Research Article

Performance Analysis of γ -Radiation Test Monitor Using Monocrystalline n+pp++ Silicon Solar Cell: CsI(Tl) Scintillator

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The silicon solar cells are largely insensitive to gamma-radiation because the radiation passes through solar cells without imparting all of its energy. In order to enhance the sensitivity to radiation, the solar cells are coupled to CsI(Tl) scintillator. With the help of n+pp++ PESC monocrystalline silicon solar cells and CsI(Tl) scintillators, a gamma-radiation test monitor (TM) is developed. Due to safety concerns, a convenience relatively intense ⁶⁰Co gamma-source is used as a suitable substitute for spent fuel. Two designs made of two representative arrays of monocrystalline solar cells are suggested. The induced current and voltage generated by these solar cells are measured. The temperature dependence of the induced current and the angular characteristic of the TM, for both designs, are presented. In comparison to conventional gamma-ray sensors, the Si solar cells exhibited better performance than the conventional types. Design II is found to be more efficient than I and superior performance for all of the measured parameters is obtained.

1. Introduction

Recently, gamma-radiation monitors are commonly used in medicine, research, and industrial facilities to protect researchers/workers from radiation accidents or emergencies where radiation-generating sources, machines, or apparatuses are installed [1]. Most γ -radiation monitors are composed of several major components such as a detector, an amplifier, a high-voltage power supply, and a meter. It costs a large amount of money as well as maintenance costs. Troubles due to rearranging such conventional monitors in a position at a short distance from high-intensity γ -emitting sources can be avoided by using low cost and safe solution.

Solar cells have received considerable research attention, because of the development of various commercially available solar-powered products and equipment. They also exhibit a fair response, to other electromagnetic radiation with a substantially shorter wavelength, for example, X- and γ -rays. Potential applications of solar cells include a γ -ray dose-rate meter [2], a monitor of high γ -ray dose rates [3], and

determination of gamma dose by monocrystalline silicon n+pp++ solar cell [4].

Conventional solar cells generally exhibit a good spectral response to visible radiation which has a wavelength from 400 to 800 nm [5]. A directionally sensitive large-area radiation monitor [6] and a gamma cell whose operation is based on γ -irradiation by radioactive wastes [7] have been done. Further developments were limited due to their unsuitable sensitivity to γ -rays as well as the small size of sensitive area.

Single crystal-type silicon solar cells are directly sensitive to gamma-radiation, although their sensitivities are very poor because gamma-radiation passes through the thin solar cells without imparting all of its energy. However, the induced current of the solar cell can be considerably improved by coupling it to a CsI(Tl) scintillator. The electric current generated by solar cells has been enhanced by improving the spectral response of the solar cells and enlarging their sensitive area [8].

In this work we have examined the characteristics of a γ -radiation monitor made of solar cells. The test monitor

TABLE 1: Dimensions and physical properties of (a) solar cell and (b) CsI(Tl) scintillator [9] employed.

(a) Solar cell n+pp++								
Cell type	Solar cell area (cm ²)	Sensitive area with CsI(Tl) (cm ²)	Peak sensitivity wavelength (μm)	Thickness (μm)	Short circuit current (A)	Open circuit voltage (V)	Conversion efficiency %	Output power (W)
Single crystal silicon	10 × 10	5 × 5	0.5 to 0.53	400	3.2	0.6	16	1.2–1.4

Note: the electrical parameters for monocrystalline solar cells n+pp++ PESC of dimensions (10 cm × 10 cm) are related to the conditions of solar irradiation 1000 W/m², air mass (AM) 1.5 spectrum, and cell temperature 25°C.

(b) CsI(Tl) scintillator						
Light output (%)	Max. emission wavelength (μm)	Decay time (nS)	H. thickness (cm)	Density (gm/cm ³)	Melting point (°C)	Dimensions (mm ³)
45–50	550	10 ³	2.0	4.51	894	50 × 50 × 10

Note: light output: light output % of NaI(Tl); H. thickness: half-thickness value for ¹³⁷Cs(662 keV).

