Radiation Measurements 146 (2021) 106625

Contents lists available at ScienceDirect

Radiation Measurements

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

Thermally assisted optically stimulated luminescence protocol of mobile phone substrate glasses for accident dosimetry

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ARTICLE INFO

Keywords:
Retrospective dosimetry
Display glass
Thermally assisted optically stimulated luminescence
Signal fading
Zero dose

ABSTRACT

A thermally assisted optically stimulated luminescence protocol for the use of display glass samples from mobile phones as a fortuitous dosimeter was developed. Glass samples from 16 different mobile phones from the Samsung Galaxy series were used. The protocol consists of a prebleach with LEDs of 470 nm for 500 s and an OSL reading for 500 s at an elevated temperature. The decay curves were measured at different temperatures from 100 to 400 °C in an interval of 50 °C. A significant baseline increase in the decay curves was observed above 350 °C. For the TA-OSL below 300 °C, the dose response from 10 mGy to 10 Gy was linear and the signals were reproducible within 5% for six repeated readings. Compared with the residual thermoluminescence after an isothermal reading, the TA-OSL protocol showed lower zero doses at the given temperature. By increasing the temperature of the TA-OSL protocol from 100 to 300 °C, the minimum detectable dose increased from 17 to 70 mGy, but the fading rate reduced from 64% to 36% after 41 days from irradiation. In the optical stability test, strong reductions in TA-OSL signals were observed after exposures up to 1000 s with several light sources, and it was found that violet LEDs are more effective than blue LEDs for bleaching. As a result, the TA-OSL protocols investigated showed some improvements in terms of the lower minimum detectable doses and reduced fading rates compared with the prebleached thermoluminescence protocol.

1. Introduction

For the past decade, thermoluminescence (TL) and optically stimulated luminescence (OSL) of components from personal electronic devices have become an emerging technique in retrospective dosimetry. Some of the widely available materials include surface mount resistors (Ekendahl and Judas, 2012; Inrig et al., 2008), surface mount resonators (Beerten and Vanhavere, 2008), and integrated circuits (Sholom and McKeever, 2016) on a printed circuit board in electric devices. Moreover, display glasses (Bassinet et al., 2010; Kim et al., 2019) and smart chip cards, including subscriber identification module (SIM) cards (Pascu et al., 2013) and ID cards (Mathur et al., 2007), are other candidates. These materials and the measurement protocols for them have provided complementary techniques for dose assessment with other methods, such as biological dosimetry and electron paramagnetic resonance dosimetry (McKeever et al., 2019; Trompier et al., 2017). Dedicated dose measurement protocols are usually material specific. For instance, an OSL measurement without heat treatment is recommended for smart chip cards because of the high intrinsic background signals generated by the heat on epoxy materials (Woda and Spöttl, 2009). Also, an OSL reading is preferred for resistors because overestimation in a dose recovery test was observed when a TL measurement was conducted, making the use of a correction factor necessary (Ademola and Woda, 2017; Fiedler and Woda, 2011). On the other hand, TL is the main signal for display glasses on a mobile phone, since the glasses are always exposed to light because of the display's backlight and daylight (Discher and Woda, 2013).

Among the various fortuitous dosimeters, display glasses are one of the most actively studied materials because of their high radiation sensitivity and greater quantity than other materials, such as electronic components. In particular, the "prebleaching with blue LEDs" measurement protocol has been shown to remove significant light-sensitive signals of the TL glow curve. This protocol was found to be useful for a dose-recovery test based on the practical use of a mobile phone (Discher

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https://doi.org/10.1016/j.radmeas.2021.106625
Received 10 February 2021; Received in revised form 17 June 2021; Accepted 21 June 2021
Available online 23 June 2021

and Woda, 2013). Also, the etching of a glass surface via mechanical methods or chemical methods was used to remove intrinsic background signals (Bassinet et al., 2014; Discher et al., 2013). Because of its robustness, the protocol was successfully applied in the international interlaboratory comparison exercises held by RENEB and EURADOS (Ainsbury et al., 2017) and further evaluated in a field experiment mimicking a realistic accident scenario (Rojas-Palma et al., 2020; Waldner et al., 2021).

On the other hand, the limitation of the prebleached TL protocol lies in the difficulty of using high-temperature signals because of the presence of an intrinsic background signal, also called a *native signal*. The source of the native signal was considered to be ultraviolet (UV) illumination during the fabrication process. Although the native signal was reduced significantly after an etching with hydrofluoric acid (HF), the minimum detectable dose (MDD) was approximately 70 mGy when the 100–250 °C integration range of the glow curve was used (Discher et al., 2013). Recent studies reported that applying the phototransferred TL (PTTL) method to touchscreen glass is useful in using stable charge carriers in deep traps, which can lead to a reduction of signal fading (McKeever et al., 2017). Another study showed remarkable fading characteristics with an optimized PTTL protocol for display glass that resulted in less than 10% signal reduction 10 days after irradiation (Discher et al., 2020). However, the zero dose of the PTTL technique was expected to be high (Chandler et al., 2019). In this regard, one could face an additional challenge for new protocols because of high amount of native signals in deep traps.

In this study, we studied whether OSL at elevated temperature can be applied to assess doses of display glasses to achieve a reduced fading rate as well as lower zero dose in comparison with those of the prebleached TL protocol for display glasses. This builds on recent research on the use of thermally assisted OSL (TA-OSL) on various phosphor materials (Polymeris, 2016), including quartz (Polymeris et al., 2015). In general, the TA-OSL protocol was devised to assess the OSL signals generated from deep traps, which are difficult to reach by optical stimulations alone. Previous studies dealing with modeling and physical mechanisms of the TA-OSL process describe it as excitation of a charge carrier into an excited state of a trap by thermal stimulation; the charge carriers are then optically stimulated into the conduction band (Chen and Pagonis, 2013; McKeever et al., 1997). In addition, most studies were focused on finding the optimum thermal stimulation for TA-OSL by using OSL at different elevated temperatures (Chruścińska and ; Kalita et al., 2017).

The fundamental assumption of the present study is that the native signals in a display glass are considered as components that are hard to bleach by extremely long light exposure during personal use. Therefore, we assumed the native signals are relatively insensitive to an OSL measurement even at an elevated temperature. This means that if a suitable TA-OSL protocol is applied, traps with a thermo-optical cross section could be used for a dose estimation under the assumption that the native TL signals will not contribute to this signal as it is hard to bleach regardless of the temperature. In this work, we focus on the characterization of the TA-OSL protocol for display glasses, such as the shape of the decay curve, reproducibility, fading, zero dose distribution, and optical stability, compared with the prebleached TL protocol.

2. Materials and methods

2.1. Glass samples and sample preparation

The models of mobile phones used for the experiment were the Galaxy S3, Galaxy S5, and Galaxy Note 4 manufactured by Samsung. The target material was a display screen developed by Samsung Display, which is a so-called super active-matrix organic LED (AMOLED) display (Samsung, 2021; Samsung Display, 2019). The glass samples were obtained from 16 different mobile phones. In a previous study, two types of glass (category A and category B) depending on the glow curve and emission spectra were found in a previously investigated AMOLED sample group (Kim et al., 2019). However, only the category A glass was used in this study to confirm the consistent characteristics of the newly developed protocol. All glass samples were etched with HF for 2–5 min, depending on the sample thickness. The sample thickness after the HF etching ranged between 0.1 and 0.2 mm. After etching, the samples were cleaned with acetone and ethanol for 5 min per sample, and then they were cut into small pieces to fit into the sample cup.

2.2. Equipment

At the Korea Atomic Energy Research Institute, the luminescence signals were measured with a Risø TL/OSL DA-20 reader upgraded with a detection and stimulation head system. Built-in blue LEDs were used as light sources for optical stimulation with an intensity of 72 mW/cm^2 at a peak wavelength of 470 nm. A blue-sensitive photomultiplier tube (Electron Tube PDM9107Q-AP-TTL-03) with a 160–630 nm entrance window was combined with a UV filter (U-340, thickness 7.5 mm) with a 280–380 nm transmission window to record optical signals. All measurements were performed in a N_2 gas atmosphere, and the gas was always flushed for 120 s before heating. Irradiation of the sample was done with a built-in beta source (^{90}Sr/^{90}Y), giving around 6 mGy/s calibrated by ^{137}Cs equivalent air kerma for glass samples.

