INFRARED REFLECTING COVERGLASSES FOR MULTIJUNCTION CELLS IN A TERRESTRIAL HIGH-CONCENTRATING PHOTOVOLTAIC SYSTEM

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ABSTRACT: Multijunction cells are composed of multiple layers of semiconductors, with different bandgaps. Among them, GaInP/GaAs/Ge cells are the most popular ones, due to their high performances [1]. These cells have higher efficiencies that silicon ones and should be really convenient in a concentrating photovoltaic plants. Photons are absorbed by a layer if their energy is equal or higher to the semiconductor bandgap. Otherwise they are transmitted to the lower semiconductor. All the photons with less energy than the lowest bandgap are converted into waste heat. They represent about the 5% of the total solar spectrum [2]. Moreover, the Germanium layer usually produces a higher current that the other subcells and even the excess current is converted into heat. Cooling is an important task in designing CPV: the higher the concentration the higher the temperature. Thus, a passive cooling effort can be obtained reducing the infrared radiation absorbed by the cell. An infrared reflecting layer placed on the top of the cell encapsulation should achieve this goal. This solution should reduce the quote of low-energy photons absorbed by the cell, decreasing both the sunlight directly converted into heat and the sunlight converted into excess current by the Germanium layer. Infrared reflecting coverglasses have been successfully tested on space applications. This research focuses on PMMA application for IR reflecting purposes in a terrestrial high CPV system.
Keywords: Multijunction Solar Cell, Concentrator Cells, Solar Cell Efficiencies

1 INTRODUCTION

The principal aim of Concentrating PhotoVoltaics (CPV) is decreasing the cost of solar energy production by reducing the amount of semiconductor material needed. In particular, a large part of semiconductor material is replaced with cheaper concentrating mirrors or lenses.

In high CPV plants, the installation of multijunction cells should be more convenient than the installation of silicon ones. Multijunction cells are made of three layers of semiconductors, each one with a different bandgap and, thus, optimized for converting a different region of the solar spectrum. In April 2011, Solar Junction, a Californian company, claimed the development of the most efficient multijunction cell: record efficiency of 43.5% was reached at 418 suns for terrestrial application [3]. GaInP/GaAs/Ge cells demonstrates the higher performances among multijunction cells under concentrated light [1].

The Concentrator Standard Test Conditions (CSTC) simulates an AM1.5 spectrum, with a direct normal irradiation (DNI) of 1000 W/m2 and an ambient temperature of 25˚C. The Concentrator Standard Operating Conditions (CSOC) consider a DNI of 900 W/m2 and an ambient temperature of 20˚C. However, in a high concentrating photovoltaic system, the III-V cells operate in the 40-80˚C range [4], depending on the cooling system. A temperature increase leads to a red shift in the spectral response of each subcells [4], a decrease in voltage output and in a thermal expansion of the components. The spectral response change means a variation in the amount of current generated by each subcell. The voltage reduction directly deteriorates the performances and the efficiencies of the cells. Finally, the thermal expansion of the components should lead to an immediate failure in fragile components or in fatigue failure [5].

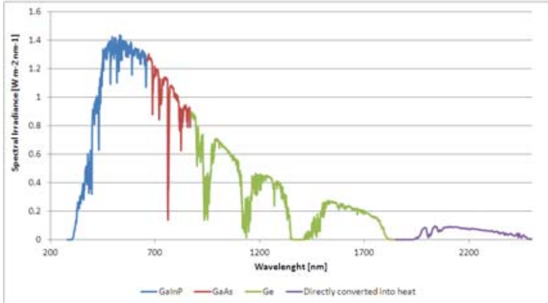

Figure 1: AM 1.5 solar spectrum [adapted by American Society for Testing and Materials (ASTM) Terrestrial Reference Spectra for Photovoltaic Performance Evaluation]

