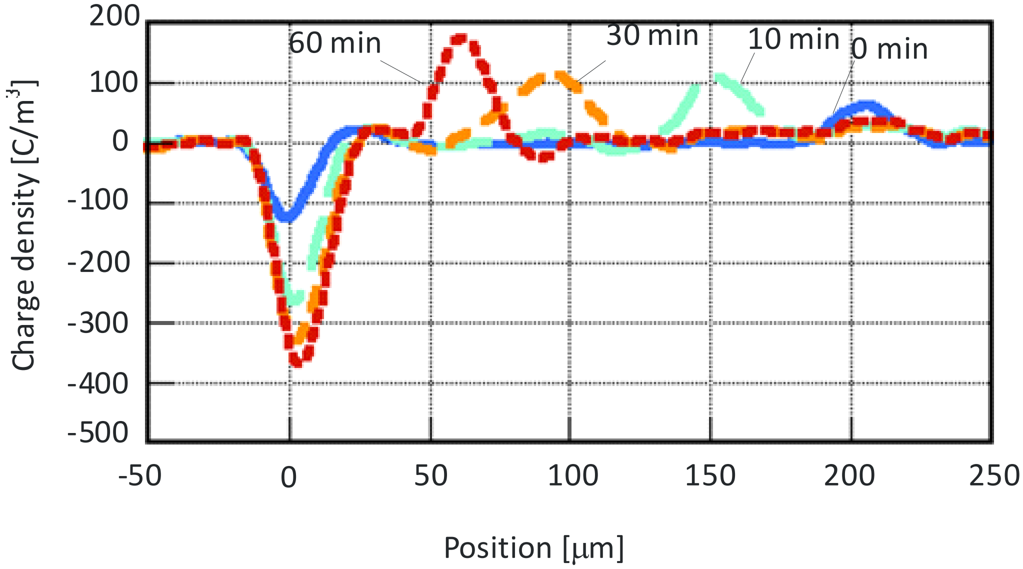


Figure 1. Cross-section of recessed polyethylene sample and experimental arrangement diagram.

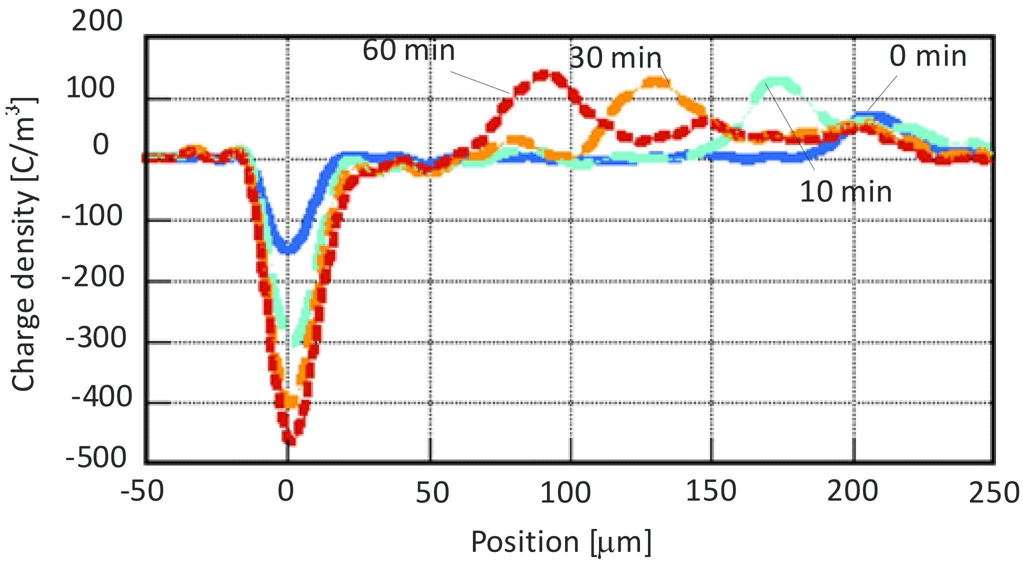
Experiments are carried out inside a thermostatic chamber at 30 °C under atmospheric pressure. The arrangement as in figure 1 is to ensure very high mean electric field, E_{mean} up to 3.0 MV/cm (corresponding to 60 kV) of can be applied to the sample. Samples are subjected to positive polarity dc high voltage. 20 samples are used in each experiment. As general rule, voltage is applied to the sample until breakdown occurs. If breakdown does not occurs within 5 hours the experiment will be stopped.

