Radiation Measurements 106 (2017) 423–430

Contents lists available at ScienceDirect

Radiation Measurements

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

Phototransferred thermoluminescence (PTTL) dosimetry using Gorilla® glass from mobile phones

S.W.S. McKeever [a, *], R. Minniti [b], S. Sholom [a]

[a] Radiation Dosimetry Laboratory, Department of Physics, Oklahoma State University, Stillwater, OK 74078, USA
[b] Radiation Physics Division, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

HIGHLIGHTS

- PTTL is observed in samples of protective Gorilla® glass from smartphones.
- The UV-induced signal can be separated from the radiation-induced PTTL signal.
- The PTTL signal is linear with radiation dose, and more stable than the TL signal.
- PTTL used to determine doses to an irradiated phone.

ARTICLE INFO

Article history:
Received 4 September 2016
Received in revised form
28 March 2017
Accepted 10 April 2017
Available online 12 April 2017

Keywords:
Emergency dosimetry
Thermoluminescence
Phototransferred thermoluminescence
Gorilla® glass
Mobile phones

ABSTRACT

Samples of Gorilla® glass (Corning®) from several touchscreen mobile phones were prepared and analyzed using phototransferred thermoluminescence (PTTL) in an attempt to retrospectively assess radiation doses absorbed by the glass for potential applications in emergency dosimetry. Samples of glass were prepared by cleaning and cutting into small pieces. Glow curves were recorded after irradiation to different doses, pre-heating to a given temperature, and exposure to ultraviolet (UV) light (365 nm) for various times. The dependencies of the thermoluminescence signals so-obtained on the pre-heat temperature and the duration of UV light exposure were studied. The stability of the PTTL signals was also studied for samples stored under ambient conditions. The PTTL signals were quite stable with little change after storage over several days. Dose response curves (PTTL versus initial applied dose) were linear up to ~20 Gy. Values of minimum detectable dose (MDD) evaluated using PTTL were determined for samples from different phone brands. A non-radiation-induced, UV-light-stimulated TL signal was also observed as a result of the UV exposure. Variability in the strength of this signal and in the PTTL sensitivity of the various glasses leads to a variation in, and places limits on, the obtained values for the MDD. Typical MDD values were found to range between 0.1 Gy and 5 Gy. A method for accounting for the UV-induced signal is suggested involving pre-heating to high temperatures (550 °C). An exploratory test of a suggested protocol for evaluating dose from smartphones using PTTL is described and the results are compared with those obtained using optically stimulated luminescence (OSL) and thermoluminescence (TL) methods from other phone components.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Mobile phones have become popular in the field of emergency dosimetry due to the potentially useful dosimetric properties of some of their electronic components, using a variety of techniques. Several components demonstrate distinct radiation-induced markers after exposure to ionizing radiation dose. These markers include optically stimulated luminescence (OSL) signals from electronic components (e.g. resistors and integrated circuits: Bassinet et al., 2014b; Sholom and McKeever, 2016) as well as electron paramagnetic resonance (EPR) and thermoluminescence (TL) signals from display screen glass (e.g. Fattibene et al., 2014; Discher and Woda, 2013). Special attention is currently also being given to the protective glass covering the screen (display) glass since in many cases it is possible to take out the protective glass without dismantling or breaking the phone. An additional

* Corresponding author.
E-mail address: stephen.w.mckeever@okstate.edu (S.W.S. McKeever).

http://dx.doi.org/10.1016/j.radmeas.2017.04.005
1350-4487/© 2017 Elsevier Ltd. All rights reserved.

advantage is that the most modern touchscreen phones use the same type of glass (namely, Corning's Gorilla® glass), a fact which could prove useful in developing a universal dosimetry technique.

One of the main problems with the use of either protective or display glass, however, is the sensitivity of both the EPR and TL signals to environmental conditions. Trompier et al. (2011) and Fattibene et al. (2014) examined EPR from display glass and Gorilla® glass and found pre-existing EPR signals in most of the samples studied. Fattibene et al. (2014) examined the EPR results from Gorilla® glass from several laboratories that participated in an intercomparison study and found that for those participants who used glass from the same batch and stored under controlled conditions, smaller errors (between the evaluated doses and the administered doses) were observed compared to those participants using glass from different phones and stored in different conditions (light, temperature, etc.). Other studies examined the TL properties of this material. For example, Bassinet et al. (2010) compared the TL and EPR signals and demonstrated that the TL curves are broad and typical of amorphous, glassy materials. However, a pre-laboratory-irradiation or 'native' signal (called a background signal, BGS, by these authors) was observed, although this was not present in all of the glasses studied. Discher et al. (2016) chemically analyzed several glasses from the same phone manufacturer and determined that high TL sensitivity, and a high sensitivity for the pre-irradiation, native signal, is related to the presence of Al and K. Glass with low Al and K showed no sensitivity to TL and no native signal. Whatever its cause, the native signal acts as interference to the TL signal induced by laboratory irradiation (and, by inference, the signal induced by an emergency dose). Radiation-induced TL is characterized by a main TL peak near 250 °C, with a lower-temperature shoulder near 130 °C (which is sometimes missing from the pre-existing, native signal, presumably due to thermal fading).

Discher and Woda (2013) concluded that the pre-irradiation, native signal is caused by prior irradiation of the sample, either by ultraviolet (UV) light or natural background irradiation, or both. Trompier et al. (2011) and Mrozik et al. (2014) speculate that the signal comes from UV light exposure during manufacturing. Discher and Woda (2013) determined the pre-irradiation signal equivalent dose for 29 screen-glass samples, and these ranged from as low as 7 mGy to as high as almost 900 mGy, with a mean of 46 mGy. The presence of this signal limits the MDD to no less than 340 mGy on average. Further work (Discher et al., 2013) demonstrated that the pre-irradiation signal could be removed entirely by etching the surface of the glass before TL analysis. Using HF acid they were able to reduce the pre-existing native signal by up to 90%, indicating that the unwanted signal is a surface effect only. These results led the authors to suggest a protocol using HF etching for determining an unknown dose and using this protocol they were able to push the detection limit down to ~80 mGy. Bassinet et al. (2014a) mechanically ground the surface of the glass and found that this too led to a reduced native signal and a similar lowering of the MDD. Using these procedures both Discher et al. (2013) and Bassinet et al. (2014a) were able to recover administered doses with small standard deviations.

