

## Microscale solar cells for high concentration on polycrystalline Cu(In,Ga)Se<sub>2</sub> thin films

Myriam Paire,<sup>1,2,3,4,a)</sup> Laurent Lombez,<sup>1,2,3</sup> Nicolas Péré-Laperne,<sup>5</sup> Stephane Collin,<sup>5</sup> Jean-Luc Pelouard,<sup>5</sup> Daniel Lincot,<sup>1,2,3</sup> and Jean-François Guillemoles<sup>1,2,3,b)</sup>

<sup>1</sup>EDF R&D, Institut de Recherche et Développement sur l'Energie Photovoltaïque (IRDEP), 6 quai Watier, 78401 Chatou, France

<sup>2</sup>CNRS, IRDEP, UMR7174, 78401 Chatou, France

<sup>3</sup>Chimie ParisTech, IRDEP, 75005 Paris, France

<sup>4</sup>UPMC, 75005 Paris, France

<sup>5</sup>CNRS, Laboratoire de Photonique et de Nanostructures (LPN), Route de Nozay, 91460 Marcoussis, France

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We report high concentration experiments on polycrystalline thin film solar cells. High level regime is reached, thanks to the micrometric scale of the Cu(In,Ga)Se<sub>2</sub> cells, which strongly decreases resistive losses. A 4% absolute efficiency increase is obtained at a concentration of  $\times 120$ , and current densities as high as 100 A/cm<sup>2</sup> can be measured. These results show that the use of polycrystalline thin films under high concentration is possible, with important technological consequences. © 2011 American Institute of Physics. [doi:10.1063/1.3604789]

In concentrated photovoltaic systems, Joule losses are increased and become the main limiting factor of conversion efficiency<sup>1</sup> due to highly concentrated light fluxes. In order to reduce resistances, front contact collecting grids are used on concentrator solar cells. The grid coverage is a trade-off between the decreased resistances and the detrimental shadowing. As a result, Joule losses remain an issue for concentrator cells. This is particularly true for thin film solar cells, where the window layer has a relatively high sheet resistance (10 to 20  $\Omega$ /square) and limits the use of concentration to very low concentration ratio<sup>2-4</sup> ( $C < \times 20$ ).

In this letter, we present experimental demonstration of microcells whose lateral dimensions are small enough to make spreading resistances vanishingly small, as predicted by theory.<sup>5,6</sup> We focus on polycrystalline thin film Cu(In,Ga)Se<sub>2</sub> (CIGS) microcells. CIGS is currently the most efficient thin film solar cell material,<sup>7</sup> and efficiencies over 20% were achieved recently. We study CIGS microcells, with a peripheral contact that collects the current without shadowing the cells. As a consequence of reduced resistances, microcells can work under high fluxes.<sup>8</sup> We report experiments under high concentration ( $>200$  W/cm<sup>2</sup>) and demonstrate a 4% absolute efficiency increase under concentrated illumination (10 W/cm<sup>2</sup>). We also study the high injection regime, and the microcell series resistance is found to decrease with illumination.

The device described in this letter is a glass/Mo/CIGS/CdS/ZnO solar cell, with a 15  $\mu$ m diameter active area. The bottom part of the cell is provided by Würth Solar, and the CdS and ZnO layers are deposited in our laboratory, using the same process as described elsewhere.<sup>5,7</sup> To create microcells, we inserted a 400 nm thick insulating SiO<sub>2</sub> layer and 20 nm/300 nm Ti/Au bilayer between the buffer and window layer. Photolithographically defined holes in the SiO<sub>2</sub> layer delimit the microcells. The Au layer plays the role of the pe-

ripheral front contact, without shadowing the cell. The complete structure is depicted in Fig. 1(b). A scanning electron microscope (SEM) cross-section image of the side of a microcell is shown in Fig. 1(a).

Solar cells of 0.1 cm<sup>2</sup>, made during the same process, are used as a reference. Under AM1.5 illumination, they yield (13.2  $\pm$  0.4%) efficiency (short-circuit current density  $J_{sc} = 28.13 \pm 0.2$  mA/cm<sup>2</sup> and open circuit voltage  $V_{oc} = 631 \pm 0.6$  mV). This efficiency is representative of standard large area deposition of industrial coevaporated CIGS.

In order to assess their performances under concentrated illumination, microcells are tested under continuous 532 nm laser illumination. The short-circuit current is linear with the incident laser power on microcells up to incident light power over  $2 \times 10^6$  W/m<sup>2</sup>. We checked that the linearity stays valid for the full solar spectrum up to  $\sim 100$  suns; we can therefore define the light concentration ratio as the ratio between the experimental short circuit current density and the reference AM1.5 short circuit current density.

