



## Quasi-crystal photonic structures for fullband absorption enhancement in thin film silicon solar cells



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### ABSTRACT

To further increase the efficiency of thin film solar cells, it is critical to enhance the absorption over the full spectral wavelength range in which solar cells generate electricity. In this letter, we present a fullband absorption enhancement method for *n-i-p* thin film silicon solar cells based on a Quasi-Crystal Structure (QCS) by superimposing Ag random nanotextures on periodically patterned Micro-Cone Substrates. Both light in-coupling and light trapping abilities are significantly improved thanks to the reduction of front-surface reflection originated from the gradually changed refractive index of preserved micro-cone profile after film deposition and the richer guided mode resonances caused by the QCS. An initial efficiency of 10.4% is obtained for QCS-based hydrogenated amorphous silicon germanium (a-SiGe:H) solar cells, which outperforms the planar (efficiency of 7.5%) and randomly nanotextured (efficiency of 8.7%) counter part by 38.7% and 19.5%, respectively. The QCS can also be duplicated for other thin film photovoltaic devices and provides a new approach for creating high-efficiency thin-film solar cells.

### 1. Introduction

One of the foremost challenges in designing high-efficiency thin film silicon solar cells (TFSSCs) is devising an efficient light harvesting system to enhance the absorption over the full spectral wavelength range in which solar cells generate electricity [1–5]. For this purpose, reducing the primary reflection loss at the front side to enable sufficient light in-coupling to solar cells (namely light in-coupling) [1–3,6] is considered to be the most direct and effective method. However, in order to fully utilize the improvement in light in-coupling, the incident light should be absorbed in solar cells without allowing it to escape from both the front and back surface. In other words, solar cells should satisfy  $ad \geq 1$ , where  $a$  and  $d$  is the absorption coefficient and the optical path length in the solar cells, respectively [2]. This is easier to realize in the short wavelength range due to the high  $\alpha$  of the solar cells [7]. If such a condition is also satisfied for the long wavelength, a similar absorption enhancement as the short wavelength can be expected. However, it is barely satisfied for TFSSCs due to the rather small

$\alpha$  in the IR or near-IR region owing to the nature of the silicon thin film [8–10]. In this case, the improved light in-coupling can only become more effective by thickening the cell substantially, which is disadvantageous to the cell electrical properties [11], or introducing an efficient light trapping structure to significantly elongate optical path length without increasing physical thickness [12–14]. Therefore, to greatly enhance the fullband absorption in TFSSCs, state-of-the-art light in-coupling and light trapping schemes should be needed together.

In the case of solar cells with substrate configuration (or *n-i-p* configuration), the strategy relies on the deposition of a thin Indium-Tin-Oxide (ITO, typical thickness of 60–80 nm) front contact which acts as an anti-reflection layer [15–17], and a textured Ag/Aluminum-doped Zinc Oxide (AZO) back reflector (BR) which is commonly used to reflect and scatter light [18–20] or couple of incident light to waveguide modes within the absorption layer [14]. In order to overcome low near-IR absorption in the TFSSCs, various advanced schemes of nanophotonic light trapping mechanisms were proposed, including random nanotextures [18–20], periodic nanostructures (photonic crystal)

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[8,21,22], metal nanoparticles [23–25], and so forth. However, significant absorption enhancements were mainly observed in the longer wavelength range compared with the flat ones, whatever which types of nanotextures were adopted [19–25]. The reason should be ascribed to the non-conformal growth during the deposition process [16,26]. The textures would tend to be flattened since the total thickness of the solar cells is larger than the feature size of the nanotextures, or at least in the same order of magnitude. In this case, a similar antireflection (AR) effect may occur due to the approximate front surfaces between the flat and textured solar cells. Therefore, besides to elongate optical path length to enhance IR or near-IR absorption via nano-texture light trapping, enormous efforts should also be focused on further reducing the front-surface reflection of the *n-i-p* TFSSCs to realize fullband absorption enhancement [27]. For this purpose, Sai et al. placed an additional nanotextured dielectric film on the ITO coating to serve as an artificial AR skin in TFSSCs [2]. By combining with a textured back reflector, broadband absorption enhancement was demonstrated. A similar approach was also reported by Lin et al. [3]. Although such advanced light harvesting schemes with dual-layer textured structures successfully lead to the desire gain in the short-circuit current density ( $J_{sc}$ ), cost reduction achieved by efficiency enhancement will be counterweighted mostly for the complicated process of the nanotextured AR skin film.

In this letter, we propose to simultaneously enhance light in-coupling and light trapping performance in substrate type *n-i-p* TFSSCs by exploring a class of structures that superposes the randomly nanotextures on periodically patterned micro-cone textures on the substrate. We term these structures ‘quasi-crystal’, as they appear periodic at first sight, yet they are random within each unit cell. After the deposition of each thin film layers, the morphology of the substrate micro-cone texture profiles were well preserved, while the randomly nanotextured profiles were tend to be flattened, thus to fulfill with two critical criteria in solar energy harvesting by (i) gradient index profile for antireflection and (ii) significantly elongating optical path length for enhanced absorption. Focus was put on *n-i-p* hydrogenated amorphous silicon germanium (a-SiGe:H) thin film solar cells as a convenient type due to its broader absorption wavelength range (300–900 nm) [28] than amorphous silicon (a-Si:H) solar cells (300–800 nm) and thinner absorber layer than microcrystalline ( $\mu$ c-Si:H) solar cells for conformal growing. This would be more conducive to reveal the light harvesting mechanism of the quasi-crystal textures.

