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Optimized multi-junction photovoltaic solar cells for terrestrial applications

Rabi Ibrahim Rabady *

Jordan University of Science and Technology, P.O. Box 3030, Irbid 22110, Jordan

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Abstract

Sunlight, undoubtedly, is the future source of energy for humans. The current conversion technologies of sunlight to electricity using photovoltaic technologies are still moderate and relatively costly. The multi-junction photovoltaic cell design offers the highest achieved conversion efficiency that already exceeded the 40%. This work aims for maximizing the conversion of the sunlight for terrestrial application using the series-multi-junction photovoltaic cells by an optimal choice for the bandgap energies.

Keywords: Solar energy conversion; Photovoltaic cells; Multi-junction; Bandgap energy; Cutoff wavelength; Optimized design

1. Introduction

Solar energy conversion to other forms of energy is essential for us. Nowadays, modern cities are run mainly by electricity; therefore, the conversion of the sunlight to electricity is the most appealing technology that utilizes the solar energy.

There are different known approaches for converting sunlight to electricity. The solar-thermal scheme that depends on producing pressurized steam yields about 15% conversion efficiency; such scheme is widely used because it can be employed at large scale solar farms with reasonable cost. Another similar solar-thermal approach is to use the concentrated sunlight to drive Stirling engine (Kongtragool and Wongwises, 2003; Exergy). The net efficiency of the last scheme is relatively high, about 35%; nevertheless, it has limited use because technically is hard to deploy at large scale and maintain reasonable cost.

The most promising technology for converting sunlight to electricity is the photovoltaic PV cell technology (IEA; Solar Technologies Market Report, 2010), which depends on converting the photons flux in the sunlight directly to a direct electric current using the photovoltaic effect. Nevertheless, the PV cells manufacturing is a high-tech that requires a costly fabrication environment that is not strongly justified by the current conversion efficiencies which is about 10–20% (Solar Technologies Market Report, 2010; Wolf, 1960). Therefore, many methods were invented and attempted to reach higher efficiencies (Kravets, 2010; Reisfeld and Neuman, 1978; Reisfeld and Jorgensen, 1982; Nelson, 2003; Bitnar, 2003; NREL; Cotal and et al., 2009; Takamoto et al., 2009; Edmondson et al., 2005). The multi-junction approach yields the most promising efficiency among all PV technologies since it employs a stack of junctions with different, but properly chosen, bandgap energies to better match the solar spectrum with maximum utilization and minimum thermalization loss (Cotal and et al., 2009; Takamoto et al., 2009; Edmondson et al., 2005; Nelson, 2003). A conversion efficiency that exceeded 40% has been reported with three-junction PV cells (Cotal and et al., 2009). Expectedly, introducing more junctions into the PV cell should improve the efficiency (De Vos, 1980); nevertheless, such approach is

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* Tel.: +962 796622279.
E-mail addresses: rabirabady@yahoo.com, rrabady@just.edu.jo.

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technologically more demanding with relatively higher cost. Therefore, careful design aspects need be accounted in order to reach optimal multi-junction design with maximum efficiency and ease the efficiency/cost trade-off issue. De Vos (1980) not only sets the theoretical limits of multi-junction solar cells based on the detailed balance limit theory, but also provides the optimal bandgap energies that yields the maximum conversion efficiency for the multi-junction solar cells that are employed for free space applications (i.e. at AM0). However, to the best of our knowledge, there was no useful attempt that optimizes the design of the multi-junction PV cells for terrestrial applications at AM1. Therefore, the author is proposing an optimization of the bandgap energies of a given number of junctions for the terrestrial multi-junction PV cells; which, indeed, has much broader application than free space multi-junction PV cells.

The limited conversion efficiency of PV cells is attributed to different kinds of losses (Solar Technologies Market Report, 2010; Wolf, 1960). The most prominent losses are the thermalization loss which is due to producing hot electrons from shorter wavelengths photons such as the ultraviolet range of the solar spectrum; and the non absorbed photons with longer wavelength such as the infrared range of the solar spectrum. Usually, the hot electrons lose their excess energy by producing phonons which are lost eventually as heat in the cell. Whereas, the longer wavelength photons have inadequate energy to launch free electrons, therefore, they are not utilized in the photovoltaic conversion process. A trade-off scenario is encountered as one attempts to find the optimal bandgap energy of a single cell that compromises the two kinds of losses. As a matter of fact, it was found that the efficiency limits of an optimized single junction and multi junction PV cell at AM0 ranges from 30% for a single junction to 68% for infinite number of junctions, which indeed sets the theoretical limit for the efficiency of the PV cell illuminated by sunlight at AM0 (De Vos, 1980; Shockley and Queisser, 1961).

