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A variety of microstructural defects in crystalline silicon solar cells

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ABSTRACT

The performance and lifetime of solar cells critically depends on bulk and surface defects. To improve performance of solar cells, localization and characterization of defects on the microscale is an important issue. This paper describes a variety of microstructural defects in crystalline silicon solar cells which appear during the cell processing steps. The set of defects have been investigated and localized using visible light emission under reversed bias voltage. A light beam induced photocurrent method allows localization of defects having impact on the sample current–voltage plot and reversed bias light emission characteristics. These are shown together with the micrographs of defective surface areas. As a result, particular defects which induce nonlinearity and local breakdown in the current–voltage plot were identified in tested solar cell structures. Furthermore, measurements at various temperatures allows to identify the breakdown mechanism of the investigated defects. An interesting result of the investigation is that the majority of defects are associated with surface inhomogeneities, but not all surface inhomogeneities act as defects.

1. Introduction

Monocrystalline and polycrystalline silicon cells represent so far the most wide-spread type of solar cells. Although the technological process is well known and improved for many years, various defects in currently fabricated solar cells still persist [1,2]. These imperfections may reduce the performance and efficiency of solar cell under particular operation conditions (mainly breakdown in the reversed bias regime). Many of these imperfections can be eliminated e.g. by laser processing used for edge isolation [3]. The elimination of the defects leads to improvement of cell performance by reducing the number of recombination centers. There are various types of defects with different levels of importance for solar cell parameters [4]. For instance, they can act as a shunt or junction imperfection. In some defects a metal contamination can also be identified [5].

The most frequent methods for the characterization of silicon solar cells are electrical ones [6]. Since a solar cell is a large area semiconductor diode, an electric field is built in to its p–n junction, which leads to the separation of charge carriers. Thus, by measuring *I*–*V* characteristics, it is possible to inspect a number of properties, such as leakage current, shunts, open circuit voltage and cell efficiency [4]. However electrical measurements mostly provide an integral investigation over the entire device area and detect averaged quantities [7–9].

Unfortunately, these methods do not allow to localize specific defects occurring in the structure. Local defects in the p–n junction are often associated with structural imperfections (such as grain boundaries, dislocations, and scratches), impurities, higher concentrations of donors and acceptors, or both [10].

To detect and localize defects in the cell, several macroscopic and microscopic mapping or non-mapping techniques are generally used.

The mapping techniques allow access to the areas of interest (usually the areas with high probability of defects). For material analysis, lifetime-mapping tools such as surface photo-voltage [11], or microwave photo-conductance decay [12] are frequently applied. Other methods, such as thermography [7], laser beam induced current [8], electroluminescence [9] and microscopy [13] show a map of spatial distribution of current over the cells' surface.

Non-mapping techniques generally give better insight into the nature of recombination centers [10].

Although the silicon does not produce visible radiation by common charge carrier recombination process, visible radiation can be produced by processes which involve hot carriers present during avalanche or Zener breakdown [14]. This phenomenon combined

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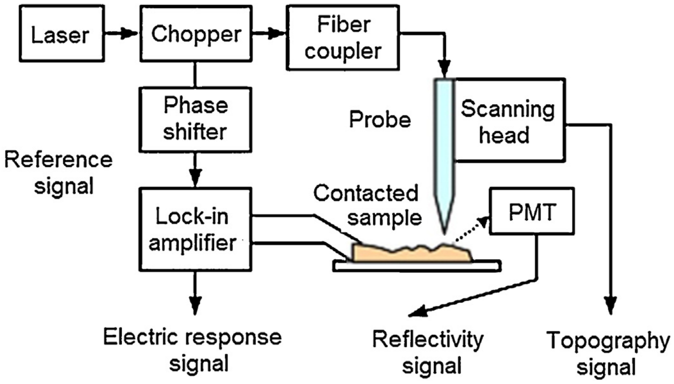

Fig. 1. Simultaneous detection of reverse-biased voltage, surface reflectivity and topography with apertureless SNOM.

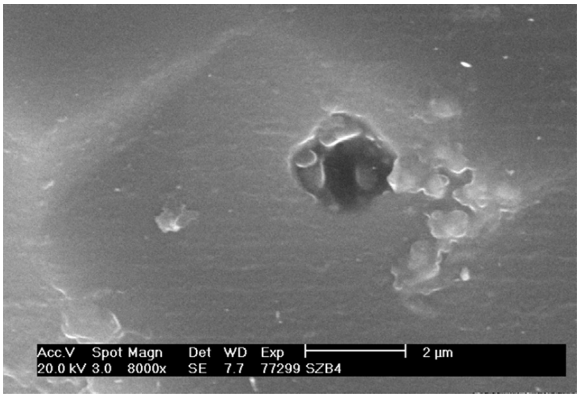

Fig. 3. Micrograph of a hole imperfection that emits light under reverse bias conditions $U_r = 3$ V, $T = 304$ K.

with SEM and scanning near-field optical microscope (SNOM) images can be used for the localization of a variety of defects.

