

Shunt detection and characterization with fluorescent microthermal imaging

E.S. Marstein¹, Ø. Haugen², A.G. Ulyashin², V. Yurchenko², I.O. Omolo¹, T.H. Johansen² and A. Holt¹

¹Section for Renewable Energy, Institute for Energy Technology, Kjeller, NORWAY

²Department of Physics, University of Oslo, Oslo, NORWAY

ABSTRACT

Defects originating from the solar cell substrate material or created during the solar cell production process can act as parasitic resistances. These defects reduce the performance of solar cells and can in extreme cases cause serious reliability problems in finished solar modules. Some defects will generate heat locally when a bias voltage is applied to the solar cells. Thermal imaging techniques can therefore be used to obtain information about the location, and hence the origin, of such defects. In this work, fluorescent microthermal imaging (FMI) is used to characterize shunted crystalline silicon solar cells. After an introduction to the technique, the suitability of FMI for solar cell diagnostics is demonstrated.

INTRODUCTION

Shunts in solar cells are defect-related, low-resistance connections that form alternative paths for a portion of the electrical current. Severe shunts are detrimental to the performance of solar cells, and can cause serious reliability problems in finished solar modules. A range of different defect mechanisms, either related to the material quality of the solar cell substrate or to the solar cell production process, can cause shunting [1].

Electrical measurements, in particular current–voltage (I-V) measurements, are commonly employed in order to determine whether a solar cell is excessively shunted. However, such measurements give little or no information about the origin of the shunts, only the resulting total shunt resistance of the solar cell (R_{sh}). Information about the origin of shunts is invaluable process feedback to the solar cell producers and suppliers of solar cell substrate materials.

Shunts will generate heat locally when a bias voltage is applied to the solar cells. Thermal imaging techniques can therefore be used to obtain information about their location. Several techniques for localizing and characterizing shunts based on thermal imaging have been developed in recent years, including various forms of lock-in infrared (IR) thermography [2,3] and liquid crystal sheet thermography [4]. In this paper, the usefulness of fluorescent microthermal imaging (FMI) as a tool for solar cell diagnostics is investigated. This technique is well known from electronic failure analysis, but its use as a tool for solar cell characterization has, to the best of the authors' knowledge, previously not been reported in the literature [5-7].

We have applied FMI to various defected crystalline silicon (Si) solar cells. After a brief description of the FMI

technique itself, the experimental setup used in this work is described. Thereafter, the suitability of FMI for solar cell defect characterization is demonstrated.

FLUORESCENT MICROTHERMAL IMAGING

FMI utilizes the known temperature dependence of the photoluminescence (PL) intensity of a luminescent thin film. The employed thin film is commonly a polymer, which has been doped with a rare earth element-based luminescent species. By imaging the PL with a CCD-camera, spatial information about absolute temperature variations across a sample is obtained. Local information about the temporal evolution of the sample temperature can readily be acquired by capturing a set of PL images.

The basic experimental setup required for performing FMI is relatively simple. It consists of an excitation source for the PL, magnifying optics and a CCD-camera. For shunt detection, a voltage source for applying a bias voltage to the solar cell is also required. In combination with an optical microscope, FMI can exhibit high spatial resolution. The spatial resolution of experimental setups has previously been shown to be diffraction-limited, and can approach $0.3 \mu\text{m}$ [5,7]. FMI can thus be used for giving very precise information about the location of solar cell defects.

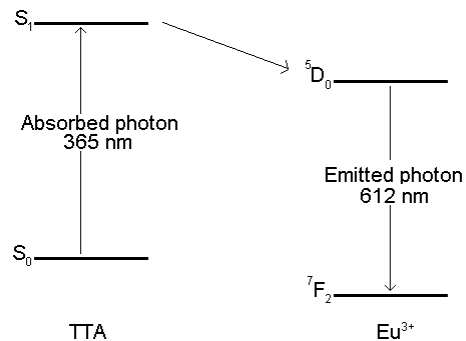


Fig. 1. The figure shows a diagrammatic representation of the energy levels involved in the PL process. First, UV-light is absorbed by the TTA ligand. The energetic electron is transferred to the Eu^{3+} ion, where a subsequent transition to the ground state results in a temperature dependent PL emission at 612 nm.

