PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2011; **19**:894–897
Published online 5 January 2011 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.1078

PAPER PRESENTED AT 25th EU PVSEC WCPEC-5, Valencia, Spain, 2010

New world record efficiency for Cu(In,Ga)Se_2 thin-film solar cells beyond 20%

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ABSTRACT

In this contribution, we present a new certified world record efficiency of 20.1 and 20.3% for Cu(In,Ga)Se_2 thin-film solar cells. We analyse the characteristics of solar cells on such a performance level and demonstrate a high degree of reproducibility.

KEYWORDS

Cu(In,Ga)Se_2 (CIGS); record efficiency; thin-film solar cells

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Received 7 May 2010; Revised 15 October 2010

1. INTRODUCTION

Cu(In,Ga)Se_2 (CIGS) has gained a reputation as the thin-film solar cell technology with the highest efficiencies. Only recently the highest efficiency obtained in a laboratory environment was 19.9% [1] (corrected with the new solar spectrum to 20.0%). After the market introduction of CIGS technology [2], it became apparent that for a real success of this new technology another boost from cost reduction and performance measures is vital. However, saved material costs very often cannot outweigh the negative impacts of such measures on device performance. Consequently, efficiency development has become one of the main focuses of the ZSW's CIGS research today.

2. EXPERIMENTAL

In order to pursue this goal, the ZSW has set up a specific high-efficiency small-area solar cell production line (measured cell area: $0.50\,cm^2$) beside its pilot production line ($30 \times 30\,cm^2$ substrates). The concept of the high-efficiency line follows the same principles as described in Reference [3]. This means that special attention is paid to clean production environments and materials. Also very short transfer times between the individual process steps and a highly standardised process sequence constitute this approach. The cell setup can be described as follows: soda-lime glass (3 mm), sputtered molybdenum (500–900 nm), CIGS (2.5–3.0 μm), chemical bath deposited CdS buffer layer (40–50 nm), sputtered undoped ZnO (50–100 nm), sputtered aluminium doped ZnO (150–200 nm) and a nickel/aluminium-grid. All results presented in this contribution have an anti-reflective coating based on MgF_2 (105 nm). Thus, a standard cell setup with standard procedures has been used. We define the cell size by mechanical scribing. The cell area equals $0.50\,cm^2$ very reliably with very little variation.

In order to achieve higher efficiencies, the following steps have been taken: (1) very strict standardisation of the process flow, (2) use of clean materials, procedures and working environments, (3) variation of the selenium rate and (4) fine-tuning of the cell stack.

3. RESULTS

We have been able, for the first time ever, to push CIGS efficiencies beyond 20%. This marks the breaking down of the barrier that has been separating thin-film solar cell efficiencies from silicon solar cell efficiencies for a long time. Figure 1 shows the *I*/*V*-curves and the electrical parameters of the new world record cells with 20.1 and

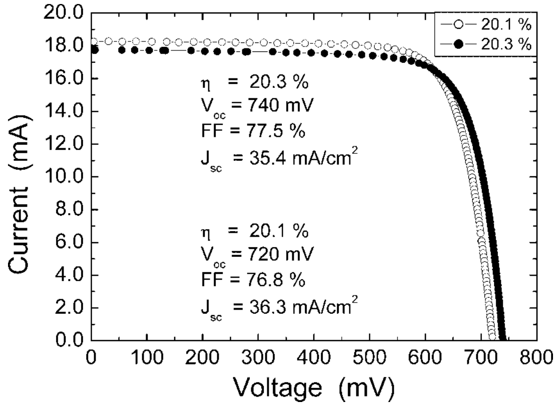

Figure 1. *I*/*V*-curve of independently certified (by Fraunhofer ISE on 15th of April and 30th of June 2010) new world record cells of 20.1% (cell area: $(0.5028 \pm 0.0015)\,cm^2$) and 20.3% (cell area: $(0.5015 \pm 0.0063)\,cm^2$) efficiency.