Figure 2 shows the characteristics of the microcell as a function of the laser power. The cell conversion efficiency is evaluated as the ratio of the maximum electric output power by the equivalent incident light power, the latter being given

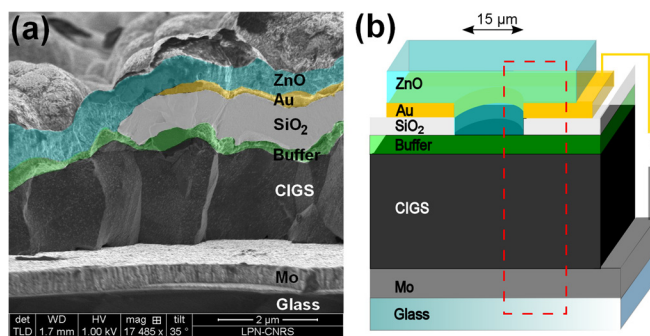


FIG. 1. (Color online) Architecture of Cu(In,Ga)Se<sub>2</sub> microcells. (a) SEM cross-section of a microcell. (b) Scheme of the structure, not to scale. The red rectangle corresponds to the part that is observed in SEM.

<sup>a)</sup>Electronic mail: myriam-paire@chimie-paristech.fr.

<sup>b)</sup>Electronic mail: jf-guillemoles@chimie-paristech.fr.

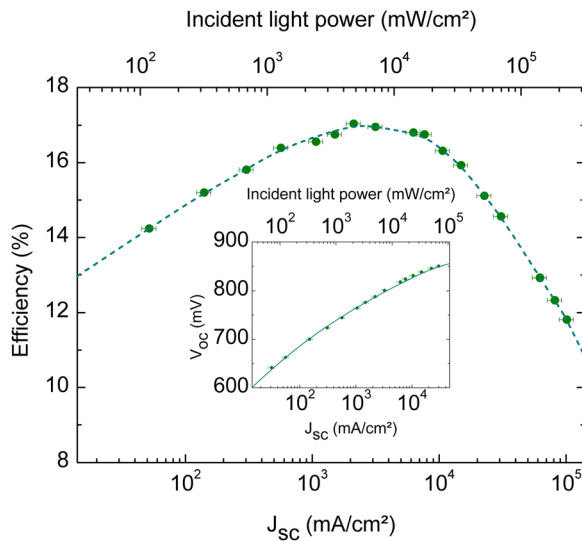


FIG. 2. (Color online) Characteristics of a 15  $\mu\text{m}$  diameter microcell. Efficiency vs short circuit current density, or laser power density ( $\lambda = 532$  nm). The dots are experimental data; the line is a guide for the eyes. The inset shows  $V_{oc}$  vs  $J_{sc}$ .

by the product of the incident light power under one sun ( $1000 \text{ W/cm}^2$ ) by the concentration ratio.

These data show that the microcell efficiency increases with laser power and reaches a maximum at 17% for an incident power around  $10^4 \text{ mW/cm}^2$  or short circuit current density of  $3.5 \text{ A/cm}^2$ . Compared to the unconcentrated case, a maximum efficiency increase of 4 points in absolute, or more than 30% in relative, is observed. At higher incident light power, the efficiency decreases and goes back to its unconcentrated value, at around  $10^5 \text{ mW/cm}^2$  or  $35 \text{ A/cm}^2$ .

The increase in efficiency with incident power is due to the photocurrent increase compared to the dark current. This effect leads to an increase of the  $V_{oc}$  as shown in the inset of Fig. 2. We can see more precisely that  $V_{oc}$  is increasing linearly with the logarithm of the laser power as expected at a fixed temperature. From the fact that  $V_{oc}$  does not deviate from this trend, we can infer that the temperature increase of the cell is very limited, less than 10 K at 1000 suns. The maximum in efficiency observed at  $10^4 \text{ mW/cm}^2$  occurs when resistive losses counterbalance the improved  $V_{oc}$  or when the product of the series resistance by the short circuit current approximately equals  $nkT/q$ .<sup>9</sup> This maximum is reached on microcells at current densities nearly ten times higher than on standard centimeter size CIGS cells,<sup>2</sup> confirming experimentally that resistances are drastically limited in this concentration range. Indeed, in microcells, spreading resistances are vanishingly small,<sup>5</sup> and the devices are then limited by size independent sources of resistance, originating from the electrical contacts and the absorber layer.

