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OSL at elevated temperature of smart chip cards for retrospective dosimetry

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ABSTRACT

Smart chip cards are a promising material in retrospective dosimetry due to their high collectability with low replacement cost. In this study, dose reconstruction using OSL at elevated temperatures for various chip cards was investigated. The approximate spectral emission of the chip cards was determined through a comparison of radiation-induced and intrinsic background TL signals using different detection filters. In the OSL decay curve, a fast component (0.0–0.4 s) was integrated to avoid high intrinsic background signals. To minimize sensitivity changes due to heat treatment, a protocol to measure OSL at 100 °C was developed and the data were compared with those from a similar protocol for OSL measured at room temperature. In the 0.1 - 5 Gy range, linear and power functions were fitted for room temperature and 100 °C OSL protocols, respectively. The minimum detectable dose was evaluated immediately after exposure, with values of 25 mGy for room temperature and 240 mGy for 100 °C OSL being determined. Signal fading was measured up to 30 days after irradiation for the investigated protocols. A dose recovery test was made 10 days after irradiation using various chip cards, and the 100 °C OSL protocol produced more reliable results than the room temperature OSL protocol. As a result, the study emphasizes the necessity of further investigation of OSL at high temperatures using chip cards.

1. Introduction

When a large-scale radiation accident occurs, it is important to quickly triage exposed individuals who will exhibit any deterministic effects and provide them with appropriate medical treatment (Bailiff et al., 2016). In recent years, thermoluminescence (TL) and optically stimulated luminescence (OSL) dose estimation techniques using personal belongings have been developed successfully, providing fast and reliable results. Smart chip cards, including identification (ID) cards (Mathur et al., 2007), credit cards (Woda and Spöttl, 2009), subscriber identification module (SIM) cards (Kandemir and Toktamış, 2018), and electronic components in mobile phones, such as resistors (Ademola and Woda, 2017; Ekendahl and Judas, 2012), integrated circuit chips (Mrozik et al., 2017; Sholom and McKeever, 2016), display glasses (Discher and Woda, 2013), and protective screen glasses (Bassinet and Le Bris, 2020; Discher et al., 2023), have been investigated for their dosimetric properties. Some of these endeavors were addressed in the ICRU report 94 as available technologies that can be used in the initial phase of radiation emergencies (ICRU, 2019). Furthermore, more recently, present limitations and perspective research direction of various retrospective techniques have been explored (Fattibene et al., 2023).

Chip cards, in particular, are promising as they are likely to be carried by individuals most of the time and are more easily obtainable than other expensive belongings in an emergency. Various approaches have been made since Göksu (2003) first demonstrated the feasibility of using telephone chip cards for exposure dose estimation using infrared stimulation luminescence (IRSL). Mathur et al. (2007) compared two different OSL protocols for ID cards, an IRSL protocol at an elevated temperature of 140 °C and a conventional OSL protocol with 470 nm LEDs at room temperature. The protocol with 470 nm LEDs showed a more linear response in doses and a lower detection limit. Woda and Spöttl (2009) established an OSL protocol for chip cards with a transparent epoxy encapsulation by demonstrating a dose recovery test up to 6 days after irradiation. In a certain type of chip card modules encapsulated with molding technology, a protocol with preheat up to 80 °C could be applicable after a chemical extraction of the silica grain using HNO_3 (Woda et al., 2012). Furthermore, Kim et al. (2020) investigated the TL of various chip cards, revealing different dosimetric properties depending on the type and manufacturer, such as spectral emission,

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sensitivity change, and signal stability. Recently, dose recovery using chip cards has been tested in several field experiments simulating a small-scale radiological accident (Discher et al., 2021; Kim et al., 2022; Waldner et al., 2021).

Common findings in the previous studies using measurement protocols with the room temperature OSL were the poor signal stability and variability of fading with different types of chip cards, resulting in systematic over- or underestimation of the reconstructed doses. To address these issues, Fattibene et al. suggested approaches such as assessing variability in the fading rate of various chip cards and exploring new protocols for isolating more stable signals (Fattibene et al., 2023). Accordingly, we investigated an OSL measurement protocol at an elevated temperature for chip cards to improve signal stability. In general, OSL at an elevated temperature, or thermally assisted OSL, has been theoretically depicted by several mechanisms, including the effect of shallow traps (Markey et al., 1996), thermal assistance from an excited state (Hütt et al., 1988), donor-acceptor hopping (Poolton et al., 1994), band tail hopping (Poolton et al., 1995), and ground state excitation (Spooner, 1994), which were summarized and reviewed in a previous study (McKeever et al., 1997). Therefore, some studies using luminescence materials have investigated and optimized the high-temperature conditions to characterize the OSL from deep traps (Chruścińska and Przegiętka, 2010; Kalita et al., 2017; Polymeris, 2016). For fortuitous dosimetric materials such as surface mount resistors, relatively low temperatures around 100 °C were used during OSL measurement (Bassinet et al., 2014) due to a trade-off relation between signal stability and the contribution of native signals at high temperatures (Beerten and Vanhavere, 2008). In the present study, we optimized parameters such as maximum temperature, hold time, OSL reading time, and integration window to address the limitations that may arise from a heat treatment during measurements, including high zero doses, signal recuperation, and sensitivity change. Additionally, we compared the dosimetric characteristics of OSL at elevated and room temperatures using various chip cards and evaluated their potential applicability through a dose recovery test.