At the University of Salzburg, luminescence measurements were made with a Lexsyg Research automated reader made by Freiberg Instruments (Richter et al., 2013). For laboratory irradiation, a built-in ^{90}Sr/^{90}Y beta source (normalized activity of 1.51 MBq) was used, delivering a dose rate of approximately 59 mGy/s. The reader is equipped with an optical stimulation module containing three stimulation wavelengths: violet LEDs (405 ± 3 nm), blue LEDs (458 ± 5 nm), and infrared LEDs (850 ± 20 nm). A built-in bialkali cathode photomultiplier tube (Hamamatsu H7360-02) was used to detect the luminescence signals. Two programmable filter wheels (each filter equipped with glass and interference filters at its six positions) are located between the optical stimulation module and the photomultiplier tube detector to block scattered stimulation light during OSL measurements and thermal background signal during TL and TA-OSL measurements. The filter combination "TL-365 nm" was used, which includes a Schott KG3 (3 mm) glass filter combined with a Delta-BP 365/50 EX interference filter (center wavelength 365 nm, full width at half maximum 50 nm). Generally, all luminescence measurements were performed in a N_2 atmosphere, and the heating rate was always set to 5 °C/s to avoid significant thermal lag. Before the measurements, the glass samples were annealed; that is, by performing a TL measurement at up to 450 °C and holding the temperature for some minutes in the luminescence reader.

For the optical stability tests, which were done at the University of Salzburg, only the violet LEDs and blue LEDs were used for bleaching at room temperature before the TA-OSL measurements with an optical power of 100 mW/cm^2 for blue stimulating light and 80 mW/cm^2 for violet stimulating light at the sample position (unless otherwise stated). A disassembled but operable mobile phone (LG G5, alternative model name LG F700L) was used with access to the TFT display to simulate the bleaching effect of the internal LEDs of a mobile phone. The display brightness was set to 100% (around 400 cd/m^2 according to the specifications for the phone (Notebook Check, 2016)) and the irradiated glass samples were placed directly inside the bottom glass layer to achieve the maximum bleaching condition of the internal white backlight LEDs. Since 1 cd is defined as a luminous intensity in a given direction of a source that emits photons with a wavelength of 555 nm and has a radiant intensity in that direction of 1/683 W per unit solid angle, the optical power of the backlight at the glass sample was converted to approximately 0.37 mW/cm^2, assuming a solid angle of 2π and monochromatic photons.

To simulate sunlight exposure, a compact SOL2 solar simulator (Dr. Hönle AG, Gräfelfing, Germany), SOL2 sunlamp, including a glass filter to reduce the UV component of the lamp was used for reproducible laboratory bleaching. According to the technical data sheet (Hönle UV

Technology, 2007), the intensity of the solar simulator is 910 W/m^2 and is about six times greater than that of direct light (Aitken, 1985; Choi et al., 2009; Wang et al., 2011). The broad spectrum of the SOL2 solar simulator including the glass filter is shown in Fig. A1 in the supplementary material and was compared with the sun spectrum measured on a cloudless day in Salzburg, Austria. Both spectra were measured in the range between 354 and 1040 nm with an Ocean Optics USB4000 spectrometer (USB4C03075) including a 1 m long light guidance cable (EOSO1425-2 400, UM VIS/BX, ZFT-6674).

2.3. TA-OSL protocol and data analysis

The suggested TA-OSL protocol is shown in Table 1. The 500 s prebleach was added to preclude light-sensitive signals and to compare the signals with those for the prebleached TL protocol. The readout temperature T_i was varied from 100 to 400 °C, depending on the experiments, and a hold time of 10 s was added to stabilize the temperature more effectively. The time per data point was set to 1 s, and the net TA-OSL signal was calculated by integrating the signal from 0 to 50 s and subtracting the signal from 50 to 100 s, taken as a background signal.

An experiment to evaluate the degree of optical sensitivity of the native signals and radiation-induced signals (RISs) was performed by measuring the residual TL (RTL) immediately after a TA-OSL measurement. Among the 16 mobile phones, the display glass that showed the highest zero dose of around 150 mGy in the prebleached TL reading was selected to maximize the influence of the native signals. Also, two adjacent fresh glass samples were extracted; one for measuring RTL after a TA-OSL reading (TA-OSL sample) and the other for measuring RTL after an isothermal reading (isothermal sample). The isothermal reading is an identical measurement to the TA-OSL reading except the blue LED switched is off during the measurement. It is assumed that the zero doses of the two samples are almost identical. The details of the sequence are presented in Table 2. For the TA-OSL sample (sample 1), we obtained information such as native TA-OSL signals ($TOL1_{native}$), native RTL after a TA-OSL reading ($RTL1_{native}$), 1 Gy TA-OSL signals ($TOL1_{1\ Gy}$), 1 Gy RTL after a TA-OSL reading ($RTL1_{1\ Gy}$), and 1 Gy TL signals ($TL1_{1\ Gy}$). For the isothermal sample (sample 2), native isothermal decay signals ($ISO2_{native}$), native RTL after an isothermal reading ($RTL2_{native}$), 1 Gy isothermal decay signals ($ISO2_{1\ Gy}$), 1 Gy RTL after an isothermal reading ($RTL2_{1\ Gy}$), and 1 Gy TL signals ($TL2_{1\ Gy}$) were acquired.

The normalization using the TL signals ($TL1_{1\ Gy}$ and $TL2_{1\ Gy}$) makes it possible to compare the RTL of the two different samples. In this regard, the distribution of thermo-optically stimulated signals according to the temperature was confirmed by comparing the $RTL1_{1\ Gy}$ and $RTL2_{1\ Gy}$ glow curves. Moreover, the degree to which native TL signals are affected by the TA-OSL reading was identified by comparing the $RTL1_{native}$ and $RTL2_{native}$ glow curves. Finally, three different zero doses evaluated on the basis of the TA-OSL readings ($TOL1_{native}$ and $TOL1_{1\ Gy}$), RTL after a TA-OSL reading ($RTL1_{native}$ and $RTL1_{1\ Gy}$), and RTL after an isothermal decay measurement ($RTL2_{native}$ and $RTL2_{1\ Gy}$) were acquired. Here, the TL integration window to estimate a zero dose was selected from 100 to 450 °C.

Table 1
Experimental procedures for thermally assisted optically stimulated luminescence (TA-OSL) of display glasses.

Step	Procedure
1	Prebleach the sample with LEDs of 470 nm for 500 s at room temperature
2	Increase the sample temperature to a certain value (T_i °C, $\beta = 5$ °C/s)
3	Hold the temperature for 10 s
4	Measure the OSL at the elevated temperature (T_i) for 500 s
5	Give a regenerative dose (D_i Gy)
6	Do the same sequence from step 1 to step 4

Table 2
Experimental procedures and corresponding measurements for residual thermoluminescence (TL) of glass samples.

Step	Procedure	Abbreviations of corresponding measurements	
		Sample 1 (TA-OSL sample)	Sample 2 (isothermal sample)
1	TA-OSL reading (steps 1–4 in Table 1) or isothermal reading (TA-OSL reading without optical stimulation)	$TOL1_{native}$	$ISO2_{native}$
2	Residual TL reading up to 450 °C (β = 2 °C/s)	$RTL1_{native}$	$RTL2_{native}$
3	Irradiation (1 Gy)		
4	Repeat step 1	$TOL1_{1\ Gy}$	$ISO2_{1\ Gy}$
5	Repeat step 2	$RTL1_{1\ Gy}$	$RTL2_{1\ Gy}$
6	Irradiation (1 Gy)		
7	TL reading up to 450 °C (β = 2 °C/s)	$TL1_{1\ Gy}$	$TL2_{1\ Gy}$

TA-OSL, thermally assisted optically stimulated luminescence.

3. Results and discussion

3.1. TA-OSL decay curves

The decay curves generated by the TA-OSL protocol are shown in Fig. 1. The measurement temperature ranged from 100 to 400 °C in steps of 100 °C. Therefore, four glass samples of similar sizes were extracted from the same mobile phone. To estimate the native signals and the reproducibility of the protocol, the glass samples were initially measured without any irradiation, and then they were measured after 1 Gy irradiation for six cycles. Fig. 1(a) shows the measured TA-OSL signals at 100 °C. The native signal of the fresh sample is negligible, and the RISs have low intensity. The decay curve appears to contain only a slowly decaying component and does not reach the background level after 500 s of optical stimulation. Also, the OSL intensity increased with each measurements. Thus, it can be assumed that the TA-OSL at 100 °C is not sufficient to remove all charges, and the residual signals after one measurement contribute to the following measurement. In the case of the TA-OSL at 200 °C in Fig. 1(b), the RIS intensity is larger than in the case of the TA-OSL at 100 °C (Fig. 1(a)), showing a fast decaying component for stimulation times below 100 s. However, an overall increase in the OSL with each measurement and a signal gap between the tails of the RIS and the native signal are still seen. The decay curves are more reproducible at 300 °C as shown in Fig. 1(c), which indicates lower residual signals after the thermo-optical stimulation at 300 °C for 500 s. On the other hand, an increase in the baseline of native signals and RISs is visible. This shift in the baseline allows the native signal to match the tail region of RISs while limiting the decay of signals in less than 200 s. The situation becomes worse at 400 °C, with native signals of nearly 25,000 counts per second in Fig. 1(d), and the RISs are located below the native signal. It is speculated that the traps responsible for the faster-decaying OSL signals have been emptied by the heating process, leaving only traps that give an almost constant OSL signal. Obviously, the increase in the baseline with an increase in the readout temperature is an obstacle for utilizing charges in a deep trap. This phenomenon is known as a flat natural TA-OSL (NTA-OSL) component, which is more prominent in quartz samples, and its origin was considered as the slowly decaying component of TA-OSL (Polymeris, 2016; Polymeris et al., 2015). In addition, TA-OSL curves at 150, 250, and 350 °C are presented in Fig. A2 in the supplementary material. The tendency of the curves with increasing temperature is similar to the previous observations.

