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Potential for photogenerated current for silicon based photovoltaic modules in the Atacama Desert

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ABSTRACT

In order to evaluate module materials, the maximum theoretical value of the photo-generated current density, was calculated. The calculation was performed for four different solar cells, a standard p-type, passivated emitter and rear contact (PERC), bifacial cell and interdigitated back contact (IBC) considering a solar spectrum of Atacama Desert, the transmittance of several glass-encapsulant-glass structures and quantum efficiency. Regarding the solar spectrum in Atacama, an average air mass (AM) at noon for this location averaged 1.17 and the photovoltaic (PV) modules tilt angle was 20°. When studying the impact of using glass and encapsulants combined with a solar cell under the same solar spectrum, ethylene vinyl acetate (EVA) with low ultraviolet (UV) cutoff led to the higher current density values, up to 2% higher with the IBC solar cell compared to the other solar cells. The highest current gain, when studying the impact of the two spectra in the 300–1200 nm wavelength range, was 7.4% for the IBC solar cell, obtained with a standard 3.2 mm glass, a thermoplastic material (TM) as encapsulant. Considering the UV part of the spectrum, the current gain was maximized with a glass with an anti reflection coating (ARC) combined with the TM encapsulant for the IBC solar cell (25%). A quantification of losses due to reflection in the glass and absorption in the encapsulant revealed that the glass with ARC and the TM encapsulant different than EVA led to the lowest reflection and absorption losses. In this case, the reflection and absorption came down to 4.8% and 0.9%, respectively, contrasting with the 7% and 2.8% loss produced with the standard glass and EVA encapsulants.

1. Introduction

The photovoltaic (PV) market is widely dominated by crystalline silicon (c-Si) based PV modules with a 93% of total production in 2015. With this regard, 69% of the c-Si technology corresponds to multicrystalline silicon (mc-Si). According to the Fraunhofer Institute for Solar Energy Systems (ISE, 2016), the worldwide cumulative PV capacity reached 242 GWp in 2015 where the Learning Curve shows a module price reduction in the last 35 years of about 19% when doubling the cumulative module production. It is pointed out that one of the important drivers for cost reductions are the technological improvements together with the economies of scale. In this way, it is expectable to achieve price reductions expressed in the learning curve.

The examination of the solar panel final price divided in different production areas in early 2016 shows that the module represents the highest part with a 41% of the cost, followed by the solar cell and wafer with a 23% each and the poly silicon with a 12% (ITRPV). Consequently, to reduce prices, material costs must be reduced and performance increased. Thus, if module materials and their performance are addressed, potential for price reduction can be obtained. While using less material can lead to a lower cost, reducing optical and resistance losses can enhance the performance of PV devices. Among the materials for PV modules such as, PV glass, encapsulant, backsheet, back foils, solder, conductive adhesive, aluminum frames are most of the main components.

Reducing the used volume such as the thickness, substituting expensive materials and reducing wastes are ways to diminish production costs (ITRPV). Regarding the performance improvement,

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increasing light transmission of cover glass by implementing anti reflection coatings (ARC) is one approach. On these lines, the encapsulant and backsheet are other key materials to be considered. Encapsulants must exhibit, as PV glass, a high transmittance, long lifetime to resist environmental and operation conditions. According to the international technology roadmap for photovoltaic (ITRPV), ethylene vinyl acetate (EVA), polyolefin (POE), polydimethyl silicone (PDMS) and polyvinyl butyral (PVB) are the expected encapsulation materials to dominate from 2015 to 2026.

Usually, manufacturers provide two warranties. After 10 years in operation, the final power output (P) is 90% of the initial maximum power (P_{mpp}). And, after 20 years, P is 80% of P_{mpp}. The reasons for performance degradation are associated to different effects. First, the power drop can be explained by a decrease in the fill factor due to series resistance increase. A second reason is given by the short circuit current I_{sc} due to optical degradation. Optical degradation can be a consequence of a diminution in the transmittance of glass and encapsulant, and of light induced degradation in boron doped silicon (see Section 1.2) (Skoczek et al., 2009). In that investigation, it was reported that after 20 years the maximum power decreased at rate of 0.8%/year for all tested modules, 1%/year for the modules connected to battery charger and 0.6%/year for the modules at open circuit condition. Another important finding was related to the module configuration. The glass-glass structure showed larger average degradation than glass-polymer. However there was a large deviation as some glass-glass modules performed very well while others did not. This result was explained by the different permeabilities of polymer backsheet materials, glass-glass design allowing interaction of EVA and aluminum, and high solar cell temperature. Nevertheless, as long the energy provided by PV modules satisfies the user, the end of life is not reached. According to (Skoczek et al., 2009), lifetime of PV modules is not, as assumed, limited to 20 years.