2. Materials and methods

The materials used in this study were divided into two groups: unused (new) chip cards from four different companies and used chip cards from individuals. The unused chip cards were obtained from Infineon Technologies AG (IT), Korea Telecom (KT), LG Telecom (LGT), and an unknown manufacturer, and all of them had a transparent epoxy layer, which is known to exhibit high radiation sensitivity due to the presence of silica in the epoxy (Barkyoumb and Mathur, 2008). IT chip cards were production modules that had not yet been pressed into smart cards, with one side covered by a metal layer and the other side revealing the transparent epoxy layer. KT and LGT chip cards were SIM cards that had recently been released, with model names KE-F2315 and U2720, respectively. The chip card from the unknown manufacturer was purchased from an online marketplace and had a model name of Power-Optical Pearl SLE 4428 chip; it was an empty card with a white color. The used chip cards were SIM cards donated by individuals, with various manufacturers. Most of them had a transparent epoxy layer, but some had an opaque layer with a black color, which is likely a molding-type encapsulation (Woda et al., 2012). For simplicity, we designate the unused chip cards as OM (the one purchased from the online market), IT, KT, and LGT, and the individual-used chip cards as C1, C2, and so on.

For the sample preparation, the metal part of the chip card was cut into a diameter of ~6 mm using a punching scissor. If there was a thin plastic vinyl on the encapsulation layer, it was removed. The chip card was then positioned in a measurement cup, with the encapsulation layer facing upwards. For the comparison of two protocols with different temperatures, a single chip card was divided into two halves and measured separately. The mentioned materials and tools are shown in

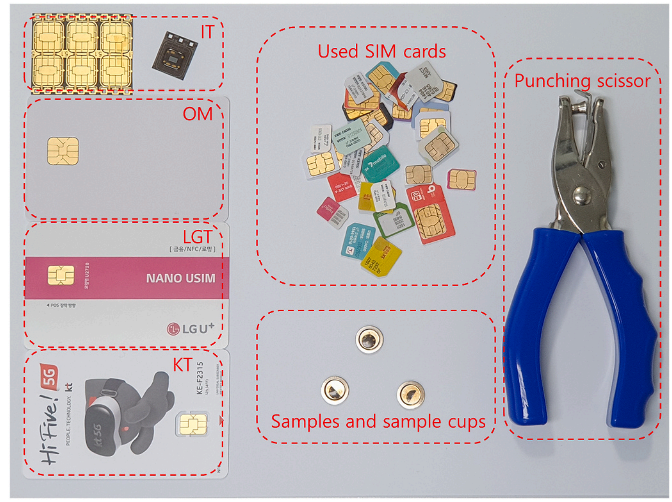

Fig. 1. Chip cards and tools used in the experiment. The chip cards from Infineon Technologies AG (IT), Korea Telecom (KT), LG Telecom (LGT), and an unknown manufacturer (OM) are new ones, and the used SIM cards are from individuals.

Fig. 1.

TL and OSL signals were measured using a Risø TL/OSL-DA-20 reader upgraded with a detection and stimulation head (DASH) (Lapp et al., 2015). Thermal stimulation was delivered to the sample cup through a Kanthal heating strip and optical stimulation was made by 470 nm blue LEDs having a maximum power of 80 mW/cm^2. The luminescence signal was passed through a U-340 Hoya filter and recorded on an Electron Tube PDM9107Q-AP-TTL-03 PMT. The samples were irradiated using a built-in beta source (Sr-90/Y-90) with a dose rate of 6.3 ± 0.8 mGy/s. To estimate the dose rate, OSL protocols at 100 °C used in this study were employed using the OM chip cards irradiated to 1 Gy with a Cs-137 source of the secondary standard irradiation facility at Korea Atomic Energy Research Institute. In the dose recovery test, samples were irradiated with a dose rate of ~10 mGy/min using the same Cs-137 source.

The maximum temperature of the TL reading was around 280 °C with a heating rate of 2 °C/s. The TL readings were always carried out in an N_2 atmosphere, and an automatic subtraction of the second TL readout was followed after every TL measurement. In the case of the OSL reading, the signal was measured at an elevated temperature. A chip card was heated to a certain temperature with a heating rate of 5 °C/s and the temperature was maintained for 10 s unless stated otherwise. The optical stimulation and measurement lasted for 500 s with 90% of its maximum power (80 mW/cm^2). For the fast OSL component, the signal was integrated from 0 s to 0.4 s with a 0.1 s interval and the average background signal between 450 s and 500 s was subtracted for the same number of channels.

To roughly measure the spectral emission of the TL, different filter combinations were used in a Lexsyg Research reader at Salzburg University. An interference filter (one of the following filters - BrightLine 340/26, BP 365/50, BrightLine 414/46, BrightLine 475/50, BrightLine 575/25, and ET Bandpass 620/60) was selectively applied with a heat absorber glass filter (Schott KG3, 3 mm). The first three digits in the filter name indicate the main wavelength of the transmission window while the latter two digits indicate their full-width half maximum (FWHM). The TL signals were detected on a bialkali cathode photomultiplier tube (PMT) Hamamatsu H7360-02. The sample irradiation was made by a built-in Sr-90/Y-90 beta source delivering ~5 Gy at a dose rate of 55 mGy/s.

3. Results and discussions

3.1. TL response using filters

The radiation-induced signal (RIS) of various chip cards has been found to have a TL peak at around 80 °C, whereas the intrinsic background signal (IBS) dominates at higher temperatures, making the use of carriers in stable traps challenging (Mathur et al., 2007; Woda and Spöttl, 2009). To identify the optimum detection window for elevated-temperature OSL, we evaluated the relative TL responses of RIS and IBS for different interference filters. Fig. 2 shows the results for IT chip cards measured with different filters. For each filter, we measured the IBS (solid line) and then recorded the RIS induced by irradiation with 5 Gy (dashed line), applying different scaling factors to bring the RISs to a similar level (see the legend in Fig. 2). It should be noted that Fig. 2 shows the relative TL emissions according to the different interference filters, which have different full-width half maximums and transmission rates. It therefore does not represent the actual emission spectrum of the chip card TL. Instead, the approximate TL emission spectrum by applying normalization factors from the detection window of the interference filters and PMT has been reported (Kim et al., 2020).