2. Theory

The problem is to find the optimal set of bandgap energies of the semiconductor materials that will be used as the active regions in the multi-junctions structure in order to optimize the cell performance with maximum electrical power delivery for terrestrial applications. The solar spectrum at AM1 (Fig. 1) is usually obtained from tabulated experimental data and is not described by a theoretical or empirical function as it was for the works of De Vos (1980) and Shockley and Queisser (1961), which handled the AM0 case, and considered accurately the solar spectrum radiating off a black body at 6000 K. This makes the problem rather not a straight forward task. The approach here depends on a careful development of a theoretical model that accounts for the major losses in the photovoltaic conversion of sunlight to electricity, and then followed by numerical optimization with respect to the cutoff wavelengths of the junctions that associate the bandgap energies of the active regions ($\lambda_{\mathrm{cutoff}}\mathrm{E}_{\mathrm{bandgap}} = 1.24$, where $\lambda_{\mathrm{cutoff}}$ is in micrometer and $\mathrm{E}_{\mathrm{bandgap}}$ is in electron volt).

As discussed above the concept of multi-junction in PV cell deals with two major issues that comes from the spectral mismatch between the solar spectrum and the conversion response of the photovoltaic junction. The first limiting effect comes from the thermalization losses which is due to the generation of hot electron by the absorption of photons with higher energy than the bandgap energy of the absorbing medium. Not only this excess energy is lost, but worse than that it is converted to internal heat that usually increases the cell's temperature, thus, lowers the performance and the life span of the cell because of the increased thermal stress inside the cell. The second limiting factor is that those low energy photons that are lower than the bandgap energy are not absorbed to be converted to electricity; therefore, they are not utilized in the conversion process. As a matter of fact, the multi-junction approach was proposed in order to deal with those two issues effectively because it depends on segmenting the solar spectrum among a cascaded group of PV junctions, similar to controlling the numerical integration error by increasing the number of segments. Moreover, the more segmentation of the solar spectrum permits broader cover for the solar spectrum with less concern of increasing the thermalization losses. Basically, as a rule of thumb, in order to better control the overall thermalization, the entering junction are assigned to absorb the shorter wavelengths of the solar spectrum as sunlight enters the multi-junction PV cell, whereas, the later junctions are used to absorb the longer wavelengths of the spectrum.

The next concern is to assign the cutoff wavelengths, which associate the bandgap energies, of the absorbing media among the solar spectrum to optimally control the overall thermalization losses and at the same time utilize as much as possible the far tail of the solar spectrum.

To start modeling this problem we assume that the number of junctions is given and the main task is to find the optimal bandgap energies that maximize the conversion efficiency; therefore, the thermalization losses in each junction is expressed by:

$$\begin{aligned} Th_k &= \int_{\lambda_{k-1}}^{\lambda_k} \phi(\lambda)(E_{ph}(\lambda) - E_{g,k}(\lambda_k))d\lambda \\ &= \int_{\lambda_{k-1}}^{\lambda_k} \phi(\lambda)\left(\frac{hc}{\lambda} - \frac{hc}{\lambda_k}\right)d\lambda \qquad (1) \end{aligned}$$

where $\phi(\lambda)$ is the photon flux density of the sunlight, $E_{ph}(\lambda)$ is the photon energy with wavelength λ, $E_{g,k}(\lambda_k)$ is the bandgap energy for the kth junction and λ_k is the corresponding cutoff wavelength, h is Plank's constant, c is the speed of light in vacuum.

Therefore, the total thermalization losses for n-junction PV cell with cutoff wavelengths $\Lambda = [\lambda_1, \lambda_2 \ldots \quad \lambda_k \ldots \lambda_n]$ could be expressed as: