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Space Charge Accumulation Phenomena in PI under Various Practicable Environment

Hiroaki Miyake and Yasuhiro Tanaka

Abstract

Polyimide is widely used insulation materials, such as power equipment, motor windings, multi layer insulated, and so on. As the operation environment is high temperature, high humidity, radiation, the dielectric insulation characteristic is decreased compared with pristine one. Especially, the space charge characteristics are obtained big different. Furthermore, the breakdown phenomenon is frequently produced. In this chapter, we discuss the dielectric phenomena through the viewpoints of charge accumulation under the following environment. High temperature, High humidity, DC application, PWM application, Radio-active rays (electron, proton).

Keywords: space charge accumulation, high temperature, high humidity, DC and PWM application, radiation environment

1. Introduction

Normally, you already know the polyimide (PI) and the super engineering plastics derivative from PI are one of best high resistive dielectric materials for any application, for example print board, motor windings, surface materials of spacecraft, and so on. However, sometimes, the PI have breakdown phenomena under high voltage application with high temperature and humidity condition. It is considered that the origin of breakdown is the electric filed enhancement in the bulk or high growth of conduction current during the bulk by the homo charges injection form the electrode, or the hetero charges accumulation due to hydrolysis by surround high humidity environment. Furthermore, concerning the radioactive rays irradiated PI, the huge space charge polarization is produced. And then, sometimes, PI has a breakdown phenomenon due to irradiation.

To understand the dielectric characteristic for the serve condition, it is important that the space charge accumulation phenomena are observed. Therefore, in this chapter, we introduce the space charge accumulation in the bulks under the high electric filed, high temperature, high humidity and radiation environment.

2. Principle of the pulsed electroacoustic (PEA) method

The PEA method is one of the widely used techniques for measuring the charge distribution in dielectrics. The principle of the PEA method is explained at the followings [1].

Figure 1 shows the schematic diagram of the PEA method. A charged sample with thickness a is used, and its both sides are sandwiched by electrodes. The pulse voltage generator is connected to both electrodes. When the pulse electric field $e_p(t)$ is applied with the electrode induced charges $\sigma(0)$ and $\sigma(a)$ accumulated on both electrode surfaces due to the accumulated charge ρ in the sample, a pulsed pressure wave $p(t)$ is generated from $\sigma(0)$, $\sigma(a)$ and $\rho(z)$ in the sample. Those pulsed pressure wave $p(t)$ is shown by the convolution equation between each accumulated charges ($\sigma(0)$, $\sigma(a)$, $\rho(z)$) and $e_p(t)$. The convolution equation is shown in the following formula.

$$\begin{aligned}
 p(t) &= p_1(t) + p_2(t) + p_3(t) \\
 &= \frac{Z_{Al}}{Z_{sa} + Z_{Al}} \cdot \sigma(0) \cdot e_p(t) + \frac{2Z_{Al}}{Z_{sa} + Z_{Al}} \cdot \frac{1}{2} \cdot u_{sa} \cdot \int_{-\infty}^{+\infty} \rho(\tau) \cdot e_p(t - \tau) d\tau + \\
 &\quad \frac{2Z_{Al}}{Z_{sa} + Z_{Al}} \cdot \frac{Z_{sa}}{Z_{sa} + Z_{BS}} \cdot \sigma(a) \cdot e_p\left(t - \frac{a}{v_{sa}}\right)
 \end{aligned} \quad (1)$$

where, Z_{Al} , Z_{sa} , Z_{BS} is the acoustic impedance of Al, sample and backing material, respectively. u_{sa} is the sound velocity of sample.

Figure 1.
The schematic diagram of the principle of PEA method.

Figure 2.
The schematic diagram of convolution model on the time function between the pulsed pressure wave and the piezoelectric device.

Those pulsed pressure $p(t)$, described the above on the Eq. (1), the intensity of the pressure wave is proportional to the accumulated charges in the sample. The propagation delay of the pressure wave is related to each charge accumulated position.

