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Review

Review of light-induced degradation in crystalline silicon solar cells

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ABSTRACT

Although several advances have been made in the characterization and the mitigation of light-induced degradation (LID), industrial silicon solar cells still suffer from different types of light-induced efficiency losses. This review compiles four decades of LID results in both electronic- and solar-grade crystalline silicon. The review focuses on the properties and the defect models of boron-oxygen LID and copper-related LID. Current techniques for LID mitigation are presented in order to reduce cell degradation and separate copper-related LID from boron-oxygen LID. Finally, the review summarizes recent observations of severe LID in modern multicrystalline silicon solar cells.

Contents

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1. Introduction

Light-induced degradation (LID) refers to a loss in the silicon solar cell efficiency that is observed during excess carrier injection by above-bandgap illumination [1] or forward biasing [2]. LID is seen as a decrease in the solar cell short-circuit current and the open-circuit voltage [3], caused by increased minority-carrier recombination in the bulk of crystalline silicon [4]. Although LID has been studied extensively for the past four decades, the recombination-active defects responsible for degradation remain yet to be identified.

In the 1970s, LID was first observed in both electron- and proton-irradiated boron-doped Float Zone (FZ) silicon solar cells [3,5,6]. LID was measured also in 1 Ω-cm Czochralski (Cz) solar cells [6], with electron irradiation further decreasing the cell power, rendering both FZ-Si and Cz-Si unsatisfactory for space applications. Since unirradiated FZ-Si remained free of LID, the first LID results compiled by Curtin and Statler [7] were soon forgotten, and all efforts were focused on understanding LID in Cz-Si solar cells. Once the light-induced defect density was observed to increase with increasing boron and oxygen concentrations, degradation was linked to the formation of a boron-oxygen complex, and the effect became known as boron-oxygen LID (BO-LID) [4,8]. BO-LID is characterized by a fast initial decrease and a second slower decay [9–11] that are fully reversible at 200 °C [6]. The current B-O complex model has been questioned after the observation of similar LID in aluminum-doped Cz-Si, together with indium-doped Cz-Si and FZ-Si [12,13].

Minimizing either the boron or the oxygen concentration was presumed to guarantee LID-free silicon [14], until Henley et al. [15] measured LID in boron-doped FZ-Si with intentional copper contamination in 1998. After interstitial copper contamination was observed to induce degradation also in phosphorous- [16] and gallium-doped silicon [17], the effect became known as copper-related LID (Cu-LID). Copper was initially dismissed as a source of LID in solar cells, as most bulk copper contamination was presumed to have gettered during emitter formation [18–21] and/or back contact firing [22]. However, copper contamination was later observed to cause increased LID in multicrystalline (mc) Aluminum Back-Surface Field (Al-BSF) cells from the top of the ingot [23], where copper is known to collect during crystallization [24].

Interestingly, several solar cell manufacturers have recently observed strong LID in Passivated Emitter Rear Cells (PERC) and Al-BSF silicon solar cells, which cannot be explained by BO-LID theory or light-sensitive iron-boron pairs (FeB) [25–30]. In order to improve LID identification in modern solar cells, this review compiles and compares properties of the two recognized degradation effects: BO-LID and Cu-LID. Section 2 reports on boron-oxygen LID in monocrystalline silicon and solar cells. Section 3 compiles properties of copper in silicon and reviews results on copper-related LID. The known properties of Cu-LID are compared to BO-LID in Section 4. Finally, Section 5 expands into LID in low-cost quasi-mono and multicrystalline silicon solar cells, with conclusions presented in Section 6. The manuscript is based on the literature overview in J. Lindroos' doctoral dissertation [31].

2. Boron-oxygen degradation

Fig. 1 shows typical BO-LID measured in clean B-doped Cz-Si [32] with an oxygen concentration above 1 ppm [8,14]. The degradation is first observed as a fast initial exponential decrease (FRC) of the minority carrier lifetime or solar cell efficiency, followed by a second slower asymptotic decay (SRC) [9–11], which dominates the degradation. The effect is called boron-oxygen degradation (BO-LID), even though boron and oxygen are yet to be confirmed responsible for the recombination-active defect formation.

Despite the name of light-induced degradation, photons are not directly involved in the formation of BO-LID. As long as the photon energy exceeds the silicon bandgap, the photon wavelength and the penetration depth are irrelevant [1], since LID is in fact caused by the injection of excess minority carriers [33]. Therefore, full BO-LID is formed also during forward biasing of the cell in the dark [33]. Although BO-LID is observed at excess-carrier concentrations as low as 1.7×10^9 cm^{-3} [34], excess carriers cannot alone account for the defect density formed during degradation [35]. Instead, Bothe et al. [2] confirmed that BO-LID formation is determined by the *total* minority carrier concentration, based on BO-LID observation in the dark at zero bias at temperatures above 300 K. Therefore, controlling the temperature and the carrier injection conditions are paramount in determining the degradation rate and the normalized defect density of the fast (FRC) and the slow (SRC) recombination centers.

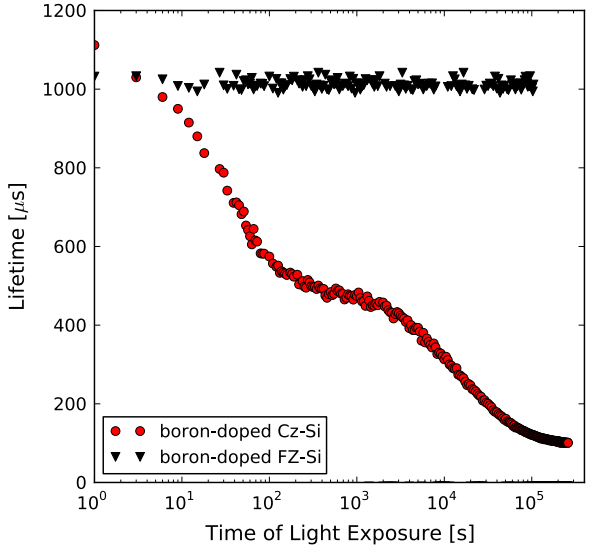

Fig. 1. Effective minority-carrier recombination lifetime as a function of illumination time in clean low-resistivity B-doped Cz-Si and FZ-Si [32]. (Reprinted with permission from Nærland, Characterization of light induced degradation in crystalline silicon, Norwegian University of Science and Technology, Trondheim, Norway, Vol. 2013:303 (2013). Copyright 2013, Nærland.)