As reported in Figure 1, in a GaInP/GaAs/Ge cell, germanium layer absorbs lower photon energies in the infrared spectrum and its band gap is about 0.67 ev, which corresponds to a wavelength of about 1850 nm. All the photons with lower energy and, thus, with longer wavelength are not collected by the subcells and are converted into waste heat. According to Geisz et al. [2], these photons represent the 5% of the whole solar spectrum. Furthermore, the Ge subcell in a GaInP/GaAs/Ge cell produces a significantly higher photogenerated current than the other two subcells connected in series. Subcells are series-connected and, thus, the less performing subcell imposes the current flowing through the whole cell. The Ge excess current is converted into heat and results in a further increase in temperature. Thus, rejecting a quote of the incident sunlight that would otherwise be absorbed and converted into heat by the heat Ge subcell can improve the system performances. In this moment two solutions have been developed to reach this goal: the use of inverted metamorphic multijunction (IMM) cells or the application of an infrared reflecting coverglass. Geisz and al. [2] investigated the improvement in performances due to the IR reflection on IMM cells. Mullaney et al. [6] obtained an efficiency increase between 2 and 6% in space-based solar cells using IR reflecting coating. The importance of the application of IR reflective coverglasses on space cells was also confirmed by Yoon et al. [7], who was the first in testing them on a 3-juntion cells. This work is unique in that it applies to multijunction cells for terrestrial application. Among several materials, PMMA sheet was chosen, due to the high transmission to the visible light and to the high reflectivity to the near IR light and to its low cost, if compared to the proper IR reflective coating.

2 MATERIALS

2.1 Solar assembly and solar cell

A 3.2 x 3.8 mm receiver developed by Azurspace was used in this study. The system is equipped with a GaInP/GaAs/Ge cell: this cell is able to reach an efficiency of 37.2% and a maximum power of 18.6 W at 500x concentration. It has an active area of 100 mm2 and a thickness of 190 um. The GaInP top cell and the GaInAs middle cell of the 3C40 are current-matched, producing a current of ca. 14.5 mA/cm2, while the bottom cell has at least 40% excess current. The effects of the temperature on the cell's efficiency are reported in Table 1 and in Figure 2.

Table 1: 500x temperature coefficients (25 – 80°C, Beginning of life)

Parameter	Value
Δ Isc / ΔT	1,596 mA /°K
Δ Voc / ΔT	- 4,130 mV/°K
Δ Pmpp / ΔT	- 6,194 mW/°K
Δ η/ ΔT	- 0,034 %(abs.)/K

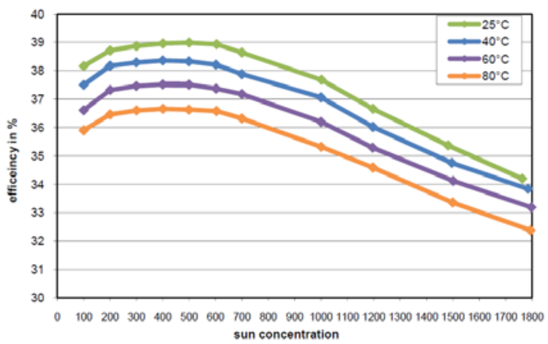

Figure 2: Cell efficiencies vs. sun concentrations

The cell is placed on a direct bonded copper receiver. The 0.3 mm-thick upper copper layer works as an electrical conductor. The 0.63 mm-thick middle layer is made of Al2O3 which acts as a dielectric. The 0.3 mm-thick lower copper layer is the heat spreader. After preliminary tests, the whole assembly has been stuck to an aluminum heat sink through a high thermally conductive silver-loaded adhesive. The original heat sink, manufactured by ABL, has ten 50mm-high fins and show a thermal resistance of 0.5 C/W. After the first experiences, two fins were cut away from the heat sink to raise the thermal resistance and to make the operating temperature closer to the real one.

2.2 PMMA

Different clear PMMA samples have been used in this work. The samples have 5x5 cm dimensions, with thicknesses ranging from 2 to 15 mm. The transmissivity of the samples is reported in Figure 3. In Figure 4, the transmissivity of a 3mm-thick PMMA sheet is compared to the transmissivity of a 2.75mm-thick Borofloat, a glass commonly used for as photovoltaic applications, due to its high and uniform transmission and to the transmissivity of a cheaper common glass.

