Possible Application of an Imaging Plate to Space Radiation Dosimetry

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Fading correction plays an important role in the application of commercially available BaBrF:Eu2+ phosphors: imaging plates (IP) to dosimetry. We successfully determined a fading correction equation, which is a function of elapsed time and absolute temperature, as the sum of several exponentially decaying components having different half-lives. In this work, a new method was developed to eliminate a short half-life component by annealing the IP and estimating the radiation dose with the long half-life components. Annealing decreases the effect of fading on the estimated dose, however, it also causes the loss of photo-stimulated luminescence (PSL). Considering an IP as an integral detector for a specific period of up to one month, the practically optimum conditions for quantitative measurement with two types of IP (BAS-TR and BAS-MS) were evaluated by using the fading correction equation, which was obtained after irradiation with a 244Cm source as the alpha-ray source having a specific radioactivity of 1.638.5 Bq/cm² including beta and gamma-ray (alpha energy of 5.763 and 5.805 MeV). Annealing at 80°C for 24 hours after irradiation for one month using BAS-MS should minimize the effect of the elapsed time, resulting in sufficient sensitivity. The results demonstrate new possibilities for radiation dosimetry offered by the use of an IP.

INTRODUCTION

In the sensitive layer of an imaging plate (IP) composed of BaBrF:Eu2+ phosphors, ionizing radiation creates a large amount of trapped centers, which record information about the deposited energy and its position. The IP has many advantages as a detector of two-dimensional images, and has been utilized in a number of fields1). However, there are relatively few reports of applying IPs for quantitative use2). The reason for this is that IPs have a large fading effect. That is, some charges stay trapped at localized defects but some recombinates with holes after irradiation for a time, depending on the temperature and the activation energy of the traps. This results in a serious problem in developing an IP into an integral-type detector. We have continued our study3–5) of measuring the fading characteristics and have observed that the fading effect increases as both the temperature and the time following irradiation increase. Considering that thermally released electrons from the F centers are dominant in the fading process, we successfully developed equations as a function of elapsed time (t) and absolute temperature (K) to correct the fading. We have also investigated the dependence of the fading effect of IP on alpha, beta, and gamma radiation and their energies by using three types of IPs: BAS-UR, BAS-TR, and BAS-MS (Fuji Film Co.). A 244Cm planchet source (specific radioactivity of 2.9 KBq, alpha energy of 5.763 and 5.805 MeV) was used as the alpha-ray source. A 14C, 32P, 36Cl source (radioactivity of 740.0, 11.7, and 4.0 KBq and maximum beta energy of 0.156, 1.711, and 0.709 MeV, respectively) was used as the beta-ray source. A 60Co and 137Cs point source (0.514 and 0.662 MeV from a 137Cs source) was used as a gamma-ray source. We found that in all types of IPs the fading effect is independent of the energy of the incident particles of beta and gamma rays. The fading effect was also independent of radiation, except for the first component, which fades out very quickly after irradiation with alpha
rays\(^5\). This result means that the whole amount of radiation dose independent of radiation or energy can be estimated after the first component caused by the alpha rays fades out.

The purpose of this paper is to report on our development of a new method that eliminates the short half-life component by annealing an IP and that estimates the radiation dose with the long half-life component for quantitative measurement. The annealing decreases the effect of fading on the dose estimate, however, it also causes the loss of photo-stimulated luminescence (PSL). Considering an IP as an integral detector for a specific period, the optimum conditions for quantitative measurement with two types of IP (BAS-TR and BAS-MS) have been evaluated by using the fading correction equation.

