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Effects of the irradiance intensity during UV accelerated aging test on unencapsulated silicon solar cells

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ABSTRACT

UV exposure test was performed on commercial unencapsulated monocrystalline silicon solar cells to characterize the changes in the functional properties and to define aging mechanisms. The UV exposed solar cells presented a significant decrease in electrical performances with a cell efficiency degradation of −11.23% after a UV exposure of about 200 kWh/m^2. The degradation is mostly due to a V_{OC} degradation of −6.24% and to a J_{SC} drop of −3.16%. The FF is less affected by the UV aging. According to IQE curves, UV exposure affects charge collection efficiency at the front (blue response) but also at the rear of the cell (red and infrared responses) indicating a degradation of the emitter or of the quality of the anti-reflection and passivation coatings. The reflectance diminishes in the range [500–900] nm owing to a photo-oxidation of the SiN_x antireflection coating and confirms the IQE analysis. The photo-oxidation of SiN_x antireflection coating which involves replacing Si—H by Si—O or Si—O—H bonds is emphasized. The global kinetic of the efficiency change rate is similar for both the irradiance intensities. It consists of a high degradation at the start followed by a stabilization of the degradation for higher UV doses. For the higher irradiance intensity (2000 W/m^2), the start of a regeneration phenomenon was highlighted because of an augmented temperature allowing the neutralization of the recombination centers (B_iO_i defect).

1. Introduction

With the growth of on-grid PV systems, identifying degradation mechanisms and their impact on the PV system performances have become expandingly crucial. Other emerging PV applications like building integrated photovoltaic (BIPV) or solar roadway (Wattway project) will reinforce the efforts in this direction. The qualification standards developed by International Electro-technical Commission (IEC) have helped to ensure long term reliability of PV modules (International Electrotechnical Commission, 2016). To secure a long warranty period (25 years or more), research in reliability and lifetime of PV modules is becoming growingly important and the feedback from consumers are essential to the deployment of PV energy.

The degradation rate which corresponds to the module power at a fixed time relative to its initial power is the lifetime indicator commonly used to compare the reliability of PV technologies. Obviously it depends on internal factors such as the type of the PV technology (crystalline or thin film), the design of module (conventional, glass-glass or concentrated) or also on the quality of fabrication and the external parameters like the environmental (temperature, humidity, wind and hail) and operation conditions (shadowing, size of the PV installation, grid-tied or off-grid…). Numerous studies of PV module degradation in the field show a steady power degradation over time rather than a sudden failure stopping the electrical production. Jordan et al. have reported nearly 2000 degradation rates of different PV technologies from field testing throughout the last 40 years (Jordan and Kurtz, 2013). A median value of 0.5%/year and an average of 0.8%/year were reported regardless the studied PV technology. The date of installation (basic technologies versus new optimized designs) impacts the degradation rate especially for thin film technologies which benefit from technological improvements and reinforced theoretical knowledge.

The degradation kinetic is not fully known to date and has to be clearly defined. Firstly almost all crystalline silicon (c-Si) PV modules show a deterioration in performance during the first exposure time to sunlight. This light-induced degradation (LID) is ascribed to boron-

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oxygen complex formed in p-type wafer by light exposure (Lindroos and Savin, 2016). Numerous works reported degradation rates of about 3% for monocrystalline silicon technology after only a few hours of exposure to light (Chianese et al., 2003; Sopori et al., 2012). Degradation kinetics throughout the operating lifetime seem to be governed by linear trends but several authors assume that exponential degradation rate is more suitable (Vázquez and Rey-Stolle, 2008). In the case of similar initial degradation rates, it should be noted that the linear and the exponential degradation rates exhibit the same trend during the first 15 years and then the linear degradation rate becomes less favorable.

The impact of climate is hardly appreciable (Kurtz et al., 2013) and more degradation analyses have to be carried out to determine reliability of c-Si PV modules taking into account the environmental conditions due to the location (temperature, humidity and radiation). Sanchez et al. investigated a crystalline silicon PV installation after 12 years of operation in Spain (Sánchez-Friera et al., 2011). Glass weathering, delamination at the cell-EVA interface, oxidation of the antireflection coating and the cell metallization grid were the most frequent defects. Moreover, a study on silicon PV modules after 20-year field exposure in the USA highlighted the effects of balance-of-system that includes auxiliary elements comprising storage and soiling in long-term field degradations (Quintana et al., 2000). Sharma et al. studied the effect of the specific Indian climatic conditions on 10 multi-crystalline silicon PV modules (Sharma and Chandel, 2016). Three of them developed serious failures after only 2.5 years of operation resulting in degradation rate reduced by about 50%. The average degradation rate per year for the other remaining modules was 0.5%. The rigorous operating conditions seem to accelerate the infant failure by generating defects due to the poor quality materials or the lean manufacturing practices.

