Photoluminescence-Based Current-Voltage Characterisation Of Individual Subcells In Multi-Junction Devices

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Abstract – We demonstrate a photoluminescence based, contactless method to determine the current-voltage characteristics of the individual subcells in a multi-junction solar cell. The method relies upon the reciprocity relation between the absorption and emission properties on a solar cell. Laser light with a suitable energy is used to excite carriers selectively in one junction and the internal voltages are deduced from the intensity of the resulting luminescence. The IV curves obtained this way on 1J, 2J and 6J devices are compared to those obtained using electroluminescence. Good agreement is obtained at high injection conditions while discrepancies at low injection are attributed to in-plane carrier transport.

Index Terms – III-V multijunction solar cell measurement, Photoluminescence, Characterization of PV

I. INTRODUCTION

Rapid and sustained growth of photovoltaic industry requires the development of new tools for solar cell characterization. This is especially important for III-V multi-junction (MJ) solar cells for concentration applications where a fast, reliable screening of the solar cell quality and properties is essential to increase the throughput, further reduce fabrication costs and secure a larger share of the PV market.

Electroluminescence and photoluminescence imaging has been extensively used for the characterisation of solar cells and modules in recent years, especially in the silicon PV industry [1]–[5]. These methods identify and spatially resolve shunts, highlight inhomogeneity in the materials, indicate the influence of grain boundaries and the quality of the metallisation or minority carrier lifetimes. Recently these techniques have been applied to thin films [6]–[8] and also to MJ solar cells, where some degree of spectral resolution, rather the spatial resolution, is necessary in order to distinguish the luminescence from the different subcells [9]–[13].

In this work we develop a fast PL-based contactless method for current voltage (IV) characterization of MJ solar cells, primarily focused on concentrator devices. Laser light is employed for selective carrier photogeneration in component junctions and the free energy of the electron-hole pairs is measured from a PL signal. While EL has been used for this

purpose before [9], [12], it has as a disadvantage that it can only be applied on completely finished devices and will include effects due to luminescent coupling between subcells [14], especially under high concentration. Additionally, as shown in [11], the apparent performance of a given junction measured by EL can be masked by the poor performance of the other junctions of the device, for example due to radiation damage. The advantages of PL-based IV include:

- independent biasing of component junctions in a multi-junction solar cell to determine the IV curve for each of the sub-cells;
- no need to account for series resistance, either in the tunnel diodes or the metal contacts;
- absence of radiative coupling between subcells;
- compatibility with both completed and partially finished solar cells. The method can be performed at every stage of the device fabrication – for example after the fabrication of each subcell - and used for monitoring and improving the manufacturing steps.

The paper is structured as follows: section 2 introduces the theoretical background of the technique; section 3 describes the samples used in the study and the experimental setup; section 4 shows the experimental results, the PL- and EL-based IV curves of the solar cells, as well as the process of calibration of the system, essential for a proper evaluation of the internal voltages; and section 5 provides a discussion of the results, the limitations of the technique and its uncertainties.

II. THEORETICAL BACKGROUND

The luminescence (photon flux) of a solar cell ϕ_{em} and their external quantum efficiency Q_e are related by the Rau's reciprocity theorem [15]:

$$\phi_{em}(E) = Q_e(E)\phi_{bb}(E) \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (1)$$

with ϕ_{bb} the emission of a black body, V the internal voltage of the cell, equal to the quasi-Fermi level separation, and $V_T = kT/q$ the thermal voltage. Considering that the luminescence is measured in arbitrary units, assuming $V > 3V_T$ and using the Boltzmann approximation, the internal voltage V_j of a particular junction j in a MJ solar cell can be re-written in the form proposed in Ref. [9]:

$$V_j = V_T \ln(\phi_{em}^j) + \frac{E}{q} - 2V_T \ln(E) - V_T \ln(Q_e^j) - C \quad (2)$$