**MATERIALS AND METHODS**

BAS-TR and BAS-MS manufactured by Fuji Film Co. are commercially available. BAS-TR has a size of 40.0 cm \(\times\) 20.0 cm and is dyed blue, lacking a protective surface layer to detect low-energy beta rays such as \(^3\)H effectively. BAS-MS, which is produced as a highly sensitive and waterproof white IP, has a smaller area of 20.0 cm \(\times\) 25.0 cm with a 9 \(\mu\)m thick protective Mylar film. Both are constructed of a 50 \(\mu\)m or 115 \(\mu\)m thick photostimulable phosphor (BaBrF:Eu\(^{2+}\)) individually affixed to a 250 \(\mu\)m or 188 \(\mu\)m thick plastic backing for support. The IP was irradiated with the \(^{244}\)Cm source (a specific radioactivity of 1,638.5 Bq/cm\(^2\) including beta and gamma-ray) for 15 minutes by placing the source directly on the IP. The fading characteristics were measured for time periods from 0.03 to approximately 500 hours after irradiation and at temperatures varied in increments of 10°C between 0 and 60°C. To obtain the net PSL densities, we subtracted the PSL densities of the background IP induced by natural radiation during the elapsed time at each temperature from the irradiated IPs. (for further experimental details, see references\(^3\)–\(^5\))

Fading correction equations after irradiation with the \(^{244}\)Cm source were thus obtained as Eq. (1)\(^4\) using BAS-TR scanned by BAS-1000 and Eq. (2)\(^5\) using BAS-MS scanned by BAS-5000:

\[
\frac{(PSL)_{t,k}}{(PSL)_{0,k}} = 
0.461 \exp \left\{ -2.19 \times 10^8 \cdot t \cdot \exp\left(-6.14 \times 10^3/K\right) \right\} 
+ 0.277 \exp \left\{ -1.60 \times 10^{13} \cdot t \cdot \exp\left(-1.02 \times 10^3/K\right) \right\} 
+ 0.230 \exp \left\{ -7.98 \times 10^{12} \cdot t \cdot \exp\left(-1.05 \times 10^3/K\right) \right\} 
+ 0.030 \exp \left\{ -1.99 \times 10^{12} \cdot t \cdot \exp\left(-1.05 \times 10^3/K\right) \right\} 
+ 0.002 \exp \left\{ -4.96 \times 10^{10} \cdot t \cdot \exp\left(-1.05 \times 10^3/K\right) \right\}
\]

(1)

\[
\frac{(PSL)_{t,k}}{(PSL)_{0,k}} = 
0.373 \exp \left\{ -2.08 \times 10^{10} \cdot t \cdot \exp\left(-8.92 \times 10^3/K\right) \right\} 
+ 0.084 \exp \left\{ -9.89 \times 10^{10} \cdot t \cdot \exp\left(-8.69 \times 10^3/K\right) \right\} 
+ 0.360 \exp \left\{ -4.37 \times 10^{10} \cdot t \cdot \exp\left(-9.31 \times 10^3/K\right) \right\} 
+ 0.144 \exp \left\{ -2.41 \times 10^{10} \cdot t \cdot \exp\left(-9.54 \times 10^3/K\right) \right\} 
+ 0.039 \exp \left\{ -2.07 \times 10^9 \cdot t \cdot \exp\left(-9.53 \times 10^3/K\right) \right\}
\]

(2)

where \((PSL)_{t,k}\) and \((PSL)_{0,k}\) refer to the PSL of elapsed time \(t\) and 0 after irradiation, respectively, and \(K\) is the absolute temperature.

Two models expressing fading curves during the elapse of \(t\) days (one model is \(t = 1\) and another is \(t = 30\)) after irradiation and a decreasing curve after annealing at \(K^\circ C\) are shown in Fig. 1. All values of PSL were normalized with the value of PSL one day after irradiation. A model of the accumulating radiation dose each day is also shown. \(T_1\) and \(T_{30}\) are the values of PSL after \(t\) days have elapsed when \(t = 1\) and \(t = 30\), each without annealing. \(T_{1,K}\) and \(T_{30,K}\) are the values after annealing with \(T_1\) and \(T_{30}\) at \(K^\circ C\) for 24 hours. \(T_1\) means the PSL value keeps high one day after irradiation with the less fading effect comparing \(T_{30}\). \(T_{30}\) means the PSL value decreases with the large fading \(t\) days after irradiation. After annealing, the PSL value steeply decreases from \(T_1\) to \(T_{1,K}\) because the fading proceeds drastically, though the PSL value does not decrease so much from \(T_{30}\).

