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Thicknesses optimization of two- and three-junction photovoltaic cells with matched currents and matched lattice constants

Rabi Ibrahim Rabady*, Hamza Manasreh

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

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ABSTRACT

Maximizing the conversion of sunlight to electricity by theoretically optimizing the utilization of lattice-matched multi-junction photovoltaic cells of the incident solar radiation was attempted. The lattice constant matching among the layers is important to avoid the internal thermal stress. In the proposed model the current mismatching, the thermalization losses, and the fill factor were all introduced to the conversion efficiency equation. The current matching can be achieved not only by suitable choice of bandgap energies, which directly decides the photon count distribution among the junctions, but also, by the absorbed amounts of those photons that could be controlled effectively by optimal choice of thicknesses; which is the significance of this research since such additional design freedom is essential to overcome the possible imperfect choice of bandgap energies that is dictated by the lattice matching requirement. Numerical search method was employed to find the optimal thicknesses for two- and three-junction PV solar cells in order to maximize the conversion efficiency. The performance of the proposed model is tested for various lattice-matched MJ samples. The results revealed that employing well-chosen bandgap energies for the active media in these samples leads to promising and efficient electricity generation using MJ solar cells. For example, 41.6% and 46.7% solar to electricity conversion efficiency can be obtained from double and triple junction solar cells, respectively, under concentrated sun regime.

1. Introduction

Nowadays, solar energy harvesting and utilization are more efficient than any other time before. This encouraged various governments to issue policies that facilitate the development and utilization of solar energy. The photovoltaic PV technology is considered one of the most reliable technologies for converting sunlight into electricity. However, the conversion efficiency of available PV cells is seriously limited because of the considerable mismatch between the photovoltaic response of the known semiconductor materials and the solar spectrum. For instance, sunlight photons with lower energy than the semiconductor bandgap energy cannot produce free electrons; therefore, they are not useful; only photons with energy larger or equal than the bandgap energy can make free electrons. Nevertheless, photons with higher energy usually produce hot electrons that quickly losses their excess energy before being transport to the electrodes in the form of internal heating, a process known as thermalization.

Interestingly, such efficiency limitations can be overcome by assigning different spectral ranges of the solar spectrum to suitable PV cells, and this is the main idea of the MJ solar cell which revolves around segmenting the utilization of the solar spectrum into various bands in order to control the energy losses and, hence, boost the conversion efficiency by accomplishing two major advantages: more sunlight utilization because wider range of the solar spectrum can be used in the photovoltaic conversion; and effective control for the thermalization losses since each spectral range can be assigned to suitable PV cell where the photovoltaic response is relatively high. The multiple PV cells can be configured as separate cells that receive their solar spectral divisions from an engineered spatially dispersive splitter (Imenes and Mills, 2004) or in a serially stacked multi-junction structure. The former configuration is more complicated, demanding and less compact. On the other hand, the series stack of multi-junction suffers major issues; for instance, the lattice matching among the layer should be accounted for in order to avoid the internal thermal stress that could seriously limits the multi-junction cell life services especially for concentrated sunlight applications. The lattice-matching requirement also limits the choices of suitable materials that could be used; therefore, reducing the possibility of finding bandgap energies that optimally matches the solar spectrum (Yamaguchi et al., 2005). Moreover, the net current of the series multi-junction structure is bottlenecked by the smallest current from the sub cells; therefore, currents from all sub cells should be matched as possible in order to control the produced electric power

* Corresponding author.
E-mail addresses: rabirabady@yahoo.com, rrabady@just.edu.jo (R.I. Rabady).

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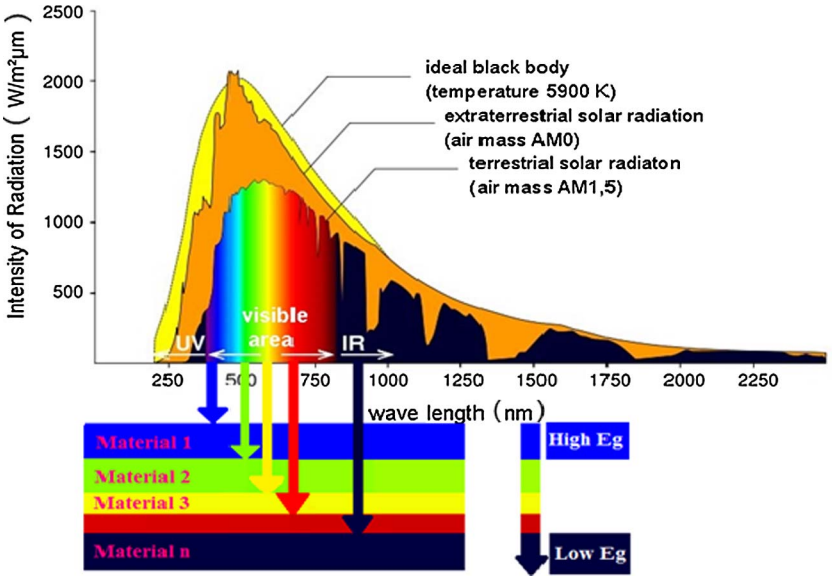

