Optical Characterization of Selectively Transparent and Conducting Photonic Crystals for Use in Thin Crystalline Silicon Photovoltaics

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***Abstract* — The potential use of selectively transparent and conducting photonic crystals (STCPCs) made of ITO and silica nanoparticles as rear reflectors in 10 µm crystalline silicon (c-Si) photovoltaics (PV) have been explored. Optical simulations comparing the performance of STCPC-reflectors and aluminum reflectors have been performed. The STCPCs outperform aluminum reflectors deposited on the crystalline silicon surface, but exhibit significantly lower reflectivity than the case where a substantial silica film layer is included between the aluminum reflector and the c-Si absorber. However, solar cells using STCPCs as the rear-reflector are capable of generating a significant amount of photocurrent from rear illumination in bifacial PV. An STCPC has been fabricated on a 10 µm c-Si membrane and the reflection and transmission spectral measurements demonstrate the expected increase in absorption in the red-to-NIR range.**

***Index Terms* — photovoltaic cells, silicon, conducting photonic crystals, light trapping, crystalline silicon, bifacial**

I. Introduction

As crystalline silicon photovoltaics move towards thinner silicon substrates, less incident light is absorbed and light trapping becomes increasingly important. Metallic reflectors are a common way of increasing the absorption in photovoltaics [1]. The best metallic reflectors use silica as an intermediate between the c-Si and metal [2]. This improves both the optical quality and passivation, but requires the fabrication of vias through the silica in order to create an electrical connection. An additional negative consequence of using a metallic reflector is that any rear illumination is blocked. This potentially has a negative effect on building integrated photovoltaics (BIPV), where there is often both interior and exterior lighting.

An alternate reflector design involves the use of 1D photonic crystals, or Bragg stacks. These have been shown to be effective in increasing the efficiency of thin c-Si solar cells whilst also having a relatively simple structure. In addition, by having a stop-gap only at some wavelengths, some illumination from the rear will be transmitted through the reflector and to the c-Si absorber layer. Both alternating layers of porous silicon [3] and c-Si/Silica [4] have been used in thin silicon solar cell designs. However, porous silicon Bragg stacks require many layers in order to reflect a significant amount of light. This is due to the small contrast in the index of refraction between adjacent layers in the structure. The use of bilayers of c-Si and silica required that all contacts be formed on the front surface, potentially increasing shadowing.

II. Selectively Transparent and Conducting Photonic Crystals (STCPCs)

Selectively transparent and conducting photonic crystals (STCPCs) are named for their ability to both reflect specific wavelengths of light ("Selectively Transparent") over a photonic stop-gap ("Photonic Crystal") and also their ability to conduct electricity ("Conducting"). This is achieved by alternating sputtered transparent conductive oxide (TCO) layers and porous nanoparticle layers. During the sputtering

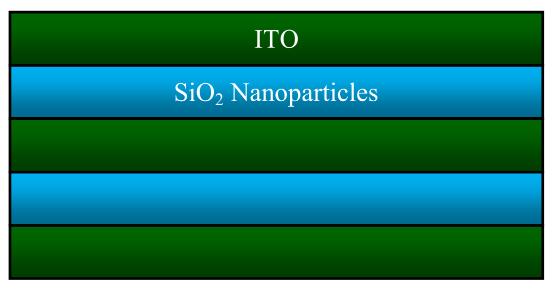

Fig. 1. Structure of an STCPC

process some of the conductive material diffuses across the porous region of the nanoparticle layers, thereby creating an electrically conductive pathway throughout the structure, while the contrast in the index of refraction between the TCO and nanoparticle films provide for their wide-band Bragg-reflectivity. The overall structure is shown in figure 1.

These structures were originally fabricated using sputtered ITO and ATO nanoparticles [5], but have since been made using sputtered ITO and silica nanoparticles [6]. STCPCs have been used in OLEDs [7] and their potential use has been explored for amorphous silicon BIPV [8] and micromorph silicon cells [9].