Additionally, TL from glassy materials is often observed to fade. Several authors (e.g. Discher et al., 2013; Bassinet et al., 2014a) observed fading curves characteristic of athermal processes. However, the fading curves were found to be monotonic and corrections for fading were simple to apply. An additional feature from these materials is the sensitivity of the TL signal to ambient temperature and UV light (Discher and Woda, 2013, 2014; Discher et al., 2013, 2016). Phone glass (whether the display glass or the protective glass) will inevitably be exposed to sunlight following any irradiation. Discher and Woda (2013) observed that part of the TL glow curve is sensitive to light, whereas part (at higher glow-curve temperatures) is insensitive. This leads to the requirement of a "pre-bleach" of the specimen following irradiation and before TL analysis. Not all phone glass is equally sensitive, however, with boron-silicate glass being more optically sensitive than lime-aluminosilicate glass (Discher and Woda, 2014). Discher et al. (2016) tested the pre-bleach protocol (using 470 nm light from blue light-emitting diodes (LEDs)) on the samples of touchscreen glass from iPhones and found disappointing results in that the pre-bleach seems to lead to an underestimation of the delivered dose.

In an effort to circumvent several of the problematic issues related above we investigated the use of phototransferred thermoluminescence (PTTL), wherein dose reconstruction is conducted using deep radiation-sensitive traps. In the PTTL method, following heating of the irradiated sample to a specified pre-heat temperature, the sample is exposed to UV light in order to phototransfer charge from deep, thermally stable traps into shallower traps that were emptied during the pre-heat. This induces a TL signal on re-heating, known as the PTTL signal (e.g. McKeever, 1985). The PTTL signal so obtained is a function of the wavelength of the UV light used, the duration of the UV light exposure, the temperature to which the sample is pre-heated prior to UV light exposure, and the initial dose of radiation received by the sample. In favorable circumstance the PTTL signal is then a function of the initial dose and is a potential method for dosimetry.

In this paper we report the main observation of our experiments using the PTTL technique on Gorilla® glass and propose a preliminary protocol to determined absorbed doses in the glass using the PTTL procedure. We also report the results of an exploratory test of the efficacy of the proposed method to determine unknown doses by conducting a multiparametric study in which complete phones were irradiated to a known dose of in a controlled exposure. Various components of the phones (specifically, surface mount resistors (SMRs), integrated circuits (ICs) and screen glass) were extracted and the doses to these individual components were evaluated. To do so, we determined the dose to the SMRs using accepted OSL methods, as described, for example, by Bassinet et al. (2014b). We also used OSL to determine the dose to ICs, as previously described by Sholom and McKeever (2016). The dose to the screen glass was determined using TL. The results from the proposed PTTL method (i.e. the evaluated doses from protective glass) were then compared to the doses obtained using the other materials and methods, and to the known delivered dose. The results of this comparison are described.

2. Materials and methods

Several touchscreen mobile phones were used in this study. For the examination of the PTTL properties we used Gorilla® glass samples from an iPhone 3GS (model A1303), an iPhone 4S (model A1387), an HTC phone (model APA6277), and a Samsung phone (model SGH-S959G). Additionally, we used a sample of Gorilla® glass obtained directly from an on-line supplier. Preparation of the glass included removing the protective plastic film using a sharp knife and a blade and then washing the samples in ethanol. They were then cut into ~ 5 × 5 mm^2 aliquots using a low-speed, water-cooled diamond saw. TL and PTTL data were normalized by aliquot mass. (For clarity, "sample" refers to the glass from a particular phone; "aliquot" refers to the small ~5 × 5 mm^2 pieces cut from each glass sample.) Three aliquots of the same sample were used for exposure to each specific beta particle dose and 365 nm UV-light exposure time. Thus, the beta particle dose and UV-light exposure time dependences reported herein are the averages of measurements from three aliquots.

All TL and PTTL glow curves were recorded in a nitrogen

atmosphere using a RisØ TL-DA-15 TL/OSL system with a BG-39 filter set and a heating rate of 2 °C/s. The RisØ internal beta source ($^{90}Sr/^{90}Y$) was used for irradiation. The source was calibrated in units of dose (Gy) to water, using a secondary standard ^{60}Co source at the National Institute of Standards and Technology (Gaithersburg, USA) using Al_2O_3 OSL dosimeters as transfer dosimeters. UV-light exposures were obtained with a 3UV™ lamp delivering a power of ~0.98 W/cm^2 and 0.64 W/cm^2 at the sample for 365 nm and 254 nm beams, respectively.

All samples were irradiated to several doses using the RisØ internal beta particle source. After the irradiation, and in order to generate PTTL curves, each irradiated sample was preheated to a given temperature, followed by cooling to ambient temperature. The samples were then exposed to UV light (of wavelength 254 nm or 365 nm) for various times. The PTTL signals were optimized with respect to the pre-heat temperature and the duration of the UV-light exposure. The stability of the PTTL signal was studied for the samples stored under different ambient conditions after irradiation but before UV-light exposure and PTTL readout. Dose response curves were obtained by recording the signal as a function of the initial radiation dose, for a given set of UV-light exposure parameters. From the dose response curves, values of minimum detectable dose (MDD) were determined for samples from different phone brands. The MDD was defined as that dose which corresponds to a PTTL signal which is three-times the standard deviation (3σ) of the background (zero radiation) PTTL signal.

For the dose recovery comparisons, in which doses obtained using PTTL from glass were compared with those determined using OSL from SMRs and ICs, two different phones were used. These were a ZTE Z820 phone and an iPhone 4S. The complete phones were exposed to a 2 Gy gamma dose, which simulated the emergency exposure. Exposure was conducted using a ^{137}Cs source located at the National Institute of Standards and Technology at a dose rate about 20 μGy/s (calibrated in the units of dose to air; Kessler et al., 2014). Al_2O_3:C Luxel® dosimeters wrapped in black film were attached to the phones' surfaces during irradiation and were later used to validate and compare the doses measured using the existing ^{60}Co calibration of the $^{90}Sr/^{90}Y$ beta-source built into the Risø TL/OSL reader and used for dose reconstruction exercises. The following phone parts were chosen for dose reconstruction. Surface mount resistors (SMRs) and integrated circuits (ICs) were tested using OSL techniques while samples of display glass as well as protective glass (Dragontail® glass for the ZTE phone and Gorilla® glass for the iPhone) were measured using both TL and PTTL techniques. All luminescent-related measurements were conducted with the Risø TL/OSL system TL-DA-15 using Hoya U-340 filter pack that was mounted at the front of a photomultiplier tube in case of OSL tests while a BG-39 filter pack was used for TL and PTTL measurements. The filters allow the detection of the luminescence but exclude the detection of stray light.