Fig. 1. Solar spectrum band assignment in multi-junction solar cell.

loss. In fact, the theoretical prediction for the conversion efficiency of infinite number of P−N junctions is of 68% (De Vos, 1980); meanwhile, experimental conversion efficiencies that exceed 40% or multi-junction PV cells were reported (Cotal et al., 2009)

Many researchers have worked on MJ solar cells by investigating new designs and experimenting different materials in order to realize higher conversion efficiencies. For example, in the early stages of MJ cells development a new cascade structure of two junctions was developed from AlGaAs/GaAs with 25% conversion efficiency; those researchers suggested that optimizing layers' thicknesses and choosing suitable bandgap combinations could improve the conversion efficiency significantly (Bedair et al., 1979). Olson et al. (1990) focused on obtaining a current matching between a two junction solar cells by optimization top-cell thickness and predicted conversion efficiency of 27.3% at AM 1.5.

During the nineties additional areas were specified and studied in order to improve the conversion efficiency of MJ solar cells; conversion efficiencies of 29.5% and t25.7% at AM1.5 and AM 0, respectively, under one sun illumination were reported (Bertness et al., 1994). Takamoto et al. (paper 1997a) developed a new optimized model of two junctions and achieved conversion efficiency of 30% for InGaP/GaAs dual junction solar cell; they also demonstrated a conversion efficiency of 33% by triple-junction cells (Takamoto et al., conference 1997b).

King et al. (2007) reported experimental conversion efficiency for triple junction GaInP/GaInAs/Ge cell of 40.7% at AM1.5 and under 240 suns illumination with the potential to exceed 45% using four or more junctions.

Usually, the delivered electricity from MJ solar cells depends strongly on the drawn current; therefore, Braun et al. (2011) experimentally studied the current-matching of GaInAsP/InGaAs tandem concentrator solar cells .As a matter of fact, because of the serial architecture of tandem MJ solar cell the current matching requirement presents a basic characteristic of a successful design (Bonnet-Eymard et al., 2013; Domínguez et al., 2013; Dincer and Meral, 2010). Hence, Guter et al. (2009) developed a lattice-matched triple junction solar cell with suitable bandgap combination to grant the current matching in the whole structure. The reported conversion efficiency was about 41.1% at AM1.5 and under 454 suns illumination.

Moreover, the bandgap energies of the used semiconductor materials were found as important factor which directly affect the MJ cells conversion efficiency. Minnaert and Veelaert (2012) presented guidelines for the material cell designer and determined the optimal bandgap energies for the structure of triple junction solar cells. In our earlier work (Rabady, 2014) with the account for currents matching, the thermalization losses and the fill factor the objective was to maximize the conversion efficiency by finding an optimal set of bandgap energies without the concern of lattice-matching between layers requirement; the predicted conversion efficiencies exceeded 50%. In this research we attempt to redo that work but for lattice-matched MJ structures in order to produce resilient device against possible internal thermal stress, especially for concentrated sunlight application. The lattice matching requirement, as a consequence, makes the choices for materials with suitable bandgap energies narrower. Nevertheless, because of such restriction we choose in this research the active layers' thicknesses as optimizing parameters in order to restore the flexibility of design. That is, the current-matching can be achieved not only by suitable choice of bandgap energies, which directly decides the photon count distribution among the junctions, but also, by the absorbed amounts of those photons that could be controlled effectively by an optimal choice of thicknesses. Such additional design freedom is essential to overcome the possible imperfect choice of bandgap energies which is dictated by the lattice-matching requirement. Therefore, the main objective of this research is to theoretically optimize a lattice-matched MJ solar cell by suitable choice of thicknesses for the active layers in order to facilitates current matching among the junctions, and controls the conversion losses by compromising the thermalization losses and the non-utilized photons which have energy below the lowest bandgap energy in the MJ structure; therefore, maximizing the solar-to-electricity yield.

Fig. 1 shows how the solar spectrum bands are assigned sequentially from lowest to highest wavelength to a stack of decreasing-bandgap-energy in MJ structure. Obviously, sunlight photons of highest energy are absorbed by the top junction to produce photo-induced free charges with highest potential, whereas, all left over sunlight photons with energy above the bandgap energy of the bottom junction are absorbed by that same junction to produce photo-induced electrons with lowest potential.

In general, MJ solar cells face fundamental limitations related to the accessibility of semiconductor materials with suitable bandgap energies. Usually, semiconductor material alloying from group III, IV and V in the periodic table is employed to obtain relatively wide range of bandgap energies that could cover and match the solar spectrum effectively (Bremner et al., 2016). Table 1 shows alloys for 2J cells with their corresponding bandgap energies.

Apparently, there are two major issues that associate the compact serial configuration of MJ structure: the lattice-matching and the