Renewable Energy 64 (2014) 98–104

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Thin film solar cells on honeycomb-structured substrates for photovoltaic building blocks

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ARTICLE INFO

Article history:
Received 29 April 2013
Accepted 1 November 2013
Available online 22 November 2013

Keywords:
Three dimensional solar cell
Thin film solar cell
Amorphous Si
Honeycomb

ABSTRACT

Honeycomb-structured solar cell is proposed for photovoltaic building block applications. Honeycomb-like substrates were prepared either by a conventional semiconductor processing or by a low cost wet-chemical method, and amorphous Si thin film solar cells were fabricated on these substrates. We have demonstrated one of the essential requirements for building block application, which is the low sensitivity of the light incidence angles on the power conversion efficiency; and we have identified the critical processing issues through the experimental study using various thin film deposition methods. This honeycomb-structured solar cell is a promising candidate for the future photovoltaic building block applications enabling the inherent high strength-to-weight ratio and higher efficiency at an oblique light incidence.

1. Introduction

Solar cell, a converter of the visible electromagnetic energies into electrostatic powers, provides one of renewable energy sources in the current human society; which may be a foundation for our sustainable future. Large scale power generation is one of the most important applications in solar cells, which can significantly contribute to CO_2 reduction via reduced usage of fossil fuels. Additionally, solar cells can change every aspect of the human society by providing an additional functionality; i.e. 'self-powered'. There are already lots of examples with this functionality: self-powered building or building integrated photovoltaics (BIPV) [1], self-powered car [2], self-powered mobile phone [3], self-powered aircraft [4], and etc. These and other potential function-added applications are currently emerging, and in our expectation, they will eventually change our lifestyle with a higher level of abundance and ubiquity in energy sources.

In abovementioned function-added applications, solar cells not only produce electrical power but also compose parts of the appliance structures. That is, the added function of the solar cell as a building block requires additional design considerations. These considerations may include structural strength with light weight, sufficient heat dissipation property, reduced dependence of power generation on the light incident angles, and so on. Honeycomb, a geometry learned from the nature, is the known strongest structure for a given weight [5,6]. Heat dissipation property plays a significant role in solar cells for a generic building block application, because the possible temperature rise of solar cells in an arbitrary structure significantly degrades output powers [7]. Honeycomb geometry is also beneficial in terms of large heat dissipation due to its large surface area compared to the footprint, which enhances heat dissipation through the air convention or the conduction via a filler material coated on the honeycomb structure. In addition, as illustrated in Fig. 1, solar cells on substrates with honeycomb geometry provide multiple reflections at low incident angles. This property is especially important in a building block application of solar cells, because the fluctuation of power generation due to various light incidence conditions can be suppressed. This property can be also attainable in nanostructured substrates [8], but light weight and heat dissipation advantages support honeycomb geometry with feature sizes much larger than nanometer scales.

Amorphous Si solar cell is one of appropriate candidates for building block application of solar cells, because it enables light weight [9], low temperature coefficient [10], and arbitrary formation [11]. Note that these criteria can be met in other kinds of thin

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http://dx.doi.org/10.1016/j.renene.2013.11.004

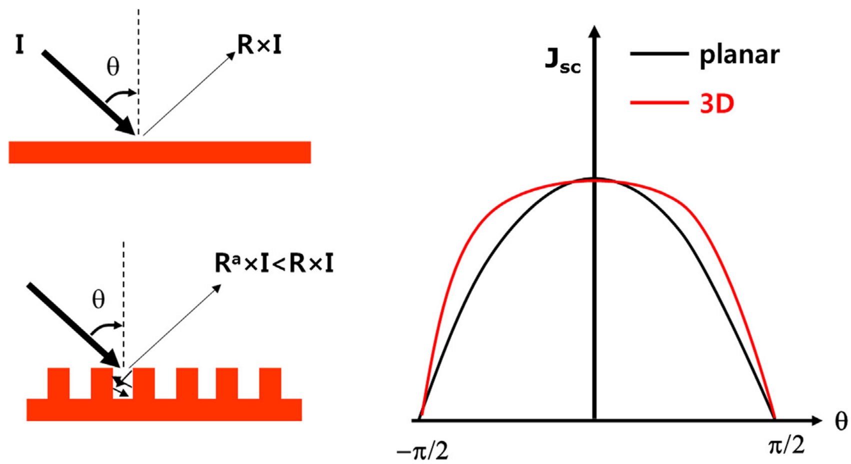

Fig. 1. Illustration describing the reflected light intensity for a planar surface (left top) and a patterned three-dimensional surface (left bottom). Arrows indicate light propagation, where thickness of the arrows roughly denote light intensity. θ is the light incidence angle, I is the intensity of the incident light, R is the reflectance of the surface material, and a is the number of multiple reflection in the patterned surface. Reflected light intensity from the patterned surface should be smaller than that from the planar surface ($R < 1$ and $a > 1$). Once a thin film solar cell is coated on each surface, short circuit current density (J_{sc}) of the three-dimensional solar cell should be larger at an oblique incidence angle due to multiple reflections, which is described in the graph on the right side.

film based solar cells such as CIGS [12], CdTe [13], or organic based solar cells [14,15] when these solar cells exhibit sufficiently low temperature coefficients.

