A bioinspired hybrid light-trapping structure and its fabrication for thin-film solar cells

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***Abstract*—*A novel hybrid of quasi-random nanostructures and Archimedean spiral arrangement light trapping coating, and its low-cost, fast-production technique are presented here. Both numerical simulations and experiments confirmed the superiority of efficiency enhancement and omnidirectional light-trapping capacity when coating the created nanostructures on thin-film solar cells.*

***Keywords*—*thin film solar cell, quasi-random pattern, Archimedean spiral arrangement, Hybrid Light-trapping structure/coating*

I. Introduction

Thin film solar cells are one of the important candidates to reduce the cost of photovoltaic production with less use of active materials. However, thin film solar cell's low light absorption is stifling its development when the photons have to be absorbed within layers as thin as a few hundreds of nanometers (or less). This optical challenge can be addressed by an effective light-trapping structure/coating to maximize the solar cell's energy conversion efficiency. Over the past decade, bioinspired by the plant epidermal structures for enhanced light trapping like sunflowers, **Q**uasi-**R**andom **N**anostructures (QRNs) have been intensively investigated for light-emitting devices and photovoltaics because they can manipulate over a broadband range of light wavelengths and over wide collection angles[1]–[3]. Nevertheless, recent botanic research exhibited that the spiral phyllotactic arrangement in plants also contributes to optimizing light capture since the structural correlation largely effects the macroscopic performance of QRNs(**Fig**.1(a))[4], [5]. Thus, here we present a **H**ybrid **L**ight **T**rapping **S**tructure/**C**oating (HLTSC) by combining the superiority of QRNs and **A**rchimedean **S**piral **A**rrangement (ASA) to maximize solar energy conversion on thin-film solar cells. Moreover, as current complex nanostructured light-trapping structures is fabricated either through expensive and time-consuming top-down nanomanufacturing or the burgeoning but not yet perfected bottom-up fabrication processes, there is an urgent need to develop a low-cost, fast-production and reliable fabrication technique. In this paper, we concurrently present a new manufacturing approach via the modern optic storage technique (e.g. Blu-Ray). As a proof-of-concept, we coat the HLTSC on the silicon thin film solar cells, confirming the improved photon absorption and energy conversion efficiency. In addition, we numerically demonstrate the advancement of this technique for enhancing omnidirectional light trapping capacity. In summary, the presented study may open up a new area that repurposes a low-cost consumer product for high-end, value-added photovoltaic applications.

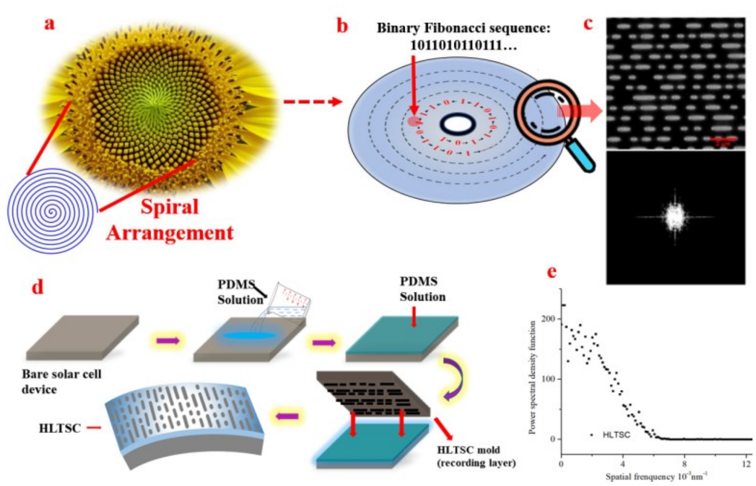

Fig. 1 (a) the sunflower image presents the spiral arrangement; (b) binary Fibonacci sequence burned into a disc; (c) the SEM image of HLTSC, and its Fast Fourier Transform; (d) schematics of HLTSC fabrication and final device configuration.

II. Method

A. QRNs Design

Here, we imported the binary Fibonacci sequence as the guide of QRNs design, because its filling ratio approximates the Golden Ratio for light capturing[6]. The Fibonacci sequence starts with two initial generations/terms: 0 and 1, and each generation afterwards (S_j) is achieved by concatenating its two prior generations[7]: $S_j=S_{(j-1)}S_{(j-2)}$, where j=3,4,5⋯ is the index of generation. The first 7 generations of the sequence go like: 0→1→10→101→10110→10110101→1011010110111 ⋯. This sequence can be

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extended or truncated as needed, and then mapped into the 2D mesh space following the ASA. Thus, the 2D Fibonacci QRN pattern is presented by the corresponding distribution of 1s (i.e., pits) and 0s (i.e., lands) as two unit building blocks (see **Fig**.1 (c)).