(TM) has been made of a slice of CsI(Tl) scintillator sandwiched between two monocrystalline silicon solar cells. That was design I, while two sandwiches formed design II. The induced current and voltage generated by both designs were measured. The angular and temperature characteristics have been studied using a ⁶⁰C γ-source.

2. TM Design

The structure of the TM is shown in Figure 1(a). The main specifications, dimensions of the solar cell, and CsI(Tl) scintillator specifications are summarized in Table 1. The TM consists of two monocrystalline silicon solar cells of the construction n+pp++ PESC (passivated emitter solar cell) with a sensitive area 10.0 × 10.0 cm² with CsI(Tl) scintillation crystal of dimensions 5.0 × 5.0 × 1.0 cm³, respectively. The CsI(Tl) scintillator slice is sandwiched by the two solar cells so that the entrance window (i.e., n-type) of each solar cell is attached to one face of the CsI(Tl) slice, and the opposite face of each cell (i.e., p-type) is protected by a 1 mm thick backing plate of aluminum supported by 3 mm glass sheet. To avoid ambient light affecting the solar cells, the TM was covered with a black cloth shielding bag. The output terminals of both solar cells/sandwich were connected in parallel to measure the induced current and in series to measure the induced voltage. The induced current was measured by an electrometer (digital nanoammeter, model DNM-121). The induced voltage was measured by a CASSY meter coupled to a microvolt bridge. The sampling time for the induced current can be controlled arbitrarily manually to be 1 min as a minimum time interval.

3. Results and Discussions

Characteristic curve (i.e., sensitivity response) and angular and temperature characteristics of the TM are examined using a ⁶⁰Co γ-source of activity of 740 kBq. Figure 2 shows the sensitivity (i.e., induced current) curves plotted on a linear graph, which is measured by changing the distance

FIGURE 1: (a) The structure of TM-design I, (b) the equivalent circuit of (a), (c) TM-design II for induced current measurements, and (d) TM-design II for the induced voltage measurements.

between the γ-source and TM-designs I and II. Each point shows the mean value of the induced current which is measured at each position during 1 min intervals in a 10 min exposure period. By least-squares fitting of the experimental

FIGURE 2: The induced current generated by TM-designs I and II.

TABLE 2

Design	Intercept	Intercept standard error	Slope	Slope standard error	R^2
I	0.47899	0.01337	-0.00412	2.04641E-4	0.98058
II	0.94553	0.02234	-0.00829	3.42085E-4	0.98653

points, we have determined the relation between the induced current from the TM and the distance for the two designs. They are given by

$$\text{For design I: } I (\mu\text{A}) = 0.47899 - 0.00412d (\text{cm}), \quad (1)$$

$$\text{For design II: } I (\mu\text{A}) = 0.94553 - 0.00829d (\text{cm}).$$

Results of linear fitting of induced current obtained by TM for designs I and II are shown in Table 2.

TM-design II shows an improvement of the induced current by nearly 100%. The enhancement in the generated induced current by the solar cells is due to adding the CsI(Tl) scintillator. This type of scintillators has a larger density, 4.5 g/cm^3 , than the other scintillators. The maximum emission wavelength of the CsI(Tl) scintillator, where the most energy can be released, is in the region of 530 nm, as shown in Figure 3, which is close to the area of maximum sensitivity of the monocrystalline silicon solar cell.

On the other hand, the obtained induced voltage as a function of distance between the gamma-source and TM-designs I and II is illustrated as shown in Figure 4. A little variation of the induced voltage is obtained. The relationship between the induced voltage and distance is given by

$$\text{For design I: } V (\mu\text{V}) = 8.63444 - 0.00817d (\text{cm}), \quad (2)$$

$$\text{For design II: } V (\mu\text{V}) = 12.21022 - 0.0118d (\text{cm}).$$

Results of linear fitting of induced voltage obtained by TM for designs I and II are shown in Table 3.

