DOSIMETRIC STUDY OF MONOCRYSTALLINE SILICON SOLAR CELL

H. DIAB, A. IBRAHIM**, R. ELMALLAWANY****

*Radiation Dosimetry Laboratory, National Institute for Standards, Egypt,
e-mail: hdiab2003200327@yahoo.com
**Physics Department, Faculty of Science, Tanta University, Egypt
***Physics Department, Faculty of Science, Menofya University, Egypt

Abstract. Monocrystalline silicon solar cell of the construction n^+pp^{++} Passivated Emitter Solar Cell (PESC) was irradiated by ^{60}Co gamma ray dose. Thermoluminescence (TL) main dosimetry peak was investigated. The results showed that it is possible to determine gamma dose more accurately from TL main dosimetry peak for Monocrystalline silicon solar cell in comparison with TLD (100). Also the various sources of uncertainty were analyzed. The expanded uncertainty at 95% confidence level should be added to the value of measurements to obtain accurate dose.

Key words: Thermoluminescence, solar cells, dosimetry, uncertainty.

INTRODUCTION

The solar cell is a key component in various commercially available solar-powered products and equipment, and conventional solar cells generally exhibit good spectral response to visible radiation, which occupies the 400–800 nm wavelength region of the electromagnetic spectrum. Silicon crystalline solar cells, however, exhibit a response to electromagnetic radiation having substantially shorter wavelengths, e.g., X- and γ-rays [3, 7, 12]. To select a detector for dosimetry three important factors are sensitivity, energy independence and convenience. Silicon solar cells have high volume sensitivity in the low-energy range associated with mammography, however, the sensitivity becomes dose dependent at low-dose rates. The dose rate dependence of sensitivity appears to be common to all silicon photodiodes but different types exhibit it to different degrees. Fortunately, it is possible to select photodiodes, the dose rate dependence of which is not significant at the levels of exposure encountered in routine mammography. In the energy range 10–50 keV silicon photodiodes with thin

Received: June 2012;
in final form September 2012.

ROMANIAN J. BIOPHYS., VOL. 22, No. 2, P. 125–135, BUCHAREST, 2012

detection volumes are relatively energy independent and are well suited for mammography. Silicon photodiodes are much less suitable for general radiographic dosimetry due to the large variation in sensitivity which occurs from 50 keV upwards [7].

Lithium fluoride is undoubtedly the most common material as thermo luminescence detector. It is considered a popular TL detector material in routine applications for personal, environmental and clinical dosimetry, commercially several chips are available and differing from each other for dopant concentration [1]. From the publication EUR 5358 Technical recommendations for the use of thermoluminescence for dosimetry in individual monitoring for photons and electrons from external sources, we can derive a list of commonly encountered sources of errors, can be driven that affect the precision and accuracy in determining the dose under geometrical conditions [11]. The effect of ^{60}Co (γ-ray) irradiation on the electrical properties of Au/SnO_2/n-Si (MIS) structures has been investigated using the capacitance-voltage and conductance-voltage measurements in the frequency range 1 kHz to 1 MHz at room temperature [8].

A new approach for hybrid metal-insulator-semiconductor (MIS) Si solar cells is adopted by the Institute of Fundamental Problems for High Technology, Ukrainian Academy of Sciences. In order to interpret the effect of illumination and ^{60}Co γ-ray radiation dose on the electrical characteristics of solar cells they are studied at room temperature. Before the solar cells are subjected to stressed irradiation six different illumination levels of forward and reverse bias I-V measurements are carried out at room temperature. The solar cells are irradiated with ^{60}Co γ-ray source irradiation, with a dose rate of 2.12 kGy/h and an over dose range from 0 to 500 kGy. Experimental results show that both the values of capacitance and conductance increase with increasing illumination levels and give the peaks at high illumination levels [15].

The purpose of this study is to provide a better understanding of the response of Monocrystalline silicon solar cell to gamma radiation to calculate and determine the sources of uncertainty to get information on the accurate gamma dose measurement.

