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Luminescence of Cr-doped alumina induced by charged particle irradiation

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Abstract

The ion-induced luminescence behavior and damage processes were investigated for Cr-doped alumina (ruby, α-Al_2O_3: 0.5 wt% Cr) under H and He ion irradiation with incident energies from 0.2 to 3.0 MeV. The total yield of the R-line luminescence (693 nm) was proportional to the projected range of the incident H ions. However, the He induced luminescence yield was not directly related to either the projected range or the incident energy. The ion-induced luminescence efficiency for the H ion was independent of the electronic energy loss, and that for the He ion decreased with increasing the electronic energy loss. The yields of the R-line luminescence rapidly diminished at the beginning of the ion irradiation. The reduction rate of the luminescence was adequately explained in terms of the nuclear energy deposition, indicating that the R-line luminescence centers were damaged by nuclear collisions.

1. Introduction

Luminescence from oxide materials induced by energetic particles can be used for detecting the flux, fluence and energy distribution of He ions generated by D–T reactions in a fusion reactor. Alumina (α-Al_2O_3) has been proposed for this application because this material not only is a sustainable source for emitting light under radiation but also is resistant to high temperature, mechanical stress and chemical reaction. However, the luminescence of the non-doped alumina is not suitable for energetic ion detection using an optical fiber, because of large absorption of the fiber in the blue light wavelength (blue: 326 and 413 nm). Since Cr-doped alumina, or ruby, emits a strong red luminescence, giving rise to the so-called R-line, under low flux of ion beam irradiation, it was recently evaluated as a luminescent material with an optical fiber under ion beam irradiation. Ion irradiation degrades the yield of the R-line luminescence, depending on the ion species and its energy. It has been suggested that the decrease of the R-line luminescence yield was due to the radiation damage of the luminescence centers under 200 keV He and Ar ion irradiation [1]. However, the decreasing behavior of R-line luminescence yield in ruby has not been studied quantitatively under MeV energy ion irradiation.

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In addition, there are no reports in the literature about the R-line luminescence efficiency as a function of the ion energy deposition. In this paper, we systematically measured the H and He induced R-line luminescence by varying incident energy and fluence to quantitatively study the R-line luminescence efficiency as a function of electronic excitation and of the damage to the luminescence centers by nuclear collisions.

2. Experimental

Samples used in the present experiment were commercially available 1 mm thick plates of ruby with 0.2 at.% Cr (Desmarquest, AF995R). The samples were attached to the sample holder in a vacuum chamber with a pressure below 10^{-5} Pa, and irradiated with H and He ions at room temperature using a 1.7 MV tandem accelerator of the Institute for Material Research, Tohoku University. The ions were accelerated with a beam size of 1 mm in diameter and with an incident angle of 45° with respect to the sample surface normal. The irradiation was performed in the flux range 5×10^{15} to 5×10^{17} ions/m^{2}sec, in the energy range 0.2–3 MeV and up to a fluence of 1.5×10^{20} ions/m^2. The incident ion flux was measured with a Faraday cup before and after the irradiation, and the current on the samples was monitored during the measurement of the luminescence. Ion-induced luminescence emitted from the samples was transmitted with an optical fiber inserted into the vacuum chamber at an angle of 45° with respect to the sample surface normal. The luminescence was measured with a multi-channel analyzer Hamamatsu Photonics PMA10 in the wavelength range of 300–800 nm.

3. Results and discussion

3.1. Incident energy dependence of R-line luminescence

Fig. 1 shows a typical ion-induced luminescence spectrum of the ruby under the 1 MeV He ion irradiation at the fluence of 1×10^{17} ions/m^2 at room temperature. R-line luminescence was clearly observed at nearly 693 nm. It is known from previous work [2,3] that this R-line luminescence derives from single Cr^{3+} ions in Al_2O_3. The shoulder peak observed at nearly 704 nm was derived from some patterned groups of Cr^{3+} ions [4,5]. The weak and broad peak at 326 nm due to F^+-centers was

