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Comparison of Electrical Properties of Ceramic Insulators under Gamma Ray and Ion Irradiation

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ABSTRACT

The electrical properties of ceramic insulators of Y_2O_3, $CaZrO_3$ and Er_2O_3 were examined under gamma ray and low energy ion beam irradiation. The gamma-ray induced currents increased with the bias voltage. Their radiation induced conductivity (RIC) evaluated from the induced current was almost within one order of magnitude of that predicted from the previous fusion neutron and fission reactor irradiations. Under low energy ion beam irradiation, the induced current from the positive bias voltage was strongly suppressed. From the point of the energy deposition, the magnitude of the ion-induced current was significantly lower than that under gamma-ray and neutron irradiations. A transient change in the induced current at the start of beam irradiation implies that the electric field in the specimen was affected by the unevenness of the distribution of the released electrons and holes.

KEYWORDS

Ceramics, Electrical property, Radiation induced conductivity, Gamma ray, Ion beam

INTRODUCTION

In the development of an insulating technique for liquid Li flow in a Li/V blanket system [1-6], the irradiation effect on the electrical properties of ceramic insulating materials is one of the important factors degrading their performance. Fusion neutron and fission reactor irradiation experiments [7,8] have been performed for the evaluation of the radiation induced conductivity (RIC) effect [9] on the candidate ceramic materials (Y_2O_3, Er_2O_3, $CaZrO_3$, AlN etc.). It is expected from previous results that the RIC effect at low temperature does not prevent such ceramic materials from having the required insulation performance, i.e. $<10^{-2}$ S/m [10], under a dose rate of several kGy/s in the fusion blanket [11]. Further evaluation for the high temperature condition is in progress with ^{60}Co gamma-ray irradiation experiments on newly developed samples. In addition to the RIC effect, the permanent degradation due to the radiation induced electrical degradation (RIED) [12,13] should be examined with ion beams, since the coating materials are exposed to high neutron fluence in a strong electric field. Comparison of irradiation effects due to different types of radiation and understanding of the difference in their effects are useful for the evaluation of the candidate materials.

In the present study, electrical properties of the candidate ceramic materials were examined under the irradiations of ^{60}Co gamma-rays and low energy ion beams. The radiation-induced currents were measured and compared between the two types of radiation. The magnitude of the induced current was also compared with the previous results obtained under the fusion neutron and fission reactor irradiations.

EXPERIMENT

Three disc specimens of Y_2O_3 (supplied from TEP Corp.), $CaZrO_3$ (from TYK Corp.) and Er_2O_3 (from TYK Corp.) were made with a sintering method. Their dimensions were 10 mm diameter by 1 mm thick. The specimens were made for examination of chemical stability in high temperature liquid lithium, and their guaranteed purity was 99.9 %. On one side of the surface of the specimens, center and guard electrodes were made with vapor deposition of silver for current measurements as shown in Fig. 1. And a circular electrode was made on the other side of the surface for applying the bias voltage. The thickness of the electrodes was ~30 nm. The electrical conductivity of the Y_2O_3, $CaZrO_3$ and Er_2O_3 specimens was order of 10^{-13}-10^{-14} S/m before irradiation.

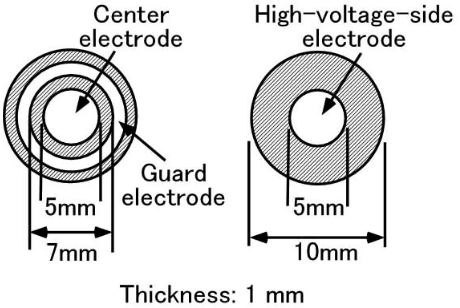

Fig. 1. Dimensions of specimens and electrodes on surfaces.

