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Amaury Delamarre, Laurent Lombez, Jean-François Guillemoles. Contactless mapping of saturation currents of solar cells by photoluminescence. *Applied Physics Letters*, 2012, 100 (13), pp.131108. 10.1063/1.3697704 . hal-03795259

**HAL Id: hal-03795259**

**<https://hal.science/hal-03795259v1>**

Submitted on 3 Oct 2022

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Cite as: Appl. Phys. Lett. **100**, 131108 (2012); <https://doi.org/10.1063/1.3697704>

Submitted: 06 February 2012 . Accepted: 08 March 2012 . Published Online: 26 March 2012

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## Contactless mapping of saturation currents of solar cells by photoluminescence

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(Received 6 February 2012; accepted 8 March 2012; published online 26 March 2012)

We report in this letter the contactless measurement of spatially resolved photocurrent–photovoltage relationship. The method is based on hyperspectral imaging, from which we record cartography of absolute photoluminescence spectra from solar cells. Using the generalized Planck’s law, it is therefore possible to derive the quantitative value of the quasi-Fermi levels splitting, related to the voltage over the junction. It allows us to directly extract optoelectronics properties of the device with a solely optical method. As a proof of concept, we derive saturation currents of a GaAs solar cell and find a good agreement with the standard electrical measurements. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.3697704>]

Photoluminescence (PL) emission of semiconductors contains a wealth of information on material properties, like absorption spectra, quasi-Fermi level splitting, or energy levels within the band gap. It became therefore a useful characterisation tool in the solar cell field. It does not require any contact and can be used at different stages of fabrication,<sup>1–3</sup> from bare absorber to complete modules. It can also be spatially resolved, from micrometer scale to centimetre scale, which is an important aspect as inhomogeneities may influence device efficiencies.<sup>4</sup> This is especially of high relevance for polycrystalline technologies like Cu(In,Ga)Se<sub>2</sub>, which exhibit variations on different length scales.<sup>5,6</sup>

To acquire maps of PL spectra, confocal microscopes<sup>6</sup> are often used, or near-field microscopes<sup>5</sup> for a higher spatial resolution. These systems record PL emitted at one location and then scan the surface to produce a map. Scanning line by line is also possible.<sup>7,8</sup> Using the generalized Planck law,<sup>9</sup> it is possible to measure this way spatial fluctuations of quasi-Fermi level splitting or energy gap. This is an interesting information as the quasi-Fermi level splitting  $\Delta\mu$  is related to the voltage of the junction.<sup>9</sup> However, due to experimental limitations, only relative intensity values are usually obtained. Absolute intensity values (i.e., in number of photons per seconds) can be acquired thanks to other measurement methods,<sup>3,10</sup> but without mapping the surface.

In the present letter, maps of PL spectra are recorded in absolute scale, using a hyperspectral imager (HI). A spatial resolution down to the micrometer scale is achievable and the spectral resolution (here 2 nm) can be used to extract parameters such as diffusion lengths.<sup>11</sup> The system presented is unique in that the data are obtained on homogeneously illuminated samples, therefore eliminating artefacts arising from lateral carriers transport due to localized excitation.<sup>12</sup>

We propose a method to derive local relationships between short circuit current and open circuit-voltage ( $I_{SC}(V_{OC})$ ) on the cell, from a solely optical measurement using PL. Similar techniques have been described<sup>13,14</sup> and investigated previously,

but required other measurement techniques for calibration (I(V), photoconductivity).<sup>2,15</sup> By fitting the obtained curves we therefore have access to the local saturation currents using a two-diode model.

Our method begins with the consideration of a homogeneously illuminated solar cell, which results in a quasi-Fermi level splitting  $\Delta\mu$ . This solar cell will emit photoluminescence by radiative recombinations at a level given by the generalized Planck law<sup>9</sup>

$$dr_{spont}(\hbar\omega) = \alpha(\hbar\omega) \frac{\Omega n^2}{4\pi^3 \hbar^3 c_0^2} (\hbar\omega)^2 \times \frac{1}{\exp\left(\frac{\hbar\omega - \Delta\mu}{kT}\right) - 1} d\hbar\omega, \quad (1)$$

