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Degradation of multicrystalline silicon solar cells and modules after illumination at elevated temperature

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ABSTRACT

In this work the performance stability of rear side passivated multicrystalline silicon solar cells and modules under carrier injection at different temperatures is investigated. Compared to most other tests the degradation procedure were extended to significantly longer time periods and include relevant module temperatures in field. Severe power degradation levels of above 10% can be detected after several hundred to thousand hours (corresponding ~5–20 years depending on the location) which cannot be explained by B–O complex formation or FeB pair dissociation. After detection of this light induced degradation at temperatures above 50°C the common abbreviation LID was renamed and state more precisely *L*ight and elevated *T*emperature *I*nduced *D*egradation (LeTID). A high number of cells and modules degraded in laboratory and outdoor using material from different wafer suppliers confirm the relevance of this effect. LeTID is a multicrystalline silicon bulk phenomenon leading to a highly injection dependent lifetime characteristic after degradation and features a regeneration phase after degradation. The time constant of this degradation mechanism accelerates with increasing temperature, however, the time span for degradation and regeneration of thousands of hours at relevant temperatures between 60 and 85°C demands for a solution on wafer material or processing side. LeTID can be significantly reduced by adapting the cell process and processing sequence.

1. Introduction

The effect of performance degradation due to excess charge carriers generated in Boron-doped silicon solar cells by either illumination or injection of external currents has received great interest in scientific research [1–3]. The preferred choice of test structure has been mostly monocrystalline Czochralski-grown (Cz-Si) material due to the typically higher oxygen content. Compared to Cz-Si, only little research was dedicated to light induced degradation of multicrystalline silicon (mc-Si) so far. However, mc-Si material achieved a market share within the c-Si PV of about 60% in 2014 [4] and will remain the dominant material within the next 10 years. Additionally, this study predicts a mainstream market for multi *P*assivated *E*mitter and *R*ear Cell (PERC). Thus, to support the PV industry, more research is needed on mc-Si material especially in next generation cell concepts. Recently Ramspeck et al. [5] and Fertig et al. [6] published results on mc-PERC cells showing unexpected strong light induced degradation of ~5% at 75°C. As stated in both publications the unexpected strong degradation is not explainable by boron–oxygen (B–O) complex and iron–boron (FeB) pair dissociation. Unfortunately, there is no standard in c-Si PV for the temperature range during LID and agreed LID test parameters at elevated temperatures (50–80°C) and time (> 48 h) to cover field relevant conditions. In this work the elevated temperatures during light induced degradation is emphasized and the well-known LID is renamed to *L*ight and *e*levated *T*emperature *I*nduced *D*egradation (LeTID). In this paper, we characterize and reduce a mc-Si "long-term" degradation and regeneration mechanism called LeTID, which can cause degradations of above 10%.

2. Characteristics and observations of LeTID on multicrystalline silicon

2.1. Experimental

Mc-Si wafer material from different wafer suppliers (several ingots with complete brick distributions) are processed to degradation susceptible lifetime samples, PERC cells and modules. The interstitial

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oxygen concentration of the Si material is measured by infrared absorption spectroscopy. The degradation experiments in the lab are carried out at different temperatures from 50°C to 95°C. Compared to most other tests we extend the procedure to significantly longer time periods (simulating over 20 years roof top operation in Germany). The excess carriers are injected either by illumination *L*ight *I*nduced *D*egradation (LID) or by current injection *C*urrent *I*nduced *D*egradation (CID). For LID we vary the excess carrier concentration by illumination and by operation in V_{oc},I_{sc} or MPP mode. For CID, the current is varied to control the minority carrier density to simulate the same excess carrier density as for operation in V_{oc},I_{sc} or MPP mode under illumination at 1000 W m^{-2}.

2.2. Results on PERC cells and mc-Si lifetime samples

Fig. 1 shows continuously measured V_{oc} data of four mc-Si (neighboring sorted material) LeTID-sensitive PERC solar cells at two different elevated temperatures (50°C and 95°C) and in two operational modes (V_{oc} and I_{sc} mode) during illumination at 300 W m^{-2}. The measured V_{oc} values are illumination and temperature corrected to STC (25°C, 1000 W m^{-2}) and normalized to the initial V_{oc}. A significant V_{oc} degradation at 95°C in V_{oc} mode of ~10% after approximately 150 h can be observed. The PERC cell hold at same conditions but operated in I_{sc} mode (thus lower injection level) shows a slower degradation behavior. From Fig. 1 we can conclude that LeTID is accelerated by either a higher temperature or higher injection level. After reaching the maximum degradation level LeTID features also a regeneration effect. After ~1000 h at 95°C in V_{oc} mode, the PERC cells are almost completely recovered.

Fig. 2 displays the degradation of mc-PERC cells representing a whole brick (from bottom to top) distribution after illumination at 1000 W m^{-2} and 60°C for 24 h. Please note that the degradation values after 24 h represent a "snapshot" only, since the degradation maximum is achieved not before several hundreds of hours (see Fig. 1). From Fig. 2 we conclude that LeTID does not correlate to the interstitial oxygen concentration. Additionally, we find in our experiments a dependency of the brick height which suggests an influence of the wafer properties on LeTID. We have verified this conclusion by varying the surface passivation layers of PERC cells and lifetime samples (Fig. 4), showing similar results. Due to the extreme low degradation rate and the mismatch with the O-concentration we exclude B–O and FeB as the root cause of LeTID.