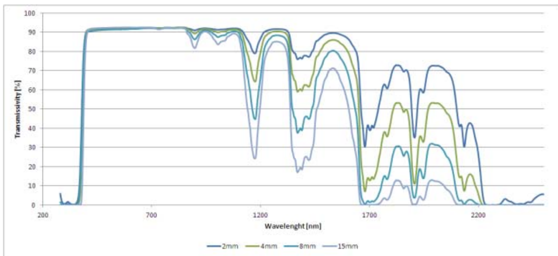

Figure 3: Transmissivity values for different PMMA samples

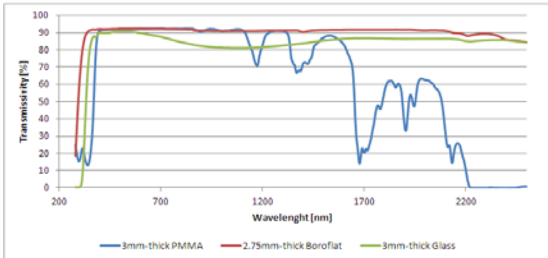

Figure 4: Comparison between PMMA, Borofloat and common glass transmission spectra

The transmissivity of the PMMA was then compared with the Direct Solar Spectral Irradiance, taking into account the values reported by the American Society for Testing and Materials (ASTM). As shown in Figure 5, when compared to Borofloat, the PMMA coverglasses allow strongly reducing the near IR sunlight, which is the aim of the work.

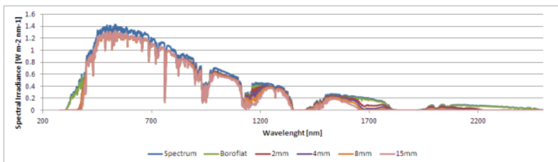

Figure 5: AM1.5 solar spectrum and the irradiances through the Borofloat and the PMMA samples

In fact, as shown both in Figure 3 and Figure 4, the PMMA transmissivity is quite high for lower wavelength, almost similar to the Borofloat one and even higher than common glass one. This fact can be seen even in Figure 5, where the PMMA spectral irradiance for PMMA is close to the Solar Spectrum up to more than 1000 nm, without remarkable differences among the different thicknesses. On the other hand, important variations are present at higher wavelengths: the PMMA Spectral Irradiances and the Solar Spectral Irradiance are rather discordant and substantial differences are present even among the PMMA transmissivity values, depending on the sample thickness. Choosing the most relevant thickness is a fundamental issue. In Figure 6 the spectral irradiances through the different PMMA sheets is reported only for wavelengths ranging from 900 to 2500 nm.

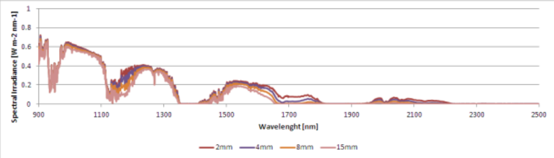

Figure 6: The solar spectral irradiances for different PMMA samples

3 EXPERIMENTAL

3.1 Solar simulator

An Abet Technologies Sun 2000 Solar Simulator has been used for experiments requiring the use of a controlled sunlight. It is equipped with Xenon Arc Lamps and his AM1.5G spectral match is grouped as Class A. The 6x6-inches-wide illuminated area has a non-uniformity lower than 5%.

Firstly, a radiation of 1000 W/m2 has been set with a silicon photodiode. Secondly, light has been focused on the cell through a Fresnel lens. An optical concentration ratio of 166x was reached. It was determined analyzing the difference between the experimental short-circuit current (Isc) and the expected Isc, obtained using the temperature coefficients reported in

Table **1.**

3.2 External circuit and the switch

The solar cell is connected to a resistor. This way, the current is allowed to flow through the cell and the electrical energy is dissipated away from the cell. Without an external circuit, the cell is not able to generate a photocurrent and, thus, all the solar energy has to be dissipated by the solar cell. The switch is needed to open the circuit: this way, the I-V tracer can determine the I-V curve at the final temperature.

