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Gaetano Bonsignore, Aurelio Agliolo Gallitto, Simonpietro Agnello, et al.

Electrical-Optical Characterization Of Multijunction Solar Cells Under 2000X Concentration

Gaetano Bonsignore[1], Aurelio Agliolo Gallitto[1], Simonpietro Agnello[1], Marco Barbera[1,2], Roberto Candia[2], Marco Cannas[1], Alfonso Collura[2], Ignazio Dentici[3], Franco Mario Gelardi[1], Ugo Lo Cicero[2], Fabio Maria Montagnino[3], Filippo Paredes[3], and Luisa Sciortino[1]

[1] *Dipartimento di Fisica e Chimica, Università degli Studi di Palermo, Via Archirafi 36 ,90123, Palermo, Italy*
gaetano.bonsignore@unipa.it, Palermo, Italy
[2] *Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Palermo "G.S. Vaiana", Piazza del Parlamento 1, 90134 Palermo, Italy*
[3] *IDEA s.r.l., Termini Imerese (PA), Italy*

Abstract. In the framework of the FAE "Fotovoltaico ad Alta Efficienza" ("High Efficiency Photovoltaic") Research Project (PO FESR Sicilia 2007/2013 4.1.1.1), we have performed electrical and optical characterizations of commercial InGaP/InGaAs/Ge triple-junction solar cells (1 cm^2) mounted on a prototype HCPV module, installed in Palermo (Italy). This system uses a reflective optics based on rectangular off-axis parabolic mirror with aperture 45x45 cm^2 leading to a geometrical concentration ratio of 2025. In this study, we report the I-V curve measured under incident power of about 700 W/m^2 resulting in an electrical power at maximum point (P_{MP}) of 41.4 W. We also investigated the optical properties by the electroluminescence (EL) spectra of the top (InGaP) and middle (InGaAs) subcells. From the analysis of the experimental data we extracted the bandgap energies of these III-V semiconductors in the range 305÷385 K.

Keywords: Multijunction InGaP/InGaAs/Ge solar cells, high concentration photovoltaic, electroluminescence, I-V curve.
PACS: 88.40.hj; 88.40.jp; 81.05.Ea; 78.60.Fi

INTRODUCTION

High concentration photovoltaic systems (HCPV) using multijunction solar cells under concentration level higher than 1000 suns try to deliver electrical power at a lower cost than flat-plate PV systems and even than conventional electricity generation by fossil fuels. To this end it is mandatory to replace expensive semiconductor materials (multijunction III-V solar cells) with cheaper optical devices (lenses and mirrors) [1]. Although the increase of the illumination levels typically rises the annual power rating of HCPV modules, working at very high concentrations (1000-2000X) is a challenge. The cell efficiency decreases because both the series resistance limits its performance at high currents and the cell temperature, without a good thermal management, inevitably increases [2].

In this work we investigated the effects of the high illumination (up to 2000X) on the InGaP/InGaAs/Ge triple-junction solar cells in terms of the key performance parameters: short circuit current I_{SC}, open-circuit voltage V_{OC}, efficiency η. Moreover, we studied the electroluminescence (EL) spectra in order to determine the temperature dependence of the microscopic parameters, such as the bandgap energy of III-V semiconductors.

EXPERIMENTAL METHODS

HCPV System

The prototype HCPV system installed in Palermo (Italy) uses an outdoor, dual-axis tracking, heliostat to reflect the direct sunlight into the lab to a rectangular off-axis parabolic mirror with aperture 45x45 cm^2. The focal spot of this mirror concentrator is located on the top face (16x16 mm^2) of a BK7 glass frustum in optical contact (Wacker Semicosil 989 encapsulant) with the active area (107.9 mm^2) of the InGaP/InGaAs/Ge solar cell under test. The frustum serves as a solar flux homogenizer thus avoiding that an inhomogeneous illumination sets anomalous current and temperature gradients on the cell [3]. A pyrheliometer measures the direct normal irradiance (DNI) incident on the mirror concentrator.

A water-cooled heat sink, in thermal contact with the receiver including the solar cell, allows to remove the heat produced by concentrated sunlight. A flow

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meter quantifies the water volumetric flow rate in the heat sink. PT100 platinum thermometers detect the cell (T_C), the inlet and outlet temperatures.