The previous field degradation studies of PV modules have to be correlated to accelerated aging tests in order to model different degradation types and ensure an accurate warranty from PV manufacturers. Wohlgemuth et al. provided a list of failure modes according to different accelerated stresses (Wohlgemuth and Kurtz, 2011). The UV test contained in the qualification standards seemed to generate only polymer degradations through delamination, discoloration or elasticity loss of the encapsulant and with ground fault due to backsheet degradation (Ndiaye et al., 2013). However, this test is only a pre-conditioning test which is not long enough to assess the sensitivity of the polymeric materials used in the PV modules under the UV exposure expected during the lifetime of the module. Due to an increasing absorption of radiation as the wavelength tails away, the effect of the UV radiation on the sustainability of the PV module cannot be neglected. It has been shown that UV exposure test can also be performed on photovoltaic material degradations and especially for surface passivation deterioration on the unencapsulated solar cells. A drastic push up of the surface recombination velocity of the SiN_x coating and the emitter saturation current, J_{0e}, were reported after a UV exposure equivalent to 275 kWh/m^2 (Veith-Wolf et al., 2016). The photolytic breaking or scission of the Si—H bond is suspected in the degradation of the electrical performances. It consists of the absorption of a photon with sufficient energy by the SiN_x coating involving a direct breaking or dissociation (Feller, 1994). It is well known that the shorter the wavelength is, the higher the energy of the photons becomes and hence the impact of the UV spectrum is theoretically more important than the one of the visible spectrum on the degradation mechanism of a PV module. However, most of the c-Si PV modules use a cover made of glass like a mechanical protection filtering a part of the incident spectrum. Although this front sheet of glass blocks the photons owing to wavelengths lower than 290 nm, a pronounced degradation is still observable with a cover of glass and EVA (Veith-Wolf et al., 2016).

This work presents the effect of UV accelerated aging test which is one of the most aggressive aging tests for silicon solar cells, on monocrystalline silicon solar cell properties. The aim of this study is to understand and define the degradation mechanisms of a typical silicon solar cell without taking into consideration the interactions taking place with the other materials of the PV module. The behavior of a solar cell under UV aging needs to be clearly defined before investigating the aging mechanism of the whole PV module which is a complex system with interactions between the different layers.

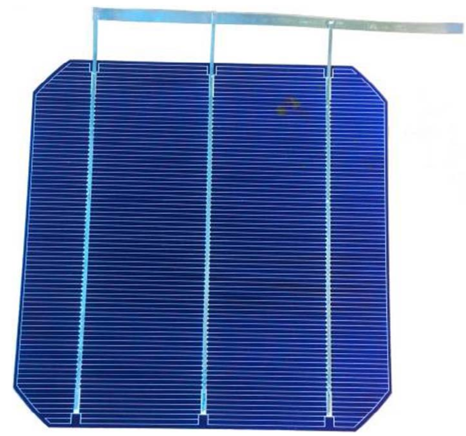

Fig. 1. Image of specimen (soldered monocrystalline silicon solar cell).

2. Experimental procedure

The experiment is carried out on unencapsulated monocrystalline silicon solar cells provided by Evergreen Solar. The cell structure consists of a PERC p-type silicon solar cell with a n-type emitter and locally diffused rear contact (contact window with Al-BSF). The solar cells have an area of 239.5 cm^2 with a 3-bus bar design. 60/40 SnPb tabbing wires were soldered at a temperature of approximately 400 °C, after applying rosin flux on each bus bar. Then the 3 tabbing wires were soldered on a 60/40 SnPb bus wire to investigate the total degradation mechanism of the soldered solar cells (Fig. 1). Commercial solar cells with relatively high performances and low dispersion were selected to ensure the reliability of this study. The 18 solar cells were split into two sets of 9 solar cells to study their aging under two different irradiances (600 and 2000 W/m^2). The average of initial electrical characteristics of the 18 solar cells is displayed in Table 1.

The UV accelerated aging test was carried out in a specific chamber (INVE 2000, Helios Quartz) with a mercury medium pressure UV lamp of 500 W with an incident irradiance running from 600 W/m^2 to 2000 W/m^2 according to the rotating plate height and to the wavelength range [250–400] nm. The chamber temperature was maintained at 50 °C and, at the end of the test, the black standard temperature (BST) steps up to 65 °C and 90 °C for an irradiance of 600 W/m^2 and 2000 W/m^2, respectively. The BST constitutes an upper limit for the surface temperature of the sample. During the UV accelerated aging test, a set of solar cells was aged under open-circuit conditions and another one was submitted to a voltage of 0.550 V corresponding to the operating voltage of such solar cells at the maximum power point in STC. The solar cells were exposed to a maximum UV dose of 691 kWh/m^2 which is equivalent to the UV dose of 15,000 h of exposure to the AM1.5G spectrum (Veith-Wolf et al., 2016).

The study of the main electrical parameters (efficiency η, open-circuit voltage V_{OC}, short-circuit current I_{SC} and field factor FF) was used to evaluate the UV aging effect. The IV characteristics of each solar cell were measured before and after UV exposure with a class-A sun simulator of Paris-Saclay Research Center, one of the Air Liquide R & D Centers. The light source used is a 6000 W Xenon lamp with AM 1.5G filter. The electronic unit uses 4-wire parallel voltage sensing terminals for excluding loss in current carrying cables. The non-uniformity of irradiance and the power reproducibility are evaluated at less than ±