To assess the influence of the optical stimulation on a TA-OSL decay compared with an isothermal decay, decay curves were recorded with the LEDs turned on and off during the measurement, as shown in Fig. 2. TA-OSL and isothermal decay curves were measured by steps 2–5 in Table 2 with a single glass sample. Three glasses were used for readings

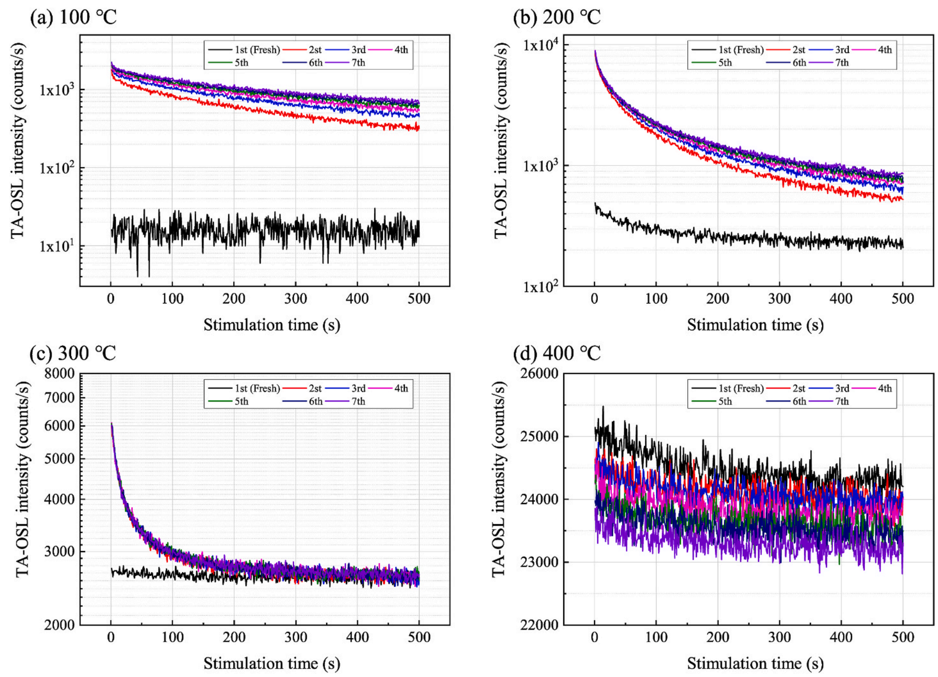

Fig. 1. Thermally assisted optically stimulated luminescence (TA-OSL) decay curves of display glasses depending on elevated temperature of (a) 100 °C, (b) 200 °C, (c) 300 °C, and (d) 400 °C. The first measurement is a native signal of the fresh sample without irradiation and the second to seventh measurements are signals after 1 Gy irradiation for the repeated TA-OSL measurements.

at 100, 200, and 300 °C. It was observed that the isothermal decay signal increased with the temperature, showing a contribution of the pure thermal stimulation to the TA-OSL signals. However, the contribution was significant only at higher temperature, since the integration of TA-OSL signals was about 13, 8, and 3 times higher than for the isothermal decay at 100, 200, and 300 °C, respectively. Moreover, the NTA-OSL effect is not shown in the isothermal decay in Fig. 2(c).

3.2. Reproducibility and dose response

Despite the high, flat NTA-OSL signals for readout temperatures above 300 °C, the reproducibility and dose response were investigated for different readout temperatures. The reproducibility of the OSL at different elevated temperatures for six recordings with a 1 Gy test dose is shown in Fig. 3. As expected, the TA-OSL for readout temperatures above 350 °C showed highly scattered points, with more than 30% difference at the maximum. The signal variations of around 5% for the TA-OSL at 100 °C are mainly due to the residual signals and low intensities. Readouts at the other temperatures (150, 200, 250, and 300 °C) result in a uniform intensity with a difference of less than 2% with respect to the initial signal despite the increase observed in the residual signals and the baseline.

The dose responses from approximately 10 mGy to 10 Gy for all readout temperatures are reported in Fig. 4. Most cases showed highly linear responses, except for those with readout temperatures of 350 and 400 °C. These results imply that the increase in the baseline is the dominant constraint in utilizing the charges located in high-temperature traps. Nevertheless, the readout temperatures from 100 to 300 °C are considered as promising candidates for achieving an optimal TA-OSL protocol.

Meanwhile, the detection limits of the TA-OSL protocol were roughly evaluated by means of the dose response curves as shown in Table 3. The samples used for each readout temperature in Fig. 4 were remeasured 10 times without irradiation, and the detection limit was calculated by dividing 3σ of the blank signals by the sensitivity (the slope of the calibration curve) (Long and Winefordner, 1983). In the case of TA-OSL at 400 °C, the slope of the dose response curve was not linear. These detection limits are for a single glass sample and can vary depending on the number and the area of the glass samples used.

Regardless of the readout temperature, the whole measurement time of the suggested protocol shown in Table 1 exceeds 2000 s, even when only a single calibration dose is used. In an emergency, a long measurement time will limit a rapid triage, and consequently it is important to optimize the measurement time. Since the integration window is less than 100 s, we varied the optical stimulation time from 100 to 500 s, and the corresponding reproducibility is compared with that for a measurement time of 100 s followed by a 450 °C thermal reset (annealing) in Fig. 5.

Fig. 5(a), (b), and (c) presents the reproducibility of the TA-OSL signals at 100, 200, and 300 °C, respectively, normalized to the first measurement. In most cases, it is concluded that the optical stimulation from 100 to 300 s is not sufficient to remove residual signals, if the readout cycles are compared with the protocol with the thermal reset, showing differences of 5%–20% from the initial signal. Only the stimulation time of 500 s was competitive with the stimulation time of 100 s with the thermal reset, which shows less than 5% difference for all readout cycles. Therefore, a reduction in the measurement time is generally possible by applying a readout time of 100 s and a thermal reset using a high heating rate of more than 5 °C/s. Nevertheless, for the following measurements, an optical stimulation time of 500 s was selected because the uniform reproducibility was confirmed and the high-temperature effect on the TA-OSL signal has not been investigated yet.

3.3. RTL comparison

RTL glow curves such as the $RTL1_{native}$ and $RTL1_{1\ Gy}$ curves of a TA-OSL sample and the $RTL2_{native}$ and $RTL2_{1\ Gy}$ curves of an isothermal sample (see Table 2) are presented in Fig. 6. Three fresh sample pairs were used for measurements at 100, 200, and 300 °C. Since each glass sample has different sensitivity because of its size and thickness, all the TL signals ($TL1_{1\ Gy}$ and $TL2_{1\ Gy}$ in Table 2) were normalized to the signal of the TA-OSL sample used for Fig. 6(a). Therefore, all corresponding RTL signals were rescaled according to its TL sensitivity normalization