A 300 W programmable DC electronic load, connected to the triple-junction solar cell, acquires automatically the I-V scan (about 1000 data points with an acquisition time lower than 10 ms).

Electroluminescence Analysis

The setup used to acquire EL spectra consists of an optical fiber spectrophotometer equipped with a CCD camera active in the range 300-1000 nm. This range allows to measure the emission around 680 nm from the top (InGaP) and the emission around 890 nm from the middle (InGaAs) subcells. The Ge peak around 0.70 eV is beyond the sensitivity of the detector.

All the EL spectral features were investigated under an injection current of 300 mA by a DC power supply operating in constant current (CC) mode and varying the temperature of the solar cell in the range 305÷385 K by a Peltier-based system.

RESULTS

In the following, we report I-V curves and EL spectra of InGaP/InGaAs/Ge triple-junction solar cells provided by Taicrystal International Technology Corporation [4].

Electrical Characterization

Figure 1 shows a typical I-V curve measured in our HCPV prototype in a sunny day at 12:30 on October 19, 2013 in Palermo. Under an indoor irradiance of 700 W/m^2 leading to a power incident on the cell P_I=142 W, we get a power extracted at maximum point P_{MP}=41.4 W; from the ratio P_{MP}/P_I we measure an overall efficiency of our prototype η=29.2 %. In the same Figure, we report the electrical parameters I_{SC}, V_{OC}, the fill factor FF, the current I_{MP} and the voltage V_{MP} extracted at maximum point.

The temperature measured via a PT100 sensor placed at the edge of the frustum in thermal contact with the direct bonded copper (DBC) substrate of the Taicrystal receiver was about 43 °C. This value probably underestimates the real cell temperature because the majority of the heat should be conducted perpendicularly to the plane of the solar cell so inducing a T gradient [5]. A correct estimation of T_C is essential to evaluate the real efficiency of the HCPV system. It can be provided by the analysis of V_{OC}, the thermal-resistance and photo-luminescence peaks [6-7]. In any case, an unwanted increase of T_C due to the overheating of the materials reduces V_{OC} and causes, therefore, a cell efficiency drop.

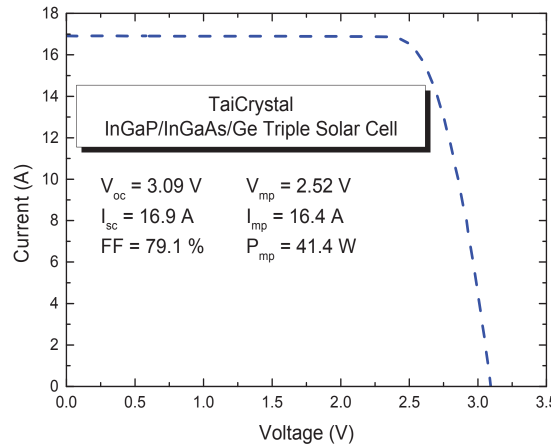

FIGURE 1. I-V curve obtained by a Taicrystal InGaP/InGaAs/Ge solar cell under test with an indoor irradiance of about 700 W/m^2.

Figure 2 shows P-V curves obtained by varying the geometrical concentration ratio in the range 225÷2025X. These intermediate concentration ratios were achieved by inserting between the heliostat and the concentrator a variable number (from one to five) of rectangular rods. Each rod partially shadowed the concentrator mirror thus reducing the irradiation level of about 360 suns. The indoor irradiance measured from the pyrheliometer varied from 580 W/m^2 to 620 W/m^2 during the tests and was considered to correct the P-V curves.

