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Solar Energy Materials & Solar Cells 85 (2005) 293–300
Solar Energy Materials & Solar Cells
www.elsevier.com/locate/solmat

Letter

Third generation multi-layer tandem solar cells for achieving high conversion efficiencies

I.M. Dharmadasa*

Solar Energy Group, School of Science and Mathematics, Sheffield Hallam University, Sheffield S1 1WB, UK

Received 19 July 2004

Abstract

Different ways of connecting solar cell structures to form multi-layer tandem solar cells have been considered by re-visiting relevant device designs. It is found that the present use of a series connection or tunnel junction approach is detrimental to charge-carrier collection in the tandem cells. Each tunnel junction introduced to the solar cell structure decelerates the charge carriers and allows them to recombine at the vicinity of the tunnel junction. The adoption of parallel connections has several advantages over series connections and there is high potential for achieving enhanced efficiencies in third generation tandem solar cells. In these devices, charge carriers are continuously accelerated across the whole device and collected in the external circuit. Multi charge-carrier production and impurity photo-voltaic mechanisms are also built into this system to enhance its performance by increasing the short-circuit current density.

Keywords: Third generation solar cells; Multi layers; Tandem solar cells; Tunnel junctions; Impurity photovoltaics

*Tel.: +44 114 225 4067; fax: +44 114 225 3066.
E-mail address: dharme@shu.ac.uk (I.M. Dharmadasa).

0927-0248/$ - see front matter
doi:10.1016/j.solmat.2004.08.008

1. Introduction

The market penetration of PV solar technology is hindered by its high cost. Various new methods have been introduced to overcome this barrier. Multi-layer tandem solar cells, new low-cost materials and device structures and the mass production of PV-modules are some of them. In the case of tandem solar cells, the present trend is to move from one-junction devices to double-junction, triple-junction and multi-junction structures. The current popular method is to use a tunnel junction to combine different cells. This communication presents other methods of achieving this aim and outlines the disadvantages of the current practice of using a tunnel junction approach.

2. Tandem solar cells

The main aim of the tandem solar cell is to absorb a major part of the solar spectrum and hence to increase the efficiency of the device by increasing the electric current. The approach is to fabricate p–n, p–i–n or any other diode structure with different bandgap semiconductors and connect them to enhance the PV conversion. As shown in Fig. 1, cell-1 at the front is fabricated with a wide bandgap material to convert high-energy photons from the blue-end whilst cell-3 at the back is fabricated with a narrow bandgap material to convert low-energy photons from the infra-red end. With this approach, the next step is to connect the cells together to form one device. There are two possible ways of achieving such a tandem solar cell; by connecting them in series or in parallel configurations.

2.1. Connection in series

This type of connection is widely used today. Adjacent devices are connected using a tunnel junction. The schematic diagram of such a tandem solar cell is shown in Fig. 2 and the corresponding energy band diagram is shown in Fig. 3. In this series connection, the n-type material of one device is connected to the p-type material of the adjacent device (Fig. 2). In other words, the conduction band of one device is connected to the valence band of the adjacent device (Fig. 3). The idea is to convert photons with different energy ranges in 3 different devices and collect the charge carriers efficiently to generate high power in the external circuit.

2.2. Connection in parallel

The other approach to fabricating a tandem solar cell is by connecting a large number of solar cells in parallel. Figs. 4 and 5 show the schematic diagram and the energy band diagram of such a device. In this case the material changes its conduction type from n^+ to p^+ through a series of layers consisting of n^+, n, n^-, i, p^-, p and p^+. In this notation, n^+, n, n^- and i denotes heavily n-doped,

