

Erratum

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Hyperspectral Imaging of Photovoltaic Conversion

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ABSTRACT

We analyze photoluminescence (PL) and electroluminescence (EL) using a hyperspectral imager that records spectrally resolved luminescence images of solar cell absorbers. The system is calibrated to yield the luminescence flux in absolute values. This system enables to quantitatively image physical parameters such as the photovoltage with an uncertainty of less than 30mV. The wide field illumination, low power excitation and fast acquisition brings new insights compared to classical setups such as confocal microscope. Several types of absorbers have been analyzed. For instance, we can investigate spatial fluctuations of the Quasi Fermi Levels splitting in CIGS polycrystalline absorbers and link those fluctuations to transport properties. The method is general to the point that third generation PV cells absorbers can also be evaluated. We illustrate the great potential of our setup by imaging carrier temperature in Hot Carriers Solar cells absorbers and quasi Fermi levels splitting in Intermediate Band Solar cells.

INTRODUCTION

Photoluminescence (PL) and electroluminescence (EL) spectra allow the determination of important optoelectronic parameters of solar cells, such as the open circuit voltage from PL [1] or the external quantum efficiency (EQE) from EL [2]. To get an accurate measurement of those parameters and thus a correct understanding, experimental conditions have to be properly set. We propose here to use a hyperspectral imager that can record spectrally resolved images. The absolute calibration of the photons flux and the wide field illumination allows to image several physical parameters of PV cell absorbers in realistic cell operation conditions.

To perform such an analysis, we will take advantage of the luminescence emission of the sample. This one can be described by the generalized Planck's law [3]:

$$\Phi(\hbar\omega, r) = A(\hbar\omega, r) \frac{1}{4\pi^2 \hbar^3 c_0^2} (\hbar\omega)^2 \frac{1}{\exp\left(\frac{\hbar\omega - \Delta\mu_{\text{eff}}}{kT}\right) - 1} \quad (1)$$

Φ is the luminescence emission, $\hbar\omega$ the photon energy, A the absorption, \hbar the reduced Planck's constant, c_0 the speed of light in vacuum, $\Delta\mu_{\text{eff}}$ the effective quasi-Fermi level splitting (averaged over the absorber's thickness) and T the temperature. Several parameters are thus accessible using this relation. Access to $\Delta\mu_{\text{eff}}$ is certainly the most unique point since, in some cases this quantity could be identified with the voltage across the cell [1-3]. Therefore, this is an electrical quantity contained in an optical signal.

We will first present the Hyperspectral imager and compare it to confocal microscope, the latter being the most common setup used to record spectrally resolved images. Then, we will present results on various absorbers ranging from thin films PV devices to third generation solar cells. A GaAs cell is first investigated, showing a good agreement between $\Delta\mu_{\text{eff}}$ and the V_{oc} , allowing us to map a $I_{\text{sc}}(V_{\text{oc}})$ characteristic. An inhomogeneous material such as CIGS is also investigated in a wide field detection and excitation. Lateral fluctuations are discussed in terms of spatial variations of transport properties. Applications are also found in third generation PV cells, where carrier temperature in Hot Carriers Solar cells absorbers and chemical potentials of photons in Intermediate Band Solar cells could be imaged. Even on homogenous materials, we will also see that inhomogeneous excitation combined with wide field detection appears to be a powerful technique.

EXPERIMENT

A. Experimental setup description

The experimental setup is based on a Hyperspectral imager (HI) from Photon etc. combined with a classical microscope. For PL measurement a wide field laser excitation at 532nm is done through a microscope objective. For EL measurement, we apply an electrical voltage to the PV device. The luminescence image is collected with the same objective and is then spectrally resolved by the HI. Acquisition is made with either a silicon or an InGaAs based CCD camera with a spatial resolution of about 1 and 2 μm respectively. The spectral resolution of this setup is 2 nm.

Besides a convenient calibration method [2], the HI setup presents several differences when compared to confocal microscope setups. Indeed, confocal microscope setups probe the luminescence from a confocal volume, and scan the sample surface to produce a map. In our case the acquisition time is therefore strongly reduced when using a HI. For example, a 150x150 μm^2 map would take hundreds of hours with a confocal setup, but only 8 minutes with a hyperspectral imager.

The main difference arises when looking at the depth probed. The confocal system can be limited by $2*n*\lambda/NA^2$ (n is the optical index at the focal point), so in the range of a few microns for n around 3. In the HI system, the only limitation of the depth probed is linked to the material absorption coefficient. Therefore, for samples rough enough so that the depth probed in a confocal microscope is comparable to roughness, the HI system could give more reliable results.

Finally, the most important point is related to the illumination condition. In confocal microscope setups both excitation and collection are made at one localised point with the consequence that the cell area surrounding this point is in the dark, but electrically connected with the illuminated part. It results in lateral carriers transport to the dark regions, where they recombine without

being collected. All these differences tend to show why the absolute calibration is difficult in confocal system. No absolute luminescence mapping has been done yet, especially when the spatial resolution goes down to the micrometer scale.

B. Proof of concept - validity

To check the validity of our method we have measured the $\Delta\mu_{\text{eff}}$ on a homogenous GaAs solar cell at several excitation power j_{gen} [1]. The $I_{\text{sc}}(V_{\text{oc}})$ curve electrically measured is compared to a $j_{\text{gen}}(\Delta\mu_{\text{eff}}/q)$. A good agreement is found as illustrated in Fig. 1. Using the reciprocity relations that exists between an LED and a solar cell, the External Quantum Efficiency map can be obtained from EL spectrum [2].

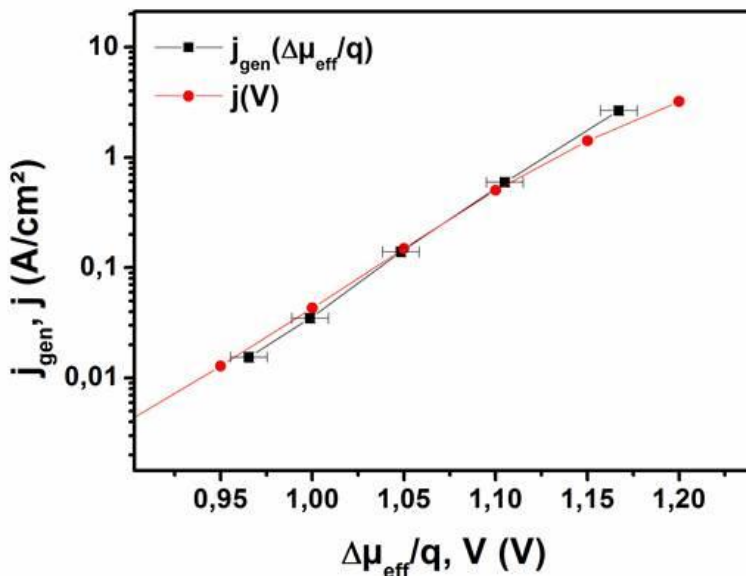


Fig. 1: Optical measurement of $j_{\text{gen}}(\Delta\mu_{\text{eff}}/q)$ compared to $I_{\text{sc}}(V_{\text{oc}})$ on GaAs solar cells.

RESULTS AND DISCUSSION

A. Inhomogeneous absorbers

The principle of the method being validated, we now investigate more complex PV cells absorbers, such as CIGS that present spatial fluctuations at the μm scale influencing the global device parameters and making it difficult to correctly evaluate the material quality. For illustration purposes, we image the spatial fluctuations of $\Delta\mu_{\text{eff}}$ from PL measurement (Fig. 2) on a CIGS microcell [4] by inverting equation (1) in a spectral region where $A \approx 1$ (high energy end of the spectra), so that it is relatively insensitive to composition fluctuations. Band gap fluctuations are also accessible from the low energy part of the spectra collected, and with an excellent spectral resolution (2nm), but appear mostly uncorrelated to $\Delta\mu_{\text{eff}}$ fluctuations. The spectral resolution could also be used, at low temperature, to identify the spectroscopic signature of the defects.

In this case also the average value (808 mV) matches very well the measured V_{oc} in the same conditions (801 mV). Local $\Delta\mu_{eff}$ fluctuations are about 15 meV (FWHM). The fluctuations appear therefore linked to transport parameters fluctuations as discussed below.

This confirms the equality between $\Delta\mu_{eff}$ and V_{oc} *on average*. The measured fluctuations are smaller than those seen using a confocal measurement on the same sample. Those fluctuations cannot be linked to local voltage fluctuations since those variations would induce a lateral current higher than the total current of the cell. Therefore, further analyses [6] showed that those fluctuations are linked to in depth transport properties variations rather than the local open circuit voltage. Moreover, a comparison with the Quasi Fermi level splitting obtained from EL allows discriminating between different failure causes.

