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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.

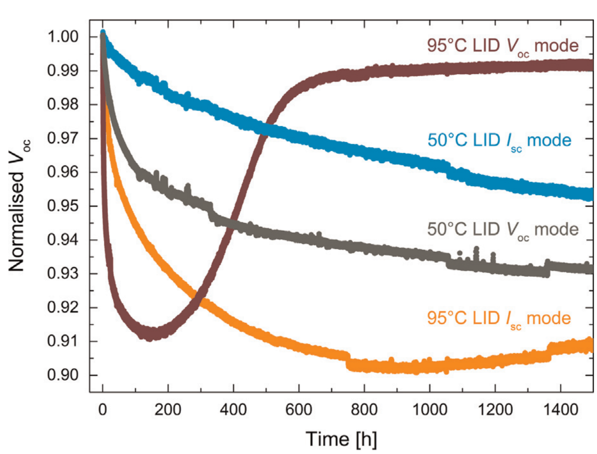

Fig. 1. Temperature and illumination corrected to STC V_{oc} data of four mc-PERC cells during illumination (300 W m^{-2}) at two temperatures and operational modes (50°C and 95°C; V_{oc} and I_{sc} mode).

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 $\Delta n = 4 \times 10^{13}$ 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. $\Delta n = 1 \times 10^{13}$ cm^{-3} than at higher injection of e.g. $\Delta n = 1 \times 10^{15}$ 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 $\Delta n = 1 \times 10^{14}$ 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

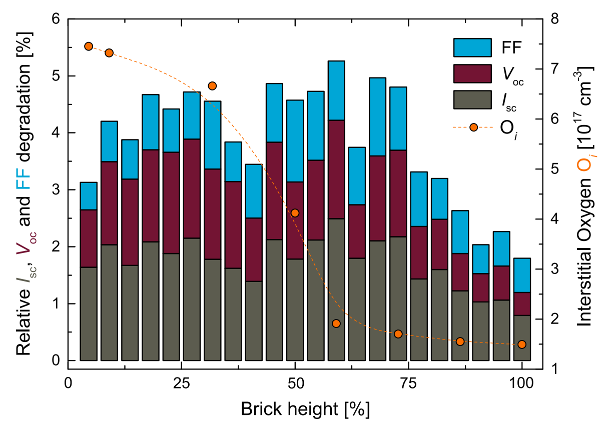

Fig. 2. Performance loss and interstitial oxygen concentration of mc-PERC solar cells (representing a brick distribution) degraded at 60°C for 24 h during illumination at 1000 W m^{-2}.

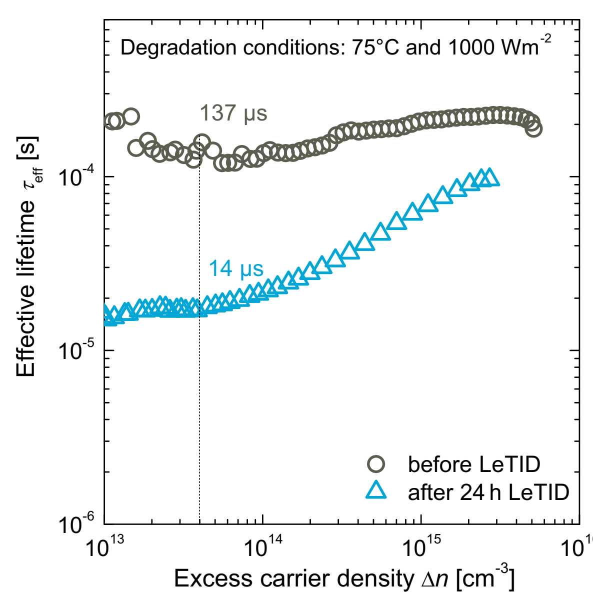

Fig. 3. Effective minority carrier lifetime of a passivated mc-Si wafer before and after 24 h degradation process.