The IBSs present two main TL peaks at around 150 °C and 190 °C with different relative intensities depending on the filters, whereas the shape of the RISs does not show any wavelength dependency. In the given temperature range, the relative IBS compared to the RIS is minimal for the 340 and 414 filters. Notably, the absolute intensity of RIS for the 414 nm filter is higher than that for the 340 nm filter, even when considering the different FWHMs of the filters, indicating that the wavelength region of 390 – 440 nm may be an optimal detection window for the chip cards. However, since the cut-off filter (GG-420) in front of the built-in blue LEDs intended to prevent PMT damage by the stimulation light suppresses the light below 400 nm, the maximum range of the detection window should be less than 400 nm when using blue OSL. Thus, we used the U-340 filter (280–380 nm), which includes 340 nm and has a wider range than the interference filters, in the following measurements.

3.2. OSL decay curves at an elevated temperature

To evaluate the impact of the heat treatment on OSL, the signals measured at room temperature and 100 °C were compared for several chip cards irradiated to 1 Gy, as shown in Fig. 3. Each measurement was

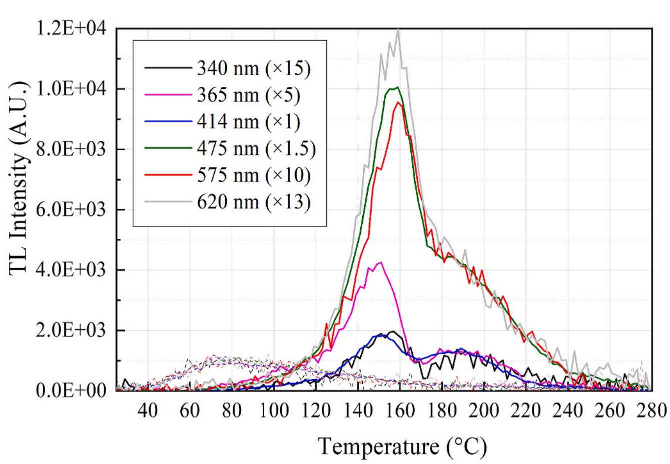

Fig. 2. TL glow curves of chip cards with different interference filters: BrightLine 340/26, BP 365/50, BrightLine 414/46, BrightLine 475/50, BrightLine 575/25, and ET Bandpass 620/60. For each chip card, signals without irradiation (solid line) were measured first, and then signals with a test dose of 5 Gy (dashed line) were recorded. Signal pairs according to the filters are displayed by color and scaled with different values in the legend.

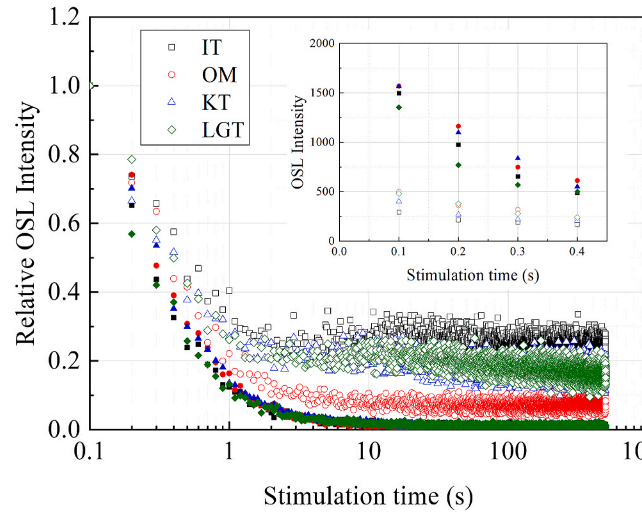

Fig. 3. Normalized OSL decay curves of four different chip cards (shown as different symbols) irradiated to 1 Gy. The samples were measured at room temperature (solid symbols) and 100 °C (open symbols). The data shown are the second measurement and the first measurements were done without irradiation to remove intrinsic background signals. The inset shows non-normalized data for the initial signals.

carried out after removing IBSs using the same measurement protocols to differentiate RISs. The data were normalized to the 0.1 s point.

It should be noted that the OSL at 100 °C exhibited reduced intensity by around 65-80% at the 0.1 s point compared to that at room temperature. In addition, for some of the OSL decay curves at 100 °C, a slight build-up was found in the 2 – 10 s region, which will be discussed in the next paragraph. In the tail region, ~5 times higher counts than at room temperature were observed, and the slow signal decay was maintained.

When the OSL of chip cards was measured without any heat treatment, the distribution of IBSs was negligible. On the other hand, the OSL at 100 °C showed significant build-up originated by IBSs, as shown in Fig. 4. This build-up in high-temperature OSL was first reported by Woda and Spöttl in 2009. The phenomenon was speculated and analyzed as a mechanism by which electrons are released from epoxy by thermo-optical stimulation and transferred to OSL traps in silica. The study also found that the strength of the build-up decreases with repeated measurements as shown in Fig. 3. As this is a non-radiation-induced signal, we refer to it in this study as the IBS of OSL. The