with C a proportionality constant that is determined during the calibration (see Section 4). A full IV curve of a PN junction relates the recombination current with the voltage of that junction, $J_{rec}(V_j)$. In EL-based IV, the recombination current density J_{rec} is given by the electrically injected current I_{el} divided by the area of the device – usually defined by an etched mesa, A_{mesa} –, assuming that radiative coupling between subcells is not present. In such conditions, J_{rec} is the same for all junctions of the cell and given by:

$$J_{rec} = J_{el} = \frac{I_{el}}{A_{mesa}} \quad (3)$$

In PL-based IV, J_{rec} is junction dependent and given by:

$$J_{rec}^j = J_{pc}^j = \frac{q P_{ex} Q_e^j(E_{ex})}{E_{ex} A_{ex}} \quad (4)$$

where P_{ex} is the excitation laser power, E_{ex} the energy per photon, and A_{ex} the area of the excitation spot. This equation assumes that all photogenerated current J_{pc} , contribute to the internal voltage of the subcell in the A_{ex} area, $J_{rec} = J_{pc}$. As we will see below, this assumption is incorrect at low injection levels when lateral currents might dominate.

III. EXPERIMENT AND MATERIALS

A. Solar Cells

We analyse four solar cells with 1, 2 and 6 junctions, all of them fabricated at the Fraunhofer Institute for Solar Energy (Freiburg, Germany). The one-junction (1J) devices are standard GaAs and GaInP solar cells grown by metal organic vapour phase epitaxy (MOVPE) on a 6° mis-oriented p-type GaAs substrate. The GaAs cell was used to calibrate the setup – to determine the value of C in Eq. 2. The 2J device comprises a top GaInP and a bottom GaAs subcells, grown on the same type of substrate. The subcells are nominally identical to the corresponding 1J devices. The 6J device is a lattice matched AlGaInP/GaInP/AlGaInAs/GaInAs/GaInNAs/Ge solar cell grown by MOVPE. Details of the growth and properties of this structure can be found in [16], [17]. The structures were processed in the form of devices with a dense front metal grid suitable for concentration/high injection measurements. The mesas for the 1 and 2 junction devices have an area of 0.0547 cm² and the 6J device an area of 0.043 cm².

B. Experimental setup

EL and PL measurements were conducted using the same collection optics (see Fig.1): a pair of lenses collected the light emitted by the samples and focused it into an optic fibre tip. The relation of the focal lengths of the lenses and the size of the core of the fibre gave a circular collection area of 650 μm in diameter. The fibre was connected to a fast Ocean Optics HR4000 spectrometer with a spectral range from 300 to 1000 nm. A halogen lamp with known spectral shape was used to correct the measurements for the spectral response of the

system. Measuring the dilute nitride (GaInNAs) and the Ge junction of the 6J device was not possible due to their weak luminescence intensity and the limited sensitivity of our spectrometer in the near infrared range.

Fig 1: Sketch of the experimental setup, indicating the relative position and sizes of the sample mesa, the collection spot and the excitation spot.

Samples were positioned such that the collection spot was centred in the device (Fig. 1). For PL experiments, a continuous wave Nd:YAC laser or a tuneable Ti:Sapphire laser were used. The contacts of the solar cells are open during PL measurements, leaving the sample at the corresponding open circuit voltage for each light intensity. The excitation spot was elliptical, 1200x1450 μm, completely covering the collection region with homogeneous illumination. The geometry and position of the sample was kept constant between measurements, ensuring that the same region is probed in both EL and PL experiments and that the calibration is also common.

External quantum efficiency (QE) measurements were taken using a spot size for the monochromatic light also of ~650 μm and probing the same region of the solar cell as for the EL/PL experiments. Since the QE is influenced by the shadowing of the metal grid, it is important to ensure similar measurement areas in order to have a common correction factor C for all samples, regardless of the exact metal grid design. This way, the influence of the metal grid is incorporated in the QE measurement.

