DEVELOPMENT OF OPTICAL MEASUREMENT SYSTEM FOR INTERNAL CHARGE DISTRIBUTION IN INSULATING MATERIALS

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Abstract

Spacecrafts are exposed to a harsh environment where high-energy charged particles, such as electrons and protons, are scattering. When a large amount of the charged particles is irradiated to an insulating materials of the spacecraft, an electrostatic discharge may occur. The electrostatic discharge sometimes gives a serious damage to the systems of the spacecraft. To investigate the process how the charged particles accumulate into the bulk of the insulating materials, we have developed the internal charge measurement system using optical method. We have already confirmed using pulsed electro-acoustic method (PEA method) that the irradiated electrons accumulate in the bulk of an acrylic resin when the electron beam is irradiated to it. However the PEA method is available under only a restricted measurement condition. Therefore, we have attempted to develop a widely usable measurement system using optical method. In this report, to estimate the reliability of the optical measurement system, we compare the distribution of the accumulated charge observed using the optical method with that obtained using PEA method.

Introduction

The dielectric materials are used for covering the surface of a spacecraft. Since they are exposed to high-energy cosmic rays, the electric potential is increased due to the accumulation of charge in the bulk and/or on surface of them. Sometimes the change of the electric potential causes an unexpected accident of electrostatic discharge with serious damage to the electric devices. To prevent the accident, it is important to investigate the relationship between irradiation of cosmic rays and dielectric materials. Therefore, we have been developing the charge measurement systems. One of typical developed measurement systems is, so called, pulsed electro-acoustic (PEA) method. The PEA method is very accurate and convenient technique to measure the charge distribution in bulk of sample. However, it is difficult to measure the thick sample with more than few mm because it needs the high voltage pulse to obtain the signal [1]. On the other hand, the optical method is available to measure the charge distributions in thick samples. Therefore, to confirm the reliability of the optical technique, we need to compare the results obtained using both techniques. We have developed a system to measure the charge distribution using optical and PEA methods simultaneously. In this report, we introduce the principles of measurements and some typical results.

The Principle of Optical Measurement Method

Electro-Optic Kerr Effect

Figure 1 shows the principle of Electro-Optic Kerr effect. When the linearly polarized laser light is illuminated to a sample with electric field E, an optical phase retardation $\Delta\theta_s$ generates in the laser light during passing through it. The generated optical phase retardation $\Delta\theta_s$ is proportional to square of the electric field E^2 as described in following equation,

$$\Delta\theta_s(x) = \frac{2\pi l}{\lambda}\gamma E^2(x) \qquad (1).$$

Where l, λ and γ are light path length in the sample, wavelength of the light and Kerr constant, respectively. When the PMMA irradiated with electron beam, the electric field E(x) generated by accumulated charges. Since the birefringence is induced due to the generation of dielectric anisotropy of permittivity, the passing light has the distribution of the optical phase retardation $\Delta\theta_s(x)$. By measuring $\Delta\theta_s(x)$, the electric field distribution E(x) is calculated using following equation,

$$E(x) = \pm\sqrt{\frac{\lambda}{2\pi l\gamma}\Delta\theta_s(x)} \qquad (2).$$

In the following experiments, we use the light with wavelength λ of 633nm, distance l of 10mm and Kerr constant γ of 1266×10^{-24} m^2/V^2 [2][3].

Poison's Equation

The charge density ρ is calculated by the electric field E. When the charges are assumed to be distributed in y-z plane as shown in Fig.2, the relationship between charge density ρ and electric field E(x) is expressed by following equations,

$$div\mathbb{E} = \frac{\partial E_x(x,y,z)}{\partial x} + \frac{\partial E_y(x,y,z)}{\partial y} + \frac{\partial E_z(x,y,z)}{\partial z} = \frac{\rho}{\varepsilon} \qquad (3),$$

$$\rho = \varepsilon\frac{d_x E(x,y,z)}{dy} \qquad (4).$$

Where, ε is a permittivity of the sample. We used the value of 2.68 in the following experiments as the relative permittivity of PMMA.

Principle of PEA Method

The PEA method is a technique to measure the charge distribution in insulating materials. A schematic diagram of principle for the PEA method is shown in Figure 1. Consider a sheet sample with thickness of d and charge distribution $\rho(z)$. When an external pulsive electric voltage Vp(t) is applied to the sample, a perturbation force is induced on each charge. This force generates a pressure acoustic wave, which is proportional to the charge density. The acoustic wave propagates and it reaches a piezo-electric transducer. The piezo-electric transducer is used to detect the acoustic wave and it transforms the propagated acoustic wave into an electric signal. 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. The details of the measurement are described elsewhere [1], [4]-[6].

