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Current–voltage characteristic of alumina and aluminum nitride with or without electron irradiation

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Abstract

The current–voltage (*I–V*) characteristics of single- and poly-crystal alumina and aluminum nitride (AlN) were measured at temperatures ranging from room temperature to 723 K with or without 1 MeV electron irradiation in a high voltage electron microscope (HVEM). Both alumina and AlN specimens exhibit non-ohmic *I–V* characteristics without irradiation. The *I–V* characteristics in alumina, however, change from non-ohmic to almost ohmic under electron irradiation. But the *I–V* characteristics in AlN is still non-ohmic under irradiation. There are remarkable differences in *I–V* characteristics between the alumina and AlN specimens. The non-ohmic behavior is due to the electronic barrier formed near the interface between the titanium electrode and the alumina or AlN specimen. No bulk and surface radiation induced electrical degradation (RIED) was found in AlN up to 1.5×10^{-5} dpa. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Alumina and aluminum nitride (AlN) are considered as the candidate materials for insulator and radio-frequency window/feedthrough applications in magnetic fusion reactors [1,2]. It is necessary to understand the basic electrical properties, such as electrical conductivity and current–voltage (*I–V*) characteristics, of the candidate materials. A considerable number of studies have been carried out for electrical conductivity in alumina under electrons [3–7], ions [8–10] and neutrons [11–13] irradiation, and they have clarified the radiation effects on electrical conductivity in alumina. In contrast, electrical properties of AlN under irradiation have been unclear, since a few studies have been performed as yet [14,15]. The investigation of *I–V* characteristics is need for evaluating electrical conductivity. Moreover, the *I–V* characteristics give us relevant information not only on the potential for insulator's applications but also on the mechanism of the electrical conductivity. A few reports of *I–V* measurement in alumina with or without irradiation [13,16] showed non-ohmic *I–V* characteristics, but did not clear the origin of them. On the contrary, to the author's best knowledge, there are no investigations of *I–V* characteristics in AlN. The purposes of the present study are to carry out the *I–V* measurements of alumina and AlN with or without electron irradiation to confirm whether the *I–V* characteristics is ohmic or not and to understand the principle to govern the electrical conductivity of them, and to measure the electrical conductivity of AlN under electron irradiation to evaluate the electric insulating potential of it under fusion reactor environment.

2. Experimental

Specimens of 5.5 mm diameter and 0.3 mm thick were prepared from single- (Kyocera) and poly-crystal (Wesgo) alumina and poly-crystal AlN doped with 1 wt% Y_2O_3 (Nippon Steel). The center, guard and ground electrodes were made on the specimens by vapor

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deposition of titanium in a vacuum pressure of 10^{-4} Pa. The diameters of the electrodes are as follows: 2 mm for the center electrode, 3.5 mm (inner) and 4.5 mm (outer) for the guard one and 4.5 mm for the ground one. A specimen holder developed for in situ measurements in a high voltage electron microscope (HVEM) [17] was used to investigate the *I–V* characteristics. Irradiation was performed with 1 MeV electrons flux of 1.4×10^{18} e/m^{2}s (8.7×10^4 Gy/s and 1.6×10^{-9} dpa/s) and 1.2×10^{18} e/m^{2}s (7.4×10^4 Gy/s and 1.4×10^{-9} dpa/s) for single- and poly-crystal alumina and AlN, respectively, in an HVEM (JEM-1000) at the HVEM Laboratory, Kyushu University. The *I–V* characteristics were measured at temperatures ranging from room temperature to 723 K with or without electron irradiation using a Hewlett Packard HP4339A high resistance meter.

3. Results and discussion

Figs. 1(a) and (b) show the *I–V* characteristics of single-crystal alumina (Kyocera) at various temperatures without and with electron irradiation, respectively. It should be noticed that the scale of the specimen current in Fig. 1(b) is 10 times larger than that in Fig. 1(a). The *I–V* curve without irradiation (Fig. 1(a)) shows a non-linear relationship, indicating that the *I–V* characteristics is non-ohmic. Moreover, the *I–V* curve without irradiation is such an asymmetric form that the current for positive applied voltage is greater than that for negative one at the same absolute value. The *I–V* curve in Fig. 1(b), on the other hand, is almost linear, that is, the *I–V* curve becomes almost ohmic under electron irradiation. The absolute value of the specimen current with irradiation is larger than that without irradiation owing to radiation induced conductivity (RIC).