20.3% efficiency, which were independently certified by Fraunhofer ISE.

The external quantum efficiency (EQE) of these 20.1 and 20.3% efficient CIGS solar cell as depicted in Figure 2 show a very nice flat spectral response between 500 and 900 nm on a high level of approximately 90–95% (in particular for the 20.1% cell). The comparison with solar cells from the ipe as described in Reference [3] shows an improved collection between 750 and 1050 nm. A qualitative comparison with NREL's 19.9% cell shows a slight superiority of our EQE between 550 and 1050 nm.

Our cells show a higher open circuit voltage V_{oc} than the optical band-gap derived from the EQE would suggest. This can be attributed to the compositional double-grading of the CIGS absorber (high Ga content at the front and at the back; low Ga content region near the front) which we normally see when employing our CIGS process. This grading separates the optical from the electrical band-gap.

Apart from this result, it is important to note that these record cells are not single incidences but part of a high-efficiency baseline. Figure 3 (baseline data up to April 2010) shows the development of the baseline results beyond 19%. A great number of over 180 cells could reach or exceed an efficiency of 19.0%. The frequency F of CIGS solar cells with efficiencies η equal to or greater than the number stated in brackets is as follows: $F(\eta \geq 19.0\%) = 186$, $F(\eta \geq 19.5\%) = 63$, $F(\eta \geq 19.9\%) = 13$, $F(\eta \geq 20.0\%) = 5$ and $F(\eta \geq 20.1\%) = 4$. These results show a high degree of stability and reproducibility of the new high-efficiency baseline.

From these results we have analysed the *I*/*V*-characteristics of cells with an efficiency of 20% or better in more detail as shown in Table I including the latest 20.3% cell. The diode parameters as the shunt resistance r_p, the series resistance r_s, the saturation current density J_0 and the ideality A are extracted from illuminated *I*/*V*-curves. Comparing the average values of the best five of these cells with the 19.9% cell form NREL ($V_{oc} = 690\,mV$, $FF = 81.2\%$, $J_{sc} = 35.5\,mA/cm^2$, $J_0 = 2.1 \times 10^{-12}\,A/cm^2$, $A = 1.14$, $r_s = 0.37\,\Omega\,cm^2$), we can see that our cells have a higher V_{oc} (+26 mV), a lower FF (−3.2%), a higher J_{sc} (+0.5 mA/cm^2), a higher J_0 (by one to two orders of magnitude), a higher A (+0.27) and a lower r_s ($-0.12\,\Omega\,cm^2$). This comparison shows that there are still several paths to the 20% efficiency level for CIGS solar cells, which allows us to assume that there is still room for improvement even on this high performance level.

These results are supported by Figures 4 and 5, which show the distribution of A and J_0 for 64 CIGS cells with efficiencies equal to or greater than 19.5%. The average value for this big set of cells for A is 1.44. Most of the cells' J_0 values range between 1.4×10^{-11} and $1.4 \times 10^{-10}\,A/cm^2$.

Finally, we have analysed the correlation between the efficiency of the same set of 64 cells and their average composition determined by X-ray Fluorescence (XRF).

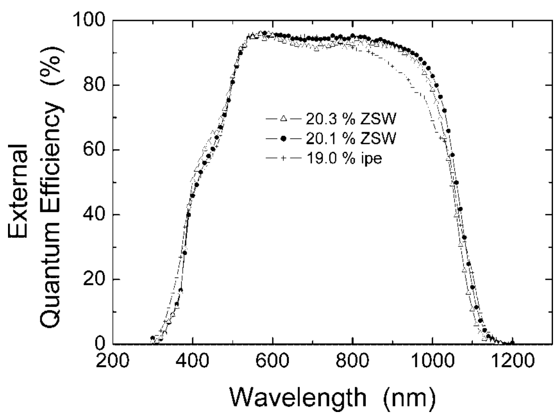

Figure 2. External quantum efficiency of the 20.1 and 20.3% record cells (measured by Fraunhofer ISE) and comparison to ipe results.