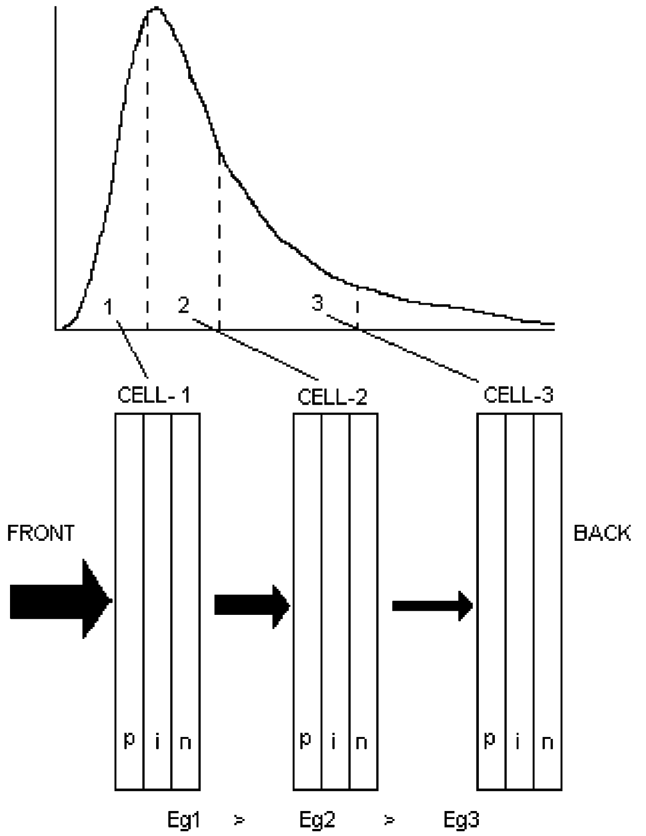

Fig. 1. The approximate shape of the solar spectrum and arrangement of three different p–i–n diodes to utilise photons in three regions. The bandgap within one cell is constant, but the cell materials have larger bandgaps in cell (1) than that of cell (3).

moderately n-doped, low n-doped and intrinsic semiconducting materials, respectively. A similar definition applies to p-type materials and similar structures could be built starting from p^+-type wide bandgap materials. In this situation, the whole structure can be sliced into a large number of different solar cells; n^+–n–n^-, n^-–i–p^-, p^-–p–p^+, etc. The large number of individual solar cells are connected to form a tandem solar cell. The conduction band of one device is connected to the conduction band of the adjacent device, and hence the connection is parallel. Full absorption of the solar spectrum can be achieved by gradually reducing the bandgap from the front to the back of the solar cell as shown in Fig. 5. However, the lowest bandgap material used is a compromise since the open-circuit voltage produced by the device depends on the minimum bandgap material used in the structure.

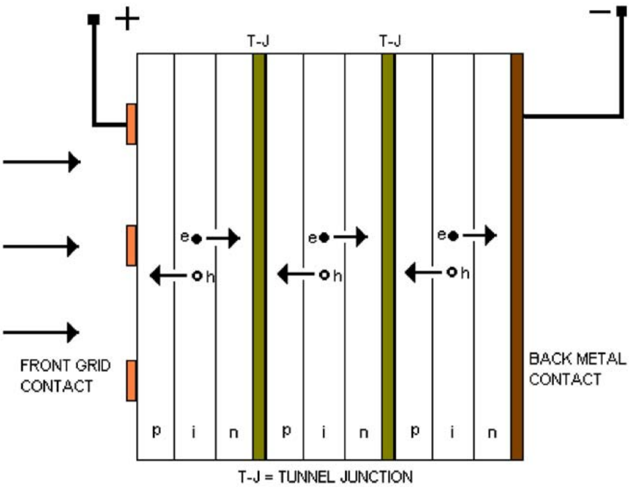

Fig. 2. Schematic diagram of a tandem solar cell fabricated by connecting three p–i–n diodes in series through two tunnel junctions.

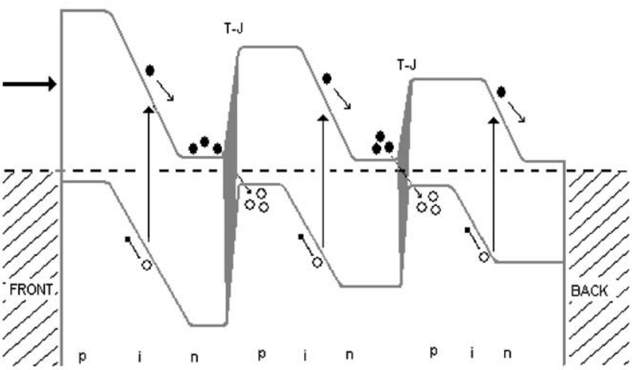

Fig. 3. Energy band diagram of the tandem solar cell shown in Fig. 2.