Sample preparation procedures for OSL-sensitive samples from dose recovery phones were conducted under laboratory red light. SMRs were extracted from circuit boards using a microscope and a sharp knife. Then the circuit boards were roughly cut with metal snips around each IC location and finally the ICs were separated from the remains of circuit boards with the diamond saw. The outer surfaces of the ICs were normally used for experiments because these surfaces do not require any additional treatment. Furthermore, these surfaces were unaffected by the cutting process. Samples of the display and protective glasses were prepared in similar way, as described above. The display glass samples were additionally etched in 40% HF acid for 4 min, according to the method of Discher et al. (2013).

For SMRs, we used a preheat of 120 °C and OSL readout at 100 °C, which was similar to the "full-mode" protocol described in Bassinet et al. (2014b). The OSL signal was collected for 300 s of stimulation time; the radiation-induced signal (RIS) was calculated as the subtraction of two OSL signals: one integrated over the first 20 s of the OSL decay curve and the second integrated over last 20 s of the same curve (corresponding to the background signal). The obtained signal (which is related to the emergency-simulation dose) was converted to units of dose by use of a 2-Gy calibration dose. At this step, we get an uncorrected value for the dose (i.e. uncorrected for fading). The procedure to correct for fading is described below.

For ICs, the procedure of Sholom and McKeever (2016) was followed except that a single-aliquot regeneration (SAR) protocol (Murray and Wintle, 2000, 2003) was used to avoid the problem with possible sensitization of the samples after repeated exposures. OSL signals were collected for 150 s of stimulation time; the OSL signals were obtained in the same way as in the case of SMRs, but with a shorter integration time (10 s). After both emergency and calibration dose OSL readouts, the sample was exposed to a 0.43-Gy test dose followed by an evaluation of the corresponding test dose OSL signal; the normalized OSL values were then used in all subsequent manipulations.

For measurement of the TL signals from the display and protective glass samples we used the same protocol as described by Discher et al. (2013). The samples were pre-bleached using the Risø blue LEDs for 500 s; two consecutive TL glow curves were recorded for each sample in the range 60–450 °C at a heating rate of 2 °C/s; the second TL glow curve was subtracted from the first to get the radiation-induced TL signal, which was integrated within the temperature range 100–250 °C. For the PTTL measurements on the glass samples, the protocol described in this paper was followed (see section 3.5 below), with a preheat of 350 °C and a 10 min exposure to 365 nm UV light.

3. Results and discussion

3.1. TL and PTTL glow curves

Fig. 1 illustrates typical TL glow curves from Gorilla® glass from an iPhone-3GS, following irradiation of glass aliquots to the beta

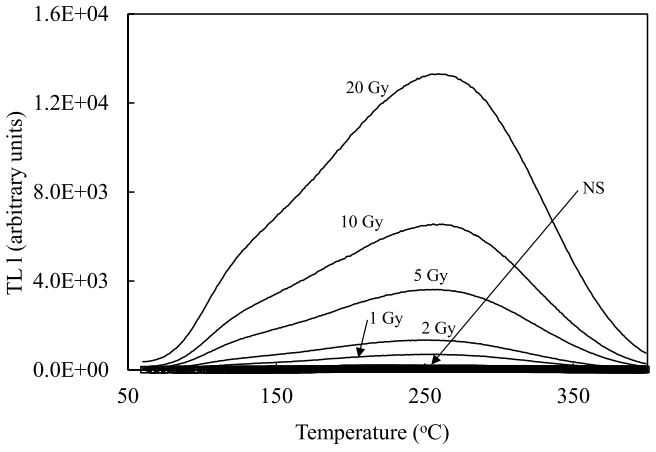

Fig. 1. TL glow curves, obtained at a heating rate of 2 °C/s, for samples of Gorilla® glass from an iPhone 3GS phone, at different beta-particle doses (ranging from 1Gy to 20Gy). The native signal (NS), obtained with 0 Gy added dose, is also shown; the NS is weak in this sample. Each glow curve is from a different aliquot but from the same original sample of glass. The sample has had the protective plastic coating removed and has been washed in ethanol, but was not etched in HF. The glow curve consists of a broad peak near 250 °C and a shoulder around 130 °C. The whole glow curve appears to grow at a similar rate such that the overall shape remains the same for all doses.

particle doses indicated in the figure. Each curve is from a different aliquot from the same sample; all curves were normalized by aliquot mass. (This, of course, assumes a uniform sensitivity over the volume of each sample, an assumption that will need verifying in future studies.) The broad glow curve shape is typical for the samples studied with a main peak at ~250 °C and a low temperature shoulder around ~130 °C. The background, pre-irradiation, native signal was quite weak in this sample, compared to the radiation-induced signal, but was nevertheless observed over a wide temperature range between 150 °C and 400 °C and demonstrated some complex structure.

Fig. 2 illustrates the PTTL signals that emerge following the irradiations given in Fig. 1. All the data shown in Fig. 2 were obtained by irradiating the samples at room temperature at the various doses indicated in the figure. Following the irradiations, the samples were subjected to a preheating at 400 °C followed by a 10-min exposure to UV light at a wavelength of 365 nm at room temperature. The PTTL curves display similar features to the original TL curves, except that the feature around ~130 °C appears even at low dose and appears to be UV-induced, whereas the radiation-induced PTTL component dominates around 250 °C.