EL images were taken using a Thorlabs DCC1545M camera sensitive in the 300-1000 nm range. For images of MJ devices, a suitable short or long pass filter was used to allow only the luminescence of the subcell of interest to reach the sensor.

IV. EXPERIMENTAL RESULTS

A. Calibration

Fig. 2a shows the EL spectra in arbitrary units of the 1J GaAs sample as a function of the injected current, from 0.6 mA to 50 mA. Using these data and the QE of the cell (not shown), the internal voltage for each current (Fig. 2b) is calculated using Eq. 2. This equation requires knowledge of C and the procedure to obtain its value is similar to that described in [9], although simpler in this case as there is only one junction: the voltages are first calculated with $C = 0$ and then they are offset using a non-zero value for C , such that at an injected current equal to

the short circuit current of the cell at 1 Sun, the voltage is equal to the corresponding open circuit voltage at 1 Sun.

It should be noted that this calibration factor will be the same for all subsequent measurements, either EL or PL based, as long as the geometry of the setup – excitation and collection areas, collection optics, detector, etc - remains unchanged. Specific properties of the samples, such as metal grid design or anti-reflecting coating, are incorporated in the QE that enters into Eq. 2.

Fig. 2c shows the resulting EL-based IV curve and the comparison with the measured dark IV of the device. The voltages are calculated by averaging the spectrally resolved voltage in Fig. 2b over the shaded region. As it can be seen, the agreement between both curves is good at low injection levels. At higher current levels, both curves diverge due to the influence of the series resistance (contact resistance and finger resistances) in the dark IV. No effects related to the sheet resistance of the emitter are observed in the EL image (inset Fig. 2c), supporting the validity of the EL-based IV. The figure also shows the IV curve calculated from PL measurements (730 nm excitation, from 1.1 mW to 80 mW) using the same calibration factor as for EL. While the voltages are roughly the same – as expected considering that the EL and PL spectra almost overlap each other in this current and laser power range (not shown), the currents appear to be overestimated. This arises as a consequence of finite in-plane carrier transport, an effect that we will discuss in detail in the following sections.

Fig. 2d shows the estimated IV results for to the 1J GaInP solar cell with the same calibration factor used for the 1J GaAs cell. The trends described above for the EL-based IV and the PL-based IV also apply to this cell, finding a good agreement of the with the dark IV at low injection and with the PL-based IV overestimating the current on the whole range. It can be seen, however, that there is a small systematic shift of ~ 6 mV in the EL-based IV, outside the measurement uncertainty, that might be consequence of the calibration process. The EL image shown in the inset suggest a high sheet resistance in the emitter, limiting the in-plane carrier transport. This leads to an inhomogeneous luminescence distribution between the metal fingers and therefore an inhomogeneous voltage and recombination current. This is important since it indicates that neither the dark IV, nor the EL-based IV represent the true IV characteristic of the solar cell at high injection: the former overestimates the voltage at a given current and the latter overestimates the current at a given voltage. The true curve will lie somewhere in between both curves.

B. 2J GaInP/GaAs solar cell

The same experiments were conducted on the 2J device using a 532 nm laser for the GaInP subcell and a 730 nm laser for the GaAs subcell. The power range was the same in both cases, from 1.1 mW to 80 mW. The correction factor C remains as obtained previously.

Fig 2: (a) EL emission from the 1J GaAs sample. (b) Calculated internal voltages, including the correction factor, as a function of energy, fairly constant over the high energy side of the EL peak. (c) and (d) EL- and PL-based IV curves and comparison to the normal dark IV curve for the 1J GaAs and 1J GaInP solar cells, respectively. “PL scaled” represents the PL-based IV calculated with A_{mesa} instead of A_{ex} in Eq. 4. Insets show an EL image of each of the devices under higher injection, where the dark, thin stripes are the metal fingers.

