Measurement of a wide-range of X-ray doses using specialty doped silica fibres

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HIGHLIGHTS
- Nominal 8 wt% Ge-doped SiO2 fibre co-doped with B or Br.
- The photonic crystal fibre (PCF) collapsed shows the greatest TL response.
- TL yield of all fibres show linear response with X-ray dose.
- High response tailor-made fibre suitable for use as a TL dosimeter.
- XPS shows less hydrocarbon in annealed capillary fibre elevating surface Ge2p3/2.

ABSTRACT
Using six types of tailor-made doped optical fibres, we carry out thermoluminescent (TL) studies of X-rays, investigating the TL yield for doses from 20 mGy through to 50 Gy. Dosimetric parameters were investigated for nominal 8 wt% Ge doped fibres that in two cases were co-doped, using B in one case and Br in the other. A comparative measurement of surface analysis has also been made for non-annealed and annealed capillary fibres, use being made of X-ray Photoelectron Spectroscopy (XPS) analysis. Comparison was made with the conventional TL phosphor LiF in the form of the proprietary product TLD-100, including dose response and glow curves investigated for X-rays generated at 60 kVp over a dose range from 2 cGy to 50 Gy. The energy response of the fibres was also performed for X-rays generated at peak accelerating potentials of 80 kVp, 140 kVp, 250 kVp and 6 MV photons for an absorbed dose of 2 Gy. Present results show the samples to be suitable for use as TL dosimeters, with good linearity of response and a simple glow curve (simple trap) distribution. It has been established that the TL performance of an irradiated fibre is not only influenced by radiation parameters such as energy, dose-rate and total dose but also the type of fibre.

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1. Introduction
The work represented herein had its beginnings in respect of developments in modern radiation therapy treatment techniques, such advances placing increasing demand on the performance of the associated radiation dosimetry systems. As will be seen later, the work has subsequently extended to encompass a desire to measure increasingly lower doses, extending applicability, the motivation for developing alternative forms of dosimeter also including the possibility of creating devices of size sufficiently small to negate the need for tissue equivalence, linked to...
the Bragg–Gray cavity theory and the ability to have intercavity dosimetry. In pursuing such aims and in regard to our use of silica fibres, it was recognized that the most basic issue concerned developments in fabrication of enhanced TL response silica material. Thus, studies were carried out to verify the extent to which there was success in the doped-silica processing method using the Modified Chemical Vapour Deposition (MCVD) technique, with further studies building on previous experiments, determining the thermoluminescence characterisation measurements themselves in the dosimetry of kilovoltage therapeutic X-ray beams.

A TL material intended for dosimetric purposes is generally doped with impurity atoms to create metastable traps between the valence and conduction band (i.e. within the forbidden band). The luminescence measured has typically been found to be proportional to the amount of energy absorbed via irradiation, allowing use of TL materials for dosimetry. The presence of the extrinsic defects (impurities) lead to a large increase in the sensitivity of thermoluminescence (Alawiah et al., 2013; Abdulla et al., 2001; Abdul Sani et al., 2014; Bradley et al., 2015). Analysis of luminescence when impurities are added into the SiO2 substrate involves a model in which the impurity centre becomes either substitutional atoms, interstitial atoms, an impurity-intrinsinc complex, or an impurity-impurity complex inside the substrate. Apart from the possibility of introducing a new luminescence band (causing localized energy levels within the forbidden energy gap), impurity atoms might also change the number of electron or hole traps. With respect to suitability, several key properties of TL media need to be established, including traps concentration, stability of the traps, efficiency of light emission arising from recombination processes, photon-energy and dose-rate dependence, reproducibility and linearity of TL yield as a function of dose.