The *I–V* characteristics of poly-crystal alumina (Wesgo) at various temperatures without and with electron irradiation are shown in Figs. 2(a) and (b), respectively. Poly-crystal alumina has the non-ohmic *I–V* characteristics with non-linearity and asymmetry before irradiation in (a), while it shows the ohmic type when irradiated in (b). But some significant differences in *I–V* characteristics are recognized between single- and poly-crystal alumina. In spite of the fact that the absolute value of specimen current in poly-crystal alumina is larger than in single-crystal without irradiation, the radiation-enhancement of conductivity is much weaker in the former than in the latter, and the current under irradiation is smaller than in the latter. The specimen current is larger without electron irradiation at 723 K than that with irradiation, which reason is unclear.

The *I–V* characteristics of AlN at various temperatures without and with electron irradiation are shown in Figs. 3(a) and (b), respectively. There are no plots for negative side of applied voltage in Fig. 3(b) because the specimen current could not be measured owing to over-ranging of HP4339A. AlN specimens exhibit non-ohmic *I–V* characteristics without irradiation as well as alumina specimens. It is found in Fig. 3(b) that the *I–V* characteristics with irradiation is also non-ohmic but the *I–V* curves are almost symmetric. The *I–V* characteristics in AlN with irradiation is different from that of alumina. Although the absolute value of specimen current in AlN without irradiation is almost the same as that of alumina at low voltage, the value of AlN with irradiation is about 10 times larger than that of alumina at high voltage.

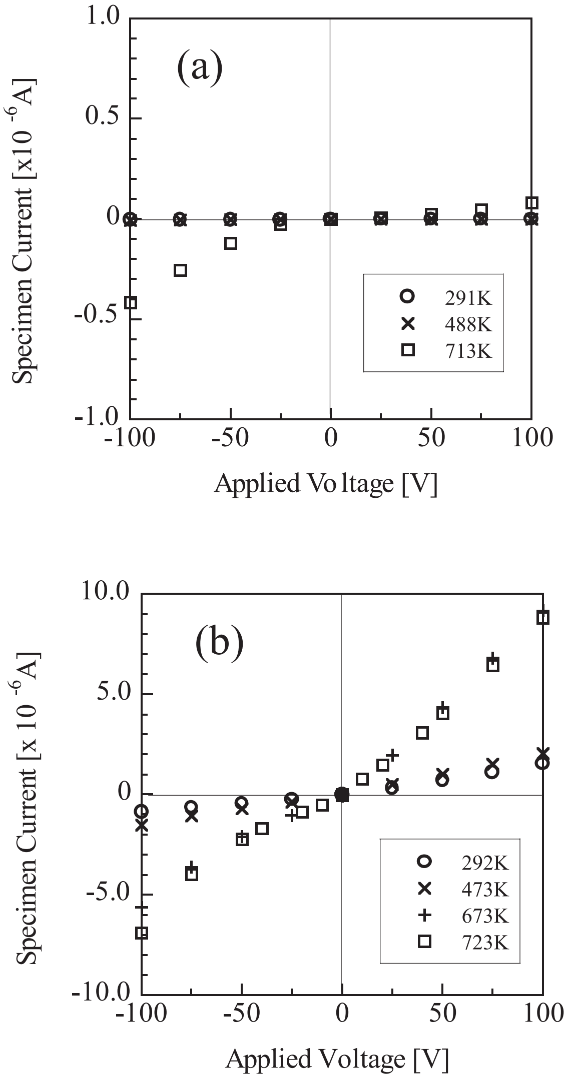

Fig. 1. *I–V* characteristics of single-crystal alumina (Kyocera) (a) without and (b) with 1 MeV electron irradiation at temperatures ranging from room temperature to 723 K. The scale of the specimen current for (b) is 10 times larger than that for (a).