In this work, we demonstrate the performance of amorphous Si (a-Si) solar cells deposited on substrates with honeycomb-like geometry, and investigate the fabrication issues in honeycomb-structured (HS) thin film solar cells. We have found that the incident angle dependence of power generation is reduced in HS a-Si solar cells, and conformal deposition of thin films is the key element in the fabrication process.

2. Experimental

We have designed and fabricated patterned substrates by imitating the honeycomb geometry. Honeycomb is composed of closed packed hexagons, but to facilitate isotropic optical characteristics we fabricated honeycomb-like geometry with closed packed circles as shown in Fig. 2. The feature sizes of the patterns in these substrates are in the range of tens of microns, which implies that the light propagation within this geometry can be described by geometrical optics. That is, experimental results on solar cells from these substrates can be applied to solar cells with any up-scaled HS substrates.

Two types of HS substrates were fabricated to demonstrate a-Si solar cells. The first type (substrate A) is targeted for a low cost processing, which was patterned by wet etching. This was fabricated from anodized Al substrates, where anodized aluminum oxide (AAO) layer with the thickness around 30 μm are covered on thick Al substrates. The AAO was patterned using a silicon nitride hard mask via photolithography, and immersed in an acid solution to remove the unmasked AAO layer. More details of this fabrication process are shown in Supplementary information [16]. The scanning electron microscopy (SEM) image shown in Fig. 3(b) (also in Fig. S1) represents large surface roughness (a few μm) both on the sidewalls of the hole and on the bottom surface due to the profiles of anodic oxides. We found that this large surface roughness degrades solar cell characteristics significantly with low open circuit voltages (V_{oc}) and fill factors (FF) in the preliminary experiments. Therefore, an additional kind of substrate with a smaller surface roughness is necessary, where we can exclude the effect of the surface roughness on the solar cell characteristics; and thereby, it is possible to identify the processing issues like deposition processes. The second type (substrate B) is targeted for controlled surface morphology to separately identify the principles of processing issues in the solar cell fabrication process, which are effects of conformal deposition and surface roughness on solar cell characteristics. This substrate is fabricated from Si wafers, and dry etching process followed by the photolithography is used for patterning hole-arrays. This process is based on a well-setup Si technology, and thus, the surface morphology of patterned surfaces can be controlled by established methods. As shown in Fig. 3(d), the surface roughness of the substrate B is around several tens of nm or less, which is much smaller than that of the substrate A. Substrate B is used to investigate the impact of processing methods on solar cell characteristics, and substrate A is our proposed substrate for HS solar cells; optimal application of which will be described based on the study using substrate B.

Once honeycomb-like substrate is prepared, an Al back electrode is deposited by thermal evaporation, and bottom Al doped ZnO thin film is deposited on the Al to prevent Al diffusion into the a-Si layers either by radio frequency magnetron sputtering [17] or metal-organic chemical vapor deposition [18]. In addition, n type a-Si (n-a-Si), intrinsic a-Si (i-a-Si), and p type amorphous SiC (p-a-SiC) layers are sequentially deposited using chemical vapor deposition systems (CVD). We have used plasma-enhanced CVD (PECVD) for the conventional method of deposition, and photo-assisted CVD (photo-CVD) [19] for the improvement of conformal deposition. Subsequently top Al-doped ZnO transparent electrode is deposited on the p-a-SiC using the sputtering or undoped ZnO transparent electrode is deposited on the p-a-SiC using a metal-organic CVD (MOCVD) system, whose patterning was finally performed to define the cell area of 0.25 cm^2. Nine cells with equivalent cell areas are fabricated in each run, and the median value of the measurement data is presented for comparison. This processing sequence is summarized in Fig. 2. For a comparative characterization, HS solar cells are compared with solar cells on planar glass substrates.

Photocurrent density vs. voltage (J–V) measurements were performed under AM 1.5G irradiation using Keithley 2400 sourcemeter. A constant energy spectrophotometer (YQ-25-MV, JASCO) was used for quantum efficiency (QE) spectra measurements, and QE spectra at various angles were characterized using a tilting jig.