Measurement System

Figure 4 shows the measurement system to measure the charge distribution in the bulk of thick sample using both optical and PEA methods. The hole of upper electrode unit makes it possible to measure the charge distribution under electron beam irradiation. The side hole of the upper electrode unit was made to be penetrated the laser beam through the sample.

Experimental Conditions

The sample of a rectangle PMMA with the size of 10mm in height, 30mm in width and 10mm in depth was used as shown in Fig.4. The electron beam with the current density of 110nA/cm^2 was irradiated to the sample with energy of 1.5MeV for 60seconds in air atmosphere. The measurement of the birefringence is carried out during and after electron beam irradiation.

Result and Discussion

Fig.6 shows the results of the optical measurement. They are two dimensional optical phase retardation distributions $\Delta\theta_s(x,y)$ in PMMA during and after electron beam irradiation. In these figures, the retardation is described using gray scale. The bright and dark colors stand for the large and small retardations, respectively. With increase of irradiation time, a large value of retardations appears near irradiation surface and middle of the sample, respectively. On the other hand, the dark line between the above bright lines becomes relatively clear. The dark line is located at the depth of about 3mm from the irradiation surface. As shown in Fig.2 the electrons should be located where the retardation is zero. Therefore, the dark line is thought that the position of accumulated electrons. Fig.7 shows the time dependent retardation distribution around the center of the sample. To show the charge of the retardation with increase of the irradiation time clearly, the averaged value of the retardation was calculated. In Fig.8, it is found that the valley of the retardation distribution at depth of 2.7mm from the irradiation surface. As mentioned above, since the retardation should be zero where the electrons are located as shown in Fig.2, the bottom of the valley is thought where the electrons are concentrated. Fig.8 shows the charge density distribution calculated using the data shown in Fig.7. It found that the negative charge density at 2.7mm depth increases with increase of the electron beam irradiation time. After irradiation, it is found that the accumulated negative charge gradually decreases. To show the accumulation and the decay process of the negative charge clearly, the peak values of the charge density was described with the time progress in Fig.9. On the other hand, Fig.10 shows the result of the charge distribution measured using the PEA method. It is found that the negative charge around the depth of 3.4mm from irradiation surface increases with increase of irradiation time. After irradiation, on the other hand, the peaks of the distribution gradually decrease. To compare the obtained result using the PEA system with that using optical method, the peak value of charge density at 3.4mm is described with time progress. Fig.11 shows the time dependent peak values of the charge distribution. Compare with the date shown in Fig.9, the shape of curve shows in Fig.11 is very close to that in Fig.9. However there are many differences between the results. In the case of optical measurement, the retardation generates from the change of mechanical stress, too. When the electron beam is irradiated to the sample, it is though that the change of temperature generated by the irradiation make the distribution of mechanical stress. That maybe the reason why there are differences between the results obtained using the two methods.

Conclusion

We developed the simultaneously measurement system that measures the charge distribution using optical method and PEA method.

Acknowledgement

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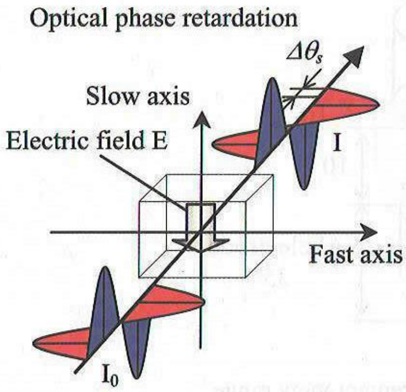


Fig.1 The optical phase retardation $\Delta\theta_s$ by Kerr effect

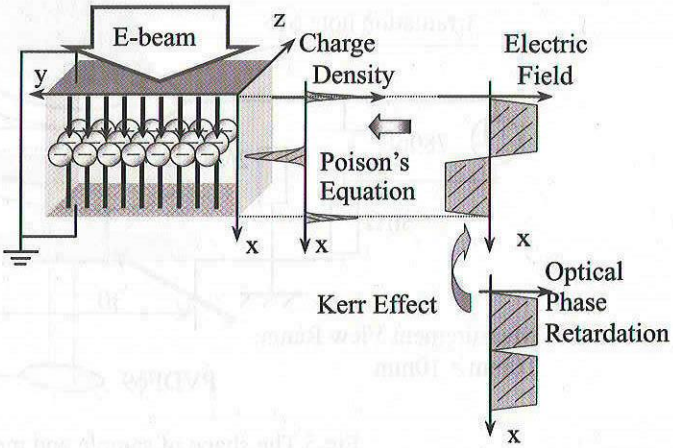


Fig.2 Model to measure charge distribution using Kerr effect and Poisson's equation

