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Periodically patterned micro-cone textures as high-efficiency light harvesting structure for broadband 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 essential to enhance the absorption over the full spectral wavelength range in which solar cells generate electricity. Here, we present a broadband absorption enhancement method for *n-i-p* thin film silicon solar cells using Micro-Cone Patterned Substrates (MCPSs). The periodically patterned micro-cone textured profiles are well preserved after the deposition of each thin film layers, thus to fulfill with two critical criteria in solar energy harvesting by enhanced light in-coupling and light trapping. The influence of the aspect ratio (height/period) of the MCPSs on the optical and electrical performance of the hydrogenated amorphous silicon germanium (a-SiGe:H) solar cells is discussed via experiment. We demonstrate that MCPSs based solar cells allow us to achieve an electrical performance (open-circuit voltage and fill factor) comparable to what we obtain on flat and randomly nanotextured reference samples. Thanks to the full-spectral light harvesting enhancement, initial efficiency of 10.1% is obtained for the solar cell based on MCPS with aspect ratio of 0.5, which outperforms the planar (efficiency of 7.5%) and randomly nanotextured (efficiency of 8.7%) counter part by 34.7% and 16.1%, respectively. The micro-cone light harvesting structure 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

Thin film silicon solar cells (TFSSCs) are promising candidates for both the global GW deployment of photovoltaic systems and portable power sources owing to the abundance and non-toxicity of their raw materials, mature fabrication processes, and compatibility with various types of substrates (Hsu et al., 2012a; Shah et al., 1999). A certified module efficiency of 12.3% has been achieved recently for Gen-5 size ($1.1 \times 1.4\,m^2$), indicating the high potential of the thin film silicon technology for large-scale renewable electricity generation (Moulin et al., 2016). However, a further conversion efficiency improvement is crucial to increase the cost-effectiveness of the TFSSCs.

One of the foremost challenges in achieving high-efficiency TFSSCs is to devise a state-of-the-art light harvesting system including in-coupling sufficient light into the solar cells via the front surface (namely light in-coupling) (Kuang et al., 2016; Sai et al., 2015; Lin et al., 2016) and efficiently trapping the incoming light in the thin absorption layers (namely light trapping) (Sai et al., 2013; Paetzold et al., 2014; Tan et al., 2015). For TFSSCs in substrate configuration (or *n-i-p* configuration, describing the deposition sequence of *n*-type, intrinsic, and *p*-type silicon layers onto the substrate), the typical thickness of the Indium-Tin-Oxide (ITO) front contact ranges from 60 nm to 80 nm to provide a workable anti-reflective quality (Haug et al., 2012; Soderstrom et al., 2009; Ferry et al., 2011). It is difficult to produce a textured surface for such thin ITO for additional light-trapping effect. Therefore, for *n-i-p* TFSSCs, light trapping primarily occurs owing to the textured back reflector (BR), which plays a more crucial role than in their *p-i-n* counterparts (Soderstrom et al., 2009; Yue et al., 2009). In order to overcome low near-IR absorption in the TFSSCs, various schemes of nanophotonic light trapping mechanisms were proposed,

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including random nanotextures (Yue et al., 2009; Yan et al., 2012), periodic nanostructures (Hsu et al., 2012a; Tanaka et al., 2015), metal nanoparticles (Tan et al., 2012; Zi et al., 2016), and so on. Optical path lengths were significantly elongated by introducing scattering at rough interfaces or coupling of incident light to waveguide modes in the absorber layers of the solar cells and thus absorption enhancement were achieved.

