Novel Interconnection Method for Micro-CPV Solar Cells

Norman Jost[1], Steve Askins[1], Richard Dixon[2], Mathieu Ackermann[3], Cesar Dominguez[1] and Ignacio Anton[1]

[1]Insituto de Energía Solar Universidad Politécnica de Madrid, Madrid, 28039, Spain
[2]Dycotec Materials Ltd, Westlea, Swindon SN5 7SW, United Kingdom
[3]Insolight SA, Lausanne, Switzerland

2021 IEEE 48th Photovoltaic Specialists Conference (PVSC) | 978-1-6654-1922-2/21/$31.00 ©2021 IEEE | DOI: 10.1109/PVSC43889.2021.9518837

***Abstract*—Micro-concentrator photovoltaics (micro-CPV) consists of the reduction in size of the components of the conventional concentrator photovoltaic (CPV) technology, attaining equally high efficiencies and reducing material costs and manufacturing costs. In this publication we focus on the implementation of high throughput manufacturing methods for the interconnection of the solar cells. The goal is to enable large area interconnection of thousands of micro-solar cells with a low cost of 3€/m². A proof-of-concept was achieved for interconnection via directly printing onto the front contact pads. Prototypes using two different cell technologies where manufactured achieving good results. The highest achieved *fill factor (FF)* is of 84.3% at 200X with a *short circuit current (Isc)* of 2.4mA and *open circuit voltage (Voc)* of 3.41V.**

Keywords— micro-CPV, multijunction solar cells, high-throughput interconnection, conductive printing

I. Introduction

Micro-concentrator photovoltaics (μ-CPV) [1] is a recent trend within the concentrator photovoltaic (CPV) technology [2]. The reduction in size of the solar cells and optics reduce material cost and enable the path to high throughput parallel manufacturing methods maintaining high module efficiencies at a low cost. In addition, the smaller size helps the integration of other qualities such as automatic tracking and hybrid systems using integrated flat plane photovoltaics (PV) [3].

To guarantee the overall reduction in cost compared to conventional CPV, high throughput manufacturing methods must be adapted to the needs of the industry. The main challenge is the necessary alignment precision between the solar cells and the optics. Cross-links with other industries can be found such as for light emitting diodes (LED) for illumination or TV screens [4] for the assembly and interconnection of the dies. Inspired in the solutions in the field we developed and tested a concept for interconnecting solar cells.

This work was completed in collaboration with two companies, Insolight SA as the end user in micro-CPV modules and Dycotech Materials Ltd. for the development of the necessary materials for the interconnection. Insolight is currently industrializing an integrated tracking micro-CPV module with two variants [3]. One, a hybrid approach combining CPV optics and high efficiency III-V cells for the conversion of the DNI with a backplane integrating silicon cells to collect the diffuse irradiance (**Fig. 1a**). And second approach, without the silicon cells, results in a translucent module where the diffuse part can be used for other applications, such as growing crops in agrivoltaic applications or lighting in building integration (**Fig. 1b**). In both cases the plane of the module on which the high efficiency multi-junction solar cells are mounted must be transparent to transmit diffuse light.

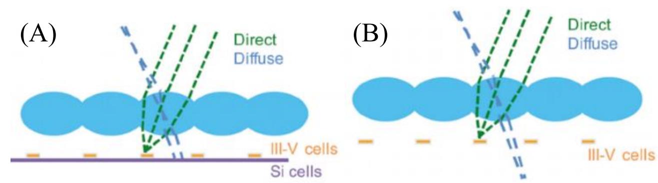

Fig. 1. Drawings of the two Insolight micro-CPV module types with integrated tracking, (A) with a hybrid CPV-flat plane PV approach and (B) semi-transparent for other applications such as agrophotovoltaics. Images from [3].

The conventional method used in CPV for the front electrical connection of solar cells is wire bonding. Due to the large size of the modules the solar cells are soldered and wire bonded on singular printed circuit boards (PCB) or other type of boards for thermal dissipation. These boards are then positioned and assembled on a large back plane and adhered again with thermally conductive adhesive, then cables are soldered for the serial or parallel connection of each board. For the conventional CPV technology this was a viable option, as modules with a dimension of 1m² would have ca. 600 solar cells in the case of a Soitec CPV module using 40x40mm² lenses, or in many cases even less, in the range of 40 cells/m² if the lenses are bigger (160x160mm²). In the case of micro-CPV setting as an example Insolight, the modules contain over 5000 solar cells/m². The conventional method is not viable due to the number of dies and the required precision throughout large areas.