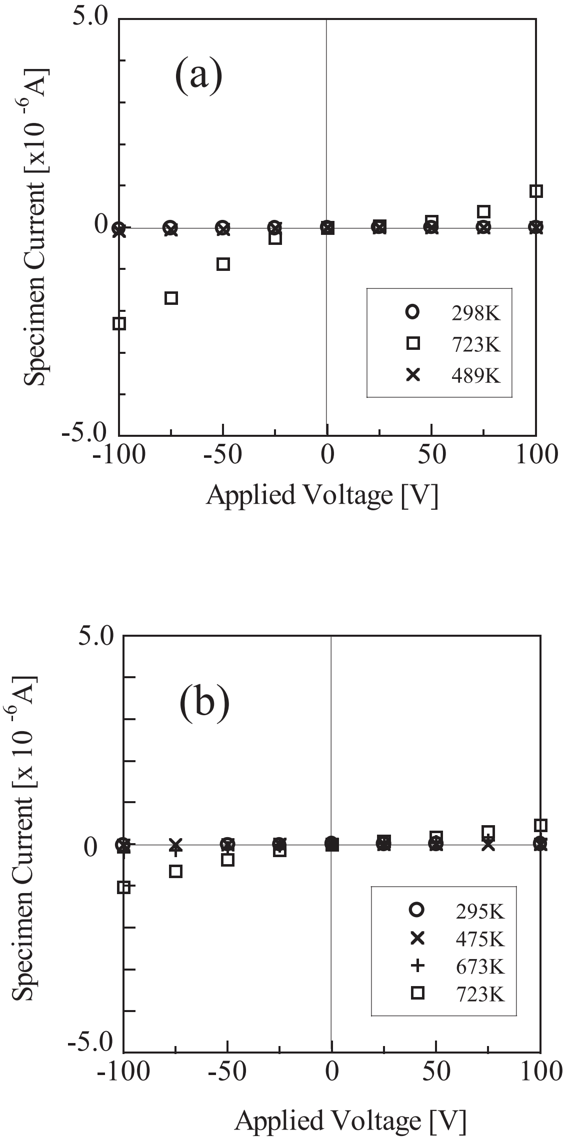

Fig. 2. *I–V* characteristics of poly-crystal alumina (Wesgo) (a) without and (b) with 1 MeV electron irradiation at temperatures ranging from room temperature to 723 K.

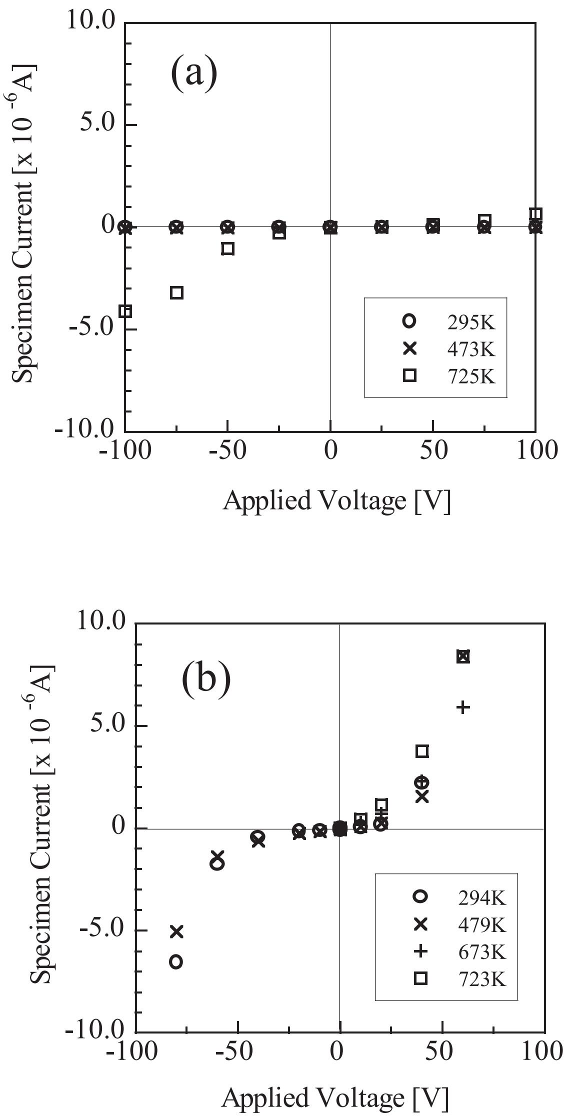

Fig. 3. *I–V* characteristics of AlN (a) without and (b) with 1 MeV electron irradiation at temperatures ranging from room temperature to 723 K.

The non-ohmic behavior is considered to be due to the electronic barrier formed at and/or near the interface between the titanium electrode and the alumina or AlN specimen. In the case of non-metallic materials, the electronic barrier, ϕ_B, is given by

