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Photocurrent enhancement for ultrathin crystalline silicon solar cells via a bioinspired polymeric nanofur film with high forward scattering

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ABSTRACT

Ultrathin crystalline silicon (c-Si) solar cells represent an important technology development direction for reducing material usage and thus lowering the cost of solar electricity. Here, we demonstrate a prototype device with high efficiency assisted by a micro-/nano-structured polycarbonate thin nanofur film inspired by water ferns. The ultrathin c-Si solar cells consist of a 17 μm-thick c-Si absorber and exhibit an efficiency of up to 17.3% and short-circuit current density (J_{sc}) of 35.8 mA cm^{-2}. With the assistance of the thin nanofur, the efficiency is increased to 18.1% due to an increase in J_{sc} to 37.4 mA cm^{-2}. The photocurrent enhancement is attributed to, firstly, a more favorable refractive index transition due to the polymer addition and, secondly, the high forward scattering of the structured film, which increases the optical pathlength within the ultrathin absorber layer of the devices. To our knowledge, the present prototype device demonstrates the highest J_{sc} and efficiency in the area of ultrathin c-Si solar cells with an absorber layer of less than 20 μm.

1. Introduction

Crystalline silicon (c-Si) solar cells have historically been the most important photovoltaic (PV) technology with a present global market share greater than 90% [1,2]. It is not expected that another PV technology will replace the dominant position of c-Si in the near future. Therefore, "bolt-on" technologies that exhibit the potential for enhancing conversion efficiencies and/or lowering costs of c-Si PV are attractive. For the future development trend of c-Si solar cells, two directions can be foreseen. The first is to continue improving the efficiency on the basis of conventional thick c-Si wafers via advanced processing techniques or cell architectures, which can be implemented by either single-junction c-Si [3,4] or multi-junction tandem solar cells [5–7]. The second direction is to significantly reduce the thickness of the c-Si absorber so that silicon material cost, which represents as much as 40% of the present PV module cost [1], is also reduced.

To enable ultrathin c-Si solar cells to realize a high photocurrent and energy conversion efficiency, a key challenge is to retain high light absorption, despite c-Si possessing an indirect bandgap. Due to the advantages of low cost and scalability, micro-scale pyramidal texture is typically employed in PV industry for light absorption enhancement; and nano-scale surface texture is often used in the studies for higher absorption [8–15]. Metallic nanoparticles were adopted to improve light absorption by means of plasmonic resonance [16–20]. Photonic crystal structure and distributed Bragg reflector (DBR) utilize high back reflection when these structures are applied at the rear of the solar cells [21–25]. Finally, the principle of refractive index grading has also been shown to improve light in-coupling to the solar cells and thus increase the photocurrent [26–32]. In the area of thin and ultrathin c-Si solar cells, several key research results for c-Si thickness less than 50 μm are summarized in Table 1.

In this work, we investigate and demonstrate photocurrent enhancement for ultrathin crystalline silicon solar cells via a bioinspired micro-/nano-structured polymeric thin nanofur film with high forward scattering [26]. The ultrathin c-Si solar cell consists of a 17 μm-thick base c-Si absorber. When we apply the micro-/nano-structured polycarbonate (PC) film as top cover to the ultrathin c-Si solar cell, the photocurrent is significantly improved. The attached nanofur film is inspired by the leaves of water fern *Salvinia cucullata* and *Pistia stratiotes* and was previously reported to exhibit very high transmittance and forward scattering, which result in positive light extraction from organic light emitting diodes and photocurrent generation from

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Table 1
Summary of key results of thin and ultrathin solar cells based on c-Si and polycrystalline silicon (poly-Si) with thickness < 50 μm.

Solar cell	Si thickness (μm)	J_{sc} (mA cm^{-2})	Efficiency (%)	Light trapping approach	Research group
c-Si (direct gas to wafer)	50	36.1	17.2	Random pyramid texture (size: 4–6 μm)	Crystal Solar [33]
c-Si (thin transfer)	43	37.8	19.1	Random pyramid texture (size: up to 4 μm)	ISFH [34]
c-Si (thin transfer)	35	38.5	21.2	Random pyramid texture (size: unknown)	Solexel [35,36]
c-Si (thin transfer)	20	34.5	16.8	Random pyramid texture (size: 1–2 μm)	UNSW [37]
c-Si (SOI wafer)[a]	10	29.0	13.7	Periodic nanocones (400 nm high, ∅ 450 nm)	Stanford [38]
c-Si (SOI wafer)	10	33.9	15.7	Periodic inverted nano-pyramids (700 nm pitch)	MIT [39]
Poly-Si on glass[b]	< 2	29.7	10.5	Textured glass and rear reflection	CSG Solar [36,40]

[a] SOI represents a silicon-on-insulator wafer.
[b] Poly-Si is formed via amorphous silicon (a-Si) deposition and then subsequent solid phase crystallization.

conventional screen-printed multicrystalline silicon (mc-Si) solar cells [26]. However, the very high forward scattering justifies further investigations in particular in combination with ultrathin c-Si solar cells considered here, because it will result in a longer optical pathlength within the c-Si absorber layer hence affording higher absorption and photocurrent. In addition, the previous work only measured the external quantum efficiency (EQE) and the photocurrent values were obtained via integration. In contrast, the present work measures the photocurrent and also investigates the power conversion efficiency. Importantly, the present prototype device shows the highest short-circuit current density and the best efficiency in the area of ultrathin c-Si solar cells with Si thickness less than 20 μm we are aware of.