The luminescent species, which is used to dope the polymer, is often a complex of the rare earth ion europium

(Eu³⁺) and an organic ligand called thenoyltrifluoroacetone (TTA). This complex, Eu(TTA)₃, is encapsulated in a polymer and coated onto the samples, for example by dripping or spinning.

An energy level diagram of the PL process is shown above (Fig. 1). The PL of the Eu(TTA)₃-complexes is excited using UV photons. The energetic photons excite the electrons in the TTA from the ground state (S₀) to an excited state (S₁). The energy is subsequently transferred from the TTA to an excited 4f electronic energy level in the Eu³⁺ ions. While several transitions are excited, the one from the excited state (⁵D₀) to the ground state (⁷F₂) is the most efficient. This specific transition contains most of the PL emission energy, and is characterized by a strong PL signal consisting of narrow and well-defined peak at 612 nm. FMI utilizes the fact that the intensity of this peak in the PL spectrum exhibits a well known exponential decrease with temperature. In the range from 5 to 90 °C, the PL intensity falls off with 4 % per °C. It has previously been demonstrated that, because of the well defined PL temperature dependence, the thermal resolution of FMI using Eu(TTA)₃-complexes is actually limited by shot noise in the CCD-camera, and can approach 6 mK [6].

EXPERIMENTAL

The fluorescent microthermal imaging setup

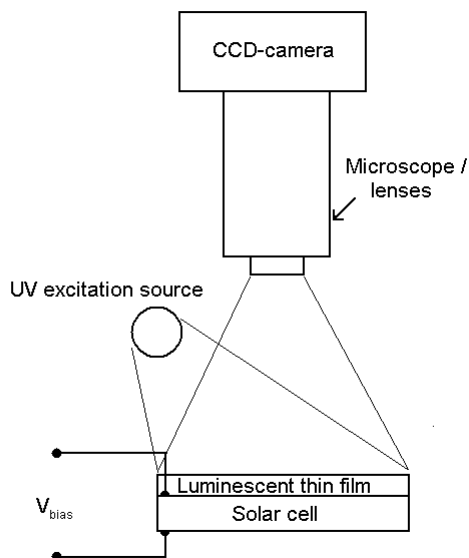


Fig. 2. The figure shows a schematic depiction of the FMI setup used in this work.

A schematic depiction of the FMI setup used in this work is shown above (Fig. 2). In our setup, a UV source emitting at 365 nm (Hamamatsu LC 6) is used to excite the PL in the luminescent thin film. A 1360 x 1036 pixel CCD-camera (Retiga EXi from Q Imaging) is used to record the variation in the PL intensity. A simple power supply (Mascot Type 8937) is used to apply a reverse bias during the FMI measurements. For high-resolution

imaging, the CCD-camera is mounted on an optical microscope (Leica).

A thermal image is obtained in the following manner. First, the UV excitation source is turned on and the PL is allowed to stabilize, typically for approximately 3 minutes. Thereafter, an initial “cold” image is recorded without the application of any external bias. At a given time ($t = 0$), a suitable bias is applied, and one or a series of “hot” images recorded. Digital division of the “hot” image with the “cold” image results in the removal of all optical contrast, leaving a purely thermal image [5].