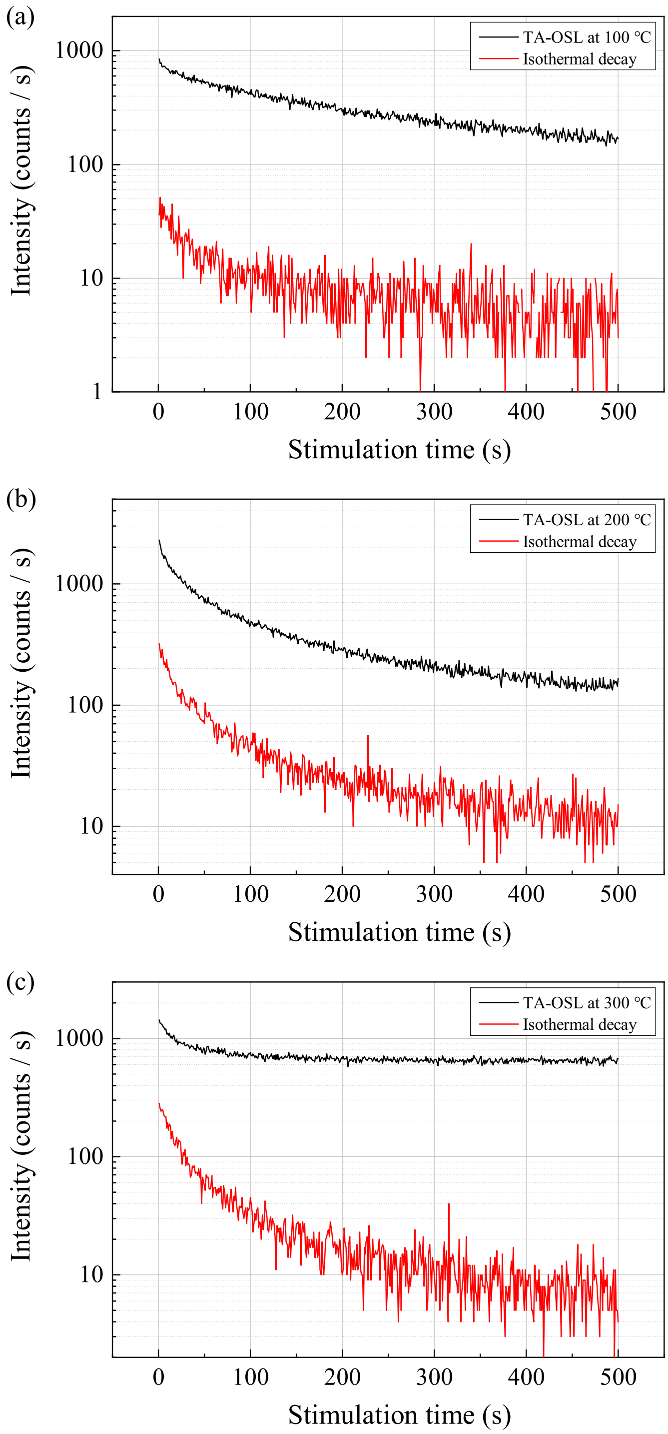

Fig. 2. Comparison of thermally assisted optically stimulated luminescence (TA-OSL) and isothermal decay curves of a display glass at (a) 100 °C, (b) 200 °C, and (c) 300 °C. Samples were irradiated with 1 Gy before the measurement and thermally annealed at 450 °C after the measurement.

factors for comparison.

First of all, the distributions of the native signals in the RTL are almost unchanged whether the TA-OSL is applied or not. In contrast, the difference between the $RTL1_{1\ Gy}$ and $RTL2_{1\ Gy}$ curves shows an obvious impact of the TA-OSL reading on the 1 Gy RISs, and it is observed that the thermo-optically stimulated charges corresponding to the difference between the two curves are distributed over the whole temperature range. Besides, the optical stimulation process become more efficient as the temperature increases since the signal ratios of $RTL1_{1\ Gy}$ to $RTL2_{1\ Gy}$ decrease from 65% to 45% when the readout temperature is increased from 100 to 300 °C. As we hypothesized, the result implies that the traps responsible for the native TL signals have a lower thermo-optical cross section than those responsible for the RISs. On the other hand, the $RTL2_{1\ Gy}$ curves, which indicate all available charges for a dose reconstruction, are significantly reduced in the integrated intensity by 44% at 200 °C and 93% at 300 °C compared with the curve at 100 °C.

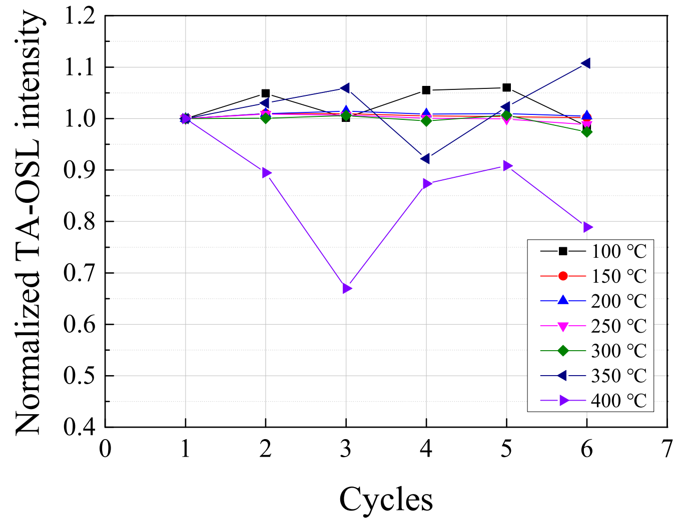

Fig. 3. Reproducibility of the thermally assisted optically stimulated luminescence (TA-OSL) signals of display glasses at different readout temperatures for the six measurement and irradiation cycle with a 1 Gy test dose.

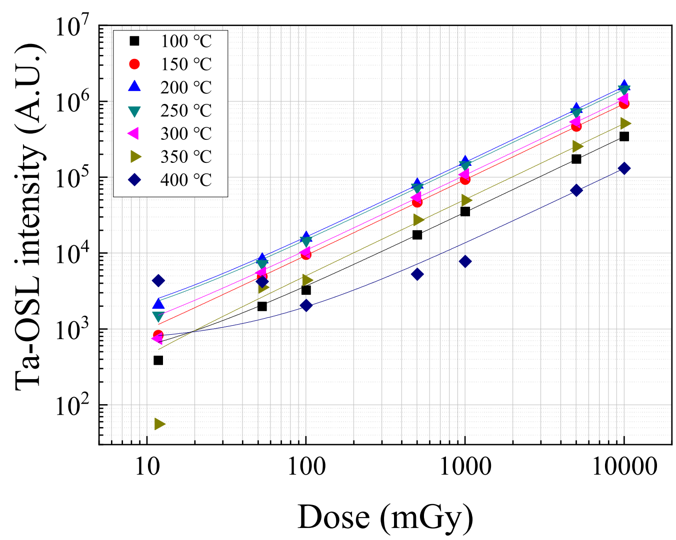

Fig. 4. Dose responses of the thermally assisted optically stimulated luminescence (TA-OSL) of display glasses for different readout temperatures from 100 to 400 °C.

Table 3
Detection limits of the TA-OSL protocol at different readout temperatures.

Readout Temperature	100 °C	150 °C	200 °C	250 °C	300 °C	350 °C
Detection limits (mGy)	7	6	4	8	28	85

For quantitative analysis, zero doses evaluated by different protocols at different elevated temperatures were compared. Although zero doses were similar between adjacent glass samples, Kim et al. (2019) observed

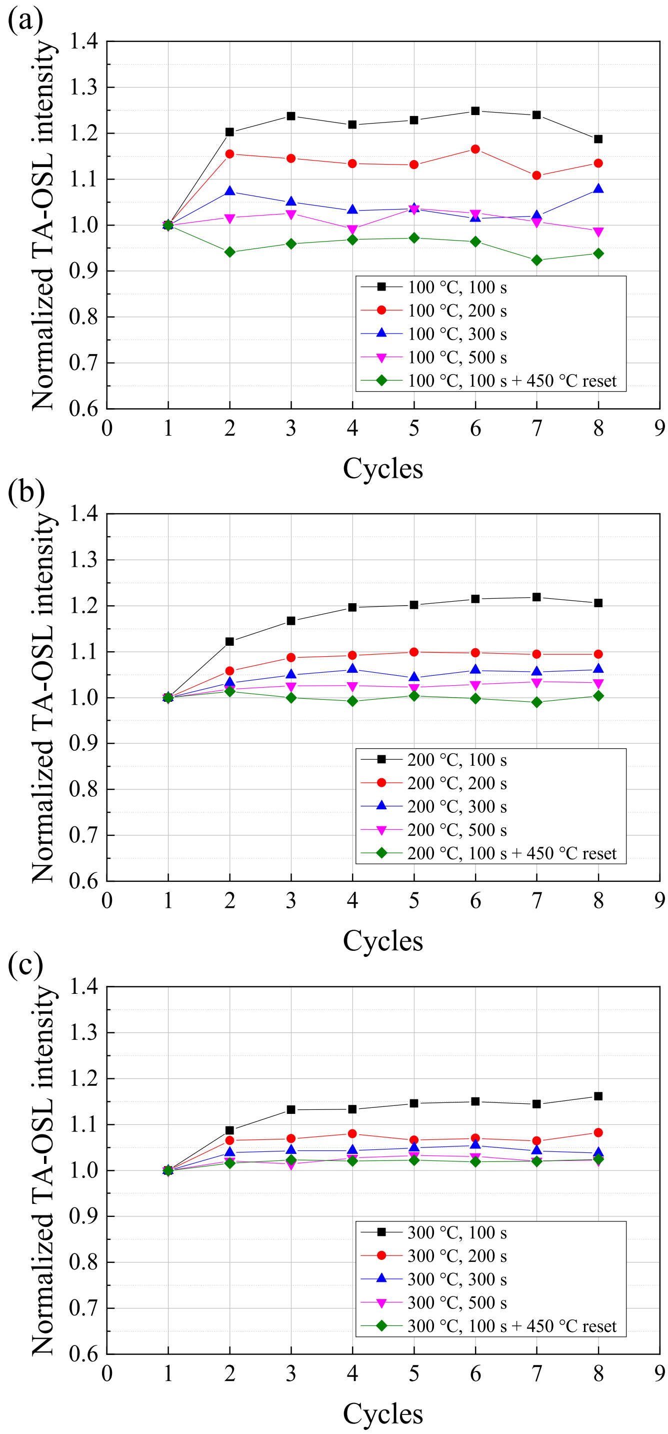

Fig. 5. Signal reproducibility of display glasses according to the optical stimulation time of the thermally assisted optically stimulated luminescence (TA-OSL) at (a) 100 °C, (b) 200 °C, and (c) 300 °C for eight measurement and readout cycle with a 1 Gy test dose. The stimulation time was varied from 100, 200, 300, and 500 s and a 450 °C thermal reset after 100 s stimulation was included as a reference.

