MEASUREMENT TECHNIQUES FOR CHARGING IN BULK OF INSULATING MATERIALS IRRADIATED BY RADIOACTIVE RAYS

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Abstract

Advanced measurement techniques for charging in bulk of insulating materials irradiated by radioactive rays, especially electron beam or gamma ray, will be introduced. Using the techniques, so called PEA and PIPWP, charge distributions accumulating in the bulk of insulating materials are measured precisely. These techniques are originally developed for measurement of charge accumulation in insulating materials of high voltage devices such as cable insulating materials. On the other hand, there are many reports for accidents of spacecraft in space environment caused by the bulk charge accumulation due to the irradiation of high-energy cosmic ray. Unfortunately, there are many unknown parts concerning to the relationship between the charge accumulation in bulk of insulating materials have been left, while the experimentally measurement of charge distribution in bulk had been difficult. Therefore authors have tried to apply above techniques to measure the charge distribution in insulating materials irradiated by electron beam or gamma ray. In this paper, the principle of the measurement will be introduced at first, then some typical measurement results will be shown.

INTRODUCTION

In space environment, especially at higher altitude such as GEO, spacecraft is exposed under high-energy radioactive rays and/or charged particles such as gamma ray, electron-beam and protons. When the radioactive rays are irradiated to the insulating materials of spacecraft such as cover glasses of solar battery or heat control polymer sheets, it is said that the charges accumulate in the bulk of them and sometimes they causes to the discharge with serious damage to the electric devices. Therefore, it is necessary to investigate the relationship between the accidents and the accumulation of charge by irradiation of radioactive rays. However, it had been difficult to measure the charge distribution in the bulk of insulating materials directly, the mechanism has not been clear yet. On the other hand, many advanced techniques for measurement of charge distribution in dielectric materials have been developed in a couple of decade [1]. The techniques have been developed for mainly the measurement of materials of high voltage devices. However, it is easy to apply these techniques to the measurement of the charge distribution in insulating materials irradiated by radioactive rays. In other words, these techniques are keys to make the mechanism of charging and discharging process clear. In this paper, the principles of these techniques are discussed and typical results are introduced as an example of applications for the problems in space environment.

PRINCIPLES OF PEA AND PWP METHODS

The PEA (Pulsed Electro-Acoustic) method is one of widely used technique to measure the charge distribution in dielectrics. The principle of the PEA method is shown in Figure 1. Consider a sheet sample with thickness of d and charge distribution $\rho(z)$. An externally applied pulsed electric field Ep(t) is applied to the sample and induces a perturbation force on each charge. This force causes the charge to move slightly. This movement launches an acoustic wave that is proportional to the charge distribution in the sample. A piezoelectric transducer is used to detect the acoustic wave and transform the acoustic wave into an electric signal. The details of the measurement is described elsewhere [3]. Since, in the PEA measurement system, the detector of piezo-electric transducer is completely shielded and it separated from the sample, we can measure the charge distribution with low electric noise. However, the high voltage pulse is applied to the sample to obtain a sufficient signal, it is difficult in vacuum environment. Therefore, it should be used for the fundamental research works to investigate the charge accumulation after irradiation at laboratory.

The PWP (Pressure Wave Propagation) method is another major technique to measure the charge distribution in dielectrics. The principle of PIPWP (Piezo-Induced PWP), which is one of PWP method, is shown in Figure 2. The acoustic wave acts as a charge probe. The charge moves as the acoustic wave propagates through it. This movement causes a change of surface charge on the electrodes. The time signal of displacement current indicates the charge distribution in the sample. By measuring the displacement current between the electrodes, the charge distribution is obtained. The details of the measurement is described elsewhere [3]. Since, in the PIPWP system, the electric pulse voltage, which is applied to the piezo-electric transducer to generate the pulsive acoustic wave, is not so high, this method is applicable to the measurement under vacuum condition. Therefore, this method may be used as a monitor in spacecraft. However, in this method, the sensitive amplifier is easily to be affected a damage by electric noise because the amplifier is connected to the amplifier. Therefore, it is necessary to make some improvement to use it as the monitoring system in space environment.

