FABRICATION OF LARGE AREA ULTRA-THIN SILICON SOLAR CELLS

Jianshu Han[1], Lu Wang[1,3], Anthony Lochtefeld[2], Andrew Gerger[2], Hongzhao Li[1], Mark Carroll[2], Yu Yao[1], Alison Lennon[1], Robert Opila[3], Allen Barnett[1]
1. School of Photovoltaics and Renewable Energy Engineering, UNSW, Sydney 2052 AUSTRALIA
2. AmberWave Inc., Salem, NH 03079 USA,
3. Department of Materials Science, University of Delaware, Newark, DE 19716 USA,

ABSTRACT: Recent development of the ultra-thin silicon (UTSi) solar cell is reported. Work presented in this paper focuses on device size scaling from 1-4cm^2 samples (previously reported) to 100cm^2. We demonstrate the capability and reliability of large area (100cm^2) ultra-thin silicon solar cells through the development and optimization of the fabrication process, plus monitored measurement and analysis after each step. Scaling up to large area devices will lead to large area, flexible modules. The solar cell fabrication tools, previously designed to fabricate 4cm^2 devices, were upgraded to accommodate larger area solar cells. The $SiON_x$ passivation layer deposited by PECVD has been tuned to obtain optimal film uniformity. Solar cell performance was monitored by quantum efficiency, photoluminescence and laser-beam-induced current (LBIC) measurements at various stages in the fabrication process. Device performance on this material with the size of 100cm^2 has been reported for the first time. Cell efficiency of 15.8% has been achieved on 100cm^2 cells as verified by NREL, and a more recent 90cm^2 cell with 16.5% efficiency was measured at UNSW.

Keywords**:** Thin Si Solar Cell, Epitaxy.

1 INTRODUCTION

Thin crystalline silicon solar cells have potential to achieve high efficiency due to the potential for increased voltage. Thin silicon wafers are fragile so means of support must be provided. One attractive design that solves this problem is the ultra-thin silicon (UTSi) solar cell on steel. The silicon layer on this device is approximately 20μm thick, and a steel alloy substrate is bonded to the cell to provide mechanical support and back plane electrical connection. The thin crystalline silicon layer growth and electrical integration with a steel substrate ensures physical robustness while remaining flexible. Based on the PERL structure [3] and utilizing laser doping, light induced plating and shallow texturing technologies, this solar cell obtains the manufacturing potential of conventional wafer based solar cells. This design has achieved a conversion efficiency of 16.8% (NREL verified) on a 4cm^2 device [1]. Scaling the design to 100cm^2 demonstrates the manufacturing viability and potential of this technology. Scaling up to 100cm^2 cells has also enabled interconnection and lamination studies.

2 CELL STRUCTURE

Figure 1 illustrates the structure of the ultra-thin Si solar cell. The solar cell is approximately 20μm thick, bonded to a 125μm steel substrate. The 18μm n-type base is sandwiched between a 2μm n-type front surface field layer and a 1μm p-type rear emitter, both with relatively light doping. Optical enhancement is achieved by shallow texturing combined with a $SiON_x$ anti-reflection coating, which also provides front surface passivation to the device. The front contact is formed by a stack of Ni and Cu with finger width of 30-60μm. The rear surface is contacted by Al through a layer of patterned thermal SiO_2. The layer of Al also functions as the backside mirror in the UTSi device.

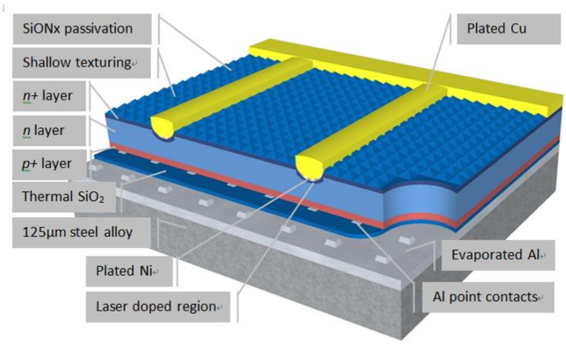


Figure 1: Structure of the UTSi solar cell

The immediate advantage of adapting an ultra-thin cell design, apart from eliminating the conventional kerf loss problem, is the potential to improve open circuit voltage by reducing bulk recombination. The modeled upper value for Voc is 767mV based on this structure [1], and can lead to 22% cell efficiency.