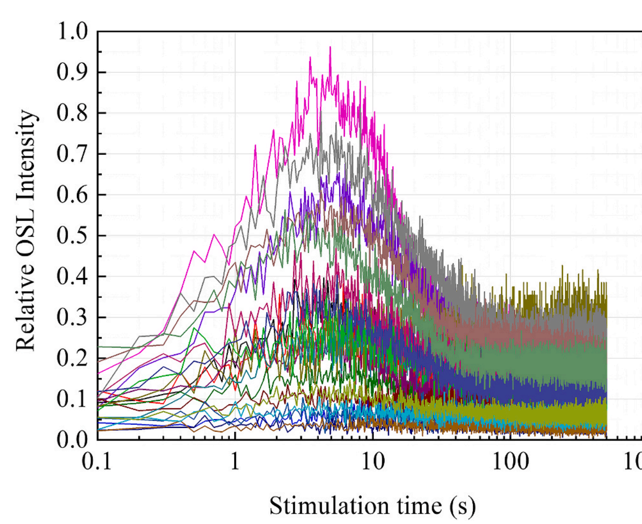

Fig. 4. OSL at 100 °C of unirradiated 20 chip cards including used and unused (new) samples. The signals were normalized to the intensity at 0.1 s of 1Gy RIS.

degree of build-up varied among chip cards, with the intensity peaking up to 95% of the maximum of 1 Gy RIS at the worst case. In most cases, the IBS dominates up to 50 s of optical stimulation, but due to the fast decay of RIS, zero-dose can be minimized by limiting the signal integration window to a narrow range (i.e. 0-0.4 s). The impact of low luminescence intensity was incorporated in the measurement uncertainty of the following data. Furthermore, a stable OSL background was achieved by maintaining optical stimulation for 500 s and the signal levels at the tail of both RIS and IBS of the same sample were found to be similar. Meanwhile, the theoretical pathways of the observed OSL decay curves are worth discussing to improve understanding of the phenomenon, but it is not covered in the present study due to the limited number of observations and being outside the current area of interest, i.e. validation of the method.

3.3. Sensitivity change

When measuring the OSL of chip cards, preheating can introduce signal recuperation that leads to changes in reproducibility during subsequent measurements (Woda and Spöttl, 2009). While test dose normalization can correct for continuous changes, it is ineffective in addressing the change that occurs between the first and second measurements. To minimize fluctuations in sensitivity during the initial measurement, we modified the temperature parameters, such as the maximum reading temperature and the hold time, as shown in Fig. 5. The hold time represents the duration of the maximum temperature before optical stimulation. In each measurement protocol, the zero doses of the samples were evaluated as less than 100 mGy, and a relatively high dose of 5 Gy was employed as a regenerative dose to ignore the contribution of the signal arising from the zero dose and to ensure sufficient signals.

The measured data exhibited slight variation depending on the type of chip cards, but the tendency with respect to the parameters was similar across the sample. During the 0 – 10 s hold time, the initial sensitivity tends to decrease as the temperature increases, consistent with observations made during TL application (Kim et al., 2020). Conversely, when the temperature lasts more than 50 s, a continuous increase in sensitivity is observed at 120 °C, indicating that the signal is sensitive to the target temperature. Therefore, the optimal condition was set to 100 °C with a 10 s hold time, as this configuration produced relatively stable signals.

When comparing the OSL reproducibility at room temperature and 100 °C conditions for several chip cards, the opposite behavior was observed, as shown in Fig. 6. At room temperature, the intensity of the second measurement increased by 5 ± 4% despite the absence of heat treatment. No further notable changes were observed in the subsequent measurements. When the regenerative dose was not applied before the second measurement to evaluate a possible residual OSL, a negligible signal was detected. The slight change at the initial measurement can be attributed to the behavior of the signal in the narrow integration window at room temperature. On the other hand, at 100 °C, the intensity of the second measurement decreased by -7 ± 9%. The deviations were varied depending on the samples from no change to -20%. When a regenerative dose of 10 Gy was applied to confirm the dose dependency, no significant difference was found compared to Fig. 6. While inevitable sensitivity changes at the initial reading were observed for both temperatures, they can be ignored considering the high uncertainties of retrospective dosimetry or corrected using the measured deviations. Additionally, test dose normalization was required, as continuous changes in sensitivity were found in some samples.

3.4. Dose-response

The dose-response of OSL at both room temperature and 100 °C ranging from 100 mGy to 5 Gy was evaluated using several chip cards in Fig. 7. A dummy reading was performed before each measurement to exclude the initial sensitivity changes, and the data were normalized using a 1 Gy test dose irradiated between each measurement.

The results presented in Fig. 7a show that at room temperature, the OSL demonstrated a consistent response across all samples and highly adjusted R-squared values obtained from the linear fittings in Table 1. However, at 100 °C (Fig. 7b), the uniformity between samples deteriorated. Notably, at doses near 100 mGy, a high degree of variability was observed, primarily due to the low intensity of OSL. Furthermore, the response in dose showed a supralinear characteristic, which required fitting with a non-linear function. The power function used in the fitting was referred from previous studies (Kim et al., 2020; Woda and Spöttl, 2009). Therefore, when using the OSL at 100 °C protocol for dose reconstruction, it is necessary to correct for non-linearity by measuring the dose-response in suspected ranges.

Table 1 reports the detection limits of individual samples depending on the measurement protocols. To calculate the detection limit of the measurement, the 3σ of blank readings (without irradiation) was

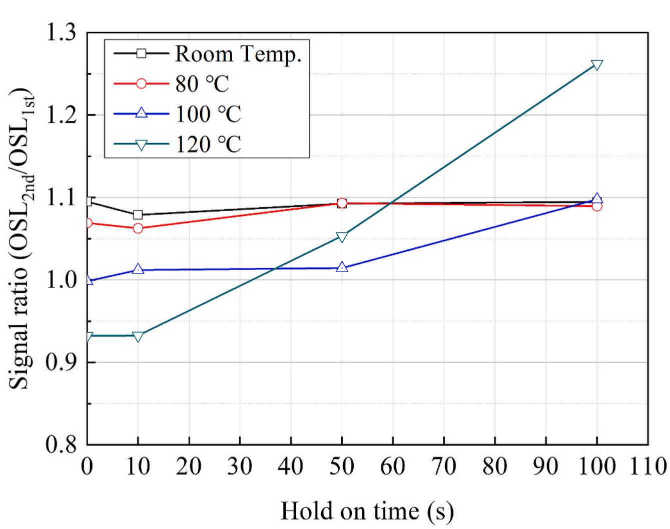

Fig. 5. The signal ratio between 1st and 2nd OSL measurements of OM chip cards according to a reading temperature and hold time. The sample was irradiated to 5 Gy in every measurement and one sample was used for each data point.