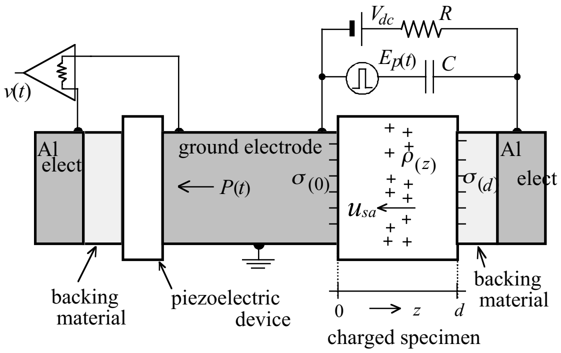

Figure 1. PEA measurement system

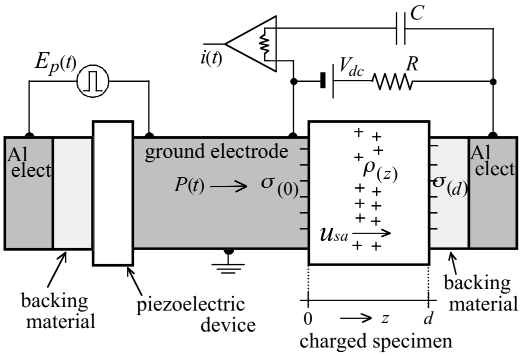

Figure 2. PIPWP measurement system

Figure 3(a) shows the typical measurement result of charge distribution in PMMA (poly-methyl-methacrylate) measured using PEA method. The thickness of PMMA is about 500μm. The measurement was carried out under 2kV dc voltage applied to PMMA. Under this measurement condition, there is no charge accumulation in the bulk, but only induced charges are observed at the interface between electrodes and PMMA. The electric field distribution calculated from the result of charge distribution is shown in Figure 3(b). Since, there is no charge accumulation in the bulk, the electric field in the bulk shows a constant value of about 40 kV/mm, which is equal to the theoretical value of average electric field generated by applied voltage. Figure 3(c) is the electric potential distribution calculated using the electric field distribution shown in Fig. 3(b). It is clear that the value of potential at position of 500 mm is 2 kV, which is equal to the applied voltage. As shown in Fig. 3, it is clear that the quantitative measurement is possible using the PEA method. Figure 4(a) shows the typical measurement result of charge distribution in PMMA measured using PIPWP method. All of measurement conditions in this experiment are the same to that of results shown in Figure 3. It is clear that the charge, electric field and potential distributions shown in Figure 4 are similar to the results shown in Figure 3. It means that both of measurement methods can be applicable to the measurement of charge distribution in the bulk of insulating materials.

