LOW-POWER PHOTOVOLTAIC CELLS BATTERIES USED AS GAMMA RADIATION DOSE ESTIMATORS

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Abstract. In this paper, the possibility of using commercial low-power photovoltaic cells batteries as sensors for the estimation of the gamma radiation dose in a certain point in space and for certain energy in particle accelerators related experiments, when the occurred nuclear reactions are involving the presence of higher or lower gamma radiation fields, was studied. Initially, three low-power photovoltaic cells batteries were exposed to three different well-known gamma radiation doses (33.45 kGy, 35.61 kGy and 37.9 kGy) and one was kept as blank (0 kGy), and then, an analysis of some of their functional parameters (short circuit current, open circuit voltage, external quantum efficiency) was performed. The functional parameters were studied with respect to the illuminance conditions and to the absorbed dose values in order to determine which of them can be used in gamma radiation dosimetry. Five different artificial lighting conditions were used, and, in each case, the values of sensitivity of the sensors (expressed in nA/Gy) and their external quantum efficiencies were determined. As it was shown in this study, low-power photovoltaic cells batteries can indeed be used as gamma radiation dose estimators, and even more, can be used in complex gamma radiation fields distribution studies.

Key words: Low-power photovoltaic cells battery, illuminance, gamma radiation, solid state dosimetry.

1. INTRODUCTION

Nuclear radiations are emissions of waves or particles, carrying energy. These energies induce some changes to the structure of exposed materials (in particular on electrical and optical properties) [1–10]. Using this “cause-effect” relation, the estimation of an unknown gamma radiation dose induced to an exposed material can be done.

In this paper, the possibility of using commercial low-power photovoltaic battery cells as sensors for the estimation of the gamma radiation dose in a certain point in space and for certain energy in particle accelerators related experiments, when the occurred nuclear reactions are involving the presence of higher or lower gamma radiation fields, was studied.

A photovoltaic cells battery is a group of photovoltaic cells which provide electrical power based on the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect. It is defined as a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light, and it is based on the following aspects: absorption of light generating either electron-hole pairs or excitons, the separation of charge carriers of opposite types and the separate extraction of those carriers to an external circuit \([11–17]\). A photovoltaic cell consists of two or more layers of semiconductor materials deposited on a surface made of a wide range of materials (FR4 type 0.5 mm glass textolite sheets in the case of the ones used in this paper). The deposited semiconductor layers have usually thicknesses between \(10^{-9}\) m and \(2 \times 10^{-7}\) m and contain in their base matrix certain chemical elements in order to form type “p” and type “n” junctions. A photovoltaic cell is basically a p-n junction. On their entire exterior surface, the photovoltaic cells are coated with epoxy resins in order to provide a satisfying mechanical resistance to them but not significantly affecting the entrance of the light in their volume. Usually, photovoltaic cells are built having relatively small surfaces, providing small quantities of electric current. By combining them in various serial or parallel connections (photovoltaic cells batteries), their current/voltage can be increased in order to be high enough for practical usability.

2. MATERIALS AND METHODS

The functional parameters (short circuit current, open circuit voltage, external quantum efficiency) of four photovoltaic cells batteries exposed to gamma radiation were studied with respect to the illuminance conditions and to the absorbed dose values in order to determine which of them can be used in gamma radiation dosimetry.

Three amorphous Si based low-power photovoltaic cells batteries were exposed to a Co-60 gamma-ray source inside the “hot cells” found in Radioisotopes and Radiation Metrology Department (DRMR) from Horia Hulubei National Institute for Nuclear Physics and Engineering (IFIN-HH), ROMANIA, in order to obtain three different well-known gamma radiation doses (33.45 kGy, 35.61 kGy and 37.9 kGy) and one was kept as blank (0 kGy). The Co-60 gamma rays source provided a constant dose rate of 395 Gy/h at 10 cm distance from it, in the place where the exposures were performed. The dose debit was measured using
a 30006 type “Farmer” ionization chamber, a waterproof standard chamber for absolute dosimetry (0.65 % combined standard uncertainty for a coverage factor $k = 2$).