B. HLTSC mold fabrication

The optic discs like Blu-ray were developed for high-density data storage. Following optic disc industry standards, our designed binary Fibonacci sequence was 1:1 converted to precise nanoscale pits and lands with lengths from 150 nm to 525 nm. The track pitch and width are 320 nm and 130 nm, respectively. Then, a QRN is generated as displayed by a representative scanning electron microscopy (SEM) image in **Fig.**1 (c) Furthermore, because the optic disc is designed for the continuous data reading with relatively few random seeks, its data track forms an ASA, This unique feature perfectly matches our proposed hybrid structures. Therefore, the generated 2D Fibonacci QRNs are naturally distributed along the Archimedean spiral data tracks (**Fig**.1 (b)).

C. HLTSC enhanced solar cell manufacturing

In this work, the coatings are directly fabricated on the thin film solar cell devices using the nano-imprinting method, as schematically shown in **Fig**.1 (d). Briefly, we trim the optical discs around the edges and carefully peel off the protective layer to reveal the nanostructures on the recording layer. We then pour the polydimethylsiloxane (PDMS) solution over the top of the commercial solar cell devices in vacuum to remove bubbles. After that, we put our master/mold (i.e. the recording layer) on the PDMS solution to conduct the nano-imprinting method and bake the device at 80°C for 2 hours. After preparation, the master can be lifted off the cured PDMS solution, and the optical disc master can be reused several times if necessary. More specifically, PDMS can be used as an encapsulating protective layer due to its resistance to the thermal and UV light. It also provides electrical insulation against condensed moisture that may lead to a grounding hazard or corrosions.

III. Results and disccusions

A. Numerical Assessment

Firstly, we computed the Fast Fourier transform of the generated two-dimensional (2D) HLTSC images to demonstrate the improvement of frequency domain and spectral spectrum power density in **Fig**.1 (e). Then we numerically evaluated and verified the reflectance improvements by the commercial LUMERICAL FDTD software among bare thin film solar cell, ASA only enhanced ones, and the HLTSC ones (see **Fig**.2 (a)). The results clearly demonstrated the significant anti-reflection improvement at 550nm, which is the critical region for light-to-electricity conversion in a-Si:H thin film solar cell.

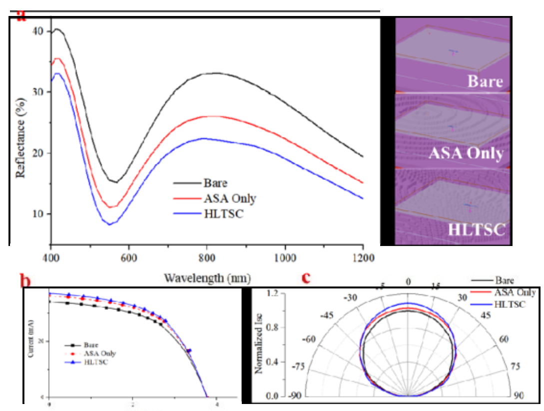

Fig. 2 (a) Simulated reflectance of a thin-film solar cell with/without HLTSC and ASA Only as comparison; (b) the I-V curves of a thin-film solar cell with HLTSC, ASA Only and without any coatings; (c) the angular dependence of a normalized photocurrent with HLTSC, ASA Only and without any coatings.

B. HLTSC enhanced thin film solar cell optical performance assessment

- Light energy conversion

A quantitative measurement is employed for evaluating the light absorption over the entire solar spectrum. **Fig**. 2 (b) illustrates the current-voltage characteristics measured under AM 1.5G illumination from a solar simulator. The chart indicates that the HLTSC enhanced thin film solar cell yields 8.62% short-circuit current improvement and 8.31% power conversion efficiency enhancement.

- Omnidirectional light-trapping

As the angle of solar irradiation varies during a day, omnidirectional light-harvesting capability is important for photovoltaic devices. According to Fresnel's law, the reflection often becomes more severe when the incident angle increases. In this study, short-circuit currents of a-Si:H thin film solar cell (with and without HLTSC, respectively) were measured for different angles of the light incidence varying from 0° to 80°, and the results in **Fig**.2 (c) indicate that a larger photocurrent improvement of over 10%.

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