The problem of interconnecting dies on a large scale has also been addressed with another interconnection method which was used for LEDs and solar cells. The method consists in the evaporation of gold or other precious metals for the interconnection [5], this method is elaborative having to use a lithography step and comes with a great waste of gold or other metal for large areas. Another, more viable approach is the use of custom solar cells with both contacts on one side, this has been experimentally proven [6]. Problems with this solution is the elaborative custom solar cells, bringing both contacts on one

Authorized licensed use limited to: Univ Politecnica de Madrid. Downloaded on November 26,2021 at 12:33:34 UTC from IEEE Xplore. Restrictions apply.

side complicates the manufacturing, cells as such are currently not commercially available.

The objective of the work reported is the development of a process to adhere and directly interconnect the solar cells on a large plane. The process would be compatible with mass population technologies with very high precision, the proven fluid self-assembly (FSA) [7] and the already applied in industry, chiplet printing [8]. Once the solar cells are populated on the plane the interconnection is an issue. The current way for interconnecting the front contact pads would be wire bonding, yet this approach is not viable due to the large quantity of dies on such a large area, cost estimation resulted in prices of €500/m². An alternative is proposed with this concept, instead of using wire bonds we directly print conductive silver ink onto the front pads for the interconnection, the goal is a cost reduction to 3€/m². A similar approach has been presented before for the interconnection of LED dies [9].

Different printing technologies are suitable for this approach, such as syringe printing, jet printing [9] and screen printing. In this study the first attempts with single solar cells were done with syringe printing, in the future screen printing will be used for a larger area. The conductive material used was Epoxy Technology Inc. Epotek H20S with a resistance of 0.0005 Ωcm. The printing technologies are harmless for the solar cells, and the curing of the silver inks does not need excessive temperatures 100-200C° for short periods of time. Wire-bonding is more likely to cause damages such as shunting of the solar cells [10].

First printing test showed that the lateral perimeter of the solar cells must be insulated to avoid short circuiting. The ideal solution would be to use solar cells which are electrically insulated during the manufacturing process of the dies by depositing the anti-reflective coating not only on the front but also on the lateral of the cell such as shown by USherbrooke [11]. Yet, no solar cell manufacturer has this technology implemented in their production line, so this option was currently not possible. Two solar cell types with different die heights were used for the study. First off, conventional Azur Space GmbH upright metamorphic triple junction solar cells (UMM) [12] with an active area of 1mm^2 and a height of 190µm and Microlink Inc. inverted metamorphic (IMM) [13] solar cells with a height of 30µm. For the lateral electrical insulation Tesa GmbH Kapton Tape was used. Both solar cell technologies used have the same two contact pads on the front used for the interconnection.

The primary goal of the method in this publication is to show a viable alternative to wire bonding without any significant losses in *fill factor (FF)* for single cells at an operating concentration of 200X which represents the current specification of the Insolight modules and a representative case study for micro-CPV applications.

II. Single Cell Prototypes

For a proof-of-concept tests were performed using an effective method of lateral insulation with Kapton tape adhered over the edge of the die. A commercially available Epotek silver epoxy was used for the interconnection. A schematic and image of how the interconnect attempt with the tape looks like can be seen in **fig. 3**.

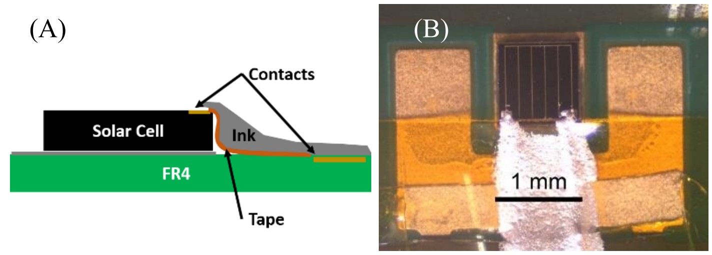

Fig. 2. Adhesive tape for the lateral insulation of the solar cell. (A) shows a schematic of how the concept looks like and (B) shows a finished prototype.

Both cell types IMM and UMM were used for the study. To see if there are any differences in the results and if the height of the UMM cells causes any problems. The printed interconnection method is also compared to wire bonds for each cell technology.

III. Single Cell Prototype Characterization

The single cells were characterized in the following order, first a visual inspection under the microscope with electroluminescence was completed. Then, the electrically characterized in dark and at 200X concentration. We characterized each cell technology interconnected by the novel printing method and traditional wire bonding (WB).