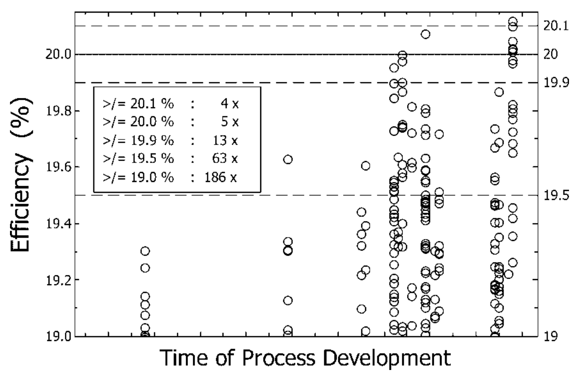

Figure 3. High-efficiency baseline statistics: frequency F of CIGS solar cells with efficiencies equal to or greater than 19%: $F(\eta \geq 19.0\%) \geq 186$, $F(\eta \geq 19.5\%) = 63$, $F(\eta \geq 19.9\%) = 13$, $F(\eta \geq 20.0\%) = 5$, and $F(\eta \geq 20.1\%) = 4$.

Table I. *I/V*-characteristics and diode analysis of one 20.3%, four 20.1%, and eight 20.0% CIGS cells (all 'in-house' measurements/ certified cells: no. 1 and no. 5).

Sample	η (%)	V_{oc} (mV)	FF (%)	J_{sc} (mA/cm^2)	J_0 (A/cm^2)	A	r_s (Ω cm^2)	r_p (Ω cm^2)	J_{ph} (mA/cm^2)
1	20.3	730	77.7	35.7	4.2E-11	1.38	0.23	880	35.6
2	20.1	712	77.9	36.3	7.6E-11	1.39	0.27	1755	36.2
3	20.1	713	78.0	36.1	7.3E-11	1.39	0.27	1360	36.0
4	20.1	712	79.0	35.7	2.9E-10	1.49	0.17	3095	35.6
5	20.1	713	77.3	36.4	1.2E-10	1.42	0.30	1465	36.4
6	20.0	702	78.0	36.6	6.8E-11	1.36	0.29	1605	36.6
7	20.0	714	78.1	35.9	7.3E-11	1.39	0.29	1580	36.0
8	20.0	713	77.5	36.2	1.3E-10	1.43	0.30	1680	36.0
9	20.0	711	77.5	36.3	1.2E-10	1.42	0.49	1495	36.4
10	20.0	710	78.2	36.0	1.3E-10	1.42	0.25	1565	36.0
11	20.0	709	77.6	36.3	6.0E-11	1.37	0.42	1825	36.4
12	20.0	714	78.1	35.8	7.2E-11	1.39	0.29	1505	35.8
13	20.0	710	77.9	36.1	2.7E-10	1.48	0.42	2710	36.4
AVG	20.04	712	77.9	36.1	1.2E-10	1.41	0.31	1732	36.1

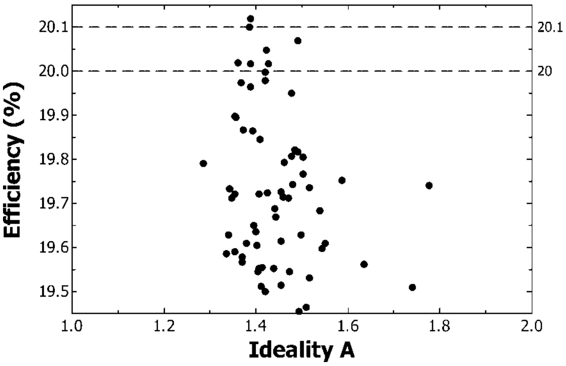

Figure 4. High-efficiency CIGS cells ($N = 64$ cells): ideality A varies around 1.44 ± 0.09.