The use of STCPCs as reflectors in thin c-Si photovoltaics appears promising due to the fact that the materials used in an STCPC have a high index contrast (n_{ITO} = 2 and $n_{SiO2\text{-}np}$ = 1.3-1.4 @ λ = 633 nm), they do not require the fabrication of vias for electrical conductivity, and they can potentially act as the rear electrode. In this paper we report on an exploration of the use of STCPCs in thin crystalline silicon solar cells, particularly in bifacial situations, via simulation and the fabrication of an STCPC on a 10 µm c-Si membrane.

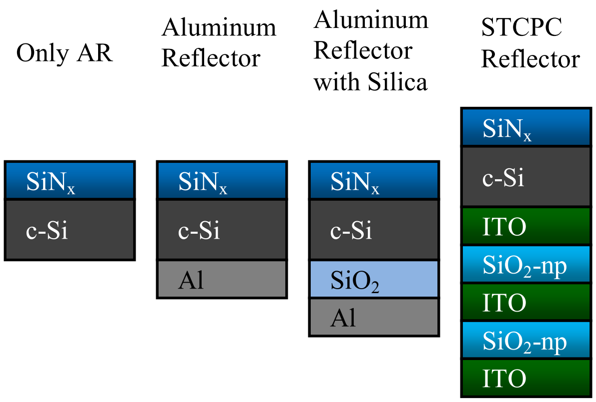

Fig. 2. The four structures modeled in the optical simulations.

III. Simulations of Bifacial Cells with STCPCs

A. Method

Optical simulations were carried out to determine the optimal midpoint of the stop-gap and the potential optical enhancement that could be achieved for a thin c-Si solar cell. Several different structures were modeled, including those with no rear reflector, an aluminum reflector, and an STCPC reflector. The different types of structures modeled are shown in figure 2, with the first three serving as a baseline for the STCPC structure.

The simulations were strictly optical in nature and used the scattering matrix technique [10] to quantify t absorption in the crystalline silicon layer for wavelengths between 300 and 1100 nm under both front and rear illuminations. To determine the photocurrent from the front illumination, the absorption was normalized to the AM1.5-g spectrum. For rear illumination, the absorption was normalized to 0, 10, 20, 30, or 40% of the AM1.5-g spectrum. It was assumed that all absorbed photons resulted in generated (and collected) carriers.

For all cell structures, the thicknesses of the different layers were varied in order to find a close to optimal structure. In particular:

- t_{SiNx}: 50-85 nm in steps of 5 nm
- t_{SiO2}: 0-310 nm in steps of 10 nm
- STCPC Bilayers: 0.5-6.5
- Bragg Peak: 250-1150 nm in steps of 25 nm

B. Results

A summary of the simulation results is given in table I. As expected, the use of aluminum reflectors significantly enhanced the generated photocurrent compared to the "Only AR" case under exclusively front illumination. The inclusion

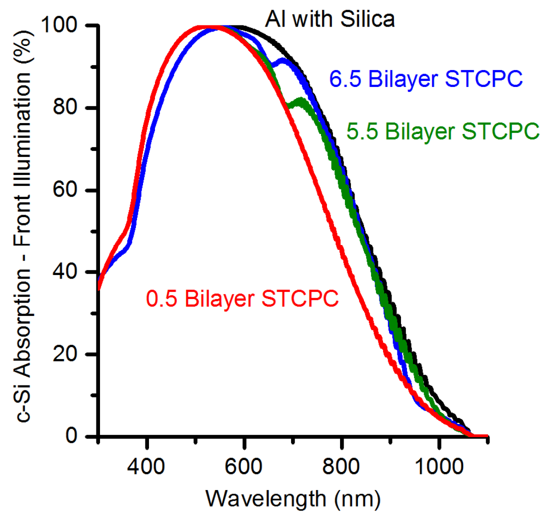

Fig. 3. Simulation results spectra for the different optimal cases (25 nm adjacent averaging). a) Al with silica optimized for 0% rear illumination; b) 6.5 bilayer STCPC optimized for 0% rear illumination c) 5.5 bilayer STCPC optimized for 10% AM1.5-g rear illumination; d) 0.5 bilayer STCPC optimized for 40% AM1.5-g rear illumination