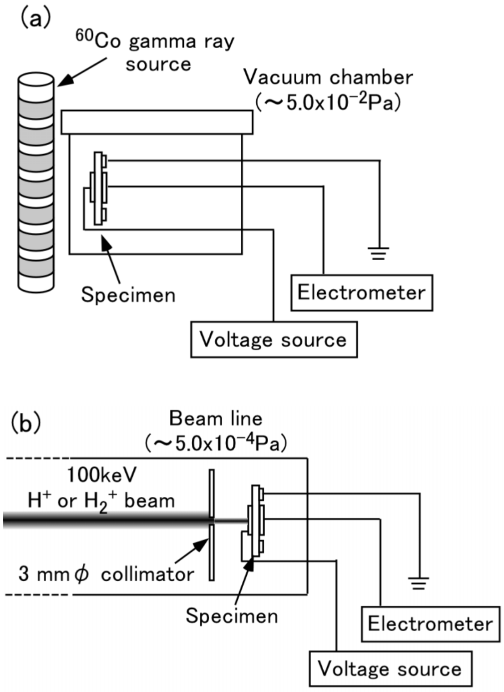

Fig. 2. Schematic arrangement of (a) gamma ray and (b) ion beam irradiations on ceramic specimens.

Gamma ray irradiation was performed in ^{60}Co irradiation facility of ISIR (Institute of Scientific and Industrial Research) of Osaka University. Figure 2 (a) shows a schematic arrangement of the experiment. The specimen was set in the vacuum chamber evacuated with a turbo molecular pump. The vacuum level was ~5.0 x 10^{-2} Pa. The high-voltage-side electrode was connected to a high-voltage source for applying the bias voltage of up to 250 V. The electrical current flowing into the center electrode on the other side was measured at room temperature with an electrometer before and during irradiation. The RIC of the samples were evaluated from increase of the current induced by gamma rays. The dose rate dependence of the RIC was examined by changing the distance between the source and specimen. The maximum dose rate at the sample position was estimated to be ~2.1 Gy/s by calculation with the MCNP transport code [14].

The same specimens were irradiated with low energy ion beams for the comparison between the gamma-ray and ion irradiation effects. As shown in Fig. 2 (b), the specimen was placed to face the ion beam. A beam of 100 keV H^+ was collimated with a mask having an aperture of 3 mm in diameter and was injected into the high-voltage-side electrode of the specimen. The beam current measured with a Faraday cup was 40 - 155 nA (0.6 – 2.2 μA/cm^2). The vacuum level was ~5.0 x 10^{-4} Pa. The arrangement for the current measurement was similar to that in the gamma ray irradiation experiment. The relation between the induced current and bias voltage was examined and compared with data obtained in the gamma ray irradiation experiment. In addition, a transient change of the induced current was measured for an Al_2O_3 mono-crystalline plate (0.5 mm in thickness) under 100 keV H_2^+ beam irradiation to examine the behavior of charge carriers in the specimen. The energy loss in the thin silver electrode was estimated to be ~6 keV for the H^+ beam and ~10 keV for the H_2^+ beam from calculations with the TRIM code [15]. The range of 100 keV H^+ was calculated to be ~500 nm in Al_2O_3. All of the ion beam irradiation experiments were performed at room temperature.

RESULTS AND DISCUSSION

The measured results of current-voltage (I-V) curve under the gamma ray irradiation were shown in Figs 3 (a) and (b). It was checked, by changing the vacuum level, that the induced current was not disturbed by the small amount of electrons and ions due to the ionization of residual gas. It is considered that the non-linearity with the low bias voltages was due to influence of photoelectrons emitted from the chamber wall, electrodes and wires. The I-V curves of the three specimens were symmetric with the polarity of the bias voltage. The RIC values evaluated from the induced currents for bias voltage of +250 V were 1.3 x 10^{-10} S/m for Y_2O_3 (1.8 Gy/s), 1.7 x 10^{-11} S/m for $CaZrO_3$ (1.8 Gy/s) and 9.4 x 10^{-12} S/m for Er_2O_3 (2.1 Gy/s), respectively.

Figure 4 shows the I-V curves under ion beam irradiation on the same Y_2O_3, $CaZrO_3$ and Er_2O_3 disc specimens. The induced currents increased with bias voltage under the ion beam irradiation. However, in contrast with the results of the gamma ray irradiation experiment, the positive current was strongly suppressed for positive bias voltage in the I-V curve. This indicates that the released electrons under the positive bias voltage could not drift a long distance in the sample, like they do for the case of the negative bias voltage. The ion-induced conductivity evaluated from the slope between 0 V and –100 V was 2.9 x 10^{-11} S/m for Y_2O_3 (beam current: 85 nA), 3.7 x 10^{-11}