The temperatures to which the sample is pre-heated after irradiation were varied during the course of the experiments, from 300 °C to 450 °C. The optimum temperature (i.e. that which gives the greatest PTTL sensitivity) was found to be anywhere in the range 350–400 °C. A pre-heat temperature of 400 °C was used to obtain the data of Fig. 2. Furthermore, two wavelengths were used for UV-light exposure, namely 254 nm and 365 nm. Exposure with 254 nm light was observed to induce a large TL signal, independent of any pre-irradiation (as also reported by others; e.g. Mrozik et al. (2014)). Therefore 365 nm light was used throughout this study. Even though this wavelength was also observed to induce its own TL (see section 3.5 below for further details) the 365 nm-induced TL was weaker than the 254 nm-induced TL. More studies of the wavelength dependence of the UV-induced TL and PTTL are required.

The TL and PTTL sensitivity of the glass samples varied from manufacturer to manufacturer, as did the TL and PTTL glow curve shape. A variety of TL curve shapes for the different samples studied is shown in Fig. 3. The TL from "as-received" glass (no irradiation) is shown in Fig. 3(a) and illustrates the variability in the NS signal among the four glasses. Following each of these TL curves the specimens were illuminated with 365 nm for 20 min. On re-heating the curves of Fig. 3(b) were obtained. There is no obvious correlation between the signal intensities (or shapes) obtained in (b) compared with (a). Fig. 3(c) shows the TL from irradiated glass (2 Gy). After pre-heating (to 400 °C) and 365 nm/20 min exposure, the TL curves of Fig. 3(d) were obtained. Here we see that the most sensitive TL signal and the most sensitive phototransferred signal are both obtained with the Samsung glass.

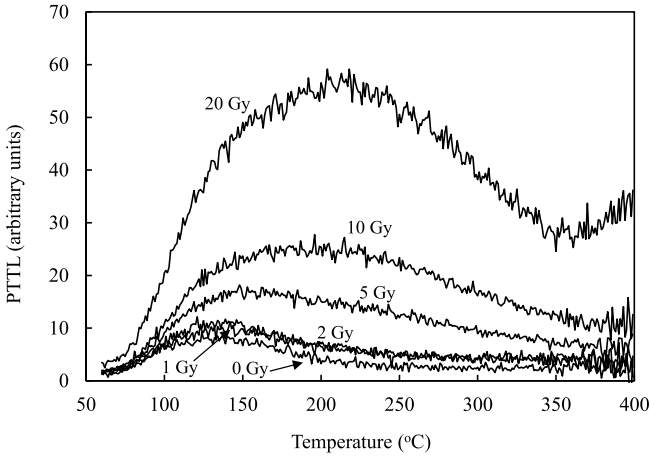

Fig. 2. TL curves from the same samples as used to obtain the data of Fig. 1 following an additional 365 nm UV-light exposure for 10 min at room temperature. Heating rate: 2 °C/s.

3.2. Fading

As noted, the TL from glass is known to fade following irradiation and this is clearly observed in Fig. 4(a) where the TL curve immediately after a dose of 20 Gy is compared to that obtained after a delay of 4 days at room temperature between irradiation and TL measurement. Even the TL at high temperatures (>250 °C) is seen to fade. Previous works describe the fading empirically as a hyperbolic function of t, or a logarithmic function of t (Discher and Woda, 2013, 2014; Bassinet et al., 2014b) where t is the delay time between irradiation and measurement, for storage times substantially greater than the irradiation time. The observed fading rates are "anomalous" in the sense that they are faster than would be expected from consideration of thermal fading only.

The phototransferred TL signal is expected to originate from charge that has been phototransferred during UV-light exposure from deeper, stable traps (McKeever, 1985). These are physically different from those that display the anomalous fading behavior observed in Fig. 4(a). Fig. 4(b) shows the TL signal following irradiation, a 400 °C pre-heat and 365 nm exposure for 20 min. Two curves are shown, one corresponding to no delay between irradiation and UV-light exposure, and another following a delay of 4 days at room temperature before UV-light exposure. PTTL is seen to be much more stable (but not perfectly so) than the corresponding TL signal. Examination of the PTTL stability as functions of pre-heat temperature and UV wavelength is needed to fully characterize the behavior, but these preliminary results are very encouraging, indicating that corrections for fading of the PTTL signal may not be needed in retrospective dose evaluation.

3.3. Dependence on UV-light stimulation time

The variation in the strength of the PTTL signal as a function of stimulation time is observed in Fig. 5 for the samples from iPhone 4S. Two sets of TL curves are illustrated. The first (Fig. 5(a)) shows the curves obtained for "as-received" samples (0 Gy), pre-heated to 400 °C, followed by 365 nm illumination at room temperature for the times shown. The second (Fig. 5(b)) shows the same, but for samples which had initially received a dose of 20 Gy before heating and 365 nm illumination. The behavior of the integrals under the glow curves (between 100 °C and 300 °C) are shown in Fig. 5(c). In both cases, the overall TL signal increases with UV-light illumination time, tending towards saturation after ~1 h. From a comparison of Fig. 5(a) and (b) it can be seen that the TL signal obtained after illumination of an as-received sample has a different shape from that of an irradiated sample. The former is dominated by a TL signal at ~115 °C, whereas the latter has a broad signal, peaking at higher temperature. Since the former is obtained without any pre-irradiation, it is proposed that this signal primarily consists of one that is directly induced by the 365 nm light, presumably from donor states near mid-gap caused by the lack of long-range order in the glassy structure. In Fig. 5(b), however, not only are these induced signals present, but there is also a phototransferred TL signal due to transfer of the charge from deep traps, stable above 400 °C. Thus, the normal PTTL procedures (irradiate – pre-heat – UV exposure – record TL) will produce both a UV-induced TL signal