With regard to the above, study of the surface oxidation state and elemental studies of Ge-doped silica glass sample have also been undertaken, using being made of the X-ray Photoelectron Spectroscopy (XPS) method. XPS study allows measurement of the energy of electrons emitted from a material, providing the ability to produce chemical state information (as distinguished from elemental presence within the material) from the first superficial layers (down to a few nm) of any surface. This makes XPS a unique and valuable technique for understanding the chemistry of elements near the surface, either as received, or after physical or chemical treatments. The chemical state can best be described here as the local bonding environment of a particular species in question (for the present study, the Ge dopant atom). The local bonding environment of such a species is affected by its formal oxidation state, the identity of its nearest neighbour atom, its bonding hybridization (overlapping) to that of the nearest neighbour atom, as well as the bonding hybridization between the atom in question and the neighbouring atom.

Ultimately, this research work is seeking to support fabrication of enhanced TL yield fibres for passive detection to extend their range of applicability, as previously alluded to, in particular to allow use in diagnostic radiology and environmental radiation monitoring (nGy down to tens of micro-Gy, respectively). As such, one is looking to provide competitive radiation sensitivity approaching or exceeding that of more well established TL dosimeters such as the LiF phosphor-based commercial product TLD-100, a dosimeter which is available in chip, disc and rod form (Mckeever, 1985).

### Table 1

<table>
<thead>
<tr>
<th>Fibres Type</th>
<th>Dimension (μm)</th>
<th>Mass × 10⁻² (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge-Single Mode Fibre (SMF)</td>
<td>Diameter of 120 ± 10</td>
<td>1.6 ± 0.01</td>
</tr>
<tr>
<td>Ge-Flat Fibre (FF)</td>
<td>(100 × 350) ± 5</td>
<td>7.0 ± 0.01</td>
</tr>
<tr>
<td>Ge-PCF (uncollapsed)</td>
<td>Diameter of 125 ± 10</td>
<td>1.6 ± 0.01</td>
</tr>
<tr>
<td>Ge-PCF (collapsed)</td>
<td>Diameter of 125 ± 10</td>
<td>1.6 ± 0.01</td>
</tr>
<tr>
<td>Ge-B-PCF (collapsed)</td>
<td>Diameter of 140 ± 10</td>
<td>1.6 ± 0.01</td>
</tr>
<tr>
<td>Ge-Br-PCF (collapsed)</td>
<td>Diameter of 140 ± 10</td>
<td>1.6 ± 0.01</td>
</tr>
</tbody>
</table>

2. Experimental procedure

2.1. Sample Preparations

The types of SiO₂ fibres used herein are presented in Table 1. They are doped using the MCVD process with a nominal 8 wt% Ge. Four of the fibres are of a uniform circular cross-section along their length, the greater cross-sectional fraction being microstructured as a periodic array of holes, forming what is commonly referred to as Photonic Crystal Fibres (PCF). Two of these PCFs have been c-doped, either with B or Br, there being prior indication of the ability to increase the TL sensitivity as a result. Further, under the application of high temperature (~ 2200 °C), in three of the PCFs the array of holes are brought into a state of collapse, causing the inner walls to fuse, creating strain-related defects in the cooled samples; these PCFs are described as ‘collapsed’ PCFs. In abbreviated form the PCFs are described as Ge-PCF (collapsed), Ge-PCF (uncollapsed), Ge-B-PCF (collapsed), Ge-Br-PCF (collapsed). In addition, we also have two simple fibre forms, fabricated from an initial cylindrical silica tube (single mode fibre) with a central relatively large (~10 s of μm) channel of Ge dopant, with application of a vacuum in one case creating a flat fibre, again creating fused faces and hence strain-related defects, the expectation being that this will also be associated with an increase in the TL yield. These are respectively referred to as Ge-SMF and Ge-FF. The fibres fabrication applied herein have been discussed in detailed by Abdul Sani et al. (2015a, 2015b); the forms are shown in Fig. 1. Prior to irradiation, the optical fibres were cut into lengths of approximately 0.5 cm using an optical fibre cleaver (Fujikura, Japan). The mass of each individual fibre was determined using an electronic balance (PAG, Switzerland), allowing TL yield to be normalized to unit mass of the irradiated fibre (see Table 1). The optical fibres were annealed in a furnace (Carbolite, UK) before receiving irradiations in order to eliminate any previous irradiation memory.