Fig. 3a shows the resulting IV curves for each subcell and the total IV curve calculated by adding together the voltages at a given current. The IV curve derived from EL matches well the dark IV at low injection, diverging just at higher values when the latter is influenced by series resistance. As with the 1J, the PL-based IV results in higher current than the EL-based IV at low injection, yet converging at higher injection. For the case of GaInP, this effect is less marked, although at higher injection the trend of the curves suggests that the PL-based IV will be below those from the EL-based IV. Fig. 3b and 3c show the EL images of the GaAs and GaInP subcells at higher injection (914 mA/cm^2). While for GaAs the emission is homogeneous between the metal fingers, in the case of GaInP there is a significant variation; a consequence of the sheet resistance of the emitter. As with the 1J, this suggests that the EL-based IV is subject to uncertainties due to non-uniform emission, possibly overestimating the current at higher injection.

Fig 3: (a) EL- and PL-based IV of the 2J solar cell, as well as the total IV curves and the dark IV. (b) and (c) EL images of the GaAs and GaInP subcells in the 2J device at 914 mA/cm^2 .

C. 6J solar cell

For the 6J solar cell we analysed only the top four junctions. Unfortunately, emission from the bottom subcells (GaInNAs and Ge) could not be measured, due to a combination of reduced luminescent yield and low sensitivity of our equipment in this spectral region.

The QE of the measured junctions is plotted in Fig. 4a, showing a strong overlap of the spectral regions each of the subcells is sensitive to. As a consequence, just two lasers with wavelengths 532 nm and 730 nm were used to excite luminescence in the top (AlGaInP and GaInP) and the middle (AlGaInAs and GaInAs) two subcells, respectively (Fig. 4b). Exciting two subcells

simultaneously might represent a problem at very high injection levels when luminescent coupling between subcells becomes a significant fraction of the total injected current [14]. In the case of the AlGaInP subcell, the tail of the nearby laser excitation, visible in the higher energy side of Fig. 4b led to a power dependent background that increased the uncertainty of the estimated voltages for that subcell. As shown in Fig. 4c, in that subcell the voltage curve do not show a clear plateau in the region of the PL.

Fig 4: (a) External QE of the top and middle subcells of the 6J device. (b) PL emission when excited with the two lasers as a function of power. (c) Calculated internal voltages for each cell.

Fig. 5a shows the EL- and PL-based IV curves. While both curves follow a similar trend that already discussed, here it becomes clearer that both curves tend to the same values at higher injection, overlapping over a relatively broad current range. This match becomes is especially good for the GaInAs and AlGaInAs junctions. As discussed, the AlGaInP junction shows more erratic voltage values due to the influence of the

tail of the laser. No issues associated with in-plane transport were observed in EL images (not shown), since this cell had a denser metallic mesh specifically designed to improve carrier collection and work at higher current densities.

Fig. 5b shows the total IV curve considering only the four top junctions. While the result cannot be directly compared with the dark IV due to the absence of the Ge and GaInNAs subcells, the difference between both is within a sensible range, 0.523 V at 1 Sun. This has to be split between the Ge junction – with typical V_{oc} at 1 Sun of 0.2-0.25 V [9], [12] – and the dilute nitride junction – with reported voltages in the 0.2-0.4 V range for a 1 eV subcell [18], [19].

Fig 5: (a) EL- and PL-based IV curves for the top and middle junctions of the 6J solar cell. (b) Total estimated IV curve and the measured dark IV of the complete device.

V. DISCUSSION

A. The role of in-plane transport

Despite the agreement of voltages in all cases, it is clear that there is a discrepancy in estimating the current density when using EL and PL, specially at low injection levels. Such discrepancy was already noted in Section 2 where we introduced Eq. 4: not all photogenerated carriers recombine in the region where they are generated; a significant fraction is transported laterally, further if the material has high conductivity, until they reach the edge of the mesa. This lateral transport of majority carriers is the basis for carrier collection in all solar cells with metal finger contacts and indeed, solar cells for concentration depend strongly on having high lateral conductivity to reach high efficiencies. A low lateral conductivity leads to high series resistance and can locally drive the tunnel junctions above their peak current, with deleterious effects at high concentrations, such a drop in fill factor and steps in the IV curve under illumination [20], [21].