MATERIALS AND METHODS

MATERIALS AND INSTRUMENTATIONS

Standard monocrystalline silicon solar cells, granted by the firm Siemens, are used in this work (Solartic Company, Czech Republic). The resistivity of the starting material for the $n^+ pp^{++}$ cells (n^+ heavy doped of phosphorus, pp^{++} heavy doped of boron) is ranged from 1 to 2.5 Ω cm (p-type). The cell area is 10.00 cm × 10.00 cm pseudo-square Czochralski Cz silicon {100} wafers. Cell thickness is 340 ± 50 μm. The silicon solar cell has a uniform colour of the active area, sharp contours of the busbars and fingers and optimum design following maximum conversion efficiency, even in lower light.

The $n^+ pp^{++}$ structure has a top contact passivation by the use of a thin oxide layer underlying this contact, as well as top surface passivation by a slightly thicker oxide layer, where the electrical contact is made directly through narrow slots in the thin oxide. In this case contact passivation is obtained by minimizing the contact area. The top contact metallization is a Ti/Pd/Ag multilayer. The use of a low work function metal such as Ti as the contact layer is essential with this approach. This is to produce an electrostatically induced accumulation layer in the underlying silicon, an important factor in reducing contact recombination. The cell used alloyed aluminium to give a heavily doped region near the rear contact and was fabricated on polished (100)-oriented 0.7 Ω cm substrates. Surface passivation is easier to achieve on polished rather than textured or "as-lapped" surfaces. To minimize reflection losses, a double layer antireflection (AR) coating layer of silicon nitride (Si_3N_4) was used [10].

TL detectors used were Harshaw LiF: Mg. Ti discs (4.5 × 0.9 mm), TLD-100 (Natural Li) TLD-700 (Isotope ^{7}Li).

Standard ^{60}Co-source dose was used at rate 5.672 rad/min at Radiation Department, National Radiation Technology.

The farmer dosimeter of the type 2570 manufactured in the U.K. by Nuclear Enterprises Ltd. with its special ionization chamber 2571 sufficiently sensitive to γ-rays under the optimum condition of pressure and temperature was used to determine the dose rate of the ^{60}Co source.

A 4500 TLD reader (Harshow, Bicorn Company) was used to measure the TL-response of gamma doses. The heating rate was 5 °C/s. The maximum reading temperature was 350 °C.

METHODS

Each of detectors was annealed in air at 400 °C for 1 h followed by 2 h annealing at 100 °C. The reading of TL-signal was carried out using TLD reader. The TLD were irradiated with doses ranging from 0.5–2 Gy.

Code of practice IAEA (1994) for the treatment of uncertainties to calculate standard uncertainty, expanded uncertainty (at confidence level 95%) combined uncertainty for different errors of our experiment was used.

RESULTS AND DISCUSSION

EVALUATION OF DIFFERENT GAMMA DOSES USING SOME TLD DOSIMETERS

Fig. 1 shows the characteristic glow curves for TLD-(100) as a function of absorbed gamma dose (0.5 Gy up to 2 Gy). Fig. 1 indicates that, for TLD-(100), there were three glow peaks at about 35 °C, 110 °C, and 210 °C respectively. The TL-intensity was significantly increased with increasing doses. This means that the heights glow curves correspond to deeper traps [2]. The maximum peak height was changed linearly with dose, which suggests detecting and monitoring the dose. The higher temperature peak was more dominant for all doses. It is stable peak; the broadness of the peak could be as a result of the existence of a closely spaced trapping center for which individual glow peaks could not be resolved. This indicates a complex trapping system in TLD-(100) [11, 14].

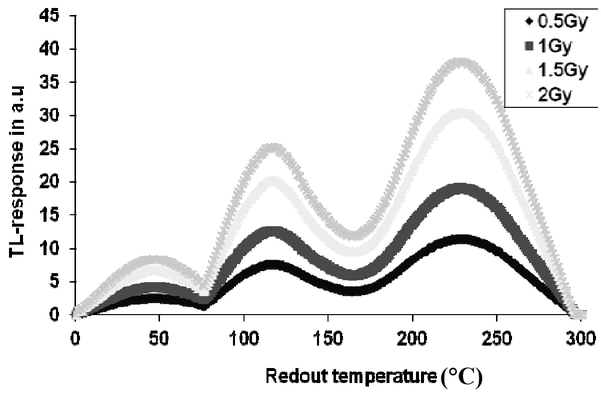

Fig. 1. The different glow curves for different doses for TLD (100).