2. Device fabrication details, characterization, and simulation method

2.1. Device fabrication details

Fig. 1 depicts a cross-sectional schematic of the device architecture under investigation in this work, while the inset at bottom-right of Fig. 1 shows a top-view image of a real device, where the active area is approximately 7 mm × 10 mm. As is shown, the front electrode consists of 50 μm-width lines and the spacing of lines is 800 μm. The front contact is made of Cu/Ni.

The ultrathin c-Si solar cells were based on a *p*-type wafer (around 20 μm) with mesoporous layers permitting layer transfer. The present ultrathin c-Si solar cell is bonding on the stainless steel substrate. The

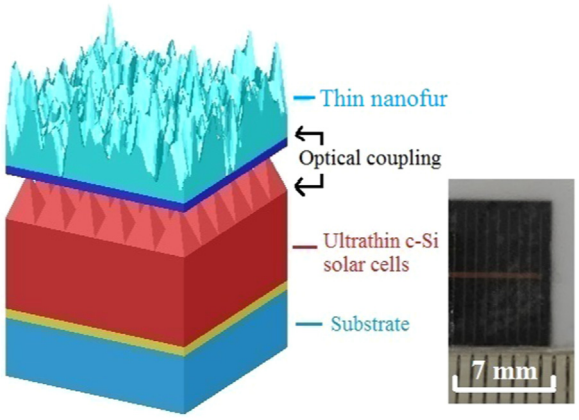

Fig. 1. A three-dimensional schematic (Not scaled) of the high-performance ultrathin c-Si solar cell device, where the thin nanofur film is optically coupled into the bottom textured ultrathin c-Si solar cell via an intermediate index matching liquid; The bottom-right inset is an image of a ultrathin c-Si solar cell with the thin nanofur coupled at the top.

boron (B)-doped epitaxial layer with 2 × 10^{16} cm^{-3} is grown via chemical vapor deposition at about 1100 °C. The rear SiO_2 thin film with 250 nm thickness is grown via plasma enhanced chemical vapor deposition (PECVD). Rear local contacts are implemented via laser drilling, which consists of openings of 18 μm and the pitch of ~250 μm. Back surface field (BSF) formation is conducted via the epitaxial growth using a recipe of doping concentration (5 ×10^{18} cm^{-3}). Metallic aluminum (Al) is used for back contact via thermally evaporation. For front surface process, the porous layer is removed via potassium hydroxide (KOH) or sodium hydroxide (NaOH) solution at 40–45 °C. The front pyramidal texture is conducted by using NaOH solution with the temperature of 82 °C. The small-sized pyramidal texture is formed in a short time of 5–7 min. The *p-n* junction is conducted via a phosphorus emitter using phosphorus trioxychloride ($POCl_3$) source at about 850 °C (the estimated junction depth in the range of 0.5–1 μm). The n^+ emitter has doping concentration of around 5 × 10^{18} cm^{-3} at front surface. A 75 nm-thick amorphous hydrogenated silicon nitride (a-SiN_x:H) is deposited via PECVD at 350 °C for realizing both front surface passivation and an anti-reflection coating (ARC).

Thin nanofur films were fabricated from PC (Makrolon LED2045, Bayer, Germany) (optical grade; n = 1.58) through a 2 step process comprising of hot embossing and hot pulling as described in previous studies [26,41] and briefly described here. First a PC foil was attached to a sacrificial cyclo-olefin-copolymer (COC) layer in a classical hot embossing process with an embossing force of 2 kN and an embossing temperature above 160 °C. In the second step (hot pulling), a finely sandblasted steel plate was heated to 215 °C and pressed into the polymer stack and retracted while still being hot. Adhesion to the retracted plate elongates the viscous polymer resulting in a dense layer of nano- and microhairs of up to 150 μm length and tip diameters down to 200 nm, which are supported by an array of microcavities. The structured PC film can finally be separated from the sacrificial COC, resulting in a self-standing thin nanofur film with thickness ranging from 70 μm to 300 μm depending on fabrication parameters and thickness of the original PC film. In addition, when the PC films are applied to the ultrathin c-Si solar cells, an intermediate index matching liquid (Cargille Laboratories, USA, n = 1.64) is used.

2.2. Characterization

Scanning electron microscopy (SEM) (Supra 60VP) was conducted to obtain the cross-sectional image of the ultrathin c-Si solar cells to determine the surface morphology. Reflectance of the solar cells with and without the attached thin nanofur was measured using a spectrophotometer (Perkin Elmer Lambda 950) equipped with an integrating sphere. The EQE curves of the c-Si solar cells were measured (PV Measurements QEX10 spectral response measurement system), while the current density-voltage (*J-V*) curves were measured with a class AAA solar simulator (Oriel Sol 3A™ class AAA, model 94023 A) with a