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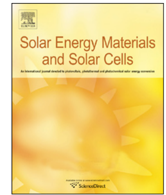

Monitoring of Si-solar cell degradation with electroluminescence

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ABSTRACT

Monitoring of the intensity of band-to-band electroluminescence (EL) from B-doped Cz-Si solar cells allowed reliable detection of their degradation under forward bias. Degradation related changes in the open circuit voltage for a cell can be well estimated from the related changes in the EL-intensity value under fixed forward current flow. Kinetics of the degradation could be accessed from the time-dependence of EL-intensity changes. The method of monitoring of the degradation process is fully applicable to the cells with complicated structure, e.g. cells with passivated emitter rear contact (PERC). Comparison of degradation process in standard and PERC solar cells indicated on faster and more severe degradation in PERC cells.

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1. Introduction

The degradation of Si based solar cells during their operation remains as one of the main concerns for the photovoltaic community. Light-induced degradation (LID), potential-induced degradation (PID), degradation related to impurities and structural defects are recognized as problems hindering further improvement of solar cell performance. Therefore, proper monitoring, determination of origins and underlying mechanisms of degradation are in the focus of investigations.

The LID for Si solar cells containing boron and oxygen atoms is known already for long time [1–7]. The LID related studies were recently reviewed by Lindroos and Savin [8]. The degradation takes place under standard illumination conditions and leads up-to 10% relative gradual loss in the efficiency value of the standard solar cells. The LID traps can be deactivated by an annealing step at 200 °C for several minutes. However, further illumination leads to re-activation of the traps again [4]. Stabilization of the deactivated state of the traps is possible by simultaneous action of elevated temperatures (70–230 °C) and carrier injection, such process was called regeneration [9] and proved to be critically dependent on the presence of hydrogen in the material of the cells [10]. After regeneration process further degradation under illumination is suppressed. Origins of LID yet have to be clarified and are widely discussed.

The effect of LID was clearly observed by carrier lifetime spectroscopy on the bulk Si material used for the production of solar cells [2–7] and was interpreted as being due to the Shockley-Read-Hall (SRH) recombination at traps formed by boron and oxygen atoms. Recently carrier traps were detected in LID-subjected solar cells by deep level transient spectroscopy (DLTS) [11], supporting trap assisted SRH-recombination mechanism of the degradation. These measurements also indicated strong influence of hydrogen on the trap activity, as it was suggested in [9,10].

The fast emerging topic in the present publications is an extremely slow and strong process of LID in multi-crystalline Si (mc-Si) cells with passivated emitter and rear contact structure (PERC, see e.g. [12–14]). Besides the much slower formation speed in comparison to the B-O related traps, these defects show different formation kinetics depending on whether the solar cell is operating under V_{OC} or I_{SC} mode [14]. Influence of temperature on formation and deactivation of these defects is also stronger compared to the B-O traps [13,14]. Since mc-Si cells occupy large share of the cell market and the PERC technology is also popular, this type of degradation became the major concern for the PV industry. Even from the short description presented above, it seems obvious that the LID processes appear as a complex interplay of various factors and requires careful investigation by various methods.

Formation of the traps under illumination can be monitored by measurement of cell efficiency, open circuit voltage or/and short circuit current (see e.g. [12]). However, changes in these parameters are usually small and high stability, homogeneous light-source is necessary for reliable monitoring, especially for the small light intensity values. Monitoring of the degradation using carrier

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lifetime spectroscopy has a significant drawback: for the measurements the cell structure, i.e. the junction(s) and all contact materials, should be removed from the bulk material of the cell and the surfaces should be well passivated. The passivation layer deposition/fabrication is performed at temperatures that cause serious changes to the LID defect content in the cell material, (viz. 150–450 °C). Therefore, it is virtually impossible to prepare a sample for lifetime measurements from the LID affected cell without significantly changing its defect status. This limitation is especially serious for the cells with complicated structure, such as, e.g., the PERC cells [15], where effect of LID is known to be even more severe and complicated than that in cells with standard structure [12–14,16].

Although the reason for the LID was usually linked to the diffusion of light-generated carriers through the bulk of the cell, we were able finding only a couple of publications devoted to the formation of defects under carrier injection by the forward bias in the dark [5,17]. The cell efficiency degradation in [5,17] was detected from the reduction of the open circuit voltage under illumination.

Electroluminescence (EL) from the n^+p diode structure of the cell is generated under forward biasing of the cell. We tried detecting the carrier injection induced degradation by monitoring the EL intensity. Previously, correlations of EL with solar cell parameters were considered by Fuyuki et al. [18], however LID and related phenomena were out of the scope of that investigation. Our first experiments applying EL detection of the degradation process showed promising results [19]. Namely, the monitoring of the intensity of band-to-band electroluminescence (EL) from B-doped Cz-Si solar cells allowed a reliable detection of their degradation under forward bias. The EL intensity from a Ga-doped cell, monitored simultaneously with the B-doped cell, did not change significantly. Annealing of the degraded cell at 200 °C for 20 min returned the EL intensity of the cell to its initial value from where it could be degraded again, similar to the fresh B-doped samples. Two stages of the degradation, a fast degradation stage (FDS) and a slow degradation stage (SDS) [5,6], were also clearly detected with short and long time constants.