Fig. 2 shows characteristic glow curves for monocrystalline silicon solar cell through heat deconvolution up to 400 °C irradiated with different low doses (0 Gy up to 2 Gy). The glow curve shows a strong peak at 230 °C, the peak changes quantitatively with dose, so the application of this peak in radiation dosimetry is withdrawn with respect to the applied dose. This was acquired at heating rate of 2°C·s^{-1}. A good fit of the main glow peak can be obtained at 230 °C. The local of the peak does not change by increasing the dose, only the response increases in linear relationship. The maximum peak height changes linearly with dose which suggests detecting and monitoring the dose. The higher temperature peak is more dominant for all doses. It is stable peak. The broadness of the peak could be as a result of the existence of a closely spaced trapping center for which individual glow peaks could not be resolved. This indicates a complex trapping system in monocrystalline silicon solar cell. Also the peak remains in the same position independently of the radiation dose used.

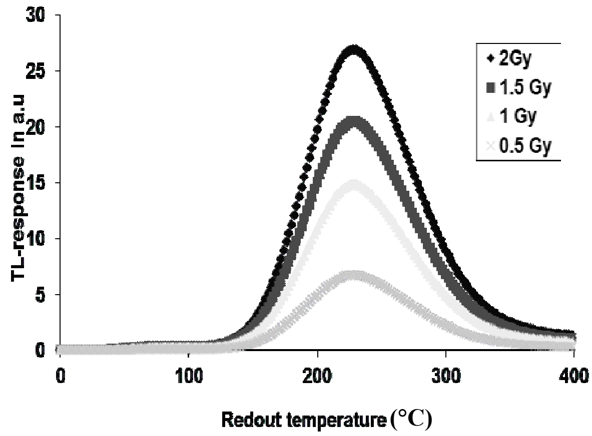

Fig. 2. The different glow curves for different doses for solar cell.

Electrical performance of silicon solar cells was degraded by irradiation by γ-rays. The power output of the cells receiving γ-radiation damage was restored to almost the value obtained before irradiation. These findings indicate that the radiation damage caused γ-rays, occur by two different mechanisms. The first is a displacement of silicon atoms from their lattice sites in the crystalline silicon solar cell. The displacement occurs by an (n, p) scattering-reaction originating in γ-rays. The second is physical damage due to α- and p-charged particles which incur a considerable ionization within the junction space charge region.

TL-responses (peak areas) for the main dosimetry peak as a function of gamma dose as given in Fig. 3. The dosimetry peak in this range showed linear dependence in each detectors, this suggest to take this parameter to detect and monitor the therapeutic dose up to 2 Gy using monocrystalline silicon solar cell.

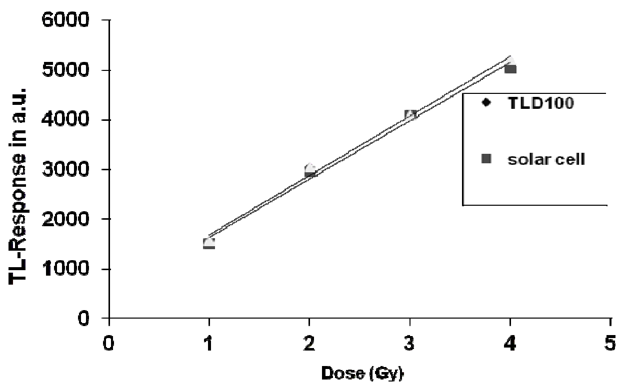

Fig. 3. TL integral value response *vs*. dose of TLD100, solar cell, for irradiation with ^{60}Co photons.

TL-responses (peak heights) as a function of gamma dose are given in Fig. 4. That shows the TL response had maximum peak height as a function of gamma dose for monocrystalline silicon solar cell. The integral value of the dosimetric peak for monocrystalline silicon solar cell was increased linearly at different doses in the covered range from (0.5 Gy up to 2 Gy). It is better to express the results as peak heights because it gave better spatial resolution than peaks areas due to smaller dissipation. The relative sensitivity of the main dosimetric peak of monocrystalline silicon solar cell in relation to TLD-100 was 0.95, 0.88 respectively.