The mean value of energies of the gamma rays emitted by a Co-60 source is 1.25 MeV, way higher than the bandgap energy of amorphous Si (a-Si), of 1.12 eV.

Each photovoltaic cells batteries was made of 12 photovoltaic cells (connected in serial), placed on 2 rows of six cells, as it can be seen in Fig. 1. The photovoltaic cells used in this paper were based on amorphous Si, which provide increased sensitivity in low light conditions. The cells batteries had the following characteristics: sensitive area – 12 cells × $(6 \times 10) \times 10^{-6}$ m$^2$, sensibility – 350 nA /lx, $V_{out}$/kIx – 5v (idle voltage), $I_{sc}$ – 350 µA (short circuit current), $r = 12$ (number of p-n junctions/elementary cells in a battery).

In order to locate each cell in a battery, a matrix approach was proposed, meaning each battery was represented as a matrix with $l$ lines and $c$ columns ($l = 1...n$, $c = 1...m$). A certain dose value corresponding to a certain cell can be defined as $D_{lc}$, if individual cell measurements are performed. These types of individual cell measurements are important if gamma ray field uniformity studies are performed [18].

In order to measure each of the functional parameters of the irradiated photovoltaic cells batteries, an experimental device was built, as it can be seen in Fig. 2.
Practically, the experimental set-up was a dark box ((60 × 60 × 110) mm³) containing the exposed photovoltaic cells batteries, a stabilized source of light and a high quality electrometer. The source of light used was a multispectral incandescent E10 type light bulb (6.3V, 2.0W). The illuminance inside the experimental device was varied by modifying the voltage provided to the light source. The voltages used were 2.1 V, 2.9 V, 3.7 V, 4.4 V and 5.2 V corresponding to the following illuminance values: 33 lx ± 0.7 %, 79.8 lx ± 0.7 %, 196.8 lx ± 0.6 %, 422.3 lx ± 0.6 % and 813 lx ± 0.7 %. The illuminance measurements were performed using a MOBILE-CASSY LD 524009 type lux-meter. For each of the four photovoltaic batteries the currents in dark, \( I_d \), were measured: 

\[
I_d^1 = 0.81 \times 10^{-9} \text{A}, \quad I_d^2 = 1.4 \times 10^{-9} \text{A}, \quad I_d^3 = 1.48 \times 10^{-9} \text{A} \quad \text{and} \quad I_d^4 = 0.1862 \times 10^{-9} \text{A}.
\]

When no light source is present, the electric current inside the short circuit is the sum of the currents provided by the major and minor carriers. Locally, the current is depending to the electric potential difference for each \( p-n \) junction, which depends to the temperature.

When a light source is involved, on the exterior circuit of the photovoltaic cells battery a photocurrent occurs [19–22], as follows (Equation 1):

\[
I = I_s \times \left( e^{ \frac{e(N_r V_0)}{k_B T} } - 1 \right) - I_f
\]

where: 
- \( I \) – electric current on the exterior circuit,
- \( I_s \) – saturation current of unirradiated \( p-n \) junctions,
- \( I_f \) – photocurrent (photo-electric current),
- \( V_0 \) – electric potential difference for a \( p-n \) junction (open circuit),
e – electron change,
\( r \) – number of \( p-n \) junctions/elementary cells in a battery,
\( k_B \) – Boltzmann constant,
\( T \) – temperature.

Short circuit current is increasing in a linear manner with the increase of the intensity of the light. The intensity of the light source (incandescent light bulb, multispectral emission) was modified by modifying the voltage to it. The obtained photocurrent is practically proportional to illuminance.