Figure 6 reveals that even on such a high efficiency level, the average composition is still a variable factor. This fact is one reason for the differences in the *I/V* characteristics between NREL's and ZSW's 20% CIGS cells.

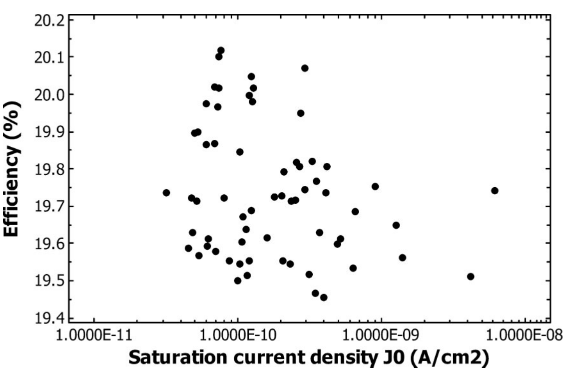

Figure 5. High-efficiency CIGS cells ($N = 64$ cells): most of the saturation current density values vary between 1.4×10^{-11} and 1.4×10^{-10} A/cm^2.

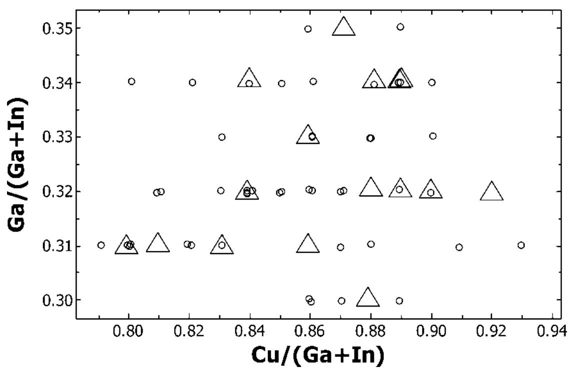

Figure 6. High efficiencies and composition (average values derived from XRF measurements/compositional gradings not considered): big triangles represent the efficiency range $19.9\% \geq \eta \geq 20.1\%$. Small circles represent the efficiency range $19.5\% \geq \eta \geq 19.8\%$. CIGS solar cells on a 20% efficiency level can still be produced with varying composition (Ga/(Ga + In) from 0.30 to 0.35 and Cu/(Ga + In) ratio from 0.80 to 0.92).

4. CONCLUSION

We have been able to surpass the 20% efficiency barrier for CIGS solar cells and have obtained a new world record efficiency of 20.1 and 20.3%. This record is the result of a highly stable and reproducible high-efficiency small-area CIGS solar cell production line. According to our own measurements, we have been able to reproduce these record values above 20% five times altogether. In addition, a significant number of 63 CIGS cells with efficiencies equal to or greater than 19.5% proves the remarkable reproducibility of this high performance level.

Scientific literature shows that there are still many basic questions in CIGS research intensely debated (grain boundaries [4], sodium [5], inverted CIGS phase at surface [6–8], defects [9], etc.). At the same time CIGS technology, despite its meanwhile obvious progress in maturity, lacks many of the refined performance boosting methods that have become a natural routine in silicon solar device production. These observations combined with the variable pathways to our new record efficiencies beyond 20% and that of NREL's 20% cell lead us to the conclusion that there is a considerable performance potential still unexploited in CIGS solar technology. In the near future, this could signify thin-film CIGS technology not only as a low-cost alternative but also as a high-efficiency competitor on the photovoltaic world market.

ACKNOWLEDGEMENTS

The authors would like to thank the CIGS team at ZSW especially Dieter Richter and Wolfgang Dittus for the very valuable technical support in the laboratory. This work was supported by the Bundesministerium fuer Umwelt, Naturschutz und Reaktorsicherheit (BMU), the German federal state Baden-Wuerttemberg and the European Commission under various contracts.

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