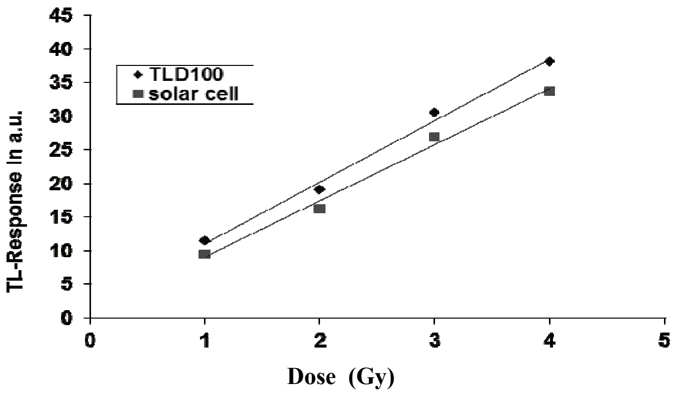

Fig. 4. TL response *vs*. dose of TLD100, solar cell, for irradiation with ^{60}Co photons, TL response is obtained as a peak height value.

The results showed that it is possible to determine gamma dose accurately by using the monocrystalline silicon solar cell. The TL enhancement response to gamma radiation makes the TLD-100 system a promising material for gamma detection dosimetry. This could be achieved in different ways:

- by lowering reading temperature up to 300 ^{o}C as shown in [14];
- by heating the samples or using the sensitization technique involving a pre dose followed by annealing, which gave good results for monocrystalline silicon solar cell detector [13].

The above properties may have important applications in developing selective detectors and dosimeter suitable to study the biological effects of ionizing radiation exposure.

The most important problem in thermoluminescence (TL) technique applied to different fields of dosimetry, i.e., personnel, environmental and clinical dosimetry, is related to the loss of the stored TL signal after irradiation, commonly called thermal fading (trapped charge effects) and to its estimation. The release of electrons from their traps and their consequent recombination in luminescence centers is a statistical phenomenon, the probability of which is a function of temperature. The TL emission, glow curve, is related to traps which lie at different depths in the band gap, between the conduction and the valence bands of a solid.

Trap levels which are near the conduction band (shallow traps) are heavily affected by fading at room temperature. In principle, deep traps should not be accepted by fading at room temperature [9]. Monocrystaline silicon solar cell is a promising material, so it does need to study its fading. Fig. 5 shows the integrated TL-intensity after storage period of three months for different dosimeters system used in TLD. The fading is high for it equals 6% due to the presence of silicon ions as a dopant which has a great value of fading in nature. The fading of TLD-100 is less than the former, it equals 5% after three months of storage at room temperature. In this paper is demonstrated that the fading of the given glasses cannot be explained only by the ionization of trapping centers. It must be considered the second process of diffusion of oxygen in glasses [4] to explain the fading of glasses on the base of rare earth metal oxides.

DETERMINATION OF THE UNCERTAINTY OF MONOCRYSTALLINE SILICON DOSIMETERS

According to technical recommendations for the use of thermoluminescence for dosimetry in individual monitoring for photons and electrons from external sources [5], a list of commonly encountered sources of errors that affect the precision and accuracy in determining the dose under geometrical conditions could be driven. These errors will consist of the detectors, the reader, the thermal history and the sensitivity of the detector to photon [6].

Table 1 shows the different uncertainty components of the detector for monocrystalline solar cell now. The Largest value of uncertainty was due to the contamination of TLD-materials which means it must pay attention to the clearance of the sample. The expanded uncertainty at 95% confidence level was 0.14 nC which should be added to the value of measurement.

Table 1

Errors due to the detector

Serial number	Source of uncertainty	Value (nC)	Probability distribution	Divisor	*C* (nC)	*Us* (nC)	Us^2 (nC)
1	Transparency and other optical properties	0.07	Rectangular	$\sqrt{3}$	1	0.04	0.0016
2	Room temperature	0.02	Rectangular	$\sqrt{3}$	1	0.01	0.0001
3	Light effect	0.06	Rectangular	$\sqrt{3}$	1	0.3	0.0009
4	Energy dependence of dosimeter response	0.02	Rectangular	$\sqrt{3}$	1	0.012	0.000144

Table 1 (continued)

5	Contamination of TLD material	0.07	Rectangular	$\sqrt{3}$	1	0.04	0.0016
6	Ineffective cleaning procedure on detector	0.03	Rectangular	$\sqrt{3}$	1	0.017	0.000289
7	Variability of the mass of the TLD material in the detector	0.02	Normal	2	1	0.01	0.0001
8	Powder distributions in the tray of the reader	0.02	Normal	2	1	0.01	0.0001
9	Changes in the detector sensitivity due to the radiation damage	0.03	Rectangular	$\sqrt{3}$	1	0.017	0.000289
10	Repeatability	0.01	Normal	1	1	0.01	0.0001
11	The same irradiated surface of Lif on the tray	0.023	Rectangular	$\sqrt{3}$	1	0.013	0.000169

Standard uncertainty = $\sqrt{US} = \sqrt{0.00539} = 0.07$ nC ;
Expanded uncertainty = (standard uncertainty) × 2 = 0.14 nC (at 95% confidence level).

