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Spectrum-Splitting Diffractive Optical Element of High Concentration Factor and High Optical Efficiency for Three-Junction Photovoltaics *

Dong-Feng Lin(林冬风)[1,2], Bao-Gang Quan(全保刚)[1], Qiu-Lin Zhang(张秋琳)[1,3], Dong-Xiang Zhang(张东香)[1,3], Xin Xu(许信)[1,2], Jia-Sheng Ye(叶佳声)[4], Yan Zhang(张岩)[4], Dong-Mei Li(李冬梅)[1,2**], Qing-Bo Meng(孟庆波)[1,2**], Li Pan(潘丽)[5], Guo-Zhen Yang(杨国桢)[1,3**]

[1] *Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190*

[2] *Key Laboratory for Renewable Energy, Chinese Academy of Sciences; Beijing Key Laboratory for New Energy Materials and Devices; and Institute of Physics, Chinese Academy of Sciences, Beijing 100190*

[3] *Laboratory of Optical Physics, Chinese Academy of Sciences, Beijing 100190*

[4] *Department of Physics, Capital Normal University; Beijing Key Laboratory for THz Spectroscopy and Imaging, Key Laboratory of THz Optoelectronics, Ministry of Education, Beijing 100048*

[5] *State Key Lab of Optical Technologies on Nano-Fabrication and Micro-Engineering, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209*

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A spectrum-splitting and beam-concentrating (SSBC) diffractive optical element (DOE) for three-junction photovoltaics (PV) system is designed and fabricated by five-circle micro-fabrication. The incident solar light is efficiently split into three sub-spectrum ranges and strongly concentrated on the focal plane, which can be directly utilized by suitable spectrum-matching solar cells. The system concentration factor reaches 12×. Moreover, the designed wavelengths (450 nm, 550 nm and 650 nm) are spatially distributed on the focal plane, in good agreement with the theoretical results. The average optical efficiency of all the cells over the three designed wavelengths is 60.07%. The SSBC DOE with a high concentration factor and a high optical efficiency provides a cost-effective approach to achieve higher PV conversion efficiencies.

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Single-junction solar cells can only utilize sunlight energy above their band gaps, and the conversion efficiency suffers from the Shockley–Queisser limit of 33%.[1] To utilize more sunlight energy efficiently, the tandem and lateral multi-junction solar cells have been developed. Currently, the highest conversion efficiency has reached 43.5%[2] for the tandem design, while there are some problems including the lattice matching and the interface transport against further improvement of cell performance. The lateral multi-junction solar cells assisted with a spectral-splitting and beam-concentrating (SSBC) system are another attractive choice to achieve higher conversion efficiency due to their lower cost and well overcoming the problems of tandem solar cells.[3−6]

So far, several SSBC systems[7−17] have been designed for photovoltaic (PV) applications, including the prisms,[8,9] dichroic mirrors,[5,6,10,11] holograms[12,13] and diffractive optical elements (DOEs).[14−17] Most SSBC systems are complicated and it is hard to simultaneously realize the functions of spectral-splitting and beam-concentrating for multi-junction solar cells. However, DOEs are simple thin transmittance slices with designated thicknesses, which can directly split incident light into different sub-spectrums and concentrate the light on arbitrary positions as well. Taking the advantage of versatility, two-bandgap[14,15] and three-bandgap[16] DOEs have been designed and fabricated[14,17] for PV applications. The above-designed structures were fabricated on the photoresist by the gray scale optical lithography, which present 80% optical efficiency with a concentration factor of 2× and 60% optical efficiency with a concentration factor of 3×, respectively. These systems have increased the utilization of solar light and reduced the cost of PV materials to a certain extent. However, the concentration is too low to achieve further improvement. The high concentration of light can not only improve the efficiency of PV cells by promoting the short-circuit current, but also can reduce the cost of PV materials significantly. Therefore, a DOE with higher concentration factor should be developed.

In this Letter, a three-bandgap DOE with a high concentration factor has been designed and fabricated by five-circle micro-fabrication according to the design principles and the optimization algorithm in our previous works.[18,19] The light is efficiently split into three sub-spectrum ranges by our as-fabricated DOE and strongly concentrated on the focal plane. The system concentration factor reaches 12×. Moreover, the

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**Corresponding author. Email: dmli@iphy.ac.cn; qbmeng@iphy.ac.cn; yanggz@iphy.ac.cn

designed wavelengths (450 nm, 550 nm and 650 nm) are spatially distributed on the focal plane, in good agreement with the theoretical results. The average optical efficiency of all the solar cells over the three designed wavelengths is 60.07%. This work provides possibilities to achieve higher conversion efficiency of photovoltaics by a cost-effective method.