3. Comparison of the two connecting methods

3.1. Disadvantages of series connections

Tandem solar cells connected through tunnel junctions have a number of disadvantages as shown in the energy band diagram (Fig. 3). The photo-generated electrons of one cell are brought closer to photo-generated holes of the adjacent cell. These carriers are slowed down at the interface due to the existence of an internal electric field acting in opposite direction. This increases the recombination of carriers at this interface through the tunnel junction. Fig. 3 shows the equilibrium situation

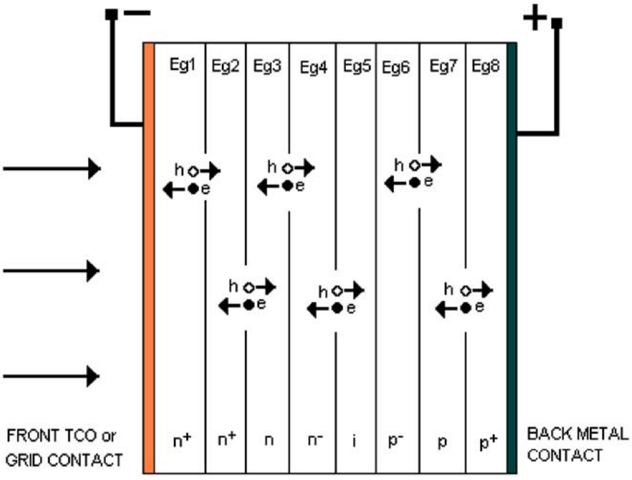

Fig. 4. Schematic diagram of a tandem solar cell fabricated by connecting a large number of cells in parallel. The bandgaps of material layers gradually reduce ($E_{g1} > E_{g2} > \cdots > E_{g7} > E_{g8}$) and the conduction type varies from n^+ to p^+, from front to back of the solar cell.

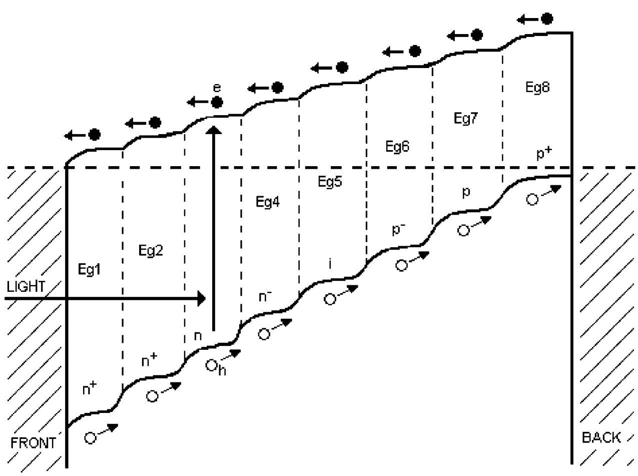

Fig. 5. Energy band diagram of the tandem solar cell shown in Fig. 4. The number of semiconductor layers included in this structure is eight including an n^+-type window material.

under dark conditions for simplicity. However, under illumination, the device structure is equivalent to a forward bias situation by a voltage, V_{oc}, supporting conditions for increased recombination. The efficiency is reduced since conditions are created within the solar cell that promote recombination of photo-generated charge carriers without allowing them to flow through the external circuit.

Ideally, the electrons created should be injected into the conduction band of the adjacent cell. Instead, the conduction electrons of one cell and holes of the adjacent cell are brought towards the tunnel junction (Figs. 2 and 3) and slowed down at that interface due to the opposite internal electric fields present near the tunnel junction. In fact, if all 3 solar cells absorb equal number of photons, the external circuit will experience only holes produced by the front cell and electrons produced by the back cell (Fig. 3). In such a situation, there is no real advantage in having more cells. Any improvements observed in the past are most likely due to improvements in the quality of the material made when more layers are grown on top of one another, starting from the back contact. In fact, more tunnel junctions introduced in the structure increase the number of interfaces where electron–hole pairs can recombine. Such an approach, in which 3 or more cells are fabricated, costs increase but the efficiency gains are comparatively small.

3.2. *Advantages of parallel connections*

With reference to the energy band diagram for parallel connections (Fig. 5), electron–hole pairs are generated by high-energy photons in the front layers and by low-energy photons in the back layers of the cell. The photo-generated electrons are accelerated towards the front contact and holes are accelerated towards the back contact. In this case the recombination process has been minimised and charge carriers achieve very high kinetic energies due to continuous acceleration across the device structure. Therefore all of the photo-generated charge carriers have the possibility of reaching the load in the external circuit. Various other loss mechanisms are common to both systems and therefore have been ignored in this discussion. Since the charge carriers undergo continuous acceleration, they can even create multiple charge carriers due to an avalanche effect increasing the electric current in the device (Fig. 6). In series connections, charge carriers are slowed down at each tunnel junction increasing recombination, hence reducing current collection in the external circuit.