In the case of the PL-based IV, at lower injection, carriers photogenerated at the excitation spot can easily move in the plane of the sample without significant impact from the sheet resistances since currents are low. In this case, recombination takes place over the entire device mesa resulting in a homogeneous V_{oc} . As injection increases and the lateral current

risks, a voltage difference is established between the illuminated and dark regions, self-biasing the solar cell in the illuminated regions. At yet higher injection, most of the photogenerated carriers recombine in the excitation region as only a small fraction moves laterally so a very abrupt voltage drop is established around the laser spot. Under these conditions, the recombination area converges to the laser spot, A_{ex} . The transition between both regimes can be seen as an inverted S-shape in the PL-based IV. In principle the same is true for the EL-based IV, however as the current is common to all the subcells, and thanks to the presence of the back and front contacts, recombination tends to homogenise across the whole mesa, except maybe in the front junction due to the spatial distribution of the metal fingers or if any of the layers of the solar cell is severely degraded [11]. The front and back contacts, with high conductivity metals, also affect the PL-based IV, specially in the case of single junctions, as carriers do not move laterally along the semiconductor layers but in the metal. In these cases – Fig. 1c and 1d –, the injected area becomes the entire mesa almost independently of the injection level.

Fig. 2c and 2d further illustrate this effect, where we show the PL-based IV curves as if photogenerated carriers were recombining across the whole mesa and not just in the illuminated area (using A_{mesa} in Eq. 4 rather than A_{ex}). For the GaAs solar cell, the PL-based IV overlaps with the EL-based IV when the data is scaled, suggesting that the recombination area is indeed the same despite the difference in the injection area. For the case of GaInP, the scaled curve becomes closer to the EL-based data, but they do not overlap, the PL curve being systematically shifted to higher voltages than the EL-based IV. This shift cannot be explained in terms of the sheet resistance, that has minimal effect in the lower injection region of the PL-based IV curve. We believe it can be related to the influence of luminescence at short circuit discussed in part C below.

While no sheet resistance measurements are available for these samples, they can be estimated from their nominal structure using the method described in Ref. [21]. The calculation for the upper layers (window + emitter) of the structure of the 1J-GaAs and 1J-GaInP solar cells gives resistances of 151 and 717 $\Omega/\square$, respectively, which could justify the different behaviour observed in both samples at higher injection.

In order to measure the true IV curve of each subcell using PL it is necessary to have large area, homogeneous illumination, ideally across the whole sample. For small devices, this does not represent a big issue but for as-grown wafers it is challenging to achieve very high equivalent solar concentrations. As an example, in order to reproduce the above experiments on a full 4-inch wafer, it will be necessary two lasers with ~ 460 W of total power each – depending on the wavelength –, and around 2.5 kW to reach 1000 Suns. However, as discussed, lateral currents are negligible compared to the recombination current in the illumination area at higher injections and therefore scanning the wafer with a much smaller spot size, of the same order that the final device, is sufficient to achieve reliable results.

B. The role of radiative coupling

In all these results, we have neglected the effect of radiative coupling between subcells. Radiative coupling takes place in multi-junction solar cells when a fraction of the photons emitted by the upper sub-cells are re-absorbed by the lower ones, contributing to their photocurrent. As described by Geisz *et al.*, the main effect of this coupling is that the actual injected current in a given junction depends on the externally injected current plus the light transferred from the upper junctions [22]. As radiative recombination becomes increasingly important under high concentration, the effect of radiative coupling on the higher injection regime of EL-based IV curves can also be important.