It is therefore important to investigate various defects in more detail with these methods and catalogue the results.

2. Materials and methods

The monocrystalline silicon solar cells (10 × 10 cm), not yet installed in a solar panel, served as the samples. The solar cells were fabricated by standard diffusion technology [15,16] but for the most samples the anisotropic etching was skipped to obtain smoother surfaces for investigation. These solar cells were consecutively mounted on a measuring electrode, reverse-biased using a DC power source with a current limit set to 10 mA preventing sample destruction under breakdown conditions, and thermally stabilized in a thermostat. The maximum reverse bias voltage was limited by the maximum current density passing through the sample before its damage. Three temperatures ($T = 304$ K, 314 K, and 334 K) simulating cell operating temperatures have been selected, and thermal stabilization and electrical bias voltage were computer controlled.

The light emission from the reverse-biased monocrystalline silicon solar cell sample indicated the defective areas or areas with inhomogeneities. Since the solar cell contained a large amount of light emission centers, it was almost impossible to characterize their individual impact on the cell properties. Therefore solar cells were cut into small pieces (12 × 12 mm). The investigation was performed with more than 100 pieces cut from different cells (pieces with bus bar). A wire saw was used for the sectioning from the back side with respect to p–n junction and to avoid additional impurities, the cell was broken into pieces and rigorously cleaned. The interesting samples were only those containing one or two defects. The excessive current flowing through the defect was clearly identified on the samples with the same defect type.

Then a light emission from defects was collected by scanning optical probe and detected by cooled photomultiplier tube with peak sensitivity in the visible range. A photon counting method was applied for sensitive detection of the weak light emission. By sample scanning the whole sample surface was macroscopically inspected for the visible range light emission. This experimental setup allows to locate the position of each defect with micrometer even sub-micrometer precision [16].

Microscale localization of individual defects was performed under reversed bias conditions. For this purpose the apertureless scanning near-field optical microscope (SNOM) has been used [17] for high-resolution LBIC measurements. Our method allows simultaneously detecting an electrical signal, figure of surface reflectivity and sample topography (Fig. 1).

The modified detection method used was described in [15]. Its principle is explained in Fig. 2. A shadow map of a probe in the case of the point light emitter is an output of this measurement. When a cell sample is reverse-biased, light emitting spots in different sites appears. Considering that each spot emits light in all directions, only a fraction of the light is emitted in the direction of the PMT photocathode. If a probe tip is situated between the emitting spot and the PMT, the probe causes a shadow that influences the light intensity detected by the PMT. An image is created by scanning the probe over the sample, and detecting the scattered light intensity variations with probe movement. If the light intensity is measured at each step of the probe trajectory, the resulting image of the probe shadow provides an image of the defective area.

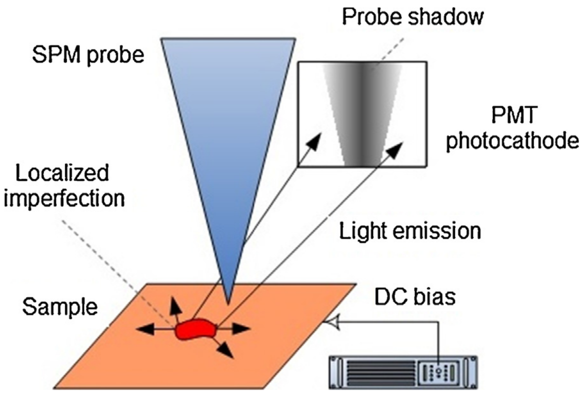

Fig. 2. Principle of microscale high sensitivity light emission measurement using SNOM [17].

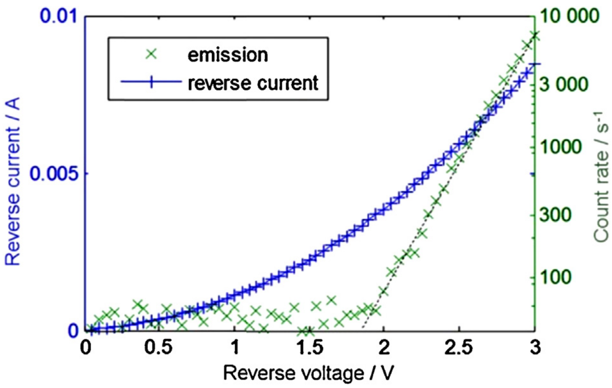

Fig. 4. Sample current and light emission from hole defect as a function of the reversed voltage, $T = 304$ K.

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