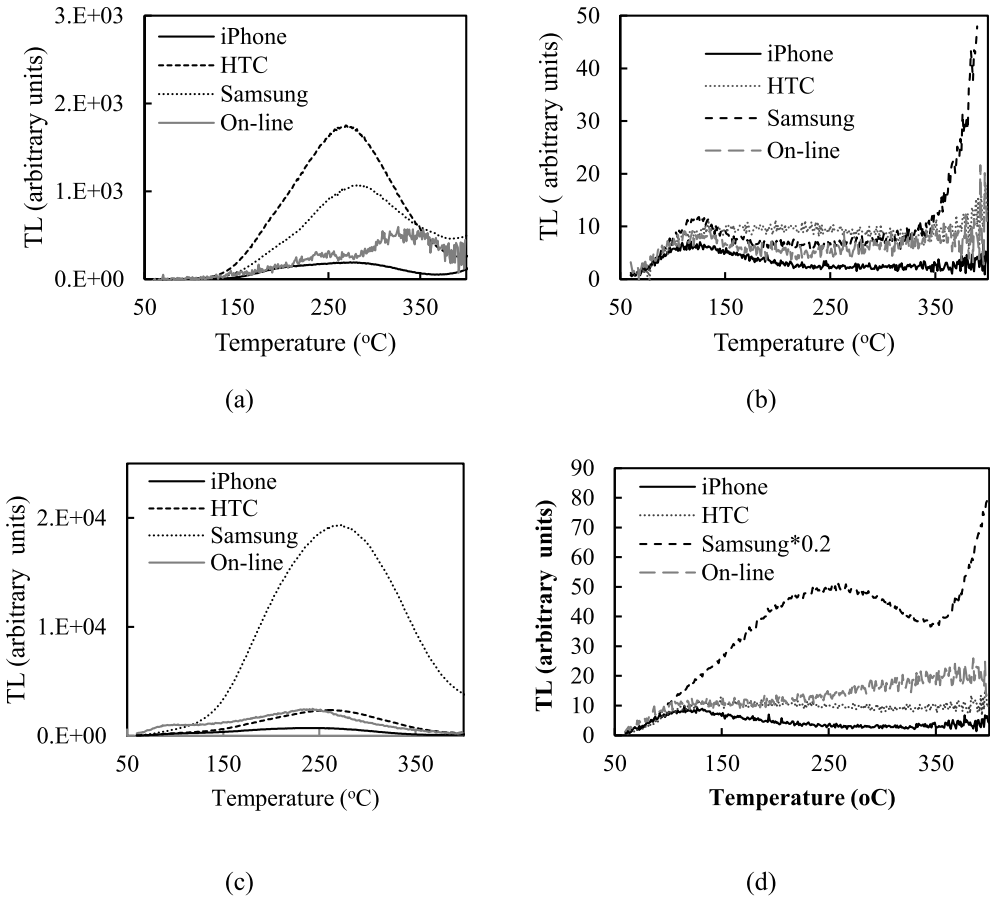

Fig. 3. Comparison of TL and PTTL glow curves from four samples of Gorilla® glass; three from phones, and one from an on-line purchase. The TL from "as-received" (i.e. no irradiation) glass is shown in Fig. 3(a) and illustrates the variability on the NS signal among the four glasses. Following each of these TL curves the specimens were illuminated with 365 nm for 20 min. On re-heating the curves of Fig. 3(b) were obtained. Fig. 3(c) shows the TL from irradiated glass (2 Gy). Following this and exposure to 365 nm UV for 20 min, the TL curves of Fig. 3(d) were obtained. Heating rates: 2 °C/s.

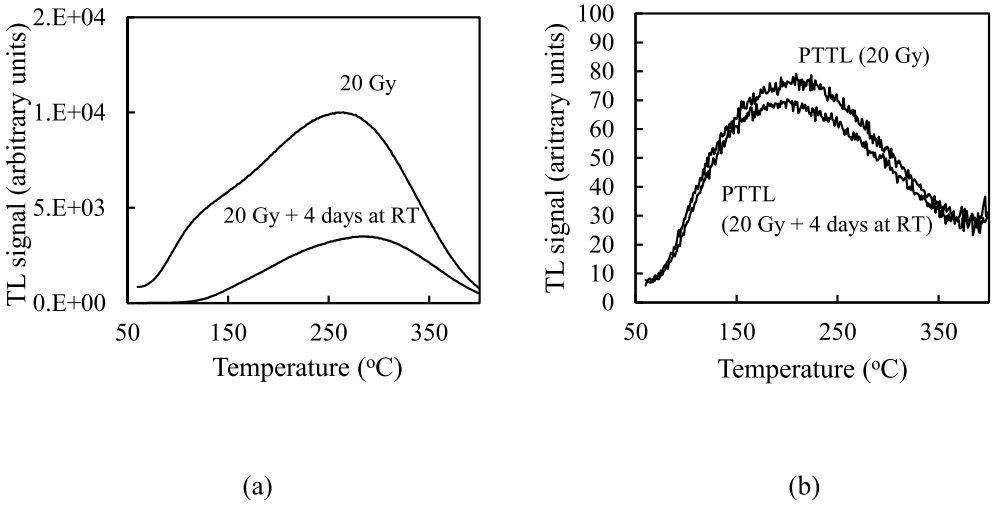

Fig. 4. Fading of the TL signal (Fig. 4(a)) and the phototransferred TL signal (Fig. 4(b)) after 4 days storage under ambient conditions. The PTTL signals were obtained following a 400 °C pre-heat and 365 nm exposure for 20 min. The initial delivered beta dose was 20 Gy.

and a phototransferred TL (PTTL) signal. For this reason the axis of Fig. 5 is labelled with a general "TL", rather than the more specific "PTTL". (We should note here that Fig. 5(a) may also contain a weak PTTL component caused by any unknown, prior irradiation of the "as received" sample. This cannot be eliminated from these measurements. However, following a subsequent dose of 20 Gy in the