In PL experiments, only one subcell is illuminated at a time. If there is radiative coupling to the lower cells, such coupling will not affect the results concerning the subcell under test. This is the case for the 2J device (Fig. 3) for example, where the GaAs and the GaInP subcells are excited and measured independently. This is not true, however, for the 6J device (fig. 4) where 2 cells are illuminated simultaneously (two with the 532 nm laser and two with the 730 nm laser). In that case, some luminescence from the AlGaInP and AlGaInAs subcells could influence the result of the GaInP and GaInAs subcells, respectively.

The generally good match between the EL- and PL-based IV curves at higher injection suggests that radiative coupling, while present, is not playing a big role in our measurements, its influence lying within the uncertainty of the technique. However, a deeper analysis would be necessary in order to quantitatively assess its real impact and separate that effect from the lateral transport processes that seem to dominate these measurements and the short circuit luminescence, described in the next section.

C. The role of the short circuit luminescence

Short circuit luminescence has been recognised as contributing to the overall emission of a solar cell in the presence of illumination and electrical bias. In the PL experiments, there is the external optical excitation while the electrical bias is imposed by the open circuit condition of the sample. Rau showed that Eq. 1 needs to be modified in this case to include both contributions to the emitted light [23], resulting in:

$$\phi_{em}(E, V) = \phi_{sc}(E) + Q_e(E)\phi_{bb}(E) \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (5)$$

with $\phi_{sc}(E)$ being the bias independent short circuit luminescence. As before, using the Boltzmann approximation and assuming $V > 3V_T$, the junction voltage can be expressed as:

$$V_j = V_j^0 + V_T \ln \left(1 - \frac{\phi_{sc}^j}{\phi_{em}^j(V_j)} \right) \quad (6)$$

where V_j^0 is the junction voltage as calculated by Eq. 2. Since the second term is always negative, this equation indicates that the actual junction voltage in the presence of illumination will be lower than for a electrical bias for a given ϕ_{em} . In other words, the junction voltages will be overestimated if the second

term is not considered. It also shows that this difference becomes smaller for higher voltages, as the ratio of luminescence in Eq. 6 reduces. Contrary to the radiative coupling, this effect adds an uncertainty to the PL-based IV measurements.

Looking at our experimental results, it can be seen that the 1J-GaAs solar cell is free from this effect, as the EL- and PL-based IV fully overlap once the lateral transport effect have been accounted for. That is not true for the 1J-GaInP where the difference of ~14 mV between both curves at lower injection could be associated to the short circuit luminescence. In the 2J device (not shown), the shift increases to ~10 mV and ~23 mV for the GaAs and GaInP subcells, respectively. For the 6J solar cell, the shifts are between 10 and 30 mV, although the data in the lower injection region is more scattered and have a higher uncertainty, making difficult to give a precise value.

In general, good quality subcells with poor transport properties (eg. low defect density and low carrier mobilities) will show the highest short circuit luminescence and therefore their PL-based IV will be more affected by it unless fully accounted for by using Eq. 6.

D. Speed and accuracy

Despite these caveats, all the results presented in Fig. 2, 3 and 5 demonstrate that PL can be used as a fast and contactless method to determine the internal voltages in a MJ solar cell. Each point in the IV curves took between 10 to 100 ms to be measured, meaning that with automation and simultaneous excitation with multiple lasers, the complete IV of all subcells in a MJ solar cell could be measured in a matter of 1-2 s, depending on the desired resolution.

Once the implied IV curves are known, solar cell intrinsic parameters such as the saturation currents associated to $n=1$ and $n=2$ ideality factors or the V_{oc} and the FF at any injection level could be estimated for each subcell.