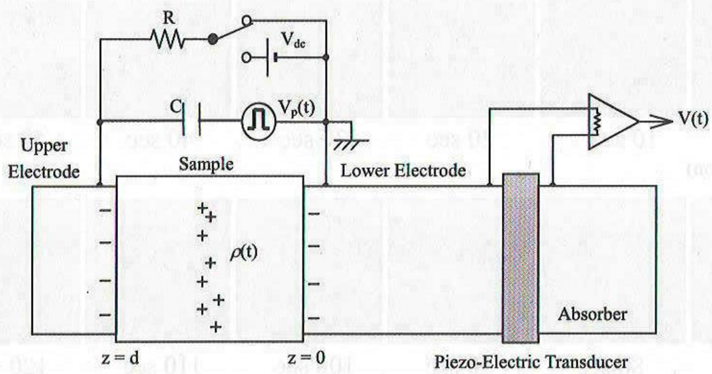


Fig.3 PEA measurement system

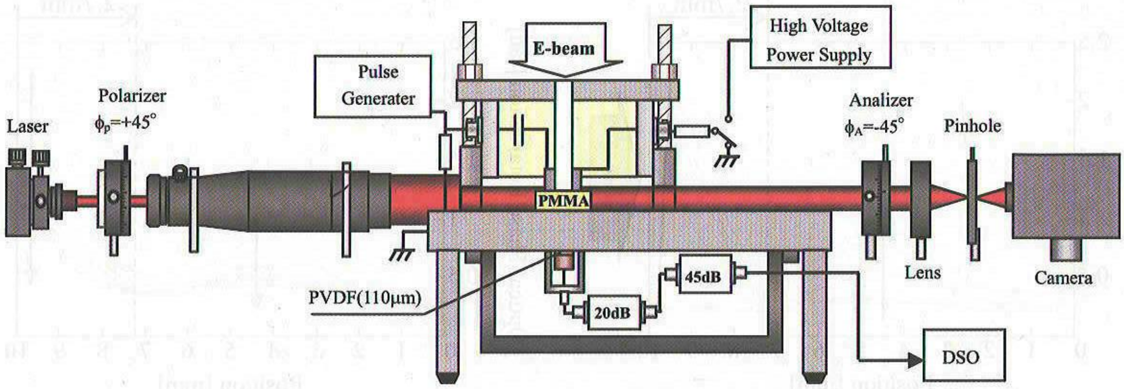


Fig.4 The simultaneously measurement system

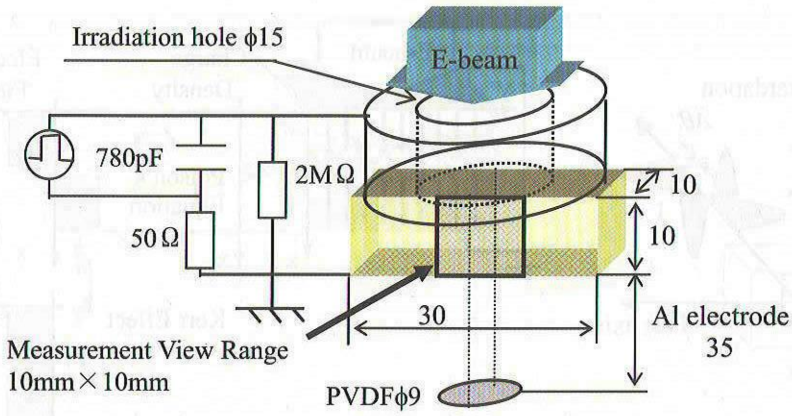


Fig.5 The shape of sample and measurement view range

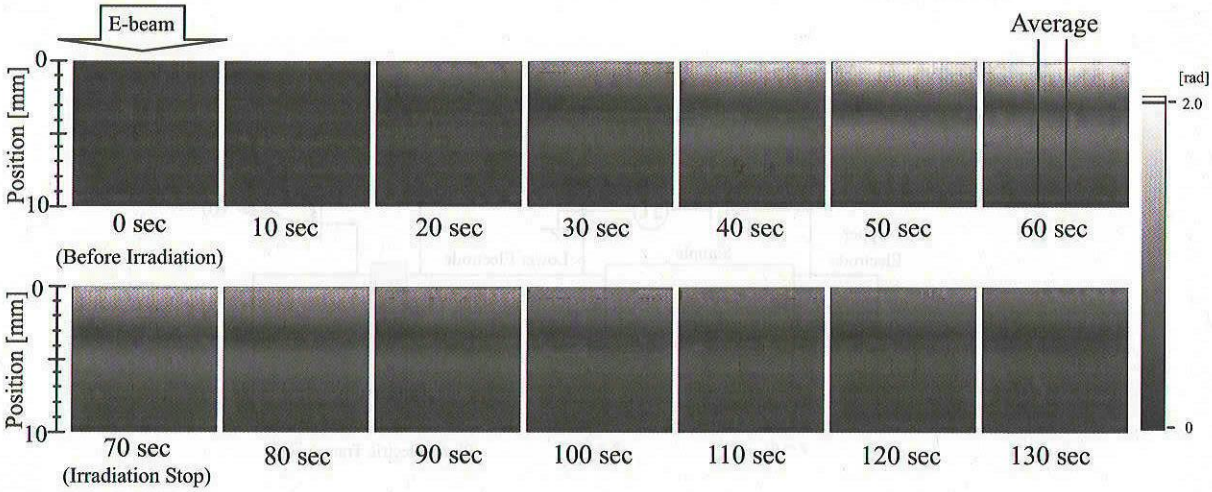