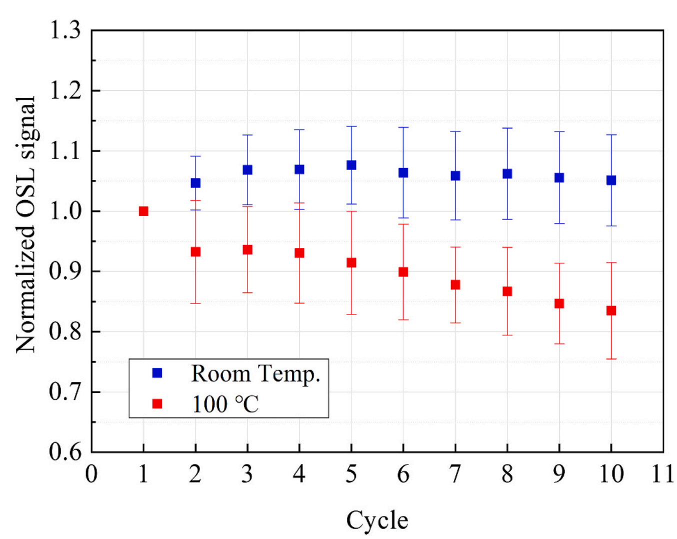

Fig. 6. Reproducibility of OSL at room temperature and 100 °C using eight different chip cards (IT, OM, KT, LGT, and four used chip cards) irradiated to 5 Gy. For comparison, one sample was halved and measured separately at both temperatures.

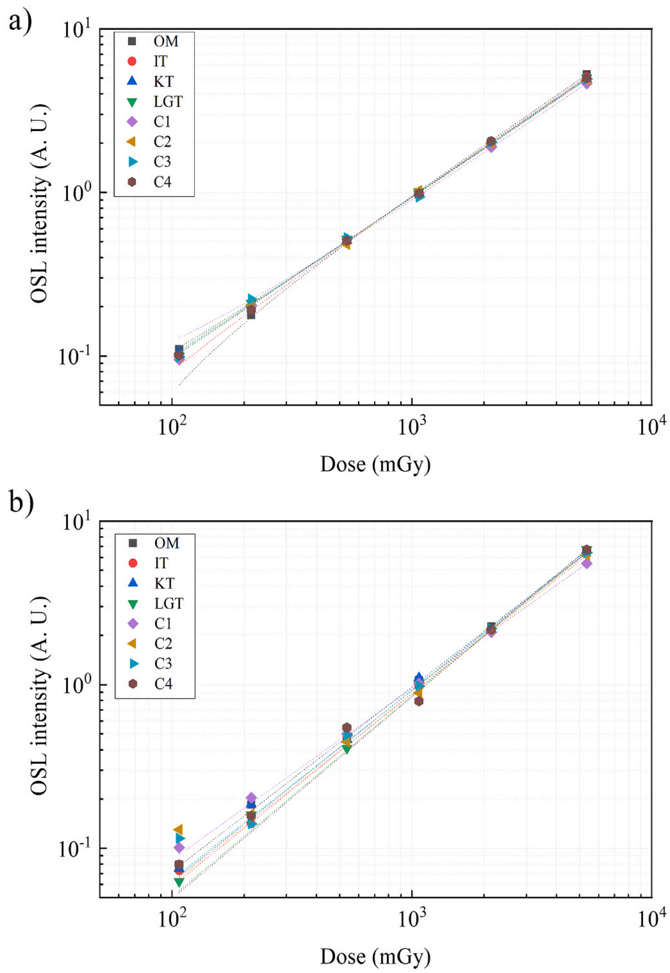

Fig. 7. Dose-response of OSL at room temperature (a) and 100 °C (b) for eight different chip cards. A single chip card was divided in half and measured separately at two temperatures. Each data point was normalized to that of 1 Gy test dose signals acquired between each measurement. The fitting functions and parameters are presented in Table 1.

divided by the slope of the dose-response curve (Long and Winefordner, 2008). The blank readings were obtained through five sequential measurements per sample after the measurement of dose-response to exclude the effect of IBS from the estimation. In addition, the slopes were recalculated using the 100 mGy to 1 Gy range to avoid the non-linearity of the curves. For most of the chip cards, the detection limit was less than 10 mGy for room temperature OSL, while the OSL at 100 °C recorded several tens of mGy.

3.5. *Zero-dose distribution*

To estimate the distribution of zero-doses in various samples, we employed 24 chip cards, including both unused and used ones. The measurement uncertainty was calculated assuming a weak OSL signal (Li, 2007).