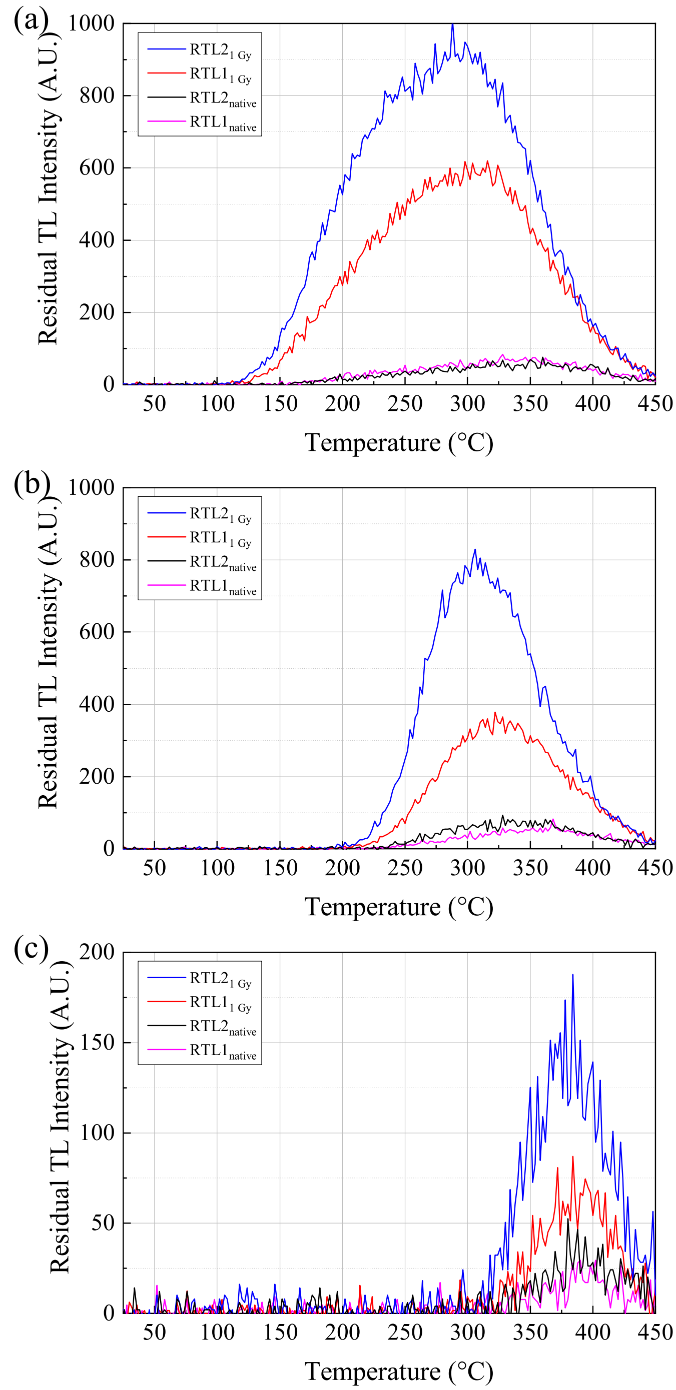

Fig. 6. Residual thermoluminescence (TL) glow curves after a thermally assisted optically stimulated luminescence (TA-OSL) or isothermal reading at (a) 100 °C, (b) 200 °C, and (c) 300 °C. $RTL2_{1\ Gy}$ is the 1 Gy residual TL after an isothermal reading, $RTL1_{1\ Gy}$ is the 1 Gy residual TL after a TA-OSL reading, $RTL2_{native}$ is the native residual TL after an isothermal reading, and $RTL1_{native}$ is the native residual TL after a TA-OSL reading in Table 2. All the glow curves were rescaled by normalization using 1 Gy TL signals of applied glass samples.

deviations depending on the location of the glass sample on the display screen. Hence, for a given elevated temperature, three sample pairs were extracted from the top, middle, and bottom of the display screen, and corresponding zero doses were averaged (Table 4). The zero doses of the TA-OSL protocol ranged from 16 to 30 mGy, which are significantly lower than for other protocols. On the other hand, the RTL signals after the TA-OSL reading are assumed to be produced mainly by traps with thermal cross sections where native signals are dominant. Therefore, their zero doses are relatively high, ranging from 152 to 305 mGy. When we calculate the zero doses using the RTL signals after the isothermal reading, the values are around 85–237 mGy, and they are located between the zero doses of the two previously mentioned protocols at the given reading temperature. This is because the RTL signals after the isothermal reading are generated by both traps having thermal and thermo-optical cross sections similar to a normal TL reading. The zero

Table 4
Zero doses (mGy) evaluated by the different protocols in Table 2.

Temperature (°C)	Protocol		
	TA-OSL	RTL after TA-OSL reading	RTL after isothermal reading
100	16	152	85
200	23	157	105
300	30	305	237

RTL, residual thermoluminescence; TA-OSL, thermally assisted optically stimulated luminescence.

doses in Table 4 were calculated by integrating the TL glow curve from 100 to 450 °C, in contrast to the narrower integration range of 100–250 °C of the prebleached TL protocol.

3.4. Zero dose

Fig. 7 shows the zero doses calculated for the various readout temperatures. The seven glass samples (one for each readout temperature) were extracted from locations close to each other from the same mobile phone display. To estimate the measurement error, the OSL decay curves were assumed to correspond to a weak OSL signal (Li, 2007) and the noise component was extracted from 50 s of the tail of each decay curve. The zero dose had the lowest value of around (2 ± 3) mGy at 100 °C, which was still in an acceptable range of less than 40 mGy for readout temperatures below 300 °C. On the basis of the detection limits in Section 3.2, the significant low zero dose of 2 mGy of the TA-OSL at 100 °C is considered to be an artifact, and the other measurements are above the detection limits. A rapid increase was found for readout temperature above 350 °C, and the maximum value recorded was (1040 ± 280) mGy at 400 °C. This rapid increase is consistent with the high, flat NTA-OSL reported in Fig. 1. Hence, the optimal readout temperatures for the TA-OSL signals were selected as 100, 200, and 300 °C.

In Fig. 8, the distribution of the zero dose for 16 mobile phones is shown according to the different readout temperatures. Each sample was taken from a random location on the display glass. Some samples showed a lower zero dose at 300 °C than at 200 °C, such samples 2, 4, 7, 10, and 16. Especially, sample 7 exhibits a negative value. The main reason is that the lower intensity of TA-OSL at 300 °C results in high scattering of data points. Moreover, the selection of signal integration window (integration of 0–50 s and subtraction of 50–100 s) is probably

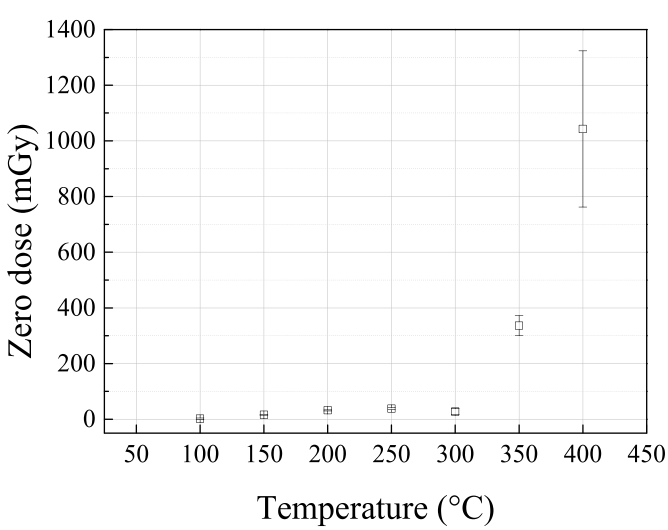

Fig. 7. Zero doses of display glasses according to the elevated readout temperatures of the thermally assisted optically stimulated luminescence protocol. The glass samples were collected from adjacent locations on the same mobile phone display and a test dose of 1 Gy was used.

