



## Reducing potential induced degradation of silicon solar cells by using a liquid oxidation technique



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### ABSTRACT

An ultrathin layer of SiO<sub>x</sub> formed on the surface of a silicon solar cell can significantly reduce the potential induced degradation effect in solar cell modules. In this work, a liquid oxidation (LO) technique was developed to oxidize silicon surfaces by using a Ti/IrO<sub>2</sub>-CoO<sub>2</sub> anode that can produce a large amount of hydroxyl radicals (OH) and other species. Our results indicate that the LO SiO<sub>x</sub> (2.5 nm) layer is very dense, thus the modules made from LO treated cells are better able to mitigate potential induced degradation than modules made from ozone oxidized cells.

### 1. Introduction

Crystalline silicon solar cells play an important role in the supply of green energy. Recently, the power loss caused by the so-called potential induced degradation (PID) effect has become a serious issue in the application of crystalline silicon solar cell modules [1,2]. Under a high voltage the metal cations (i.e. Na<sup>+</sup>) in the soda lime front cover glass of a solar cell can migrate through the ethyl vinyl acetate copolymer, which is the encapsulation material, to the silicon surface and accumulate around the stacking faults. This results in PID shunt [1,3,4]. Additionally, Naumann [5] has also reported that contamination from the solar cell's surface can also lead to the generation of shunting crystal defects.

It has been reported that a high quality silicon-SiO<sub>2</sub> interface enables a surface recombination velocity of the carriers of less than 30 cm s<sup>-1</sup> [6]. Generally, thermal deposited SiO<sub>2</sub> with a thickness of ~10 nm that is applied as a barrier layer under the silicon nitride antireflection coatings of silicon solar cells can effectively prevent the over-plating of metal through pinholes in SiN<sub>x</sub> [7,8]. Such a SiO<sub>2</sub> contact passivation layer can mitigate the PID effect by minimizing the leakage current through the antireflection coating [2]. However, thermal deposited oxides require long oxidation times and high temperatures, which can reduce the minority carrier lifetimes in silicon wafers through thermal stress, oxygen precipitation, or contamination

during the high temperature process. Alternatively, SiO<sub>2</sub> can be grown by immersing silicon wafers in an oxidizing media (e.g. a hot nitric acid solution) [9]. A light induced anodization (LIA) method [10] was also introduced by researchers to grow SiO<sub>2</sub> passivation layers. However, this oxidation process requires an acid solution and a high annealing temperature, which makes it unsuitable for reducing PID effect. The oxidation of silicon with ozone avoids the disadvantage of the wet LIA process [9,11–13]. It is, however, worth noting that neither ozone nor LIA processes are environmentally friendly. We have previously developed an atmospheric pressure plasma jet technique that efficiently oxidizes multicrystalline-Si (mc-Si) surfaces [14]. However, this technique still faces problems that hinder its implementation for large area applications in solar cell production lines.

Electrochemical oxidation is a technique that is widely used for the treatment of colored wastewater (caused by 50–70% mineralization) because of its strong oxidation performance [15–17]. In this technique, the anode for the electrochemical reaction is a noble metal oxide coated titanium anode, which is usually referred to as a dimensional stable anode (DSA) [18]. In this study, a liquid oxidation (LO) method was developed to oxidize the mc-Si surface in deionized water with a specific electrical conductivity (set by adding a specific electrolyte at a known concentration). As the DSA is applied under a set positive voltage, hydroxyl radicals, ozone, and hydrogen peroxide are produced at the anode surface. When these groups (hydroxyl radicals, ozone, and

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hydrogen peroxide), which are strongly oxidizing, are transported onto the mc-Si, the surface will be oxidized. Since hydroxyl radicals have an oxidation potential of  $\sim 2.85$  eV, which is much higher than that of ozone (2.08 eV), the DSA-based LO method provides stronger oxidation capabilities and is expected to yield much better ability to anti-PID.

## 2. Experimental procedures

### 2.1. Preparation of the DSA material

A binary oxide ( $\text{IrO}_2\text{-CoO}_2$ ) film was coated onto Ti meshes ( $100 \times 100 \times 1 \text{ mm}^3$ ) with thicknesses of about  $20 \mu\text{m}$ . Before coating, the Ti meshes were immersed into a 10% sodium carbonate solution for 10 min for ultrasonic cleaning, etched in a 15% boiling oxalic acid solution for 15 min, and then rinsed with deionized water. The precursor coating solution was a mixture of citric acid (CA) in ethylene glycol (EG) at  $60\text{--}70^\circ\text{C}$ . After total dissolution of the CA,  $\text{H}_2\text{IrCl}_6\cdot\text{H}_2\text{O}$  and  $\text{CoCl}_4$  were added to the mixture according to a molar composition of EG:CA:Ir:Co of 16:12:0.06:0.02, and the temperature was maintained at  $60\text{--}70^\circ\text{C}$  for 30 min.

The precursor mixture was uniformly painted onto the pre-treated Ti meshes. After painting, the Ti meshes were heated to  $110^\circ\text{C}$  for 5 min in a furnace to evaporate the solvent. This procedure was repeated 16 times to obtain the desired thickness; then, the electrodes were annealed at  $550^\circ\text{C}$  for 1 h to calcinate the polymer and form the metal oxides.