By assigning the zero value to the electrical current thru the exterior circuit, the expression of the electric potential difference (open circuit) for an \( r \) number of \( p-n \) junctions \( (r \times V_0) \) is the following, Equation (2):

\[
r \times V_0 = \frac{kT}{e} \times \ln \left( \frac{I_f}{I_s} + 1 \right). \tag{2}
\]

Equation (2) also shows the dependence between the electric potential difference – open circuit voltage \( (V_0) \) and the temperature. The influence of the temperature was diminished as much as possible in the experiment performed in this paper by using the photovoltaic cells batteries in current generator regime. This way, the serial circuit of the \( p-n \) junctions is closed on a negligible resistance related to the internal one, for which \( r \times V_0 = 0 \). The short circuit current becomes

\( I_{\text{short}} = -I_f \)

and it is not depending to the temperature anymore (ambient temperature during experiment was 22 °C).

The dependence of the short circuit current value to the photovoltaic cell parameters, dose, time and illuminance is given by the Equation (3), [23]:

\[
I_{\text{short}_{i,j}} = R_i \times \frac{S \times l \times \rho \times e \times g(L_j)}{\varepsilon}, \tag{3}
\]

where:
\( I_{\text{short}_{i,j}} \) – measured short-circuit current expressed in A,
\( R_i = \frac{D_i}{l} \) – dose rate \( (D_i) \), expressed in Gy/s,
\( S = p \times A \) – cross-section area expressed in \( \text{m}^2 \),
\( l \) – minority-carrier diffusion length expressed in m,
\( \rho \) – density of the material (2330 kg/m\(^3\) for Si),
\( e \) – electronic charge \( (1.6 \times 10^{-19} \text{ A s}) \),
\( \varepsilon \) – average energy required to produce one electron-hole pair \((5.76 \times 10^{19} \text{ J})\).

The Equation (3) becomes Equation (4):

\[
I_{\text{short},i,j} = 6.47 \times 10^8 \times D_i \times S \times l \times g(L_j)
\]  

(4)

where:

\( g(L_j) \) – photo-generation rate,
\( L_j \) – illuminance expressed in lx.

The illuminance is expressed as follows, Equation (5):

\[
L_j = \frac{\Phi_j \times C \times P}{S_L},
\]  

(5)

where:

\( \Phi_j \) – luminance per lamp expressed in lm;
\( C \) – utilization coefficient;
\( P \) – light loss factor;
\( S_L \) – area per lamp expressed in m\(^2\).

Equation (4) shows the linear dependence between short circuit current and the absorbed dose, but also the influence of the illuminance.

For a photovoltaic cell, in normal functioning conditions, a very important factor of its efficiency is the filling factor (FF). This factor is a measure of the quality of a cell, and it is defined by determining its current-voltage characteristic. The filling factor is dependent to the internal resistance of the photovoltaic cells battery (FF is higher when the internal resistance is lower). Unlike the short-circuit current, the open circuit voltage \((V_0)\) is not depending to the internal resistance of the photovoltaic cells battery.

By exposing a photovoltaic cells battery to increasing gamma radiation dose, its internal resistance is increasing, leading to a decreasing short circuit current. This phenomenon is the base of the possibility of using photovoltaic cells battery as instruments for gamma radiation doses estimations.

The evaluation of the absorbed dose is a very important task to be fulfilled, especially in the cases of high dose values (> 100 Gy). In this direction, many materials and devices were studied in order to determine their behaviour when exposed to ionizing radiation [24]. As an example, the glass based dosimeters showed their functionality on a wide range of absorbed dose values. Their usability was proven in literature [25–28] by using various types of photo-spectrometric measurements (optical densitometry). These types of dosimeters already showed their potential in different fields as: applied physics experiments, nuclear medicine, industry etc. [29–33].
In the case of photovoltaic cells batteries, their usability was shown for higher energy gamma radiation (hundreds of keV) and for higher dose values.

Due to the fact that in this paper the short circuit current measurement was performed (unaffected by temperature variations), its dependence to absorbed dose is linear, as Equation (6) shows:

$$D = f(I_{\text{short}} = I_f) = -n + m \times I_{\text{short}},$$

where: $$I_{\text{short}}$$ – short circuit photocurrent of photovoltaic cells battery ($$I_{\text{short}} \neq 0$$),

$$n, m$$ – fitting parameters.