2.2. Sample Irradiations

The doped SiO₂ fibres were irradiated over a wide range of doses from 2 cGy up to 50 Gy at 60 kVp nominal energy, obtained using an X-ray tube facility (Comet, Switzerland) located in the Department of Physics, University of Surrey. The optical fibres were attached to sticky paper (the self-stick notes type) and subsequently located on an MDF board which was then positioned 30 cm away from the uncollimated X-ray beam. With the X-ray tube facility, two focal spot sizes of the X-ray beam are available, between 1.0 mm and 5.5 mm. The smaller of the two focal spot sizes is generally used at relatively low power (low kV and mA) settings. The large focal spot is used when the machine is operated at power levels exceeding the rated capacity of the small focal spot. The power supplied is in the range 640–3000 W, with a supply voltage of 225 kV. The X-ray tube utilized herein has an 0.8 mm Be filter. The filament voltage and tube current is controlled through use of the Comet MXR225/22 X-ray tube software. Prior to irradiations, the X-ray tube was prepared through a warm-up process of enhanced TL response silica material. Thus, studies were carried out to verify the extent to which there was success in the doped-silica processing method using the Modified Chemical Vapour Deposition (MCVD) technique, with further studies building on previous experiments, determining the thermoluminescence characterisation measurements themselves in the dosimetry of kilovoltage therapeutic X-ray beams.
up cycle, taking approximately 30 min.

Subsequent results were attained by exposing the doped optical fibres to a dose of 2 Gy using an orthovoltage X-ray generator (Gulmay, UK), with photons generated at an accelerating potential of 80 kVp, 140 kVp and 250 kVp, as well as using a Varian Linac 2100 linear accelerator operated at a nominal photon energy of 6 MV. For the first of these sources, the sticky papers to which the dosimeters were attached were placed on the surface of a 30 × 30 × 6 cm slab of the water-equivalent Solid Water® phantom and standard output setups were obtained for each nominal beam energy. For the second of these sources (the linac), use was made and standard output setups were obtained for each nominal beam energy. For the second of these sources (the linac), use was made.

2.3. X-ray photoelectron spectroscopy

Ge-doped capillary fibre with dopant in the inner central region, containing 10.08 ± 0.07 wt% Ge (measured by electron dispersive X-ray analysis (EDX)), were cleaned using an ultrasonic bath of 10–20% nitric acid solution in a 15 min cycle. Prior to the investigations, the samples were annealed at 400 °C for 1 h, followed by slow cooling to room temperature for 6 h, seeking to help minimize surface contamination. The sample analysis was performed under ultra-high vacuum (UHV) conditions in a Thermo Fisher Scientific (East Grinstead, UK) theta probe spectrometer. The instrument employs a monochromatic Al Kα X-ray source (hν = 1486.6 eV). The area of analysis was approximately defined by an 800 μm diameter. The pass energy was set at 50 eV for core level high-resolution spectra of all elements of interest and at 300 eV for all survey spectra. The preform sample was held in place on the instrument sample stage by a Cu/Be clip. All data were obtained and quantified using the manufacturer’s Avantage v4.84 software, which incorporates the appropriate sensitivity factors and corrects for the electron energy analyser transmission function (Hinder et al., 2005). All spectra were charge referenced against the C1s peak at 285 eV to correct for charging effects during acquisition.

3. Results and analysis

3.1. Dose response

To investigate the response over a wide range of doses (from 2 cGy to 50 Gy), the fibres loaded on sticky paper (each containing three individual fibres) were irradiated by a 60 kVp X-ray beam.

Ge-PCF (collapsed) showed a TL response some 4 × lower than that of the SMF. This is in line with expectation, given the greater detection efficiency of fibres at the lower photon energy used herein (obtained at 60 kVp). The comparison underlines the impact of collapsing down the holes, with surface fusion of the optical fibre occurring, generating additional strain-related defects and thereby greater TL response. In use of Ge-B and Ge-Br dopants, the defect centres in the internal wall surface of the fibres are much greater than in the case of the Ge-doped fibre. It is therefore to be expected that there will be elevated induced defect centres/strained bond ruptures in the Ge-B-PCF and Ge-Br-PCF, with associated increase in TL response. However, it is also apparent that the Ge-Br-PCF exhibit greater sensitivity compared to pure Ge-PCF (collapsed) from 2 cGy to 25 Gy, saturating beyond that, the additional sensitivity of the Ge-Br-PCF being presumed to be due to extrinsic co-doping with Br. The occurrence of non-linear response of a detector does not preclude its use in TLD provided that it is calibrated and corrected, as appropriate (McKeever, 1985).