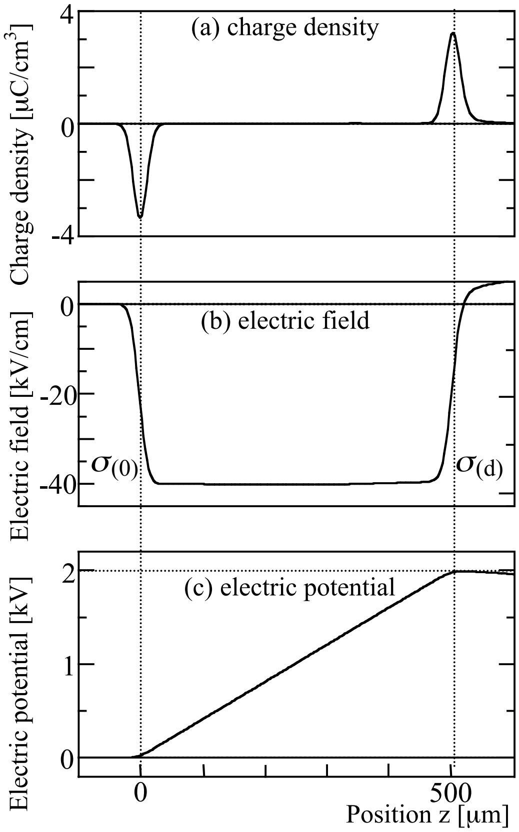

Figure 3. Experimental result using PEA method

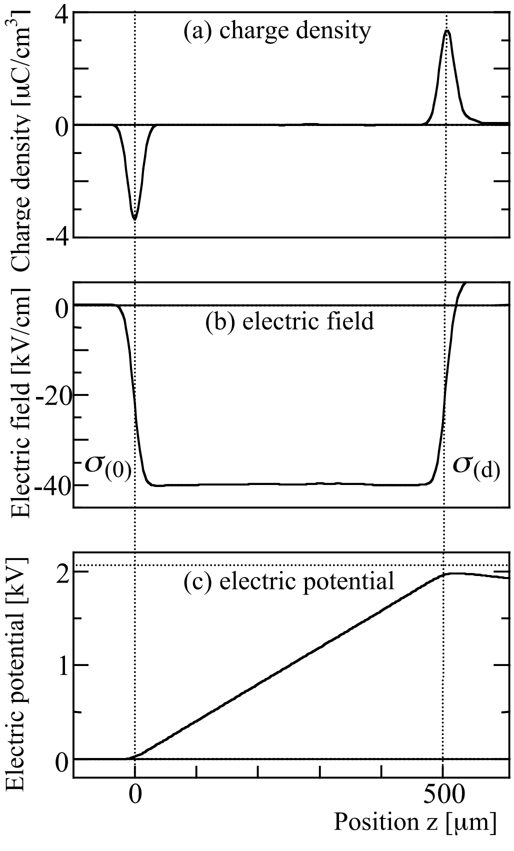

Figure 4. Experimental result using PIPWP method

RESULTS AND DISCUSSION

Gamma ray irradiated LDPE

Figure 5 shows the charge accumulation process in γ-irradiated LDPE (Low-density polyethylene) under dc voltage stress. The charge distributions were measured using PEA method. The thickness of LDPE is about 630 μm and the applied voltage is 15kV. The sample was irradiated by γ-ray from ^{60}Co source with dose rate of 12Gy/h and total dose of 2.4 kGy in air atmosphere. Before voltage application, no charge was observed in the bulk. After voltage application, however, the positive charge appeared near cathode, then it broadened towards the anode. Finally, the change of the charge distribution becomes to be saturated. Figure 6 shows time dependent charge distribution under short circuit condition after voltage application. The positive charge near cathode decreased gradually, and positive charge appeared near anode. To analyze the charge accumulation and decay process, we assume a simple model shown in Figure 7. Consider electrons and parent positive ions with density ρ_0, which is escaped from recombination, remained in γ-ray irradiated LDPE with thickness of *l*. Here, we assume if dc voltage is applied to this LDPE sample, only the electrons are mobile, and there is no injecting charge from electrode. These assumes are reasonable judging from our experimental results described in the report [4]. When some of the electrons are drifted and swept out into an anode by the applied dc voltage, some of positive ions become observable. In such a case, apparent positive charge distribution appears from cathode side and the positive charge distribution spread towards the anode side. Details of analysis model are described in elsewhere [5]. Figure 8 is a time dependence of the electric field at cathode interface. The calculated curves in Fig. 8 are obtained by giving the value of mobility obtained from experimental value. Here, three curves are calculated for example. Judging from the characteristics of curves, we can estimate the value of the mobility.