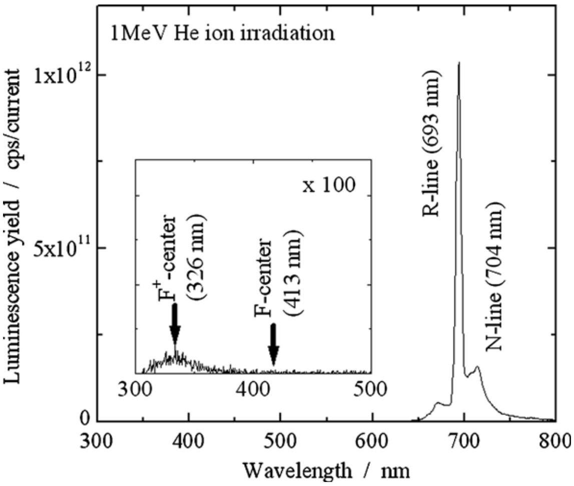

Fig. 1. A typical luminescence spectrum from Cr-doped alumina during irradiation with 1 MeV He ions at room temperature.

observed, while the F-center peak was not observed. It has also been reported that under 200 keV He and Ar ion irradiation, F-type centers luminescence of ruby containing 0.02 at.% of Cr was suppressed due to the interaction of the excited F-center and impurity Cr^{3+} ions [1].

Fig. 2 shows the fluence dependence of the yields of R-line luminescence during He ions irradiation for various incident energies. It appears that luminescence decreases with increasing fluence. The quenching of the R-line luminescence corresponded to the annihilation of the R-line lumines-

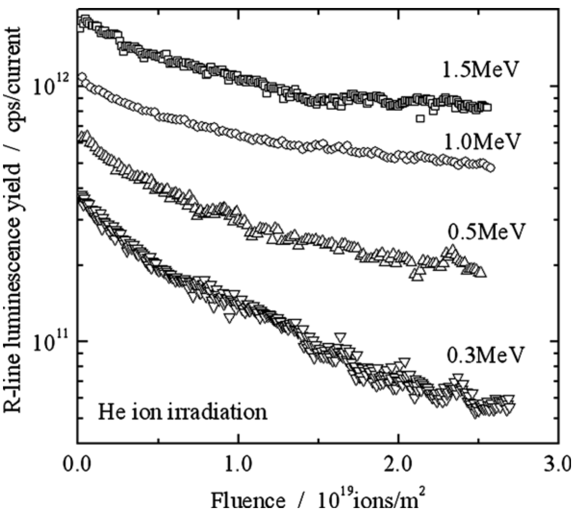

Fig. 2. The R-line luminescence yields plotted against the He irradiation fluence for various incident energies, 0.3 (▽), 0.5 (△), 1.0 (○) and 1.5 (□) MeV.

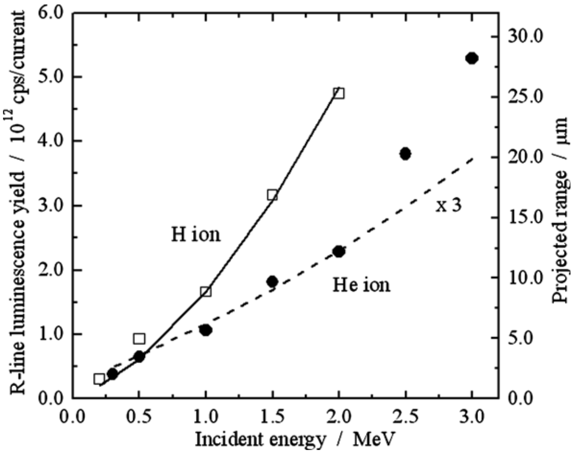

Fig. 3. The energy dependence of the initial R-line luminescence yields for H (open square) and He (solid circle) ion irradiation. The projected ranges for the ions calculated by TRIM98 are inserted as a solid line and dotted line, for H and He ions, respectively.

cence centers caused by ion irradiation. To examine quantitatively the relation the R-line luminescence yields and the incident energy of the H and He ions, we evaluated the luminescence yields at zero fluence, where the luminescence centers were not damaged by ion irradiation. The H and He ion-induced R-line luminescence yields at zero fluence were plotted against the incident energy from 0.2 to 3.0 MeV in Fig. 3. The projected range of H and He ion calculated by TRIM 98 was inserted in Fig. 3. The R-line luminescence yield increases in a monotonous way with incident energy, similarly for both H and He ion irradiation. The energy dependence curve of the initial luminescence yield for H ion irradiation is identical to that of the projected range of the incident H ion, while the observed initial luminescence yield is not proportional to the incident energy. This suggests that the MeV H ion-induced luminescence is mainly related to the number of the luminescence centers. It has been reported that the ion-induced luminescence depends on the projected range of the incident ion under MeV energy ion irradiation [6,7], and it is consistent with the present H ion-induced luminescence. On the other hand, the He ion-induced luminescence yields deviate at the larger projected ranges of He ions. This indicates that the luminescence efficiency varies with the electronic energy loss.