$dr_{spont}$  is the photon emission from a volume element,  $\alpha$  is the absorptance,  $\Omega$  is the solid angle of the emission,  $n$  is the material optical index,  $\hbar$  is the Planck constant,  $c_0$  is the speed of light in vacuum,  $k$  is the Boltzmann constant,  $T$  is the temperature, and  $\hbar\omega$  is the considered photon energy. The quasi-Fermi level splitting  $\Delta\mu$  varies as a function of depth in the junction. Generally this splitting is considered to be the maximum achievable voltage.<sup>3,6</sup> However, if the carrier diffusion length is longer than the thickness, this splitting, noted  $\Delta\mu_{eff}$ , is constant over the depth and  $\Delta\mu_{eff} \approx qV$ ,  $V$  being the voltage of the cell for a given excitation power and  $q$  the elementary charge.<sup>9,14</sup> From Eq. (1), we can also write the emission of a surface element at a location  $r$ , taking into account the emission from the whole absorber

$$dj_r(\hbar\omega, r) = A(\hbar\omega, r) \frac{\Omega \cos(\theta)}{4\pi^3 \hbar^3 c_0^2} (\hbar\omega)^2 \times \frac{1}{\exp\left(\frac{\hbar\omega - \Delta\mu_{eff}(r)}{kT}\right) - 1} d\hbar\omega. \quad (2)$$

$A(\hbar\omega)$  is the absorption probability of an incident photon on the surface element.  $\theta$  is the angle made by the emitted light direction and the surface normal. It appears here in a  $\cos(\theta)$  factor, as

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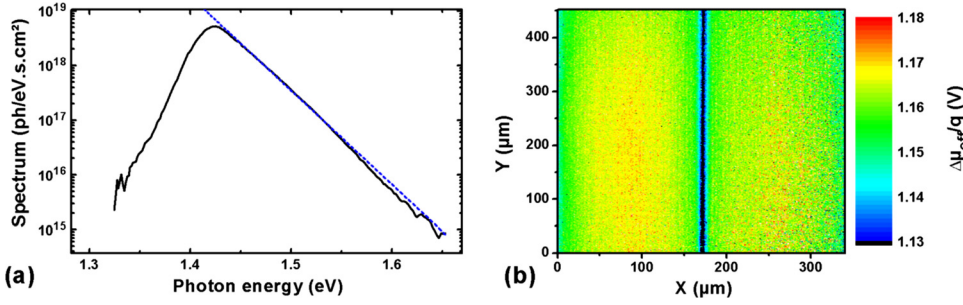


FIG. 1. (a) Spectrum measured in absolute values under laser excitation of  $\Phi_{\text{Laser}} = 1.7 \times 10^{19}$  ph/s  $\text{cm}^2$  in logarithmic scale and (b) map of quasi-Fermi levels splitting. Dashed line in (a) is the slope  $-1/kT$  describing the high energy wing of the luminescence ( $T = 293$  K). Dark part in the centre of (b) is an electrical contact deposited on the cell.

the emission from the surface follows the Lambert's law.<sup>9</sup> By measuring the photon flux out of the cell in absolute values, we are able to access  $\Delta\mu_{\text{eff}}$ , knowing all other terms in Eq. (2).

For the next step of the method, let us have a closer look on the homogeneously excited cell. We have the same carrier generation everywhere  $j_{\text{gen}} = A(\hbar\omega_{\text{Laser}}) \times \Phi_{\text{Laser}}$ , with the laser at energy  $\hbar\omega_{\text{Laser}}$ . Moreover, if we use a homogeneous cell and operate under open-circuit condition, we expect no lateral current, neither in the absorber nor in the window layer. Therefore in average, an equal number of carriers are generated and recombined at a location  $r$  of the cell. This leads to the equality  $j_{\text{gen}}(r) = j_{\text{rec}}(r)$ ,  $j_{\text{rec}}(r)$  being the recombination current. If we assume moreover that recombination paths in the junction follow a two-diode model, it is possible to write

$$j_{\text{gen}}(r) = j_{01} \left[ \exp\left(\frac{qV(r)}{kT}\right) - 1 \right] + j_{02} \left[ \exp\left(\frac{qV(r)}{2kT}\right) - 1 \right], \quad (3)$$

$j_{01}$  and  $j_{02}$  are, respectively, the saturation currents for the diode with ideality factor 1 and 2. By changing the laser excitation, one varies the generation current  $j_{\text{gen}} = A \times \Phi_{\text{Laser}}$  and is able to measure the resulting  $\Delta\mu_{\text{eff}} \approx qV$ . It is therefore possible to plot Eq. (3), which is similar to a local  $I_{\text{SC}}(V_{\text{OC}})$  curve.