### 2.2. Oxide coated Ti mesh array and control system

The fabricated Ti meshes were arranged in a  $3 \times 3$  array as shown in Fig. 1(a). The pure Ti mesh and the oxide coated Ti mesh were separated by a hollowed PTFE plate. All the Ti meshes were connected with stainless steel strips and the oxide coated Ti meshes were connected with the same oxide coated Ti strips; then, both were connected to the terminal lines. To protect from erosion, the terminals of the wires were sealed with hot melted glue. Subsequently, the whole Ti-based electrode array was placed at the bottom of a chamber loaded with

deionized water, as shown in Fig. 1(b). The unit was powered by a 1 kW DC supply with the voltage range of  $0\text{--}30$  V and current range of  $0\text{--}30$  A. In our experiments the current applied to the Ti-based unit was controlled by injecting the electrolyte solution into the deionized water via a metering pump with a resolution of  $0.1 \mu\text{L}$  under a set voltage. With the onset of the DC power a large amount of bubbles were generated accompanied by  $\cdot\text{OH}$  radicals as well as other species. When a basket with mc-Si wafers was submerged in the liquid, both sides of each mc-Si wafer were oxidized within one minute, with the exact time depending on the DC current or on the concentration of  $\cdot\text{OH}$  radical in the liquid.

### 2.3. Mc-Si surface measurements and characterization

Mc-Si wafers from Canadian Solar Inc. were cleaned using alcohol, dried under an airflow, and then immersed in a 1% HF solution at room temperature for 1 min before the LO treatment. The hydrophilicity of the mc-Si samples before and after the LO treatment was characterized using water contact angle measurements (JC2000DM). X-ray photoelectron spectroscopy (Thermo Scientific Escalab 250Xi) was used to monitor the evolution of the surface chemical composition of the treated samples. The cross section of the treated mc-Si sample was investigated using high resolution transmission electron microscopy (FEI Tecnai G2 F20).

### 2.4. PID testing and characterization

Except the generation of the oxidation layer (between the silicon nitride layer and the mc-Si) using the LO or OO method, the other solar cell fabrication processes follow current production line technology. The typical structure of an mc-Si solar cell with a  $\text{SiO}_2$  layer is shown in Fig. 1(c). A commercial p-type-based mc-Si solar cell (size of  $156 \text{ mm} \times 156 \text{ mm}$  and thickness of  $200 \mu\text{m}$ ) was used in this study. The standard Si photovoltaic (PV) module consisted of a 3.2-mm-thick front cover glass (CSG Holding Co., Ltd.), two films of commercial ethyl vinyl acetate for encapsulation, the p-type Si cell, and a commercial back sheet with a structure of polyvinyl fluoride/polyethylene

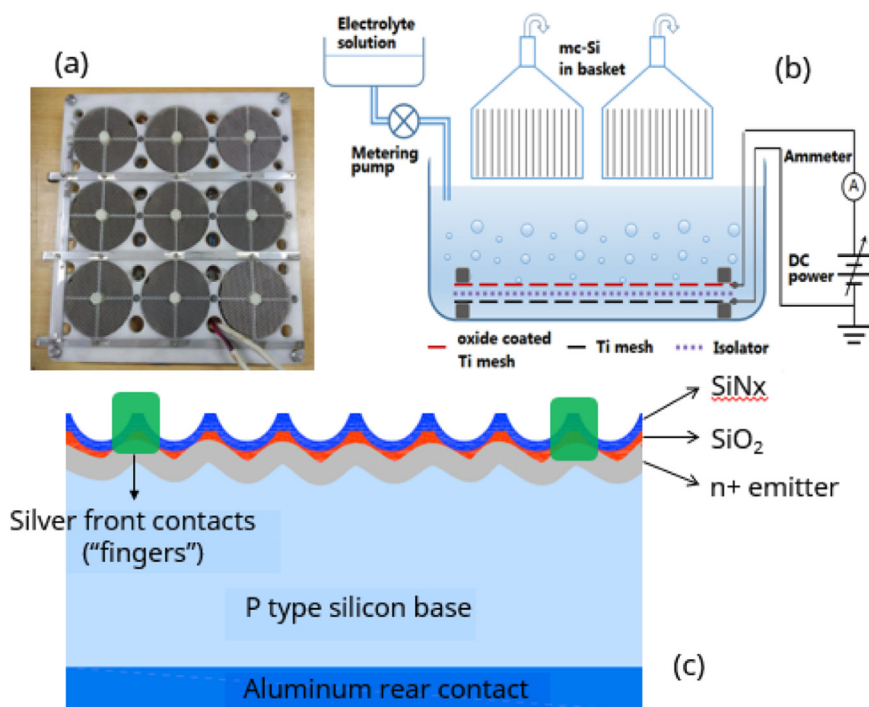


Fig. 1. (a) Photograph of the Ti DSA components. (b) Diagram of the liquid oxidation (LO) cell equipped with Ti-based meshes. (c) Illustration of a p-type mc-Si solar cell with a  $\text{SiO}_2$  layer.

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