Overall, the EL degradation behavior closely follows the light-induced degradation (LID) process of B-doped Si solar cells [19]. The experimental evidence suggested that the relative suppression of the EL signal from a sample cell occurs homogeneously for various locations inside the sample area; therefore the monitoring of the degradation could be performed using the EL signal originating virtually from either location. Moreover, the EL intensity integrated from the whole sample surface also behaves similar to the local EL intensity [19]. Therefore, it seems justified to integrate the EL signal from the whole sample surface and scale it by the sample area to obtain comparable EL signals from various samples. The results also indicated the necessity to precisely control the sample temperature during the degradation measurements. In the present work we determine the proper measurement procedures for the EL detection of the degradation and designate the potential application areas of the method for the study of LID phenomena. As a demonstration of the potential of the method, we will compare the behavior of standard and PERC cells during the degradation.

2. Materials and methods

Several Cz-Si solar cells fabricated in standard Si PV-cell technology (SSC) [20] and/or with passivated emitter rear contact (PERC) [21], were used in our investigations. The details of the absorber materials of the cells and of the efficiency in the fresh state are presented in Table 1. The standard procedure of complete

Table 1
Characteristics of the absorber material, the cell structure and PV-parameters of solar cells used in the present investigation.

Sample	Absorber material, cell structure, dopant, and resistance (Ω cm)	Oxygen content $[O_i]$ ($\times 10^{17}$ cm^{-3})	Efficiency in the fresh state (%)	ΔV_{OC} caused by LID (mV)
SSC	Cz-Si, standard, Boron, 1	7	18.3	-14 ± 0.5
PERC	Cz-Si, PERC, Boron, 2	8 ± 3	20.5	-25 ± 1

LID under AM1.5 conditions for the cells led to changes in their open circuit voltage (V_{OC}) which is also presented in Table 1. Before starting our degradation experiments each sample was pre-annealed in dark at 210 °C for 20 min for deactivation of possibly existing LID traps. After the annealing procedure precautions were taken to protect the samples from any light exposure.

Due to the size limitation of our cooling stage, square-shaped pieces ($\leq 3 \times 3$ cm^2) were cut out from the cells for our measurements. The samples contained a part of busbar line for electrical contact and were mounted on a thermostat by thermo-conductive glue. Temperature of the samples could be controlled in the range 19–55 °C with ± 0.5 °C precision. For time-dependent measurements the samples were biased by a PC-controlled power source (Agilent Technologies N5767A) in fixed current or in fixed voltage modes. Current-voltage dependencies were measured using Keithley 2601B Sourcemeter using 4-point contact method. All measurements were done in a light-tight cabinet. The band-to-band EL from the samples under forward bias conditions during time-dependent or/and during current-voltage measurements was detected by an InGaAs camera (Xeva-FPA-1.7.−320), through a bandpass filter (CT 1160/180bp2), with peak transparency at 1160 nm. The time dependence of the EL intensity was monitored during periods up to 155 h by storing EL intensity images from the samples at predefined moments. A matrix of EL intensity for each stored image was integrated and divided by the sample area to obtain characteristic EL intensity – I_{EL}. Simultaneously with the EL intensity measurements values of current and voltage were recorded.

In the present report we will discuss data obtained from four different cells. All these samples were degraded at 25 °C. The sample labeled SSCJ with area 9 cm^2 was degraded under fixed current conditions with J_F=38.5 mA/cm^2. The SSCV sample with area 3.8 cm^2 was degraded under fixed voltage conditions with V_F=700 mV. The PERCJ sample with area 4 cm^2 was degraded under J_F=125 mA/cm^2 and the PERCV sample with the similar area was degraded under V_F=700 mV.

3. Results and discussion

Time dependencies of the integrated EL intensities for SSC samples under forward bias conditions at T_{MEAS}=25 °C, normalized by the sample surface area are presented in Fig. 1. The data for the fixed current conditions (SSCJ sample) are presented in Fig. 1(a), while Fig. 1(b) represents data for fixed voltage (SSCV sample). Under the fixed voltage conditions the current increases upon the EL-intensity degradation (see Fig. 1(b)). In the case of fixed current conditions the voltage across the cell falls with the degradation (Fig. 1(a)). Such behavior corresponds well with the formation of recombination centers in the bulk of the cells during EL. Using a simple diode model for EL in J_F=const. mode (see e.g. [18]) one can obtain the following relation between EL intensities (I_{EL}), effective minority carrier diffusion lengths (L_e) and open circuit

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