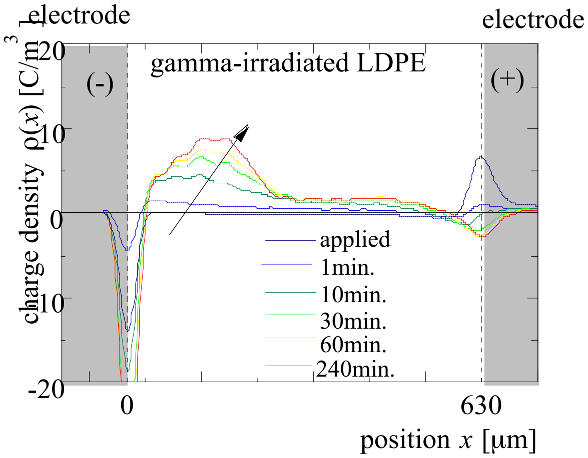

Figure 5. Charge distribution in γ irradiated LDPE under dc voltage application

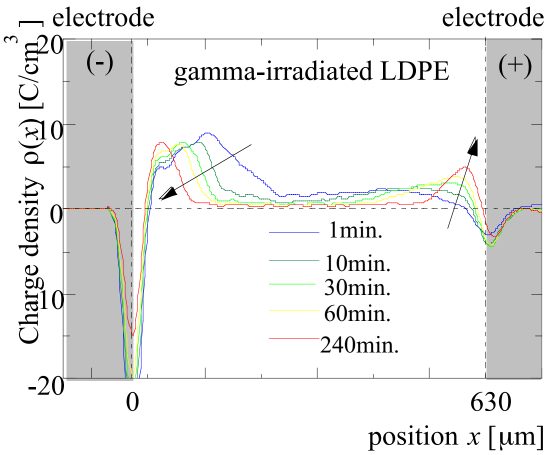

Figure 6. Charge distribution in γ irradiated LDPE under short circuit condition

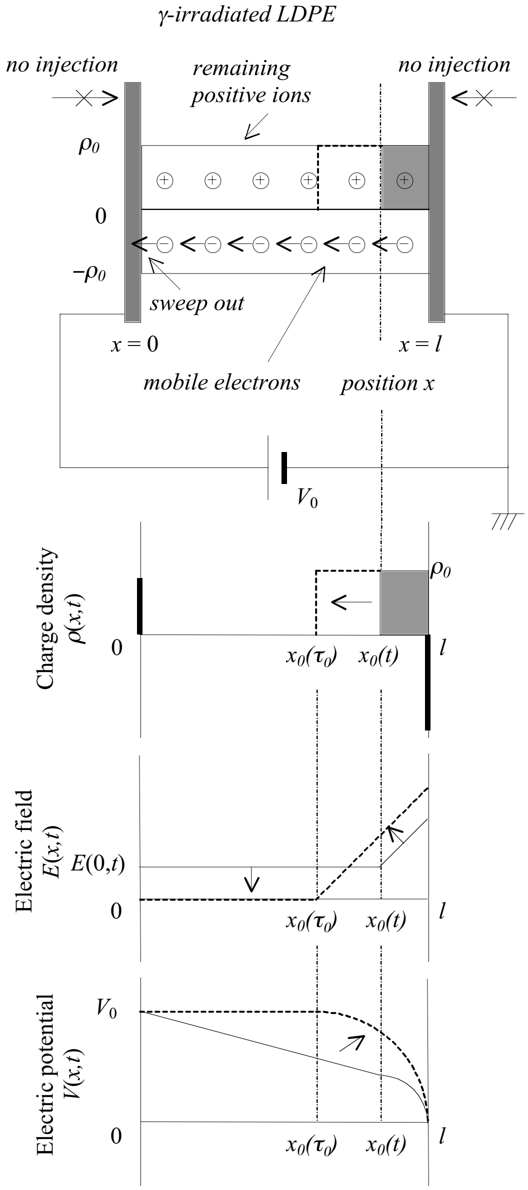

Figure 7. Model of charge behavior in γ irradiated LDPE

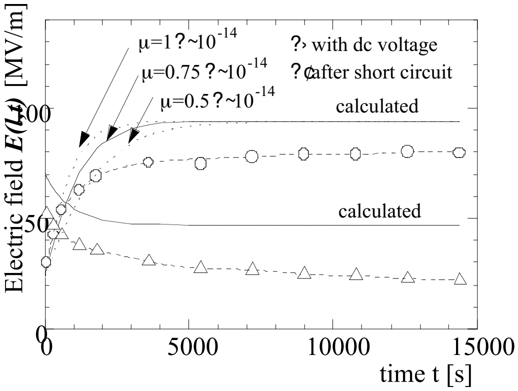

Figure 8. Time dependent electric field at cathode interface

Electron beam irradiated Kapton®

Figures 9 and 10 show the charge distribution in Kapton® irradiated by electron beam with acceleration energy of 75 and 100 keV, respectively. The charge distributions were measured after irradiation using PIPWP method. The thickness of the samples is about 135 μm. The electron beam is irradiated from right hand side in the figures. It is clear that the injected electrons are accumulated in the middle of the sample as shown in Figure 9. On the other hands, the injected electrons are accumulated near left side electrode when the acceleration energy of electrons are 100 keV as shown in Figure 10. It is clearly shown that the penetration depth depends on energy of the electron-beam. Figure 11 shows the decay process of the accumulated electrons in the bulk of the sample under short circuit condition. The result was obtained measuring the charge distribution following the result shown in Figure 10. It is interesting that the injected electrons remain in the bulk for long time. Even a week after irradiation, the charge distribution still stays in the bulk of Kapton® shown in Figure 11. Judging from our experimental experiences, the accumulated charge in Kapton® tends to stay for long time. As it is generally well known that the Kapton® is widely used for an insulating material in space environment because of its high performance of dielectric and mechanical properties at high temperature. Therefore, it seems to be important to investigate the charging properties of Kapton® under cosmic rays is important.