A piezoelectric transducer is used to detect the pressure wave by transforming into an electric charge signal. The electric charge signal $q(t)$ on the piezo electric device is expressed by the convolution model between pressure wave function $p(\tau)$ and piezoelectric device function $h(\tau)$ as shown in formula (2)

$$q(t) = \frac{v_p}{b} \int_{-\infty}^{\infty} h(\tau) p(t - \tau) d\tau \quad (2)$$

where, v_p and b is sound velocity and thickness of piezoelectric device, respectively. The convolution model is also shown in **Figure 2**. Normally, we observed charge distribution signals obtained by the above convolution model. However, as the real measurement system has a system function, which is the low pass filter between the amplification circuit and and the capacitance of the piezoelectric device, the observed wave form signal is distorted like as the differentiated wave-form by the system function.

The details of the principle of PEA are described elsewhere [1].

3. Space charge measurement system

Using the pulsed electroacoustic (PEA) method which is described above, we developed several space charge measurement systems for high temperature. **Figures 3** and **4** shows the developed system [2, 3]. On the **Figure 3**, it is the developed PEA system for high temperature (up to 80 °C). This system is enabled to measure the space charge accumulation in dielectric materials. In this system, temperature (30–80 °C) of silicone oil is control using a band heater and a controller.

Furthermore, as the IGBT using SiC is operated over 150 °C, the space charge measurements under more high temperature are also required. Therefore, we developed newly PEA system for high temperature (up to 150 °C), which is shown in **Figure 4**. From the figure, to measure the space charge distribution at high

Figure 3.
Schematic diagram of the space charge measurement system for high temperature up to 80 °C.

Figure 4.
Schematic diagram of the space charge measurement system for high temperature up to 150 °C.

temperature, the P(VDF/TrFE) is used as the piezo-electric sensor. By combining the sensor and a water-cooling system, the space charge measurement at maximum 150 °C becomes possible. A band heater is fitted to the high voltage electrode unit to increase temperature of the sample. In ordinary PEA measurement, to improve an acoustic impedance matching between the sample and the metallic electrode, a semiconductive (SC) layer, which is used for power transmission cable, is used for a high voltage electrode. However, the base material of this SC layer is usually polyethylene, and it is not available at high temperature. Therefore, in such high temperature measurement, we used a SC layer made of PEEK. In all measurements, the positive voltage was applied to the sample through the upper SC electrode.

4. Heated and humidified sample charge accumulation behavior

In this chapter, we discuss the relationship between space charge distribution and breakdown phenomena of polyimide under heating and humidified condition.

Recently, various and many electronic devices have been used the flexible Print-Circuit Board (PCB) to reduce the size of them. At the moment, polyimide film is usually used for PCB [4]. Polyimide film has an appropriate flexibility and it shows a good insulating performance even at high temperature. On another front, since the devices are improved for downsizing and lightweight every year, it is necessary to reduce the thickness of PCB. When the thickness of PCB becomes thinner, the applied electric field becomes higher. It means that the possibility of electrical breakdown in PCB becomes higher. It is necessary that inverter can control at high frequency and drive at high voltage for high efficiency of inverter control. But inverter surge becomes high voltage in these conditions. The partial discharge happens and insulating covering material becomes depleted. And these insulating materials using electric devices need to become high insulating capacity at high temperature and high humidity. Therefore, it is necessary to understand the mechanism of breakdown in polyimide film to prevent the breakdown. Thus, we tried to measure the space charge distribution in polyimide under heating and humidified condition for understanding the phenomena.

4.1 Samples and measurement procedure

In this chapter, a commercially available polyimide film, Kapton® 500H (nominal thickness 125 µm) supplied from Dupont-Toray Co.Ltd. is used.

For simulating the real usage condition, Heat with humidifying treatment and heat treatment are applied before measuring space charge as pre heat and humidifying treatment. The samples are set in a thermostatic chamber IH 400 manufactured by Yamato Scientific Co., Ltd., (80 °C and 80 or 60%) for one hour.

Furthermore, we prepared the heated sample whose were set in silicone oil boiled at 100 °C in beaker to dry off moisture of sample.