We examined the luminescence yields per unit path length from total luminescence yields as follows. Fig. 4 shows a schematic illustration of the ion-induced luminescence for the two different incident energies.

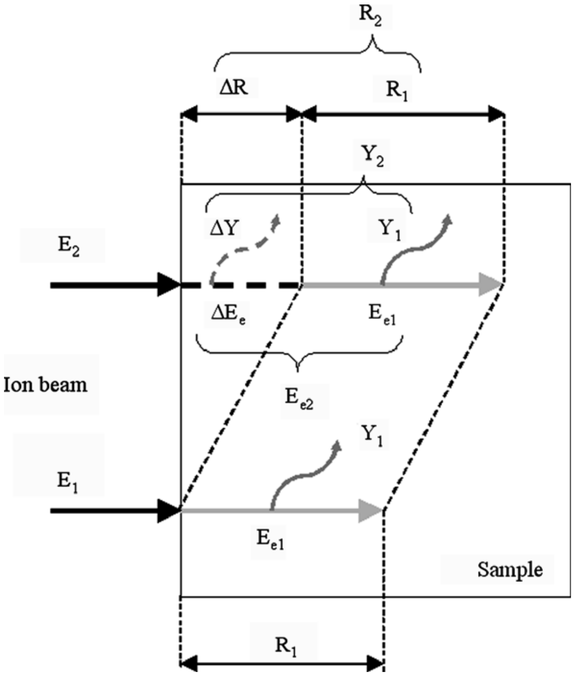

Fig. 4. The schematic illustration of the ion-induced luminescence for the two different incident energies.

dent energies. The R_1 corresponds to the mean projected range of the ion with incident energy E_1. The ions with the higher incident energy E_2 has longer projected range R_2. If we assume that the difference of the total luminescence yield $(Y_2 - Y_1)$ arises from the difference of the path length $(R_2 - R_1)$, the luminescence yield per unit length was estimated to be $(Y_2 - Y_1)/(R_2 - R_1)$. The deposited electronic energies E_{e1} and E_{e2} of the ion with the respective incident energies E_1 and E_2 were calculated by TRIM 98. The initial luminescence yields per unit length were plotted in Fig. 5, as a function of the electronic energy loss. It is clearly shown that the yield per unit length for the H ion irradiation is almost constant for electronic energy loss from 0.05 to 0.15 MeV/μm. This suggests that the yield of R-line luminescence was proportional to the number of luminescence centers, independent of deposited electronic energy. On the other hand, the yield by the He ion monotonically decreased with increasing electronic energy loss in the range between 0.4 and 0.6 MeV/μm.

3.2. Fluence dependent behavior of R-line luminescence

If the annihilation rate of the R-line luminescence centers is proportional to the number of the centers

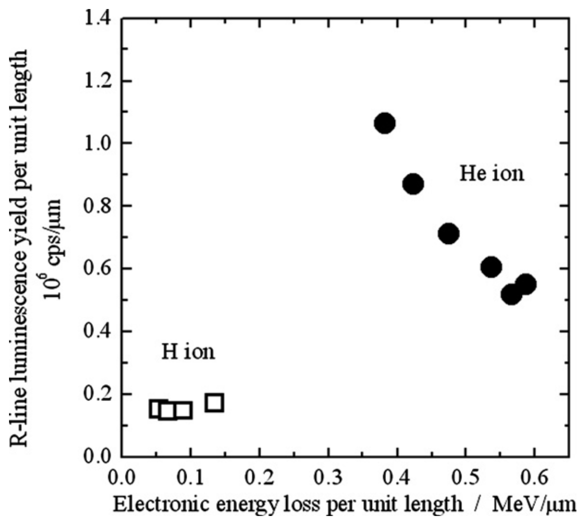

Fig. 5. The relation between the initial luminescence yields of the R-line for per unit path length of the ions in sample and the electronic energy deposition by H (open square) and He (solid circle) ions.

