Characterization of Polymer Solar Cells and Modules by Luminescence Imaging

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Application Note

Introduction

Due to their advantages in terms of low production costs and high-throughput processing by use of printing techniques, polymer solar cells are a promising technology for the thin-film photovoltaics. The most studied and best developed material system for such cells consists of a semiconducting polymer:fullerene composite that is sandwiched between a metallic and a transparent electrode [1]. During the last few years, considerably higher power conversion efficiencies, recently exceeding 9%, have been achieved [2]. However, the lifetime and stability of those devices still plays a key role for obtaining wider acceptance on the market. Polymer solar cells are generally very frail to processes involving reactions with the ambient. Specifically, reactions of the organic and metallic components with water and oxygen result in device degradation and reduced stability. To prevent polymer solar cells from degradation, hermetical sealing as well as intrinsically more stable materials are required. Furthermore, printing techniques are prone to processing deficiencies with various natures, inducing defects during film deposition and local malfunctions which may cause the failure of the entire cell or module. For observation of device degradation and testing the performance of the sealing but also for quality control during the processing of polymer solar cells, fast, versatile and non-destructive characterization methods are highly demanded.

In this application note, we report about the laterally resolved detection of luminescence emitted from the solar cell by using a CCD camera. This investigation method called 'luminescence imaging' meets the above mentioned requirements for characterization of polymer solar cells very well if a suitable detector with certain specifications is chosen. Luminescence spectroscopy revealed for many material combinations that photoluminescence emitted from the organic semiconductor is in the visible part of the optical spectrum, whereas electroluminescence is emitted in the near infrared. Furthermore, due to photoluminescence quenching by efficient charge transfer after optical excitation as well as low electroluminescence efficiencies, the overall luminescence intensities are rather low. Therefore, the camera must have a high sensitivity in the range of 600 to 1100 nm and only little thermal noise. The Andor iKon-M DU934N-BR-DD camera features these specifications while having a proper resolution of 1024 x 1024 pixels.

Experimental Setup

A schematic of the luminescence imaging setup is shown in Figure 1. The polymer solar cells are mounted in a chuck with electrical contacts and placed underneath the CCD camera. For electroluminescence imaging (ELI) a constant current at positive driving voltage is applied to the solar cell under test, leading to radiative recombination within the organic active layer. For photoluminescence images (PLI) the organic semiconductor is optically excited and the subsequent radiative decay of photogenerated excitons is detected. To block the excitation light a cut-off filter is placed in front of the CCD camera. As the overall luminescence intensities are very low, the whole setup is placed in a light blocking housing. The camera takes images of the photons emitted by the organic semiconductor with typical exposure times of several seconds.

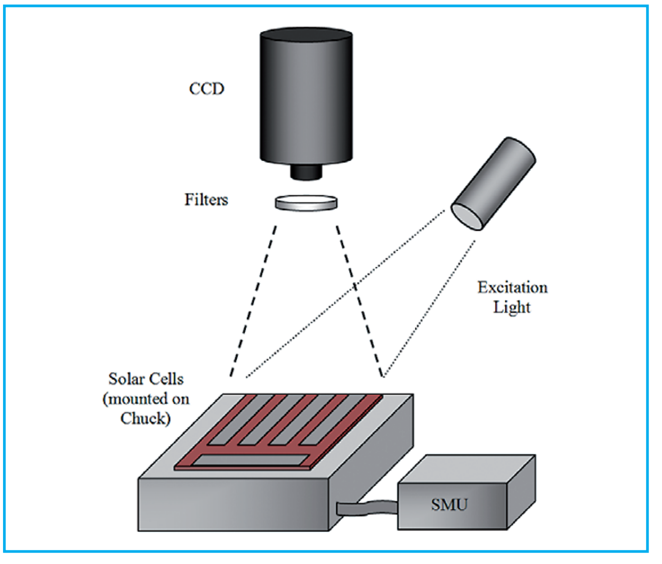

Fig. 1: Schematic of the luminescence imaging setup. For electroluminescence, charge carriers are injected into the semiconductor by using a chuck with electrical contacts, whereas for photoluminescence measurements the device is optically excited and optical filters are used to block the excitation light.

