Investigations of touchscreen glasses from mobile phones for retrospective and accident dosimetry

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**Abstract**

Touchscreen glasses of mobile phones are sensitive to ionizing radiation and have the potential of usage as an emergency dosimeter for retrospective dosimetry for the purpose of triage after a radiological accident or attack. In this study the TL glow curves and dosimetric properties of touchscreen glasses were studied in detail, such as intrinsic background dose, dose response, reproducibility, optical stability and long-term stability of the TL signal.

Preliminary results are additionally presented to minimize the intrinsic background dose by mechanically removing the surface layer of the glass samples. Additionally chemical element analyses of the touchscreen glass samples were carried out to investigate the difference between glass samples which show a TL signal and samples which show neither an intrinsic zero dose signal nor a radiation induced TL signal.

An irradiation trial using glass samples stored in the dark demonstrated a successful dose recovery. However, when applying a realistic, external light exposure scenario, dose underestimation was observed, even though samples were pre-bleached prior to measurement. More investigations have to be carried out in the future to solve the challenge of the low optical stability of the TL signal, if touchscreen glasses are to be used as a reliable emergency dosimeter.

*Keywords:* Retrospective dosimetry; accident dosimetry, touchscreen glass of mobile phones; emergency dosimeter; Thermoluminescence

1. **Introduction**

The use of ionizing radiation sources for industrial, medical and research increases the possibility of accidental exposure of operators and civilians. Attention is also given to the possibility of intentional exposure due to a radiological attack with a high number of potentially exposed people. In the event of such an emergency, the dosimetric triage (using methods of biological and physical retrospective dosimetry) is extremely important to identify the people with high exposures and to distinguish them from the lower and non-exposed, including the so-called “worried-well”, i.e. those who only need to be reassured.

Most of the methods of retrospective dosimetry are based on the measurement of the radiation damage induced in tissues (mainly blood cells) or in personal items worn by the individual (Ainsbury et al., 2011). The possibility to use personal objects such as watches, electronic devices, ID cards, etc. as individual dosimeters has been successfully investigated (Bassinet et al., 2014a; Ekendahl and Judas, 2012; Ekendahl et al., 2015; Fiedler and Woda, 2011; Mrozik et al., 2014a; Mrozik et al., 2014b; Pascu et al., 2013; Pradhan et al., 2014; Sholom and McKeever, 2014; Trompier et al., 2011a; Trompier et al., 2011b; Woda et al., 2009; Woda et al., 2012).

In particular, electronic components mounted on a circuit board, like resistors, inductors or resonators, and display screens of electronic devices appear particularly effective. Previous studies carried out on glass collected from display screens of mobile phones using thermoluminescence (TL) technique provided encouraging results. The investigated dosimetric properties allow using display glass for accident dosimetry (Bassinet et al., 2010; Discher and Woda, 2013; Discher et al., 2013; Discher and Woda, 2014). For instance a good reproducibility of the TL signal and linear response in the studied dose range between 0.1 and above 10 Gy were observed.

Additionally the photon energy dependence and angular response were experimentally investigated for different display glasses used in mobile phones (Bassinet et al. 2014b; Discher et al., 2014) and experimental results validated using radiation transport simulations (Discher et al. 2015).

However, limits related to the fast fading and the presence of an intrinsic background signal, which partially overlaps the radiation induced signal, have been reported (Bassinet et al., 2010; Discher and Woda, 2013; Discher et al., 2013; Discher and Woda, 2014). To correct for signal loss due to light exposure, Discher and Woda (2013) proposed a measurement protocol for dose evaluation, including a partial bleaching of the TL signal by exposure to 500 s of blue light from LEDs of the luminescence reader. Regarding the intrinsic background signal, its origin is not yet understood. The UV exposure at the production or manufacture stage has been suggested as one possible cause (Bassinet et al., 2010). In literature it is also reported that this signal is mainly present in the surface layer of the glass display and can be removed by either chemical (Discher et al., 2013) or mechanical treatments (Bassinet et al. 2014b).