![Fig. 1. Schematic model of fading and annealing curves during the elapse of \(t\) days after irradiation.](image-url)
to $T_{30,K}$ because the fading already proceeded during $t$ days. Comparing the differences between $T_1 - T_{30}$ and $T_{1,K} - T_{30,K}$, it is clearly shown that the fading effect on PSL becomes smaller after annealing than before annealing. Thus, the annealing can make the fading effect on PSL small to present a possibility of IP for an integral type detector. However, the process also causes a loss of sensitivity.

RESULTS

A comparison of the effects of days elapsed (2, 7, 15, and 30) after irradiation on the value of PSL without annealing, and with annealing at 60, 70, and 80°C were evaluated. Figure 2 shows the results: (a) for BAS-TR and (b) for BAS-MS. All values of PSL were normalized with the value of PSL left at 20°C for one day after irradiation, indicated as PSL$_1$. For BAS-TR, the ratio of PSL$_K$ to PSL$_1$ shows a large difference (0.78 and 0.07) between 2 and 30 days without annealing. The difference becomes very small (< 5%) when the IP is annealed at 60°C. In contrast, for BAS-MS, the difference of the ratio of PSL$_K$ to PSL$_1$ between 2 and 30 days is not as large as BAS-TR (0.94 and 0.53) without annealing. The difference does not get smaller when the IP is annealed at 60°C, but does decrease by about 15% when the IP is annealed at 80°C.

As for the loss of PSL, for BAS-TR, even without annealing, the ratio of PSL$_K$ to PSL$_1$ is 7% 30 days after irradiation. After annealing at 80°C, it goes to 0.4%. For BAS-MS, no drastic decrease of PSL was observed. The ratio remains above 13% after annealing at 80°C 30 days after irradiation. This level is considered sufficient for practical use as a month-long integral detector.

In this study, PSLs were calculated by using the equations with annealing temperatures basically varied in increments of 10°C between 60 and 80°C. For BAS-MS, higher annealing temperatures up to 100°C were also evaluated in Fig. 2(b). At 90°C annealing, the ratio of PSL$_L$ to PSL$_1$ decreases below 10% even 2 days after irradiation. Therefore, the practical optimum condition for quantitative measurement appears to be to anneal BAS-MS at 80°C for 24 hours after irradiation for a month-long detector. This can decrease the effect of the elapsed time, retaining sufficient sensitivity.

DISCUSSION

In this work, two types of IPs were investigated. The effect of annealing is clearly demonstrated by the difference in the decrease of PSL. That is, annealing even at a relatively low temperature (60°C) causes a large amount of emission of luminescence for BAS-TR, but causes less for BAS-MS (see Figs. 2(a) and (b)). This result could be explained by the difference of the activation energies and the component amplitudes between the two IPs. We showed that the activation energy increases as the components proceed4). This result satisfies the idea that fading occurs in the order of the component having the lower activation energy. The activation energies of each component in Eq. (1) for BAS-TR are 0.53, 0.88, 0.90, 0.90, and 0.90 eV. For each component in Eq. (2) for BAS-MS, the values are 0.76, 0.75, 0.80, 0.82, and 0.82 eV5). The amplitude of the first component for BAS-TR is larger than that for BAS-MS: 0.461 in Eq. (1) and 0.373 in Eq. (2). Annealing accelerates
advance of fading. Emission of the first component of BAS-TR should be drastically affected by annealing. In contrast, each component for BAS-MS has a relatively high activation energy, so it can retain sufficient sensitivity after annealing.

IP has a linearity of PSL from 10⁻⁴ mSv to 10¹ mSv to irradiated dose from γ rays with a ⁶⁰Co source. In our preliminary experiment, the upper limit of the dose could be extended to over 10¹ Sv by annealing method, that is, a dynamic range of IP could be extended to more than 10⁸. The upper limit of the measurable dose does not depend on the property of IP but on that of the photomultiplier (PMT). PSLs from an IP irradiated with over 10¹ mSv saturate the PMT. However, PSLs decreased by annealing can be measured quantitatively without saturation of PMT. For cosmic-radiation dosimetry, some detectors have already been evaluated. However, this advantage makes IP one future candidate. The results of this study demonstrate new possibilities of radiation protection dosimetry offered by IP.

REFERENCES


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