Electron beam irradiated PMMA (Measurement under irradiation)

As shown in above terms, the charge distribution in dielectrics after irradiation of radioactive rays is possible to measure using PEA or PIPWP method. However, it is necessary to measure the charge distribution under irradiation when we would like to have a monitoring system for spacecraft. Therefore, authors attempted to develop a new design of a system to measure the charge distribution under electron beam irradiation. Figure 12 shows a schematic diagram of the newly developed apparatus for a real-time measurement system under radioactive irradiation. In an ordinary system, the sample is set on the grounded metal lower electrode and the signal is detected from the top electrode [3]. On the other hand, the new apparatus must have a window for the irradiation of the radioactive rays to the sample. Therefore, a window is made on the topside of the apparatus as shown in figure 12. However the room for the sample should be completely shielded to reduce the noise from outside.

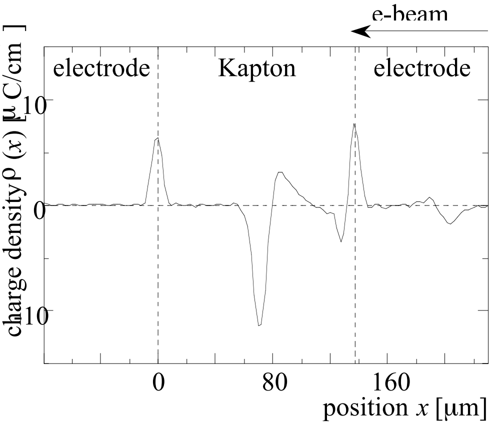

Figure 9. Charge distribution in e-beam irradiated Kapton® (75keV)

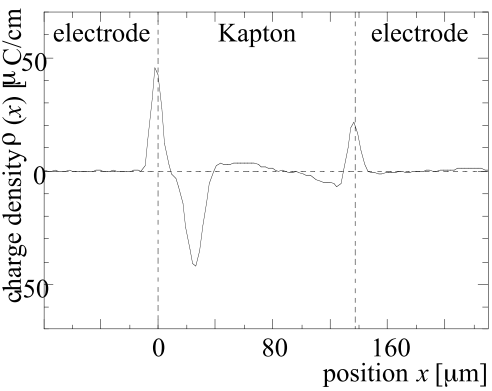

Figure 10. Charge distribution in e-beam irradiated Kapton® (100keV)

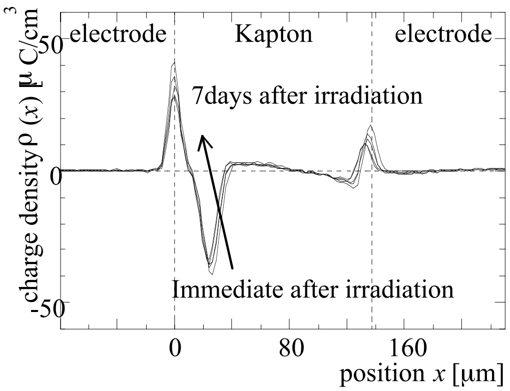

Figure 11. Decay of charge distribution in e-beam irradiated Kapton (100keV)

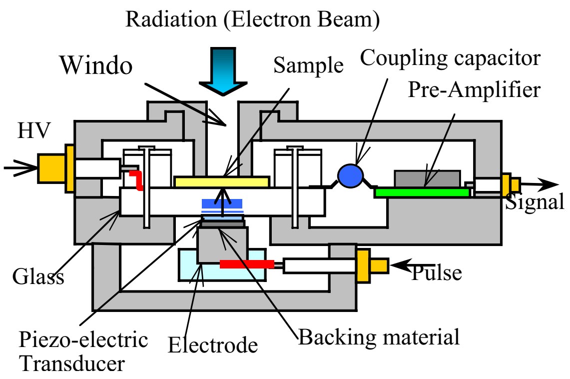

Figure 12. Diagram of the main apparatus.

Therefore the sample has an evaporated aluminum electrode on the topside surface, and it is connected tightly to the grounded flange of the window. To obtain the electric signal from the bottom side of the sample, a glass plate is inserted between the sample and the piezo-electric device. This glass plate is used to isolate the bottom side of the sample from the grounded level. As the aluminum electrode is evaporated on the bottom side of the glass plate for the shielding, the sample is completely covered by the grounded shield. The glass plate also has an evaporated electrode on the topside surface and it is connected to the detecting amplifier.