The glass investigated so far was mainly obtained from liquid crystal displays (LCDs). In Fattibene et al. (2014) touchscreen glasses of mobile phones were investigated using electron paramagnetic resonance (EPR) and results of an inter-laboratory comparison are presented. The advantage using a touchscreen glass is that it can easily be replaced compared to other materials, like electronic components. The latter have to be extracted from the circuit board and consequently the mobile phone is irreparably damaged or destroyed.

In the present work touchscreen glasses of mobile phones were studied using the TL technique. In particular, TL glow curves were investigated and samples characterized according to their dosimetric properties, such as intrinsic background dose, dose response, reproducibility, optical stability and long-term stability of the TL signal.

**2. Materials and Methods**

This study was carried out with touchscreen glass samples of different touchscreen modules of an iPhone 4 mobile phone produced by Apple Inc.. Aliquots of glass samples were extracted from the touchscreen glass module with dimensions of approx. 5 x 5 mm2, fitting into the measuring cup of the TL readers. If necessary prior to the first measurement the paint on the surface of the glass was removed by scraping its surface with a metal blade or screwdriver and cleaning the sample with ethanol.

TL measurements were performed using an automated luminescence reader Risø TL-DA-15, equipped with a Thorn-EMI 9235Q bialkali photomultiplier. The TL signal was detected through a Hoya U-340 filter with a transmission window between 290-370 nm. All TL measurements were carried out in a nitrogen atmosphere with a heating rate of 2 °C/s to a maximum temperature of 450 °C and with a second TL measurement for thermal background subtraction.

Pre-bleaching of the samples was applied using the blue LEDs (470±30 nm, approx. 36 mW/cm2 at the sample position) of the Risø TL/OSL-DA-15 luminescence reader. Irradiations for TL measurements were done using the built-in beta source (Sr-90/Y-90) with a dose rate of approx. 27.6 mGy/s, calibrated for display glass using a Cs-137 source of the Secondary Standard Dosimetry Laboratory (SSDL) of the Helmholtz Zentrum München.

For a preliminary investigation both surfaces of the glass samples were mechanically treated with a grinding pencil to study the effect of this treatment on the intrinsic background TL signal. The measurements were carried out at the Istituto Superiore di Sanità (ISS) on a Risø TL/OSL-DA-20 (Hoya U-340 filter, detection window of 290-370 nm) and a Harshaw luminescence reader model 3500. The measurement protocol does not include a pre-bleaching and the heating was set from 50°C to a maximum temperature of 450 °C with a heating rate of 2 °C/s.

The material analysis measurements were carried out at the Department of Archaeology of Durham University. The chemical analyses of the touchscreen glass samples were performed on a Hitachi TM 3000 tabletop scanning electron microscope (SEM) employing an electron voltage of 15 kV (analysis mode). Elemental analysis was performed using a Swift ED 3000 attached to the SEM system, equipped with a silicon drift detector for the energy dispersive X-ray microanalysis. Each non-coated glass specimen was measured at least four times using the area analysis mode.

**3 Results and Discussion**

**3.1 TL glow curves after irradiation and optical stability**

Touchscreen glass samples were irradiated with a dose of 1.1 Gy and were bleached using the blue LEDs of the luminescence reader before the TL measurement. The effect of bleaching the TL signal with different light exposure durations was examined with the same time delay of 500 s between end of irradiation and the TL readout (independent of the light exposure duration) to exclude the effect of signal fading. Optical stability and shape of the radiation induced TL glow curve were investigated on thermally annealed samples.

The radiation induced TL signal is a broad peak with a peak maximum between 190 - 220 °C for the unbleached measurement. It is similar in shape to the TL signal of display glass category A which was investigated in Discher and Woda (2013) and characterised as lime-aluminosilicate glasses by EPR measurements.

In Fig. 1 a the TL glow curves after irradiation and for different pre-bleaching times of sample #2 are shown. Similar results are obtained for all investigated samples.

The light exposure duration was varied between 0 s (unbleached) and 500 s. Optical bleaching leads to a slightly stronger reduction in intensity in the lower temperature part compared to the higher part and to a shift in the peak temperature towards higher temperatures.