However, besides to elongate optical path length to enhance light absorption within the intrinsic layer via light trapping, enormous efforts should also be focused on further reducing the front-surface reflection of the devices to enable more light couple into the solar cells (De Jong et al., 2014). This requires that textured morphology should be needed for both front surface and back surface of the solar cells (Sai et al., 2015; Lin et al., 2016), where the former one is beneficial for light in-coupling and the latter one is advantage for light trapping. There are two methods that might realize above purpose for double-surface textures, that is, two steps and one step. For two steps, the completed solar cell was first deposited on a textured back reflector, and then an addition transparent textured layer was attached on the top of the front electrode. Sai et al. placed a dielectric sub-wavelength moth-eye film on the ITO coating to serve as an artificial AR skin in an *n-i-p* microcrystalline (μc-Si:H) thin film silicon solar cell (Sai et al., 2015). By combing with a honeycomb textured back reflector, broadband enhancement in both optical absorption and quantum efficiency was found and a significant photocurrent enhancement was demonstrated. A similar approach was also reported by Yinyue Lin et al. and Chi Zhang et al. by attaching a polymer nanopillar membrane on top of an *n-i-p* amorphous silicon (a-Si:H) thin film solar cells with a nanodent textured back reflector (Lin et al., 2016) and a patterned polyimide substrate (Zhang et al., 2017), respectively. For one step, the textured morphology of the back reflector was directly transported to the front surface of the solar cell after film deposition, and no extra textured layer on top of the front electrode was needed (Leung et al., 2014; Xiao et al., 2015). Obviously, one step is more promising for cost-effective due to its simple process with respect to the two-step method. Huang et al. demonstrated a novel substrate with patterned aluminum nanodent arrays for constructing amorphous TFSSCs (Huang et al., 2013). After the silicon layer deposition, the nanodent arrays transformed to nanodome arrays because of the shade effect, and a broadband absorption enhancement was observed thanks to the double-surface texture. It is worth noting that the nanodomes could become larger and emerge with each other when increasing the thickness of the absorbing layer such as over 100 nm, thus to easily introducing crack or void at the interface of the neighbouring nanodomes, leading to a reduction of open-circuit voltage (V_{oc}) and fill factor (*FF*) (Zhu et al., 2010).

Besides the nanodent substrates, random nanotextures or Ag nanoparticles back reflector were always adopted as the efficient light harvesting structure (Yue et al., 2009; Yan et al., 2012; Tanaka et al., 2015; Tan et al., 2012; Zi et al., 2016). However, absorption enhancements were mainly observed in the longer wavelength range compared with the flat ones for these substrates. The reason should be also ascribed to the non-conformal growth during the deposition process (Soderstrom et al., 2009; Sever et al., 2013). 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, less absorption enhancements were observed in the medium and short wavelength ranges since no light or less light transmit to the back side of the solar cells to arouse extra light trapping effect in this wavelength region. Overall, due to the non-conformal growing on the nano-texture back reflector, it is uneasy to realize an ideal double-surface textures that could enhance broadband absorption enhancement without sacrificing electrical properties such as V_{oc} and *FF* via one-step method.

In this work, we report on Micro-Cone Patterned Substrates (MCPSs) for *n-i-p* TFSSCs which can simultaneously improve light in-coupling and light trapping effect by realizing an identical textured morphology on both side of the solar cell. The waviness of the substrate micro-cone texture profiles were copied to the following deposited thin film layers, thus to fulfill with two critical criteria in solar energy harvesting by (i) effective antireflection and (ii) elongating optical path length for enhanced absorption. Periodic arrays of micro-cone structures were fabricated on the sapphire substrates. Patterned Sapphire Substrates (PSS) were widely used in light-emitting diode (LED) industry to enhance light extraction and reduce the threading dislocations (Hsu et al., 2012b; Gao et al., 2008; Sun et al., 2011; Zhou et al., 2012), ideally suited to such a study as they allow the fabrication of features with precisely defined shape. 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. 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) (Yan et al., 2011) than a-Si:H solar cells (300–800 nm) and thinner absorber layer than μc-Si:H solar cells for conformal growing. This would be more conductive to reveal the light harvesting mechanism of the micro-cone textures. We demonstrate that a proper aspect ratio (Height/period) of the MCPS allows us to achieve an electrical performance comparable to what we obtain on flat and random nanotextured reference samples, while benefiting fully from a powerful light harvesting enhancement, resulting in solar cells with an excellent initial power efficiency of 10.1%.

2. Experimental

Preparation of MCPS. A well-known thermally reflowed photoresist and dry etching method was used to fabricate MCPS (Hsu et al., 2012b; Zhou et al., 2012). The preparation of MCPS is as follows. An array of circular photo resist patterns was fabricated first on c-oriented sapphires by standard photolithography technology. The wafers were then baked out on a hot plate at different temperature as the thermal photo resist reflow method. The inductive coupled plasma dry etching process was performed on these convex-patterned sapphire substrates employing reactive Cl_2 gas. With different reflow temperatures, different pattern shapes can be fabricated on sapphire substrate surface after the inductive coupled plasma etching process.

Fabrication of BRs and solar cells. Ag/ZnO:Al (AZO) stacked film (100 nm/100 nm) was deposited on the MCPS by sputtering at room temperature to obtain a micro-rough but nano-flat surface of MCPS/Ag/AZO BR. For comparison, a flat and a randomly nanotextured Ag/AZO BR were deposited on stainless steel (SS) by the same sputtering system, respectively, where the textures were controlled by changing the substrate temperature and film thickness. 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).

Measurements and Characterization. The surface morphology of the fabricated substrates, BRs and solar cells were observed with a scanning electron microscope (SEM). 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