16.8% EFFICIENT ULTRA-THIN SILICON SOLAR CELLS ON STEEL

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ABSTRACT: This paper reports on an 18 um silicon solar cell. Silicon for this solar cell is grown on porous Si so it can be separated and layer transferred. This ultra-thin silicon is transferred to and integrated with a steel substrate. The National Renewable Energy Laboratory confirms this solar cell's efficiency of 16.8%, the highest efficiency found for any silicon solar cell under 40 um, either free-standing or on a foreign substrate. We describe the design, modeling and fabrication of this solar cell.

Keywords: 18 um, ultra-thin silicon solar cell

1 Introduction

Thin silicon solar cells offer the potential of achieving high performance because their reduced bulk recombination can lead to high open circuit voltage (Voc). This high voltage can be attained if the device has a long lifetime, excellent surface passivation and low contact recombination. Moreover, high current density that further increases the voltage can be achieved with light trapping.

In 1999, Fraunhofer ISE (Institute for Solar Energy Systems) reported an efficiency of 17.6% for a thin silicon solar cell grown on a single crystal silicon substrate [1]. Its epitaxial layer thickness was 37 um on 0.01 ohm-cm silicon substrate. However, its current density (Jsc) was 32.5 mA/cm^2 due to reduced light absorption.

Recently, IMEC (Interuniversity Microelectronics Centre) reported 16% efficiency for a 30 um epitaxial silicon solar cell with a porous silicon Bragg reflector formed on a silicon substrate [2].

For free-standing thin silicon solar cells, UNSW (University of New South Wales) was the first to demonstrate a high efficiency of 21.5% with a Voc of 698.5 mV [3]. Their 47 um thin silicon wafer was chemically thinned from a good quality 400 um float-zone wafer. A 43 um free standing epitaxial layer was grown on a porous silicon structure on a silicon substrate and then detached. This layer demonstrated 19.1% efficiency [4]. However, these free-standing thin silicon wafers pose a problem because they are fragile and difficult to handle.

A solution to this fragility is attaching the thin solar cell to a mechanically strong substrate. In 2012, Solexel developed a 43 um solar cell that was created by layer transfer of the silicon layer onto a resin and fiber carrier [5]. This solar cell had an all back contact design, i.e., both emitter and base contacts were processed on what became the rear surface before layer transfer. This solar cell's efficiency was 20.6%.

We have developed an 18 um mono-crystalline silicon solar cell that is electrically integrated with bonded steel substrate. The thin layer is grown epitaxially on porous silicon, thus enabling layer separation and transfer. The steel substrate provides robust handling and a conductive back plane. It is thermal coefficient matched with the silicon layer over the temperature range of processing, which is below 500 ℃. This design allows both thin silicon surfaces to be processed separately, enabling independent passivation of each surface. Moreover, this structure is compatible with module manufacturing [6].

2 DESIGN AND MODELING

2.1 Design

Figure 1 shows the 3D structure of the ultra-thin silicon solar cell.

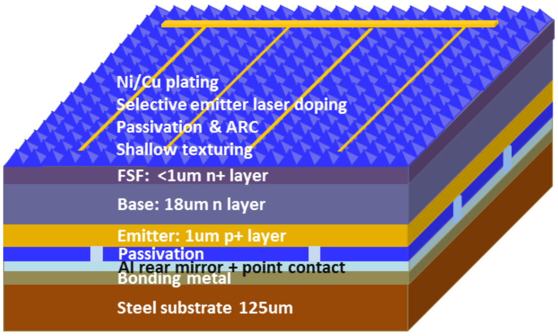

Figure 1: Diagram of ultra-thin silicon solar cell on steel substrate.

The semiconductor layers are epitaxially grown by reduced pressure chemical vapour deposition (RPCVD) [7]. These layers include a thin n+ front surface field (FSF) (5e17 cm^{-3}), an 18 um n base layer as an absorber (5e15 cm^{-3}) and a 1 um rear p+ emitter (5e17 cm^{-3}).

