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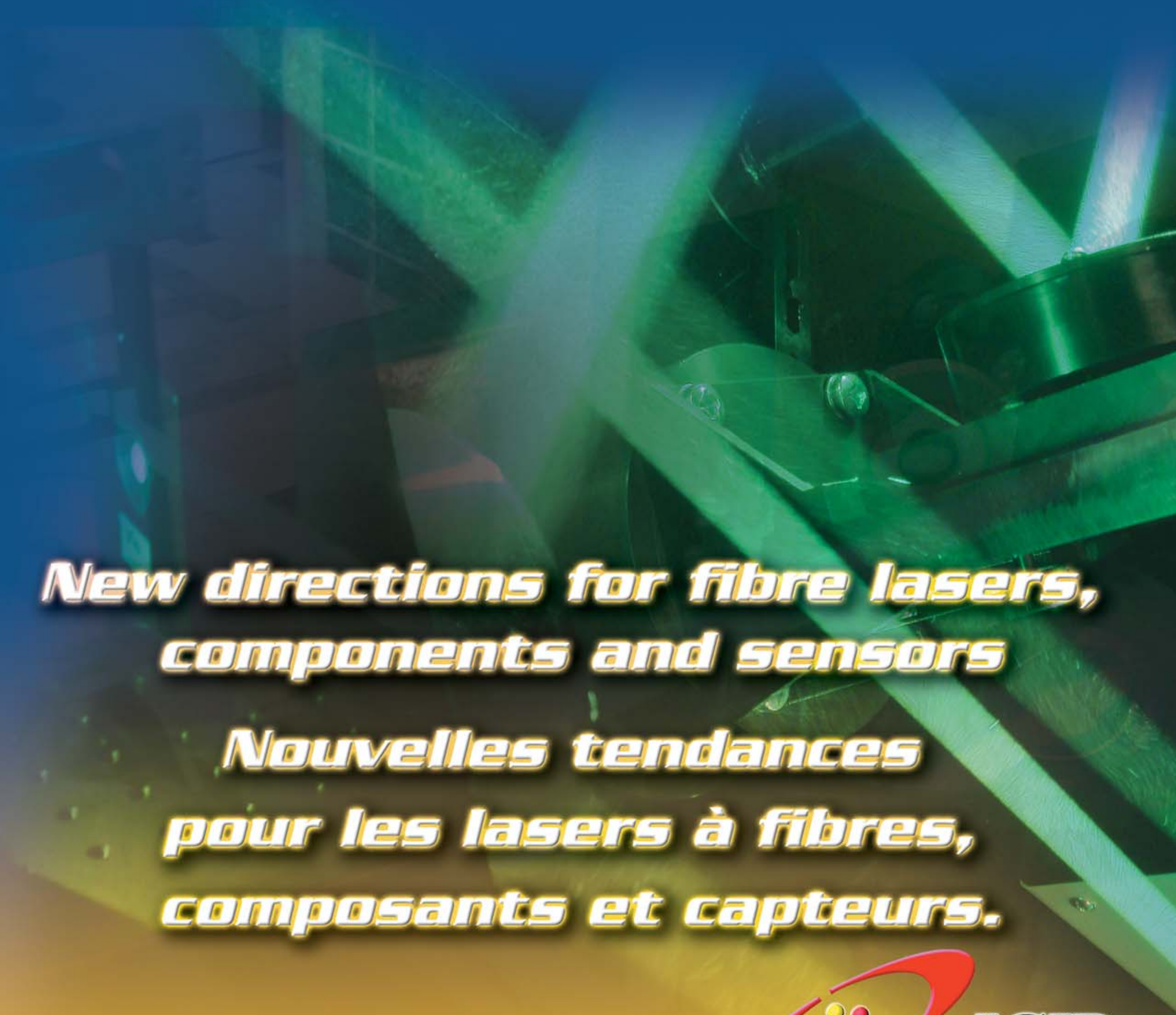
Technical Review of the Canadian Institute for Photonic Innovations
Revue technique de l'Institut canadien pour les innovations en photonique



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Vol. 9 Nº1
Spring 2011 / Printemps 2011

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The Viability of Spectral Splitting for the Reduction of Recombination Losses in Multi-Bandgap Solar Photovoltaic Devices

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ABSTRACT - As the search intensifies to produce low-cost high-efficiency solar photovoltaic cells, several device designs have been proposed to split the solar spectrum and focus only photons of a bandgap appropriate for a given absorber layer in a sub-cell or graded bandgap cell. The intention of such designs is to decrease the electrical path length of charge carriers and the concomitant recombination losses observed in conventional tandem multi-bandgap devices. This article explores the viability of such spectral splitting photovoltaic designs by investigating amorphous silicon and microcrystalline silicon tandem and individual cells using numerical simulation with D-AMPS.