In addition, the impurity photovoltaic [1] or interband photovoltaic effect [2] is also built into devices that are connected in parallel. The low-energy photons at the infra-red (IR) end travel towards the back of the solar cell. Any semiconductor material contains a number of defect levels in the bandgap and these levels are useful for the device structure. Combination of two IR photons could create one e–h pair in any region and these charge carriers are well separated, accelerated and collected in the external circuit (Fig. 6). Various combinations of IR photons could produce many e–h pairs using different impurity levels present in the semiconductor layers, anywhere from the front to the back. This effect could also contribute to the PV activity as shown in Fig. 6, enhancing the current collection from this type of device structure.

Recent advances in the growth of p^+-, p-, i-, n- and n^+-type $CuInSe_2$ based materials [3,4] using electrodeposition are very relevant to the fabrication of multi-layer devices connected in parallel. In addition, the simultaneous bandgap engineering needed to achieve values in the range of $\sim$2.20 to $\sim$1.00 eV has been

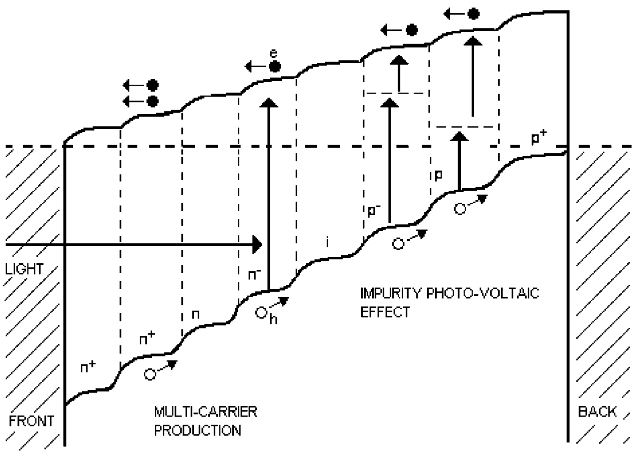

Fig. 6. The possibility of multi-charge carrier creation by avalanche effect and the multi-step charge carrier creation using IR photons through impurity photovoltaic effect in tandem cells connected in parallel configuration.

established [5]. By varying both the bandgap and the conduction type, using previously described electrodeposition teachniques [3–5], it is possible to grow device structures of the type shown in Figs. 4 and 5. In addition, the use of electrodeposition satisfies a number of key criteria necessary for PV development; namely its low cost, scalability and manufacturability, ultimately contributing to increased device efficiencies and low production costs.

4. Conclusions

The re-consideration of the solid-state device principles behind the fabrication of tandem solar cells allows us to draw several conclusions:

The fabrication of tandem solar cells using a series configuration, through tunnel junctions, is inefficient at charge carrier collection. At each tunnel junction, photo-generated electrons and holes approach one another, are decelerated and allowed to recombine. The addition of more tunnel junctions is actually detrimental to charge-carrier collection. Any improvement observed in the device performance to date, is likely due to improvements in the quality of the material, achieved due to growth of a number of layers on top of one another.

The fabrication of multi-layer tandem solar cells using a parallel configuration, on the other hand, has several advantages. Variation of the conduction type from n^+ to p^+ combined with bandgap variation from high to low, from front to back of the solar cell, provides many positive results. The photo-generated charge carriers at any depth of the device are effectively separated, accelerated and collected in the external circuit. Continuous acceleration across the whole device could produce hot carriers and therefore create multi-charge carriers through an avalanche effect. In addition, the impurity photo-voltaic activity could also pump electrons into the conduction band using different combinations of most of the IR radiation. These e^-–h^+ pairs are also effectively separated, accelerated and collected in the external circuit enhancing the short-circuit current density of the device. The improvement in performance of tandem solar cells will manifest itself mainly in high short-circuit current densities since both the open-circuit voltage and fill factor values will be approaching their maximum values in such devices.

Removal of tunnel junctions from tandem solar cells and adoption of a parallel configuration could lead to high performance third generation solar cells in the future.

Acknowledgements

The contributions made by John Young, Nandu Chaure and Anura Samantilleke to the solar energy programme and constructive comments made by Phil Gardiner are gratefully acknowledged.

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