To the best of our knowledge there exist no previous reports showing SMFs to outperform TLD-100 to the extent presently reported. However, one should also mention that recently Benabdelsalam et al. (2013) reported TL glow curve analysis of a multimode fibre (MMF) with 62.5 μm diameter with 2-layer Ge-doped fibre compared with TLD-500 and TLD-600. The MMF was shown to be more sensitive than TLD-500 and TLD-600. Zahaimi et al. (2014) demonstrated that the TL yield in a SMF of 8–9 μm diameter can be improved upon by up to 6 times using a larger core MMF with 50 μm diameter with the same cladding size. In the present work, SMFs with 120 μm diameter have been shown to be more sensitive than that of TLD-100 irradiated with photon energy (60 kVp).

It is further apparent that doses of less than 0.2 Gy were undetectable under the present exposure conditions. In respect of particular fibres types, analysis suggests Ge-PCF (uncollapsed) to be significantly less sensitive than the other types of fibre, the sensitivity depending on structural defects in the materials, due herein to fusing of hole surfaces in the PCF (uncollapsed) during the fibre drawing process. It has further been shown herein that the TL response of the Ge-FF is greater than that of Ge-PCF (uncollapsed). In the Ge-PCF (uncollapsed), 168 capillaries were fused together at their outer circumference only, inducing lesser numbers of defects as a result, and hence a relatively lower TL response. The TL yield of the Ge-FF is observed to have similar albeit marginally lower sensitivity than that of Ge-SMF. Further studies are required in order to better understand the complex interplay between the increase in inner surfaces contact length as the fibres become progressively thinner, a matter discussed by Abdul Sani et al. (2015a, 2015b), with respect to the PCF (uncollapsed) and SMF. It is also required in order to understand the type of defects induced in the collapsing region of the doped PCFs and FFs.

3.2. Glow curve

Fig. 3 represents the glow curves of Ge-B-PCF (collapsed), Ge-PCF (collapsed), Ge-B-PCF (collapsed), Ge-SMF, Ge-FF and Ge-PCF (uncollapsed) from irradiation at 60 kVp, delivering doses of 2 cGy, 5 and 50 Gy. In comparing between all the samples, the curves have been normalised to dosimeter mass, the channel profile covering temperatures from 150 °C to 300 °C. In all such cases, the glow curve yield increases with dose as expected, a similar pattern of TL distribution with temperature being seen for each of the three displayed dose regimes. The glow curve area is given in terms of TL yield per unit mass of fibre per unit dose (TL yield mg⁻¹ Gy⁻¹) for a particular source of radiation. The glow curve produced by Ge-B-PCF (collapsed) at 2 cGy peaks at slightly lower temperature (~236 °C), compared to that obtained at 50- and 5 Gy, at around 245 °C, as can be seen in Fig. 2. The glow curve shape and peak temperature differences between PCF (collapsed), PCF (uncollapsed), FF and SMF, indicates that even small changes in the fibre properties are detectable, all manifestations of change in defect centre constitution. The changes suggest the formation of new defect centres in the PCF (collapsed) and FF, not available in the PCF (uncollapsed) and SMF.

3.3. Energy response

It is important in use of the fibres that any energy dependence be characterized. It is apparent at greater photon energy (i.e. that associated with an accelerating potential of 6 MV herein) (Fig. 4) that the TL yield response decreases due to the lower mass energy absorption coefficient at the more elevated photon energies. The greater energy dependence of doped optical fibres in the lower energy range can be explained by the non-soft tissue equivalence of glass, in accordance with the associated energy absorption coefficients, dominated by the photoelectric effect at lower photon energies (Bradley et al., 2014).