For stability and degradation investigations, unsealed photovoltaic devices were systematically aged in a home-built stability setup enabling periodic in-situ current-voltage characterization. The stability setup consists of a high power illumination source under which up to 40 solar cells can be exposed to approximately 100 mW/cm² illumination intensity. The solar cells are electrically connected to a computer controlled source-measure-unit and periodic IV-characterizations are sequentially performed on each solar cell by multiplexing.

Results

Control of Processing by Luminescence Imaging

The detection of luminescence emitted from the organic semiconductor allows identification of processing deficiencies especially in the active layer and the cathode. EL and PL images of a 2" x 2" polymer solar module [3] are shown in Figure 2. Caused by handling and the spin coating process on a relatively large module area of 25.8 cm², various defects of different nature can be observed within both excitation modes [4]. The highlighted defects in Figure 2 include holes in the cathode as introduced by scratching (red ellipses) and handling induced defects (blue rectangles). Furthermore undissolved material and dust particles are observed (orange pentagons), which lead to defects during film formation and inhomogeneities in the active layer thickness.

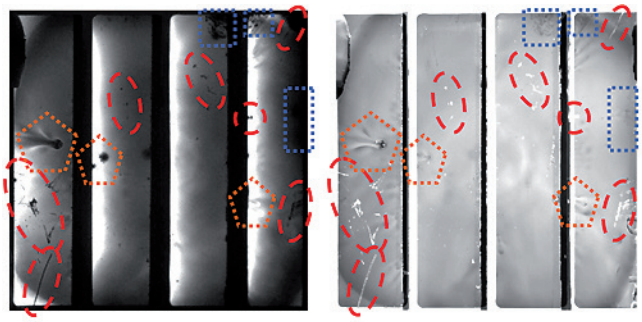

Fig. 2: EL (left) and PL (right) images of a 2" x 2" polymer solar module. Various defects, such as holes in the cathodes (red ellipses), handling problems (blue rectangles), undissolved materials and dust particles (orange pentagons) have been identified by luminescence imaging.

Visualization of Progressing Degradation

Besides detection of processing deficiencies luminescence imaging is well suited for revealing defects occurring under aging of the photovoltaic devices [5]. The non-invasive nature of this investigation method furthermore allows time-resolved characterization of one and the same device stressed under continuous aging. The inhomogeneous degradation patterns of an unsealed polymer solar cell kept for one week under constant irradiation of 100 mW/cm² in ambient conditions are shown in Figure 3. Dark spots nucleated and grew with time, yielding a pinhole induced oxidation of the cathode followed by delamination from the active layer. Photochemical degradation of the active layer is observed by PLI at the sites locally corresponding to the cathode delamination. The combination of these two methods – ELI focussing on injection and thus the electrode-organic interfaces and PLI revealing the integrity of the organic semiconductor – allows discrimination between active layer photodegradation and corrosion as well as delamination of the electrodes.

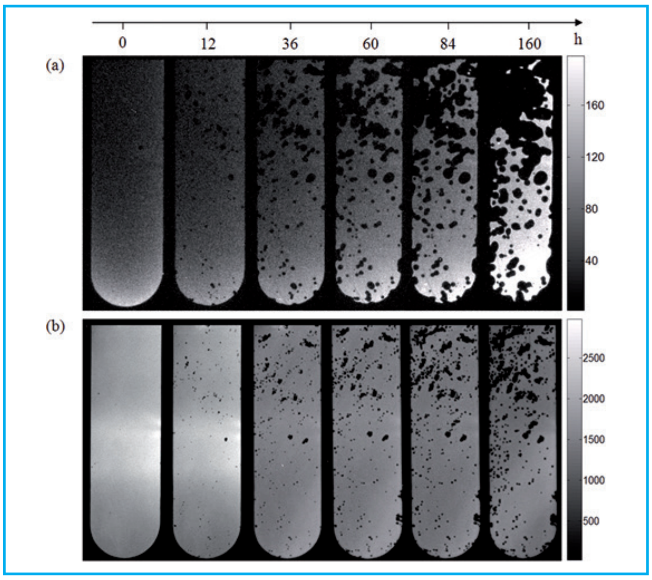

Fig. 3: ELI (a) and PLI (b) photographs of an unsealed polymer solar cell within 1 week of ambient storage under 100 mW/cm² illumination.