The rear surface design includes a mirror with thermal oxide passivation, limited area aluminum (Al) contacts, and a steel substrate. The oxide is patterned for limited area rear contacts. The vias are 15 um x 15 um on 200 um centers. This design is known as PERC (Passivated Emitter and Rear Cell) [8] solar cell rear surface design, and its mostly passivated rear surface contributes a high open circuit voltage. The use of Al with SiO2 together provide two important functions. First, the rear Al contact and the heavily doped p+ emitter form an ohmic contact without firing [8], and the 1 um 5e17 cm^{-3} p+ emitter leads to a low series resistance of 0.073 ohms-cm^2. Second, Al together with SiO2 forms a high reflective rear mirror that increases the optical path length of the light, thus allowing increased long wavelegth light absorption. The conductive bond integrates the ultra-thin silicon solar cell with the steel substrate. This 125 um steel substrate is a strong, flexible carrier that forms the rear electrode.

The front surface design includes shallow texturing, passivation, selective emitter laser doping and Ni/Cu (nickel/copper) plating. The shallow texturing etches away much of the n+ layer and yields uniform pyramids with heights of less than 2 um. The front surface is passivated by 75nm SiON (silicon oxynitride) with a refractive index of 2.0 that is deposited by PECVD (Plasma-enhanced chemical vapor deposition) [9] and acts as an anti-reflection (AR) coating. The contacts are formed by laser doping [10] because this provides local heavy doping that reduces contact resistance. The dielectric layer opening is between 15 um to 20 um. Ni/Cu is plated through light induced plating [11] and produces a Cu thickness of more than 10 um.

2.2 Modeling

A thin silicon solar cell has the potential of providing high performance due to its high voltage. To study the potential of an ultra-thin silicon solar cell, we used PC1D [12] to model the maximum possible Voc and the maximum efficiency of this solar cell. We set the lifetime of the n+ layer and p+ layer to 10 us and the lifetime of the n base to 500 us so that the Voc and efficiency wouldn't be limited by the quality of the material. We modeled the maximum current density as 39.6 mA/cm^2 and will further discuss this choice in section 4. Our modeling gave a theoretical maximum for the Voc of 767 mV and for the efficiency of 25.4% as shown in Figure 2 and Figure 3 respectively. The modeling also demonstrated that surface passivation is important for these thin silicon solar cells.

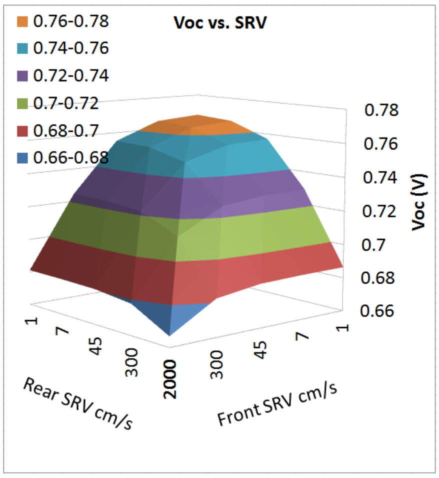

Figure 2: Open circuit voltage vs. surface recombination velocities of front and rear surfaces

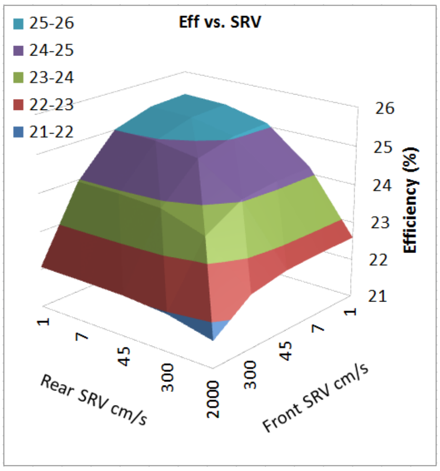

Figure 3: Efficiency vs. surface recombination velocities of front and rear surfaces