3.3 Temperature

It was firstly demonstrated, as reported by Muller et al. [8], the difference between heat sink and the cell temperatures can easily reach 30˚C in steady-state conditions. During our tests there was a difference of 20 Celsius degrees in temperature between the cell and the backplate, within a total increasing in temperature from 30C to 70C. These data are reported in Figure 7.

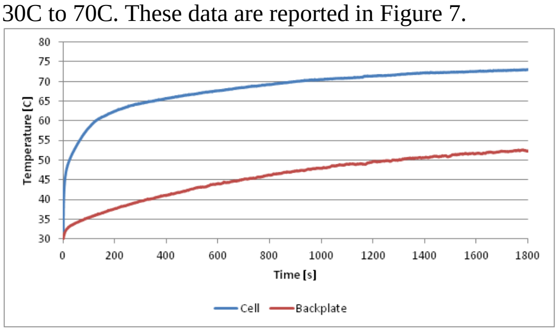

Figure 7: Difference in temperature between the cell and the backplate

Furthermore, the difference in temperature depends on several factors, such as the heart sink design, the thermal attachment and the irradiance. Heat sink temperature can be simply measured: in this study a thermo couple has been used to determine the heat sink condition. For calculating cell's temperature, different approaches are available. A shuttering procedure for calculating cell temperature is reported by Muller et al. [9]: their calculation is based on the measurement of the open circuit voltage during shuttering of the cell, but their results underestimate the cell temperature by as much as 5-10˚C. In this case a thermocouple has been use for this purpose. Thermocouple was firstly located in touch with the cell connectors. But the current flowing into the connectors influences their temperature. Thus, the thermocouple was placed in touch with the cell side, away from connectors. A software developed in LabVIEW allowed to acquire the temperature value each 0.2 seconds.

As shown in Figure 8, the cell's temperature strongly influences its performances. The raise in temperature leads to a decrease in voltage and to a variation in current generation. Thus, the higher the temperature, the lower the power in output. The cell used in this experience shows a cut higher than 12% between the power at 60C and the power at 140 C.

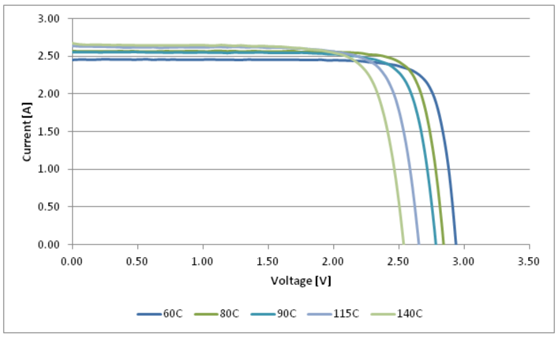

Figure 8: Change in performances due to temperature rising

All the experiments were started at a cell's temperature not higher than 30C, with a room temperature of 25 C. Firstly, the circuit was closed and the temperature had been measured for 30 minutes. After this time, the circuit had been opened and the I-V curve was determined.

3.4 Sourcemeter

The I-V curves of the PV cells tested in the solar simulator have been measured using a Siemens 2440-C 5A Sourcemeter. The instrument can measure voltages up to 42V and currents up to 5.25A.

4 DISCUSSION & RESULTS

Some preliminary studies have been carried out working on the AM1.5 solar spectrum values, as reported by the American Society for Testing and Materials (ASTM). The cell's External Quantum Energy, as reported on the datasheet (Figure 9), has been studied. The range of each subcell has been determined: GaInP operates between 302 and 716 nm, GaAs between 352 and 952 nm and Ge between 858 and 1804 nm. Thus, all the sunlight with a wavelength longer than 1805 nm cannot be used by any cell. This quote represents the

3.58% of the total amount of sunlight hitting the Earth's surface. This value is a little bit lower than that the 5% reported by Geisz et al. [2].