4.2 Results and discussion

Figure 5 shows space charge [2] behaviors in non-treated (1) and heated and humidified (2) sample under DC stress of 60(a), 100(b), 120(c) kV/mm at 80 °C. Measurement interval is 5 s. Amount of accumulated space charges are displayed using color chart. As shown in **Figure 5(a)**, positive and negative homo charges are observed near anode and cathode from the start of measurement in non treated sample. The amounts of homo charges are increasing until about 10 mins later,

Figure 5. Space charge behaviors in non treated (1) and heated with humidified (2) sample under DC stress of (a) 60, (b) 100, (c) 120 kV/mm at 80 °C.

but notable changes are not observed after 10 mins. On the other hand, positive and negative homo charges are observed near anode and cathode from the start of measurement in heated and humidified sample. But the amounts of homo charges are increasing until about 5 mins later. In 60 kV/mm, there is no difference point except time to increasing of homo charge and space charge behavior of end of measurement is similar to each other. The time to saturating space charge accumulation in heated and humidified sample is shorter than one in non treated sample. It is appeared that moisture of heated and humidified sample is larger than one of non treated sample. So, moisture of sample is large, it is easily occurs to ingress space charge and migration speed of space charge is more fast.

As shown in **Figure 5(b)**, positive and negative homo charges are observed near anode and cathode from the start of measurement in non treated sample along with space charge behavior of 60 kV/mm(a). But migration speed of space charge is faster and migration position of space charge is larger than one of 60 kV/mm in non treated sample. On the other hands, positive and negative homo charges are observed near anode and cathode from the start of measurement in heated and humidified sample. And positive hetero charge becomes to be observed near cathode. The amount of positive hetero charge is increasing until breakdown at 43 mins later. In our previous research⁽¹⁾, it is observed that positive and negative homo charges are observed near anode and cathode and positive hetero charge becomes to be observed near cathode and breakdown occurs. It is similar process of space charge behavior to heated and humidified sample. And moisture of sample is large, it is easily occurs ingress of space charge and migration speed of space charge is more fast. So, in heated and humidified sample, space charge behavior process until breakdown occurs faster than non treated sample.

As shown in **Figure 5(c)**, homo charges are observed near anode and cathode and positive hetero charge becomes to be observed near cathode and breakdown occurs at 25 mins later in non treated sample. On the other hands, breakdown in heated and humidified sample occurs at 5 mins in same space charge behavior process at non treated sample. However, negative hetero charges are observed near anode from the start of measurement.

In these results, space charge behavior process of non treated sample and heated and humidified sample until breakdown is same. It is said that the breakdown process is promoted by increasing moisture of sample and rising applied electric field. Therefore time to breakdown is shorter than ingress of space charges and migration speed of space charges are faster.

From the above results, we describe process of charge accumulation behavior to breakdown under DC stress. **Figure 6** shows typical process of space charge accumulation behavior in Kapton® under high DC stress (130 kV/mm).

As shown in the figure, a few positive and negative hetero charges are observed near anode and cathode from the start of measurement (charge behavior annotation number 1 in the figure). These hetero charges are same hetero charge in heated sample. Therefore, these space charge accumulations are looked when moisture of sample is low and sample is applied at high electric field. After hetero charges are observed, positive and negative homo charges are observed near anode and cathode and hetero charges decrease (charge behavior annotation number 2 in figure). These homo charges are injected from anode and cathode. When moisture of sample increase, amount of accumulation of homo charges is large. In fact, injection of charge easily happens from electrodes when moisture of sample is large. And charges can easily move in the bulk. And positive and negative hetero charges may disappear by accumulating homo charges. These homo charges decrease and large positive hetero charge accumulated at next period (charge behavior annotation number 3 in figure). And accumulation of positive hetero

Figure 6.
Typical process of space charge accumulation behavior in Kapton® under high DC stress (130 kV/mm).

charge is larger than that of negative hetero charge. However large hetero charge is observed in **Figure 6**, a few hetero charges can be observed at some sample. Amount of hetero charge is influence at amount of homo charges mentioned at the charge behavior annotation number 2 in figure. Because hetero charge is observed before breakdown happens, this hetero charge promote breakdown. But accentuation of electric field by accumulating these space charges is a little. And so, it is not say that accumulation of space charge is cause which breakdown happens by. But this phenomenon is distinct pre-breakdown phenomenon. After this hetero charge was observed, positive hetero charge decreases a little in this measurement result (charge behavior annotation number 4 in figure). This behavior is not always observed in all samples. In fact, breakdown occurs when accumulation of space charge was saturated or decreased. Therefore, the processes of accumulating of the hetero charge and decreasing ones are equilibrium condition. And electric field around electrode is large by accumulating hetero charge. And given the accumulation of homo charge before hetero charge is observed, homo charge injected from electrode and hetero charge generated from bulk is saturated. In this research, source of hetero charge is not clear up. It is considered that hetero charge is generated by ion breaking the molecular chain or ionization of impure substance of the sample.