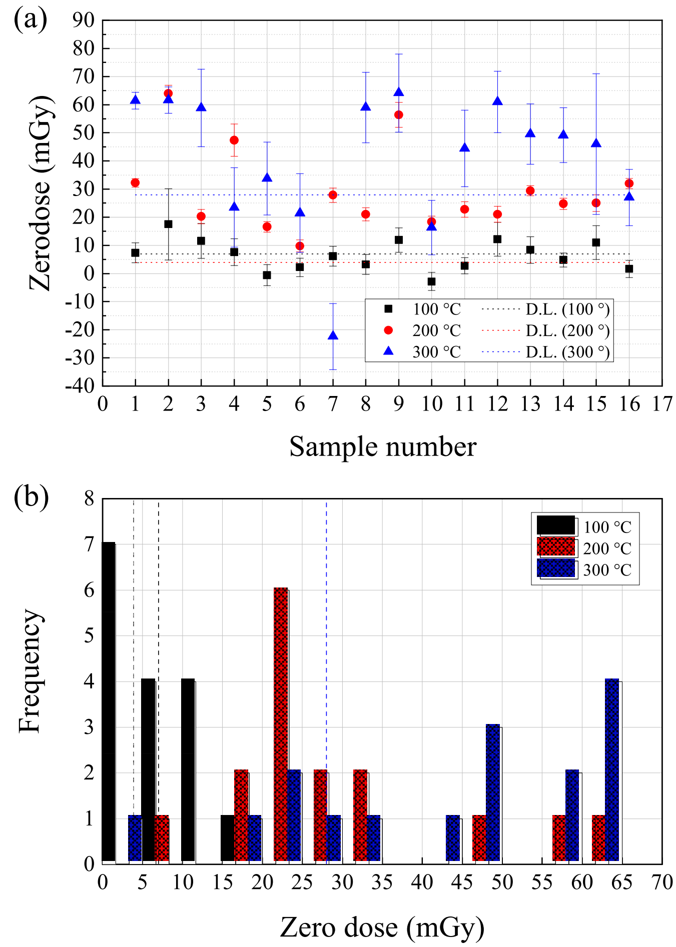

Fig. 8. (a) Zero doses of display glasses from 16 mobile phones according to the different elevated readout temperatures of the thermally assisted optically stimulated luminescence protocol and (b) the corresponding histogram with a 5 mGy bin size. A calibration dose of 1 Gy was applied. The detection limits (D. L.) were calculated from the dose response curves in Fig. 4 and are shown as colored dotted lines (black for 100 °C, red for 200 °C, and blue for 300 °C). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

not optimized for the TA-OSL protocol. The average zero doses and MDDs depending on the readout temperatures are shown in Table 5. The MDD was calculated as 3σ of the zero dose distribution. The estimated MDD at 200 °C results mainly from a variable zero dose signal since the distribution of zero doses is beyond the detection limit. However, some zero doses of the TA-OSL at 100 °C and TA-OSL at 300 °C are below the detection limit, indicating that their MDDs are affected by the insufficient sensitivity of an OSL measurement.

3.5. Signal fading

Two separate measurements were performed for the signal fading of the TA-OSL protocol. First, three samples from the same mobile phone were selected and measured with the readout temperatures of 100, 200, and 300 °C from 1 s to 600 h after 1 Gy irradiation (Fig. 9). Second, 15

Table 5
Averaged zero doses and MDDs of the TA-OSL protocol at different readout temperatures.

Readout Temperature	100 °C	200 °C	300 °C
Average zero dose (mGy)	7	29	41
MDD (mGy)	16	44	70

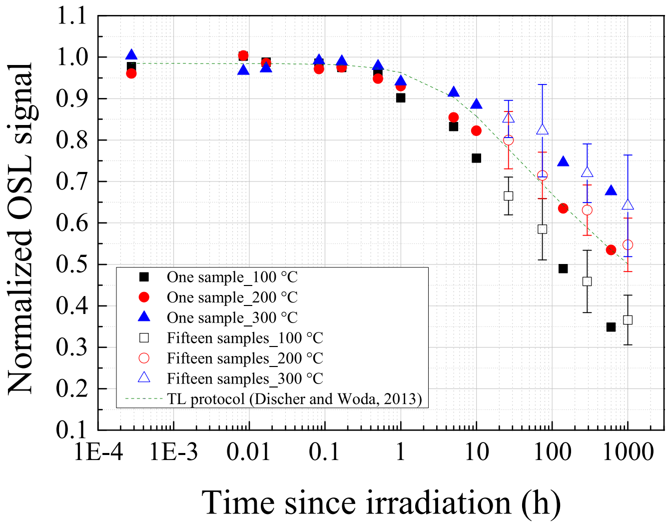

Fig. 9. Fading rates of one glass sample (filled symbols) and 15 glass samples (open symbols) according to the different elevated temperatures of the thermally assisted optically stimulated luminescence (TA-OSL) protocol with a 1 Gy test dose. The olive colored dotted line is referred from the fading curve of the pre-bleached thermoluminescence (TL) protocol (Discher and Woda, 2013).

glass samples from different mobile phones were used to estimate the statistical behaviors with regard to four different fading times of 1, 3, 12, and 41 days with the three elevated temperatures. All samples were annealed at up to 450 °C before irradiation. In Fig. 9 the open symbols and the corresponding error bars indicate the average fading rates of the 15 glass samples and the corresponding standard deviations depending on the readout temperatures and fading times. The trends of the averaged fading points are well aligned with the single fading curves taking into account the error bars. The averaged remaining signals after 41 days are increased from 36% to 64% as increased the readout temperature from 100 to 300 °C. In addition, the relative errors increased with increasing fading time. For instance, the relative errors were ranged around 5–9% for 1 day after the irradiation, and they were around 12–19% for 41 days after the irradiation. The uncertainty is higher than for the prebleached TL protocol (Discher and Woda, 2013). This observation is explained by the larger data scattering due to the lower signal in comparison to the TL reading.

For the different readout temperatures of the individual samples, the fading curves show different characteristics. The results are compared with the fading rate of the prebleached TL protocol, which is added to Fig. 9 as an olive-colored dotted line. In general, the integration window of the prebleached TL protocol is considered from 100 to 250 °C to have a reasonable MDD, and the fading rate is around 53% for 600 h after irradiation (Discher and Woda, 2013). The TA-OSL at 100 °C has stronger fading characteristics than the prebleached TL protocol. It can be speculated that the traps with a higher thermo-optical cross section are more unstable than the traps with only a thermal cross section. The fading rates become comparable for the TA-OSL at 200 °C, and a slower rate are observed for the TA-OSL at 300 °C.

3.6. Optical stability

The TA-OSL protocol developed for three different readout temperatures (100, 200, and 300 °C) were studied with regard to the optical stability of the TA-OSL signal. Various light sources, such as blue (470 nm) LEDs, violet (405 nm) LEDs, a backlight unit of a mobile phone, and a solar simulator, were applied. Although it does not have a significant impact on the results, the detection window of the optical stability test is from 340 to 390 nm (TL-365 nm filter combination) and the range is slightly different from that for the previous measurements from 280 to 380 nm (U-340 filter). The prebleach in step 1 in Table 1 was excluded from the first test to identify the bleaching capability of different light sources but was included in the second test to determine the optical stability of remaining signals. The bleaching durations were 100, 250, 500, and 1000 s, and the signals were normalized to the unbleached signals after the same pause of 1000 s between the end of irradiation (1 Gy test dose) and the start of the TA-OSL measurement to avoid the influence of signal fading.

Fig. 10 shows the bleaching capability of the different LEDs of the reader. Generally, a significant decay of TA-OSL signals is observed with increasing bleaching times. The bleaching effect is stronger for the violet LEDs, showing a remaining signal of less than 15% after 1000 s of illumination for the TA-OSL at 300 °C compared with around 40% for the same readout temperature when blue LEDs are used. In addition, a more effective bleaching was identified when a lower elevated readout temperature was used for both LEDs. As a result, the bleaching capability of the built-in LEDs was a more than 80% signal reduction for a bleaching time of 500 s, except for the combination of the TA-OSL at 300 °C and blue LEDs. On the other hand, it is interesting to note that there are still signal reductions between 500 and 1000 s for all measurements as shown in Table 6.

