Preliminary study of the portable Optically Stimulated Luminescence dosimetry system for measuring radiation doses more than 100 Gy *

T. Okazaki†, T. Hashizume[1], V. LE Cruz, W. Cheng, I. Kobayashi[2],
Nagase-Landauer, Ltd., 300-2686 Tsukuba, Japan
Y. Hashimoto, M. Shirakata, H. Nakamura, H. Yamazaki,
High Energy Accelerator Research Organization, KEK, 305-0801 Tsukuba, Japan
H. Hayashi, Kanazawa University, 920-0942 Kanazawa, Japan
[1]The Guraduate University for Advanced Studies, SOKENDAI, 240-0193 Hayama, Japan
[2]Research Institute of Nuclear Engineering, University of Fukui, 914-0055 Tsuruga, Japan

Abstract

In the high intensity accelerators of the Japan Proton Accelerator Research Complex (J-PARC), a small size dosimeter for measuring radiation dose of more than 100 Gy is required. We studied the applicability of a commercialized Optically Stimulated Luminescence (OSL) dosimetry system using Al_2O_3:C crystals for radiation detection. To evaluate the dose response characteristics of the OSL dosimeter, the dosimeters were exposed to 0.09 – 696 Gy of ^{60}Co gamma-rays and read using a portable OSL reader. A fitting curve for interpolating the experimental results was in good agreement with the response of dosimeters at ±3%. Based on the results, we concluded that our dosimetry system can evaluate the radiation dose of up to 245 Gy of ^{60}Co gamma-rays.

INTRODUCTION

A semiconductor device is essential for the monitoring and/or management of equipments. At the same time, a semiconductor device exposed to radiation are damaged through the ionization and/or the generation of lattice defects. In some semiconductors, the radiation tolerance is less than several hundred Gy [1]. Thus, it is important to manage the dose of more than 100 Gy when we use a semiconductor in the irradiation field. We forcus our attention on the radiation dose in accelerator facilities, especially in the high intensity accelerators of the Japan Proton Accelerator Research Complex (J-PARC). The semiconductor devices installed in the proton accelerator are damaged by the secondary-induced radiations which were generated by beam losses from primary accerelated particles [2]. Therefore, a small size dosimeter which can evaluate the dose distribution is required in the field. In addition, it is important to establish the ease of measurement of the system and its low cost for the dosimeter. We studied the applicability of an Optically Stimulated Luminescence dosimeter composed of Al_2O_3:C crystal for dose evaluation of more than 100 Gy. The Al_2O_3:C exposed to ionizing radiation creates free electrons and holes, which are trapped to the defects in the crystal. The trapped electrons and holes recombine and emit the luminescence when the crystals are stimulated by green light. The OSL dosimeter can evaluate the absorbed dose of the Al_2O_3:C by measuring the amount of luminescence. Currently, a 10×10×2 mm of small type OSL dosimeter, nanoDot (Landauer, Ltd., Illinois, U.S.A.), is comercialized. The absorbed dose can be evaluated easily by using a portable OSL reader named "microStar" (Landauer, Ltd., Illinois, U.S.A.). The microStar can read the nanoDot repeatedly and this technique can improve the accuracy of the measurement [3]. Thus, the nanoDots are widely used especially in the medical field [4, 5] and its basic characteristics in the diagnostic and therapeutic dose regions are reported [6-12]. However, there are few reports about the dose response characterisitics of the nanoDot to more than 100 Gy because the main application of the OSL dosimeter is dose evaluation in the health physics region. Furthermore, it has been reported that the dose response characteristics of Al_2O_3:C crystal exposed to more than 1 Gy shows supralinear and/or sublinear response[12], thus, we should evaluate the dose response characteristics precisely. In a previous study [13], we irradiated ^{60}Co gamma-rays to nanoDot OSL dosimeters of up to 2000 Gy and evaluated the dose response characteristics. We found that the amount of luminescence emitted from Al_2O_3:C crystals was saturated when the radiation dose is more than 250 Gy; we then obtained the fitting curve for interpolation with accuracy of ±16.8%. We also found that the uncertainty of the responses became larger when the irradiation distance of the nanoDots were closer than 0.3 m from the ^{60}Co source. Hence, we paid attention to the uncertainty effect of the irradiation distance. We were also concerned of the sensitivity to ionizing radiation of each nanoDot OSL dosimeter in this experiment. Although the sensitivity of each nanoDot is determined at the time of manufacture, it has a ±5% of uncertainty. That means that the uncertainty of the dose response characteristics in the previous experiment included the uncertainty of the sensitivity of the OSL dosimeters. Therefore, in this experiment, we used the same lot of dosimeter and repeated the irradiation and the measurement for evaluating the relationship between the accumulated dose of each OSL dosimeter and the amount of luminescence counts.