5. Charge accumulation behavior in the PI (polyimide) bulk under high temperature (100–150 °C)

Currently, polyimide is demanded for using an insulating material for power electric devices using SiC(silicon carbide) is required [2]. As it is developed enough to be used at high temperature under high electric stress, the insulating materials supporting the device must also exhibit extremely excellent insulation properties at high temperatures under high electric stresses.

In recent years, evaluation methods using storage characteristics of space charge has been as an effective technique to evaluate the character is tics under high electric stress. Under the stress, the current-electric field characteristic often deviates from the Ohm's law and the reason of it is considered that the space charge accumulates in the material [1, 3, 5]. Therefore, if the space charge accumulation state becomes clear, the insulation performance of the material under a high electric field can be evaluated.

Recently our laboratory, has P(VDF/TrFE) (vinylidene fluoride/ ethylene tri-fluoride copolymer), has been used as a piezoelectric sensor that can be measured even under high temperature, and we can obtain the space charge distribution in the insulating materials even at relatively high temperatures of up to 150 °C using the developed apparatus. In this report, we introduce some typical measurement results of the space charge accumulation behaviors in the polyimide (PI) obtained using the developed system.

5.1 Samples and measurement procedure

The Kapton®500H (Dupont-Toray Co.Ltd., nominal thickness is 125 µm) was used as measurement sample. Further, heating and humidifying treatment was previously applied to some samples. In this treatment, the sample were kept in a thermostatic chamber IH 400 set at 80 °C with humid of 80% for 1 hour.

Time dependence of the space charge distribution in the sample was measured using the apparatus (up to 150 °C), which is described at the chapter 3, for 100–150 °C. In the measurement, at first, a dc voltage corresponding to 25 kV/mm was applied to the sample for 30 min at the designated temperature, and the distribution was measured with interval of 5 s by applying a pulse voltage of 200 V with a pulse width of 5 ns. The repetition frequency of the pulse voltage application was 400 Hz and the averaged signal was obtained from 700 signals. Then, the circuit was shorted for 5 min, and the measurement was also carried out using above procedure. After the measurement, next measurement was started under elevated electric stress. The increment of the voltage was corresponding to 25 kV/mm, then the applied stresses were 25, 50, 75, 100, 125, and 150 kV/mm.

5.2 Space charge distribution at 100°C

Figures 7(A) and (B) show the measurement results of space charge distributions at 100 °C in non-treated and treated PI films respectively. In these figures, (a), (b) and (c) show a time dependence of space charge distribution, a charge density distribution and an electric field distribution profiles, respectively. In figure (a), the charge density is described using a color scale put above each result. In figures(b) and (c) show the profiles at 30 min under each applied electric stress.

From the results of PI shown in **Figure 7(A-a)**, accumulation of positive and negative homo charges was observed in the vicinity of both anode and cathode electrodes, respectively, under the applied stress of 100 kV/mm or less in the untreated PI sample. When the stress became 125 kV/mm or more, accumulation of positive hetero charge was observed on the cathode side. Finally, a dielectric breakdown was observed at about 10 min later after 150 kV/mm was applied to this sample. In PI sample, the breakdown occurred after such positive hetero charge accumulation was also observed in other reports [1, 3]. It can be considered that the positive hetero charge accumulation may be a kind of “sign” for the breakdown in PI sample under dc high stress. On the other hand, in treated PI, as shown in **Figure 7(B-a)**, an accumulation of positive homo charge was observed on the anode side from under 25 kV/mm, and it spread towards the cathode side with increase of the applied stress. Then, finally in this sample, a breakdown was observed at about a few minutes later after stress of 125 kV/mm was applied. Judging from the electric field distribution in non-treated PI shown in **Figure 7(A-c)**, while the electric field near electrode seem to be enhanced slightly by the hetero charge accumulation, it can hardly expect to be a main reason for the breakdown. On the other hand, as shown in **Figure 7(B-c)**, a relatively large electric field enhancement was observed

Figure 7.
Space charge distribution in PI at 100 °C.

in the treated PI near the cathode. Therefore, the enhancement might affect the breakdown under lower applied stress in the treated PI than that observed in the non-treated PI.