A. Visual Inspection of the single cells

Images under the microscope were taken to inspect the interconnects and cells. From the images different quality issues can be seen such as partial shading of the solar cell or cracks. The shading can occur due to the printed silver ink which not only covers the contact pads but also active areas of the solar cell (**fig. 4**). For the IMM solar cell (**fig. 4B**) a simpler approach was used, the syringe printing was done on the pad used for testing the cells on the wafer level. The UMM solar cells were contacted exclusively on the two contact pads on the edge (**fig. 4A**). The contact area for the IMM cell is slightly larger, also more over-flowing on the ink occurred with the MM cell causing more shading of the active area.

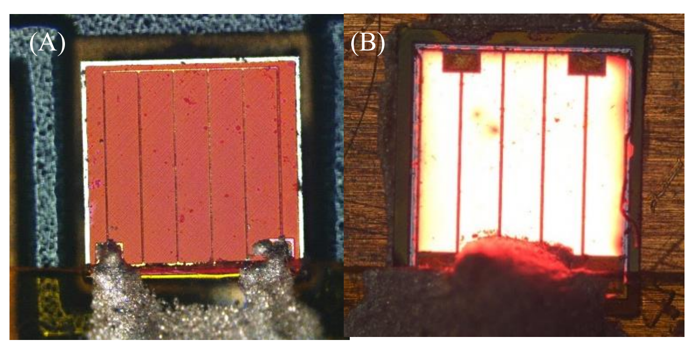

Fig. 3. Microscope images under a magnification (x5) of the 1mm² Azur UMM (A) and IMM solar cell (B) with syringe printed Epotek silver epoxy. The silver ink covers the active area of the 1mm² solar cell a little by exceeding the area of the pads, this over-flow happened slightly more for the IMM cell (B). No cracks can be seen on any of the inspected solar cells.

Authorized licensed use limited to: Univ Politecnica de Madrid. Downloaded on November 26,2021 at 12:33:34 UTC from IEEE Xplore. Restrictions apply.

B. Electrical characterization of the single cells

1) Dark-IV measurements

The dark-IV measurement is done using a Keithley 2400 with the solar cells on a cooling plate to keep the device under test at 25°C. The measurement of the single cell boards is shown in **Fig. 4**. Results show similar IV curves for the same technology with low *shunt resistance (Rsh)* and some *series resistance (Rs)*. The *Rs* is very low for the WB Azur UMM solar cell compared to the cell with the printed Epotek interconnection. The Epotek silver ink is not the ideal material due to high resistance using very little ink. To avoid this the ink was used in abundance, with cases of the ink over-flowing the contact pad.

In the case for the Microlink IMM the *Rs* is similar for both cases (printed and WB). The results show functional solar cells for a current range which corresponds to concentrations of 100-200X.

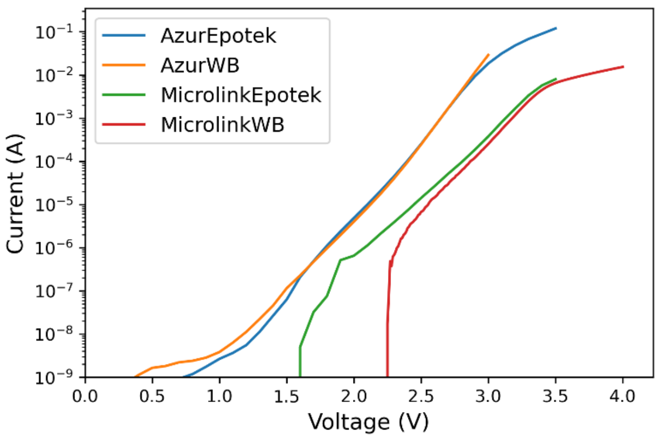

Fig. 4. Single cell board dark IV measurements, comparing the printed interconnection with wirebonds.

2) Concentrated light-IV measurement

The full board is measured with a Solar Added Values S.A. Helios 3030 CPV simulator [14]. For these measurements, the concentration was kept at 200X. The sample is placed on a cooling plate at 25°C. An equivalent AM1.5D spectrum is controlled by means of component (also called isotype) lattice matched solar cells [15]. When the spectral matching ratio (SMR) [16] equals 1, the ratio of the generated currents in the corresponding subcells is the same as the current ratio under the reference spectrum. For the case of UMM solar cells, the procedure described in [17] is applied for the conversion between lattice match component cells and upright metamorphic device under test.

A Sandia single diode equation fit was applied using pvlib [18] to extract resistance parameters for a better comparison between the Epotek interconnection and the WB. Results of the fits and measurements are collected in **table 1**. The first difference which can be seen is the slightly lower *Isc* for the printed interconnection, this is due to small shading of the active area of the solar cells and can be avoided with an optimized screen-printing process.

