



Electrochemical mechanisms of leakage-current-enhanced delamination and corrosion in Si photovoltaic modules



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ABSTRACT

This paper analyzes the mechanisms for corrosion and delamination observed in Si photovoltaic modules subjected to high temperature and humidity with a negative-ground bias testing. Based on the thermodynamic data, the ionic component of the leakage current causes reduction reactions of water on the cathodic metallization, producing hydrogen gas and hydroxide ions. Ag fingers are strong catalysts for this reduction reaction compared to other materials used in solar cells and can be the initiation sites of corrosion and delamination caused by the electrochemical reactions. The produced hydrogen gas accumulates inside the module potentially producing a high gas pressure that can promote delamination, which is often preferentially initiated on metallization where the adhesion strength is lower [1–3]. The local basicity near the metal surface increases due to the hydroxide ion generation. Thus, the environment inside the encapsulant can be alkaline despite the presence of acetic acid decomposition products from the encapsulant. Corrosion of materials such as Si used in solar cells occurs and the extent depends on their corrosion resistance to the alkaline solution. This suggests that corrosion and delamination are interactive and promote the formation and propagation of one another.

1. Introduction

The system voltage of solar panels drives a leakage current between the solar cells and the grounded metal frames. It is well understood that Na^+ ions from the glass drift toward the cell through the encapsulant under the electrical field and can accumulate near the metallization fingers, in silicon stacking faults, and on the SiO_xN_y surface when the cells are at negative potential [4–6]. With the cells at positive bias (negative ground), metals dissolve, form metal ions, and lose electrons with the cell acting as an anode. While at a negative bias (positive ground), metals are mostly stable as a cathode, consuming electrons through reduction reactions of other reagents. The work done by Mon et al. at Jet Propulsion Laboratory shows that dissolution of metallization occurs on cells under positive polarity relative to the frame, and the dissolved metal ions drift to the frame under the electrical field and deposit to form dendritic crystallites [7–9]. The cells with negative polarity relative to the frame can produce gas bubbles at the cell/encapsulant interface, mostly on the metallization fingers [7–9]. However, the formation mechanisms of these bubbles are not discussed, and their composition is not clear.

In thin film modules, Jasen and Delahoy showed that delamination occurs in the presence of moisture [10], and that water and bias are important factors for the delamination associated with thin conductive oxide (TCO) corrosion. Delamination and/or bubble formation may also occur when the gas generation rate, which is closely related to the leakage current, is higher than the gas out-diffusion rate. This is discussed by Mon et al. where delamination was observed at a glass/TCO interface which was augmented by the use of poly vinyl butral (PVB) as compared to poly(ethylene-co-vinyl) acetate (EVA) [11]. Similar delamination phenomenon at high leakage currents was also reported by Hacke et al. for crystalline silicon modules [12]. These studies point to the importance of leakage current in many delamination and corrosion mechanisms. The accumulated charge, obtained by integrating the leakage current, has been used to evaluate the impact of potential-induced degradation [4,9,13–18]. The leakage current is strongly dependent on temperature [14,19], humidity [19,20], geometry [13], voltage, and impurities [21].

However, the electrochemistry caused by the leakage current is not well understood, and their effect on delamination and corrosion induced by these reactions are not well reported. This work aims to

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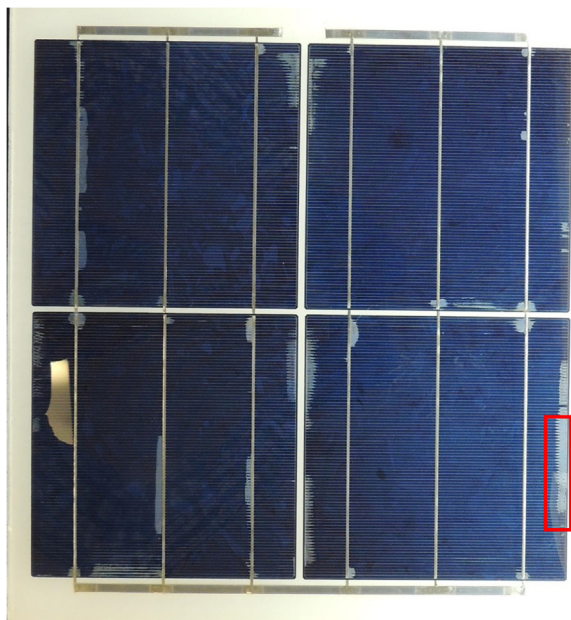


Fig. 1. Degraded mini-modules after 292 h bias testing at 72 °C/95% RH. Area in red rectangle used for SEM and associated EDS mapping on Ag fingers.

analyze the electrochemical reduction reactions induced by the ionic component of the leakage current under negative bias conditions and discuss their effects on corrosion and delamination