5.3 Space charge distribution at 150 °C

Figures 8 shows the measurement results of space charge distribution at 150 °C in PI. From the measurement results of PI in Figure 8(A-a), accumulation was not observed under the stress of 75 kV/mm or less. While the positive homo charge was

Figure 8.
Space charge distribution in PI at 150 °C.

observed under the stress of 100 kV/mm or more, the amount of it was not so large and breakdown was not observed by the end of measurement. In this case, the electric field was not distorted by the accumulation of charge as shown in **Figure 8(A-c)**. On the other hand, in the measurement results of the treated PI sample, positive charge accumulation near the anode was observed under 50 kV/mm or more as shown in **Figure 8(B-a)**. When the applied stress increased, the positive charge distribution spread towards the cathode, then the negative homo charge accumulation was also observed near the cathode under 100 and 125 kV/mm. Furthermore, in this condition, a negative charge accumulation was also observed near the anode. Finally, the negative and the positive charges were located near the cathode and the anode, respectively, at the end of the measurement. The electric field distribution in this sample was, of course, distorted by the accumulated charges, and the electric field near the cathode and the anode were enhanced to 150 kV/mm as shown in **Figure 8(B-c)**, but the increments of them are not so large.

This process observed in the treated PI at 150 °C is similar to that in non-treated PI at 100 °C, except for the breakdown. The space charge accumulation seems to be affected by the moisture content in the sample, as mentioned above. Therefore, the measurement at 150 °C was also affected by it. In other words, the moisture in both of the non-treated and treated PI sample might be vaporized by the heating. Similar results were obtained in annealed PI sample in silicone oil [1].

6. Charge accumulation behavior in the PAI bulk under simulated high voltage PWM application and high temperature (80 °C)

Recently, the needs of fast measurement are demanded, day by day [5–7]. It is because that many high-speed voltage applications are widely used all over the world. The motor system is one of the examples. The PWM signal is driven by over several tens of kHz. Therefore, under the above situation, the space charge measurement is also required under such high frequency rectangular voltage. Therefore, we can solve such requirement by cooperatively controlling the pulse voltage and the application high voltage.

In this chapter, measurement results in PAI using cooperative operation system between the pulse voltage and the application voltage are introduced.

6.1 Samples, PWM voltage application and space charge measurement timing during PWM application

All measurements were carried out at 80 °C using the high temperature PEA system which is already described in **Figure 3** at chapter 3. In this section, we used commercially available polyamide-imide (PAI) films as measurement samples, which are actually used as the covering insulating materials for the general motor windings. Since the PAI are usually distributed in varnish form, we made a film shape sample from the varnish. The thicknesses of the films were about 100 μm .

Figure 9 (a), (b) and (c) show a schematic model of the applied half-wave of AC, unipolar square rectified wave and unipolar square rectified wave with surge shape voltages to the samples, respectively. In this figure, the timings of the application of pulse voltage, which is applied to the sample to obtain the measurement signal, are also described using green lines. The peak voltage of it was corresponding to the average electric field of 50 kV/mm in each measurement. Also, the peak surge voltage of it was corresponding to the electric field of 60 kV/mm in each measurement. Frequency of the half-wave of AC, unipolar square rectified wave, unipolar surge square wave rectified wave voltage was 50 Hz. Duty ratio of the square wave voltage was basically

Figure 9.
Time sequence of various wave voltages and pulse voltage applications for PEA measurement. ((a) Half-wave of AC, (b) square wave and (c) square wave with surge shape).

50%. To generate waveforms mentioned above, low voltage waveforms are created digitally using a computer at first, then the waves are amplified using a high voltage amplifier. Therefore, the timing of the pulse voltage application is also controlled using the computer. The pulse voltage to observe the space charge distribution was applied to the sample under the voltage application (“volt-on” duration) and the short circuit (“volt-off” duration) conditions alternatively. To obtain a clear space charge distribution, it is usually used an averaging technique to reduce noise. In this measurement, we tried to create one space charge distribution under voltage application by averaging the sequential 200 signals obtained at “volt-on” durations. In the case to obtain one space charge distribution under short circuit condition, 200 sequential “volt-off” signals were also averaged. Since the frequency of the square wave voltage was 50 Hz, one averaged signal was composed of 200 signals during 4 s. It means that the observation interval of the space charge distribution was 4 s under “volt-on” and “volt-off” conditions, alternatively. To simulate a practical test condition, some measurements were also carried out on samples, which were kept at a high temperature (80 °C) with a high humidity (80%) condition for 60 min before the measurement.