Al_2O_3/SiN_x-stack (negative surface charge). The other sample is only passivated with SiN_x (positive surface charge). For both passivation types the same time-dependent degradation behavior is observed. In contrast to the lifetime degradation snapshot after 24 h of τ_{eff}= 18 µs, after 1100 h, a further severe lifetime degradation up to τ_{eff}= 5 µs is measured. From Fig. 4 we can conclude that the degradation of mc-Si is independent of surface passivation charge and passivation layer type. This is another indication for a Si bulk degradation effect. In contradiction to solar cell measurement (red dots in Fig. 1) the lifetime samples feature no regeneration phase after more than 1000 h degradation process.

2.3. Relevance of LeTID on mc-PERC modules in field

Fig. 5 shows the degradation–regeneration cycle of a LeTID-sensitive PERC module installed during summer on the outdoor test field (located in Germany). The sequence starts in calendar week (CW) 25 with a homogenous EL image and a power normalized to 100%. An acceleration of the degradation–regeneration cycle was reached by isolating the module rear side with Styrofoam in order to increase the module temperature to the ones recurrent in hot climates and by operating in V_{oc} mode. After 5 weeks, the module performance decreased by nearly 10% and a strong inhomogeneity appears in the EL image. Different cells show different degradation effects and time constants, although processed under the same conditions. Between CW30 and CW32, the module started to regenerate. In CW41, almost the full original module power is recovered. However, in MPP mode or in central European climate conditions the regeneration takes too long to take effect during the warranty period of a commercial PV module (see time scale of orange triangles in Fig. 6).

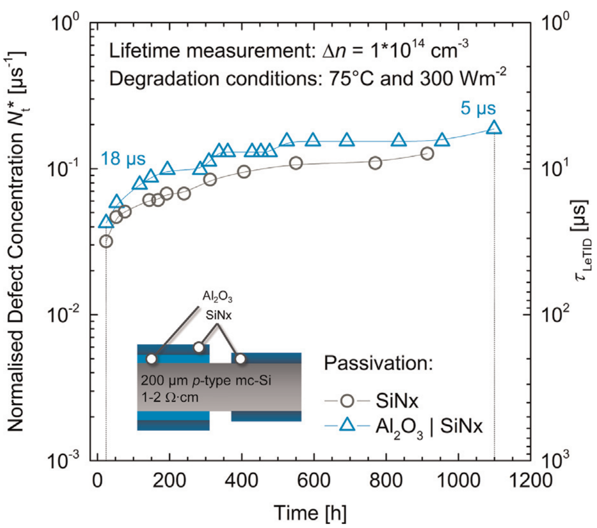

Fig. 4. Effective minority carrier lifetime of a passivated mc-Si wafer after long time degradation of different passivation layers.

3. Avoidance of LeTID and proposal for test conditions

Fig. 6 shows the time-dependent module power degradation for different carrier injection densities. The left side of the graph shows the equivalence of LID and CID at 85°C and V_{oc} mode. In MPP mode, LeTID-sensitive modules lose more power but at a much smaller rate compared to V_{oc} mode. The right side of the graph shows the power loss of modules with reduced LeTID at 75°C in MPP mode. We propose CID under these conditions to identify power losses in the field due to LeTID at a reasonable speed. With this method, high numbers of modules can be tested in parallel at moderate cost. We measured real module temperatures over several months and years at our different worldwide test fields. Together with a model for the temperature dependency of LeTID deduced from experiments we calculate a test site specific corresponding time period for the proposed test at 75°C; e.g. 10/20 years Germany roof top or 5 years Cyprus field as plotted in Fig. 6.

By adapting the process conditions and sequence we are able to influence LeTID. Fig. 6 plots time-dependent degradation of PERC modules with varying LeTID sensitivity (max $>$10% and medium in the range of 3–4%). Applying our optimized defect engineered process, we are able to fully avoid any LeTID with a degradation level of $<$1% after 1000 h. This time corresponds to more than 20 years of module life time in a roof top installation in Germany. We can conclude that our Q.ANTUM [8] module is not susceptible to LeTID.