In order to determine the variance associated to the estimated dose, the Uncertainties Propagation Law is applied to Equation (6). In this case, the general analytical relation is a function depending on three variables, $$D = D(I_f, n, m)$$, leading to Equation (7):

$$\sigma_D^2 = \left(\frac{\partial D}{\partial n}\right)^2 \times \sigma_n^2 + \left(\frac{\partial D}{\partial m}\right)^2 \times \sigma_m^2 + \left(\frac{\partial D}{\partial I_f}\right)^2 \times \sigma_{I_f}^2.$$  

The concrete form of Equation (7) is given by Equation (8), which contains only known quantities:

$$\sigma_D^2 = \sigma_n^2 + \sigma_m^2 \times \left(I_f\right)^2 + \sigma_{I_f}^2 \times m^2.$$  

By solving Equation (8), the uncertainty associated to a determined dose value can be estimated using Equation (9):

$$\sigma_D = \sqrt{\sigma_D^2}.$$  

3. RESULTS AND DISCUSSIONS

The accumulation of radiation induced defects in the structure of irradiated photovoltaic cells batteries is the cause of the reduction of their function parameters. The graphical representation of functional parameters as a function of absorbed dose value ($$i = 1, 2, 3, 4$$) and illuminance, $$L_j$$ ($$j = 1, 2, 3, 4, 5$$), allows us to determine the relation between them and to decide if any of them can be used as dosimetric parameter.

In Fig. 3, the short circuit current as a function of illuminance, for each of the four studied photovoltaic batteries, is presented.
As it can be seen from Fig. 3, the fitting relations have the following form, Equation (10):

\[ I_{\text{short}} = -a_i + b_i \times L. \]  

(10)

It can also be seen that the short circuit absolute values are increasing with the increase of the illuminance and are lower for higher absorbed dose values. As it can be seen in Fig. 3, the square of the sample correlation coefficient \( R^2 \) takes values over 94% in all cases, showing the goodness of fits.

The variation of the open circuit voltage as a function of illuminance, for each of the four studied photovoltaic batteries is shown in Fig. 4. It can be seen that the open circuit voltage value is decreasing with the increase of the absorbed dose. An increase of the open circuit voltage value with the increase of illuminance can be also seen. For values of illuminance over 200 lx, a saturation effect is starting to be observed.
The sensibility of photovoltaic cells batteries reported to absorbed dose and illuminance are shown in Table 1.

Table 1

<table>
<thead>
<tr>
<th>Sensibility [Gy/nA]</th>
<th>0.52</th>
<th>0.32</th>
<th>0.21</th>
<th>0.12</th>
<th>0.11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illuminance [lx]</td>
<td>33.0</td>
<td>79.8</td>
<td>196.8</td>
<td>422.3</td>
<td>813.0</td>
</tr>
</tbody>
</table>

From Table 1 it can be observed that with the increase of the illuminance a lower dose value is needed to obtain a nA of short circuit current, meaning an increased sensibility [34]. A saturation trend can also be observed, starting from around a 422.3 lx illuminance value. Table 1 also shows that the five illuminance values chosen in this paper are optimal.

The variation of the external quantum efficiency with illuminance, for each absorbed dose value, η (%), is presented in Fig. 5. The external quantum efficiency represents the fraction of the incident light that is converted in electrical energy, and it is given by Equation (11):
\[ \eta_{i,j} = \frac{I_{\text{short},i,j} \times V_{0ij}}{P_{i,j}} \times 100 \]  

(11)

where \( P_i \) represents the power of the optical radiation reaching the surface of the photovoltaic sensor.