2. Experiments

2.1. Bias testing in environmental chambers

The first test sample configuration was a 4-cell mini-module (Fig. 1), first stressed at 85 °C/ 85% RH damp heat (DH) for 1000 h according to IEC 61215–2 MQT 13 and then negatively biased (at -1000 V) for 292 h with an Al foil placed on the glass in an environmental chamber at 72 °C/95% RH [22]. These four cell mini-modules were constructed for exploring accelerated stress test conditions that reproduce delamination. They were constructed with layers consisting of; glass (tempered, low Fe)/EVA/cells/EVA/polyethylene terephthalate (PET) and Tedlar. The cells were conventional $n^+/p/p^+$ back surface field cells with screen printed metallization including three bus bars of 1.5 mm width, Ag grid finger of approximately 70 μm width in a 1.8 mm pitch. Lead-tin solder coated tabbing ribbon was used. The stress sequence used was non-optimized and exploratory in nature to find accelerated stress conditions to reproduce the delamination mechanism found in the field [22]. Delaminated regions were analyzed in this study by scanning electron microscope (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS).

A second type of sample was made and exposed to negative bias testing (-1000 V) at 85 °C/85% RH in an environmental chamber for up to 300 h. These samples consisted of Sn-coated Cu ribbon, without using a PV cell. A front ~ 100 μm thick, polyolefin-based encapsulant on the Cu ribbon was used in one test construction and EVA used in a second. A pH paper was placed on the front of the ribbon laminated using glass, with encapsulant on both sides, but no cell, to monitor the local acidity. A similar pH paper went through a high-temperature lamination process to check that it still worked properly.

2.2. Electrochemical measurements

A paint corrosion-testing cell was used to conduct electrochemical testing of front-contact cells (FCCs) and back-contact cells (BCCs) in deionized water [23], Fig. 2. The FCC cells were typical commercial Al

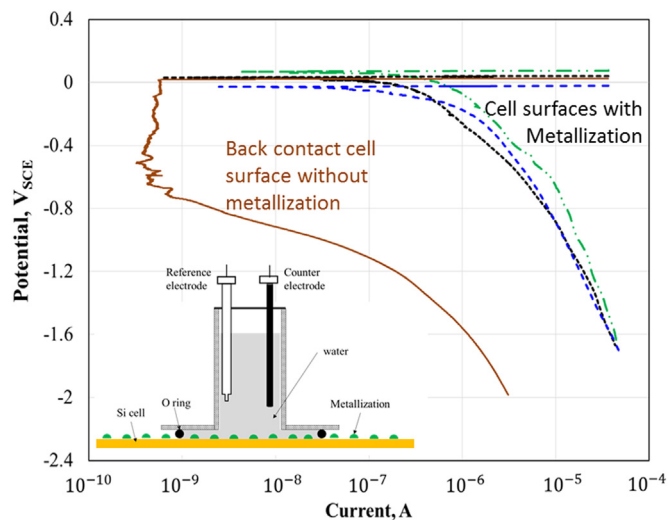


Fig. 2. Cathodic polarization curves of front-contact cells and back-contact cells in aerated DI water (the total test area is 13 cm²). Brown line – Front side of back contact cell. Blue line – Back side of back contact cell over metallization. Black line – front side of front contact cell over metallization only. Green line – front side of front contact cell over metallization and tabbing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

back surface field cells and the BCC cells were commercial SunPower cells. The total test area was 13.1 cm², with a solution volume of 40 mL. Vacuum grease was applied to the O-ring to prevent water leakage between the corrosion cell and the samples. A graphite rod was used as a counter electrode, while a saturated calomel electrode (SCE) was employed as the reference electrode. The cathodic polarization measurement was initiated from 10 mV vs. open circuit potential after 10 min delay in the deionized water (to obtain steady-state), and the scanning rate was 0.5 mV/s. Si cells were rinsed with ethanol and deionized water to clean the surface and were then dried using compressed air.

2.3. Surface characterization

Samples of the Si cells were removed from mini-modules where delamination occurred. The delaminated region in the mini-module (rectangular area shown in Fig. 1) were cut through the backsheets, back encapsulant and solar cell from the backside. Because the cell already detached from the front encapsulant, it was peeled off using a tweezer. The solar cell is not separated from the back encapsulant and back sheet, and it is directly used for surface characterization without any further surface treatment to avoid damaging the surface morphology. Scanning electron microscope (SEM) coupled with energy dispersive X-ray spectroscopy (EDS) analysis were performed on a JEOL SEM. The working distance was 8 mm and the accelerating voltage was 15 kV.

3. Results and discussion

In negative bias testing, metallization on the cells acts as a cathode, while the grounded frame or the other counter electrode is an anode (Fig. 3). The high potential between the metallization and the frame, which can be up to -1500 V, induces a leakage current through an electrical field in the encapsulant, glass, and antireflective coating on the cell. In the glass, charge carriers with a positive charge, (e.g. Na^+ , K^+ , Ca^{2+} or Mg^{2+} ions), migrate to the metallization through the encapsulant. Because of the high abundance in glass and its relatively high mobility, Na^+ is expected to be the dominant positive ionic charge carrier. Electrons are the only charge carrier in the metal to flow to the cell metallization via the applied bias to the cell. Because there is a

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