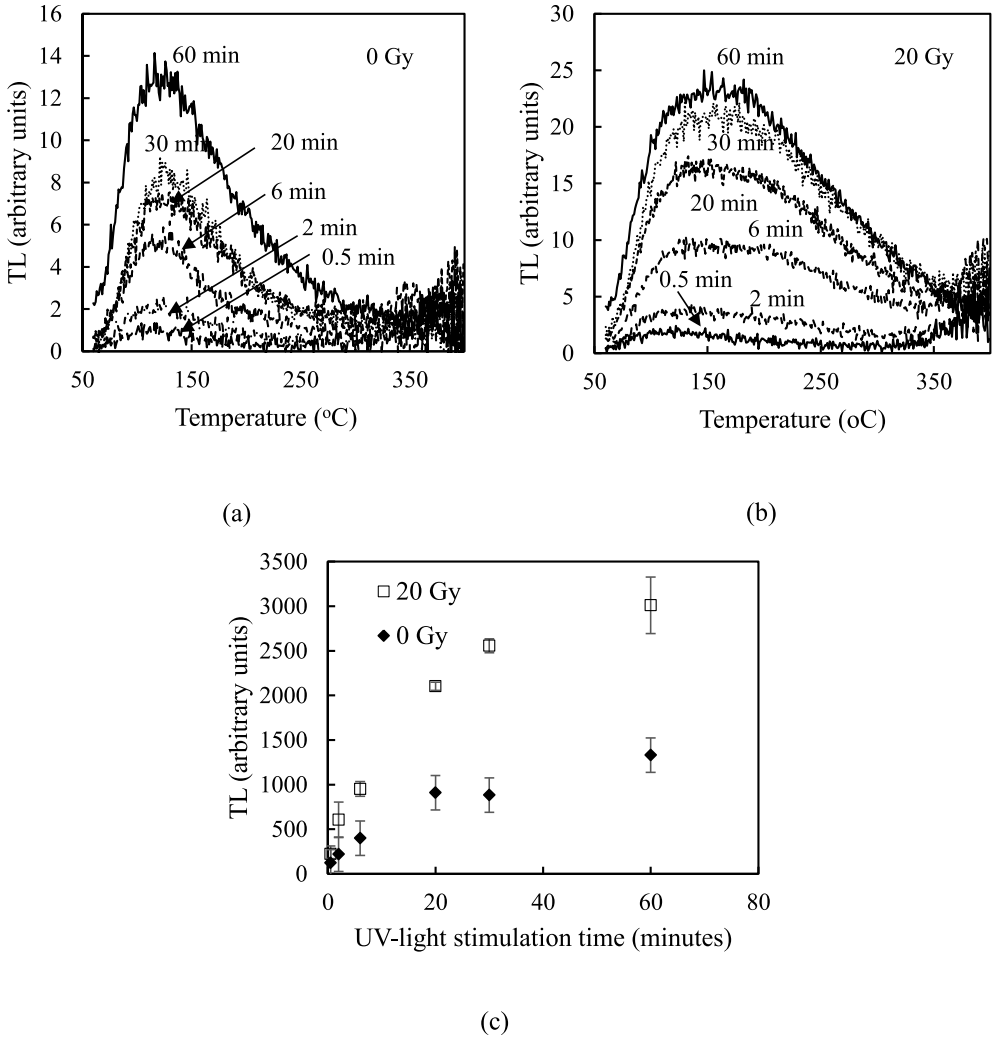

Fig. 5. Variation in the photo-induced TL signal as a function of UV-light stimulation time (365 nm at RT; heating rate: 2 °C/s) for samples of Gorilla® glass from an iPhone 4S phone. In Fig. 5(a) we show the TL curves obtained for the "as-received" samples (no-irradiation) after pre-heating to 400 °C and illuminating with 365 nm light for the times shown. Fig. 5(b) shows the same, but for irradiated (20 Gy) samples. Fig. 5(c) shows the variation in the TL signal, integrated between 100 °C and 300 °C for the two cases.

laboratory, as in Fig. 5(b), the difference in shape is quite clear. Similar observations can be noted in Fig. 3.)

3.4. Dose response

Fig. 6 shows the dose response of the TL signal following 400 °C pre-heat and 20 min of 365nm UV-light exposure at room temperature. Each data point shown in Fig. 6 was obtained by integrating the corresponding glow curve, generated for each dose, over four different temperature intervals. Fig. 6 clearly shows that the dose response of the PTTL signal is linear over the range of doses studied in this work namely between 1 Gy and 20 Gy. Obviously, the larger the integration region the larger the signal and the greater the sensitivity (slope). Since fading is minor over the whole glow curve (Fig. 4(b)) the wider the integration interval may be used for dosimetry. Note also that the dose response does not pass through zero since the TL signal includes the UV-induced signal, which is independent of dose, plus a possible component due to any "as received" dose. Similar dose response curves were obtained for each of the samples studied, although the sensitivity was found to be highly variable among them (see Fig. 3). MDD values extracted from the PTTL dose response curves gave a range of MDDs, from 0.1 Gy to 5.0 Gy.

3.5. Dependence of the phototransferred signals on pre-heat temperature

The dependence of the shapes of the photo-induced TL signals on pre-heat temperature is observed in Fig 7. Fig. 7(a) shows the data for a sample exposed to 15 Gy after 365 nm/20 min at room temperature. It is seen that the TL demonstrates a strong dependence on pre-heat temperature; the signal drops significantly in the pre-heat temperature range 400–500 °C and then remains practically unchanged up to a pre-heat of 600 °C. That is, for the pre-heat temperatures 550 °C and higher the curve shapes become the same. These observations are consistent with the explanation offered in Section 3.3. All the charges accumulated in deep traps due to the 15 Gy irradiation were thermally released by heating to temperatures >550 °C, and all that remains after these higher pre-heat temperatures is a TL signal related to direct stimulation of TL by the 365 nm UV-light exposure. The latter signal is not related to radiation dose.

This observation suggests a method to extract the UV-induced TL signal from a glass sample that has been exposed to an

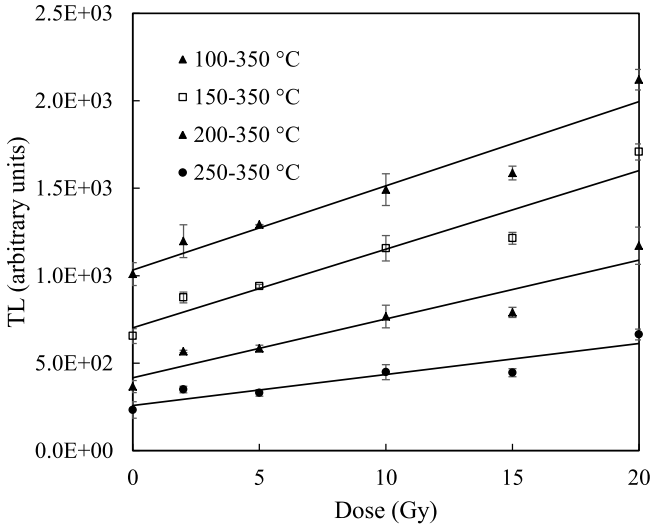

Fig. 6. Dose response curves for the TL after illumination with UV-light (365 nm at room temperature for 20 min following a pre-heat at 400 °C), integrated over the temperature intervals shown (iPhone 4S glass). The TL signal includes both the UV-induced TL component and the radiation-induced PTTL component.