To design a spectrum-splitting and beam-concentrating DOE for a three-junction solar cell system (Fig. 1(a)), the design principles and optimization algorithm are applied as described in Refs. [18,19]. For three-junction photovoltaic applications, the whole diffractive spectrum is divided into three sub-spectrum ranges, which can be absorbed by three spectrum-matching solar cells. The wavelength range of 400–500 nm (sub-spectrumI) is concentrated on cell 1, 500–600 nm (sub-spectrum Ⅱ) concentrated on cell 2 and 600–700 nm (sub-spectrum Ⅲ) concentrated on cell 3 (as shown in Fig. 1(a)). The corresponding designed wavelengths are 450 nm, 550 nm and 650 nm. The designed pattern is one dimensional in the X-direction and is uniform in the Y-direction while the light diffraction is modulated by the thickness in the Z-direction. The thickness of our DOE is derived from the thickness optimization of three lens-grating combinations and ranges from 0 to 7.15 μm (Fig. 1(b)).

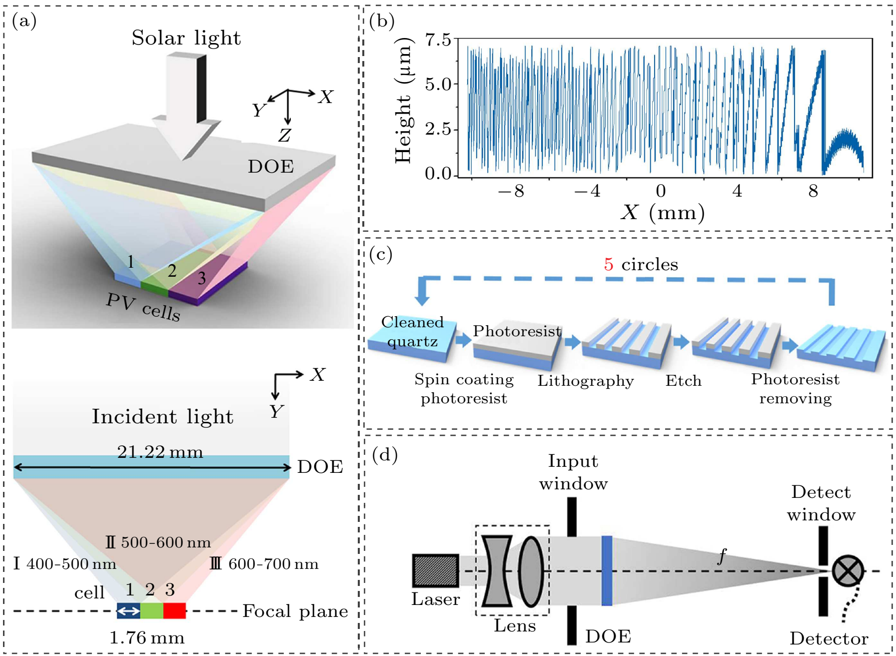

Fig. 1. (a) Schematic diagram of the DOE with spectrum-splitting the solar light and beam-concentrating on three solar cells. (b) Thickness profile of the DOE. (c) Schematic diagram of five-circle reactive ion etching process. (d) Schematic diagram of the optical measurement set-up.

For convenience of fabrication, the DOE thickness is 32-level quantized and five etching circles are applied (Fig. 1(c)). The one-circle micro-fabrication procedure is as follows: first, quartz substrates were cleaned sequentially in de-ionized water, isopropyl alcohol and acetone in an ultrasonic bath, and dried with nitrogen stream. Before spin coating the photoresist (AZ6130), the quartz substrates were heated on a 180℃ hotplate to remove the residual water and subsequently treated by hexamethyldisiloxane vapor priming process to improve the adhesion between the substrate and photoresist. The photoresist was then spun on the quartz substrates at the speed of 4000 rpm for 40 s and then prebaked at 105℃ for 2 min. Secondly, photoresist-coated substrates were exposed to the UV-light on Karl Süss MA-6 contact mask aligner system to fabricate the lithography patterns. The exposure time was 6.5 s and the development time was 1 min. The O_2 plasma reactive etching was followed for 3 min to remove the residual photoresist. Thirdly, the ICP-RIE system (Oxford Plasmalab 100) is applied to etch the quartz. The patterns on the photoresist were transferred to the quartz substrates. The reaction gases were C_4F_8 and Ar, and the etch rate was about 5 nm/s. By controlling the etch time, different thicknesses etched on the quartz will be obtained. Finally, the residual photoresist was cleaned out in acetone. Till now, one etch circle has finished and the quartz substrate with a binary-level structure was obtained. To fabricate the whole DOE, the other four similar circles are carried out subsequently.

