Beam-splitting versus tandem cell approaches for converting the solar spectrum into electricity: A comparative study.

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Beam-splitting versus tandem cell approaches for converting the solar spectrum into electricity: A comparative study.

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Abstract – **There are two main approaches for converting efficiently the maximum of sunlight into electricity. Both of them involve a maximum of solar cells with different energy band-gabs in one single system. The first approach consists in stacking solar cells with different energy band gaps on top of each other. The second approach consists in integrating solar cells with different energy band-gaps in an optical system with beam-splitting features. In this study, an optimized tandem solar cell is presented. The involved solar cells are made of AlGaAs and Si. The same solar cells are integrated in a system with beam-splitting features. On the basis of the response of the two systems, the two approaches are compared.**

Keywords - Photovoltaics, beam splitting, optical filters, tandem cells.

1. Introduction

In photovoltaics (PV), for converting the maximum of the solar spectrum into electricity, four main design approaches have been used [1]. The first approach is to concentrate light on a material which absorbs the maximum of sun rays and emit photons with specific energies. Those photons are then absorbed by a solar cell which has the optimum energy band-hap. This approach is called thermophotovoltaics.

The second approach is to split the sun beam into two sub-beams. One sub-beam is directed towards a photovoltaic cell, and then converted to electricity. The other sub-beam is directed through a light-guide and converted into thermal energy. The generated electricity and thermal energy are ultimately used for running a thermal process. For instance, this technique has been used for running high temperature steam electrolysis for generating hydrogen.

The third approach is to split the beam into several sub-beams. Each sub-beam consists of photons with specific energies. These photons are then directed towards a photovoltaic cell that has a close energy band-gap. This approach has been demonstrated for systems involving up to four solar cells and efficiencies as high as 38% were recorded on laboratory scale demonstrations. The main advantage of this type of systems resides in their low cost. Another advantage is that there is no theoretical maximum number of cells that can be integrated in such systems. The main disadvantages are the fact that these systems have complex shapes, and their efficiency degrades as the number of optical components increase.

The fourth approach is to stack several solar cells with different energy band-gaps on top of each other. The top cell is the one with the highest energy band-gap, and the other cells are put beneath it in the order of decreasing energy band-gaps. The bottom cell is the one with the lowest energy band-gap. Photons with energies higher than the energy band-gap of the solar cell are absorbed, and photons with less energy are transmitted to the cell below. Systems with three cells are already available in the market, and systems with four cells are expected to be in the market in 2011. Theoretically, cells with six junctions can be made. A lab-scale five-junction cell was made and tested under high concentration at the University of New South Wales, Australia, in 2009 and an efficiency of 43% was recorded.

The four approaches are summarized in table 1.

In PV, approaches three and four have been used alternatively for the same purpose. Both of them are based on the same concept which is the use of a maximum number of solar cells in one system. Systems with two stacked solar cells have been well investigated. Optical systems with two not-stacked solar cells have also been studied.

In a previous study, we optimized and investigated a double junction solar cell made of AlGaAs and Si [2]. In another study, we designed and optimized an optical system with beam splitting features and two receivers holding the same cells: AlGaAs and Si [3]. In this study, the two systems are compared under the same conditions of solar irradiance and temperature.

Table 1. Summary of the approaches used for improving the efficiency of PV systems (adapted from Reference [1]).

Approaches used to increase PV systems efficiency.			
Selective emitter to shift and adapt the wavelength to the device energy bangap (Thermophotovoltaic systems).	Stacking PV cells on top of each other either mechanically or monolithically	Split the beam to run a photothermal process and a photovoltaic process.	Split the beam and direct the beams towards different solar cells.

2. The tandem approach

As described earlier, the tandem approach consists in stacking monolithically or mechanically several cells with different energy band-gaps [4]. One study demonstrating this approach was published by the authors. In that study, a double-junction solar cell was optimized for concentrating and thermo photovoltaic systems [2]. The cell was composed of an $Al_{0.3}Ga_{0.7}As$ cell with an energy band-gap equal to 1.817 eV, and a Si cell with an energy band-gap equal to 1.124 eV.

The cell was optimized using PC1D, and the optimum thickness of the two cells as well as the optimum doping levels were determined.

For the top cell (i.e. AlGaAs cell), thicknesses of 0.01 μm and 2 μm were optimal for the emitter and the base respectively. The optimum doping level in the emitter was estimated at 10^{18} cm^{-3}. In the base, the optimum doping level was 10^{17} cm^{-3}.

The performance parameters of the tandem cell under one sun are summarized in table 2.

The overall efficiency of the optimized double-junction cell under the AM1.5G spectrum was 24.6 %.

Table 2. Performance parameters of the tandem cell under AM1.5G.

	Jsc (mA/cm^2)	Voc (mV)	Efficiency (%)
AlGaAs top cell	19	1238	20
Si bottom cell	9.3	616	4.65

In the beam-splitting approach, the systems should be assessed under the AM1.5D spectrum, because the diffuse rays cannot be tracked. For this reason, the optimized tandem cell was tested under the AM1.5D spectrum. Table 3 summarizes the obtained results.

Table-3: Performance of the tandem cell under AM1.5D.

