Data Article

Data on the design optimization, indoor characterization and outdoor testing of GaAs/Bifacial Si heterojunction four-terminal photovoltaic systems

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**A R T I C L E S T R U C T U R E**

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**A B S T R A C T**

The development of a highly efficient multijunction technology is a key challenge for the future of photovoltaic and for the transition to more renewable energy sources. In this scenario, four-terminal architecture (4T) compared to the classic tandem design allows a large intrinsic robustness to the variations of the solar spectrum, which continuously occur under normal outdoor operation conditions. On the other hand, bifacial solar cells and modules have already proven to be able to increase the energy yield of solar farms at reduced costs. For these reasons, a thorough investigation of the compatibility between these two solutions has been performed by combining a III-V semiconductor with the silicon heterojunction technology in a four-terminal device.

This work has been designed in support of the research article entitled “Outdoor performance of GaAs/Bifacial Si Heterojunction four-terminal system using optical spectrum splitting” [1], which showed, through data modeling and an accurate daily analysis of the spectral distribution of solar...
Specifications Table

| Subject                  | Energy: Photovoltaic system performance characterization phase |
|--------------------------|-----------------------------------------------------------------|
| Specific subject area    | Analyzed                                                        |
| Type of data             | Table, graph, figure.                                           |
| How the data were acquired | All the current-voltage (I–V) measurements were performed by varying the voltage in the range from -0.1 V to +2.2 V. by using a Keithley 2651A high power source measurement unit combined with a Keithley 196 digital multimeter connected via an IEEE-488 general purpose interface bus (GPIB) to a PC for operation control. Such bias range allows an accurate sweep of the mini-module voltage, that includes the short-circuit and the open-circuit condition at 2.1 V. The solar cells and the mini-modules were illuminated by a 92191–1000 Newport solar simulator. The sample holder was a 25 × 25 cm² gold plated metal chuck with a thermostat controlling the chuck temperature with an accuracy of 0.1°C. A 15 W fan ventilating toward the devices under test has been used to avoid device overheating due to the exposure to the light of the solar simulator. |

Outdoor experimental phase

The whole system was anchored to an EGIS EPR-203 dual-axis solar tracker in order to continuously receive solar radiation at the desired angle of incidence (AOI). The spectral distribution of the solar light was monitored using an optical fiber mounted on the tracker connected to a monochromator (Newport, model: CS130-RG–1–MC). The system was used to measure the solar spectrum from 300 nm to 1100 nm throughout the day. The voltage across the device was swept by a variable load, applied by driving an P75NF75 power MOS from OFF to ON condition with a linear staircase signal applied to the transistor gate. The current was evaluated by the voltage drop across a 10 Ω MOSFET connected in series to the device. Data, collected from 9 am to 5 pm in clear sky conditions, were acquired through an USB-6343 National Instrument data logger.

Data format

Analyzed

Description of data collection

The four-terminal device characteristics and spectra were taken in outdoor in January 2022 with the 4T device mounted on a bi-axial solar tracker following the sun position. Excluding barely predictable or unpredictable atmospheric phenomena such as humidity level, wind, clouds, etc., the solar spectrum depends mainly on the Air Mass (AM). In the present experiment the AM values vary in a very large range, between 1 and 5. Therefore, though the data were acquired only in January, we believe that they cover a large range of conditions in terms of solar spectrum variations. Therefore, studies on seasonal variations are not strictly necessary.

Data source location

- Institution: Institute for Microelectronics and Microsystems (IMM), Italian National Research Council (CNR)
- City: Catania
- Country: Italy
- GPS coordinates for collected data: 37° 30’ 28.358” N 15° 4’ 58.909” E

Data accessibility

Repository name: Mendeley Data

Data identification number: DOI: 10.17632/b32v9n63vk.1

Direct URL to data: https://data.mendeley.com/datasets/b32v9n63vk/1

(continued on next page)
Value of the Data

- Cell scribing is a fundamental aspect of modern cell fabrication and has been the focus of an extensive research [2]. As the mini-module manufacturing process is a fundamental step of the realization of our device, we report the I-V characteristics of several mini-modules showing the variability introduced by the mechanical scribing;
- The distance between the solar cells and the dichroic mirrors has a considerable impact on the device performance, and the investigation on this aspect reported in this article illustrates an important step of the device optimization process which should be taken into account for the realization of similar devices;
- Most experimental studies of photovoltaic systems in outdoor conditions employ inverters in order to keep the system operating at its maximum power point [3]. It is here reported an example of our experimental I-V curves to propose an alternative data acquisition setup which can simultaneously monitor the short-circuit current and open-circuit voltage of the system;
- The correlation between the fraction of photons reflected to the GaAs mini-module and the central spectrum wavelength (CSW) of the solar spectra illustrated in this work will help to understand the importance of solar spectrum variations for an accurate design of multijunction photovoltaic systems [4].
- These data will be useful to researchers who aim to design and characterize two- and four-terminal photovoltaic systems, especially in the context of outdoor operating conditions.