Laue plot of breakdown time lag is plotted. Space charge measurement is carried out during the breakdown test. The corrected PEA measurement data by a deconvolution technique [17] [18] is also presented in this paper. Maximum electric field, $E_{max}(t)$ is defined as maximum field strength in the bulk of LDPE under the dc step voltage as a function of time. The $E_{max}(t)$ is derived from the space charge measurement data by using *Poisson's* equation. Distortion ratio, $D(t)$ is defined as peak value of $E_{max}(t)$ divided by E_{mean}.

3. Results and Discussion



(a) E_{mean} = 2.0 MV/cm



(b) E_{mean} = 3.0 MV/cm

Figure 2. Space charge distribution in the no breakdown sample after 0 min, 10 min, 30 min, and 60 min for (a) 2.0 MV/cm and for (b) 3.0 MV/cm of mean field strength.

Figures 2 (a) and 2 (b) show space charge measurement profile for 2.0 MV/cm and 3.0 MV/cm in no-breakdown samples respectively. The horizontal axis represents the distance from ground electrode surface along the direction of electrode axis. Position 0 µm in the axis represents the location of ground electrode and position 200 µm represents the location of high voltage electrode. In other word, position of 0 to 200 µm is the thickness of the sample. Vertical axis in both figures represents charge density. These figures show typical space charge penetration behavior as measured by others [15][19]. In both figures, space charge distribution profiles during 0 min, 10 min, 30 min and 60 min are shown so that the evolution of space charge behavior can be understood.