Results from these studies can be compared with previous work, specifically for Ge-PCF (collapsed), Ge-PCF (uncollapsed) and Ge-SMF at 80 kVp accelerating potential, being respectively some 5.4, 1.6 and 8.9 times greater than the mean TL response generated by 6 MeV electrons and 6 MV photons (Amouzad Mahdiraji et al., 2015a). The significant energy dependence of the doped fibres in the kV range point to a potential for energy discrimination of the incident photons if these SiO2 fibres are used in conjunction with another TLD type such as TLD 100. In Table 2 presentation is made of the mean energy response of the Ge-B-PCF (collapsed), Ge-PCF (collapsed), Ge-PCF (uncollapsed), Ge-CF and Ge-FF, for X-rays generated at 80, 140 and 250 kV compared to that at 6 MV photons.

![Fig. 3. Combination glow curves of Ge-B-PCF (collapsed), Ge-PCF (collapsed), Ge-Br-PCF (collapsed), Ge-SMF, Ge-FF and Ge-PCF (uncollapsed), irradiated at 60 kVp for 50 Gy, 5 Gy and 2 cGy doses respectively.](http://dx.doi.org/10.1016/j.radphyschem.2016.03.008)
3.4. X-ray mass attenuation coefficients

The mass attenuation coefficient, \( \mu_{\text{en}}/\rho \), as a function of photon energy for the Ge-SMF, Ge-FF, Ge-PCF (collapsed) and capillary fibres, were calculated within the energy range 1–100 keV, using the XCOM program provided by the National Institute of Standards and Technology (NIST) (Berger et al., 1990, 1998). Table 2 shows the values of mass attenuation coefficients of NIST B-100 Bone-Equivalent Plastic. From 100 keV to 1000 keV, with the reduced energy dependence of Compton scattering events dominating, there is more general accord between the various media.

Table 2
Summary of the average ratio of energy response for doped optical fibres generated at 80, 140, and 250 kV, normalized to that of 6 MV photons.

<table>
<thead>
<tr>
<th>Fibres Type</th>
<th>Average Ratio of Energy Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 kV: 6 MV</td>
</tr>
<tr>
<td>Ge-B-PCF (collapsed)</td>
<td>5.2</td>
</tr>
<tr>
<td>Ge-PCF (collapsed)</td>
<td>6.8</td>
</tr>
<tr>
<td>Ge-Cylindrical Fibre (CF)</td>
<td>8.2</td>
</tr>
<tr>
<td>Ge-Flat Fibre (FF)</td>
<td>3.5</td>
</tr>
<tr>
<td>Ge-PCF (uncollapsed)</td>
<td>3.3</td>
</tr>
</tbody>
</table>

3.5. X-ray photoelectron spectroscopy

Nominal 10 wt% Ge-doped capillary fibres with dopant in the inner central region and fabricated in each case from the same Ge-doped preforms have been measured. The fibres were cut into an approximate two halves to allow scanning on the inner dopant area (see inset Fig. 6(b)). The high resolution \( \text{Ge}_{2p3/2} \) core level peak is shown in Fig. 7. The summary binding energy and atomic percentages of the detected elements are presented in Table 3.

In Fig. 6, it is apparent that the concentration of C1s of the annealed capillary fibre is less than that of non-annealed capillary fibre. Many surfaces are known to adsorb hydrocarbon from ambient air, including SiO2 (Shinozaki et al., 2003, Choi et al., 2003).

Fig. 6. A survey spectrum is shown for the example Ge-doped non-annealed and annealed capillary fibres, revealing the XPS transitions made accessible using Al Kα radiation (1486.60 eV). The comparative study has been made using samples treated using two different approaches, non-annealed and annealed capillary fibres, examining possible effect upon reproducibility. The inset shows; (a) The Scanning Electron Microscope (SEM) image from the cross-section of nominal 10 wt% capillary fibre being doped with Ge in the inner ring region, and (b) two pieces of split capillary fibres used for the investigation, allowing access to the doped region.