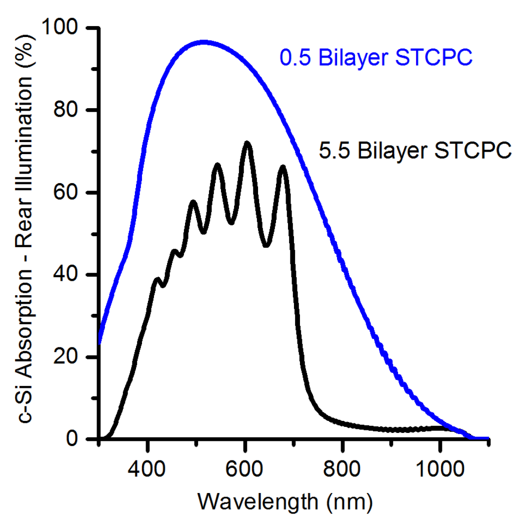

Fig. 4. Simulation results spectra for the different optimal cases (25 nm adjacent averaging). a) 5.5 bilayer STCPC optimized for 10% AM1.5-g rear illumination; b) 0.5 bilayer STCPC optimized for 40% AM1.5-g rear illumination

TABLE I
SUMMARY OF SIMULATION RESULTS

Rear Illumination	**AR Only**	**Aluminum**	**Aluminum w. Silica**	**STCPC**
None	J_{ph} = 26.0 mA/cm^2 SiN_x: 65 nm	J_{ph} = 27.4 mA/cm^2 SiN_x: 65 nm	J_{ph} = 28.4 mA/cm^2 SiN_x: 70 nm SiO_2: 120 nm	J_{ph} = 27.6 mA/cm^2 SiN_x: 70 nm # Bilayers: 6.5 λ_{peak} = 775 nm
10% AM1.5-g	J_{ph} = 27.7 mA/cm^2 SiN_x: 65 nm			J_{ph} = 28.7 mA/cm^2 SiN_x: 65 nm # Bilayers: 5.5 λ_{peak} = 825 nm
20% AM1.5-g	J_{ph} = 29.4 mA/cm^2 SiN_x: 65 nm			J_{ph} = 30.1 mA/cm^2 SiN_x: 65 nm # Bilayers: 0.5 λ_{peak} = 450 nm
30% AM1.5-g	J_{ph} = 31.1 mA/cm^2 SiN_x: 65 nm			J_{ph} = 32.5 mA/cm^2 SiN_x: 65 nm # Bilayers: 0.5 λ_{peak} = 475 nm
40% AM1.5-g	J_{ph} = 32.8 mA/cm^2 SiN_x: 65 nm			J_{ph} = 34.9 mA/cm^2 SiN_x: 65 nm # Bilayers: 0.5 λ_{peak} = 500 nm

of a silica layer between the aluminum reflector and the crystalline silicon further improved performance.

When only front illumination is used, the aluminum /silica reflector outperformed all the STCPC designs. This was not true of the aluminum reflector without silica, however, as the STCPC-based design resulted in a larger generated current.

The generated current increased in the STCPC design as the number of bilayers increased. However, the relative improvement leveled off as the number of layers was increased; the photocurrent increased by just 0.1 mA/cm^2 when the number of bilayers was increased from 4.5 to 5.5 and from 5.5 to 6.5. In addition, there was an increase in the optimal anti-reflection (AR) coating thickness as the number of bilayers increased. This is due to the fact that as more red and NIR (near infrared) light gets reflected back through the cell, the more beneficial it is to have the anti-reflection coating optimized for longer wavelengths.