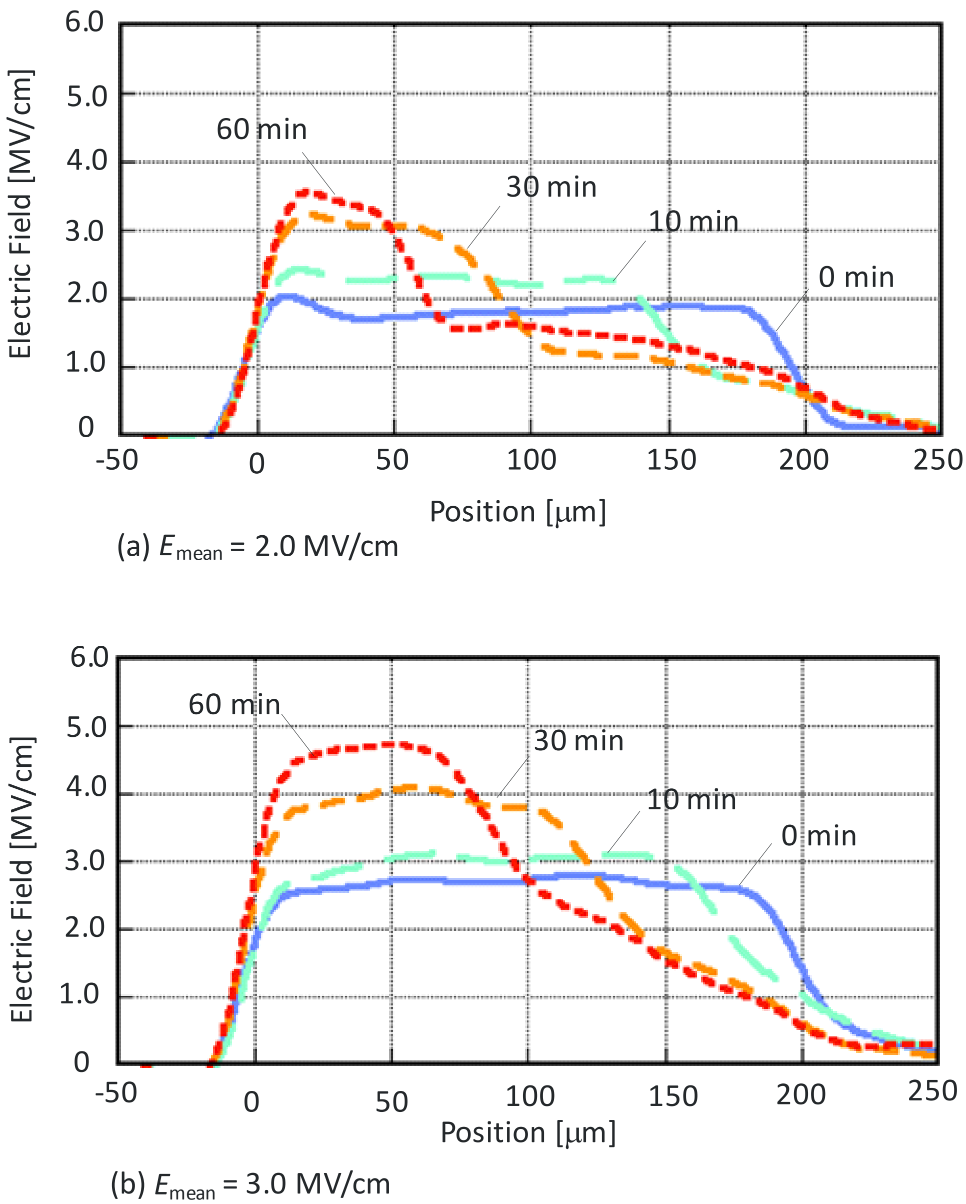


Figure 3. Electric field in the no breakdown sample after 0 min, 10 min, 30 min, and 60min for (a) 2.0 MV/cm and for (b) 3.0 MV/cm of mean field strength.

From both figures, it is understood that space charges penetrate from high voltage electrode and then propagates towards the counter electrode. Space charge density under 2.0 MV/cm as shown in figure 2 (a) increases during penetration. The peak of the space charge at 60 min is 175 C/m^3 .While under 3.0 MV/cm as shown in figure 2 (b), there is an increase of space charge density from 0 min to 10 min. From 10 to 60 min, space charges spread widely in the bulk of sample while penetrating. This is the reason why the increment of peak value is almost unseen. Space charge penetration depth is deeper under 2.0 MV/cm than that under 3.0 MV/cm. This characteristics is similar to a previous report [20].

Figures 3 (a) and (b) show the $E_{max}(t)$ value of figures 2 (a) and (b) respectively. From figure 3 it is understood that $E_{max}(t)$ under 3.0 MV/cm is higher than that under 2.0 MV/cm. However, $D(t)$ of sample under 2.0 MV/cm is 1.9 at t = 60 min and under 3.0 MV/cm it is 1.5 at same time. This shows that local electric field in sample under 2.0 MV/cm is more distorted than that under 3.0 MV/cm.

Figure 4 shows a laue plot of breakdown time lag under 2.0 MV/cm and 3.0 MV/cm. Under 2.0 MV/cm, breakdown occurs in 15 out of 20 samples whereas breakdown occurs in 16 out of 20 samples under 3.0 MV/cm. At this point, breakdown probability within 5 hours for 3.0 MV/cm is slightly higher than that for 2.0 MV/cm. It should be remarked that 50 % survivor probability T_{50} , corresponding to time in which breakdown occurs for 10 samples out of 20, is 70 min for 40 kV, whereas it is 90 min for 60 kV. For 2.0 MV/cm, breakdown occurs mainly from 60 to 80 min region. Mean breakdown timelag for the 15 samples under 2.0 MV/cm is 45 min. While for 3.0 MV/cm, breakdown occurs mainly from 80 to 110 min region. Mean breakdown timelag for the 16 samples under 3.0 MV/cm is 68 min. From figure 4, it is understood that breakdown occurs faster under lower voltage application.

