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The Role of Dark Annealing in Light and Elevated Temperature Induced Degradation

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Abstract

We study the lifetime instability in p-type boron-doped mono-like silicon during light soaking (LS) and dark annealing (DA) at different temperatures, and their behaviours upon LS / DA cycling at various degradation and regeneration stages. It is found that the degradation behaviours observed under illumination and in dark could stem from two separate reactions, with hydrogen being the common precursor. A model for light and elevated temperature induced degradation (LeTID) is presented based on our experimental findings. It is proposed that hydrogen atoms originally bounded in the silicon nitride layer are released into the silicon bulk at above a certain firing temperature, which then interact with some other species in the silicon bulk under illumination, causing the LeTID degradation. During the cooling ramp of the firing process or extended DA, hydrogen in the silicon bulk starts to effuse into the ambient, altering the amount of hydrogen remained in the silicon bulk and correspondingly their LeTID behaviours. The proposed model provides new insight to understand complex LeTID behaviours observed in various works, including its correlation with the firing profile, sample thickness, dopant type and DA pre-treatment.

Introduction

LeTID can lead to a significant performance loss in photovoltaics modules. One major difficulty in understanding LeTID is the lack of an universal model that can provide an explanation for the different observed characteristics of LeTID. In this work, we aim to develop a model for LeTID based on the measured degradation kinetics of p-type boron-doped mono-like Si upon LS / DA cycling.

Experiments

Industrially-grown p-type boron-doped mono-like Si wafers ($1.6\ \Omega \cdot \mathrm{cm}$) and Cz-Si wafers ($1\ \Omega \cdot \mathrm{cm}$) were processed into lifetime test structures, based on a PERC fabrication process in an industrial production line. The process involves texturing, $POCl_3$ diffusion, rear-side etch, plasma enhanced chemical vapour deposition (PECVD) SiN_x disposition on front, SiN_x/AlO_x stack deposition on rear, and firing in an industrial belt furnace without the metallisation paste. Degradation test was performed on a hotplate either in dark or under 1 sun illumination with a white LED light source. The effective carrier lifetimes were measured at defined time steps during the degradation by quasi-steady state photoluminescence (QSSPL) technique. Normalised defect density (NDD) is used to present lifetime evolution in this work. It is defined as: $NDD = 1/\tau_{eff}(t) - 1/\tau_{eff}(t=0)$, where $\tau_{eff}(t)$ denotes the effective minority carrier lifetime measured at different time steps of the degradation and $\tau_{eff}(t=0)$ is the lifetime measured before any degradation test.

Result and discussion

Fig. 1 shows the NDD evolution in the samples upon various cycling between LS and DA at $140℃$. While both DA and LS lead to a comparable degradation extent at $140℃$, the degradation and regeneration rate during DA is orders of magnitude slower than that in LS. Fig. 1(b) shows the DA response of a sample that went through a full degradation-regeneration cycle under illumination. The sample exhibits a second degradation and regeneration cycle upon the subsequent DA. Fig. 1(c) and (d) shows the DA response of samples previously degraded under illumination. The LS degraded sample shows a rapid recovery of lifetime during DA, but exhibits a second degradation afterwards upon longer period of DA, as shown in Fig. 1(c), occurring at similar timeframe as the individual DA reaction shown in Fig. 1(a). Moreover, as shown in Fig. 1(d), the sample recovered in dark degrades again upon a second LS. Our results suggest the involvement of more than one defect, or a defect with more than one recombination active state, as being responsible for the observed degradation during DA and LS respectively. This hypothesis is in agreement with the five-state model proposed by Luka *et al.* [1], involving two recombination active states.

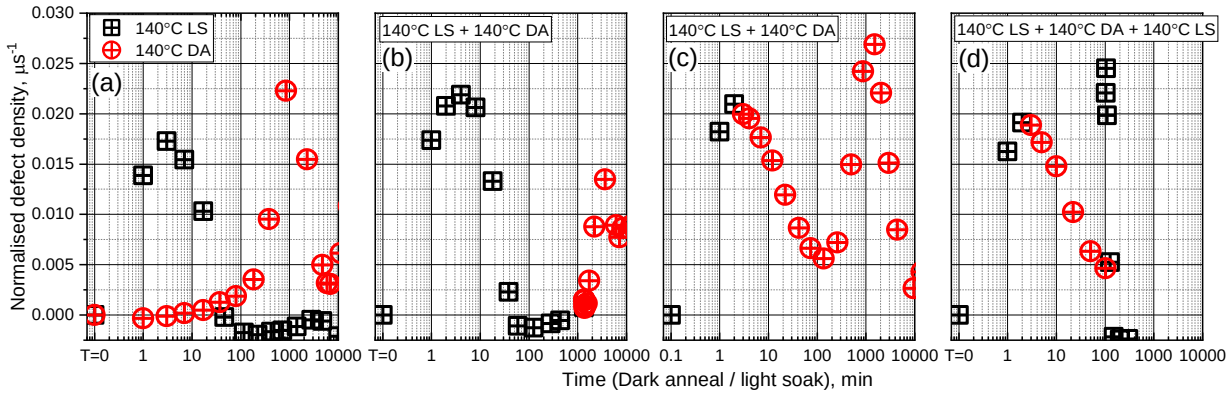

Figure 1 - NDD of mono-like Si samples upon LS (1 sun) and DA cycles, applied at 140℃.