When there was rear illumination, however, the advantages of using a metallic reflector quickly diminished. By 10% AM1.5-g rear illumination, a 5.5 bilayer STCPC was the optimal case, while by 20% AM1.5-g rear illumination, a rear ITO AR coating (0.5 bilayers) was optimal.

The resulting absorption spectra for the optimized cases can be seen in figure 3. The raw spectra was averaged over 25nm in order to reduce the size of the interference pattern (since perfectly coherent light is used in the simulation) while still maintaining the same area under the curve. This is true of all spectra in this paper. The 5.5 and 0.5 bilayer cases had improved absorption at short wavelengths due to a reduction in AR-coating thickness when compared to the other cases. From figure 3 it is apparent that the aluminum/silica reflector outperforms the STCPCs in small bands near 700 nm and 950 nm.

The absorption spectra under rear illumination for the optimal 5.5 bilayer cell and the 0.5 bilayer cell are shown in figure 4. The 0.5 bilayer cell greatly outperformed the STCPC-based design due to the lack of a stop-gap (from 700-1100 nm) and lower parasitic absorption.

IV. FABRICATION AND CHARACTERIZATION OF STCPCS ON THIN SUBSTRATES

A. Method

With the goal of creating STCPC contact solar cells with a 10 µm crystalline silicon absorber layer, efforts have been undertaken to fabricate STCPCs on thin substrates. Because thin crystalline silicon foils are extremely brittle, 10 µm SOI wafers have been used as the starting point, and then thinned down to a 10 µm membrane using a previously described process [11]. This process produces a 10 µm thick c-Si membrane with thick surrounding areas that can be used for handling. Reflection and transmission spectra were taken of these samples as a baseline reference using a Perkin-Elmer Lambda 1050 spectrophotometer.

The membranes were then attached to a 500 µm handle wafer using photoresist as an adhesive. STCPCs were then fabricated on the recessed-side of these membranes using RF-sputtering for the ITO layers and spin-coating for the silica nanoparticle layers. The targeted stop-gap midpoint was

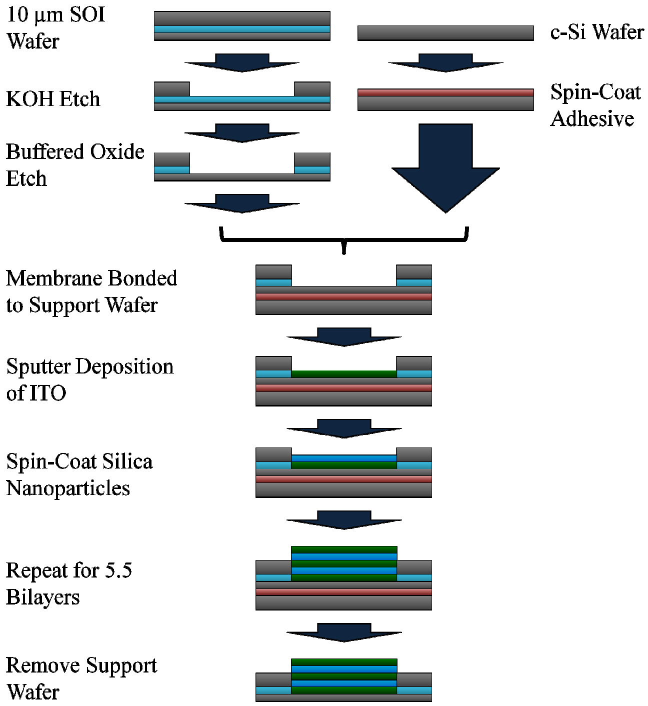

Fig. 5. Fabrication process for depositing an STCPC on a c-Si membrane

~800 nm. The STCPC was also fabricated on a 1.1 mm thick corning eagle XG glass piece to check the optical parameters matched the intended design. The entire fabrication process can be seen in figure 5.