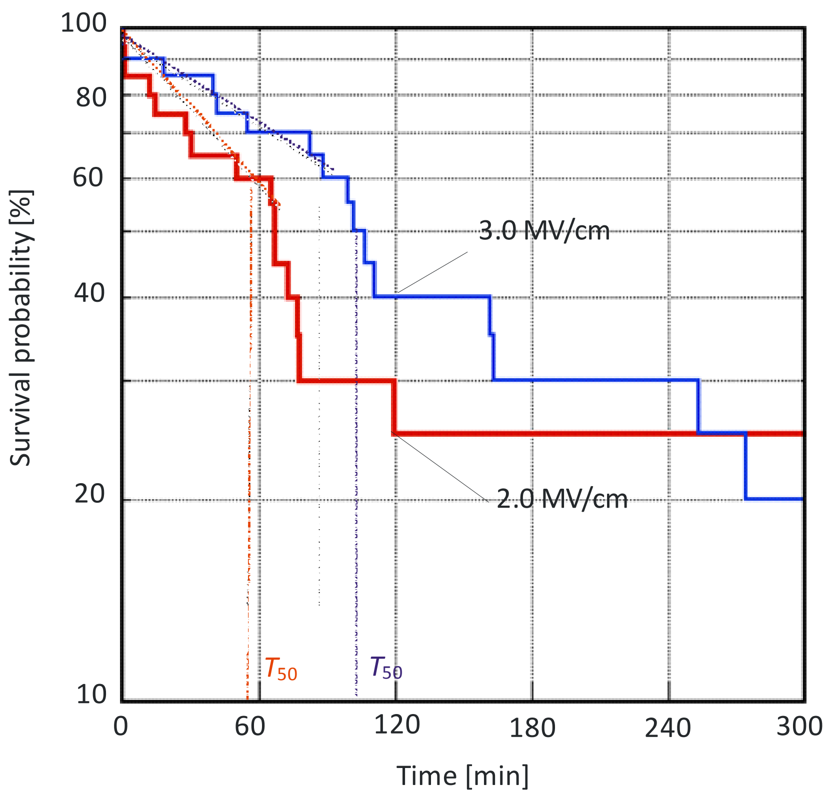


Figure 4. Laue plot of the breakdown time lag in each applied field

Figures 5 and 6 show temporal changes in space charges distribution in two of the breakdown samples in which breakdown occurs in within 60 min and over 60 min respectively. Horizontal axis in both figures represents time whereas vertical axis represents position. From figure 5, it is understood that penetration speed in sample under 2.0 MV/cm is faster than that under 3.0 MV/cm. For instance, in figure 5 (a), in 10 min space charges already reached 100 μm while in figure 5 (b), a space charge do not reach that position yet.

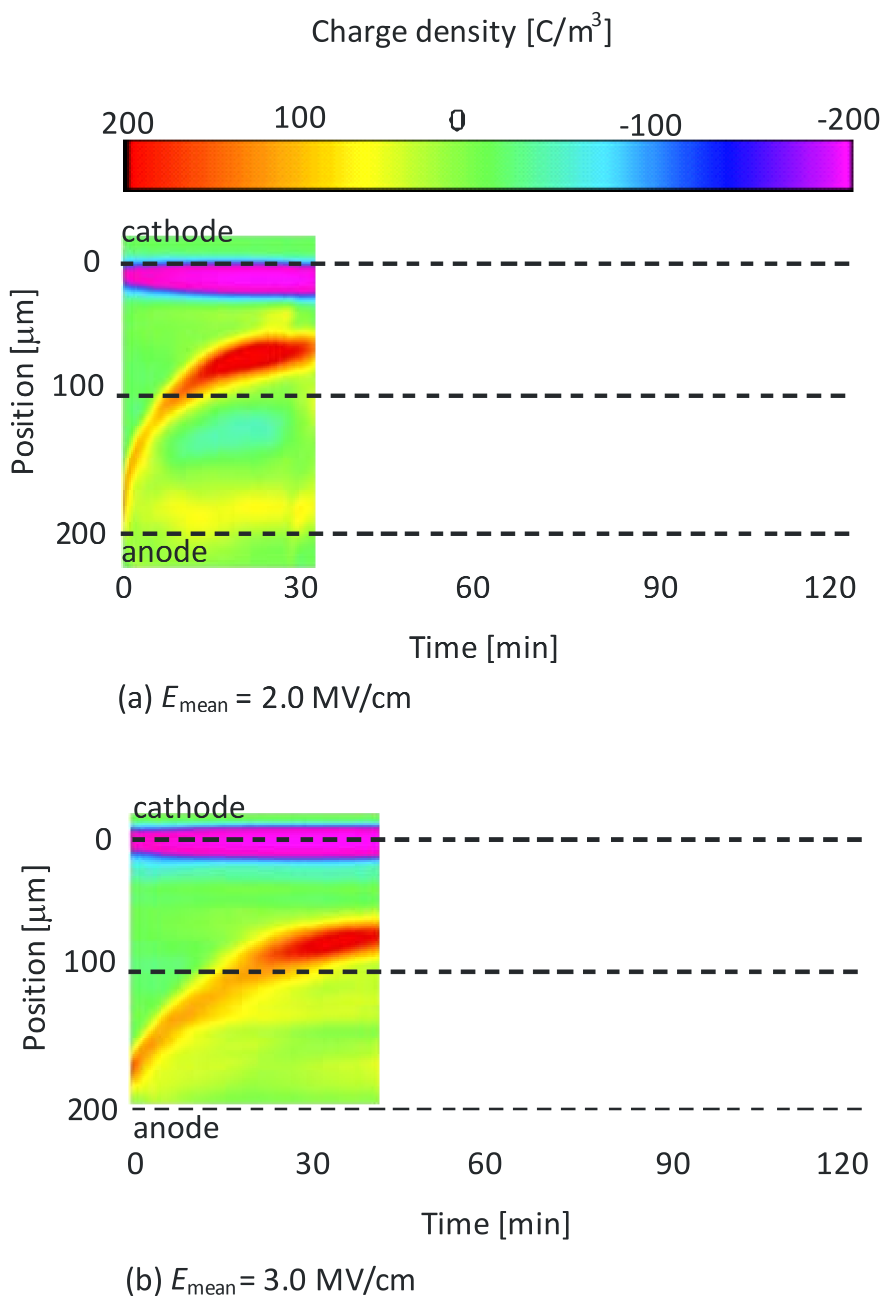


Figure 5. temporal changes in space charge distribution in one of the breakdown sample (in less than 60 min).