Fig. 8 shows that the zero-doses measured using the OSL at 100 °C ranged from -240 to 125 mGy, while those measured at room temperature showed a distribution lower than one order of magnitude. Besides, the OSL at 100 °C delivered relatively high uncertainty due to low signal intensity. Some samples exhibited negative values originating from the signals used for OSL background subtraction (450 – 500 s) being higher than the initial signals. The OSL tail signals decayed slowly, requiring longer optical stimulations, but the stimulation time was limited to 500 s to facilitate fast readout. No correlation was found between the zero

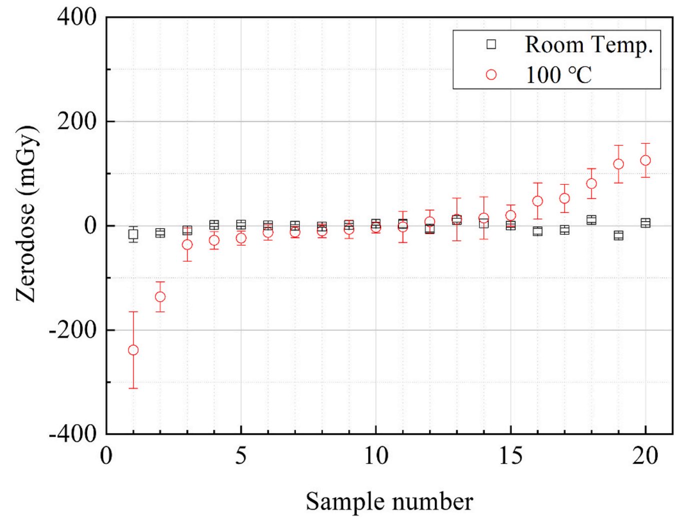

Fig. 8. Zero doses of 20 chip cards measured by OSL at room temperature and 100 °C. A single chip card was divided in half and measured separately at two temperatures. The samples were irradiated to 1 Gy and ordered based on increasing zero-dose values of the OSL at 100 °C.

doses evaluated from the two measurement protocols for the same sample. This indicates that the BIS presented in Fig. 2 does not contribute at room temperature or has a slower build-up. The average zero doses of OSL at room temperature and 100 °C was -2 mGy for both, and the minimum detectable dose (MDD), calculated as three times the standard deviation, was 25 mGy and 240 mGy, respectively. Although the higher variability in zero dose signals is a major detriment of the investigated protocols, the level is still lower than the threshold dose for triage of acute radiation syndrome (i.e. about 1 Gy) (Bailiff et al., 2016).

3.6. *Signal fading*

Chip cards have been proposed as a material with a potential for dose reconstruction using the TL/OSL technique in emergencies, along with resistors and display glasses. However, their relatively low signal stability (ICRU, 2019) requires measurement as close to the time of exposure as possible. Moreover, anomalous fading, which varies depending on the sample and type, can increase the deviation of results (Discher et al., 2021). Therefore, we evaluated the signal stability of various chip cards for the investigated OSL protocols, as shown in Fig. 9. The chip cards were stored in the reader after exposure, and measurements were taken with a delay of up to 30 days. We used OM chip cards for measurements below 30 h of the time since irradiation and 20 different types of chip cards (OM, IT, KT, LGT, and individual-used chip cards) for measurements above 30 h. Previously measured samples were used to avoid initial sensitivity changes. We applied the same non-linear function for data fitting of room temperature and 100 °C OSL, and the fitting curves showed higher stability for OSL at 100 °C in the given period. After 30 days of irradiation, however, the enhancement of signal stability was not remarkable, with the OSL at 100 °C signal showing ~25% of the initial signal, compared to 15% for room temperature OSL. Higher temperatures were attempted for better signal stability, but this was accompanied by higher zero doses, initial sensitivity changes, and lower signals. Regarding the sample variation, the relative standard deviation was ~10% for 100 °C and 16% for room temperature for the samples measured after 30 h. The dependence of relative deviation on fading time was not significant.

The observed difference in the two OSL fading rates is attributed to signal stability according to trap levels, but an explicit underlying mechanism is unknown due to the variety of the chemical compound of chip cards. Experimentally, in a prior investigation of chip card TL, the

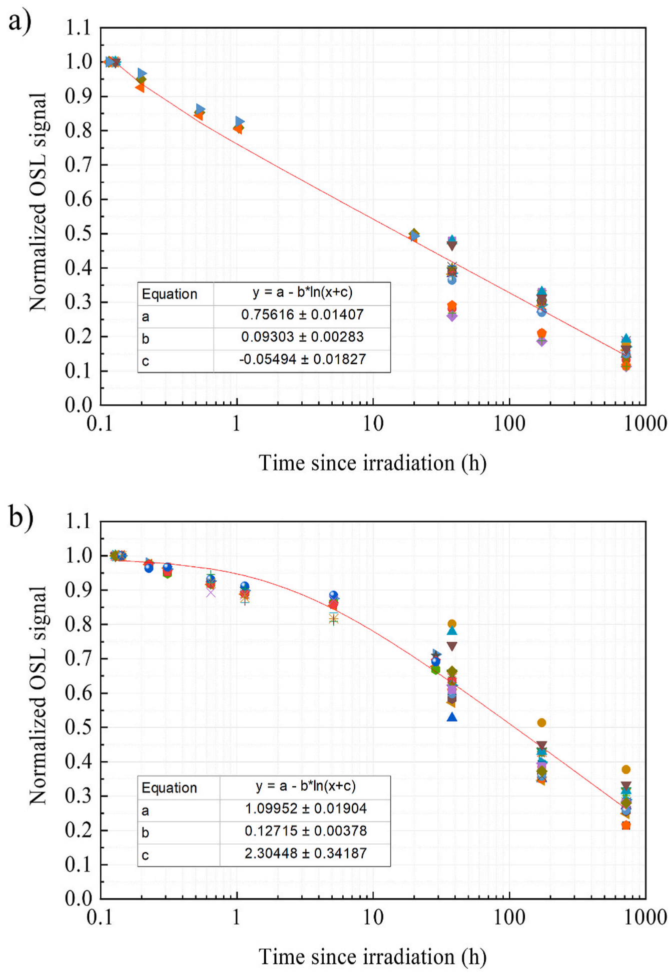

Fig. 9. Signal fading of various chip cards using OSL at room temperature (a) and 100 °C (b). A single chip card was divided in half and measured separately at two temperatures. A test dose of 5 Gy was applied, and each data was normalized to the signals measured immediately after the irradiation (the elapsed time from the midpoint of the test dose irradiation to the measurement was 0.129 h). The fitting curves (red line) and parameters calculated by concatenating all data are presented in the figure.

