Analysis of Conduction Current in E-beam Irradiated PMMA Based on Simultaneous Measurement of TSC and Space Charge Distribution

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Abstract: An analysis of conduction current distributed in dielectrics based on simultaneous measurements of TSC and time dependent space charge distribution is proposed. The PEA (Pulsed Electro-acoustic) method is a non-destructive and direct method to observe a charge distribution in dielectrics such as polyimide using as a thermal insulator of spacecraft. A new PEA system has been developed to enable simultaneous measurement of the thermally stimulated current (TSC) and the dynamic space charge and electric field distributions as a function of temperature within dielectrics. With the new system, the relationship between the TSC and the time dependent electric field distribution in electron beam irradiated PMMA has been investigated. From the time dependent electric field, displacement current in dielectrics is obtained. The TSC is typical external current which is represented as an addition of the displacement current and a conduction current in dielectrics. This report makes it clear that the conduction current as a function of position is determined by the simultaneous measurement of the external current and the dynamic charge distribution.

1. Introduction

In space environment, the dielectrics, which are used as thermal or electric insulators in spacecraft, are charged by plasma or radiation effect. Consequently, the accidents caused by charging some damage to the spacecraft. To avoid such accidents, it is necessary to study the charging mechanism of dielectrics in space environment. The charging phenomena have been usually estimated using a surface potential measurement. To make a charging mechanism clear, however, it seems necessary to observe a charge distribution in dielectrics directly. The PEA (pulsed electro-acoustic) method has been developed to measure the charge distribution in dielectrics. Many significant data obtained using this technique have been reported in the field of high voltage engineering [1]. The PEA method seems to be useful for analysis of charging mechanism in space environment. To show a typical example of benefit from the measurement of dynamic charge distribution in dielectrics, the following analysis is introduced.

To estimate the electrical characteristics of dielectrics, many researchers have made a great effort to measure the conduction current. Usually, the external current measured using pico-ammeter is reported as it is a conduction current of the sample. However, the external current itself is not equal to the conduction current when the charge is distributed in the sample, because the external current is composed of conduction and displacement currents. To obtain the conduction current, it is necessary to measure the external current and time dependent electric field distribution simultaneously.

The authors have developed several types of apparatus for measuring space charge distributions in insulating materials using a pulse electro-acoustic method [2]. In our previous report, a newly developed PEA system for measurement at high temperatures[3] was introduced. Using this system, the TSC (thermally stimulated current) [4] and a change of charge distribution in electron-beam (e-beam) irradiated PMMA have been measured simultaneously. Since the TSC is a typical external current, the simultaneous measurement enable to obtain the conduction current in e-beam irradiated PMMA. In this report, the temperature dependence of the conduction current in e-beam irradiated PMMA is calculated as a typical example of an analysis of behavior in an insulating material.

2. Principle of PEA method

A representation of this method is given in Figure 1. The principle is based on the Lorentz force law in one dimension. Consider a plate sample with thickness of d containing a charge distribution $\rho(x)$. An externally applied pulsed electric field $e_p(t)$ of dulation ΔT and short rise and fall times, is applied to the plate sample inserted between electrodes A and B, and induces a perturbation force $\Delta f_3(\lambda_k,t)$ on charge distribution $\rho(x)$ at position λ_k on a thin slice. This force causes charge $\rho(\lambda_k)\Delta\lambda$ to move slightly. This movement launches an acoustic wave $\Delta p_3(\lambda_k,t)$ which propagate through the sample and electrode B towards the transducer. The propagation is assumed to occur along the x axis. At the transducer, the total acoustic wave $p_3(t)$ consisting of $\Sigma\Delta p_3(\lambda_k,t)$ is transformed into an electric signal

Vs(t). The detail of the principle is described elsewhere [2].