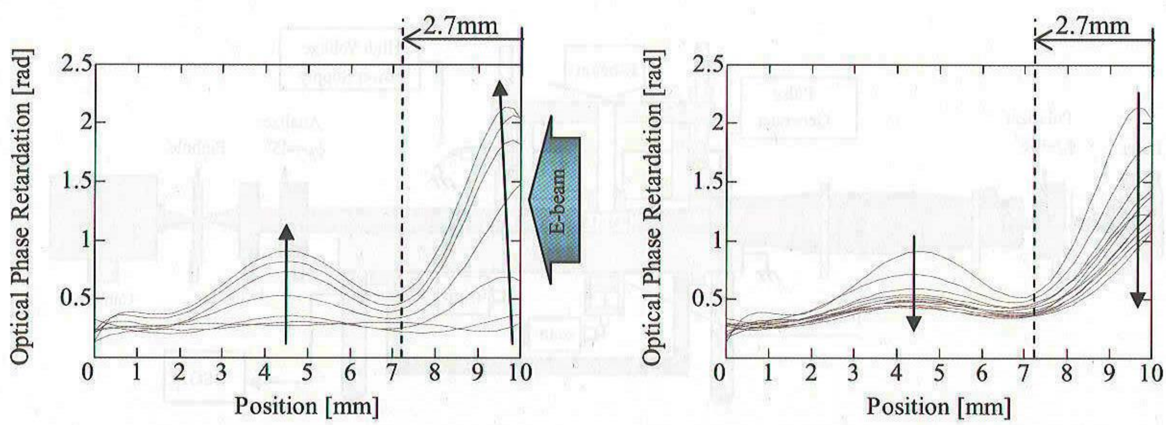


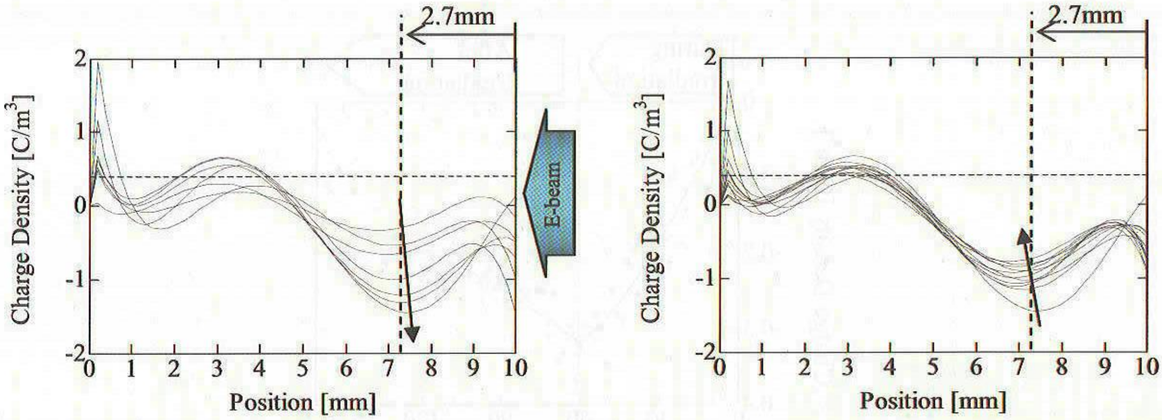
Fig.6 The two-dimensional distribution of retardation$\Delta\theta_s$ in PMMA sample



a. Optical phase retardation $\Delta\theta_s$ during the electron beam irradiation

b. Optical phase retardation $\Delta\theta_s$ after the electron beam irradiation