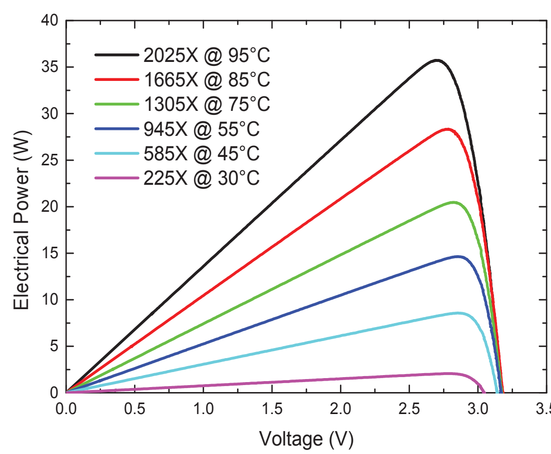

FIGURE 2. Power vs. Voltage extracted from the InGaP/InGaAs/Ge solar cell at different levels of concentration.

The results show how T_C, measured with the PT100 sensor, increases dramatically from 30 °C to 95 °C as the concentration ratio changes of one order of magnitude from 225X to 2025X. It is evident that in the same cooling condition (water at 25 °C with a flow rate of 1 liter/min) the heat sink does not maintain a low T_C [8].

Figure 3 shows the concentration ratio dependence of the module efficiency (η_{mod}), taking into account the optical efficiencies of the mirror concentrator, the frustum and the encapsulant: η_{mod} reaches a maximum value of 31.2% around 1000X concentration. The decreases at higher concentration follows the cell-efficiency degradation due to the increase of losses in the series resistance of solar cell with the the increase of the concentration and to the rise of T_C [9]. Moreover, it is evident that the reduction of η_{mod} in the range 1665X÷2025X is greater than that measured in the range 1305X÷1665X even if the increment of T_C measured in these two ranges is not changed. This result suggests that at 2025X, in our prototype HCPV module, the intrinsic ohmic losses induced from the high current become more important than that induced by the heating of the solar cell.

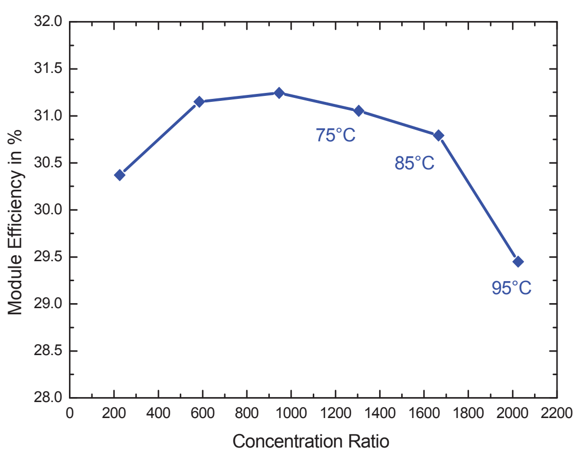

FIGURE 3. Concentration-Ratio dependence of η_{mod} delivered from the our prototype HCPV module. The indoor irradiance measured from the pyrheliometer varied from 580 W/m^2 to 620 W/m^2 during the tests. The temperatures indicated are that measured with the PT100 sensor.

To identify the effects of the heating on the performance of the module it is convenient to plot V_{OC} as a function of concentration ratio [9]. Figure 4a shows the data extracted from Figure 2 and evidences the deviation from a logarithmic law as due to the increase of T_C on increasing the concentration ratio.

Figure 4b reports the concentration dependence of the ratio of I_{SC} to DNI: a small deviation from the linearity is visible to high level of concentration.