3 FABRICATION

This research is a collaborative work between UNSW and AmberWave Inc. The fabrication process of the ultra-thin silicon solar cell is as follows:

1) Layer formation of porous silicon on p+ wafer;
2) Epitaxial growth on porous silicon layer;
3) Passivation (thermal oxide) & metallization (PERC rear structure) of rear surface;
4) Transfer, bonding & integration;
5) Shallow texturing of front surface;
6) Passivation & Anti-reflectance coating (PECVD SiON) of front surface;
7) Laser doping of front surface selective emitter;
8) Light-induced plating of self-aligned Ni/Cu;

4 EXPERIMENT RESULTS

4.1 Shallow texturing and Jsc prediction

For thin silicon solar cells with indirect band gaps, light trapping is essential. The effective light path length, *P*, can be calculated using the following equation [8];

$$P = \frac{2W(1+R)}{[1-R(1-f)]}$$

where W is the physical thickness of the cell, R is the average reflectivity at the rear surface, and f is the fraction of light coupled out each time the light strikes the top surface. For textured surfaces, $f=\frac{1}{n^2}$ where n is the refractive index of silicon. Since the rear surface reflectivity measured for our test structure is 96.1% for 1200 nm wavelength light, we get a P of 32 times the physical thickness of the solar cell.

To determine this thickness, we must consider the shallow texturing that has been applied. This texturing creates pyramids of ~ 1um in diameter. Figure 4 shows an SEM image of the textured surface and Figure 5 plots the reflection from this surface with a single layer of AR coating as a percentage of the reflection from a planar surface. SEM image of Figure 4 indicates that the thickness of the solar cell is about 18 um.

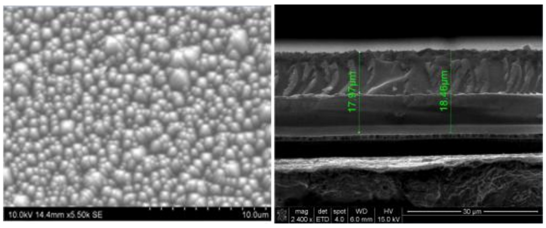

Figure 4: SEM images of shallow textured front surface and its cross section

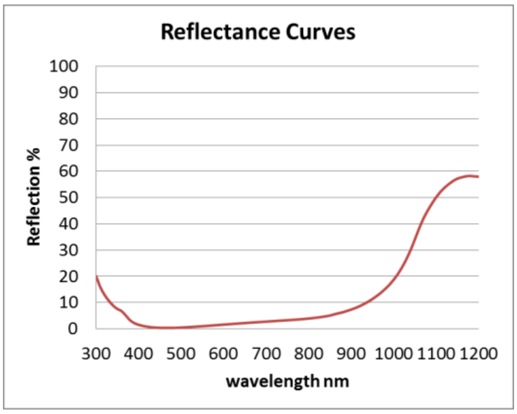

Figure 5: Reflection of the shallow textured cell with a single AR coating as a percentage of reflection from a planar surface.

To calculate the maximum Jsc, we make the following assumptions: 1, the effective light path length is 600 um (around 32 times the 18 um thickness of the textured thin silicon solar cell); 2, all absorbed photons are collected; 3, photon losses are produced by front ARC reflection and 2% shading. Using these assumptions, we calculate a maximum Jsc of 39.6 mA/cm^2. We use this value for our calculations in Section 2.2 above.

4.2 Results and discussion

The solar cell we have developed has been evaluated at UNSW and at NREL as in Table I. Our modeled maximum efficiency of 25.4% indicates the high efficiency potential for this design. To our knowledge The NREL measured Jsc of 34.5 mA/cm^2 is the highest reported for any silicon solar cell under 40 um.

Table I: Solar cell performance for an 18 um cell.