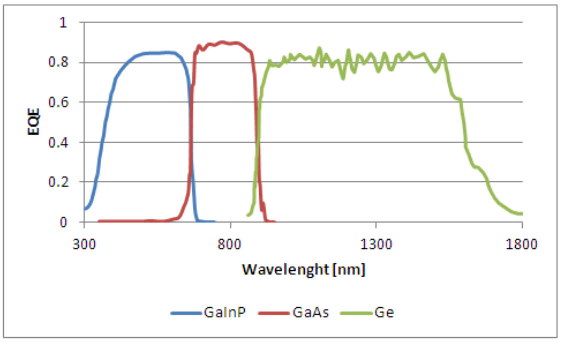

Figure 9: EQE vs. wavelength (adapted by Azurspace datasheet)

The transmissivity of PMMA samples have been studied to understand the perspectives of their application in CPV systems. The results of the investigations are reported in Table 2. As expected, the transmissivity of PMMA in the GaInP and GaAs ranges is almost comparable to that one of Borofloat. Thus, the application of PMMA should not influence really much the performances and the current-matching of the first two subcells. Germanium's performances with PMMA are slightly reduced: this should help in reducing the current mismatch and, thus, in reducing the heat generation inside the cell. The most important feature of PMMA is the cut in transmissivity of the wavelengths over 1804 nm. This case, the transmissivity is almost one third than that one of Borofloat or even less. This cut should reduce as well the heat generated by the cell, passively cooling the system.

Table 2: percentages of transmissivity for PMMA compared to the Borofloat ones, grouped according to the subcell's ranges

	2mm	*4mm*	*8mm*	*15mm*
GaInP	97.55%	97.18%	96.88%	96.67%
GaAs	100.39%	100.21%	99.62%	99.45%
Ge	98.09%	94.44%	89.18%	82.54%
(>1804nm)	35.53%	19.63%	8.99%	2.93%

Six different settings were tested. In the first one no coverglass was used. In the second one a 3mm-thick Borofloat sheet was used. In the other cases, PMMA sheets with different thicknesses were tested. In order to avoid the risk of PMMA melting, the PMMA samples as well as the glass sample were placed three centimeters higher than the cell.

All the experiments were stopped after 30 minutes, when the temperature rising slowed down in all the settings. The most interesting results are reported in Figure 10, which shows the temperature increasing for each setup. The introduction of a PMMA layer slows down the raising in temperature, thus contributing in cooling the whole assembly. After 1800 seconds, the bare cell reached a temperature of 80C, while using Borofloat it was lower than 75C. In all experimented setups, the PMMA coverglasses allow to cut the cell final temperature, which ranges between 60 and 70C.

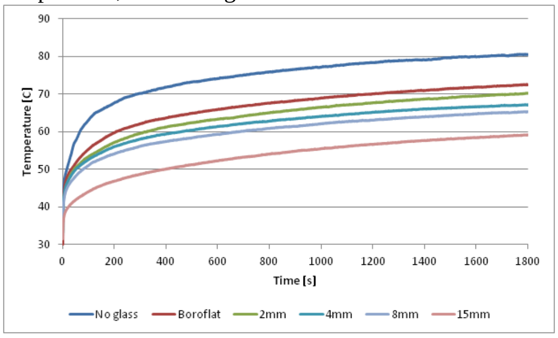

Figure 10: Temperature rising with different settings

The decrease in temperature rising is essentially due to the low transmissivity of the PMMA in the wavelength's range between 1900 and 2500 nm. In this range, the average transmissivity is about 14% for a 5mm-thick and less than the 2.5% for a 15mm-thick PMMA sheet. In the same range, the 3mm-thick Borofloat transmissivity is higher than 89%. The second issue is the reducing of excess current generated by the Germanium substrate. The Germanium substrate absorbs all the wavelengths ranging from 900 to 1800 nm and, as already reported above, produce a current which is 40% higher than the other subcells' currents. A Borofloat sheet has an average transmissivity of about 91% in that range, while a 5mm-thick PMMA sample shows a transmissivity of 67% and a 15mm-thick of 48%. Thus, a cut in transmissivity respectively of 26% and 47% was demonstrated with PMMA compared to Borofloat. These assumptions are confirmed by the behavior of the cell covered with Borofloat.