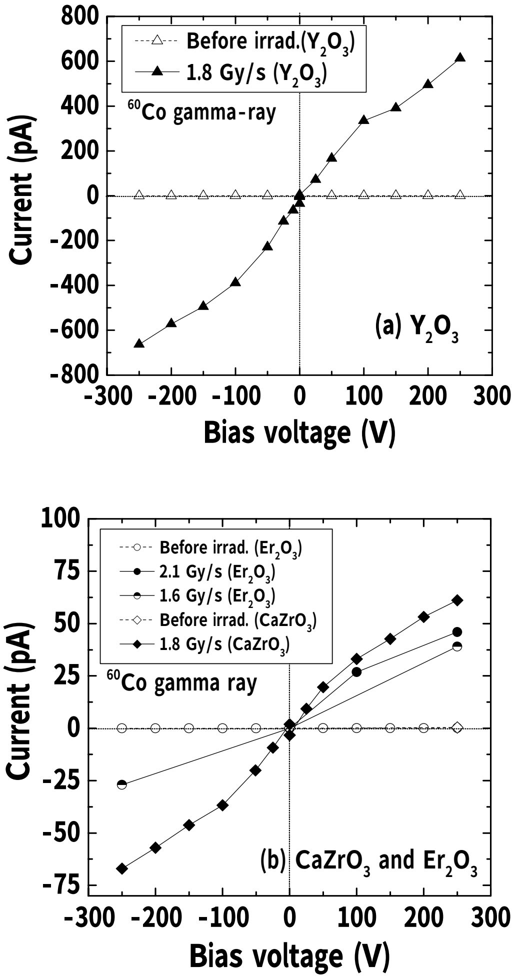

Fig. 3. Results of current-voltage (I-V) curve measurement under gamma ray irradiation. (a) Y_2O_3 and (b) $CaZrO_3$ and Er_2O_3.

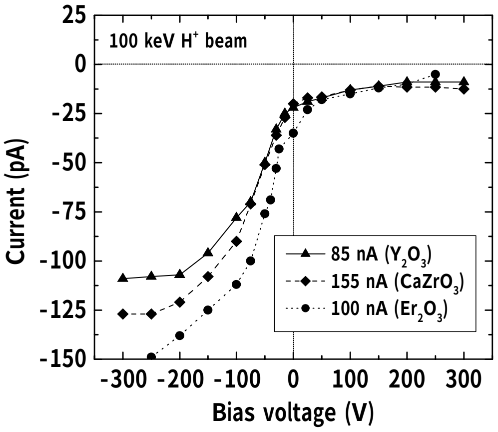

Fig. 4. Results of current-voltage (I-V) curve measurement under 100 keV H^+ beam irradiation.

S/m for $CaZrO_3$ (155 nA), 3.9 x 10^{-11} S/m for Er_2O_3 (100 nA), respectively.

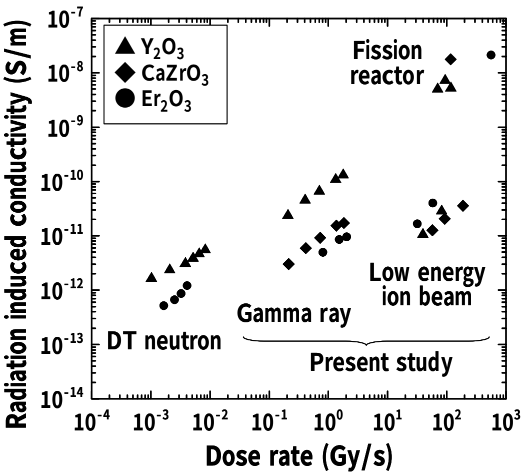

Fig. 5. Comparison of radiation induced conductivity evaluated in present experiment with that in previous DT neutron and fission reactor irradiation.

The RIC data evaluated from the present gamma ray irradiation experiment were compared with our previous data obtained by fusion neutron and fission reactor irradiation experiments. The dose rate for the fission reactor irradiation [8] was reevaluated by detailed calculation of the neutron and gamma ray spectra with the MCNP transport code. As shown in Fig. 5, the present data were plotted almost within one order of magnitude of that predicted from the previous irradiations. The results indicate that the RIC effect in the candidate materials is correlated with dose rate under neutron and gamma ray irradiations, which deposit the energy uniformly in materials.

