Nuclear Instruments and Methods in Physics Research A 793 (2015) 6–11

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Time-resolved dose evaluation in an X- and gamma-ray irradiated silver-activated glass detector for three-dimensional imaging applications

T. Kurobori [a,*], H. Itoi [a], Y. Yanagida [b], Y.Q. Chen [c]

[a] Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa 920-1192, Japan
[b] Oarai Research Center, Chiyoda Technol Corporation, Oarai 311-1313, Japan
[c] China Techwin Co., Ltd, Dongguan, Guangdong 523467, China

ARTICLE INFO

Article history:
Received 24 February 2015
Received in revised form
8 April 2015
Accepted 28 April 2015
Available online 7 May 2015

Keywords:
Ag-activated phosphate glass
Time-resolved spectra
3D imaging
Radiophotoluminescence (RPL)
Passive dosimeter

ABSTRACT

Ag-activated phosphate glass based on the radiophotoluminescence (RPL) phenomenon has been used as the most commonly known RPL material and as an accumulated-type passive detector. In this work, the transient-state evaluation of the dose distributions achieved by X- and gamma-ray irradiations within the Ag-activated phosphate glass was performed using a time-resolved technique for the first time. Specifically, the blue RPL intensity ascribed to the electron-trapped Ag^0 centres as a function of the depth at the vicinity of the surface was investigated for different types of radiation and a wide range of energies. In addition, the dose distributions at each layer within the glass confirmed by the time-resolved measurement were compared with those reconstructed by a disk-type transparent glass detector based on the blue RPL with a diameter of 100 mm.

1. Introduction

A commercially available silver (Ag)-activated phosphate glass dosimeter based on the radiophotoluminescence (RPL) phenomenon is a type of passive dosimeter, which is still in demand and is frequently obligatory in radiation protection, and is recognized to possess several desirable characteristics, such as non-destructive readout capability, long-term stability against fading, a wide dynamic range and uniformity/batch homogeneity [1–3].

The basic principles for acquiring the doses and/or images using Ag-activated phosphate glass are as follows: before exposure, the Ag-activated phosphate glass consists of a substrate that contains positively charged silver ions (Ag^+) and negatively charged phosphate (PO_4^{3-}) ions. After exposure, the radiation-induced Ag-related species, mainly electron-trapped (Ag^0) and hole-trapped (Ag^{2+}) silver centres are produced within the glass. By optical pumping in the ultraviolet (UV) light, the Ag^0 and Ag^{2+} centres emit an intense blue and orange luminescence, respectively. This phenomenon is generally known as RPL [4]. As the RPL intensity is proportional to the amount of the irradiation received; therefore, it is suitable for long term personal dose monitor or environmental radiation monitor. Heating to 360 °C for 10 min following readout of the doses and/or images allows the detectors to be reused.

Other passive dosimeters based on the optically stimulated luminescence (OSL) [5], thermoluminescence (TL) [6] and photoluminescence (PL) [7] phenomena have been widely used for personal and clinical dosimetry and also used as a tool for micro radiography [8], proton beam diagnostics [9], heavy charged particle spectroscopy [10] and radionuclide imaging spectroscopy [11]. Although these types of passive luminescent dosimeters have each advantages and disadvantages, however, there have been a few detectors capable of accumulating three-dimensional (3D) images over large areas and reconstructing dose distributions within several minutes.

Recently, we proposed and demonstrated a novel disk-type two-dimensional (2D) imaging detector with the aforementioned superior characteristics of Ag-activated RPL glass for the first time [12]. In addition, we performed a comparative investigation of the 2D dose images acquired using Ag-activated phosphate glass based on the orange RPL of atomic-scale Ag-related species and those acquired using LiF thin films based on the PL of the F-aggregate colour centres (CCs). In addition, we evaluated the performances of the two detectors [13,14].

In this paper, the transient-state evaluation of dose distributions in an Ag-activated phosphate glass detector via a time-resolved spectral technique is presented for the first time to evaluate and understand accurate 3D dose imaging. Specifically,

* Corresponding author. Tel.: +81 76 264 5478; fax: +81 76 234 4132.
E-mail address: kurobori@staff.kanazawa-u.ac.jp (T. Kurobori).

http://dx.doi.org/10.1016/j.nima.2015.04.062
0168-9002/

the intensity in Ag-activated glass based on the blue and orange RPL as a function of the depth at the vicinity of the surface within the material is investigated for different types of radiation, such as X- and gamma-rays, and a wide range of energies. In addition, it is demonstrated that the use of a confocal detection system and a transparent disk-type glass detector allows one to reconstruct the 3D dose distribution by combining images collected at different depths, which are obtained using a home-made readout system [13]. Finally, a comparative investigation between the reconstructed 3D dose distribution and aforementioned time-resolved dose distribution taken as a function of the depth within the sample is demonstrated.

2. Experimental procedure

2.1. Ag-activated phosphate glass

A commercially available Ag-activated phosphate glass plate was used for the optical and imaging measurements. Although the weight composition of the material used in this study was the same as that of FD-7 (Asahi Techno Glass Co., Ltd.), i.e., 31.55% P, 51.16% O, 6.12% Al, 11.00% Na and 0.17% Ag, the size and shape were different. The detector was a disk-type plate with a diameter of 100 mm and a thickness of 1 mm. For all of the optical measurements, such as absorption, excitation, RPL and time-resolved spectra, the samples were cut into rectangular plates of a suitable size (approximately $10 \times 7 \times 1\ mm^3$) from the original glass dosimeter plate.