4. Summary

Based on high number of cells and modules degraded in lab and outdoor and utilizing material from different wafer suppliers we characterized a mc-PERC degradation effect called LeTID. Lifetime sample experiments including variation of the surface passivation layers and investigations on cells within brick height dependency allowed us to conclude that LeTID is a strong Si material effect. Higher injection densities or increased temperature accelerates the degradation. After reaching the maximum degradation level, there is also a regeneration effect shown on the cell samples. However, the time span for degradation plus regeneration of thousands of hours is too long to take effect during warranty period. Our proposal for a LeTID test norm with moderate implementation effort and costs is CID at 75°C in MPP mode.

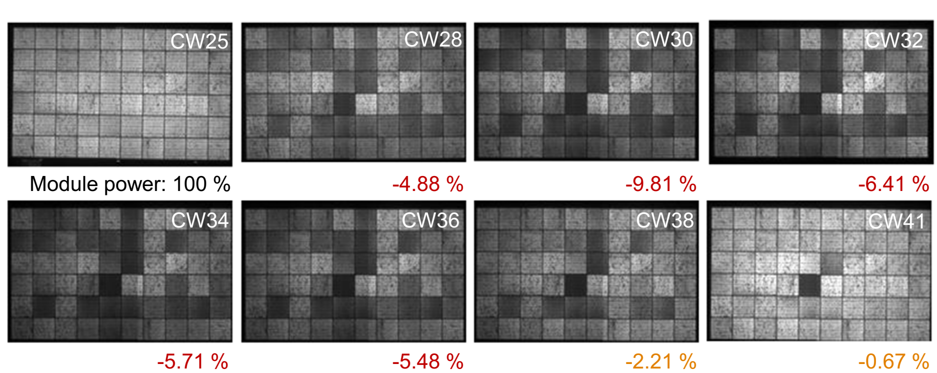

Fig. 5. EL and module power measurement (STC) sequence showing the degradation–regeneration cycle and the time-resolved contribution of single cells.

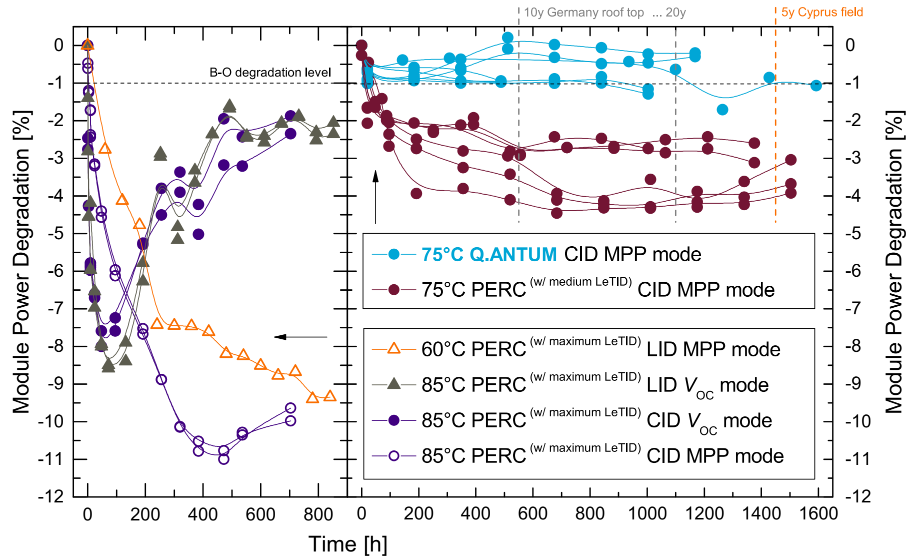

Fig. 6. 60-cell mc-PERC module degradation measurements at T=60–85°C in V_{oc} and MPP mode. Left panel: LID & CID show similar LeTID behavior on 60-cell PERC modules at 85°C and V_{oc} mode. Temperature range between 60°C and 85°C is covered in MPP mode. Right panel: Data according to proposed degradation standard in CID (MPP mode) at 75°C. PERC modules with less LeTID sensitivity show a significant reduction in degradation (from > 10% to < 4%); however, our defect engineered Q.ANTUM modules are completely free of LeTID.

By adapting the cell process and processing sequence Q.ANTUM modules are not susceptible to LeTID. Nevertheless more research work is necessary in order to create a deeper understanding of the LeTID process on mc-Si solar cells.

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