1. Data Description

1.1. Mini-module manufacturing

The I-V characteristics of the silicon heterojunction (SHJ) mini-modules are reported in Fig. 1a. These data have been collected to characterize the mini-module and choose the best candidate to be implemented in the 4T device. The curves show the differences in shunt and series resistance among the mini-modules introduced by the mechanical cut (see Section 2.1 for the sample fabrication details). Fig. 1b reports the power output of the samples: Sample 2 achieved the highest value, and was therefore chosen for the realization of the 4T device [1].

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**Related research article**

A. Scuto, R. Corso, M. Leonardi, R.G. Milazzo, S. M. S. Privitera, C. Colletti, M. Foti, F. Bizzarri, C. Gerardi, S.A. Lombardo, Outdoor performance of GaAs/bifacial Si heterojunction four-terminal system using optical spectrum splitting, Solar Energy, 241 (2022) 483-491.

https://doi.org/10.1016/j.solener.2022.06.032.
Fig. 1. I-V characteristics of the SHJ mini-modules (a). Power output of the SHJ minimodules (b).
1.2. Device optimization

Fig. 2a reports the I-V characteristics of the SHJ mini-module for three different distances from the dichroic mirror. The current produced by the cell reduces as the distance increases: therefore, it is clear that the distance from the mirror should be as short as possible, in order to reduce the angular dispersion of the light reflected by the dichroic mirror. The minimum distance from the mirror in the device is limited to 5 cm because of the width of the GaAs cell housing. The same trend, reported in Fig. 2b, has been observed for the GaAs mini-module. The minimum distance achievable in the device is 3 cm.
1.3. Device characterization

Table 1 reports the values of short-circuit current ($I_{SC}$), open-circuit voltage ($V_{OC}$), series resistance ($R_s$), fill factor (FF) and power conversion efficiency (PCE) of the mini-modules and of the 4T device [1]. Values reported by the manufacturers for the single cells are included for reference. The active area considered for the mini-modules and for the device for the calculation of PCE is 8 cm$^2$. Considering that the SHJ mini-module is made up by 3 cells and the GaAs mini-module is made up by 2 cells, the values show a decrease in $V_{OC}$, FF and PCE as well as an increase in $R_s$ for the SHJ mini-module compared to the nominal cell values; the GaAs mini-module exhibits a slight decrease in $I_{SC}$ and PCE.

|                | SHJ mini-module | SHJ cell, nominal | GaAs mini-module | GaAs cell, nominal | 4T match |
|----------------|-----------------|-------------------|------------------|--------------------|----------|
| $I_{SC}$ (mA)  | 32.49           | 9530              | 89.72            | 100.0              | 122.21   |
| $V_{OC}$ (V)   | 1.96            | 0.73              | 2.04             | 1.02               | 2.01     |
| $R_s$ (mΩ)     | 4.4             | 4                 | 0.6              | 0.6                | 1.1      |
| FF (%)         | 77.07           | 81.2              | 82.09            | 82.2               | 78.83    |
| PCE (%)        | 6.29            | 23.27             | 18.78            | 20.90              | 24.83    |

1.4. Outdoor I-V measurements setup

An example of the electrical signals is reported in Fig. 3. The load on the device is swept by a power MOS, in order to acquire the whole I-V characteristics of the system. The gate voltage $V_G$ follows a linear staircase from 1.5 V to 2.7 V. Below the channel opening voltage, the system acquires current and voltage points in the open-circuit region of the I-V curve; when the gate...
voltage rises above the channel threshold, the system moves to the short-circuit region, crossing the high-power region in-between. The setup registered a single point of the I-V curve every 0.05 s and a complete I-V curve [1, Fig. 8] every 26 s. This means that this setup can constantly monitor $I_{SC}$, $V_{OC}$ and power at the maximum power point ($P_{MPP}$) of any PV system simultaneously.

1.5. Spectral measurements

In Fig. 4, two of the spectra acquired during the measurement period [1] are compared. In particular, we compare the solar spectra registered at 12:00 and at 16:30. The number of photons reflected to the GaAs mini-module decreases dramatically in the afternoon. The central spectrum wavelength (CSW) increases of about 80 nm between the two spectra, while the percentage of photons reflected to the GaAs cells (calculated as the ratio of the blue area over the total area of the spectrum) decreases from 58.9% to 44.6%.