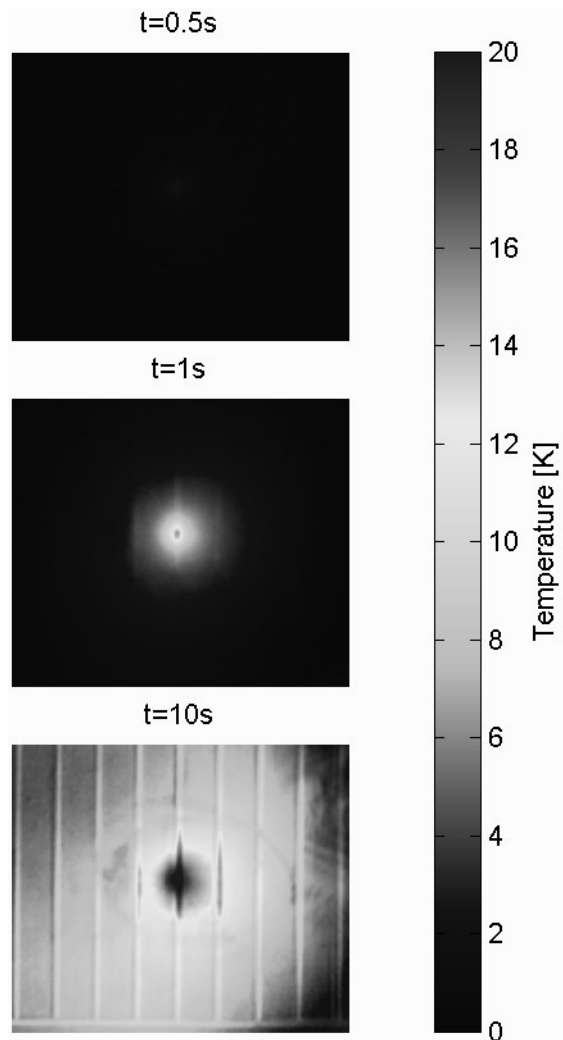


Fig. 3. The figure shows FMI images of a solar cell after the application of a reverse bias of 5 V. The images show the temporal evolution of the temperature at a hotspot. Upon application of the bias voltage ($t = 1$ s), heat evolves at a hot spot and, with time, dissipates throughout the solar cell ($t = 10$ s).

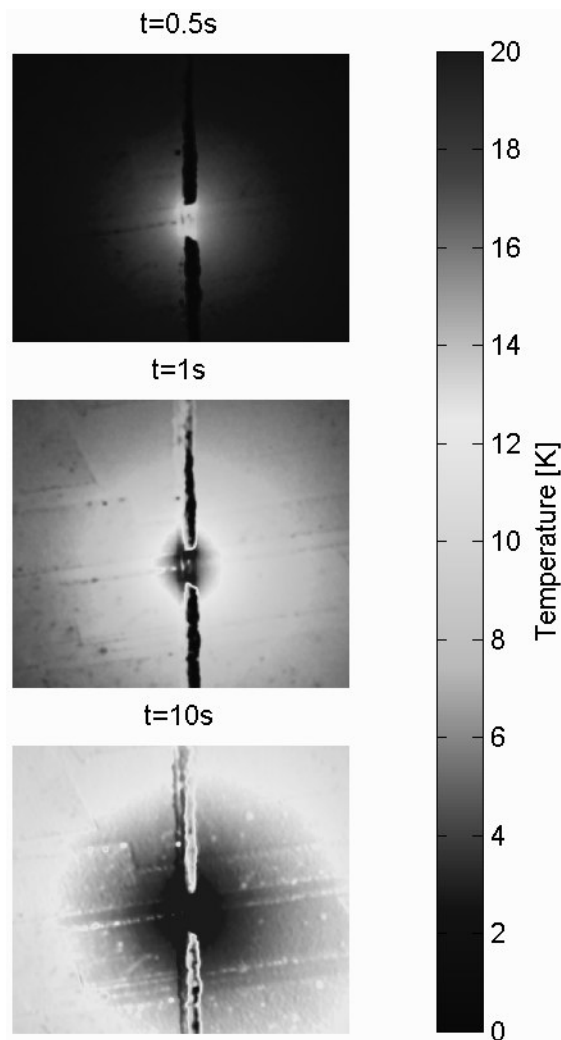


Fig. 4. The figure shows high-resolution FMI images of the same solar cell as previously shown (Fig. 3). Immediately upon application of a reverse bias of 5 V ($t = 0.5$ s), heat is generated at a defect in a finger contact and dissipates into the surrounding parts of the solar cell ($t = 10$ s).

Sample preparation

In this work, thin films of the polymer polymethylmethacrylate (PMMA), which were doped with $\text{Eu}(\text{TTA})_3$ -complexes were used. The sample solar cells were drip-coated in a solution of this doped polymer in acetone. The coated samples were subsequently dried in an oven at 125°C for 30 min before FMI measurements.

The sample solar cells investigated in this work were conventional screen-printed multicrystalline silicon (mc-Si) solar cells with an alkaline pyramid texture, a phosphorous emitter diffused from a spray-on source, an aluminum back surface field and silver electrodes. Some of these cells were accidentally shunted during solar cell processing, while others were intentionally shunted. The intentional shunting was introduced by over-firing the contacts. The solar cells characterized with FMI were selected based on their R_{sh} , which was measured using

conventional I-V measurements. In some cases, thermochromic liquid crystal sheets were used for a preliminary localization of hotspots.