After depositing 5.5 bilayers, transmission and reflection measurements were retaken under both front and rear illumination.

B. Results

The spectra of the STCPC fabricated on glass are shown in figure 6. The STCPC had a stop-gap peak at around 800-825 nm, which is very close to our design wavelength. In addition, is should be noted that the STCPC has a strong absorption coefficient for wavelengths shorter than 400 nm.

The absorption spectra under frontal illumination of the membrane with and without the STCPC, shown in figure 7, exhibit the expected "hump" of improved absorption around 800 nm.

When illuminated from the rear, the structure also exhibits high absorption, but this is more likely to be due to parasitic absorption in the STCPC and not current generating absorption. This can be seen in figure 8.

V. Conclusions and Summary

Using scattering matrix simulations, it has been demonstrated that the use of STCPCs as the rear reflector in thin crystalline photovoltaics instead of aluminum may be optically advantageous in cases where bifacial performance is desired. However, their optical performance falls short of the

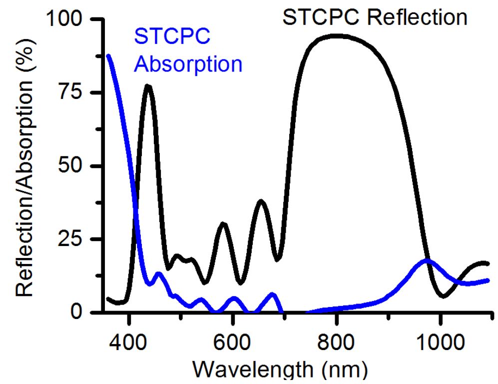

Fig. 6. Absorption and reflection spectra for an STCPC fabricated on glass (25 nm adjacent averaging)

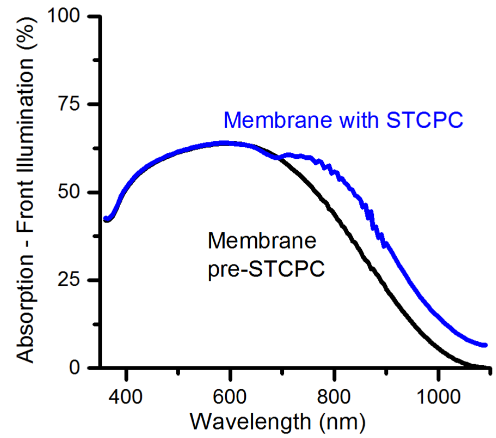

Fig. 7. Absorption spectra for a 10 um c-Si membrane with an STCPC fabricated on it illuminated from the front.

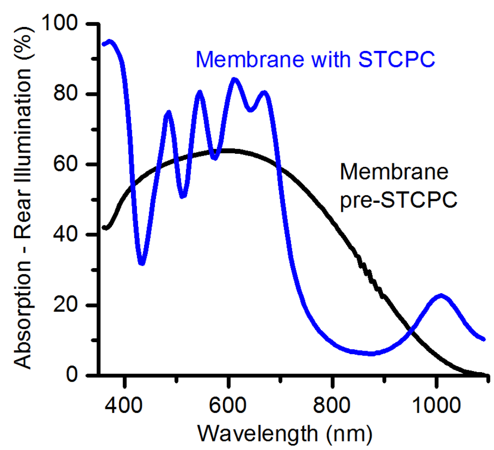

Fig. 8. Absorption spectra for a 10 um c-Si membrane with an STCPC fabricated on it illuminated from the rear.

aluminum/silica case when only front illumination is considered. Depending on the complexity of fabricating the vias in the silica for aluminum contacts, there may be fabrication advantages to using an STCPC.

In addition, STCPCs have been fabricated on 10 μm crystalline silicon membranes. The integration of the STCPC significantly improves the absorption in the infrared, confirming the optical simulations. This process can potentially be used as a starting point for the fabrication of proof-of-concept 10 μm STCPC-back-reflector bifacial PV cells.

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