![Fig. 4. Photon flux of the spectra at 12:00 and at 16:30. The blue area indicates the fraction of wavelengths reflected to the GaAs cells, while the red area indicates the fraction transmitted to the SHJ cells. The border between the two regions corresponds to the cut-on wavelength of the dichroic mirrors, 805 nm. The CSW of each spectrum is reported with a dashed vertical line.](image-url)
Comparing the fraction of photons reflected to the GaAs mini-module \((PF_{GaAs})\) and the CSW of each spectrum reveals a linear dependence between these quantities. In particular it results \(PF_{GaAs}(\%) = -0.1692 \cdot CSW(\text{nm}) + 178.5\) with an \(R^2\) value of 0.9965.

Fig. 5. Fractions of photons reflected to the GaAs mini-module against the CSW of the solar spectra during one day of measurements. Linear fit is indicated by the red dashed line.

2. Experimental Design, Materials and Methods

2.1. Mini-module manufacturing

As described in [1], the SHJ mini-module is made up by 3 cells connected in series. The cells have been obtained by manually splitting a single \(15.6 \times 15.6\, \text{cm}^2\) bifacial cell. Since the manual procedure can produce defects in the cells, seven mini-module samples have been realized and characterized under standard test conditions (STC). The mini-modules, laying on a glass slide, have been placed on a gold-plated metal chuck and illuminated by a solar simulator. A 15 W fan has been used to prevent the overheating of the samples, as the glass slide blocked heat diffusion to the temperature-controlled chuck. The I–V measurements were performed by varying the voltage in the range from -0.1 V to +2.2 V by using a Keithley 2651A high power source measurement unit to force the current and a Keithley 196 digital multimeter to sense the voltage drop.

2.2. Device optimization

Before assembling the device, a preliminary test has been performed to determine the optimal distance between the GaAs and SHJ mini-modules and the dichroic mirrors. The dichroic mirrors have been placed on two holders with adjustable height, and the SHJ mini-module has been placed below the mirrors on the chuck as reported in the previous section. The GaAs cells have been placed at the same height of the center of the dichroic mirrors. For each mini-module the I–V characteristics have been acquired with the same setup as described above.
2.3. Device characterization

After the device has been assembled as described in [1], each mini-module has been characterized by placing the device on the gold-plated metal chuck and illuminating it with the solar simulator. At this stage, the mini-modules were electrically independent, while the dichroic mirrors split the light coming from the solar simulator. Then, the mini-modules have been connected in parallel and the 4T device has been characterized with the same setup.

2.4. Outdoor I-V measurements setup

Fig. 6 reports the electrical scheme of the experimental setup used to acquire the I-V characteristics of the 4T device. This setup has already been validated in other works [5]. The voltage across the device was swept by a variable load, applied by driving an P75NF75 power MOS from OFF to ON condition with a linear staircase signal applied to the transistor gate. The staircase signal of the power MOS has a period of about 26 s and ranges from 1.5 V to 2.7 V. The current was evaluated by the voltage drop across a 10 Ω resistor connected in series to the device. Current and voltage data, collected from 9 am to 5 pm in clear sky conditions, were acquired through an USB-6343 National Instrument data logger and analyzed with a custom LabVIEW interface [6].

![Electrical scheme of the I-V measurement setup.](image)

2.5. Spectral measurements

The solar spectrum has been measured with a monochromator (Newport, model: CS130-RG-1-MC) connected to an optical fiber mounted on the bi-axial tracker. The system was used to measure the solar spectrum from 300 nm to 1100 nm throughout the day. Each spectrum was acquired in 220 s. Data from the monochromator have been acquired by a second custom LabVIEW interface [6].
Ethics Statements

The presented data involved none of the following: human subjects, animal experiments, or data collected from social media platforms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

DIB Scuto1 (Original data) (Mendeley Data).

CRediT Author Statement

A. Scuto: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Resources, Writing – original draft, Visualization; R. Corso: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization; M. Leonardi: Conceptualization, Methodology, Software, Validation, Writing – original draft, Visualization; R.G. Milazzo: Conceptualization, Methodology, Validation, Visualization; S.M.S. Privitera: Supervision; C. Colletti: Resources, Funding acquisition; M. Foti: Resources, Funding acquisition; F. Bizzarrri: Resources, Funding acquisition; C. Gerardi: Resources, Funding acquisition; S. Lombardo: Conceptualization, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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