TL below 100 °C was significantly unstable compared to those above 100 °C, with signal loss of less than 10% after 10 h (Kim et al., 2020). Besides, another study has speculated that the athermal fading characteristics of OSL at room temperature can contribute to long-term signal loss (Woda and Spöttl, 2009).

3.7. Dose recovery test

A dose recovery test was carried out using the investigated measurement protocols. Three doses of 0.5, 2, and 5 Gy were selected, and the measurements were taken ~9.5 days after irradiation. The new and used chip cards were exposed to the Cs-137 gamma field at the same location for 50, 200, and 500 min. Samples were light-shielded with black tape and stored at room temperature until measurement. The evaluated doses and their corresponding uncertainties were calculated using the equations presented below for both measurement protocols.

$$D = (D_{unc} - D_{zd}) \bullet S \ / f \tag{1}$$

Here, D_{unc} is an uncorrected dose calculated by the fitting function and the universal factors (a' and b') in Table 1. D_{zd} stands for zero dose, S stands for sensitivity change, and f indicates the fading factor of the signal. After 10 days in Fig. 9, the remained signals at room temperature and 100 °C were approximately 26% and 40%, respectively, and the relative standard deviations of 16% and 10% were used, respectively, to estimate uncertainty.

Fig. 10 shows the ratio of the evaluated dose to the given dose for different chip cards. The individual chip card names were used for convenience, and the samples used in this figure differ from those in Fig. 7.

The first observation is that the uncertainty interval for OSL at 100 °C is wider than that at room temperature. This outcome is primarily due to the weaker OSL signal and higher sample variation of the OSL at 100 °C, including the variations in zero doses and dose responses. The uncertainty of zero doses is particularly significant at low doses, resulting in the highest uncertainties in the 0.5 Gy test.

Interestingly, the results of OSL at room temperature underestimated the given dose by about half. When assessing the average dose ratios of the applied chip cards for OSL at room temperature, relative to the given dose, values of 45%, 50%, and 56% were observed for dose levels of 0.5, 2, and 5 Gy, respectively. Whereas that of OSL at 100 °C showed around 119%, 89%, and 83% as the given dose increased. Among the correction factors in Eq. (1), the fading rate was the most influential factor, which implies that there was an overestimation in the non-linear fitting in Fig. 9a. However when the signal fading was re-measured using the samples used in the dose recovery test, a similar signal stability was confirmed, with the remaining signal of 27% after 10 days from irradiation. Furthermore, there was no significant difference with a correction using the individual dose responses. To address the observed discrepancy, two speculations were considered. First, the stability of the room temperature OSL can be affected by unforeseen factors, such as the temperature of sample storage, working under red light, mechanical sample cutting, and so on. Second, the signal stability can be influenced by the dose cycle, i.e. dosing and readout, resulting in a deviation of fading characteristics between previously measured and fresh chip cards. This assumption is supported by the findings of the field experiment (Discher et al., 2021), wherein chip card results manifested a systematic underestimation when individual fading factors obtained from the measured samples were used. On the other hand, estimated doses corrected by the fading factors obtained from the fresh modules aligned more closely with the reference dose. However, even if this explanation predominantly contributes to the effect, obtaining fresh chip cards identical to the measurement sample to have better fading characteristics becomes impractical when an individual fading correction is required. In this context, the dose reconstruction results for OSL at OSL at 100 °C exhibited a reduced impact of systematic underestimation in comparison to room temperature.

For the sample variation according to the given dose, the relative standard deviations of the estimated doses were around 26%, 11%, and 29% at room temperature and 41%, 16%, and 21% at 100 °C for 0.5, 2, and 5 Gy, respectively. The highest variation was observed at 0.5 Gy with OSL at 100 °C, with up to 1 Gy estimated for some samples. This is because the given dose was below the MDD at the time of measurement (~650 mGy) as shown in Table 2.

A correlation between the two measurement protocols for the same chip cards is not evident, but for C8 and C10, which were the only two chip cards underestimated outside the uncertainty interval of OSL at 100 °C, significant underestimations are observed for both protocols.

For the OSL at 100 °C, the reference dose was outside the uncertainty interval for only five out of the 22 chip cards. Moreover, if the uncertainty interval was expanded with k = 2, most of the results of the OSL at 100 °C included the given doses. As a result, the OSL at 100 °C demonstrated more stable estimations than room temperature, but due to its higher zero-doses, it is necessary to consider the MDDs according to the time since irradiation. Additionally, to overcome possible bias resulting from sample variation, measuring as many chip cards as possible is necessary for dose reconstruction in an accident scenario. Fortunately, several candidates that are believed to be carried during exposure, such as credit cards, a SIM card in a mobile phone, and ID