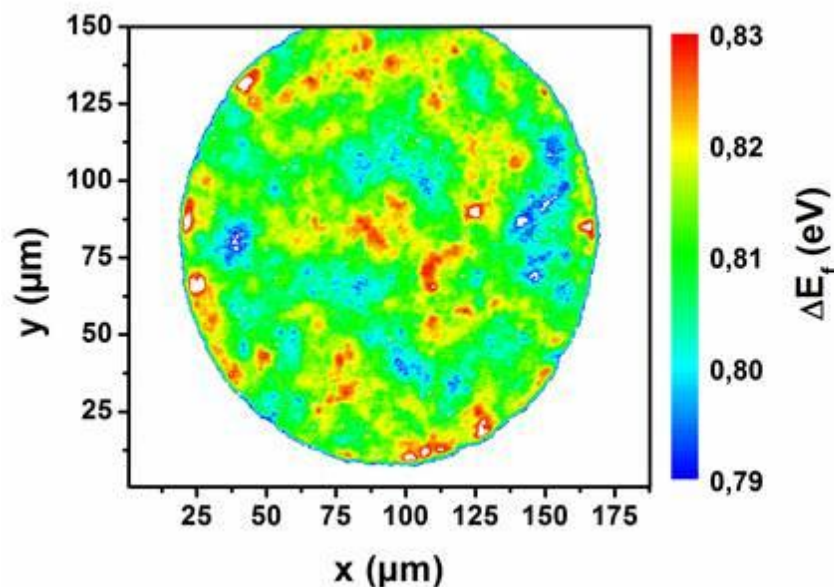


Fig. 2: Map of $\Delta\mu_{eff}$ on CIGS μ -cell measured from PL. The active region of the μ -cell is the disk in the middle and the white background is the surrounding contact.

The comparison of the EL and PL spectra are done in a correlation map [6] therefore exacerbating the variations of local properties. When PL and EL signals are correlated, the signal strength is not dependent on (long range) carrier transport and therefore the signal reflects essentially the local material (or stack) properties. When the EL and PL signals are both high (correlation 1, experimentally observed), this is a high quality area with both good transport and lifetime properties. When both signals are small (correlation 2, experimentally observed), it is a low performing area, where at least lifetime is poor. When PL and EL signals are anti-correlated, the difference in signal strength is dependent on carrier injection and transport and not to local material properties such as band gap or lifetime that would change both EL and PL in a correlated way. When the PL signal is high, but EL signal is low (anti-correlation 1, experimentally observed) we have a defective area, most likely affected by local series resistance (poor front or back contact) or hindrance in carrier injection (low mobility), while the lifetime can be high, and can be estimated from the intensity of the PL response. The case when the EL signal is high, but PL signal is low (anti-correlation 2), is not experimentally observed.

Evolution of the quasi Fermi levels splitting within the IBSC as a function of wavelength

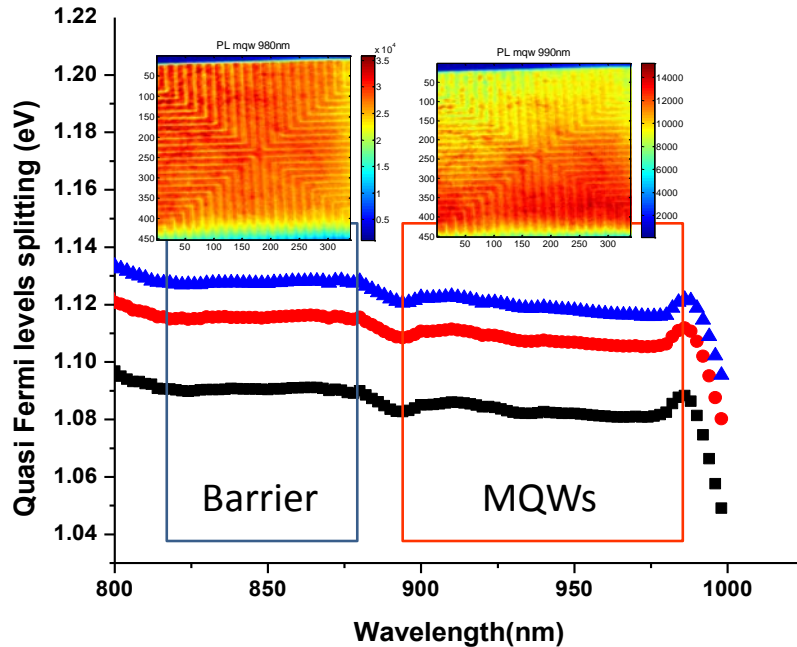


Fig. 3: Quasi Fermi level splitting as a function of the wavelength for the Barrier (850nm region) and the Multi Quantum Wells (MQWs) (950 nm region) for 3 excitation powers. The corresponding images of the PL intensity of the full 5x5 mm² cell are displayed in the insets. The $\Delta\mu_{eff}$ have been extracted at the center of the cells.