Table 2 shows the different errors due to the reader and evaluation procedure. The reading must be normalized to the light source and PMT noise, because the uncertainty component has great value even if normalized. The reading must be taken after 30 min to reach the stability. The uncertainty value was high for light source. The expanded uncertainty is 0.192 nC. The readings must be normalized to light source before counting the expanded uncertainty at 95% confidence level should be added to the measured value for all.

Table 2

Errors due to the reader and the evaluation procedure

Serial number	Source of uncertainty	Value (nC)	Probability distribution	Divisor	*C* (nC)	*Us* (nC)	Us^2 (nC)
1	PMT noise	0.12	Triangular	$\sqrt{6}$	1	0.05	0.0025
2	Light source	0.16	Triangular	$\sqrt{6}$	1	0.065	0.00423
3	Time readings of the detectors after irradiation	0.13	Triangular	$\sqrt{6}$	1	0.05	0.0025

Us (standard uncertainty) $= \sqrt{0.0092} = 0.096$ nC ;
Unexpended = $Us \times 2 = 0.192$ nC.

Table 3 shows the different errors due to the thermal treatment. The annealing process is a very important factor. The expanded uncertainty equals 0.04 nC. The expanded uncertainty at 95% confidence level should be added to the value of measurements for all.

Table 3

Errors due to the thermal treatment

Serial number	Source of uncertainty	Value (nC)	Probability distribution	Divisor	*C* (nC)	*Us* (nC)	Us^2 (nC)
1	Annealing	0.05	Triangular	$\sqrt{6}$	1	0.02	0.0004
2	During readout	0.03	Triangular	$\sqrt{6}$	1	0.012	0.000144

Us (standard uncertainty) = $\sqrt{.000544}$ = 0.02 nC;
Unexpended = *Us*×2 = 0.04 nC.

Table 4 shows the different uncertainty components, the observed over response is attributable to electrons originating in the radiation source holder and the surrounding air that are scattered in the TLD material. However, for higher energy gamma dose, many electrons can penetrate the TLD, resulting in a great dose, this effect will also be observed with any dosimeter that has small sensitive volume surrounded by a thin wall [17]. Gamma dose detectors have small dimensions compared to the range of the most energetic; secondary electron can exhibit over response errors when exposed in broad beam conditions. The TLD over response is appreciable for gamma rays greater than 0.66 MeV, and the over response decreases with increasing TLD thickness over response. And probably most common in TLD became the dimensions of the TLDS and TLD holders are often not large in comparison to the secondary electrons. The expanded uncertainties for cobalt-60 irradiated was 0.193 nC. The factors affecting the errors are shown in tables the expanded uncertainty at 95% confidence level should be added to the value of measurements for all. The observed over response is attributed to a previously mentioned discussion.

Table 4

Errors due to over response of TLD (Co):

Serial number	Source of uncertainty	Value (nC)	Probability distribution	Divisor	*C* (nC)	*Us* (nC)	Us^2 (nC)
1	Several holders Co	0.09	Normal	2	1	0.045	0.00203
2	Distance away from the source Co	0.07	Normal	2	1	0.035	0.00123
3	Several radionuclide Co	0.12	Normal	2	1	0.06	0.0036
4	Effects of beam size	0.05	Normal	2	1	0.025	0.00063
5	TLD size	0.01	Normal	2	1	0.005	0.000025

Us (standard uncertainty) = $\sqrt{0.00774}$ = 0.088 nC;
Unexpended = *Us*×2 =0.19 nC;
Uc (combined uncertainty) = 0.14 + 0.192 + 0.047 + 0.19 = 0.569 nC.