For the voltages, the accuracy of the method depends on the accuracy of the measured Q_e , the luminescence and the temperature, as well as the calibration factor. While a 10% relative error in the Q_e or the luminescence only produces an absolute change in the voltage of around 2.6 mV each at room temperature, according to Eq. 2, the noise in the signal, the influence of the background, the tail of the laser and temperature drift with the excitation power increases that uncertainty, specially for low luminescence intensities. In the end, weak luminescence is the main limitation of the method, shared with the EL-based IV curves: the solar cells have to emit enough light to be measured, meaning that poor quality materials or low injection conditions cannot be measured quickly or accurately with low sensitivity equipment.

For the current, the main uncertainty arises from knowing the actual injected area. Assuming that lateral transport is negligible, then the uncertainty of the injected current will be proportional to the uncertainty in the power of the laser and the uncertainty of the quantum efficiency at the wavelength of the laser, typically on the order of 5% for the latter.

TABLE I:
SOLAR CELL PARAMETERS ESTIMATED FROM THE EL- AND PL-BASED IV CURVES FOR THE SUBCELLS IN THE 6 JUNCTIONS DEVICE AT 100 SUNS.

Subcell	$I_{sc}/100$ (mA/cm ²) (from QE)	V_{oc} (V)		ΔV_{oc} (mV)	FF (%)		ΔFF (%)
		From EL	From PL		From EL	From PL	
AlGaInP	4.489	1.621	1.621	0	90.2	90.6	-0.4
GaInP	3.966	1.444	1.431	13	90.0	88.1	1.9
AlGaInAs	4.752	1.209	1.201	8	86.7	84.8	1.9
GaInAs	4.462	1.119	1.119	0	86.4	83.4	3.0

Figure 6: Light IV curves estimated for the subcells in the 6 junctions device at 100 suns. Lines are a fit to a two diode model of the EL data (continuous line) and the PL data (dashed line).

E. Pseudo light IV characteristics

The main advantage of this contactless technique is its capability to quickly diagnose the performance of a given subcell in a MJ device, without the influence of other subcells, series resistances in the metal contacts or in the tunnel diodes. The IV curve measured in this way will be intrinsic to the subcell under test and limited only by its recombination and transport properties, representing thus an upper limit to the overall performance of the MJ solar cell.

Using the EL- and PL-based dark IV curves estimated above (Fig. 5) and calculating the short circuit current from the QE (Fig. 4a) and the standard air mass 1.5 direct solar spectrum, we can find the open circuit voltage, V_{oc} , and the fill factor, FF , of each subcell in the 6 junctions device for 100 suns. The resulting light IV curves are shown in Fig. 6 together with a fit to a two diode model. Table I shows the comparison of the parameters calculated using the EL and PL data. The V_{oc} is very similar in all cases, regardless of the technique, being in agreement within the uncertainty of the voltages calculated above and in the order of 5-10 mV. Larger differences can be observed in the FF . The origin of such disagreement is in the aforementioned in plane carrier transport and short circuit luminescence, which partly compensate one another. At 100 suns, this is equivalent to underestimating the current around the maximum power point, resulting in the observed lower FF for the PL-based light IV curve. At higher concentrations – or using large area illumination – this issue will disappear and accurate values will be obtained for the FF on all subcells.

VI. CONCLUSIONS

A PL-based IV characterization method for MJ solar cells has been demonstrated that allows for a fast, contactless measurement applicable even in unfinished devices. Results have been presented for 1J, 2J and 6J devices and compared to EL-based IV measurements. At higher injection conditions, the PL-based IV curves overlap with those obtained from EL measurements and normal dark IV measurements. At lower injection, however, currents and voltages are overestimated in the PL measurement. We attribute this to in-plane carrier transport from the region under illumination to the region in the dark and to the effect of short circuit luminescence. This issue can be partly solved by using a larger illumination area.

Using the superposition principle, we have calculated the open circuit voltage and fill factor of each of the subcells in the 6 junction device, showing the potential of the technique for contactless diagnosis of the solar cell performance. The results confirm the technique as a fast characterization tool capable of screening the internal IV curves of an arbitrary number of subcells in a MJ device.

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