From figure 6, the situation is almost similar to that in figure 5. The different is that breakdown does not occurs as early as that in figure 5 (within 60 min). From figure 6 (a) which shows space charge penetration under 2.0 MV/cm, reveals that breakdown occurs after positive space charge is neutralized (the red color disappear and the region turn into green). From figure 6 (b), after space charge penetrates and freezes, it takes time to gradually disappear.

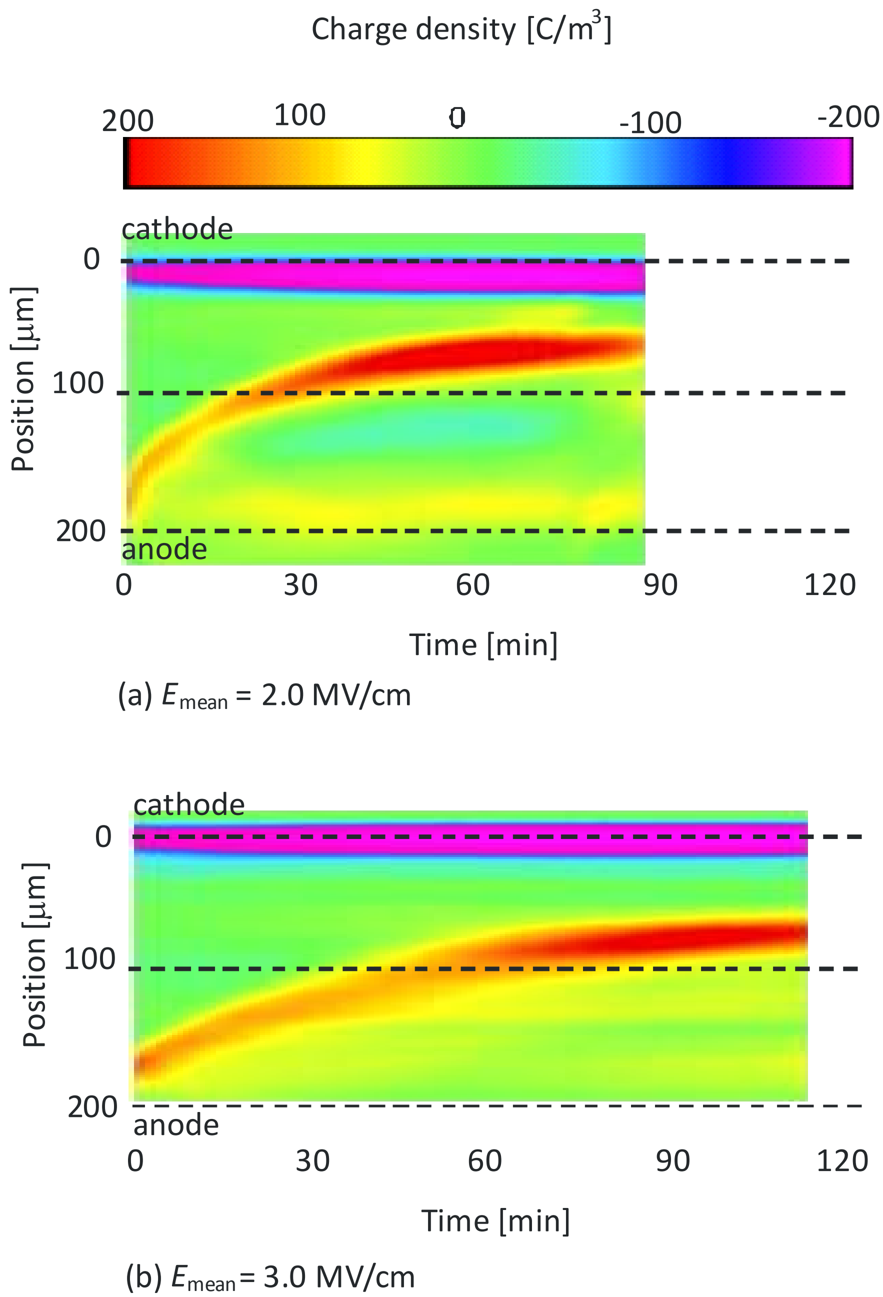


Figure 6. Temporal changes in space charge distribution one of the breakdown sample (in more than 60 min).