emergency dose before laboratory analysis. The first, cumulative TL measurement for such a sample will consist of a summation of the UV-induced TL signal plus the radiation-induced PTTL signal. It is, of course, necessary to isolate the latter and the present results suggest that this can be done by subtraction of the UV-induced signal from the measured, cumulative PTTL signal. Therefore, in order to account for the unknown UV-induced component of the TL signal from the sample exposed to radiation we propose measurement of the original TL (composed of UV-induced TL plus PTTL) after a pre-heat to 400 °C (I_{irr}), followed by a pre-heat to 550 °C and UV exposure and measurement of the UV-induced signal (I_{UV}). The difference I_{irr}-I_{UV} is then the radiation induced PTTL signal (I_{PTTL}) of interest.

Example data obtained following these steps are given in Fig. 7(b). Curve (1) is the TL obtained for an irradiated sample (5 Gy) following a 400 °C pre-heat and UV-light exposure (I_{irr}). While recording this glow curve the sample was heated to 550 °C. The sample was then re-exposed to UV light, and TL curve (2) was recorded (I_{UV}). This is the UV-induced signal. Curve 3 is the difference between the two (I_{irr}-I_{UV}) and is the true PTTL signal due to the original 5 Gy irradiation (I_{PTTL}). It should be noted that, to date, this proposed approach is suggested only from the data from iPhone glasses. It is yet to be verified on the phones from other brands and its robustness across many glass types needs to be fully tested in dose recovery experiments.

4. Exploratory dose recovery tests

Two phones (ZTE Z820 and an iPhone 4S) were exposed under controlled conditions to a dose of 2 Gy in the NIST reference ^{137}Cs gamma-ray beam (Kessler et al., 2014). SMRs, ICs and protective and display glass were removed as described in the Materials and Methods section. Doses to the SMRs and ICs were obtained using OSL. (The reader is referred elsewhere for detailed protocols; Bassinet et al., 2014b; Sholom and McKeever, 2016.) The display and protective glass samples were examined using both TL, according to the protocol described by Discher and colleagues (Discher et al., 2013) and PTTL, according to the procedure described in this paper. For the latter a preheat of 350 °C was used along with 10 min 365 nm UV-light exposure at room temperature.

Corrections for fading were necessary with TL and OSL from display glass, SMRs and ICs. This was achieved by exposure of the samples to some known laboratory dose D_β and reconstruction of this dose at the delayed time that was chosen to be the same as that between the NIST irradiations and the TL or OSL measurement (5 or 6 days in the current experiments). It should be noted here that, due to the low dose rate of the source at NIST exposure to 2 Gy took about 28 h, which leads to some uncertainty in defining of fading time. In all our tests, therefore, the fading (delay) time was approximated to be the time interval between the corresponding OSL/TL readout and the time at which half of the exposure was reached (i.e. fading time equals half the exposure time plus the time between the end of the exposure and the readout).

Table 1 summarizes the results. The doses recovered by the PTTL method are comparable with those determined by the OSL and TL methods, but with a much greater uncertainty. These preliminary and exploratory results suggest that more research into the efficacy of PTTL from protective glass is warranted. It is too early to say if the technique will ultimately find universal application. However, we do note that the protective glass from the ZTE phone is not Gorilla® glass, but is Dragontail® glass. The current results are therefore

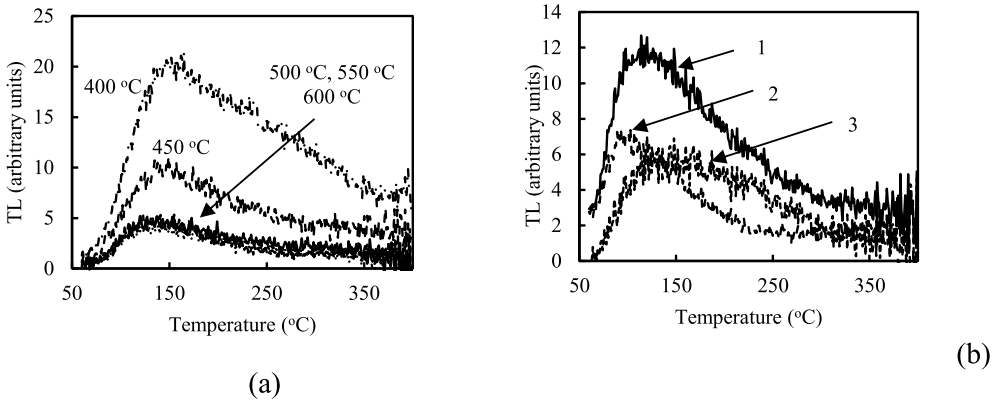

Fig. 7. Comparison of the shapes of the TL signals from various samples (all iPhone 3GS Gorilla® glass) after UV-light illumination. All UV-light exposures, at a wavelength of 365 nm, were for 20 min at room temperature. (a) Dependence on pre-heat temperature, from 400 °C to 600 °C, for a sample irradiated with 15 Gy before pre-heating. (b) Curve (1) - an irradiated (5 Gy) sample following a 400 °C pre-heat and UV exposure (I_{irr}); (2) - the same sample but after pre-heating to 550 °C and UV exposure (I_{UV}); (3) - the difference between curves (1) and (2) (I_{irr}-I_{UV}=I_{PTTL}).

Table 1
Results of the dose reconstruction tests with different materials/techniques. The first and second columns show the measured doses using different components of the ZTE and iPhone respectively. Both the phone components and the method used to determine the dose for each component are indicated in the Table. The standard deviations for the measured doses (stdev) are also indicated in the Table and were determined from dose determinations on three separate aliquots from the same glass samples.