From the three functional parameters studied, the one chosen to be used as dosimetric parameter was the short circuit current, due to the fact that it is not affected by other external parameters as the temperature. In Fig. 6, the variation of the short circuit current with the absorbed dose value, on the entire doses range is presented.
As it can be seen in Fig. 6, the short circuit current absolute value is decreasing with the increase of the absorbed dose value and increasing with the increase of illuminance. For a certain illuminance value, the analytical relation between the short circuit current and absorbed dose is a relation of the type of Equation (6).

Short circuit current as a function of absorbed dose, for each illuminance conditions on the (0–35.6) kGy interval is presented in Fig. 7. This interval was chosen for its higher linearity.

By using the fitting relations from Fig. 7, the analytical relations between the absorbed dose and short circuit current, for each illuminance conditions, were determined (calibration curves). The results are presented in Table 2.

### Table 2

Analytical relations between absorbed dose and short circuit current on (0–35.6) kGy interval

<table>
<thead>
<tr>
<th>Calibration curve for each illuminance value</th>
<th>( \frac{I_{\text{short}}}{[\text{A}] \times 10^3} ) for (0–35.6) kGy interval</th>
<th>Illuminance [lx]</th>
<th>( R^2 ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_1 ) [kGy] = 333.3 + 1.6 \times 10^7 \times I_{\text{short}} ) ((-2.06) + (-1.75))</td>
<td>33.0</td>
<td>64.8</td>
<td></td>
</tr>
<tr>
<td>( D_2 ) [kGy] = 341.7 + 4.2 \times 10^6 \times I_{\text{short}} ) ((-8.1) + (-7.0))</td>
<td>78.9</td>
<td>75.2</td>
<td></td>
</tr>
<tr>
<td>( D_3 ) [kGy] = 366.7 + 3.3 \times 10^6 \times I_{\text{short}} ) ((-11.1) + (-9.7))</td>
<td>196.8</td>
<td>73.1</td>
<td></td>
</tr>
<tr>
<td>( D_4 ) [kGy] = 383.0 + 2.1 \times 10^6 \times I_{\text{short}} ) ((-18.0) + (-16.0))</td>
<td>422.3</td>
<td>88.0</td>
<td></td>
</tr>
<tr>
<td>( D_5 ) [kGy] = 280.0 + 10^6 \times I_{\text{short}} ) ((-27.8) + (-24.0))</td>
<td>813.0</td>
<td>99.6</td>
<td></td>
</tr>
</tbody>
</table>
By measuring the short circuit value and using the relations from Table 2 according to the chosen illuminance conditions, an unknown absorbed dose value can be determined. These relations are valid only on the studied (0–35.61) kGy interval due to the fact that the calibration “short circuit current – absorbed dose” was performed only on this interval. Having more dose values spread on a larger interval, new calibration curves can be obtained. As it can be seen from $R^2$ values, the calibration curve corresponding to the 813.0 lx illuminance fits best the experimental points due to the fact this value is closest to the one recommended by the producer of this type of photovoltaic cells batteries (working regime).

4. CONCLUSIONS

In this paper, the functional parameters (short circuit current, open circuit voltage, external quantum efficiency) of low-power photovoltaic cells batteries after their exposure to gamma radiation were studied. It was shown that all of these parameters are affected by the energy deposited in their volume. Do to this fact, it was shown that low-power photovoltaic cells batteries can be used as sensor in...
gamma radiation dosimetry. It was also determined which of these parameters is the best parameter to be use in dosimetry. The best parameter to be use in dosimetry was found to be the short circuit current.

By studying the short circuit current variation with the absorbed dose value, calibration curves were obtained. Using these calibration curves, any unknown dose value can be determined. The calibration curves are valid only on the studied (0–35.61) kGy interval due to the fact that the calibration “short circuit current – absorbed dose” was performed only on this interval. Having more dose values spread on a larger interval, new calibration curves can be obtained.

The uncertainty associated to the proposed gamma radiation dosimetry method was also estimated. The main qualities of this dosimetry method are that it is fast, easy to be applied in various situations and economically efficient.

REFERENCES