Quantitative Interpretation of Electroluminescence Profiles

Apart from pinhole induced degradation, the electroluminescence emission patterns of polymer solar cells are highly inhomogeneous. From Figure 3 (a) it can be observed that the electroluminescence intensity is decreasing over the length of the device (in Figure 3: from bottom to top). This is attributed to the thin-film solar cell geometry employing a transparent electrode with limited conductivity, which results in decay of the electric potential applied to the active layer. As a result, the local voltage is a function of the longitudinal position on the device with respect to the current transport direction along the solar cell length. For quantitative description of the resulting lateral electroluminescence signal a model was developed in which local diodes are interconnected by resistors representing the sheet-resistance of the transparent electrode [4]. In Figure 4, experimental and calculated current profiles along the length of the solar cell are shown together with the evaluated voltage profile applied to the active layer. The developed model allows precise description of the current and voltage distribution and allows extraction e.g. of the sheet-resistance of the transparent electrode.

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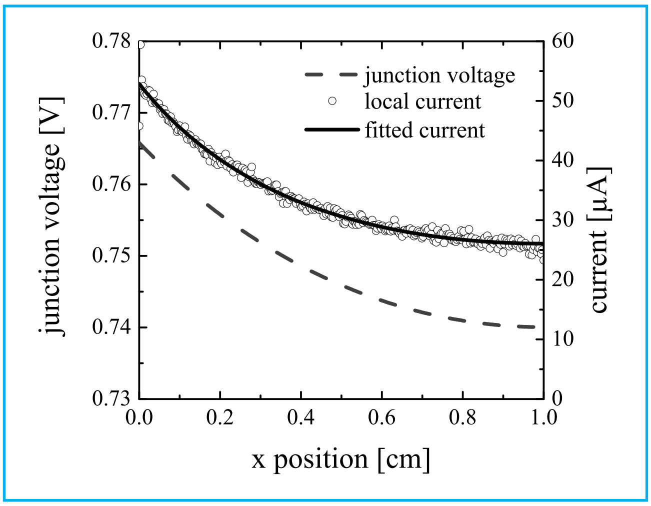

Fig. 4: The local current profile along the length of the solar cell (empty dots) can be calculated from ELI measurements. Fitting this current profile allows calculation of the voltage profile and extraction of the sheet-resistance of the transparent electrode.

Characterization of Silicon Solar Cells

Using appropriate optics and quantitative methods also allows characterization of silicon solar cells with respect to the distribution of minority charge carrier diffusion length [6] or local saturation current j_0 and quasi-external series resistance R_s [7]. In Figure 5, images displaying the distribution of j_0 and R_s as evaluated from two ELI measurements on a polycrystalline silicon solar cell are shown.

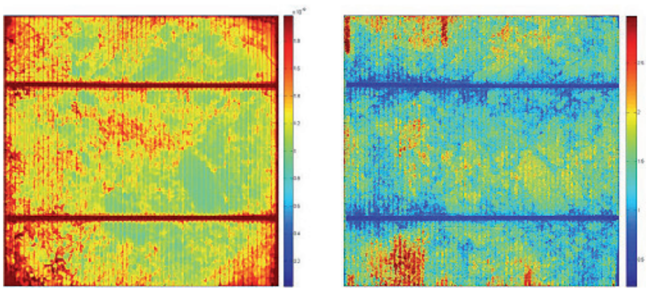

Fig. 5: j_0 image (left) and R_s image (right) evaluated from two ELI measurements of a polycrystalline silicon solar cell. The maximum values on the scales are 2 x 10^{-12} A/cm² and 3 Ω/cm², respectively.

Conclusion

Using the Andor iKon-M DU934N-BR-DD camera for luminescence imaging measurements yields versatile applications in solar cell characterization. The high sensitivity of this camera allows short exposure times of several seconds coupled with sufficiently good signal-to-noise ratio and image quality. The deep-depletion technology of the detector enables efficient measurement of the near infrared electroluminescence emitted from polymer solar cells as well as conventional silicon solar cells. In addition to the easy to realize experimental setup, the applications of the luminescence imaging method are various: ranging from processing and material control of polymer as well as silicon solar cells to studying degradation processes and evaluation of physical parameters by the use of appropriate quantitative models.

References

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