Fig. 1 b shows the optical stability of the TL signal normalized to the unbleached TL signal. The degree of bleaching strongly depends on the duration of the light exposure. For reasons to be explained further below the TL signal was integrated between 100-175 °C.



\*\*\*\* Figure 1: TL glow curves of irradiated glass sample #2 measured after different duration of bleaching using the blue LEDs of the reader (a) and optical stability of the integrated TL signal of sample #1 - #4 (b). \*\*\*\*

The optical stability of the TL signal of touchscreen glass is comparable to the investigations of display glass, as observed in Discher and Woda (2014) and Discher and Woda (2013). In general touchscreen glass is exposed to external light sources in a daily use of a mobile phone. A measurement protocol using blue LEDs of the reader for pre-bleaching is appropriate to carry out the dosimetry only on the hard-to-bleach component of the TL signal. In the further study the “pre-bleached with blue LEDs” measuring protocol developed in Discher and Woda (2013) was used.

**3.2 Intrinsic zero dose signal and background dose**

**3.2.1 Comparison of intrinsic and radiation induced TL glow curves**

The investigation of the TL glow curves were carried out with five glass samples. One out of the five samples (sample #5) shows neither an intrinsic zero dose signal nor a radiation induced TL signal. For the other four glass samples a natural, intrinsic zero dose signal was detected even if not exposed to ionizing radiation (see Fig. 2, upper panel). Similar observations were made on display glass samples of mobile phones (Discher and Woda, 2013). However, the intrinsic zero dose signal of touchscreen glass is broader than the signal of display glass, ranging from 150 to 450 °C and peaks at temperatures between 230 and 260 °C. The broad shape of the radiation induced TL signal after pre-bleaching starts at approx. 75 °C up to approx. 400 °C with a maximum between 220 and 250 °C.

As a compromise between maximizing the radiation induced signal intensity and minimizing the influence of the intrinsic zero dose signal, the integration interval of TL signals was set between 100 and 175 °C. These values were used for all investigations to follow in this study.

The TL signals of the intrinsic zero dose signal with the radiation induced TL signal after 1.1 Gy irradiation are additionally shown in Fig. 2, lower panel. For this investigation a new set of glass samples were cut from each touchscreen. The respective glow curves of the same sample can be compared and the superposition of the radiation induced signal with the intrinsic background signal is observed. The investigation explicitly demonstrates the influence of the natural, intrinsic zero dose signal on the TL signal for an unannealed and irradiated sample and justifies the choice of the upper temperature limit.



\*\*\*\* Figure 2: The upper panel shows TL glow curves of the intrinsic zero dose signal (black) and radiation induced calibration signal (red) of the same glass aliquot, previously annealed through the first readout. The lower panel shows the superposition of the intrinsic zero dose signal (black) with the radiation induced calibration signal (red) of the same glass aliquot. All TL signals were recorded after pre-bleaching for 500 s with blue LEDs. \*\*\*\*

**3.2.2 Calculating the background dose**

The intrinsic background dose was calculated for each touchscreen glass sample using the radiation induced calibration TL signal from Fig. 2, upper panel. The protocol “pre-bleached with blue LEDs” (Discher and Woda, 2013) was used for calibration measurements and from the corresponding intrinsic zero dose signal the intrinsic background dose was calculated. Table 1 gives the corresponding background dose for the investigated touchscreen samples.

|  |  |  |
| --- | --- | --- |
| **Sample no.** | **Sample ID** | **Corresponding background dose (mGy)** |
| #1 | iPhone4#12 | 158 |
| #2 | iPhone4#15 | 252 |
| #3 | iPhone4#20 | 141 |
| #4 | iPhone4#23 | 152 |
| #5 | iPhone4#16 | no measureable intrinsic background or radiation induced TL signal |