remaining, the yields of the R-line luminescence should decrease exponentially during ion irradiation. As shown in Fig. 2, for all incident energies, the yields rapidly decreased at the beginning of irradiation but the rate of reduction reduced at higher fluence. It can be considered that there are some annihilation mechanisms of the R-line luminescence centers. To investigate the damage of the R-line luminescence centers by ion irradiation, we focused on the annihilation at the beginning of the irradiation where there are few effects of radiation damage. We measured the reduction rate of the R-line luminescence yield at low fluence below about 1×10^{18} ions/m^2, where the yield decreased almost exponentially. The reduction rates of the R-line luminescence yield was estimated for yields at zero fluence and this was plotted against the nuclear energy loss of incident ion, shown in Fig. 6(a). The reduction rates of the yields under both H and He ion irradiation were proportional to the nuclear energy loss as the same line shown in Fig. 6(a). This suggests that the R-line luminescence centers were mainly damaged by the nuclear collision of the incident ions. On the other hand, the reduction rates of the R-line luminescence were plotted against the electronic energy loss, like Fig. 6(a) shown in Fig. 6(b). The reduction rates of the yields by H ion irradiation were almost constant, but under He ions irradiation it decreased

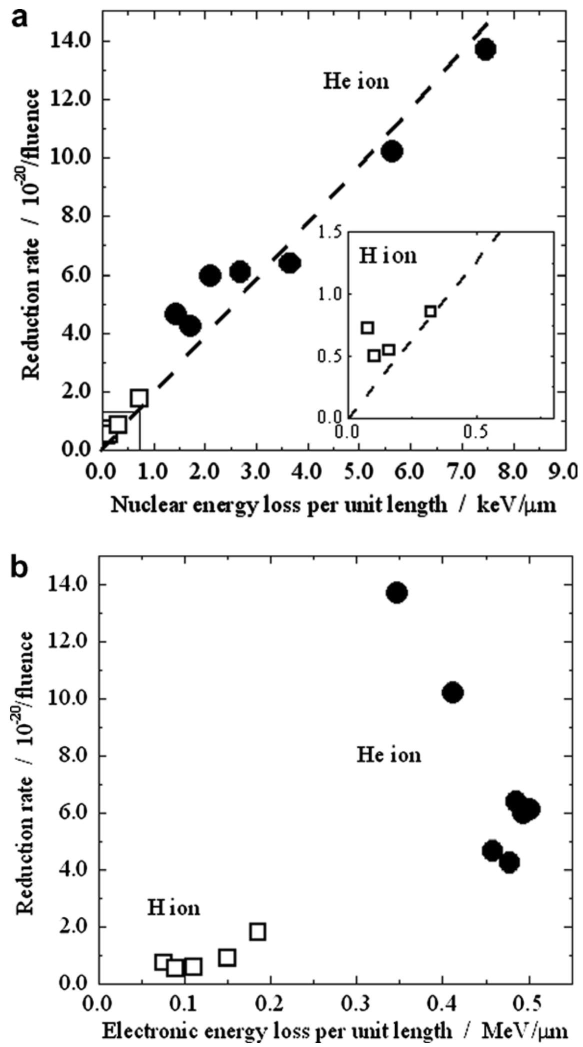

Fig. 6. Reduction rates of the luminescence yield at low fluence below 1×10^{19} ions/m^2 under H (open square) and He (solid circle) ion irradiation plotted against the nuclear energy loss and the electronic energy loss of the incident ion, for (a) and (b), respectively.

rapidly with increasing electronic energy loss. These results are similar to the report that the R-line luminescence centers were annihilated effectively by the nuclear collision of the 200 keV Ar ions and electronic excitation of 200 keV He ions [1]. These authors suggested that the Cr^{3+} ions, which are the R-line luminescence centers, were decreased by the oxygen vacancies produced by the nuclear collision. It can be concluded that the reduction rates of the R-line luminescence yields at low fluence were clearly matched by the nuclear energy deposition, unlike the electronic energy deposition.

4. Summary

The R-line luminescence (693 nm) of Cr-doped alumina (ruby, α-Al_2O_3: 0.5 wt% Cr) induced by H and He ions were studied with the incident energy varying in the range from 0.2 to 3 MeV and the fluence below 1.5×10^{20} ions/m^2. From the results of energy dependence of R-line luminescence yields, it was understood that the luminescence yield for unit path length of the incident H ion trajectory was almost constant. However, under He ion irradiation, the luminescence efficiency decreased with increasing electronic energy deposition. From the results of the fluence dependence of the R-line luminescence, it was concluded that the initial reduction rate of the R-line luminescence was related to the nuclear energy loss of the incident ions under both H and He ion irradiation.

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