1. INTRODUCTION

Typically, single junction solar photovoltaic (PV) devices have an efficiency of 8.2-25% depending on the material, while multijunction devices can provide efficiencies over 40% [1]. Efficiencies are limited in part by the ability of conventional solar cells, normally with a single bandgap, to absorb the solar spectrum. A solar cell can only absorb a photon if the photon's energy is equal to or greater than the bandgap and any energy in excess of the bandgap is lost due to thermalization. The ideal PV device would involve matching the bandgap of the cell to the sun's spectrum of photon energies for optimal absorption and conversion to electricity. Multijunction cells provide a proxy to this ideality with various layers of different bandgap materials allowing the cell to optimally absorb a greater spread of photons. However, multijunction PVs are more complex and thus more costly to manufacture.

Another approach to capture the entire solar spectrum is through spectral splitting (SS). SS utilizes various reflectors, splitters and/or uses refraction to direct and focus a specific section of the light spectrum onto a specific cell designed for that wavelength of light [2]. It has been claimed that SS systems are more efficient since the cells can be better optimized for specific wavelengths, are not limited to optical properties of the upper layer cells like multijunction cells and if a concentrator is used can have efficiencies of 45-60% [3-6]. Furthermore, since the cells will be easier to build and the splitters easy to manufacture, SS could be achieved at lower costs than conventional PV [6].

The fundamental difference between SS and a multijunction cell approaches is one of geometry; with SS using cells horizontally aligned on the same substrate, whereas in a multijunction cell, the cells are stacked vertically on top on one another as seen in Figure 1a and 1b. Another difference is that SS does not require current matching, which limits multijunction PV performance to the lowest current produced from one of the cells not the combination of the multiple layers. Furthermore, the absorptivity of the material used in a multijunction cell is important, as the photons must pass through the upper layers to reach the lower layers [7]. One promising idea is to combine SS with a multijunction (SSM) in an attempt to improve its efficiency shown in Figure 1c, by reducing electron-hole recombination because at any given time and location within the multijunction cell the charge carrier density would be lower than in conventional un-split multijunction cells [8]. To determine whether SSM is a viable option for improving the efficiency of a PV system, this paper will analyze the results for a single hydrogenated amorphous silicon (a-Si:H) and single microcrystalline silicon (μc-Si) cell compared to its tandem cell counterpart using the computer simulation program called D-AMPS.

2. METHODOLOGY

D-AMPS (Analysis of Microelectronic and Photonic Devices with new Developments) was used for numerical modelling with Hurkx tunnelling and field dependent mobilities in the tunnel recombination junction and the improved optical model that incorporates wavelength dependent Fresnel coefficients for reflection and scattering [9]. The experimental results modelled were on non-optimized (e.g. no optical enhancement) a-Si:H/μc-Si tandem cell created at Utrecht University with an efficiency of 6.1% [10]. The simulations in this article used the same parameters as in the original model; however the thicknesses of the intrinsic (i) layers were changed in an attempt to improve the efficiency of the cell. The original cell had an i-a-Si:H of 200 nm and an i-μc-Si of 1500 nm, and had a buffer layer between the p-doped layer and the i-layer, which was removed for clarity and to slightly improve performance for the μc-Si layer.

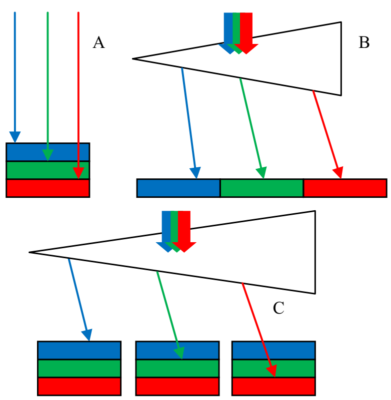

Figure 1: *a) Multijunction Tandem Cell; b) Spectral Splitting; c) Spectral Splitting Multijunction Tandem Cell*

Since changing the top cell's i-layer in a tandem cell will have a larger impact on the cell's efficiency [11], the top i-layer was simulated in a range from 75 to 500 nm. To further optimize the cell, the bottom thickness was then adjusted in a range from 1300 to 2000 nm. The optimized thicknesses for the top and bottom cell were used to test the effects of SS and the SSM cell. In the SS case, the light spectrum was dividing into 340 to 680 /700 nm and 700 / 720 to 960 nm, which illuminated the a-Si:H and μc-Si cells, respectively. The SSM cell had each individual wavelength from 340 to 960 nm in increments of 20 nm simulated separately and summed to determine the total efficiency.

3. RESULTS AND DISCUSSION

When the i-layers of both the top and bottom were changed to determine the optimal thicknesses using parameters which modelled the Utrecht cells, it was found that 100 nm was the optimal for the top cell with a buffer layer and that the optimal thickness of the bottom layer was 1500 nm without a buffer layer.

The a-Si:H/μc-Si tandem cell was simulated under three conditions: i) a full solar spectrum (FS) to demonstrate normal multijunction conditions, ii) separately as if each sub-cell underwent a solar spectrum light individually, iii) under conditions of SS where 340 to 680 /700 nm and 700 / 720 to 960 nm went to a-Si:H and μc-Si cells respectively, and iv) under SS conditions in a multijunction where the tandem cells were only exposed to a single wavelength of light one photon energy at a time from 340 to 960 nm at every 20 nm.