2.2. X- and γ-ray irradiations

X-ray irradiations were performed at room temperature (RT) using an X-ray unit, i.e., the voltages and current of the X-ray tube were 20, 30 and 40 kV and 10–20 mA, respectively, and the energies were 46 and 165 keV. The absorbed doses delivered to the samples ranged from 15 mGy to 3.0 Gy. Gamma irradiations were performed at RT using ^{137}Cs (662 keV) and ^{60}Co (1.17, 1.33 MeV) sources that delivered doses from 15 mGy to 1 Gy. The dose rate was calibrated using a commercially available detector. All of the samples were heated to 100 °C for 10 min to suppress the 'build-up' kinetics after the X- and gamma-ray irradiations [4].

2.3. Steady-state optical properties

The optical absorption was determined at RT using a Hitachi U-3900H UV–vis spectrophotometer with a 1 nm step. The RPL and excitation spectra were obtained using a Hitachi F-2500 fluorescence spectrophotometer with a 2.5 nm spectral bandwidth.

2.4. Transient-state optical properties

The time-resolved RPL spectra and decay curves for the blue and orange RPL signals were acquired using the combination of a high-repetition-rate *Q*-switched laser (Explorer One, Spectra Physics) at 349 nm and a multichannel analyser (PMA-12, Hamamatsu Photonics), as illustrated in Fig. 1. The pulse duration of the laser was less than 5 ns full-width at half-maximum (FWHM) at a repetition rate of 1 kHz for a pulse energy of 120 μJ in this work. The area of the beam on the glass sample through a rectangular metal slit ($3 \times 0.5\ mm^2$) and a cylindrical lens with a 60 mm focal length was $3 \times 0.14\ mm^2$, and the fluence was 48 $\mu J/mm^2$ (20 μJ/pulse). The time-resolved RPL spectra were measured in the wavelength range from 300 to 700 nm with a 1 ns step and a 10 ns gate time using a PMA-12 analyser equipped with an image intensifier (II). Therefore, the total temporal resolution was approximately 10 ns. The blue and orange RPL signals were acquired through a long-pass filter (#84-754, Edmund Optics) and an optical fibre. The transient-state dose distributions in the direction of the depth up to 1.0 mm within the Ag-activated phosphate glass were measured with a step of 5 μm.

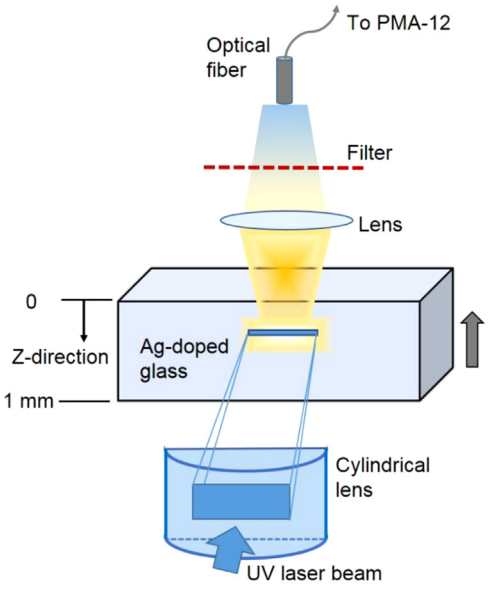

Fig. 1. Acquisition setup for the measurement of the time-resolved RPL spectra and decay curves of the X-ray-irradiated Ag-activated phosphate glass. A laser beam with a rectangular beam shape was incident on a side facet of the sample. The grey arrow indicates the sample movement direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

Typical time-resolved RPL spectra of the UV-laser irradiated glass after 693,000 excitation pulses for several pulse delays from −20 to 200 ns are presented in Fig. 2(a). Before UV exposure, the sample was irradiated with X-rays. The X-ray tube was operated at 30 kV and 20 mA with an absorbed dose of 3 Gy. For a delay less than a zero delay, the luminescence signal was indistinguishable from the background. After a zero delay, a broadband spectrum that peaked at 450 and 650 nm was observed. The orange RPL peaked at 650 nm and was attributed to the hole-trapped Ag^{2+} centres. There was another band that peaked at 450 nm, which is known as the blue RPL, and was attributed to the electron-trapped Ag^0 centres [15]. Blue and orange RPL signals were simultaneously emitted at excitation wavelengths of 349 nm and 371 nm for acquiring the time-resolved spectra and 2D and 3D imaging, respectively. The characteristic excitation peaks of the blue and orange RPL signals occurred at 345 and 310 nm, respectively.

At further delays from 3 to 150 ns, the intensity of the blue RPL band rapidly decreased, whereas the intensity of the orange RPL band progressively decreased while maintaining the same spectral shape. Plotting the RPL intensity of the bands at 450 and 650 nm versus the delay time after the pulse, as shown in Fig. 2(b), revealed the luminescence decay lifetimes. The observed lifetime values were compatible with those measured previously [16] using a fluorescence lifetime spectrometer (Quantaurus-Tau C11367-14, Hamamatsu Photonics) for X-ray irradiated glasses subjected to a dose of 1 Gy, which were found to be 4.5 and 2300 ns for the blue and orange RPL signals, respectively. Here, 'delay 0' represents the