3 DEVICE FABRICATION

The fabrication process of the UTSi solar cell begins at AmberWave Inc., with formation of a layer of porous Si on heavily doped p-type substrate wafers via anodic etching. The active layers of ultra-thin silicon are epitaxially grown over the porous Si by reduced pressure chemical vapor deposition at temperatures above 1000°C. During the growth, dopants are introduced into the layers resulting in formation of the n-type front surface and base regions, and the p-type emitter region. The n-type cell structure minimizes the potential of boron-oxygen defect problems, and the rear emitter prevents junction shunting during the laser doping process.

Once the semiconductor layers are formed, AmberWave then grows a layer of thermal SiO_2 on the rear side and creates point contact patterning followed by Al evaporation. The wafer is subsequently bonded to a 125μm steel alloy substrate and detached from the original silicon substrate, with the porous Si serving as a splitting layer [6]. These devices are then shipped to UNSW for solar cell fabrication.

At UNSW, the process starts by chemically removing the remaining porous silicon residues on the front surface from the detaching process. Shallow pyramidal textures are then formed using a KOH based solution, with isopropanol and polyethylene glycol as additives. The average pyramid size is 1-2um to ensure good light coupling and minimal loss of silicon material. After cleaning in RCA#1 and then diluted-HF solutions, a layer of high quality $SiON_x$ is grown in a plasma enhanced chemical vapour deposition (PECVD) tool at 400°C. This provides good passivation to the surface, hydrogen to the bulk and anti-reflection coating (ARC) to the device. The front contacts are patterned and doped by a 532nm continuous-wave laser with the assist of spin-on dopant [4]. Then a stack of Ni and Cu forms the fingers and busbars using self-aligning light induced plating technology [5]. The edges of the device are then isolated with a combination of laser cutting, mechanical trimming as well as chemical etching.

4 RESULTS AND DISCUSSION

The $SiON_x$ film produced by the PECVD process has a consistent refractive index of 2 to 2.1; however, the deposited film thickness varied across the sample surface. This was caused by sample warping under heat, a result of thermal mismatch between the device layer (Si) and the substrate layer (steel). The film uniformity was optimized by varying PECVD gas ratios and measuring the deposition rate at different locations in the chamber. To characterize this shift of uniformity, Light Beam Induced Current (LBIC) is used to scan the cell surface with a 404nm laser. The tool measured and plotted the corresponding percentage reflection as shown in Figure 2.

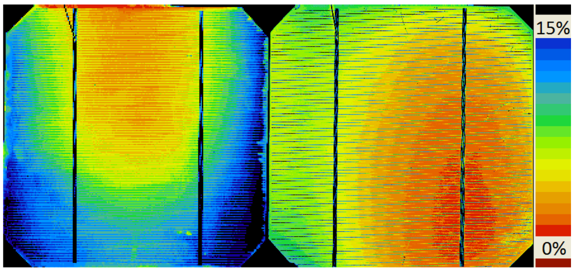


Figure 2: Reflection measurement with a 404nm laser on LBIC shows performance of the $SiON_x$ film before (left) and after (right) optimization

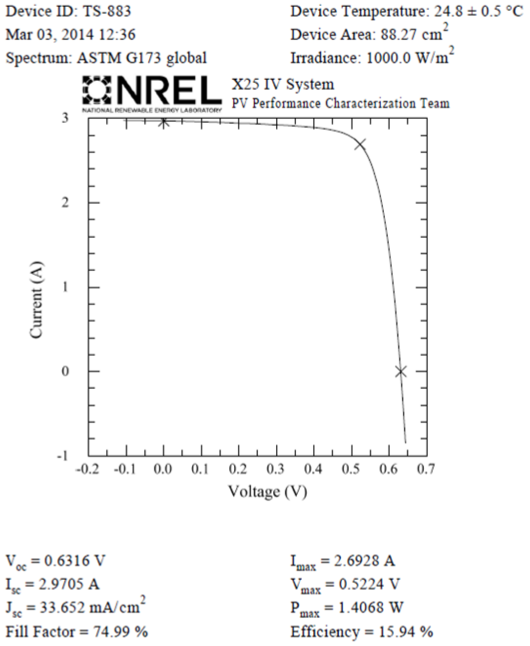
The I-V characteristics were measured in an h.a.l.m. cetisPV-Celltest3 tester at UNSW. Table I summarizes some of the milestone results of the large UTSi solar cell fabrication project.