Fig.7 Time dependence of optical phase retardation$_s$ distribution



a. Charge density ρ during the electron beam irradiation

b. Charge density ρ after the electron beam irradiation

Fig.8 Charge density calculated using Poison's equation

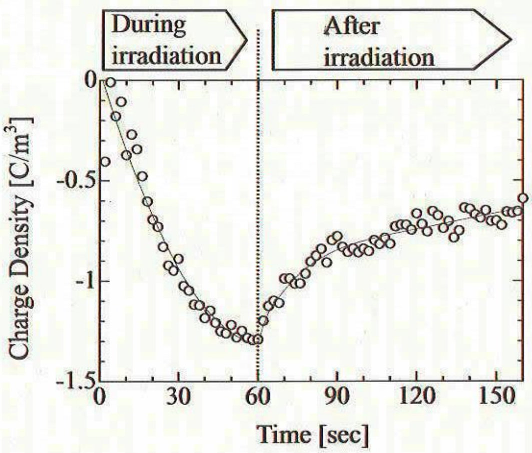
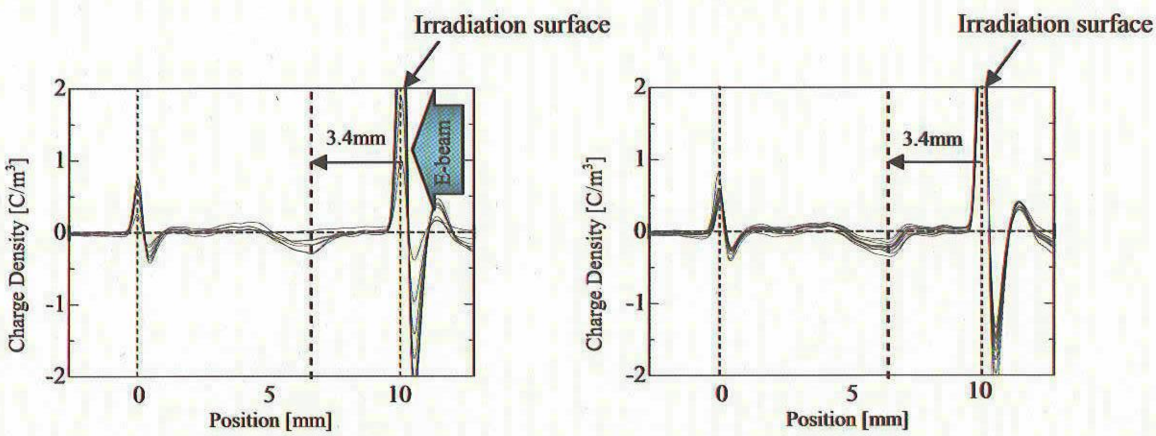


Fig.9 Peak value of charge density distribution with passing time by the optical method



a. Charge density during the electron beam irradiation

b. Charge density after the electron beam irradiation

Fig.10 Charge density calculated using Poison's equation

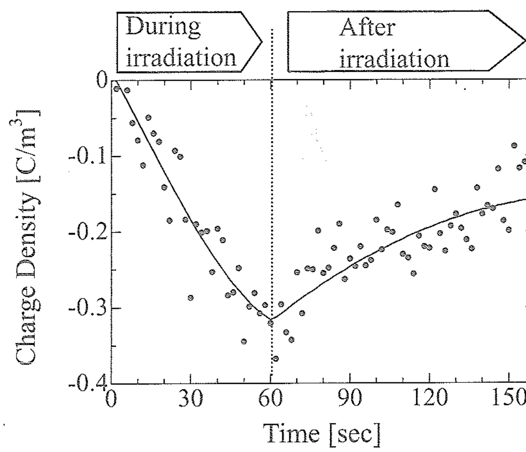


Fig.11 Peak value of charge density distribution with passing time by the PEA method