Figure 7 shows $E_{max}(t)$ value corresponding to figure 5 and 6. By comparing figure 5, 6 and 7, it is understand that breakdown occurs after $E_{max}(t)$ crossing its peak. This shows that breakdown is not directly related to peak value of $E_{max}(t)$.

Figure 8 (a) and (b) show temporal changes in space charge distribution for 2.0 MV/cm and 3.0 MV/cm in no-breakdown samples respectively. From both figures it is understood that space charges penetrate faster and deeper under 2.0 MV/cm than that under 3.0 MV/cm applied field. For instance, at 30 minutes, under 2.0 MV/cm, space charges penetrate up to 100 µm. While under 3.0 MV/cm, in the same period, space charges do not reach that position yet. Under 2.0 MV/cm as shown in figure 8 (a), the space charges freeze at 60 min. At 80 min, space charges are suddenly neutralized. After that negative space charges disappear from the middle region of the sample bulk. While under 3.0 MV/cm case as shown in figure 8 (b), the positive space charges freeze earlier at 50min. The frozen space charge do not disappear instantly as that under 2.0 MV/cm (refer figure 8 (a)). The space charges gradually disappear after 270 min. During this time, negative charges also become slowly visible starting from 260 min. After 270 min, the region where positive space charges froze before turn green.

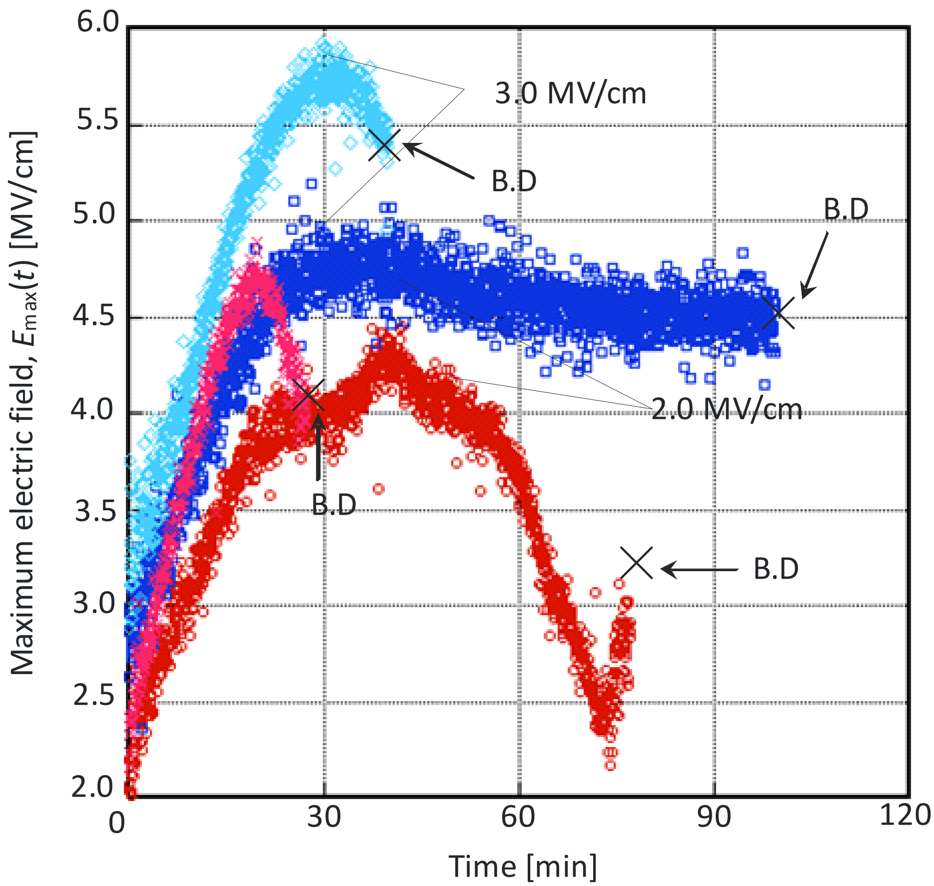
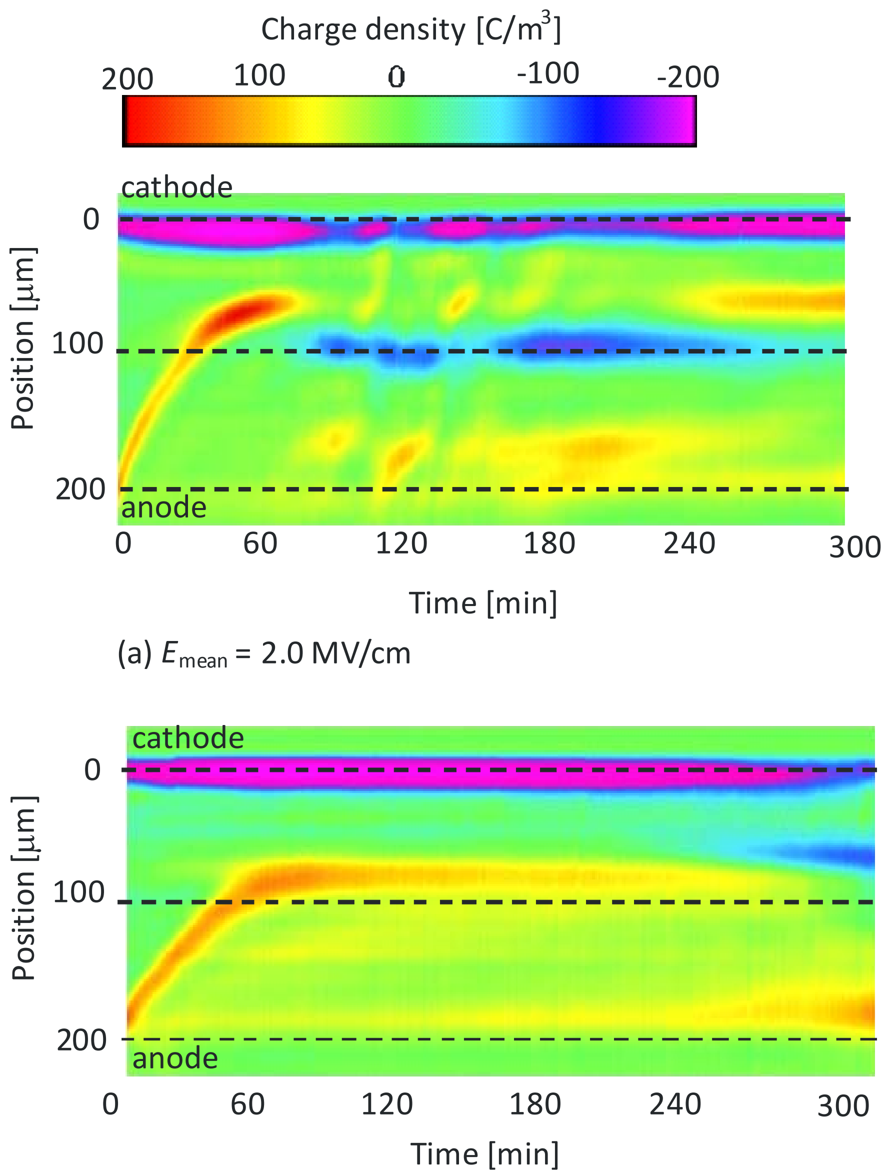