RESULTS

A solar cell that was subjected to over-firing was investigated. After letting the system become thermally stable under UV illumination, a reverse bias of 5 V was applied to the solar cell. A set of “cold” and “hot” PL intensity maps were simultaneously recorded using the CCD-camera (Fig. 3). Immediately after the application of the reverse bias ($t = 0.5$ s), heat generation at a local hotspot is observed. As the time under applied bias increased, the temperature at the defect increased significantly and dissipated throughout the solar cell. Although not clear at this resolution, the location of the hotspot is determined to be at or close to one of the finger contacts.

In order to obtain a more exact determination of the location of the hotspot, the solar cell was put under a microscope on which the CCD-camera was subsequently mounted. Thereafter, the solar cell was subjected to the same FMI measurement procedure as above. “Cold” and “hot” PL intensity maps were once again captured (Fig. 4).

These images, still recorded with the microscope set only at a relatively low magnification, clearly indicate that the heat is generated at or directly beneath a finger contact. The heat is detectable immediately upon application of the reverse bias, and the excess temperature at the hotspot increases towards 20°C after only 10 s.

Comparing the high-resolution thermal images (Fig. 4) with optical images taken with the CCD-camera at the exact same location on the sample reveals that the heat in this case emerges from a small, visible defect on the finger contact (Fig. 5).

DISCUSSION

Our first investigations demonstrate that FMI can be a powerful technique for solar cell defect characterization. A precise localization of defects can be obtained with relatively little sample preparation using a relatively flexible experimental setup. Both absolute temperature maps, as well as information about the temporal evolution of the heating can be obtained. It is straightforward to switch from low-resolution imaging of entire, or large parts of, solar cells to high-resolution imaging under an optical microscope.

The FMI technique, at least in the form described above, is mostly restricted to being a laboratory technique. The fact that the samples have to be coated in a luminescent thin film, which subsequently must be subjected to a certain heat treatment, imposes practical restrictions on the number of samples that can be characterized, and also reduces its usefulness in the case of extremely temperature sensitive solar cells.



Fig. 5. The figure shows an image taken with the CCD-camera image of the hotspot described above (Fig. 4). The heat evolves at the precise location of a weak spot in the finger contact.

An additional challenge is met when coating non-polished, large area samples with the luminescent thin film. In early measurements (not shown), the coating was uneven, and in some spots even absent. However, such defects are readily recognized during FMI measurements, since they appear as spots in which no temperature change occurs. The surfaces of most mc-Si solar cells are textured, and the application of an even coating is not straightforward, either with dripping or spinning. Further work will have to address this issue.

CONCLUSION

In this work, we show that FMI is a suitable technique for solar cell defect characterization by applying the technique to shunted mc-Si solar cells. Very precise information about the localization of the defects, as well as about the absolute temperature changes, can be readily obtained. Work is currently underway in applying FMI for further analysis of a number of different solar cells, and for determining the practical limits of this technique.

REFERENCES

- [1] O. Breitenstein et al., "Shunt types in multicrystalline solar cells", *Proceedings 3rd World Conference on Photovoltaic Energy Conversion*, 2004, pp. 987-990.
- [2] O. Breitenstein et al., "Microscopic lock-in thermography investigation of leakage sites in integrated circuits", *Rev. Sci. Instrum.* **71**, 2000, pp. 4155-4160.
- [3] J. Isenberg and W. Warta, "Realistic evaluation of power losses in solar cells by using thermographic methods", *J. Appl. Phys.* **95**, 2004, pp. 5200-5209.
- [4] J. Schmidt, and I. Dierking, "Localization and Imaging of Local Shunts in Solar Cells Using Polymer-dispersed Liquid Crystals", *Prog. Photovolt: Res. Appl.* **9**, 2001, pp. 263-271.

[5] P. Kolodner and J.A. Tyson, "Remote thermal imaging with 0.7- μm spatial resolution using temperature-dependent fluorescent thin films", *Appl. Phys. Lett.* **42**, 1983, pp. 117-119.

[6] P. Kolodner and J.A. Tyson, "Microscopic fluorescent imaging of surface temperature profiles with 0.01 $^{\circ}\text{C}$ resolution", *Appl. Phys. Lett.* **40**, 1982, pp. 782-784.

[7] J-Y. Glacet and S. Berne, "A practical system for hot spot detection using fluorescent microthermal imaging", *Microelectron. Reliab.* **36**, 1996, pp. 1811-1814.