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† okazaki@nagase-landauer.co.jp

Table 1: The Irradiation Conditions

Exposure No.	Distance [m]	Air kerma rate [Gy/h]	Exposure time [min]	Air kerma[Gy]	Accumurated dose [Gy]	Cooling time [min]	Response	Error
1	7.20	0.15	36	0.09	0.09	19	67	90
2	4.50	0.38	64	0.41	0.50	22	256	18
3	4.00	0.49	60	0.49	1.0	15	511	22
4	0.80	10.85	60	10.9	12	982	6741	153
5	1.20	5.09	60	5.09	17	16	10962	214
6	1.20	5.09	70	5.94	23	14	16168	236
7	1.20	5.09	60	5.09	28	10	20688	519
8	1.50	3.28	80	4.37	32	70	24447	286
9	1.00	7.11	40	4.74	37	30	29137	425
10	0.90	8.60	35	5.02	42	27	33634	578
11	1.00	7.11	50	5.92	48	23	39177	529
12	5.50	0.25	979	4.08	52	47	41985	605
13	1.30	4.37	60	4.37	56	40	45133	670
14	1.30	4.37	49	3.57	60	40	47644	864
15	1.10	6.00	60	6.00	66	27	52069	808
16	0.30	65.50	15	16.4	82	25	64789	1595
17	0.30	65.50	20	21.8	104	24	77845	1355
18	0.30	65.50	120	131	235	24	117554	1562
19	0.20	130.00	50	108	344	26	126532	2698
20	1.00	7.11	991	117	461	73	126063	2173
21	0.30	65.50	96	105	566	57	129516	2594
22	0.20	130.00	60	130	696	66	131625	3075

MATERIAL AND METHODS

The same lot of nanoDots, meaning that the sensitivity of them were the same, were optically bleached before irradiating them with ^{60}Co gamma-rays. They were irradiated behind a 5 mm thickness of PMMA plate which is for establishing secondary electron equilibrium. The 14.9 TBq of ^{60}Co source installed at QST Takasaki (Japan) was used for the experiment. Because the source was distributed at 0 – 45 cm height, the nanoDots were set at 22 – 24 cm height for the irradiation. The absorbed dose of nanoDots were evaluated by geometrical arrangement. To measure the luminescence of nanoDot OSL dosimeters, we used microStar, a portable OSL reader. To prevent the satulation of signal in the PMT of the reader, we used a neutral density filter, ND-2.0 (Fujifilm, Ltd., Tokyo, Japan) behind the OSL element. It reduced the luminescence incident on the PMT by 1/100.

To verify the relationship between the irradiation distance and the uncertainty of the measurement counts, we exposed 3 groups of nanoDots at 0.1 m (410 Gy/h), 0.3 m (65.5 Gy/h) and 1.0 m (7.11 Gy/h) with exposure time of 60 min, 80 min and 70 min, respectively. Immediately after the exposure, they were measured continually for evaluating the effect of fading of the luminescence.

To evaluate the dose response characteristics of the nanoDot, 5 nanoDots were used for the experiment. The detailed irradiation conditions are summarized in Table 1. The "cooling time" in the table means the time from the irradiation of the dosimeter to the on-set time of the measuement. The 5 nanoDots were exposed 22 times and after each exposure, all of them were measured 5 times with more than 10 minutes of cooling time. The 25 datasets of measured counts were averaged and the value of (averaged counts) / (sensitivity) was defined as the response of the nanoDots. To evaluate the dose response characterisitcs of the nanoDot in different doses between 0.09 – 696 Gy of ^{60}Co gamma-rays, the distance from the souce to the dosimeter and the exposure time were changed for each exposure.