The optical stability was investigated with other light sources, such

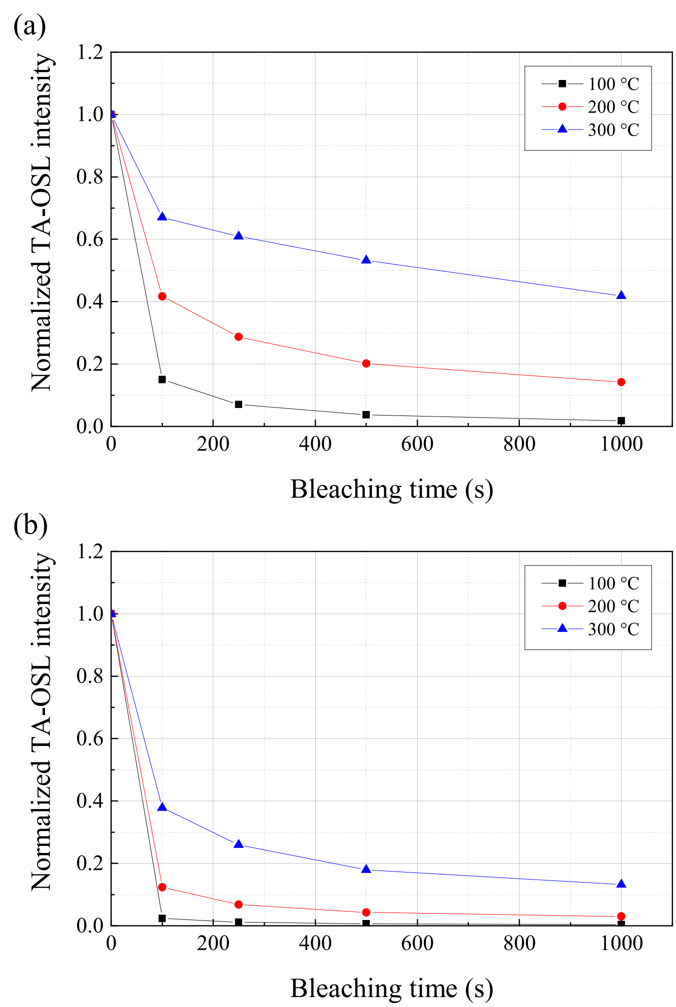

Fig. 10. Bleaching capability of the (a) 470 nm blue (100 mW/cm^2) and (b) 405 nm violet (80 mW/cm^2) LEDs with regard to thermally assisted optically stimulated luminescence (TA-OSL) signals according to the bleaching time. The readout temperature of the protocol was varied and the 500 s prebleach with light with a wavelength of 470 nm in the proposed TA-OSL protocol was excluded. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 6
Signal reduction ratios for a bleaching time between 500 and 1000 s according to the readout temperatures and the bleaching LEDs.

Readout Temperature	100 °C	200 °C	300 °C
Signal ratio at 470 nm (%)	48	70	78
Signal ratio at 405 nm (%)	54	70	74

as a SOL2 solar simulator and the backlight unit of a mobile phone display. Both light sources are relevant during routine use of a mobile phone, and the results for a bleaching time of 500 s are given in Table 7. Each result shown is the average value of three different glass samples with the calculated standard deviation. The results indicate that the bleaching effect of the TA-OSL signal is probably negligible for the internal background lighting of the phone display compared with the effect of the solar simulator. The bleaching effect of the SOL2 solar simulator demonstrates a strong signal reduction, especially for the TA-OSL at 100 °C. The difference in signal reduction between the backlight unit and the solar simulator is assumed to be because of the stronger optical power and UV components of the light source. The glass substrate is not directly exposed to sunlight in normal use of a mobile phone, and further tests are necessary to simulate the real bleaching effect of the solar simulator for an intact phone.

3.7. Comparison with the prebleached TL protocol

Since the prebleaching with 470 nm LEDs for 500 s is the same preprocess for the TA-OSL protocol developed here and the prebleached TL protocol (Discher and Woda, 2013), a comparison of the two protocols can be done for the same available signal. Both protocols exhibit high linearity in the dose response and high reproducibility (Discher and Woda, 2013). Moreover, the calculated MDDs of TA-OSL measurements ranged from 17 to 70 mGy with increasing readout temperature, and these results are quite promising in comparison with the MDD of the prebleached TL protocol, which is about 100 mGy for a similar sample group (Kim et al., 2019). In terms of signal fading, there were no outstanding enhancements for readout temperatures below 200 °C, and the TA-OSL at 300 °C had the better fading characteristic. Because of these behaviors, it is considered that the TA-OSL protocol, according to temperature, can be applied complementarily depending on the time after exposure. For instance, a dose assessment with a lower MDD is possible through the TA-OSL at 100 °C within several weeks after exposure, and enhanced fading characteristics can be obtained through the TA-OSL at 300 °C after several months from the exposure.

Optical stability is a crucial part for a dose reconstruction for the display glass of mobile phones because the display glass is illuminated by a backlight unit as well as sunlight after exposure. Although the prebleach leaves the same available signal for both protocols (TA-OSL and prebleached TL), the TA-OSL protocol uses more light-sensitive signals, which results in the lower optical stability reported in Section 3.6. However, the light sources used in the optical stability test were extreme cases with high intensity and a long illumination time. Besides, a signal reduction of around 20% was also observed in the prebleached TL protocol with a bleaching time between 500 and 1000 s (Discher and Woda, 2013), which is approximately the same ratio between 500 and 1000 s bleaching of blue LEDs for the TA-OSL at 200 °C and TA-OSL at 300 °C in Table 6. Therefore, a new prebleach for TA-OSL should not only be optimized but its validated effectiveness should also be evaluated in the practical use of a mobile phone after exposure. Moreover, as can be seen in Table 7, the main factor affecting the low optical stability of TA-OSL is UV components. Therefore, the influence of UV light on a display glass through several upper layers such as a touchscreen glass and a polarization filter should be identified.

Table 7
Relative residual signals after 500 s bleaching of exposed samples (1 Gy). The average value of three samples and the standard deviation (1σ) is given. The estimates of the optical powers at the sample position are given.

Protocol used	Light source used for signal bleaching (500 s duration)	
	Mobile phone display (0.37 mW/cm^2)	SOL2 solar simulator (91 mW/cm^2)
TA-OSL at 100 °C	(97 ± 18) %	(21 ± 4) %
TA-OSL at 200 °C	(97 ± 18) %	(67 ± 22) %

TA-OSL, thermally assisted optically stimulated luminescence.

4. Conclusions

In the present study, the TA-OSL of display glass samples was evaluated and tested as a new protocol for dose reconstruction in a radiation emergency scenario. Various elevated readout temperatures from 100 to 400 °C were studied, and the inherent flat NTA-OSL was one of the main constraints for the exploitation of charge carriers in a deep trap above 350 °C. On the other hand, the TA-OSL signals indicate a linear dose response and high reproducibility for readout temperatures below 300 °C. Moreover, the native signals were relatively insensitive to the TA-OSL because the native signals in a display glass were sufficiently bleached because of the long-time use of a mobile phone. Therefore, significantly lower MDDs ranging from 16 to 70 mGy were achieved with the new TA-OSL protocol compared with the prebleached TL protocol, and the fading rates ranged between 36% and 64% for 41 days after irradiation depending on the readout temperature of the TA-OSL protocol. On the other hand, some limitations of the protocol were observed in the optical stability of the TA-OSL signal. Since the protocol utilizes trap charges having a thermo-optical cross section, the charges induced by irradiation are sensitive to external light sources. Therefore, additional optimization is still required for the protocol (i.e., the prebleaching step can be optimized with a stronger light source and different wavelengths to get a more optically stable TA-OSL signal). Moreover, the prebleach should be studied in a dose recovery test under real use after radiation exposure. Another limitation of the present study is that only a single category of glass samples extracted from an obsolete mobile phone model was used. The protocol needs to be verified for various glass samples from other brands and models. Nevertheless, the results suggest that the TA-OSL protocol is worth investigating because of the improvements compared with the prebleached TL protocol.

The TA-OSL protocol developed in this study opens the possibility of additional applications for dose reconstructions. It may be applicable to other components of the phone, such as touchscreen glasses, which show limits of use due to a high intrinsic background (Chandler et al., 2019; Discher et al., 2016; Kim et al., 2019). Also, by applying the TA-OSL protocol at different temperatures for the same substance, various information, such as a low dose estimation by low MDDs and long-term evaluation by low fading rates, can be obtained.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The study was conducted mainly under the National Long- & Intermediate-Term Project of the Nuclear Energy Development of the Ministry of Science and ICT, Republic of Korea (no. 2017M2A8A4015255) and the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONs) (no.

1803014). The scientific cooperation was partially conducted in the framework of the Eurasia-Pacific UNINET network and was partially funded by funds of the Federal Ministry of Education, Science and Research (BMBWF), Austria (project period 2019–2020), and the international collaboration between the Korea Atomic Energy Research Institute, the University of Salzburg, and Helmholtz Zentrum München was supported by an EURADOS young scientist grant (2019). The authors express special thanks to the two reviewers and associated editor for their dedicated review.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radmeas.2021.106625.