To apply this method, we use an experimental setup based on the HI from Photon, etc., a device that records spectrally resolved images. Laser excitation is made through a microscope objective with a numerical aperture (NA) of 0.4, by a 532 nm laser from Laser Quantum. PL image is collected through the same objective and is then spectrally resolved by the HI. At the output, acquisition is made with a silicon CCD camera Tucsen 1.4 mega pixels. The probed sample is a standard GaAs solar cell from the Fraunhofer Institute for Solar Energy Systems (ISE).

The absolute calibration of the setup is made in two distinct steps. First, a relative calibration is obtained with a halogen lamp of known spectrum, coupled into an integrating sphere. The latter has a spatially homogeneous output, which we image with the system, allowing us to correct sensitivity variations in space and spectrum. Second, we realize the absolute calibration at one wavelength. A fibre output of  $\text{NA} = 0.22$  is imaged, in which a 783 nm laser is coupled. The NA of the fibre is smaller than the NA of the objective (0.4), ensuring us to collect all the photon flux out of the fibre, which we are also able to measure with a power meter. We have therefore an absolute calibration of the system at the wavelength of the laser, from which we extrapolate to the whole system thanks to the first relative calibration.

The GaAs cell is excited homogeneously at open-circuit over its entire surface with a green laser flux  $\Phi_{\text{Laser}} = 1.7 \times 10^{19}$  ph/s  $\text{cm}^2$ . The emitted spectrum is plotted in absolute values in Fig. 1(a), from which we can extract  $\Delta\mu_{\text{eff}}$  with Eq. (2). Only the spectrum part above 1.44 eV is taken into account where the absorption is constant. Indeed, the high energy region in Fig. 1(a) follows an exponential decay  $\exp(-E/kT)$  confirming this approximation (see dashed line). Moreover, we can consider  $A = 1$  as the cell is sufficiently thick and an anti-reflective coating is applied on the surface. Since the cell is a GaAs homojunction grown on a GaAs buffer, there are no interferences and reflections, which would have modified Eq. (2).  $\Delta\mu_{\text{eff}}$  is plotted over a portion of the cell surface in Fig. 1(b). Non-emitting line at the middle of the image is a contact deposited on the cell, and the extreme left and right are the cell edges.  $\Delta\mu_{\text{eff}}$  is measured at  $1.167 \pm 0.010$  eV with a decrease towards the contact and the sides. We note here a good agreement with the open-circuit voltage measured simultaneously at 1.15 V, verifying the assumption  $\Delta\mu_{\text{eff}}/q \approx V$  at the contact. We also carried out experiments with lower excitation power, exhibiting uniform cartography of  $\Delta\mu_{\text{eff}}$ .

In a second step, we use different excitation intensities to extract values of  $\Delta\mu_{\text{eff}}$  corresponding to different generated currents. As absorption  $A$  does not depend on intensity in these carrier concentration ranges, we are able to plot Eq. (3) in Fig. 2. By fitting the resulting curve, we extract saturation currents  $j_{01}$  and  $j_{02}$  given in Table I. For comparison, we also plot the  $j(V)$  curve of the cell and we give the saturation currents determined from it.

Values of  $j_{01}$  and  $j_{02}$  obtained from PL and electrical measurements are in the same order of magnitude, showing that the approximations made are quite reasonable. The inflexion of the electrical  $I(V)$  curve is due to series resistances, to which the method is insensitive. Values of  $j_{02}$  could

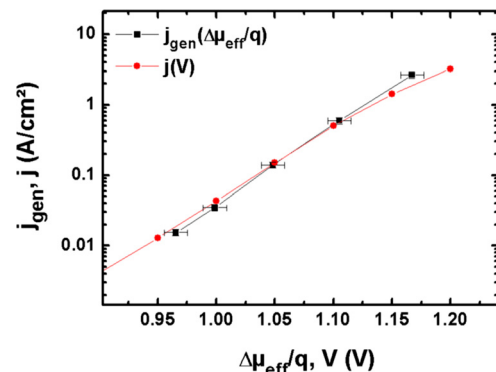


FIG. 2.  $j_{\text{gen}} = f(\Delta\mu_{\text{eff}})$  deduced from laser excitations from  $9.6 \times 10^{16}$  to  $1.7 \times 10^{19}$  ph/s  $\text{cm}^2$  (squares). For comparison,  $j(V)$  is also shown (circles).