Fig. 2(a) shows the evolution of NDD of sister mono-like Si samples during LeTID test performed under 1 sun illumination at 100℃, after subjecting to an initial DA at 300℃ for different durations. It is observed that a short duration (1 min) of DA at 300℃ increases the maximum extent of degradation upon the subsequent LS, when compared to the control sample without any DA pre-treatment. Increasing the DA duration, however, introduces an opposite effect. Samples subjected to a 10 minute DA treatment at 300℃ show a reduced extent of LeTID, whereas samples subjected to a 1200 minutes (20 hours) DA treatment show substantially less LeTID. Similar observations have been reported in Ref. [2].

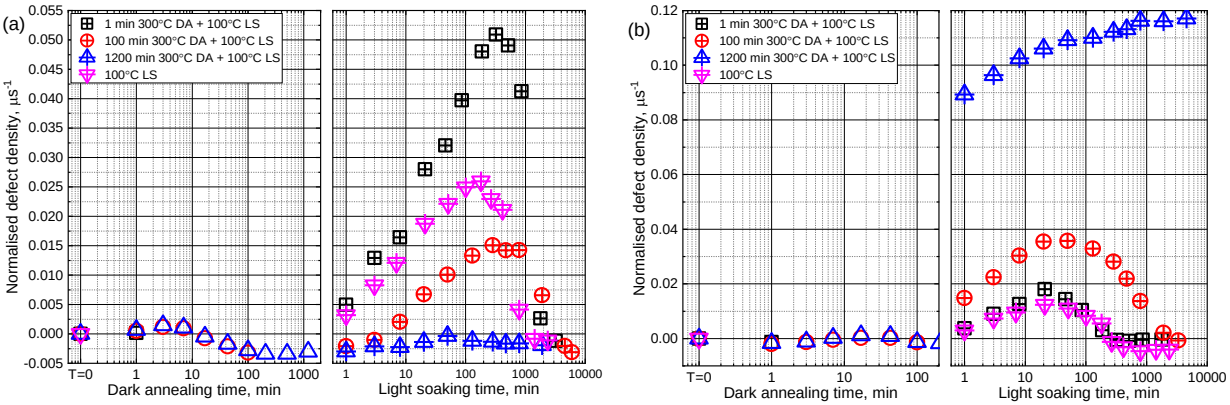

Figure 2 – NDD of (a) mono-like Si samples and (b) Cz-Si samples during LS under 1 sun illumination at 100℃, after subjecting to an initial DA at 300℃ for different durations.

As for comparison, Fig. 2(b) shows the evolution of NDD on boron-doped Cz-Si samples during the LeTID test after DA pre-treatment. Surprisingly, an opposite trend is observed on Cz-Si samples, where DA significantly increases the extent of degradation upon subsequent LS test. In particular, no clear sign of regeneration is observed within our experimental timeframe (≈ 4500 min) on the Cz-Si sample that received a 1200 minutes DA pre-treatment at 300℃. Similar observations have been reported by Wilking *et al.* [3] and Sen *et al.* [4]. This distinct behaviour could be due to boron-oxygen (BO) defects in Cz-Si. It was suggested that the regeneration rate of BO defects depend heavily on the amount of atomic hydrogen silicon presented in the bulk [5]. Here, the application of DA could potentially drive hydrogen effusion from the silicon bulk or convert hydrogen into another form, thus slowing down the regeneration rate of BO defects in the Cz-Si samples during subsequent LS test.

A model is developed to describe the observed behaviours. The model, as shown in Fig. 3, involves two competing reactions individually responsible for the degradation/regeneration activities during DA and LS: a fast reaction that govern the main LeTID behaviour, and a slow reaction that mainly occurs during extended annealing, with hydrogen being the common precursor for both reactions.

The fast reaction can be described by the traditional three-state model known for BO defect [6]. Here, it is assumed that LS would drive the forward reaction, whereas DA would drive the reverse reaction. This three-state reversible model can explain the lifetime instability in the re-generated

samples upon a second LS/DA treatment, as shown in Fig. 1(d). In contrast to the fast reaction, the slow reaction occurs mainly during extended annealing. It is speculated that this slow reaction could involve an out-diffusion of hydrogen from the silicon bulk to ambient, limiting the amount of hydrogen available for the fast reaction, and hence reduces the LeTID degradation.

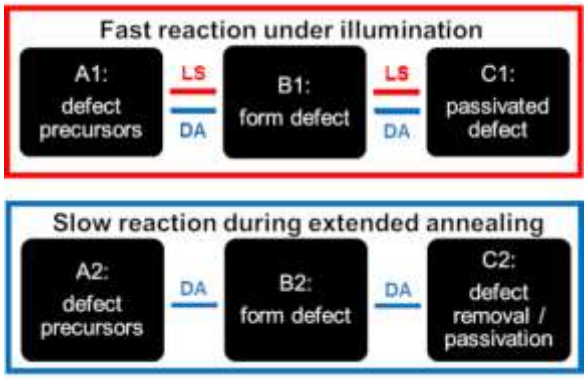

Figure 3 – Proposed model for the LeTID

One important characteristic of LeTID is that it depends heavily on the firing profile, affected by the peak firing temperature [7] and the cooling rate [8]. In our model, it is proposed that hydrogen atoms originally bound in the SiN_x layer are released into the Si bulk above a certain firing temperature, which then interact with some other species in the Si bulk under illumination, causing the LeTID degradation. During the cooling ramp of the firing process or extended annealing, hydrogen in the Si bulk starts to out-diffuse into the ambient. The amount of hydrogen remaining in the silicon bulk, thus their correspondingly LeTID behaviours, depends on the properties of the dielectric films, the peak firing temperature and the cooling rate, which govern the balance between in-diffusion and effusion of hydrogen.

In the full paper, we will apply our proposed model to explain complex LeTID behavours reported in literature, including its correlation with the firing profile, dielectric films, sample thickness, dopant type and DA pre-treatment.

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