References

Ademola, J.A., Woda, C., 2017. Thermoluminescence of electronic components from mobile phones for determination of accident doses. Radiat. Meas. 104, 13–21.
Ainsbury, E., Badie, C., Barnard, S., Manning, G., Moquet, J., Abend, M., Antunes, A.C., Barrios, L., Bassinet, C., Beinke, C., Bortolin, E., Bossin, L., Bricknell, C., Brzoska, K., Buraczewska, I., Castano, C.H., Cemusova, Z., Christiansson, M., Cordero, S.M., Cosler, G., Monaca, S.D., Desangles, F., Discher, M., Dominguez, I., Doucha-Senf, S., Eakins, J., Fattibene, P., Filippi, S., Frenzel, M., Georgieva, D., Gregoire, E., Guogyte, K., Hadjidekova, V., Hadjiiska, L., Hristova, R., Karakosta, M., Kis, E., Kriehuber, R., Lee, J., Lloyd, D., Lumniczky, K., Lyng, F., Macaeva, E., Majewski, M., Vanda Martins, S., McKeever, S.W., Meade, A., Medipally, D., Meschini, R., M'Kacher, R., Gil, O.M., Montero, A., Moreno, M., Noditi, M., Oestreicher, U., Oskamp, D., Palitti, F., Palma, V., Pantelias, G., Pateux, J., Patrono, C., Pepe, G., Port, M., Prieto, M.J., Quattrini, M.C., Quintens, R., Ricoul, M., Roy, L., Sabatier, L., Sebastia, N., Sholom, S., Sommer, S., Staynova, A., Strunz, S., Terzoudi, G., Testa, A., Trompier, F., Valente, M., Hoey, O.V., Veronese, I., Wojcik, A., Woda, C., 2017. Integration of new biological and physical retrospective dosimetry methods into EU emergency response plans - joint RENEB and EURADOS inter-laboratory comparisons. Int. J. Radiat. Biol. 93, 99–109.
Aitken, M.J., 1985. Thermoluminescence Dating. Academic Press, London.
Bassinet, C., Trompier, F., Clairand, I., 2010. Radiation accident dosimetry on glass by TL and EPR spectrometry. Health Phys. 98, 400–405.
Bassinet, C., Pirault, N., Baumann, M., Clairand, I., 2014. Radiation accident dosimetry: TL properties of mobile phone screen glass. Radiat. Meas. 71, 461–465.
Beerten, K., Vanhavere, F., 2008. The use of a portable electronic device in accident dosimetry. Radiat. Protect. Dosim. 131, 509–512.
Chandler, J., Sholom, S., McKeever, S., Hall, H., 2019. Thermoluminescence and phototransferred thermoluminescence dosimetry on mobile phone protective touchscreen glass. J. Appl. Phys. 126, 074901.
Check, Notebook, 2016. LG G5 smartphone review. https://www.notebookcheck.net/LG-G5-Smartphone-Review.165016.0.html. (Accessed 23 April 2021).
Chen, R., Pagonis, V., 2013. Modeling TL-like thermally assisted optically stimulated luminescence (TA-OSL). Radiat. Meas. 56, 6–12.
Choi, J., Murray, A., Cheong, C.-S., Hong, S., 2009. The dependence of dose recovery experiments on the bleaching of natural quartz OSL using different light sources. Radiat. Meas. 44, 600–605.
Chruścińska, A., Przegiętka, K.R., 2010. The influence of electron–phonon interaction on the OSL decay curve shape. Radiat. Meas. 45, 317–319.
Discher, M., Woda, C., 2013. Thermoluminescence of glass display from mobile phones for retrospective and accident dosimetry. Radiat. Meas. 53–54, 12–21.
Discher, M., Woda, C., Fiedler, I., 2013. Improvement of dose determination using glass display of mobile phones for accident dosimetry. Radiat. Meas. 56, 240–243.
Discher, M., Bortolin, E., Woda, C., 2016. Investigations of touchscreen glasses from mobile phones for retrospective and accident dosimetry. Radiat. Meas. 89, 44–51.
Discher, M., Woda, C., Lee, J., Kim, H., Chung, K., Lang, A., 2020. PTTL characteristics of glass samples from mobile phones. Radiat. Meas. 132, 10621.
Ekendahl, D., Judas, L., 2012. Retrospective dosimetry with alumina substrate from electronic components. Radiat. Protect. Dosim. 150, 134–141.
Fiedler, I., Woda, C., 2011. Thermoluminescence of chip inductors from mobile phones for retrospective and accident dosimetry. Radiat. Meas. 46, 1862–1865.
Hönle, UV Technology, 2007. Simulation of natural sunlight. http://www.yuanch.com/pdf/hoenle%20sol2.pdf. (Accessed 26 April 2021).
Inrig, E.L., Godfrey-Smith, D.I., Khanna, S., 2008. Optically stimulated luminescence of electronic components for forensic, retrospective, and accident dosimetry. Radiat. Meas. 43, 726–730.
Kalita, J.M., Chithambo, M.L., Polymeris, G.S., 2017. Thermally-assisted optically stimulated luminescence from deep electron traps in α-Al_2O_3:C,Mg. Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 403, 28–32.
Kim, H., Kim, M.C., Lee, J., Chang, I., Lee, S.K., Kim, J.-L., 2019. Thermoluminescence of AMOLED substrate glasses in recent mobile phones for retrospective dosimetry. Radiat. Meas. 122, 53–56.
Li, B., 2007. A note on estimating the error when subtracting background counts from weak OSL signals. Ancient TL 25, 9–14.
Long, G.L., Winefordner, J.D., 1983. Limit of detection. A closer look at the IUPAC definition. Anal. Chem. 55, 712A–724A.
Mathur, V.K., Barkyoumb, J.H., Yukihara, E.G., Göksu, H.Y., 2007. Radiation sensitivity of memory chip module of an ID card. Radiat. Meas. 42, 43–48.
McKeever, S.W.S., Bøtter-Jensen, Agersnap Larsen, N., Duller, G.A.T., 1997. Temperature dependence OF OSL decay curves experimental and theoretical aspects. Radiat. Meas. 27, 161–170.
McKeever, S.W.S., Minniti, R., Sholom, S., 2017. Phototransferred thermoluminescence (PTTL) dosimetry using Gorilla ® glass from mobile phones. Radiat. Meas. 106, 423–430.
McKeever, S.W.S., Sholom, S., Chandler, J.R., 2019. A comparative study of EPR and TL signals in Gorilla(R) glass. Radiat. Protect. Dosim. 186, 65–69.
Pascu, A., Vasiliniuc, S., Zeciu-Dolha, M., Timar-Gabor, A., 2013. The potential of luminescence signals from electronic components for accident dosimetry. Radiat. Meas. 56, 384–388.
Polymeris, G.S., 2016. Thermally assisted OSL (TA-OSL) from various luminescence phosphors; an overview. Radiat. Meas. 90, 145–152.
Polymeris, G.S., Şahiner, E., Meriç, N., Kitis, G., 2015. Experimental features of natural thermally assisted OSL (NTA-OSL) signal in various quartz samples; preliminary results. Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 349, 24–30.
Richter, D., Richter, A., Dornich, K., 2013. Lexsyg—a new system for luminescence research. Geochronometria 40, 220–228.
Rojas-Palma, C., Woda, C., Discher, M., Steinhäusler, F., 2020. On the use of retrospective dosimetry to assist in the radiological triage of mass casualties exposed to ionising radiation. J. Radiol. Prot. 40, 1286.
Samsung Display, 2019~2010. Samsung Display | company profile - history. https://www.samsungdisplay.com/eng/intro/history/2010s.jsp. (Accessed 23 April 2021).
Samsung, 2021. GALAXY S III (16GB) | GT-I9300MBDTGY | Samsung Hong Kong. https://www.samsung.com/hk_en/smartphones/galaxy-s/galaxy-s-iii-16gb-gt-i9300mbdtgy/. (Accessed 23 April 2021).
Sholom, S., McKeever, S.W., 2016. Integrated circuits from mobile phones as possible emergency OSL/TL dosimeters. Radiat. Protect. Dosim. 170, 398–401.
Trompier, F., Burbidge, C., Bassinet, C., Baumann, M., Bortolin, E., De Angelis, C., Eakins, J., Della Monaca, S., Fattibene, P., Quattrini, M.C., Tanner, R., Wieser, A., Woda, C., 2017. Overview of physical dosimetry methods for triage application integrated in the new European network RENEB. Int. J. Radiat. Biol. 93, 65–74.
Waldner, L., Bernhardsson, C., Woda, C., Trompier, F., Van Hoey, O., Kulka, U., Oestreicher, U., Bassinet, C., Rääf, C., Discher, M., 2021. The 2019–2020 EURADOS WG10 and RENEB field test of retrospective dosimetry methods in a small-scale incident involving ionizing radiation. Radiat. Res. 195, 253–264.
Wang, X., Wintle, A., Du, J., Kang, S., Lu, Y., 2011. Recovering laboratory doses using fine-grained quartz from Chinese loess. Radiat. Meas. 46, 1073–1081.
Woda, C., Spöttl, T., 2009. On the use of OSL of wire-bond chip card modules for retrospective and accident dosimetry. Radiat. Meas. 44, 548–553.