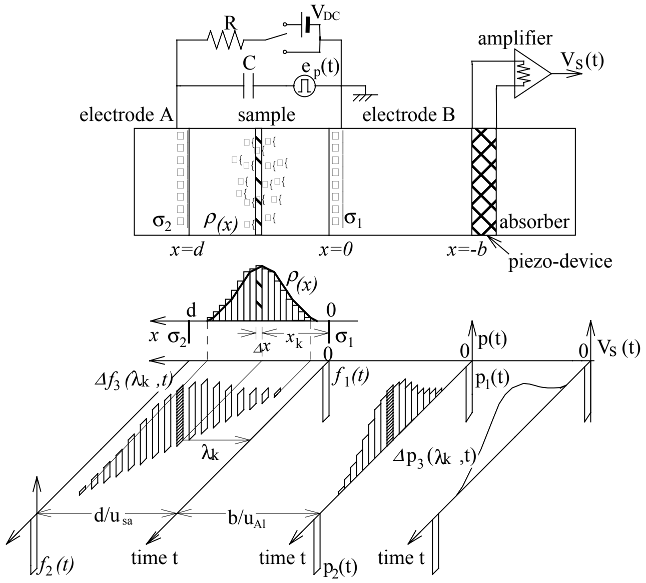

Figure 1. Principle of PEA Method

3. Model for Analysis

Figure 2 shows a schematic model for the conduction current analysis in e-beam irradiated PMMA. The e-beam is irradiated into the PMMA sample from the right side surface in the figure and the injected electrons are trapped in the sample with a charge density distribution $\rho(x,t)$. When the temperature is increased, detrapped electrons drift under the electric field $E(x,t)$ and the charge distribution $\rho(x,t)$ changes gradually, with the consequence that a TSC (J_{TSC}) is measured in the external circuit.

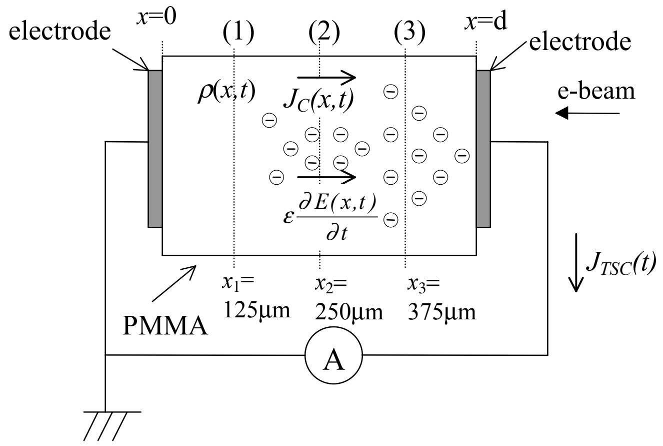

Figure 2. Schematic diagram for current analysis.

The Poisson equation for time dependent, space charge flow for single charge carrier in dielectric materials of constant permittivity, ε, is given as

$$\frac{\partial E(x,t)}{\partial x} = \frac{\rho(x,t)}{\varepsilon} \qquad (1).$$

The equation is an one dimensional function of distance through the sample. Owing to the drift of the electrons and the consequential change of the electric field distribution, conduction $J_c(x,t)$ and displacement $J_d(x,t)$ currents flow in the sample. The relationship between the conduction current $J_c(x,t)$ at a position x and the time dependence of space charge distribution $\rho(x,t)$ is expressed by the following equation,

$$\frac{\partial J_c(x,t)}{\partial x} + \frac{\partial \rho(x,t)}{\partial t} =$$

$$\frac{\partial}{\partial x}\left[J_c(x,t) + \varepsilon \frac{\partial E(x,t)}{\partial t} \right] = 0 \qquad (2).$$

The component in square brackets is constant with respect to position (x). From conservation of charge, the external current $J_{TSC}(t)$ is described using $J_c(x,t)$ and $J_d(x,t)$ with the following equation,

$$J_{TSC}(t) = J_c(x,t) + \varepsilon \frac{\partial E(x,t)}{\partial t}$$

$$= J_c(x,t) + J_d(x,t) \qquad (3).$$

From the Eq. (3), $J_c(x,t)$ at any point in the sample is calculated by subtracting $J_d(x,t)$ from $J_{TSC}(t)$.

4. Experimental Procedure

The sample used in this measurement is commercially available PMMA with a thickness of 500 μm. The electron-beam irradiation is carried out using transmission electron microscope (TEM) with energy of 200 keV and current density of 1.0 nA/cm^2 for 3 hours. The change of charge distribution is measured using the PEA system shown in figure 3. The details of the PEA system for high temperature are described elsewhere [3]. The TSC is measured by increasing the temperature under short circuit condition from room temperature to 110 °C at a rate of 1 °C/min.

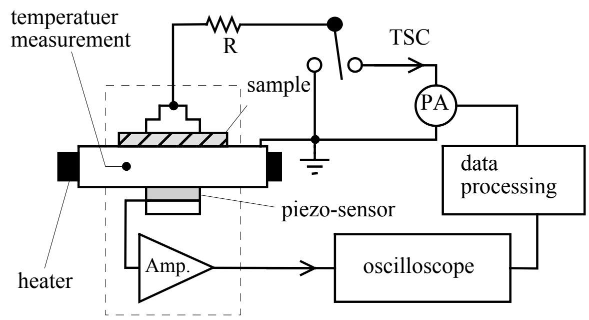

Figure 3. PEA and TSC measurement system for high temperature measurement

5. Results and Discussion

Figure 4 shows the TSC Spectrum. In this figure, the negative current is observed when electrons move towards the e-beam irradiated electrode (right side electrode in figure 2). A peak is observed near 60 °C. Figure 5 shows the change of the space charge distribution with increasing temperature. Negative electrons (peak A) inside the bulk and induced positive charges (peaks B and C) on the electrodes are observed. The electrons are located in a region between the irradiated surface (x=500 μm) and a position at x=125 μm. Therefore the region between x=0 and 125 μm has not been damaged by the e-beam irradiation. From the Fig. 5, it is clear that the negative charge disappears with increasing temperature. It is difficult, however, to estimate the charge movement from this result alone.