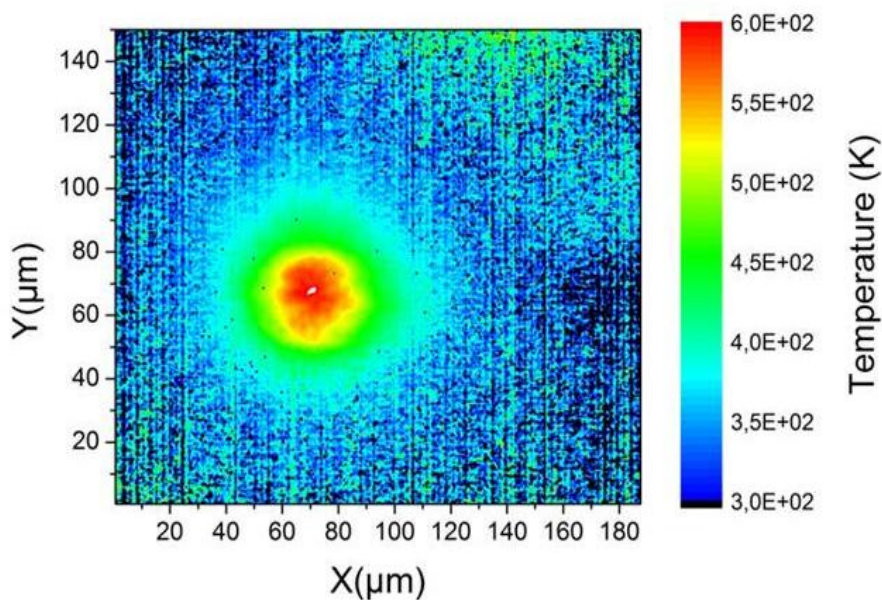


Fig. 4: Spatial variations of carrier temperatures on Multi Quantum wells InGaAs/InP lattice matched sample. Here the excitation is focused onto the sample surface (spot <10 μm) while keeping a wide field detection.

We also present an investigation of InGaAs/GaAsP strain compensated Multi Quantum Wells structure (fig. 3) in order to measure the QFLs in the barrier and in the quantum well QW region. Access to these values is a major step towards the evidence of Intermediate band effect. As it is

seen in Fig 3 a difference of less than 15mev is found between the $\Delta\mu_{\text{eff}}$ of the barrier and the QW. This value is not sufficient for proper intermediate band solar cells operation [7]. We also observed spatial inhomogeneities in the PL emission from the QW (not from the barrier) attributed to a thickness variations of the wells. This experiment is also an illustration of a characterization made on a field of view of 5x5 mm².

B. Inhomogeneous excitation

Hyperspectral imaging presents a strong interest when investigating inhomogeneous solar cells but another advantage is found when looking at homogeneous absorbers with an inhomogeneous excitation. To illustrate this affirmation we have excited an InGaAs/InP lattice matched Multi Quantum Wells absorber suitable for Hot Carriers Solar Cells with a focused laser beam. From the spectrally resolved images we could map the carrier temperature at each spatial location (see Fig. 4) [5]. This measurement is used to evaluate the carriers' diffusion and therefore have a better understanding of the lateral transport properties. Image of the Quasi Fermi level splitting was also recorded [5].

CONCLUSIONS

Spectrally resolved luminescence images have been recorded using a hyperspectral imager. An absolute calibration of the emitted photons flux allows us to record in absolute value several cell parameters using the generalized Planck's law such as the temperature or the quasi Fermi levels splitting. The mapping of the latter parameter is unique to the method presented. The wide field excitation gives a fast acquisition time that could be suitable for in-line characterization. Several excitation and detection conditions are possible. Applications are found in a wide range of PV absorbers, from the thin films to the third generation concepts.

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