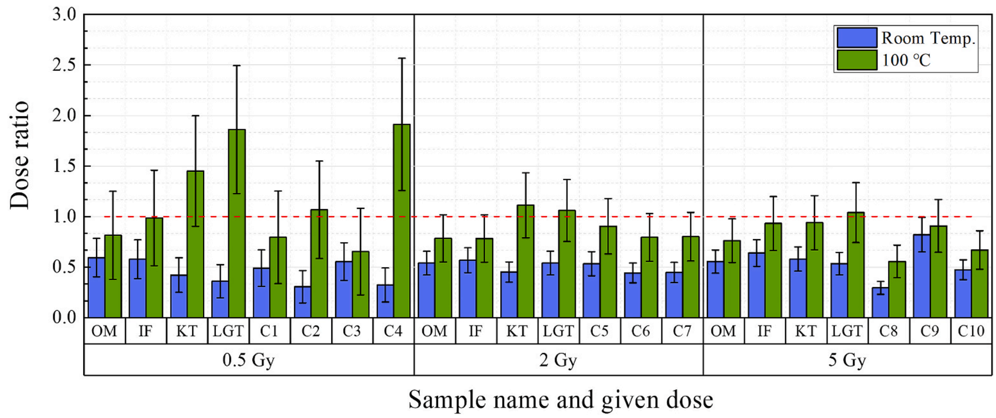

Fig. 10. Results of dose recovery test using OSL at room temperature and 100 °C for various chip cards. For each chip card, the sample was split in half and measured separately at two temperatures. Samples were irradiated with three doses (0.5, 2, and 5 Gy) and measured ~ 9.5 days after irradiation. A calibration dose of 1 Gy was applied, and the estimated dose-to-given dose ratio was reported.

Table 1
Detection limits (D.L.) and fitting information for the OSL dose responses shown in Fig. 7. The variable D represents the dose, while a and b are constants that vary depending on the chip cards. The fitting constants a' and b' were obtained by concatenating all individual curves into a single dataset.

Temp.	Chip card	D.L. (mGy)	Fitting function	a	b	Adj. R-sq	a'	b'
Room Temp.	OM	3	$y = a + b \times D$	-3.91E-02	9.87E-04	0.9995	3.93E-3 ± 1.44E-2	9.27E-4 ± 5.99E-6
	IT	6		-1.47E-02	9.52E-04	0.99993		
	KT	3		1.43E-02	9.18E-04	0.99999		
	LGT	7		2.90E-03	9.37E-04	0.99986		
	C1	6		3.70E-02	8.60E-04	0.99974		
	C2	7		1.59E-02	9.10E-04	0.99982		
	C3	5		9.60E-03	9.22E-04	0.99957		
	C4	25		5.59E-03	9.33E-04	0.99975		
100 °C	OM	16	$y = a \times D^b$	4.01E-04	1.13E+00	0.99996	2.92E-4 ± 5.40E-5	1.16E0 ± 2.19E-2
	IT	80		2.56E-04	1.18E+00	0.99984		
	KT	14		2.84E-04	1.17E+00	0.9992		
	LGT	41		1.77E-04	1.23E+00	0.99952		
	C1	13		6.83E-04	1.05E+00	0.99997		
	C2	57		2.93E-04	1.16E+00	0.99957		
	C3	80		3.15E-04	1.16E+00	0.99981		
	C4	70		1.66E-04	1.24E+00	0.99836		

Table 2
Minimum detectable doses (MDDs, mGy) of OSL at room temperature and 100 °C according to time since irradiation. Fading curves in Fig. 9 were applied.

Time since irradiation	0.129 h	1 h	5 h	10 h	50 h	100 h	500 h	1000 h
Room temp.	25	32	41	46	64	76	141	220
100 °C	240	253	284	308	403	469	777	1086

cards, are available.

3.8. Isolating defective samples

Variances in radiation specificity and response have been reported among chip cards from different manufacturers and technologies (Bassinet et al., 2010; Kim et al., 2020; Woda et al., 2012). In the present experiment, some of the chip cards were excluded from the results after the measurements. Specifically, the chip cards with black-colored encapsulation exhibited significantly lower radiation sensitivity at both room temperature and 100 °C OSL. Additionally, certain chip cards with transparent encapsulation presented unique behaviors at room temperature OSL. For instance, their initial OSL signal decayed within 0.2 s, and anomalous fading and zero doses outside of the overall statistics were identified. The signals from these samples were not observed for OSL at 100 °C. About 20% (7 out of 36 individuals used chip cards) of the measured chip cards were outliners, requiring a thorough examination of the raw measurement data.

4. Conclusions

In this study, we investigated the dose reconstruction technique using OSL of chip cards and compared protocols with two different readout temperatures. The characterization of the protocols showed that the OSL at elevated temperatures resulted in reduced signal intensity and higher sample variation compared to room temperature, but the protocol was still practically useable for dose estimation. In the dose recovery test, an unexpected underestimation of the room temperature OSL by around 50% of the given dose was observed. On the other hand, the OSL at 100 °C produced more reliable results, but the higher zero doses require consideration of MDD over time, which can reach up to 1 Gy in 30 days after exposure. The significance of the present study is that various chip cards were applied to estimate the parameters of dose recovery, including new and used ones. Some of the chip cards were identified to have poor radiation sensitivity or an unusual response, which we distinguished by their color or by analyzing raw measurement data. Overall, the findings of this study emphasize further investigation into chip card OSL at high temperatures. Further studies encompass the fine-tuning of high-temperature conditions, necessitating a sensitivity change test with narrower elevated temperature steps than the 20 °C used in this study and finer resolution of the hold time, and statistical analysis of dosimetric characteristics using various chip card samples, such as radiation specificity, repeatability, fading, dose-response, and so on. Validation by intercomparison between different laboratories can also be performed.

CRediT authorship contribution statement

Hyoungtaek Kim: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Clemens Woda:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Michael Discher:** Conceptualization, Investigation, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hyoungtaek Kim reports travel was provided by EURADOS.

Data availability

No data was used for the research described in the article.

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