6.2 Space charge accumulation results under various voltage wave form

Figure 10 (A), (B), (C) and (D) show the measurement results of time dependent space charge distributions in PAI by applying DC, half-wave of AC, unipolar square rectified wave and square rectified wave with surge shape voltages, respectively. In this figure, (a), (b), (c), (d) and (e) show a time dependent charge density distribution using a color chart at “volt-on”, a time dependent charge density distribution using a color chart at “volt-off”, profiles of a charge density distribution at “volt-on”, a charge density distribution at “volt-off”, and electric field distribution at “volt-on”, respectively. In these figures, red, black and blue lines were obtained at just after (4 s), 2 min and 5 min later after the beginning of the voltage application.

Figure 10. Space charge distributions in PAI films under various voltage application (50 kV/mm).

As shown in **Figure 10(A-d)**, **(C-d)** and **(D-d)**, in the cases by applying the DC, the square wave and surge voltages, it is found that homogeneous negative charge accumulations across the bulk of the sample were observed from 2 min later after the voltage applications, and it was obviously recognized from the result shown in **Figures 10(A-a)**, **(C-a)** and **(D-a)**. As shown in **Figure 10(A-a)**, the accumulation of the negative charge seemed to be stable after 5 min later. By the negative charge accumulation, the electric field was distorted near the anode as shown in **Figure 10(A-e)**. On the other hand, in the case of result obtained by applying the half-wave of AC voltage, while a negative charge accumulation near the cathode was observed as shown in **Figure 10(B-b, d)**, the amount of it was small and it was only located near the cathode. By the negative charge accumulation, the electric field was distorted near the anode as shown in **Figure 10 (B-e)**, but it was very tiny.

Figure 11 (a) and **(b)** show the maximum electric field and amount of charge in the sample calculated from the distributions obtained by applying DC,

Figure 11.
Maximum electric field and amount of accumulated charge.

half-wave of AC, square wave, square wave with surge shape voltages. As shown in **Figure 11 (a)**, it was found that the maximum electric field value is larger in the order of DC, square wave with surge shape, square wave and half-wave of AC voltages. Furthermore, it was found that the charge accumulation amounts were large in the order of square wave with surge shape, DC, square wave and half-wave of AC. However, there was almost no difference among them except for that obtained by applying half-wave of AC. From the above, it is clear that the space charge is not accumulated, nor consequently the electric field is not distorted by applying the half-wave of AC to the sample.

7. Polyimide for space application

Polyimide (PI) is also used for the materials of multilayer insulators (MLIs) of spacecraft. Many researchers studied space charge characteristics in PI irradiated by electron [8, 9]. And recently, the space charge behavior in PI irradiated by proton is also focused. It is because that many satellite had operation anomaly due to charging by radiation and discharging [10]. In this chapter, few examples of charge accumulation behavior in PI irradiated by radio-active rays are explained.

7.1 Negative charge accumulation in PI irradiated by an electron

The space charge [8] distributions in Kapton®500H (Dupont-Toray Co.Ltd., nominal thickness is 125 μm , a surface with Al evaluation layer) are irradiated by an electron are discussed. The electron beam irradiation condition is 40 and 60 keV, with 40 nA/cm² current density in 10⁻⁵ Pa order vacuum chamber. The in-site space charge measurements were carried out using PIPWP method [1, 8, 11]. Charge distributions and integrated charge amount in the bulk are shown in **Figures 12** and **13**, respectively. The measurement interval is 30 s.

In the **Figure 12**, the charge profile waveform is the data of maximum negative charge accumulation in the bulk during 20 min irradiation. From the figure, we can see the negative charge accumulation in the bulk. Such negative charges distributed from the irradiation surface to depth of 34, 60 μm (with the broken perpendicular line). Those accumulated positions have a good correlation with the calculated penetration depth using Karz and Penfold's experimental equation.

Figure 12.
Negative charge accumulation in PI under electron irradiation.

Figure 13.
Total negative charge amount in the bulk of PI under And after electron irradiation.