Fig. 7. A high resolution spectra of the \( \text{Ge}_{2p3/2} \) of the non-annealed and annealed capillary fibres, revealing the peak binding energy to be located at 1218.20 eV and 1216.60 eV with atomic percentages of 0.18% and 0.84% respectively.

Such hydrocarbon adsorption decreases the surface energy of the substrate. Removing the hydrocarbon by thermal annealing (at 400 °C) resulted in a concurrent increase of the Ge2p3/2 by factor 4 (Fig. 7). This is due to the disproportionate relation of the kinetic energy and the binding energy of Ge2p3/2 electrons. The Ge2p3/2 has a low kinetic energy and will thus have a much smaller attenuation length than the Si2p transition. A layer of carbon will thus reduce the intensity of the Ge2p3/2 signal more significantly than that of the Si2p. The reduction of C1s in the annealed capillary fibre is a consequence of the partial removal of the adventitious hydrocarbon contamination from ambient air exposure as mentioned above.

Comparisons of calculated electron attenuation lengths (EALs) for XPS with Al Kα X-rays in a range of measurement configurations for two illustrative cases have been reported: Si2p photoelectrons in C (for which elastic-electron scattering effects are relatively strong) at 1385 eV and Ge2p3/2 photoelectrons in C (for which the elastic-electron scattering effects are relatively weak) at 150 eV. The determination of electron attenuation length (AL) is important in XPS for the determination of layer thicknesses in the nanometer range for a particular electron kinetic energy. The signal intensities of the early overlayer-film depend quasi-exponentially on film thickness, and it is thus natural to refer to the exponential parameters as the attenuation length. For that the following simple relation can be used:

$$I_\text{f}\left(E\right) = I_\text{i}\left(E\right)\exp\left(-\frac{E}{\lambda_\text{c} \cos \theta}\right)$$

where $I_\text{c}(E)$ and $I_\text{i}(E)$ are the respective intensity for a photoelectron peak of energy $E$ for a layer of thickness $d$ of the substrate material and that for the bulk substrate. In Eq. (1), the electrons are detected at an angle $\theta$ to the surface normal and $\lambda_\text{c}$ is the AL of the substrate photoelectrons in the overlayer material. With a path length of one $\lambda_\text{c}$ 65% of all electrons are scattered. Sampling depth is defined as the depth from which 95% of all photoelectrons are scattered by the time they reach the surface ($3\lambda_\text{c}$). Most AL’s are in the range of 1–3.5 nm for AlKα radiation. So the sampling depth ($3\lambda_\text{c}$) for XPS under these conditions is 3–10 nm (Watts and Wolstenholme, 2003).

The relative sensitivity of the EALs ($\alpha_{\text{EAL}}$) is evaluated directly from the software for Quantitative Analysis of Surfaces by Electron Spectroscopy (QUASES), characterizing surface nano-structures by analysis of electron spectra (Tanuma et al., 1994). The ratio of the average EALs for Si2p photoelectrons is found to be 3.68 whereas for the Ge2p3/2 photoelectrons it is 0.86 in the C layer. To compute the effects, some parameters are required for Si2p and Ge2p3/2 and these are the thickness of the substrate material of 1 nm and the angle to the surface normal of 52°. The relative intensity of electrons for Si2p photoelectrons and Ge2p3/2 photoelectrons in the C layer are therefore found to 0.163 and 0.695 respectively, being consistent with the disproportionate attenuation of the Ge2p3/2 electrons.

The nominal binding energy of the C1s electron is 284.6 eV, subtle but reproducible shifts in the actual binding energy, the so-called chemical shift, provide the chemical state information referred to here. Abdul Sani et al. (2015a, 2015b) have found that the surface oxidation state of Ge-doped silica fibres are predominantly in the form of GeO₂ (±4 oxidation state) within the core.