In the ion beam irradiation, energy deposition is concentrated only in the thin layer below the high-voltage-side electrode. Considering the sensitive volume of the specimens, the energy deposition corresponded to several hundreds Gy/s in the present experiment. However, the magnitude of induced current was 1 or 2 orders lower than that predicted from the gamma ray and neutron irradiations as plotted in Fig. 5. The response under the ion beam irradiations was complicated and included various factors to be considered. Since the thin layer below the high-voltage-side electrode had high ion induced conductivity, the specimen was a series of two regions with low and high conductivities. The density of electron-hole pair production under ion beam irradiation was estimated to be 10^5 times higher compared with the gamma ray irradiation. Therefore electrons and holes may recombine effectively and it is imagined that the electrical field near the high-voltage-side electrode may be weakened due to the existence of the space charge (charge up).

To examine the behavior of the released charge carriers, the transient response of the induced current was measured for mono-crystalline Al_2O_3 under 100 keV H_2^+ beam irradiation. The transient change of the induced current is shown in Fig. 6. For

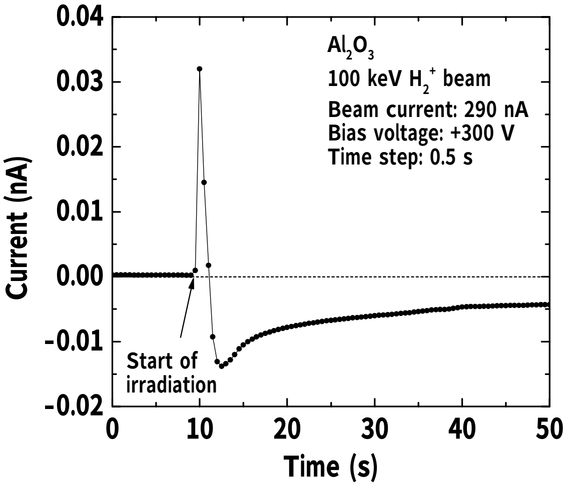

Fig. 6. Transient change of induced current in Al_2O_3 under 100 keV H_2^+ beam.

positive bias voltage, the induced current increased in positive direction at the start of the irradiation. Then the direction of the current was inverted and settled to be negative. The result implies that the electric field of the thin layer below the high-voltage-side electrode was affected by the unevenness of the distribution of electrons and holes produced by the ion beam. The induced current settled down to an equilibrium state in several tens seconds after the start of the irradiation. It is also imagined that an increase in temperature of the region irradiated with an ion beam affects the behavior of the charge carriers. More precise ion beam irradiation experiments on thin coating specimens [16] are planned for the examination of dominant factors for their ion induced conductivity and for the discussion on its mechanism.

CONCLUSION

Electrical properties of Y_2O_3, $CaZrO_3$ and Er_2O_3 specimens were examined under irradiation by ^{60}Co gamma rays and low energy ion beams. The induced current under the gamma ray irradiation increased with the bias voltages. The radiation induced conductivity (RIC) was evaluated to be 1.3 x 10^{-10} S/m for Y_2O_3 (1.8 Gy/s), 1.7 x 10^{-11} S/m for $CaZrO_3$ (1.8 Gy/s) and 9.4 x 10^{-12} S/m for Er_2O_3 (2.1 Gy/s), respectively. These values are almost within one order of magnitude of that predicted from previous fusion neutron and fission reactor irradiations. These results mean that the RIC effect in the candidate materials is correlated with dose rate under neutron and gamma ray irradiations, which deposit the energy uniformly in materials. In the ion beam irradiation experiments, the positive current was strongly suppressed for the positive bias voltage in the I-V curve. This is because the released electrons could not drift in a long distance in the sample like that for the case of the negative bias voltage. From the viewpoint of the energy deposition in the specimens, the magnitude of current induced under 100 keV H^+ beam was 1 or 2 orders lower than that under the gamma ray and neutron irradiations. The transient change in the induced current observed at the start of the ion beam irradiation implies that the electric field of the thin layer below the electrode was affected by the unevenness of electrons and holes produced by ions. Further experiments on the response of the induced current in thin coating specimens are planned for the understanding of the mechanism and for the further evaluation of the candidate materials.

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