	Jsc (mA/cm^2)	Voc (mV)	Efficiency (%)
AlGaAs top cell	12.9	1220	16.94
Si bottom cell	7.47	608.5	4.83

The overall efficiency of the optimized double-junction cell under the AM1.5D spectrum is then 21.77 %.

3. The beam-splitting approach

As described earlier, the beam-splitting approach consists in integrating several cells with different energy band-gaps separately in one optical system. The optical system should have beam-splitting features. In the system, the sun beam is split into several parts, and each part is directed towards a solar cell. Each sub-beam represents a set of photons with specific energies, and should be directed towards a cell with the corresponding energy band-gap.

Because the tandem-cell was optimized under one sun, we searched for an optical system that has beam-splitting features and no concentration features. The optimum design found is the one in figure 1 [5].

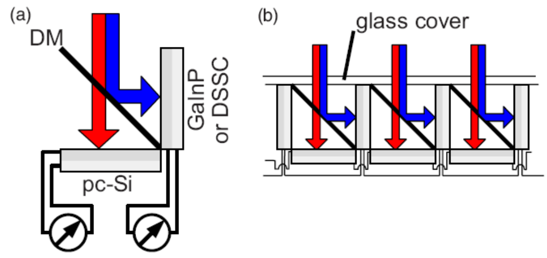

Figure 1. Experimental setup of the optical system ((a): measurement setup and positionning of the cells; (b): the module) [5].

Even though the system was originally optimized to hold a Si solar cell and a GaInP solar cell or a Dye Sensitized solar cell, in this study, the DSSC or the GaInP solar cell is replaced by the optimized AlGaAs solar cell and Polycrystalline Si solar cell is replaced by the optimized Si solar cell. A modeling set-up was developed for assessing the system. The parameters for the AlGaAs cell used in the model are the optimum ones as determined in the optimization of the tandem cell. This is because the AlGaAs is the top cell and it receives the entire spectrum, and its behavior does not depend on the bottom cell. The optimum parameters of the optimized Si solar cell depend on the top cell properties. For the sake of making a consistent comparison, the parameters of the optimized cells (i.e. Si and AlGaAs) were conserved and used in our model.

The beam-splitter consists of a sheet of glass with a realistic multi-layer optical filter. The filter has its transition band-gap at 780 nm, and it was made of a high-pass filter and two band-stop filters all stacked together.

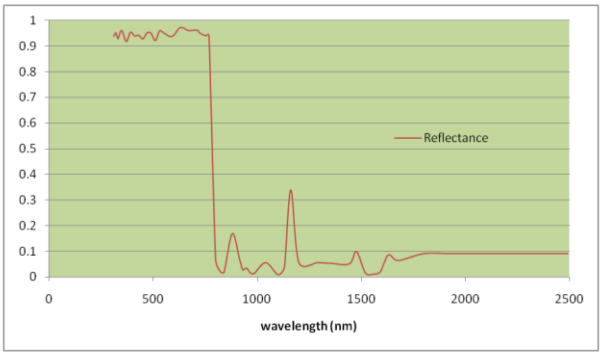

Figure 2. Reflectance of the optical filter.

The performance parameters of the system are summarized in table 4.

Table 4. Performance parameters of the cells in the optical system under AM1.5D.

	Jsc (mA/cm^2)	Voc (mV)	Efficiency (%)
AlGaAs	12.4	1211	16.42
Si	4.51	619.2	2.88

The overall efficiency of the system under AM1.5D is then 19.3 %.

4. Conclusion

Two tandem solar cell made of AlGaAs and Si cells was optimized in a previous study. The same cells were incorporated in a beam-splitting photovoltaic systems where the cells were kept apart. The two systems were tested under the AM1.5D spectrum and the results obtained are summarized in table 5.

In the tandem cell, the overall efficiency was estimated at 21.77%, while in the beam-splitting approach, the overall efficiency was estimated at 19.3%. It is important to remind that this does not mean that the tandem cells perform better, because the Si cell was kept the same in the two models. Optimizing the Silicon cell in the beam-splitting system will normally improve the efficiency of the system. Also, the optical filter had a cut-off wavelength at 780 nm, and was made of a three optical filters. A Better filter could be a single high-pass optical filter with a cutoff-wavelength slightly above the wavelength that corresponds to the AlGaAs cell (i.e. above 682 nm).

It is interesting to note that the tandem cell had better performance under the AM1.5G spectrum. Furthermore, the tandem cell converts the diffuse and the direct rays. On the contrary, the optical systems with beam-splitting features are usually designed for converting the direct incident solar rays only. For this reason, consistency of comparing the two systems under the same spectrum remains disputable.

Finally, it is not straightforward to know which approach is better as the performance of the two systems depend on the design parameters used for each. Also, it depends on the application, because

CPV systems with beam-splitting features are designed usually for converting the direct solar rays, while the tandem systems are designed either for converting the direct concentrated sunlight or the global sunlight (i.e. space applications). Cost analysis will probably make one approach better than the other from a purely economic point of view.

Table 5. Summary of the results.

	Jsc (mA/cm^2)		Voc (mV)		Efficiency (%)	
	Tandem	Beam-splitting	Tandem	Beam-splitting	Tandem	Beam-splitting
AlGaAs	12.9	12.4	1220	1211	16.94	16.42
Si	7.47	4.51	608.5	619.2	4.83	2.88

5. Acknowledgement

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