The I-V curves obtained in all the tests after 1800 seconds are reported in Figure 11, while the power outputs are shown in Figure 12.

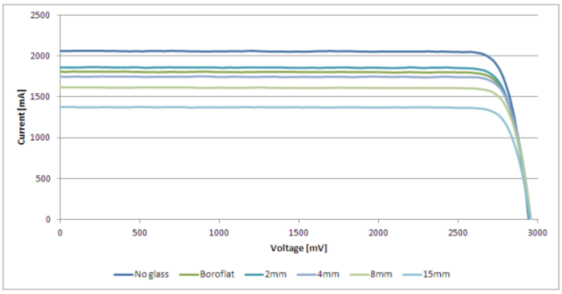

Figure 11: I-V curves of the cell with different coverglasses

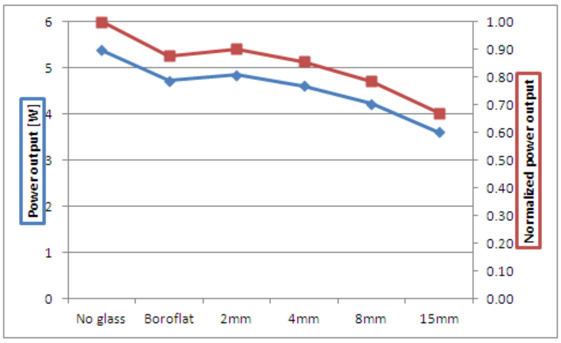

Figure 12: Power outputs of the cell with different coverglasses

Replacing the Borofloat with a thin PMMA layer can lead to an improving in performances. As expected and shown in the figures above, the bare cell has a production always higher than all the cases with a coverglass. The performances of the thinnest-PMMAs cases are comparable with those of the Borofloat case. On the other hand, the thickest PMMA samples are not convenient: even if they grant a lower temperature, the cut in solar irradiance is too important to lead any improvement in performance.

According to the predictions and the obtained results, the PMMA should be a good material to replace the more-expensive borosilicate glasses, usually employed as coverglasses in CPV applications. The unaged thin PMMA samples used in these experiments grant good performances: the exploitation of high-quality PMMA samples should even lead to better performances, according to the theoretical calculations.

Anyway, further investigations on the behavior of PMMA have to be carried out. In particular, the deterioration of PMMA due to the harsh conditions of CPV is an important issue. Studies on the energy production of a PMMA-covered cell for terrestrial CPV should definitively prove the advantages and the limits of that solution.

5 CONCLUSIONS

Clear PMMA sheets have been used as coverglasses for a CPV application. Several samples with different thicknesses were tested at AM1.5 condition on a 166x concentration sunlight. The aim of the work was studying the potentials of this solution for multijunction cells cooling.

PMMA was chosen due to its transmissivity spectrum: the average transmissivity is high for UV and visible light, while is lower for near-infrared. This characteristic allows to decrease the excess current photogenerated by the Germanium subcell and to reflect an important part of the sunlight with a wavelength higher than 1900 nm, which cannot be used by any subcell.

The results show a decrease in temperature rising when a PMMA coverglass is applied. The thicker is the PMMA sheet, the higher the reduction. In some cases the output power at steady state of a PMMA-covered cell was found higher or similar to that of a Borofloat-covered cell. In particular, the important role of the thickness of the PMMA sheet in cell performances has been shown.

According to the results, the use of a PMMA sheet as coverglass should improve the cooling of multijunction cells. It can be considered a proper passive cooling system, since no electrical or mechanical power is needed in input. The thickness of the PMMA coverglass must be chosen looking for the best balance between the improvement in cooling and the reduction in transmissivity. Further investigations on aged PMMA are required to understand how this solution can perform in a long time period.

ACKNOWLEDGEMENTS

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