Regarding solar cell glass-encapsulant structures, it is important to consider the behavior of the incident light since optical losses occur due to the interaction between light and the structure of PV device., For instance, when the encapsulant is silicone rather than EVA (McIntosh et al., 2009), a 0.9–1.6% increase in the module photo generated current density is obtained. This gain is primarily produced due to the transmission of short wavelength light, $300 < \lambda < 420$ nm. The gain is even higher when low-absorbing glass and cells with a high internal quantum efficiency (IQE) at these wavelengths are used. Considerable improvements could be obtained by using encapsulants with higher refraction index n ($n_{EVA} = 1.5$, for conventional modules with glass-EVA encapsulant) (McIntosh et al., 2006). Nevertheless, optical losses are not trivial to assess due to the following reasons. First, the behavior of refractive index and extinction coefficient of silicon, the antireflection coatings (ARCs) and encapsulants varies with wavelength. Second, solar cells are usually textured in such a way that light reflects multiple times from the front surface, among others (Baker-Finch and McIntosh, 2010). The use of softwares offers the possibility to compute optical losses and to determine the optimal thickness of an antireflection coating with or without encapsulation (McIntosh and Baker-Finch, 2012).

Photovoltaic modules are designed based on rated data under standard testing conditions (STC) meaning that measurements are performed with 1000 W/m^2 solar irradiation, a temperature of 25 °C and reference AM1.5 spectrum (where AM stands for air mass). The STC conditions are an approximation to the noontime close to spring and autumn equinoxes in the United States. However, the real sunlight and environmental conditions where PV systems are installed can strongly differ to those defined by STC. As a consequence, PV modules may not produce the expected maximum power output. Spectral effect must be taken into consideration (Simon and Meyer, 2011). The fact that the solar spectrum varies from site to site throughout each day and year due to changes in the air mass, turbidity, precipitable water, clouds and albedo can cause large variations in the efficiency of PV modules. The highest increase in relative efficiency (0.5–1.5%) for solar cells with a good 'blue response' and for silicones encapsulant of a higher refractive index rather than EVA have been studied in McIntosh et al. (2010) (with the spectrum treated as normally incident light). Additionally, significant contributions have been found for short wavelengths in the morning or late in the afternoon (6–10%) depending on the power distribution of the spectra. The application of luminescent down shifting layers (LDS) in combination with CdS/CdTe solar cells as a function of the solar spectrum irradiance and power distribution has been considered in Alonso-Álvarez et al., 2012.

Subsequently, a great motivation is the design of PV modules with adapted module materials to perform best under local conditions. One place, which has experienced a rapid PV grow and shows further potential for PV implementation and technology development, is the Atacama Desert in Chile. The cumulative installed PV capacity in this country already reached 1.1 GW in March 2016 with 2 GW of approved PV projects to be added next (CIFES Report). Many of these large solar projects are conceived in the Atacama Desert. The Chilean desert exhibits environmental conditions in which the solar spectrum can differ from what is usually found in the north hemisphere (Cordero et al., 2016). In fact, this location represents one of the places with highest surface irradiation on Earth. The high mean altitude, a large number of days with clear skies and low absorption ozone and water vapor columns are characteristics determining the solar resource. Global horizontal irradiation (GHI) can surpass 8 kW h/m^2 per day resulting in more than 2500 kW h/m^2 per year (Escobar et al., 2012). Atacama Desert is located along the Pacific coast in South America between latitudes 20°S and 30°S with a length close to 1000 km and a surface of approximately 105,000 km^2. It is characterized as hyper arid with annual precipitations lower than 50 mm (Larraín and Escobar, 2012). Mean temperature values are 10–20 °C in winter and 20–30 °C in summer, with an air temperature below 38 °C (McKay et al., 2003). Regarding chemical composition, nitrates accounting for 28% of the soil and water-soluble salts such as perchlorates and iodides, which rarely exist anywhere else, are found (Navarro-González et al., 2003).

Solar cells are encapsulated into modules to ensure long-term environmental stability. Improved module performance can be achieved by ensuring that the light initially reflected by the solar cell is confined by its encapsulant and covering glass. In this sense, the regular array of inverted pyramids geometry as a surface texture of the solar cell provides enhanced antireflection and favorable light trapping characteristics. Such an advantage may have driven its use in record efficiency solar cells (Baker-Finch and McIntosh, 2011). The key metric to quantify optical performance of a PV device is the short-circuit current density J_{sc} which depends on front surface transmittance, light trapping and the spatial profiles of photogeneration $G(\zeta)$, where ζ is the shortest optical path, and collection efficiency η_c. In this way, the relatively high J_{sc} attributable to the capacity of the texture to improve front surface transmission, and determining that for certain designs, losses due to recombination depend on the front surface morphology, is determined (Baker-Finch and McIntosh, 2012).

1.1. Goal and approach

The main idea of this work is to evaluate the module materials in terms of photo current densities considering the reference and Atacama solar spectra. This analysis is performed for different encapsulated crystalline silicon (c-Si) solar cells. The technologies consisted of (1) a standard p-type mono c-Si, (2) a passivated