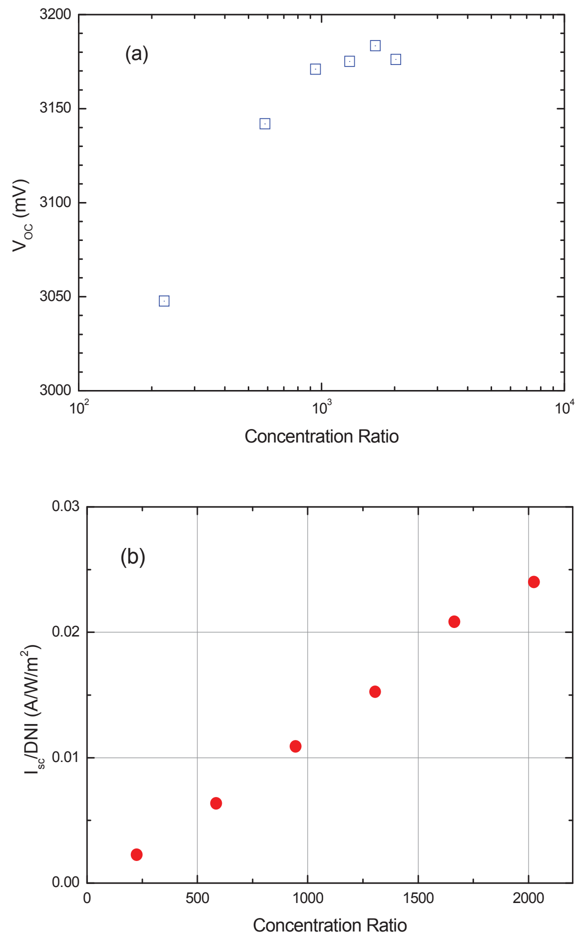

FIGURE 4. Concentration-ratio dependence of V_{OC} (a) and I_{sc}/DNI (b).

Optical Characterization

Figure 5 shows the temperature dependence, in the range 305÷385 K, of the spectrally resolved EL from the top (InGaP) and middle (InGaAs) subcells. These spectra present common features: by increasing the temperature the EL peak intensity decreases, its position redshifts and the FWHM increases.

Figure 6 shows the temperature dependence of the energy gap E_G of the InGaP and InGaAs subcells. These values are extracted by measuring for each temperature the position of the onset (10% of the EL Peak Intensity). In this range, E_G decreases linearly following the equation:

$$E_G(T) = E_G(300K) - \alpha(T - 300) \qquad (1)$$

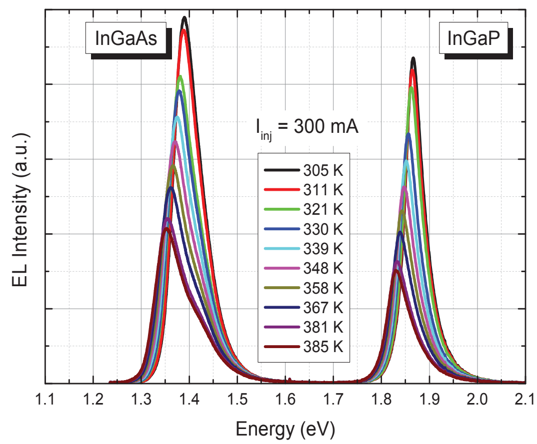

FIGURE 5. Temperature dependence of the EL emission from the top subcell (InGaP) and middle subcell (InGaAs) of the triple-junction solar cell investigated.

For both alloys, we get the best-fit parameter $\alpha = (5.10 \pm 0.03) 10^{-4}$ eV/K. These results are in good accordance with previous studies interpreted with the empirical Varshni's law [10-12].

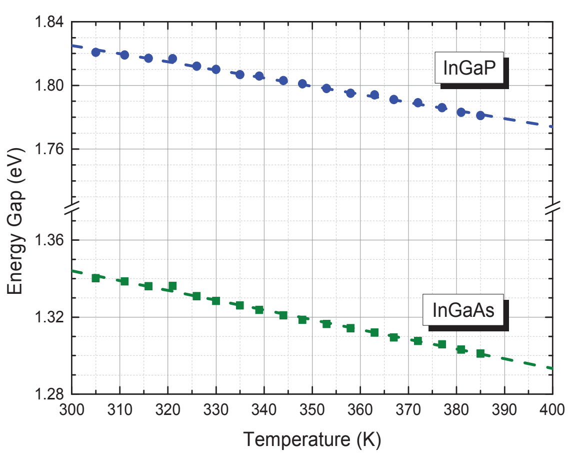

FIGURE 6. Temperature dependence of the Energy Gap of the InGaP and InGaAs materials as extracted from EL spectra of Figure 5. Dash lines show a linear fit of data.

CONCLUSION

We have performed electrical and optical studies on commercial InGaP/InGaAs/Ge triple-junction solar cells mounted on a prototype HCPV module (2000X), based on a concentrator with reflective optics. The reported tests demonstrate the good performance of this system, its efficiency being close to 30%, and are promising for the outdoor installation.

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