Form **Figure 13**, those negative charges were saturated during the irradiation time progress. And in the case of 60 keV irradiation, those negative charges were decreased in spite of irradiation progressing. The total accumulated charge amount

in the bulk is decided due to the balance between the amount of charges supplied by the irradiation and the amount of charges released due to change of the bulk conductivity. Therefore, in this case, it is considered that the amount of accumulated charges was reduced because the amount of change in conductivity inside the bulk became largely dominant.

7.2 Positive charge accumulation in PI irradiated by a proton

In this section, the space charge distribution in PI irradiated by a proton is explained [12]. **Figure 14** shows space charge distribution in PI irradiated by a proton with several irradiation energy. PA and PB shows the polyimide materials, and the differential between PA and PB is the fabrication company. The irradiation condition is 1.0–2.0 MeV for energy with 0.3–30 nA/cm² under 1 × 10⁻⁵ Pa, and those irradiation times is 30 min. The space charge measurement was carried out with each 30 s for the irradiation and 10 min relaxation following from the above irradiation. The irradiation was carried out using 3 MeV tandem type ion accelerator facility of Takasaki Advanced Radiation Research Institute of National Institutes for Quantum and Radiological Science and Technology (QST), 3.75 MV Van de Graff of High Fluence Irradiation Facility at the University of Tokyo and the space environment examination facility at Japan Aerospace Exploration Agency (JAXA).

From **Figure 14**, those space charge distributions show the only maximum charge accumulation during irradiation with the 30 nA/cm² current density. In the figure, the irradiation direction is described on the right side of the figure. From the figure, it is found that positive charges are accumulated in the bulks under all irradiation condition. The charge accumulated position is moved become from the bulk near the irradiation side to middle of the bulk with irradiation energy progress. The

Figure 14.
Positive charge accumulation in PI under proton irradiation.

Figure 15.

Total positive charge amount in the bulk of PI under And after proton irradiation.

ideal penetration depths calculated by the SRIM code are shown with broken line in the bulk on the figure. From these results, we found that the calculated penetration depth has a good correlation with charge accumulated position. Therefore, it is considered that the irradiated proton is the origin of those positive accumulated charges in the bulk.

Figure 15 shows the time dependence of the amount of accumulated positive charges in those bulks irradiated by 2.0 MeV proton. Those are obtained by integration calculation of the charge distributions shown in **Figure 14**. From the figure, concerning accumulation behavior, the increases of the amounts of charges saturate within 3 minutes from the start of irradiation. The accumulated positive charges saturated for a brief time with the current density increasing. After the saturations, the amounts of charges decreased with irradiation time progress.

Furthermore, while we also observed that those accumulated positive charges remained after irradiation with low current density 0.3 nA/cm^2 , no charge was observed immediate after irradiation with high current density irradiation.

From the above charge accumulation penonena, we considered that the origin of those phenomena was produced due to the generation of radiation induced conductivity (RIC). Form the previous research, we could find that conductivity κ of the PI irradiated a proton with an energy of 2 and 1.5 MeV is 10^3 and 10^2 higher than non-treated sample, respectively. It is though that the strength of activation is depended on the irradiation energy. Furthermore, the charge accumulation phenomena may be strongly affected by proton dose. The origin of the RIC is considered activation of material, sission of molecular chain, ionization, and vacancy [13]. Furthemore, after the irraidaion, we could confirm the condirectivity was 10^4 times larger than prisitn sample's. It is one of evidence about molecule chain modification such as mentioned above.

8. Conclusions

It this chapter, we introduced the dielectric phenomena of PI and PAI materials using space charge measurement results using the PEA method. And you could understand the PEA method is very useful for understanding the charge accumulation phenomena. However, the PI is applied for various condition, it is necessary that the measurement system should be modified for the condition and environment

applicable. And then, we could discuss the dielectric phenomena. From the described above, although we could understand the PI has a good insulation performance, since the characteristics may deteriorate depending on the environment, an analysis simulating the usage environment is required.

Acknowledgements

This research was partly supported by a KAKENHI from The Ministry of Education, Culture, Sports, Science and Technology, Japan. We are also grateful to the Tokyo University and National Institutes for Quantum and Radiological Science and Technology (QST) for providing us the proton irradiation facility according with their facility share program.

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