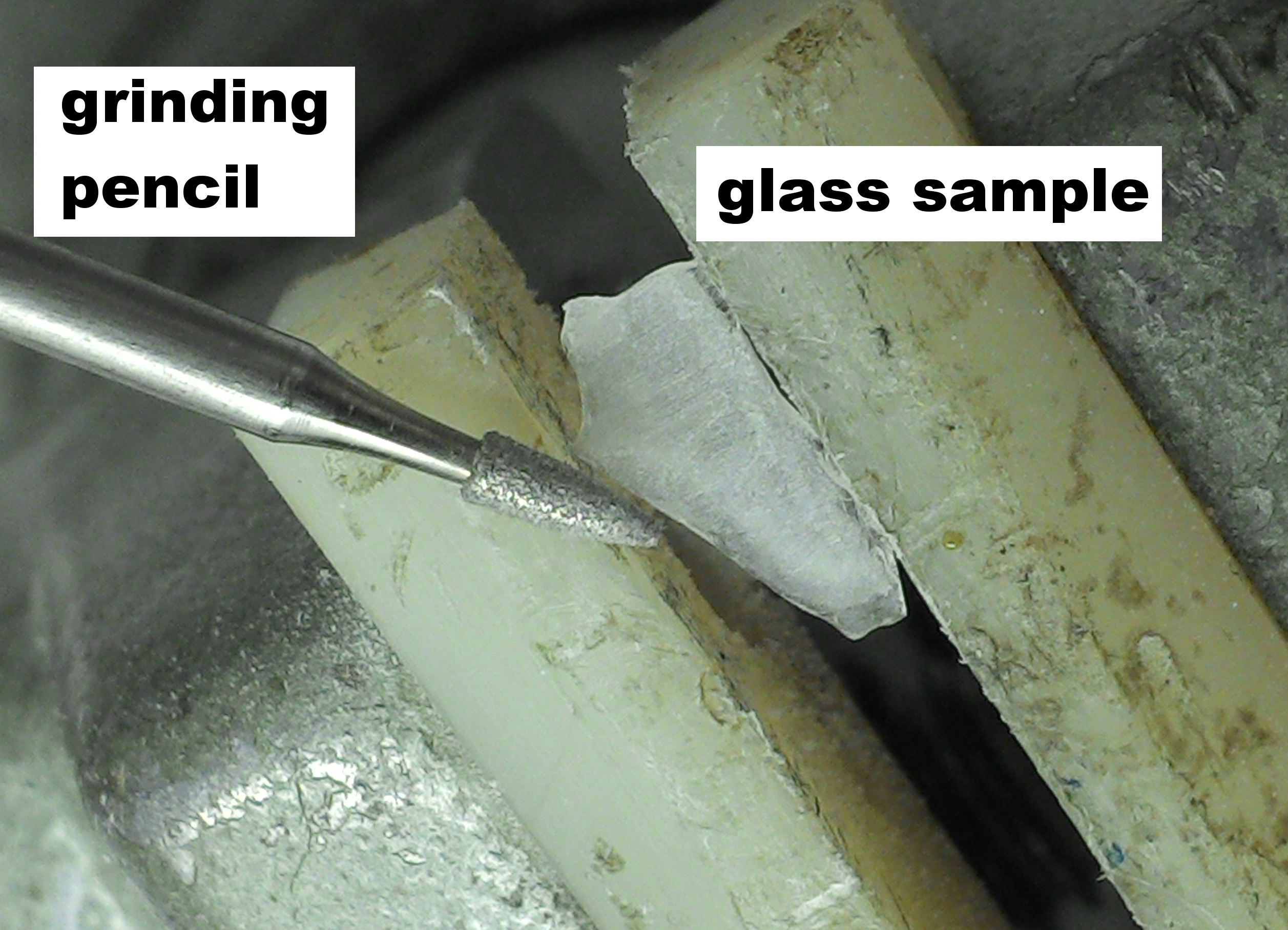
\*\*\*\* Table 1: Corresponding background dose for the investigated touchscreen glass samples. The temperature interval between 100 and 175 °C was used for signal integration. \*\*\*\*

**3.2.3 Abrasion of the glass surface to reduce the intrinsic zero dose signal**

In Discher et al. (2013) a large reduction of the intrinsic background signal of the display glass was observed by etching glass samples with hydrofluoric acid (HF). It was concluded that the intrinsic background signal originates from the surface layer of the glass and that the minimal detectable dose can be significantly reduced by etching.