Figure 7. Temporal change of the maximum electric field of 4 no-breakdown sample.

Figure 9 shows mean $E_{max}(t)$ values of 4 no-breakdown samples under each voltage application. From this figure, it is understood that samples under 2.0 MV/cm voltage application reach $E_{max}(t)$ faster than that under 3.0 MV/cm. While samples under 3.0 MV/cm show higher $E_{max}(t)$ value than that under 2.0 MV/cm. After reaching peak value, $E_{max}(t)$ decreases gradually under 3.0 MV/cm but declines instantly under 2.0 MV/cm of voltage application. The change in $E_{max}(t)$ value indicates that there is also changes in number of charge in the region. Under negative polarity voltage application (-40 kV and -60 kV), no breakdown occurs in all samples.



(b) E_{mean} = 3.0 MV/cm

Figure 8. Temporal changes in space charge distribution in the no-breakdown samples.

Figure 10 shows temporal changes in space charge distribution for sample under -40 kV voltage application. Under negative polarity even after 5 hours of voltage application, breakdown does not occur in all cases. From figure 10, there is a small amount of negative space charges from semicon electrode penetrates along with the penetration of positive space charge from ground electrode and then freeze. Positive space charges penetrate deeper than negative space charges. At 180 min, both of the charges disappear from the region. At 200 min, negative space charges re-appear at a deeper region than the previous one while positive space charge remain with no further penetration.