To generate a pressure wave, a pulse voltage is applied to the piezo-device. In this experiment, the PVDF film with 9 μm thick was used as piezo-device. The pressure wave generated at the piezo-device propagates through the glass layer and then it arrives at the sample.

To reduce the noise, the signal is averaged using the oscilloscope. The averaged signal is transmitted to the computer and then the charge distribution is calculated using the averaged signal with the adequate data processing and the calibration processes [6]. Since the pulse generator and the oscilloscope are controlled and synchronized each other using the computer, the charge distributions are measured automatically within the period of 10 seconds.

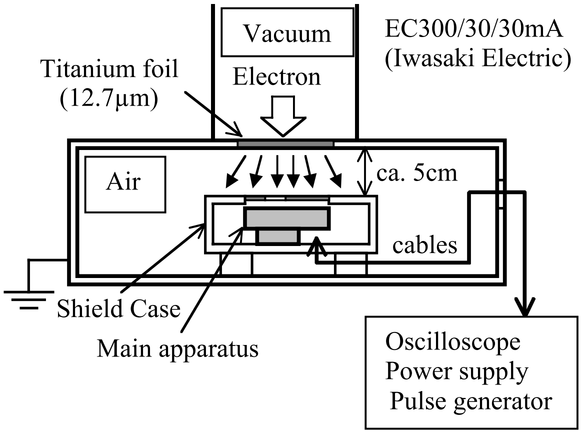

Figure 13. Set up for electron beam irradiation

The electron beam irradiation was carried out in the air using the EC300/30/30mA (Iwasaki Electric Co. Ltd.,) with the energy of 230 keV and the current of 10 mA/cm^2 for 5 minutes. Figure 13 shows a diagram for a setup of electron beam irradiation. The electrons are accelerated in the vacuum chamber and they come down through the titanium foil of 12.7 μm thick. After passing through the foil, the electrons arrive at the surface of the sample through the air gap of about 5 cm. Because the energy of the electrons are reduced during the passing through the foil and the air gap, the actual acceleration energy of the electrons which arrive at the sample surface are expected to be lower than 230 keV. The main apparatus is put into the shield case. The diameter of the irradiation window of the electron beam source is 30 mm and that of the main apparatus is 6 mm. A titanium shielding foil covers the main apparatus except for the area of the irradiation window.

The measurement was carried out with the period of 30 seconds for 5 minutes during electron beam irradiation. After the irradiation, the decay process of the charge distribution was also measured under short circuit condition with the period of 30 seconds for 30 minutes. The electric field and potential distributions were calculated using the obtained charge distributions.

Figure 14, 15 and 16 show the changes of the charge, the electric field and the potential distributions in PMMA of 510 μm thick during the electron beam irradiation. The results shown in these figures are obtained at 30 seconds before the irradiation and every 1-minute during the irradiation. Within 1 minute after start of the irradiation, no remarkable peak was observed in the charge distribution. After 1 minute from the start of the irradiation, a negative peak appeared at the depth of about 200 μm from the irradiation surface. The peak height gradually increased during the irradiation and finally it reached the value of about –33 C/m^3. Judging from this result, the deepest position of the electron beam penetration seems to be at 315 μm from the irradiation surface. It means that the area of left-hand side of the position at 315 μm in this figure is non-damaged area by the electron beam irradiation.

The electric field distributions shown in figure 15 were calculated using the charge distributions shown in figure 14. It is clearly shown that the direction of the electric field distribution is separated into two areas. The areas of the left and right hand sides in the figure 15 are the positive and the negative electric fields, respectively. Each border seems to be located near the peak of the charge distribution shown in figure 14. The negative electric field gives a force towards the right-hand side to the injected electrons. In other words, the negative electric field works as a return force for the injected electrons towards the irradiation surface. The increase of the negative electric field might cause the saturation of the increase of the charge distribution shown in figure 14. The maximum of the negative electric field is about 990 kV/mm near the vicinity of the irradiation surface. In a former report, the authors suggested that the mobility in the irradiated area is higher than that in non-irradiated area [7]. Since the area where the electrons passed through may be damaged by the energy of the electrons, the mobility in the damaged area must be higher than that in the non-damaged area. Therefore, it may be easier for the injected electrons to return towards the irradiation surface rather than pass through the non-damaged area according to the positive electric field.

Figure 16 shows the electric potential distribution calculated using the electric field distribution shown in Figure 15. Each potential distribution shows the peak near the peak of the charge distribution shown in Figure 14. The maximum of the potential is about 16.8 kV.