$$\phi_B = \phi_m - \chi_s,$$

where ϕ_m is the work function of the metal electrode, and χ_s is the electron affinity of the specimen [18]. A non-ohmic contact is maintained in accordance with the condition, $\phi_m > \chi_s$ or $\phi_m < \chi_s$ for the n-type or p-type semiconductor. Based on this criterion, alumina, whose electron affinity is 1 eV [19], is considered to be a wide-band gap n-type semiconductor [20]. Non-ohmic behavior, therefore, is expected for alumina combined with Ti electrode with 4.33 eV of work function [21]. In the case of AlN, on the other hand, the *I–V* characteristics without irradiation should be non-ohmic, based on the criteria along with its n-type nature and its electron affinity of 1.9 eV [22]. The electron irradiation does not change both the work function and the electron affinity, but it excites electrons in the specimen beyond the electronic barrier, which leads apparent electronic barrier to become zero. Thus, electron irradiation changes the *I–V* from non-ohmic characteristics to ohmic. However, AlN still keeps the non-ohmic *I–V* characteristics under irradiation. In the case of AlN, the origin of *I–V* characteristics will be the trap of electron to the energy levels formed at specimen surface. The energy levels do not change under irradiation, leading the *I–V* characteristics in AlN to be non-ohmic both without and with irradiation. The results of *I–V* measurements indicate that the electrical conductivity should be evaluated from *I–V* curve in alumina and AlN with Ti electrode.

The electron flux dependence of RIC in AlN was measured. The RIC is proportional to electron flux and reaches 7×10^{-5} S/m under electron flux of 1.2×10^{18} e/m^{2}s (7.4×10^4 Gy/s) at 677 K. This conductivity is smaller than the limiting value of 10^{-4} S/m required for the insulators in international thermonuclear experimental reactor (ITER).

The measurements of thermally stimulated conductivity (TSC) in AlN under 1 MeV electrons irradiation show that the value of TSC is smaller than 10^{-4} S/m and that no TSC peak over 10^{-4} S/m is found.

Fig. 4 shows the electron fluence dependence of bulk and surface conductivity of AlN in an electric field of 150 kV/m at 723 K. The electrical conductivity increases stepwise when irradiation starts, and then further increases gradually with the fluence up to 1.7×10^{22} e/m^2 (1.5×10^{-5} dpa). When the irradiations stopped, the electrical conductivity decreases to a value smaller than the preirradiation value. AlN shows the bulk conductivity of 2×10^{-6} S/m, which is smaller than the limit of 10^{-4} S/m for ITER, with 1 MeV electrons flux of 1.2×10^{18} e/m^{2}s (corresponding dose rate of 7×10^4 Gy/s) at 723 K. It is seen in Fig. 4 that there is no catastrophic increase of bulk and surface conductivity. That is, no bulk and surface radiation induced electrical degradation (RIED) was found in AlN up to 1.5×10^{-5} dpa. It is indicated that AlN has enough electric insulating potential for use as insulator under ITER environment.

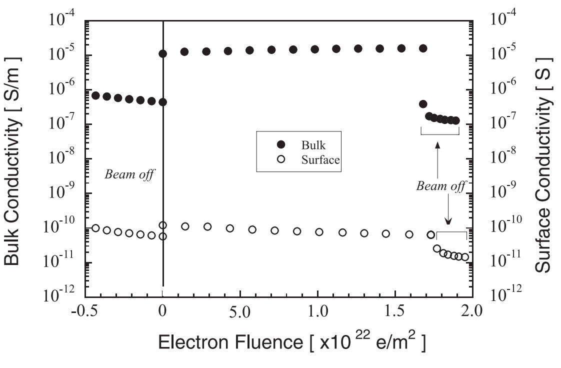

Fig. 4. The electron fluence dependence of bulk and surface conductivity in AlN with 1 MeV electrons flux of 1.2×10^{18} e/m^{2}s in a electric field of 150 kV/m at 723 K.

4. Summary and conclusions

In this study, the *I–V* characteristics of single- and poly-crystal alumina and AlN were measured at temperatures ranging from room temperature to 723 K with or without 1 MeV electrons irradiation in a HVEM. The results obtained are summarized as follows:

(i) Both single- and poly-crystal alumina exhibit non-ohmic *I–V* characteristics without irradiation. The *I–V* characteristics, however, change from non-ohmic to almost ohmic under electron irradiation.
(ii) The *I–V* characteristics in AlN are non-ohmic without and with irradiation.
(iii) The non-ohmic behavior is considered to be due to the electronic barrier formed at and/or near the interface between the titanium electrode and the alumina or AlN specimen. The electron irradiation excites electrons beyond the barrier height, leading to the change from non-ohmic to ohmic *I–V* characteristic.
(iv) The electrical conductivity in alumina and AlN combined with Ti electrode should be evaluated from *I–V* characteristics.
(v) The electrical conductivity of AlN at the dose rate of 7.4×10^4 Gy/s at 677 K is 7×10^{-5} S/m, which is smaller than the limiting conductivity of 10^{-4} S/m required for the insulators in ITER.
(vi) No bulk and surface RIED was found in AlN up to 1.5×10^{-5} dpa.
(vii) AlN has enough electric insulating potential for use as insulator under ITER environment.

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