In the study of Bassinet et al. (2014b) the intrinsic background dose of display glasses was reduced by removing the glass surface layers with a diamond grinding bit. It is important to mention that the main difficulty with this surface treatment was encountered for thin display glasses (such as smartphone glasses) because the glass samples can easily break during this treatment.

Compared to display glass, touchscreen glass is much thicker (approx. 1 mm compared to 0.5 mm). The method of abrading the glass surface was therefore applied to touchscreen glasses. With a grinding pencil both glass surfaces of the touchscreen glass were treated (see Fig. 3) and material of approx. 200-500 µm thickness was removed from both sides.



\*\*\*\* Figure 3: Mechanical treatment of a touchscreen glass sample fixed in a bench vice with a grinding pencil. \*\*\*\*

Fig. 4 a and b show the TL measurements of the same touchscreen sample (sample #1) measured on a Risø (Fig. 4 a) and a Harshaw luminescence reader (Fig. 4 b) for comparison.



\*\*\*\* Figure 4: Glow curves measured on a Risø (a) and a Harshaw luminescence reader (b). In general, a strong reduction of the intrinsic zero dose signal is observed in both measurements. The increase of the TL intensity at high temperatures on the right hand panel is due to the black body emission, as measurements on the Harshaw reader were carried out without a thermal background correction. \*\*\*\*

After mechanical treatment a significant reduction of the intrinsic zero dose signal is observed and the peak of the zero dose signal is no longer clearly visible. The relative reduction in the integration interval 100 – 175 °C can be calculated as between 75 % and 82 % for the measurements using the Risø or Harshaw reader respectively.

In order to check whether the abrasion leads to the generation of a TL signal, a measurement was performed on another sample that was thermally annealed before mechanical treatment (see green symbols in Fig. 4 a and b). The results show that abrasion of the touchscreen samples does not generate any TL signal.

The preliminary study of abrasion of the glass surface to reduce the intrinsic zero dose signal is very promising. However, in this study the further investigations are carried out using mechanically untreated touchscreen glass samples.

**3.3. Results of the elemental analysis of the glass composition**

A chemical element analysis of the touchscreen glass samples was carried out to investigate the difference between the glass samples which show a TL signal (sample #1 - #4) and the sample which shows neither an intrinsic zero dose signal nor a radiation induced TL signal (sample #5). The chemical analyses were performed on a tabletop scanning electron microscope (SEM) equipped with a silicon drift detector for the energy dispersive X-ray microanalysis (see Materials and Methods section for details).



\*\*\*\* Figure 5: Chemical element analysis of the five investigated touchscreen glass samples. The results show the composition of the chemical element as the mean value in weight %. \*\*\*\*

In Fig. 5 the results of the chemical element analysis of the touchscreen glass samples are shown as the mean values with the corresponding standard deviation (3σ) of the element weight %. The mean values are calculated from at least four different measurement areas of each individual glass sample.

The elemental composition of glass sample #5 is quite different compared to the other glass samples: A calcium (Ca) concentration of 4.1 % was detected and the sodium (Na) content is much higher (10.0 %) compared to the other samples (average 3.0 %). However, in contrast, the percentage of aluminium (Al) of 1.5 % and potassium (K) of 1.1 % is minor compared to the other samples (average 14.4 % for Al and 16.6 % for K). The content of magnesium (Mg) is quite similar (≈2 %).

The investigated touchscreen glass is possibly made of Gorilla Glass which is produced by Corning Inc. (Isaacson, 2011). Gorilla Glass is an alkali-aluminosilicate glass (Corning Inc., 2015) which was chemically strengthened by alkali ion exchange. In this process the glass is bathed into a molten alkali nitrate salt at temperatures below the glass annealing point. Host alkali ions of glass (Na+) are substituted by salt ions (K+) at the glass surface layer (Varshneya and Kreski, 2012).

The glass analysis of sample #1 - #4 shows the same chemical elements and can be connected to alkali-aluminosilicate glass. Due to the fact that the glass composition of sample #5 is different it could possibly be a replica after replacing and changing the touchscreen module of the mobile phone.

**3.4 Dose response and reproducibility**

The dose response was measured on the four different aliquots (sample #1 - #4) immediately after irradiation (see Fig. 6). The pre-bleached TL signals show a linear dose response curve in the investigated range of 0.1 to 5.5 Gy.