As seen in Table 1 the tandem cell had an efficiency of 7.60% while the a-Si:H and μc-Si cells had efficiencies of 6.27% and 4.94%, respectively. However, it should be noted that the single cells are not optimized single cells (e.g. an a-Si:H cell would normally be much thicker), but optimized cells for a tandem simulated. In the next simulation, we split the spectrum for the a-Si:H and μc-Si cells to their specified bandgaps. Since the bandgap of this a-Si:H was 1.8 eV (690 nm), the simulation was run above and below this value. It was found that although the SS was higher than the single cells, it was still significantly lower than the tandem cell.

The last simulation was of the cells with one wavelength at a time and the output was summed. The results for wavelengths 340 nm, the short circuit current peak and 960 nm are given to display the response of the cells. As shown in Table 1, the a-Si:H and μc-Si cells, although lower, were not as low as the tandem cell. This can be explained by looking at the bandgap of the cells seen in Figure 2.

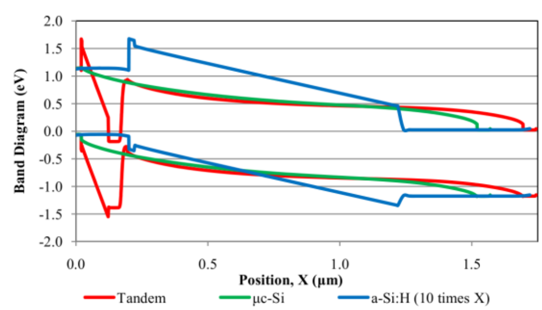

Figure 2: *Band Diagrams of Tandem, μc-Si and a-Si:H Cells*

The reason the efficiency is lower in the SSM cells compared to the FS cells is that when only one specific wavelength is interacting with the cell stack, one cell will generate the vast majority of electron-hole pairs. The current for the entire multijunction stack, however, will be limited by the junction delivering the lowest photocurrent, which in this case will be close to zero for any of the sub-cells not receiving an appropriate spectrum of light.

Table 1: *Summary of Short-Circuit Current, Open-Circuit Voltage, Fill Factor and Efficiency of the Situations*

Cell Type (wavelength)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff (%)
a-Si:H (FS)	8.88	0.88	0.81	6.27
μc-Si (FS)	16.17	0.50	0.61	4.94
a-Si:H/μc-Si Tandem (FS)[a]	7.65	1.357	0.74	7.60
a-Si:H (340-680 nm) + μc-Si (700-960nm)	8.54 / 3.20	0.88 / 0.43	0.81 / 0.58	6.88
a-Si:H (340-700nm) + μc-Si (720-960nm) [b]	8.66 / 2.57	0.88 / 0.42	0.81 / 0.58	6.79
a-Si:H (SSM; 340 ,480, 960 nm)	0.04, 0.88, 5.14E-06	0.71, 0.81, 0.39	0.81, 0.83, 0.66	5.72
μc-Si (SSM; 340, 560, 960 nm)	0.04, 1.11, 0.08	0.24, 0.38, 0.27	0.57, 0.61, 0.56	3.49
a-Si:H/μc-Si Tandem (SSM; 340,560,960 nm) [a]	1.67E-04, 0.47, 5.91E-06	0.71, 1.14, 0.66	0.45, 0.78, 0.74	2.59

Note: FS – Full Spectrum ; SSM – Spectral Splitting Multijunction Tandem; Range: 340 nm – 960 nm
[a] Multijunction cell (top cell / bottom cell)
[b] a-Si:H(incident wavelengths) and μc-Si (incident wavelengths): efficiency added after splitting spectrum on the two cells

A solution to the current matching problem in an SSM type PV device is if the bandgap is graded through a single cell rather than capture light individually in a multijunction arrangement. Therefore, the SSM mechanism would only work with a material that had the potential to change the bandgap slightly with thickness of the absorber layer as it is grown. This is extremely challenging to accomplish with most tradiational photovoltaic materials, which have a discrete bandgap (e.g. c-Si) or those whose properties are poor over large bandgap ranges (e.g. a-SiGe:H). One such material family that makes this bandgap engineering possible is indium gallium nitride (InGaN). With a bandgap between 0.7eV (InN) and 3.4eV (GaN), InGaN is currently under fundamental microstructure and PV device studies [12, 13].

4. CONCLUSIONS

This article explored the viability of spectral splitting PV designs by investigating amorphous silicon and microcrystalline silicon tandem and individual cells using numerical simulation with D-AMPS. The results show that spectral splitting used in conjunction with traditional tandem structures greatly reduces efficiency because of current matching limitations. This challenge could be overcome using single junctions with graded bandgaps to match the solar spectrum for which future work is needed.

ACKNOWLEDGEMENTS

This work was supported by the Natural Sciences and Engineering Research Council of Canada, Canada Foundation for Innovation, Ontario Ministry of Research and Innovation, Canadian Solar Buildings Network and PV Measurements Inc.

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