These results show that polycrystalline thin film CIGS microcells, under concentration, have a behaviour comparable to monocrystalline III–V monojunction solar cells:<sup>10</sup> the best GaAs solar cell to date reaches a maximum efficiency at a concentration ratio of  $\times 117$ . The 15  $\mu\text{m}$  device presented here has a maximum efficiency at a concentration ratio of  $\times 120$ . This is a breakthrough compared to previous experiment on CIGS, as the maximum efficiency was obtained at  $\times 14$ .<sup>2</sup>

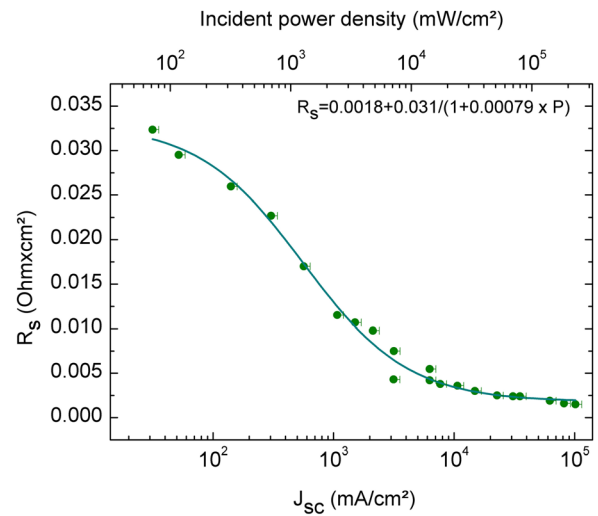


FIG. 3. (Color online) Series resistance of a 15  $\mu\text{m}$  microcell that is determined by fitting the current-voltage characteristics, as a function of the incident power density or short circuit current density. The dots correspond to experimental data; the line is the fit according to Eq. (1).

A feature of the high injection regime is that the series resistance is decreasing with increasing incident light power density as displayed in Fig. 3. Indeed, carriers that are photo-generated in the absorber reduce its resistivity, resulting in lower series resistance. The increase in photogenerated carrier density is proportional to the incident light power density; therefore, the total series resistance of the microcell  $R_{smicrocell}$  can be expressed as:<sup>11</sup>

$$R_{smicrocell} = R_c + R_{sabs} = R_c + \frac{R_{s0}}{\left(1 + \left(1 + \frac{\mu_p}{\mu_n}\right) \times \left(\frac{L_n}{t}\right)^2 \times \frac{q^2 \times EQE \times R_{s0} \times P_{light}}{kT \times hv}\right)}, \quad (1)$$

where  $R_c$  is the light independent series resistance;  $R_{sabs}$ , the light modulated series resistance associated with the CIGS absorber layer;  $R_{s0}$ , the absorber resistance in dark condition;  $R_{s0} = t/q\mu_p p_0$ , with  $q$  the elementary charge,  $t$  the absorber thickness,  $\mu_n$  ( $\mu_p$ ) the electron (hole) mobility,  $P_{light}$  the incident light power density,  $L_n$  the minority carrier diffusion length in the absorber,  $EQE$  the external quantum efficiency at 532 nm,  $kT/q$  the thermal voltage, and  $hv$  the energy of the incident photons. In Fig. 3, the experimental data are fitted according to Eq. (1), with  $R_c = 1.8 \times 10^{-3} \Omega \text{ cm}^2$ ,  $R_{s0} = 3.1 \times 10^{-2} \Omega \text{ cm}^2$ . Given that  $EQE = 84\%$  at 532 nm, the absorber thickness is 2.5  $\mu\text{m}$ , and assuming  $\mu_p/\mu_n \ll 1$ , we evaluate  $L_n$  to 3  $\mu\text{m}$ , which is above reported value from  $EQE$  measurements.<sup>12</sup> Our results show that the resistance modulation is sufficiently important to decrease the series resistance by more than one order of magnitude in the explored concentration range. Maximum efficiencies at concentration ratios  $\sim 1000$  would require improved  $R_c$ , now limited by the contact of the probe on Au. Increased  $L_n$  (or reduced  $t$ ) would make the absorber contribution to Joule losses negligible at all incident power.

The potentiality of strongly scaling down thin film solar cells for a use under concentrated illumination has been demonstrated. We showed that the microcell structure leads to a drastic reduction of resistances and is therefore particularly

suitable for high flux performance. Polycrystalline thin film microcells on glass were fabricated and showed a 4% absolute improvement in efficiency at a concentration ratio of  $\times 120$  and an improvement in  $V_{oc}$  up to  $\times 1000$ . The modulation of series resistance with illumination, i.e., a distinctive feature of the high injection regime on CIGS microcells, is highlighted. These results open interesting perspectives. New architectures for the microscale concentration of light need to be developed. Microcells could be grown with selective deposition methods, such as electrodeposition or printing, which are already developed for thin films. As a consequence, microcells could lead to important material saving, by a factor between 10 and 1000, depending on the concentration used. This is particularly important for thin film technologies relying on In or Te, such as CIGS or CdTe. Our results suggest the use of microcells under high injection is of interest for industrial applications as well as for fundamental studies.

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