CONCLUSIONS

Monocrystalline silicon solar cell is preferable to measure gamma dose as well as other dosimeters such as TLD-100, due to its good agreement with ionization chamber reading in linear relationship. Also the investigated TL-main dosimetric peak increases by increasing the dose. According to the results, it could be concluded that if gamma dosimeter such as monocrystalline silicon solar cell is used for measurements of absorbed gamma dose, it is properly to take a single dosimeter peak height for measuring absorbed gamma doses. The expanded uncertainty at 95% confidence level should be added to the value of measurements to obtain accurate doses. The TL enhancement response to gamma radiation makes the monocrystalline silicon solar cell system a promising material for gamma detection dosimetry. These properties may have important applications in developing selective detectors and dosimeter suitable to study the biological effects of ionizing radiation exposure.

REFERENCES

1. AITKIN, J.M., *Physics and Archeology*, Oxford University Press, Oxford, 1974.
2. ASDUL-MAJID, S., Use of a solar panel as a directionally sensitive large-area radiation monitor for direct and scattered X-rays and gamma-rays, *Appl. Rad. Isotopes*, 1987, **38**, 1057–1082.
3. BECKER, K., *Solid State Dosimetry*, CRC Press, 1973.
4. CHVOJ Z., A. BOHUN, To the fading problem of various glasses on the base of P_2O_5, *Czechoslovak Journal of Physics*, 1979, **29**(9), 1055–1060.
5. DIAB, H.M., *Uses of solid state detectors and its application in radiation protection*, MSc Thesis, Cairo University 1999.
6. DIAB, H.M., *Standardization, calibration and development of some dosimeters using different techniques*, PhD Thesis, Cairo University, 2003.
7. EDMONDS, I.R., U. RAJAPPA, C. HIRST, P. ROWNTREE, Photovoltaic cells for low energy X-ray dosimetry, *Phys. Med. Biol*., 1990, **35**, 571–578.
8. GOKCEN M., A. TATAROGLU, S. ALTINDAL, M.M. BULBUL, The effect of ^{60}Co (γ-ray) irradiation on the electrical characteristics of Au/SnO2/n-Si (MIS) structures, *Radiation Physics and Chemistry*, 2008, **77**, 74–78.
9. HORIUCHI, N., T. NOZAKI, A. CHIBA, Improvement in electrical performance of radiation-damaged silicon solar cells by annealing, *Nuclear Instruments and Methods in Physics Research A*, 2000, **443**,186–193.
10. IBRAHIM, A., *Non Destructive Testing of Silicon Solar Cells*, Ph.D Thesis, Technical University of Brno, Czech Republic, 2001.
11. KITIS, G., R. CHEN V. PAGONIS, E. CARINOU, P. ASCOUNIS V. KAMENOPOULOU, EUR 5358 Technical recommendations for the use of thermoluminescence for dosimetry in individual monitoring for photons and electrons from external sources. Thermoluminescence for dosimetry in individual monitoring for photons and electrons from external sources, *Journal of Physics D: Applied physics*, 2005, **39**, 1508–1514.
12. MUSILEK, L., P. FOWLES, Directional dependence of solar cells used as monitors of high gamma ray dose rates, *Int. J. Appl. Rad. Isotopes*, 1982, **33**,1473–1482.

13. NECMEDDIN YAZICI, A., Z. ÖZTÜRK, Thermoluminescence properties of newly generated glow peak 3a in TLD-100 after pre-irradiation heat treatment at 150 °C, *Nuclear Instruments and Methods in Physics, Section B: Beam Interaction with Materials and Atoms*, 2003, **201**, 503–512.
14. SUNTHARALINGAM, N., J.R. CAMERON, J.F. FOWLER, Fading characteristics of thermoluminescent lithium fluoride, *Physics in Medicine and Biology*, 1988, **13**, 97–106.
15. TUZUN, O., S. ALTINDAL, S. OKTIK, Effects of illumination and ^{60}Co γ-ray irradiation on the electrical characteristics of porous silicon solar cells, *Renewable Energy*, 2008, **33**, 286–292.
16. UKS, *Uncertainty of Measurement*, Training course, United Kingdom Accredits Service M 3003, 1997.
17. ZIMMERMAN D., J.R. CAMERON, R. BLAND, R. GIANT, Thermoluminescent radiation dosimetry utilizing lithium fluoride, *Health Physics*, 1964, **10**, 25–29.