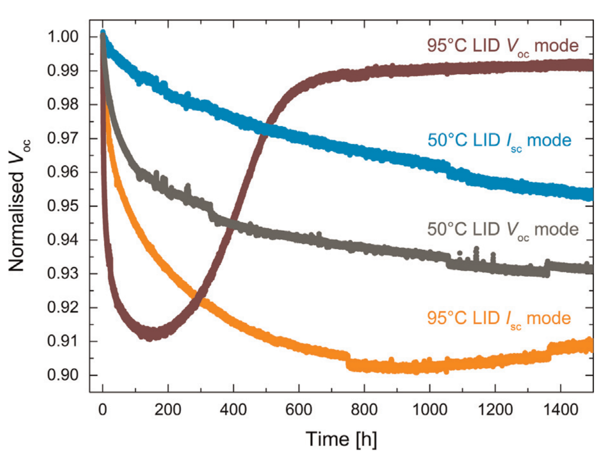

Fig. 1. Temperature and illumination corrected to STC V_{oc} data of four mc-PERC cells during illumination (300 W m^{-2}) at two temperatures and operational modes (50°C and 95°C; V_{oc} and I_{sc} mode).

Fig. 3 displays the injection dependent minority carrier lifetime characteristic of a symmetrical surface passivated mc-Si wafer before and after the degradation process (1000 W m^{-2}, 75°C, 24 h). At an injection level of $\Delta n = 4\times10^{13}$ cm^{-3} (MPP operation mode) we detect a drop in lifetime from τ_{eff}= 137 μs (before) to τ_{eff}= 14 μs after 24 h of illumination (as discussed in Fig. 1 due to the low degradation rate of LeTID a further degradation is caused for the next few hundreds of hours). However, beside of the reduced lifetime also a change of the injection dependency can be observed. LeTID causes an increased lifetime degradation effect at lower injection levels of e.g. $\Delta n = 1\times10^{13}$ cm^{-3} than at higher injection of e.g. $\Delta n = 1\times10^{15}$ cm^{-3}. This increased injection dependency of the minority carrier lifetime can explain the observed degradation characteristics as displayed in Fig. 2. The increased injection dependency causes a main loss in I_{sc} and additionally leads also to an increased non-ideality of the solar cell causing a loss in FF.

Fig. 4 shows the longtime lifetime measurement at $\Delta n = 1\times10^{14}$ cm^{-3} plotted as normalized defect concentration N_t^* [7] of two different surface passivation types after degradation (300 W m^{-2}, 75°C). τ_{LeTID} represents the inverse N_t^* and upper lifetime limit. One sample type is symmetrical coated by an

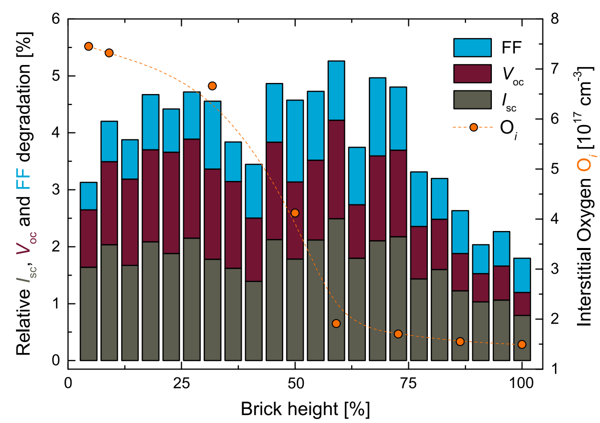

Fig. 2. Performance loss and interstitial oxygen concentration of mc-PERC solar cells (representing a brick distribution) degraded at 60°C for 24 h during illumination at 1000 W m^{-2}.

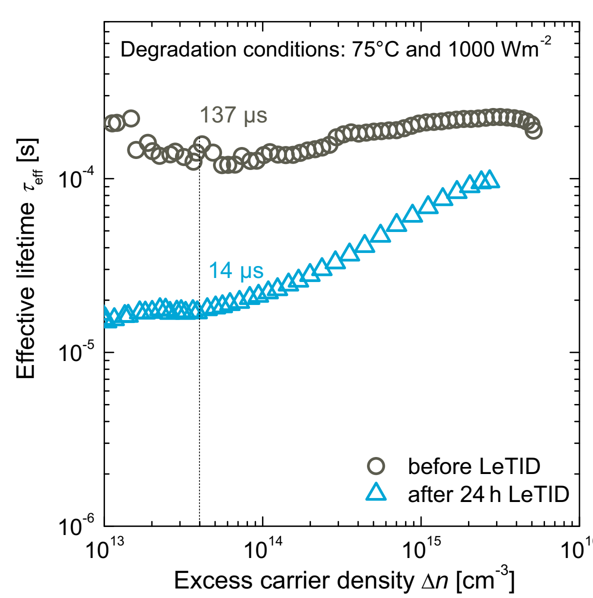

Fig. 3. Effective minority carrier lifetime of a passivated mc-Si wafer before and after 24 h degradation process.