Figure 17 shows the decay process of the charge distribution after electron beam irradiation. Within 10 minutes after the irradiation, the peak decreased to the half value of the initial. It is found that the peak gradually shifts towards the left-hand side with the time. The right-hand side in this figure may be the damaged area and the mobility in this area is expected to be higher than that non-damaged area. Since the electrons are expected to escape from the bulk toward the irradiation surface, the decrease of right-hand side of the peak should be faster than that of the left-hand side of the peak. This may be the reason that the peak shifts towards the left-hand side gradually. A similar phenomenon of the peak shift was observed in the decay process of the space charge accumulated at the interface between two different layers [8].

CONCLUSION

Advanced measurement techniques, so called PEA and PIPWP methods, for charging in bulk of insulating materials irradiated by radioactive rays, especially electron beam or gamma ray, are introduced. Many results suggest that the techniques are effective to investigate the bulk charge distribution in dielectric materials exposed by high-energy radioactive rays.

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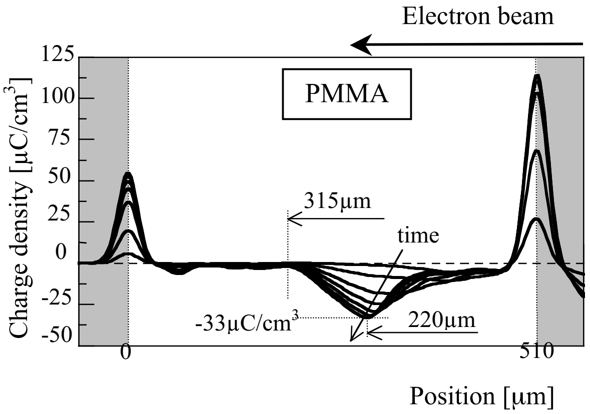

Figure 14. Charge distributions in PMMA under electron beam irradiation.

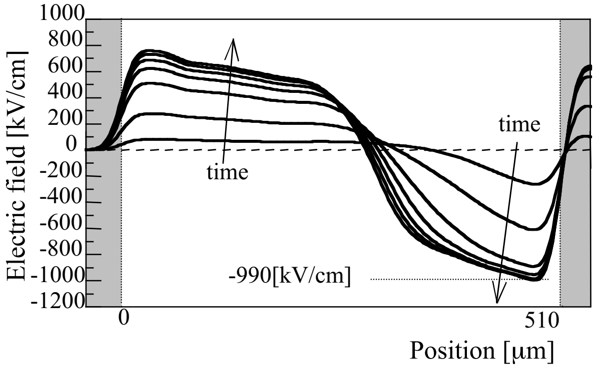

Figure 15. Electric field distribution in PMMA under electron beam irradiation

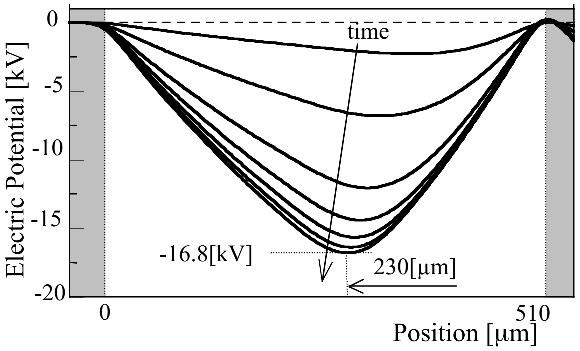

Figure 16. Electric potential in PMMA under electron beam irradiation

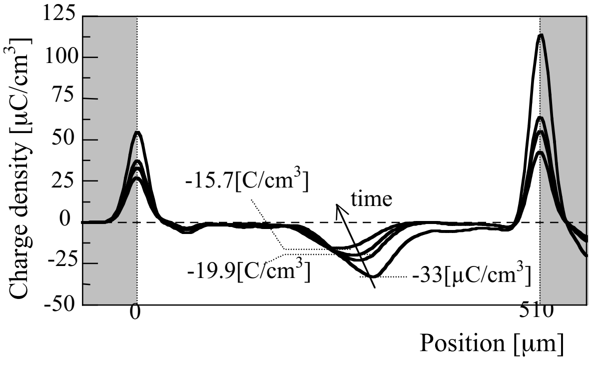

Figure 17. Charge distribution in PMMA after electron beam irradiation