RESULTS AND DISCUSSION

To evaluate the influence of the irradiation distance during an exposure, the nanoDots were exposed at different distances of 0.1 m, 0.3 m and 1.0 m. The readings started 6 - 7 minutes after the irradiation and they were measured continually. We defined the cooling time as the time between the end of exposure and the start of the reading. The relationship between the measured counts and the cooling time is shown in Figure 1. The trend of measured counts shows the initial fading effect and it is not dependent on the distance of the irradiation.

Additionally, we found that the initial fading continued for around 20 minutes after the irradiation and the measurement of nanoDots with only 10 minutes of cooling time made the counts 20% higher. The results were consistent with the results from our previous study[12]; the measurement results varied at ±16.8% because a number of nanoDots were measured after a cooling time of more than 20 minutes and some of them were measured after 10 minutes.

The dose response characteristics of nanoDot OSL dosimeters are presented in Table 1. The response of nanoDots were measured in the accumurated doses of 0.09 – 696 Gy. When the accumurated dose was more than 1 Gy, the responses were higher than 500 and the coefficient of variation were less than 5%. The response of nanoDots increased depending on the accumulated dose and they were matched within the range of error bar when the

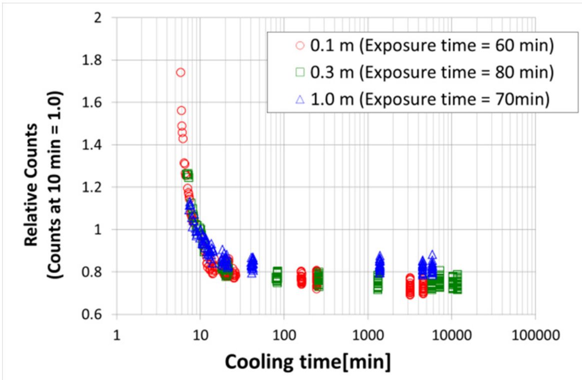

Figure 1: Relationship between relative counts and cooling time. The data were obtained with the arrangement having 3 different distances. A cooling time is the time between the end of exposure and the start of reading. The reduction of the measurement counts appeared during 20 minutes caused by the initial fading of luminescence.

accumulated dose was more than 344 Gy. This phenomena may be explained by the excitation of electrons by ^{60}Co gamma-rays. The electrons promoted to the conduction band by ^{60}Co gamma-rays are traped at the crystal defects. When the absorbed dose of Al_2O_3:C is more than 344 Gy, all of the defects are filled with electrons and the number of trapped electrons does not increase any more. Then, the number of trapped electrons (N) can be estimated by the function of the number of defects (α) in Al_2O_3:C crystal and the absorbed dose of Al_2O_3:C (D) as shown in equation (1):

$$\frac{\mathrm{dN}}{dD} = \gamma \times (\alpha - \mathrm{N}), \quad (1)$$

where γ is a constant. Based on the equation, we modeled a fitting curve of the nanoDots dose response characteristics as follows:

$$\text{Response} = 135000 \times (1 - e^{-0.0055 \times Dose}). \quad (2)$$

The ratio of the nanoDots response and the fitting curve were compared and is shown in Figure 2. Most of the responses were within ±30% from the fitting curve. Therefore, we divided the fitting area into 3 regions; linear (less than 1 Gy), supralinear (1 – 60 Gy) and sublinear (greater than 60 Gy) as follows:

Dose < 1.0 Gy: Linear region

$$\text{Response} = 519.98 \times \text{Dose}, \quad (3)$$

1.0 Gy ≤ Dose < 60 Gy: Supralinear region

$$\text{Response} = -0.01355 \times Dose^3 + 14.126 \times Dose^2 + 432.14 \times \text{Dose} + 73.8495, \quad (4)$$