Table I: Large area UTSi cell milestones

Area	UNSW			NREL		
	Voc(mV)/Jsc (mA/cm^2)/η			Voc(mV)/Jsc (mA/cm^2)/η		
50cm^2	569	28.2	11.9%			
50cm^2	616	33.7	15.6%			
100cm^2	593	31.7	14.4%			
100cm^2	609	35.0	16.2%	612	33.9	15.8%
90cm^2	632	35.0	**16.5%**	632	33.7	**15.9%**

TS883 is the cell with highest efficiency, measured as 16.5% at UNSW and 15.9% by NREL (Figure 3). The device was shunted at two fingers after the standard fabrication process, and the problem was rectified using a mechanical shear (Figure 4). The effective cut with this shear confirms the robust nature of the UTSi structure. It also allows cutting over laser doped fingers and busbars without causing shunt problem. The initial results show a 1-3% fill factor loss compared to a good-clean laser isolation.

Note that Jsc in the NREL measurement of TS833 was via multi-point probes which introduced some shading losses. Using a Kelvin probe on the same device, NREL measured Jsc of 34.5mA/cm^2, an increase of 0.8mA/cm^2. This allows an extrapolation to a no-shading efficiency value of 16.34%, close to the 16.5% efficiency measured by UNSW.


Device ID: TS-883
Mar 03, 2014 12:36
Spectrum: ASTM G173 global

Device Temperature: 24.8 ± 0.5 °C
Device Area: 88.27 cm^2
Irradiance: 1000.0 W/m^2

V_{oc} = 0.6316 V
I_{sc} = 2.9705 A
J_{sc} = 33.652 mA/cm^2
Fill Factor = 74.99 %

I_{max} = 2.6928 A
V_{max} = 0.5224 V
P_{max} = 1.4068 W
Efficiency = 15.94 %

Figure 3: IV measurement of the 90cm^2 ultra-thin Si cell

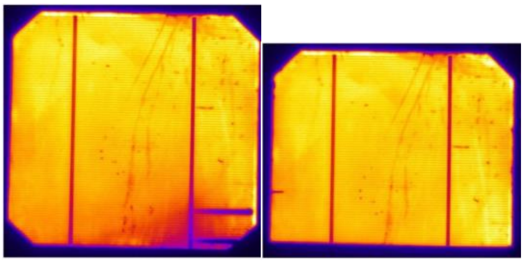


Figure 4: photoluminescence image of TS883 before (left) and after (right) a mechanical cut to remove two shunted fingers.

The reflection and internal/external quantum efficiency (IQE/EQE) of TS883 are shown in Figure 5.

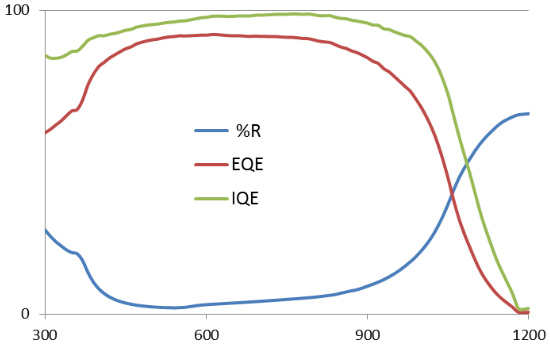


Figure 5: IQE/EQE/Reflection measurement of the champion ultra-thin Si cell with device area of 90cm^2

5 CONCLUSION

This paper discussed the design, fabrication process and progress in the development of large area (100cm^2) ultra-thin Si on steel solar cells. Improvement in the fabrication process has enabled a 90cm^2 champion cell with measured efficiency of 16.5% to be developed.

6 ACKNOWLEDGEMENT

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