Measured by	**UNSW**	**NREL**
Area (cm^2)	4.41	4.00
Voc (mV)	634.9	632.2
Jsc (mA/cm^2)	35.4	34.5
FF %	77.6	77.2
Eff %	17.4	16.8

Figure 6 plots the IV curve for the solar cell measured by the National Renewable Energy Laboratory (NREL).

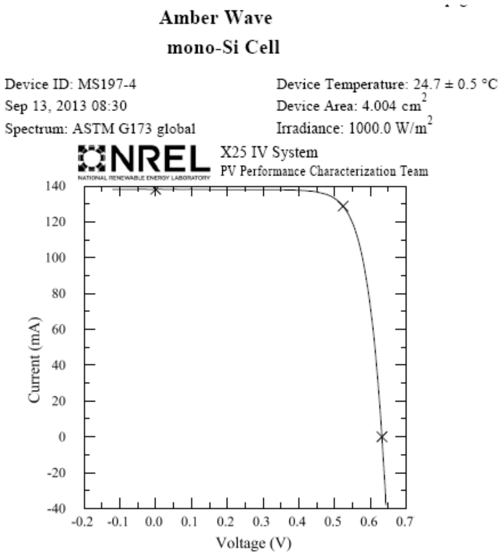

Figure 6: IV curve verified by NREL

Figure 7 compares the external quantum efficiency (EQE) curves of our ultra-thin silicon cell and the record 25% efficiency PERL cell [13]. The difference between these two curves indicates the areas of the Jsc losses. It also plots the measured reflection curve for the thin silicon solar cell 'Thin Si reflection' and the 'ARC+grid reflection' represents the reflection from front AR coating and grid without considering the reflection due to rear surface. At wavelengths below 700 nm, the two EQE curves are similar. However, the PERL cell displays better EQE at long wavelengths because its thickness is 450 um [13] 25 times the thickness of the ultra-thin silicon solar cell. The difference between the two plotted reflection curves is partially caused by escape reflection, a measure of the light that couples out when the light strikes the inner top surface.

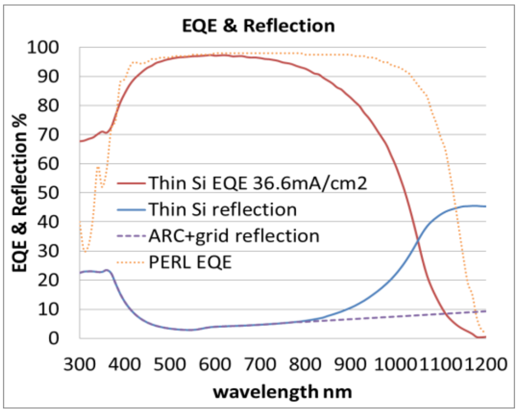

Figure 7: EQE of our ultra-thin silicon cell and the PERL cell; reflection and ARC + grid reflection for our ultra-thin silicon cell. The integrated EQE of ultra-thin silicon solar cell indicates a Jsc of 36.6 mA/cm^2 which is higher than the measured Jsc 34.5 mA/cm^2. The differences are partially due to 1) EQE measurement didn't take into the consideration of busbar area; 2) EQE measurement was done near the center of the soalr cells where there was no edge recombination.

Table II lists the best measured values for Voc, Jsc and FF of ultra-thin silicon solar cell. Their product indicates an efficiency 18.0%. These best measured values and their product indicate the efficiency potential of thsi design.

Table II: Best measured values for Voc, Jsc, FF for ultra-thin Si solar cell and their product (Eff)

Parameters	Voc (mV)	Jsc (mA/cm^2)	FF %	Eff %
Best Value	651	35.5	78.0	18.0

5 CONCLUSION

This paper details the design and development of a high efficiency ultra-thin silicon solar cell, a collaborative work between UNSW and AmberWave Inc. The NREL has confirmed an efficiency of 16.8%.

6 ACKNOWLEDGEMENT

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