For the Azur UMM solar cell (**fig. 6A**), a high series resistance caused by the epoxy (*Rs* =9Ω) leads to a significant reduction of 7.8% in the *fill factor (FF)*. On the contrary, for the case of the IMM solar cell (**fig. 6B**) the printed connection provides excellent results showing a slightly higher *FF* (84.3%) and lower *Rs* (5.46). Noteworthy, the *FF* measured at one sun with probes directly contacting on the wafer level by the manufacturer is 84%.

TABLE I. MEASUREMENT- AND SINGLE-DIODE FIT RESULTS

Prototype	*Voc (V)*	*Jsc (mA/cm²)*	*FF (%)*	*Rs (Ω)*	*Rshunt (Ω)*	*Suns (X)*
Azur UMM WB 1mm²	2.79	16.42	86.1	1.58	6630	200
Azur UMM Epotek 1mm²	2.78	16.13	78.3	9.00	152387	200
Microlink IMM WB 1mm²	3.49	12.21	83.6	6.47	4504	200
Microlink IMM Epotek 1mm²	3.41	11.51	84.3	5.46	3510	200

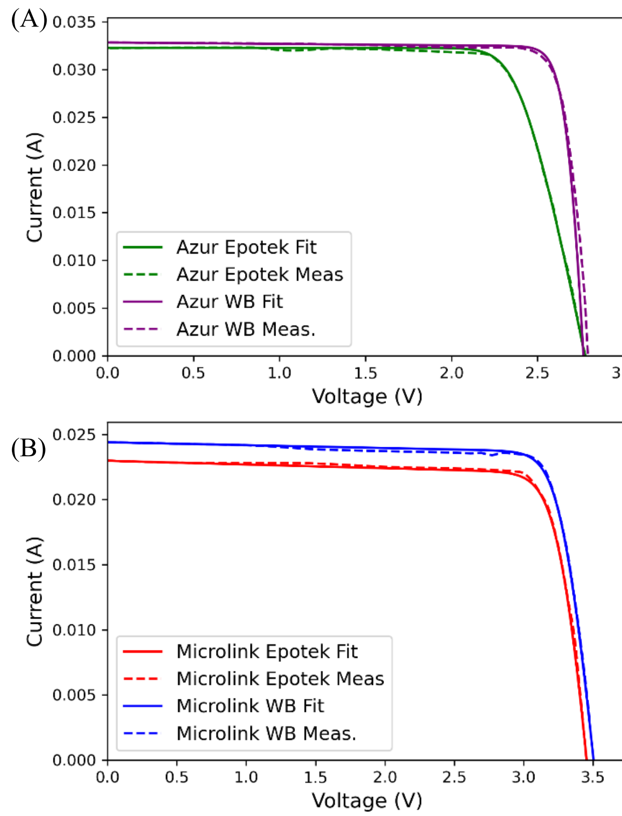

Fig. 5. Single cell board IV curves. (A) wire bonded and printed interconnction Azur UMM solar cell, high currents cause series resitance and loss in fill factor. Lower current Microlink IMM solar cells show better results with the best achieved fill factor of 84.3%. Slight reduction in current is caused by shading of the silver ink.

Results show that the novel interconnection method via silver ink printing works. Upscaling is possible using screen-printing, this would also avoid issues with the syringe printing such as over-flowing of the silver ink on active areas of the solar cell. Better silver inks developed by Dycotec will decrease the *Rs* and improve the *FF*. The current use of Kapton tape can be avoided by a further printing step of a dielectric for the lateral insulation or passivation of the solar cells.

Authorized licensed use limited to: Univ Politecnica de Madrid. Downloaded on November 26,2021 at 12:33:34 UTC from IEEE Xplore. Restrictions apply.

IV. Conclusion

A novel interconnection method using silver printing with a syringe was proven to work micro-CPV scale solar cells of $1mm^2$. The best result was achieved for a Microlink IMM solar cell with a *fill factor* of 84.3%, 0.7% higher compared to using wire bonds, at a concentration of 200 suns. The scalability of this proposed technology is also given with the use of screen printing instead of syringe printing. Prototypes are currently being manufactured. The lateral insulation with tape is also avoidable by using dielectric printing or lateral passivation of the solar cells. Further work is needed, yet good first results are shown giving the path towards cheap interconnection (goal 3€/m^2) of micro-CPV solar cell on a large scale.