The induced voltage generated by TM is almost independent of the incident angle of the gamma-radiation.

FIGURE 3: Light output versus wavelength for NaI(Tl), CsI(Tl), and BC400 scintillators [8].

FIGURE 4: The induced voltage generated by TM-designs I and II.

TABLE 3

Design	Intercept	Intercept standard error	Slope	Slope standard error	R^2
I	8.63444	0.06536	-0.00817	0.001	0.89131
II	12.21022	0.0651	-0.0118	9.96608E-4	0.94565

The solar cells themselves, without scintillators, are essentially unresponsive to gamma-radiation. Since only a part of the gamma-radiation energy is absorbed by the solar cells, most of the induced photovoltage is produced by the light generated in the CsI(Tl) scintillator [8]. This means that the light is uniformly generated by gamma-rays entering the CsI(Tl) scintillator and the amount of generated induced voltage is decided only by the volume of the scintillator, regardless of the incident angle of gamma-rays.

The angular characteristic of the TM is shown in Figure 5. The induced current is measured at a distance of 50 cm away

TABLE 4

Design	Intercept	Intercept standard error	Slope	Slope standard error	R^2
I	0.24221	3.86911×10^{-4}	5.77143×10^{-4}	7.73718×10^{-6}	0.9991

FIGURE 5: The angular characteristic of the induced current obtained by TM-designs I and II.

from the γ -source. The orientation of the TM exposed to γ -rays at the 0° source angle is also plotted in the figure as a starting point. The TM was rotated at 30° steps around a central axis, and the induced current is measured each time. The measured induced currents are normalized to the value obtained at the position of 0° source angle. The generated induced current by the TM receiving γ -radiation is slightly dependent on the angle of incidence. Attenuation of about 26% was observed at 90° and 270° source directions with TM-design I, respectively, in agreement with measurements of [10].

While the angular characteristic of TM-design II shows an attenuation of nearly 8%, observed at 90° and 270° , respectively, the amount of the induced current depends mainly on the effective area of the CsI(Tl) scintillator seen by the γ -source. It is clear from the graph that TM-design II is more efficient as a γ -ray monitor due to its uniform angular distribution.

Results of linear fitting of induced current with temperature obtained by TM for design I are shown in Table 4.

The temperature characteristic of the TM is shown in Figure 6. The induced current as a function of temperature is linear, given by

$$I (\mu A) = 5.77143 \times 10^{-4} T (^\circ C) + 0.24221. \quad (3)$$

The TM is placed in an oven until its temperature reaches $80^\circ C$. Then the induced current is measured while the TM, at a distance of 50 cm from the γ -source, is left to cool. The induced current slightly increases with increasing temperature. This suggests that the scintillation efficiency of TM slightly increases with temperature over this range. The induced current change per degree is $0.577 \text{ nA}/^\circ C$, which is a very small value. This suggests that TM is a good γ -monitor,

FIGURE 6: The temperature dependence of the induced current generated by TM-design I.

temperature independent. Design II is not recorded because it is expected to give the same value $dI/dT = 0.577 \text{ nA}/^\circ C$ with higher levels of induced currents.

4. Conclusion

The present study is carried out to investigate the performance of a gamma-ray monitor composed of a monocrystalline silicon solar cell coupled to CsI(Tl) scintillator. Two designs have been used. Experiment has shown that the TM exposed to gamma-radiation demonstrates the following characteristics.

- TM is able to generate larger induced current more than the solar cell without CsI(Tl) scintillator crystals.
- TM exhibits a good linear response to the gamma-ray exposure. It is easy to use, with good sensitivity, relative to the conventional ones.
- TM is relatively inexpensive and requires no electrical power supply or any complex electronic equipment.
- Radiation, with very large doses, would cause some degradation; hence recalibration will be needed.
- TM-design II is more efficient than TM-design I.
- The induced voltage is almost independent of the incident angle of the gamma-radiation entering the cell, particularly design II.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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