TABLE I. Saturation currents derived from PL using the HI and classical current-voltage measurement. The radiative saturation current  $j_{01,\text{rad}}$  being the fraction of  $j_{01}$  resulting in a photon emission from the surface is also determined.

Measurement method	$j_{01}$ (A/m <sup>2</sup> )	$j_{02}$ (A/m <sup>2</sup> )	$j_{01,\text{rad}}$ (A/m <sup>2</sup> )
PL with HI	$(1.8 \pm 0.6) \times 10^{-16}$	$(8.9 \pm 1.5) \times 10^{-7}$	$(4.6 \pm 1.5) \times 10^{-18}$
$j(V)$	$(7.4 \pm 0.1) \times 10^{-16}$	$(5.6 \pm 0.7) \times 10^{-7}$	—

be more accurate with measurement at lower excitation power, which is possible using longer acquisition time. Note that from Eq. (2), the radiative saturation current  $j_{01,\text{rad}}$  can be obtained, consecutively to the derivation of  $\Delta\mu_{\text{eff}}$  with the high energy part of the spectrum. A value of  $(4.6 \pm 1.5) \times 10^{-18}$  A/m<sup>2</sup> is found corresponding to a  $j_{01,\text{rad}}/j_{01}$  ratio of 2.6%.<sup>16</sup> In a similar way a derivation of the absorption around the gap is possible.<sup>17</sup>

From the obtained saturation currents, an evaluation of the solar cell efficiency can also be calculated, assuming that the superposition principle is valid, and series resistances are negligible. The short circuit current  $j_{\text{SC}}$  at one sun excitation power is also needed. By measuring it at 21.08 mA/cm<sup>2</sup>, an efficiency of 16.5% is evaluated, to be compared to 17.2% effectively measured with a solar simulator. As the absorption is also contained into the PL signal, a solely optical evaluation of both  $j_{\text{SC}}$  and the efficiency would be possible with increasing the setup accuracy.

At the highest excitation power, we saw a slight lateral voltage gradient (Fig. 1(a)), which corresponds to a lateral carrier transport within the front layer. This has been studied in other contributions<sup>18,19</sup> and can occur because of recombinations at the cell edges and at the contacts, or recombination currents at shaded parts of the diode, for instance under the electric contacts. This does not impact our results here, but could invalidate our approximation  $j_{\text{gen}}(r) = j_{\text{rec}}(r)$  if strong gradients were present. It points out that the usefulness of the spatial information and that the treatment of lateral currents will be crucial for further studies, for example on inhomogeneous polycrystalline solar cells.

Transport issues highlight also differences between our setup and confocal microscopes commonly used for PL investigations of solar cells. In such experiment both the excitation and the collection are made at one localised point: the cell region surrounding the illuminated point is in the dark and in parallel with the illuminated diode. It results in carriers transport to non-illuminated regions, where they recombine. As a consequence, the information extracted is strongly influenced by the surroundings. If a material without transparent conducting electrode is probed, the confocal measurement has a resolution depending on the diffusion length. In a completed device carrier density uniformisation proceeds via isopotential electrode, so that local measurement is influenced by recombination in all the device. The PL signal is then significantly reduced, so that the excitation power needs to be increased far from the operating point of the cell (typically more than 1000 suns<sup>6,12</sup>). The probed volume is also depth limited in confocal, which could bring measurement artefacts for rough or thick samples. These different aspects explain why the absolute calibration is difficult, especially when the spatial resolution goes down to the micrometer scale. Therefore, the ability of the HI to directly

record images of the surface gives more pertinent information, with comparable spatial and spectral resolutions. The time needed for a mapping is also reduced by 2 or 3 orders of magnitude,<sup>20</sup> and even more if spectral resolution is compromised.

We presented in this letter PL spectra mapping on solar cells in absolute values. This allowed us to access optoelectrical properties of the cell, such as the quasi-Fermi level splitting  $\Delta\mu_{\text{eff}}$  over the junction in absolute values. Saturation currents of the cell are then derived, and therefore we estimate the device efficiency. The major interest of such optical experiment is the absence of contacts. The experimental setup takes advantages of the HI, a device able to acquire spectrally resolved images.

As a proof of concept, we got good agreement between saturation currents measured with our optical method and obtained from classical electrical measurements. This was done on a well known GaAs solar cell, and the next step will be to probe less ideal devices such as polycrystalline cells.

Authors are grateful to Marc Verhaegen and Brice Bourgoïn from Photon etc. for their help in improving the experimental setup and for fruitful discussions.

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