\*\*\*\* Figure 6: Dose response curve after pre-bleaching for 500 s with blue LEDs. A straight line though the origin was fitted to all datasets. Values for R2 are all better than 0.999. \*\*\*\*

Thermally annealed glass samples #1 - #4 were used to test the reproducibility and possible sensitivity changes of the radiation induced TL signal. It appears that the pre-bleached TL response to a given dose of 1.1 Gy remains within 6 % of the average value of the integrated TL signal. The sequential irradiation and measurement cycles are shown in Fig. 7.



\*\*\*\* Figure 7: Reproducibility of sample #1 - #4 for 10 cycles of irradiation and measurement. The changes are within 6 % of the average value of the integrated TL signal. \*\*\*\*

**3.5 Long-term stability of the pre-bleached TL signal**

The long-term stability up to 51 days is shown for four glass samples in Fig. 8. A signal fading of the pre-bleached TL signal is observed when storing irradiated samples (1.1 Gy) at ambient temperature in the dark.



\*\*\*\* Figure 8: Long-term stability of the pre-bleached TL signal. A logarithmic function of the fading rate is shown for each individual sample (dotted lines) and for the average values (bold, dashed line). \*\*\*\*

Additionally the average values of the TL signals of the samples #1 - #4 were calculated for the different storage times. The variability is 13 %, 19 % and 40 % for storage times of 1 day, 8 days and 51 days, respectively. The fading rates are almost equal for samples #2 - #3. However, for sample #1 the signal fading is a more pronounced, compared to the other samples.

The fading data of each individual sample can be approximated by a logarithmic function of the form: y(t)=a+b•log10(t), with two parameters a and b. The calculated parameters with the R2 value as the goodness of the fit are given in table 2.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Sample #1** | **Sample #2** | **Sample #3** | **Sample #4** | **Averaged fading values** |
| **a** | 0.575 ± 0.028 | 0.680 ± 0.012 | 0.696 ± 0.022 | 0.759 ± 0.035 | 0.678 ± 0.077 |
| **b** | -0.223 ± 0.021 | -0.166 ± 0.009 | -0.159 ± 0.016 | -0.137 ± 0.025 | -0.171 ± 0.037 |
| **R2** | 0.9757 | 0.9920 | 0.9719 | 0.9086 | - |

\*\*\*\* Table 2: Individual parameters a and b of the logarithmic function y(t)=a+b•log10(t) to calculate signal fading with a given storage time t. The parameters of the averaged fading values in the last column are calculated from the parameters of sample #1 - #4 with a given uncertainty (1•σ). \*\*\*\*

**3.6 Irradiation trials**

Two sets of extracted touchscreen glass samples were irradiated in the Risø TL/OSL-DA-15 reader with a beta dose of 2.5 Gy (“accident dose”). Each set consisted of eight glass samples of sample #1 - #4: four annealed glass samples and four unannealed samples, whose natural, intrinsic zero dose signal had not been deleted.

One set of the glass samples which served as a reference was stored in the dark at ambient temperature. The other set was exposed to different external light sources: 2 h of direct sunlight and 16 h of office light exposure. This realistic exposure scenario should simulate a normal, daily use of a mobile phone.

For both sets of samples the dose reconstruction was carried out 5 days after irradiation. Signal loss due to signal fading was individually corrected for each glass sample using the logarithmic function with the sample specific parameters presented in Tab. 2.



\*\*\*\* Figure 9: Results of the irradiation trials and realistic dose reconstruction scenario. A set of touchscreen glass samples consists of four annealed and four unannealed samples. One set was stored in the dark (filled square symbols) and the other set was exposed to external light (open circle symbols). An “accident dose” of 2.5 Gy was applied for both sets of touchscreen glass samples. The corresponding green symbols show data corrected for the intrinsic background (BG) dose. Plotted error bars were calculated from measurement and calibration uncertainty. \*\*\*\*

Fig. 9 shows the results for both set of bleached and unbleached glass samples. The reconstructed dose indicates a fair agreement with the 2.5 Gy “accident dose” for the annealed and unbleached samples.