60 Gy ≤ Dose: Sublinear region

$$\text{Response} = 159000 \times e^{-0.011 \times Dose} - 29232.79. \quad (5)$$

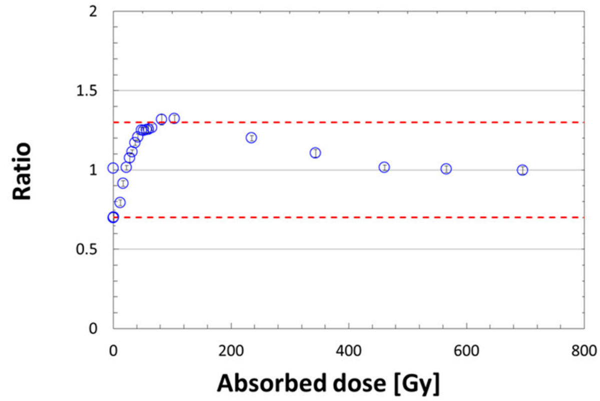

Figure 2: The dose response characteristics of nanoDots was fitted by using equation (2). Most of the responses were inside of ±30% of the fitting curve.

We compared the fitting curve and the responses obtained by the experiment as shown in Figure 3. The upper figure is the relationship between the absorbed dose of the nanoDot and the fitted responses. The lower figure represents the ratio of the response and the fitting curve. The fitting curve has a good agreement with the response of the nanoDots exposed to more than 0.5 Gy within ± 3%. When the absorbed dose of the nanoDots reaches 350 Gy, the response of the nanoDot seems to be saturated. Then, the response of the nanoDots can be estimated to be

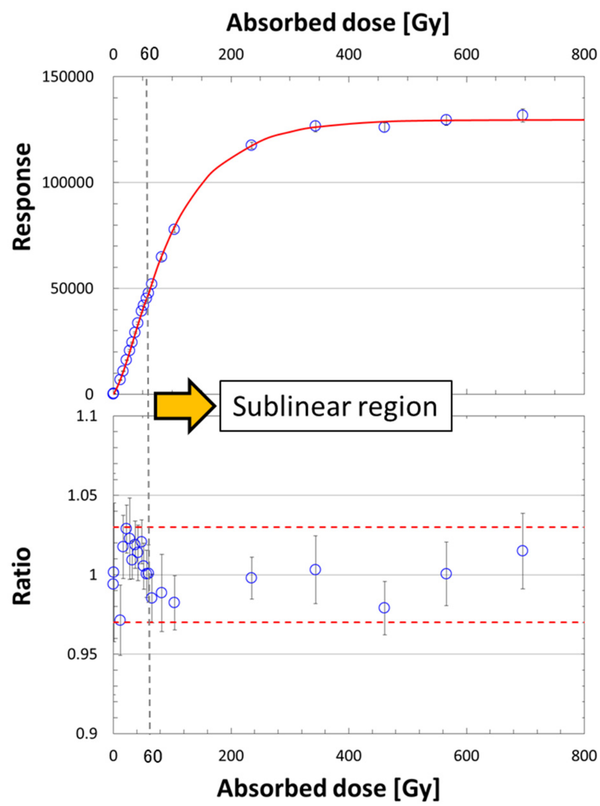

Figure 3: The relationship between the ressponse of nanoDot and the improved fitting curve. The fitting curve derived for each of the dose range were consistent with the responses of nanoDot within ±3% in all of the dose range.

122600 - 130200 from the fitting curve. At the same way, we can estimate the response of the nanoDots to be 115400 – 122600 when the nanoDots were exposed to 245 Gy. Based on the results, we concluded that the response of the nanoDots exposed to less than 245 Gy can be distinguished by that exposed to more than 350 Gy.

CONCLUSION

We examined the dose response characteristics of a commercialized optically stimulated luminescence (OSL) dosimetry system using Al_2O_3:C crystal for radiation detection material. To prevent the satulation of the signal of PMT, the exposed dosimeters, nanoDots were measured by an OSL reader, microStar inserting a neutral density filter. To reduce the uncertainty of dose response characteristics, we used the same purchase lot of nanoDots and evaluated the relationship between the accumurated doses and the responses of them with repeatedly exposures and measurements. As the results, we found that the response of nanoDots exposed to more than 350 Gy were saturated and the dose response characteristics can be approximated in ± 3% of uncertainty by a derived fitting curve. Based on the results, we concluded that we can evaluate the response of nanoDot exposed up to 245 Gy of ^{60}Co gamma-rays by commercialized dosimetry system.

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