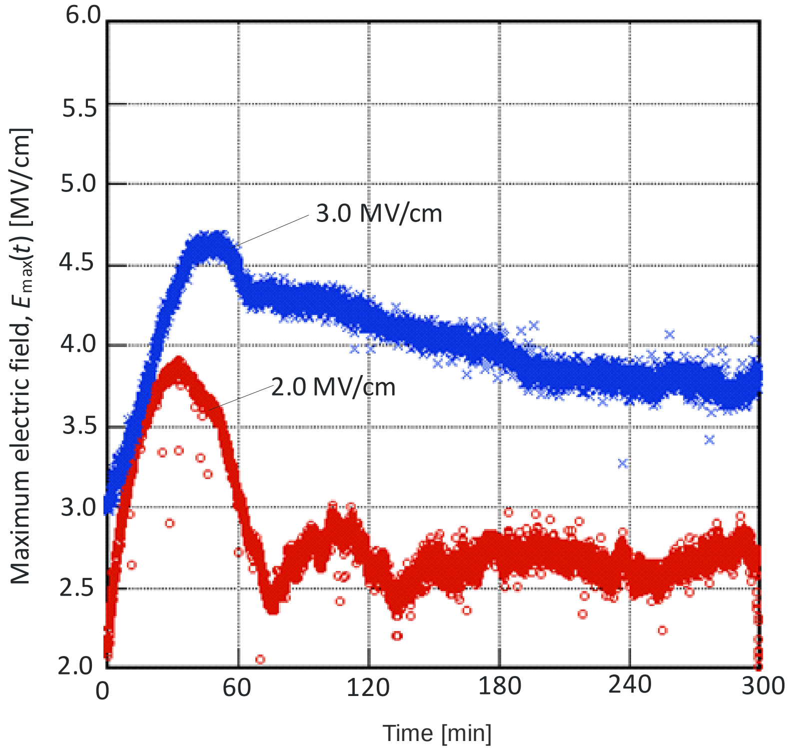


Figure 9. Temporal change of average of the maximum electric field in the no breakdown sample.

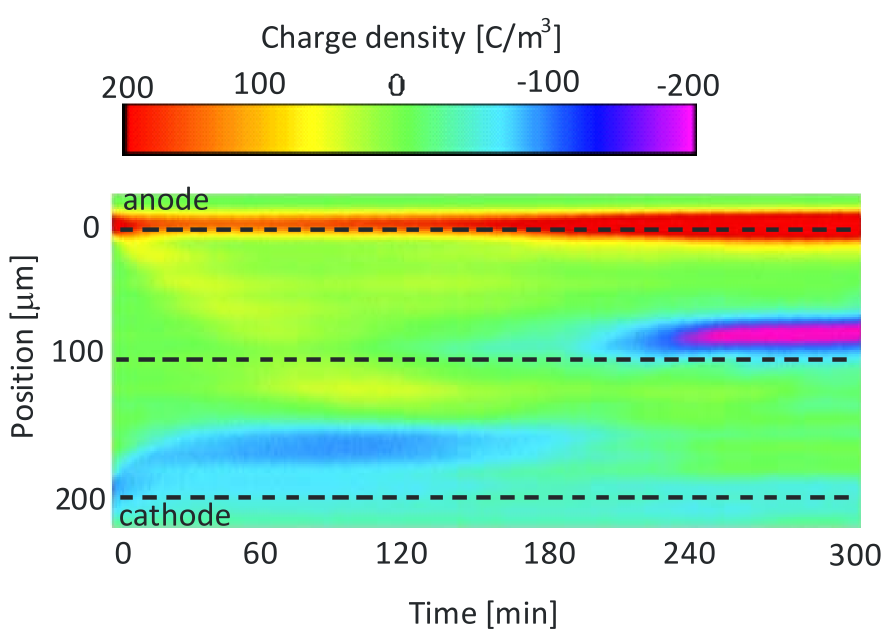


Figure 10. Temporal changes in space charge distribution of -40 kV applied sample.

Conclusion

Space charge penetration is faster and deeper under 2.0 MV/cm than that under 3.0 MV/cm applied field. Breakdown in those samples occurs after $E_{max}(t)$ value passes its peak value. It is suggested that successive process during / after space charge penetrate such as bipolar injection and recombination of space charges affect the delay of breakdown in the samples. Under higher (3.0 MV/cm) applied field, it is suggested that space charges are difficult to move causing the the successive proces to occur later than that under lower (2.0 MV/cm) applied field. This leading to the delay in breakdown under higher voltage application than that under lower one. Further work such as the relationship between electroluminescence and breakdown is needed to explain this very high field phenomena.

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