Phone component (technique)	Phone models			
	ZTE		iPhone	
	Dose, Gy	stdev,Gy	Dose, Gy	stdev,Gy
SMR (OSL)				
Regular resistor size	1.72	0.038	n/a	–
Small resistor size	1.71	0.039	2.00	0.055
ICs (OSL)	2.13	0.21	1.92	0.21
Display glass (TL)	1.98	0.11	n/a	–
Protective glass (PTTL)	1.85	0.45	2.60	0.80

encouraging and the PTTL procedures described here may prove to be applicable to other forms of glass from smartphones.

5. Observations, conclusions and the need for further research

PTTL (and TL) was observed from all the Gorilla® glass samples studied. Both the PTTL and the TL sensitivity varied considerably from sample to sample, by a factor of 327 and 35, respectively, with glass from the Samsung phone being the highest for both TL and PTTL. (To calculate sensitivity, the PTTL/TL signals were integrated between temperatures 250 °C and 350 °C (PTTL) or 150 and 350 °C (TL), followed by subtraction of the corresponding background (including the UV-induced signal for PTTL) and division by the corresponding dose.) Similarly, the signal for the as-received (0 Gy) samples varied across the different glasses. It is clear from this that not all Gorilla® glass samples are the same in terms of their TL and PTTL properties. This weakens one of the initial motivations for focusing on Gorilla® glass, namely that it can be found in most smartphones and therefore may be a common material for use in dosimetry. (However, the second reason for focusing on protective glass, namely its ease of extraction from the phone, remains.)

The radiation-induced PTTL demonstrated a linear dependence upon added dose. Furthermore, initial measurements indicate that it has good stability during storage under ambient conditions. The stability needs further examination, using different pre-heat temperatures, different wavelengths and different UV-light illumination times.

The current results also have revealed the presence of a non-radiation-induced TL signal that is directly excited by exposure to UV light (365 nm in the current experiments). This signal is present in all PTTL curves obtained from irradiated samples and is almost independent of the pre-heat temperature for high pre-heat temperatures. For irradiated samples and pre-heats > 550 °C followed by UV-light exposure, it is the only TL signal that is observed in the subsequent glow curve. It must be accounted for when relating the PTTL signal to the absorbed dose. We propose a potential method to account for this signal involving pre-heating an irradiated sample to high temperature (550 °C) and illuminating with UV light. The TL signal so obtained (I_{UV}) can then be subtracted from the PTTL curve initially obtained after pre-heating the irradiated samples to 400 °C, followed by 365 nm exposure (I_{irr}). The difference I_{irr}-I_{UV} is then related to the radiation dose. Dose recovery experiments using iPhone Gorilla® glass and ZTE Dragontail® glass were shown to recover the actual delivered dose, albeit with greater uncertainty than the doses recovered using well-tested OSL and TL techniques from other phone components. Optimization of the parameters to be used in photostimulation and phototransfer (UV wavelength, exposure time, pre-heat temperatures, etc.) should be a goal of future research, after which more detailed and robust dose recovery tests can be carried out on a wider variety of phone types. Although the results presented here are encouraging, no conclusions can yet be reached about the viability of PTTL as an emergency dosimetry tool without these essential additional studies.

Acknowledgements

The authors are pleased to acknowledge financial support from the state of Oklahoma.

References

Bassinet, C., Pirault, N., Baumann, M., Clairand, I., 2014a. Radiation accident dosimetry: TL properties of mobile phone screen glass. Radiat. Meas. 71, 461–465.
Bassinet, C., Woda, C., Bortolin, E., Della Monaca, S., Fattibene, P., Quattrini, M.S., Bulanek, B., Ekendahl, D., Burbidge, C., Cauwels, V., Kouroukla, E., Geber-Bergstrand, T., Piasjkowski, A., Marczewska, B., Bilksi, P., Sholom, S., McKeever, S.W.S., Smith, R., Veronese, I., Gallim, A., Panzeri, L., Martini, M., 2014b. Retrospective radiation dosimetry using OSL from electronic components: results of an inter-laboratory comparison. Radiat. Meas. 71, 475–479.
Bassinet, C., Trompier, F., Clairand, I., 2010. Radiation accident dosimetry on glass by TL and EPR spectrometry. Health Phys. 98, 400–405.
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., 2013. Thermoluminescence of glass displays from mobile phones for retrospective and accident dosimetry. Radiat. Meas. 53–54, 12–21.
Discher, M., Woda, C., 2014. Thermoluminescence emission spectrometry of glass display in mobile phones and resulting evaluation of the dosimetric properties of a specific type of display glass. Radiat. Meas. 71, 480–484.
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.
Fattibene, P., Trompier, F., Wieser, A., Brai, M., Ciesielski, B., De Angelis, C., Della Monaca, S., Garcia, T., Gustafsson, H., Hole, E.O., Juniewicz, M., Krefft, K., Longo, A., Leveque, P., Lund, E., Marrale, M., Michalec, B., Mierzwińska, G., Rao, J.L., Romanyukha, A.A., Tuner, H., 2014. EPR dosimetry intercomparison using smart phone touch screen glass. Radiat. Environ. Biophys. 53, 311–320.
Kessler, C., Allisy-Roberts, P.J., Minniti, R., 2014. Comparisons of the radiation protection standards for air kerma of the NIST and the BIPM for ^{60}Co and ^{137}Cs gamma radiation. Metrologia 51 (Tech. Suppl), 0613.
McKeever, S.W.S., 1985. Thermoluminescence of Solids. Cambridge University Press, Cambridge.
Mrozik, A., Marczewska, B., Bilski, P., Klosowski, M., 2014. Investigation of thermoluminescence properties of mobile phone screen displays as dosimeters for accidental dosimetry. Radiat. Phys. Chem. 104, 88–92.
Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiat. Meas. 32, 57–73.
Murray, A.S., Wintle, A.G., 2003. The single-aliquot regenerative dose protocol; potential for improvements in reliability. Radiat. Meas 37, 377–381.
Sholom, S., McKeever, S.W.S., 2016. Integrated circuits from mobile phones as possible emergency OSL/TL dosimeters. Radiat. Prot. Dosim. 170, 398–401.
Trompier, F., Della Monaca, S., Fattibene, P., Clairand, I., 2011. EPR dosimetry of glass substrate of mobile phone LCDs. Radiat. Meas 46, 827–831.