Acknowledgments

We would like to acknowledge the FEDER/Ministerio de Ciencia, Innovación y Universidades - Agencia Estatal de Investigación under the project named Micro-PV and referenced ENE2017-87825-C2-1-R. We also acknowledge de financial support from the Programas de Actividades de I + D entre grupos de investigación de la Comunidad de Madrid en Tecnologías under the Project named Madrid-PV2 and referenced P2018/EMT-4308. And finally, the SOLAR-era-net cofund named ENMESH (ENabling Micro-ConcEntrator PhotovoltaicS with Novel Interconnection MetHods) by the funding agency MINECO under the reference PCI2018-093168.

Refrences

[1] C. Domínguez, N. Jost, S. Askins, M. Victoria, and I. Antón, "A review of the promises and challenges of micro-concentrator photovoltaics," in *AIP Conference Proceedings*, 2017, vol. 1881, no. 1, p. 080003.

[2] M. Wiesenfarth, I. Anton, and A. W. Bett, "Challenges in the design of concentrator photovoltaic (CPV) modules to achieve highest efficiencies," *Appl. Phys. Rev.*, vol. 5, no. 4, p. 041601, Nov. 2018.

[3] G. Nardin *et al.*, "Industrialization of hybrid Si/III–V and translucent planar micro-tracking modules," *Prog. Photovoltaics Res. Appl.*, 2020.

[4] K. Ding, V. Avrutin, N. Izyumskaya, Ü. Özgür, and H. Morkoç, "Micro-LEDs, a manufacturability perspective," *Appl. Sci.*, vol. 9, no. 6, 2019.

[5] M. P. Lumb *et al.*, "Design, modeling, and experimental results for CPV arrays built using heterogeneously integrated III-V micro-cells," vol. 1127504, no. March, p. 3, 2020.

[6] H. Arase *et al.*, "A novel thin concentrator photovoltaic with microsolar cells directly attached to a lens array," *IEEE J. Photovoltaics*, vol. 4, no. 2, pp. 709–712, 2014.

[7] M. Kaltwasser *et al.*, "Fluidic Self-Assembly on Electroplated Multilayer Solder Bumps with Tailored Transformation Imprinted Melting Points," *Sci. Rep.*, vol. 9, no. 1, pp. 1–8, 2019.

[8] Y. Wang *et al.*, "Chiplet micro-assembly printer," *Proc. - Electron. Components Technol. Conf.*, vol. 2019-May, no. Figure 1, pp. 1312–1315, 2019.

[9] A. Rudorfer *et al.*, "A study on Aerosol jet printing technology in LED module manufacturing," *Fifteenth Int. Conf. Solid State Light. LED-based Illum. Syst.*, vol. 9954, p. 99540E, 2016.

[10] I. Rey-Stolle and C. Algora, "Analysis of wirebonding techniques for contacting high concentrator solar cells," *IEEE Trans. Adv. Packag.*, vol. 26, no. 1, pp. 47–53, Feb. 2003.

[11] P. Albert, "Développement de cellules multijonctions submillimétriques pour le photovoltaïque à concentration (micro-CPV) et évaluation de leur robustesse," Bordeaux, Nov. 2020.

[12] W. Guter *et al.*, "III-V multijunction solar cells - New lattice-matched products and development of upright metamorphic 3J cells," *AIP Conf. Proc.*, vol. 1407, no. 10, pp. 5–8, 2011.

[13] J. F. Geisz *et al.*, "High-efficiency GaInP / GaAs / InGaAs triple-junction solar cells grown inverted with a metamorphic bottom junction," *Appl. Phys. Lett.*, vol. 91, no. 2, p. 023502, 2007.

[14] C. Domínguez, I. Antón, and G. Sala, "Solar simulator for concentrator photovoltaic systems," *Opt. Express*, vol. 16, no. 19, p. 14894, Sep. 2008.

[15] R. R. King *et al.*, "40% efficient metamorphic GaInPGaInAsGe multijunction solar cells," *Appl. Phys. Lett.*, vol. 90, no. 18, p. 183516, May 2007.

[16] M. Victoria *et al.*, "Tuning the current ratio of A CPV system to maximize the energy harvesting in a particular location," in *AIP Conference Proceedings*, 2013, vol. 1556, pp. 156–161.

[17] R. Núñez *et al.*, "Determination of spectral variations by means of component cells useful for CPV rating and design," *Prog. Photovoltaics Res. Appl.*, vol. 24, no. 5, pp. 663–679, May 2016.

[18] W. F. Holmgren, C. W. Hansen, and M. A. Mikofski, "pvlib python: a python package for modeling solar energy systems," *J. Open Source Softw.*, 2018.

Authorized licensed use limited to: Univ Politecnica de Madrid. Downloaded on November 26,2021 at 12:33:34 UTC from IEEE Xplore. Restrictions apply.