## 2. Experimental

Periodic arrays of micro-cone textures were achieved by patterning sapphire substrates (PSS) [29] using a well-known thermally reflowed photoresist and dry etching method in light-emitting diode (LED) industry [30,31]. Firstly, an array of circular photo resist patterns was fabricated on c-oriented sapphires by standard photolithography technology. Then the wafers were baked out on a hot plate at different temperature as the thermal photo resist reflow method. Finally, inductive coupled plasma dry etching process was performed on these convex-patterned sapphire substrates employing reactive  $\text{Cl}_2$  gas. With different reflow temperatures, different pattern shapes can be fabricated on sapphire substrate surface after the inductive coupled plasma etching process. Nowadays the technique for PSS is very mature in the LED industry and the technique to pattern a 6-in. PSS is well established. Patterning a microstructure is much easier to realize than the nanostructure when both using optical lithography and dry etch processes. One advantage of using lithography is that it can improve the uniformity of the solar cells since every-texture morphology is identical with each other. This is beneficial for the performance improvement of large-area cell. If the process by directly patterning the micro-cone morphology on the cheap substrate such as plastic, flexible stainless steel or glass is realized in the near future, a further cost-effective improvement for the TFSSCs is expected.

To form Quasi-Crystal Structures (QCS), a randomly nanotextured Ag layer was sputtered on the above micro-cone pattern sapphire substrates, which simultaneously serves as back electric contact and back reflector. The feature size of random textures was controlled by changing the substrate temperature and film thickness. When deposited on room temperature without heating, the surface of the Ag layer was relatively flat. In this case, the waviness of the micro-cone patterns were well retained after the deposition of Ag layer. We denoted these Micro-Cone Structures with flat Ag layer as MCS. For comparison, a flat and a randomly nanotextured Ag layer were deposited on stainless steel (SS) using the same sputtering parameters as MCS and QCS, respectively. In order to suppress the parasitic plasmon absorption generated on the rough surface of metallic layer, an addition 100-nm thick AZO layer was deposited on all the Ag films by the same sputtering system, forming composited Ag/AZO BR. Substrate-type *n-i-p* a-SiGe:H cells were fabricated on these BRs by conventional radio frequency plasma-enhanced chemical vapor deposition (RF-PECVD). The structure of the solar cells consists of BR/*n*-a-Si:H (15 nm) /*i*-a-SiGe:H (200 nm)/*p*-nc-Si:H (15 nm)/ ITO (80 nm).

We used scanning electron microscope (SEM) to observe the surface morphology of the fabricated substrates, BRs and solar cells. Optical behaviors of the different BRs were characterized with an UV-VIS-NIR spectrometer (Carry 5000) with an integral sphere. Current–voltage ( $J$ – $V$ ) characteristics and spectral response were measured with a Wacom solar simulator (WXS-156S-L2, AM1.5GMM) and a quantum efficiency system (QEX10, PV Measurement), respectively. From these  $J$ – $V$  curves, the open-circuit voltage ( $V_{oc}$ ) and fill factor ( $FF$ ) were obtained and current densities were normalized with short-circuit current density ( $J_{sc}$ ) values calculated from external quantum efficiency (EQE) measurements by weighting with the AM1.5 spectrum. The total absorptance (1- $R$ ) of the solar cells was deduced from the reflectance  $R$  measured in the spectrophotometer mentioned above.

## 3. Results and discussions

In this work, the period of the micro-cone textures was fixed at 3  $\mu\text{m}$  ( $P = 3 \mu\text{m}$ ), which is significantly larger than the total thickness of the solar cells ( $\sim 0.5 \mu\text{m}$ ). It is well known that a U-shape valley is more benefit for the growth of high-quality silicon materials than the V shape [4,32]. Therefore we set aside an interval of 0.4  $\mu\text{m}$  between the two neighboring cone-shaped pattern to form a quasi U shape, as illustrated in Fig. 1. In order to provide a relatively moderate surface for the

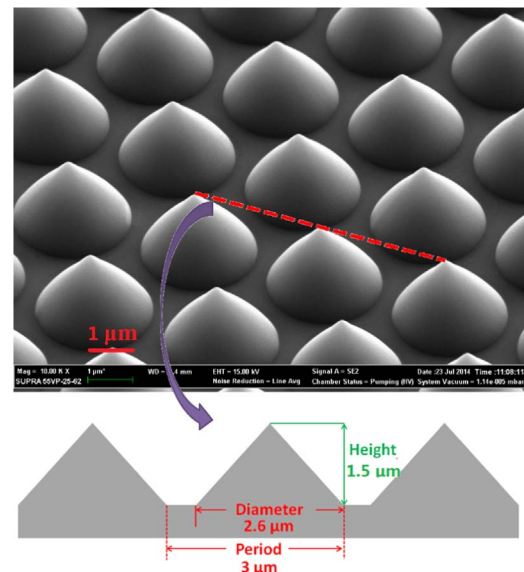


Fig. 1. SEM image of the pattern sapphire substrate and schematic structure of the micro-cone patterns.

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