### 4. Conclusion

The present studies in this investigation have been aimed at characterising the doped silica optical fibre system as a 1-D dosimeter for applications in radiation therapy. Studies have been carried out to establish the extent of dose linearity and energy response of the Ge-B-PCF (collapsed), Ge-Br-PCF (collapsed), Ge-PCF (collapsed), Ge-PCF (uncollapsed), Ge-SMF, Ge-FF in comparison to that of TLD-100 at various photon energies. The dosimeter showed good linearity of response up to a dose of 50 Gy (the largest dose applied) for photon beams. Over the range of doses delivered (2 cGy–50 Gy), for the nominal X-ray energy of 60 kVp investigated, linearity of TL yield normalised to unit mass of the fibres has been obtained, the correlation coefficient ($R^2$) being observed to be greater than 0.9482 for Ge-B-PCF (collapsed), Ge-PCF (collapsed), Ge-PCF (uncollapsed), and Ge-SMF. However, the Ge-Br-PCF (collapsed) is observed to produce a linear response only over the more limited dose range from 2 cGy to 25 Gy, with saturation of TL yield beyond that (up to 50 Gy) with a correlation coefficient of 0.8945. It should also be noted that Ge-FF produces a correlation coefficient of 0.8212. Ge-doped FF and Ge-doped PCF (uncollapsed) produced the least TL yield of all of the fibre types, a result that is again expected to be linked to the rather unusual geometry of these compared to the other fibre types, a matter which again could be explored in greater detail in simulation studies. In comparison to the response to 60 kVp X-rays for TLD-100, the performance of all of the tailor-made doped fibres of this work is significantly enhanced. With consideration to energy response, a marked reduction in TL yield is observed with increase in nominal photon energy over the range 80 kVp, 140 kVp, 250 kVp and 6 MV, due to the lower mass energy absorption coefficient at the more elevated photon energies. Comparison studies have been conducted on non-annealed and annealed capillary fibres, the latter of these indicating the presence of less hydrocarbon components thus elevating the Ge2p3/2 electrons from the surface layer, used being made of X-ray Photoelectron Spectroscopy (XPS). The capillary fibres used herein were washed in acetone in an ultrasonic bath, advantageously removing surface contamination species resulting from sample handling and fibre pulling.

These results are expected to help in understanding the influence of the doped silica structure, also involving characterisation of the fundamental parameters that control thermoluminescence yield of the media under investigation.

### Acknowledgement

We would like to thank the scientific and technical staff of the Royal Surrey county Hospital (RSCH) and Structure Analysis Laboratory and Micro Structural Studies Unit, University of Surrey for their help in carrying out X-ray irradiations and surface analysis. We would also like to acknowledge the TM R&D/MMU lab, sited at the Multimedia University, for fabricating the fibres. The authors are grateful for a University of Malaya – Ministry of Higher Education of Malaysia UM - MOHE High Impact Research Grant UM.C/625/1/HIR/33. The fibres used herein were all fabricated using the University of Malaya Fibre Drawing System, supported by the University of Malaya - Ministry of Higher Education of Malaysia UM-MOHE High Impact Research Grant A000007–90001.

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**Table 3** Summary XPS analysis for Ge-doped non-annealed and annealed capillary fibres.

<table>
<thead>
<tr>
<th>Capillary Fibre - non annealed</th>
<th>Binding Energy (eV)</th>
<th>Atomic Percentage (At%)</th>
<th>Capillary Fibre - annealed</th>
<th>Binding Energy (eV)</th>
<th>Atomic Percentage (At%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge2p3</td>
<td>1218.20</td>
<td>0.18 ± 5.00</td>
<td>Ge2p3</td>
<td>1216.60</td>
<td>0.84 ± 5.00</td>
</tr>
<tr>
<td>Si2p</td>
<td>99.20</td>
<td>22.62 ± 2.00</td>
<td>Si2p</td>
<td>99.60</td>
<td>23.91 ± 2.00</td>
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<tr>
<td>C1s</td>
<td>528.60</td>
<td>62.68 ± 2.00</td>
<td>C1s</td>
<td>528.60</td>
<td>65.88 ± 2.00</td>
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<td>C1s</td>
<td>282.00</td>
<td>14.52 ± 2.00</td>
<td>C1s</td>
<td>281.40</td>
<td>9.38 ± 2.00</td>
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References