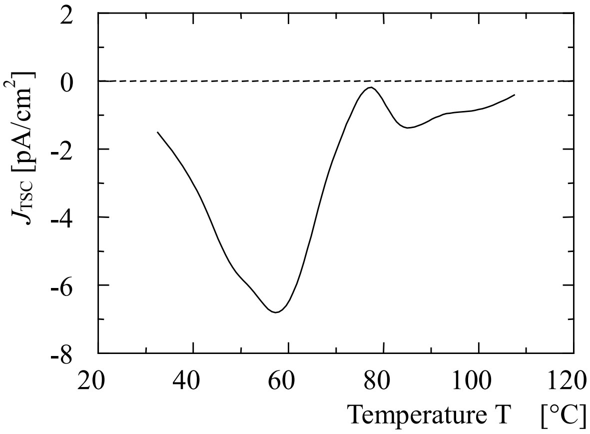

Figure 4. TSC spectrum of electron-beam irradiated PMMA

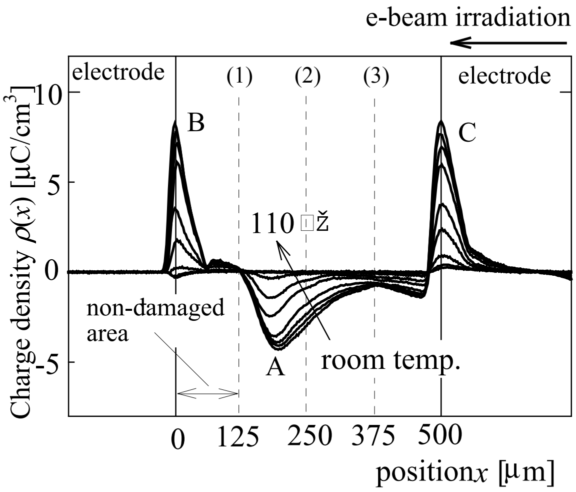

Figure 5. Change of charge distribution with increase of the temperature.

Figure 6 shows a change of electric field distribution with increase of temperature. The electric field distributions are obtained from integral calculation of charge distribution shown in Fig. 4. It is found that the electric fields are positive and negative at position (1) and (3), respectively. At the position (2), the electric field is nearly zero. With increase of temperature, absolute value of electric field decrease, and it disappears at 110 °C.

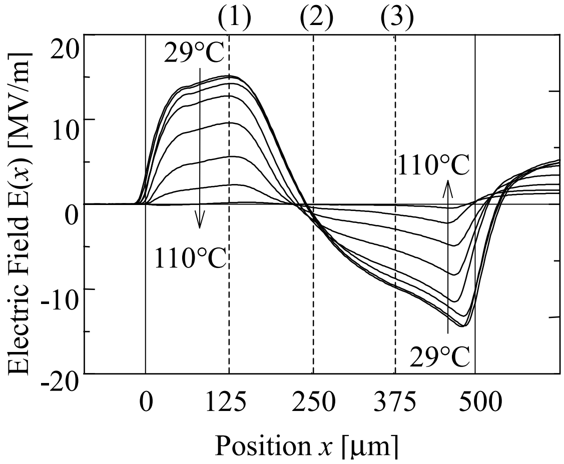

Figure 6. Change of electric field distribution with increase of the temperature.

To investigate the charge behavior, the conduction current in the sample is calculated at three points at x_1=125μm(1), x_2=250μm (2) and x_3=375μm (3). As mentioned before, the displacement currents $J_d(x,t)$ are calculated from the electric field profiles shown in Fig.6. As the increase rate of temperature is constant of 1 °C/min., the time dependent electric field at any position is easily calculated from the result shown in Eig. 6.