For the unannealed and unbleached samples, however, an overestimation of the reconstructed dose is observed. For sample #2 and #3 a value of approx. 136 % of the “accident dose” is calculated. An obvious explanation is the intrinsic background dose, which is calculated in Tab. 1 and can be individually subtracted for each sample (see green symbols in Fig. 9). However, this does not lead to an essential improvement in the dose reconstruction due to a possible variation of the background dose within different areas of the touchscreen glass.

The bleached glass samples show a value of about 51 % of the “accident dose” for the annealed samples and about 57 % of the “accident dose” for the unannealed samples. The results indicate that the pre-bleaching protocol is not [sufficient](http://dict.leo.org/ende/index_en.html#/search=sufficient&searchLoc=0&resultOrder=basic&multiwordShowSingle=on) to correct the strong signal bleaching of the [realized](http://dict.leo.org/ende/index_en.html#/search=realised&searchLoc=0&resultOrder=basic&multiwordShowSingle=on) external light exposure scenario. An explanation is the bleaching efficiency of a light source which strongly depends on the wavelength of the source. For display glass a strong reduction of the TL signal (about 86 % compared to an unexposed sample) is observed after exposure to direct sunlight for 500 s, while exposure to the blue LEDs for the same time leads to a reduction of 78 % (Discher and Woda, 2013). Whereas display glass is protected against direct sunlight to a certain degree because of its internal position in the mobile phone, in general the touchscreen glass is not covered and consequently directly exposed to various light sources, including direct sunlight.

The irradiation trials show that with the applied measurement protocol an underestimation of the reconstructed dose is possible, if an external bleaching of the touchscreen glass cannot be excluded.

**4. Summary and conclusions**

The investigations of touchscreen glass samples (Apple iPhone 4) show suitable dosimetric properties.

The radiation induced TL signal is similar in shape to the TL signal of display glass (category A). Investigations of optical stability show a rapid initial decay with quasi-stabilisation after 500 s blue light exposure. This motivated the application of the pre-bleaching protocol.

The dose response up to 5.5 Gy is linear after irradiating the glass samples with the beta source of the TL reader. Investigations of the long-term stability show that the TL signal loss due to signal fading plays an important role and has to be corrected with a signal fading function.

The TL signal of an unexposed glass sample shows a natural, intrinsic zero dose signal, which can be translated to a corresponding background dose (between 140 and 250 mGy for the investigated glass samples) using the radiation induced calibration TL signal with the “pre-bleached with blue LEDs” measuring protocol (Discher and Woda, 2013). The detection limit will be mainly determined by a possible variation in the intrinsic background dose. However, the limit has not been estimated due to the lack of a sufficient number of different glass samples.

Preliminary investigations of mechanically treated glass samples demonstrate a significant reduction of the intrinsic zero dose signal by abrading the glass surface with a grinding pencil. A relative reduction of approx. 80 % was calculated for the background dose which is a good improvement.

Additionally chemical element analyses of the touchscreen glass samples were carried out to investigate the difference between glass samples which show a TL signal and a sample which shows neither an intrinsic zero dose signal nor a radiation induced TL signal. Differences of the glass composition of the elements Na, Al and K and Ca were detected.

The results of an irradiation trial of extracted touchscreen glass samples demonstrate the limitation of the currently applied method. The results of the dose assessment show that the pre-bleaching protocol is not sufficient to correct the strong signal bleaching due to a realistic, external light exposure scenario of the irradiated samples. An underestimation of the reconstructed dose is possible, if an external bleaching of the touchscreen glass cannot be excluded. Future work has to be done to overcome this problem.

In conclusion, dose assessment is in principle possible using glass samples extracted from the touchscreens of modern mobile phones. It is an additional material to existing dose reconstruction methods of other components of a mobile phone, for example components on the circuit board or the display screen glass. The advantage using a touchscreen glass is that it can easily be replaced compared to other materials and that the mobile phone is not irreparably damaged or destroyed by its removal. Nevertheless, more investigations have to be carried out to solve the challenge of the optical signal stability and to estimate the detection limit in order to establish touchscreen glass as a reliable emergency dosimeter.

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