Figures 7, 8 and 9 show J_{TSC}, J_d and J_c at position of x=x_1, x_2 and x_3, respectively. At the position of x=x_1 shown in Fig. 7, J_c (x_1,t) is nearly equal to zero from room temperature up to near 60 °C. In spite of the J_{TSC} being large in this temperature range (R.T.-60 °C) , almost no current flows at this position. Above 60 °C, J_c (x_1,t) is positive and increases rapidly with the maximum of J_c becoming larger than that of J_{TSC}. The large positive J_c means a large amount of electron flows towards the left side electrode which locates at the opposite side of the e-beam irradiated surface. This result clearly shows that J_{TSC} does not reflect the behavior of the carrier movement at this position. At the position of x=x_2, the value of the conduction current $J_c(x_2, t)$ is similar to $J_{TSC}(t)$ at all temperatures . This point is near to the zero field plane, and the displacement current is relatively small over the temperature range. At the position of x=x_3, a negative large value of $J_c(x_3,t)$ is observed throughout the temperature range. The large negative current means that a large amount of electron flows towards the right side electrode which is e-beam irradiated surface.

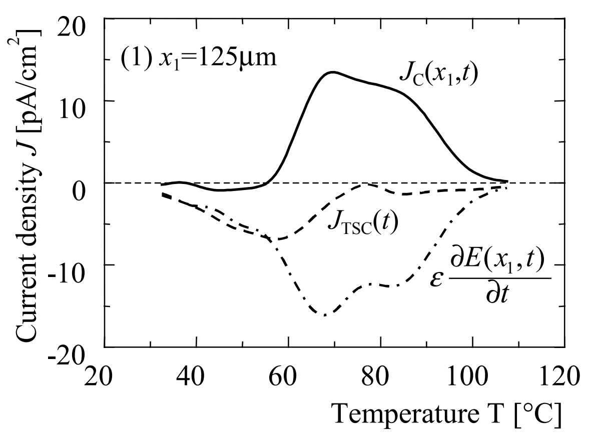

Fig.7. Temperature dependence of current at point (1)

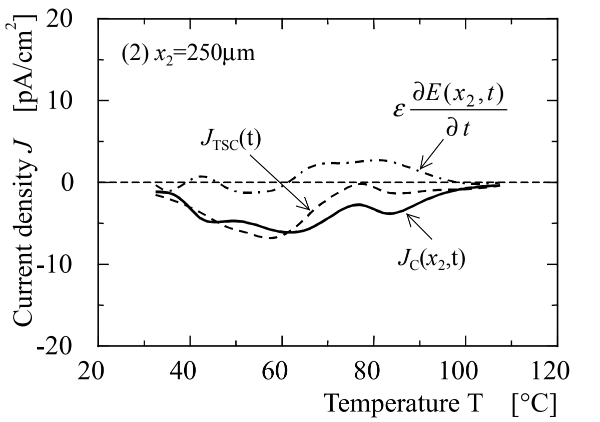

Fig.8. Temperature dependence of current at point (2)

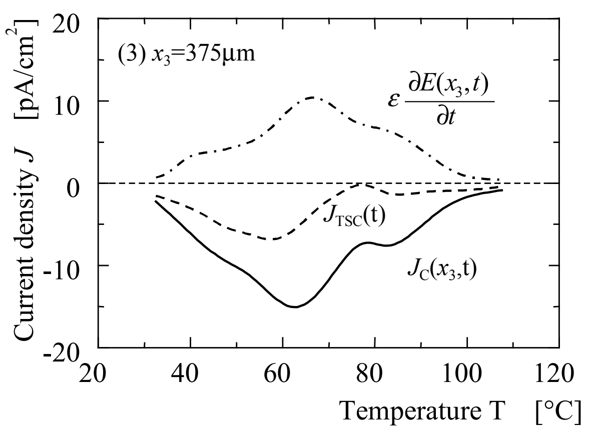

Fig.9. Temperature dependence of current at point (3) (x=x_3).

Judging from the above results, it is plausible that the mobility at x_1 is significantly smaller than that at x_3 at temperatures under 60 °C. The difference of mobility may be caused by the difference in damage due to e-beam irradiation. In the region including the position of x=x_1, there is no damage due to e-beam irradiation and the sample in this region has the original characteristics of the insulating material. On the other hand, in the region including x=x_3, the sample has been damaged by e-beam irradiation.

There are many reports that the conductivity in insulating material damaged by the e-beam irradiation is increased, and the analysis in this paper is in agreement with previous work [5], where the mobility within e-beam damaged regions was found to exceed that of non damaged areas.

5. Conclusion

The temperature dependence of the conduction current in electron-beam irradiated PMMA has been calculated directly from the simultaneous measurement results of TSC and the change of space charge distribution with increase of temperature. From the analysis of the conduction current, it is evident that the mobility in damaged area is larger than that in non-damaged area.

Furthermore, it is clear that a full analysis of TSC measurements requires simultaneous determination of the dynamic space charge and hence, the electric field distribution within the sample under study.

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