As the DOE is designed to split light into spectra and to concentrate the spectra on the focal plane, the parameters including spatial distribution, optical efficiency and concentration factor are important and measured as follows. The optical measurement setup is as shown in Fig. 1(d). The monochrome light coming from a 10 Hz passively/actively mode-locked Nd:YAG laser passes through a series of lenses and diaphragms, then passes through a rectangle input window to form a light window with a specific size, and then illuminates the DOE sample. The monochrome light wavelengths (defined as characteristic wavelength, the same as the designed wavelength) we choose are 450, 550 and 650 nm to characterize the performance of the DOE compared with the theoretical design. The width of input window can be controlled by the diaphragm and the input window is 21.22 mm. Then, the light diffracted by the DOE finally focuses on the focal plane ($f = 80$ cm away from the DOE) and is collected by the light detector. On the one hand, the detector moves along the focal plane to measure the spatial distribution of the diffracted light. On the other hand, to obtain the intensity of input light and output light, the detector is placed separately before the DOE and on the focal plane. The intensity of output light divided by the intensity of input light, is defined as the optical efficiency, η. The concentration factor is defined as the ratio between the widths of incident light and sub-spectrum according to Refs. [14,17]. Moreover, the macroscopic image and 3D topography of the DOE sample are obtained by a general CCD camera and a white-light interferometer (Bruker Contour GT).

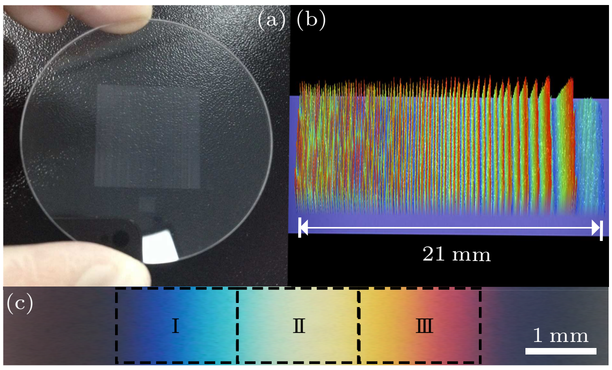

Fig. 2. (a) The DOE sample fabricated. (b) The 3D topography of the DOE measured by a white-light interferometer. (c) The spectrum split by the DOE under the actual sunlight.

The fabricated DOE sample and its whole 3D topography are shown in Figs. 2(a) and 2(b). The DOE is transparent and the width (X-direction) of the DOE is 21.22 mm (the same as the theoretical design). The thickness of the DOE in the Z-direction varies and the shape is the same as the theoretical design. Meanwhile, a continuous rainbow-like pattern spectrum is obtained under the actual sunlight (as shown in Fig. 2(c)).

The rainbow-like pattern spectrum is divided into three sub-spectrum ranges (Fig. 2(c)) and absorbed by three spectrum-matching solar cells. The width of each sub-spectrum matches with the width of each solar cell and is 1.76 mm (Fig. 1(a)). According to Refs. [14–17], the definition of concentration factor in one directional function DOE is the ratio between the width of incident light and sub-spectrum. Here the width of incident light is 21.22 mm and the sub-spectrum width is 1.76 mm. Therefore, the concentration factor of DOE is 12×. The high concentration not only can improve the efficiency of PV cells by promoting the short-circuit current but also can reduce the cost of PV materials significantly.

To investigate the energy spatial distribution on the focal plane, three beams of monochrome characteristic laser light wavelength are applied, respectively. The width of monochrome characteristic light on the incident plane is kept at 21.22 mm and the detector moves along the focal plane to obtain the energy spatial distribution of three wavelengths. As shown in Fig. 3(a), the characteristic wavelength is spatially distributed on the focal plane orderly and the distances between two adjacent characteristic lights are about 1.8 mm. The spectrum positions agree well with the simulation result (Fig. 3(b)). Meanwhile, the widths of three output characteristic wavelengths are all smaller than 2 mm and all the characteristic wavelengths can be well concentrated on the focal plane.

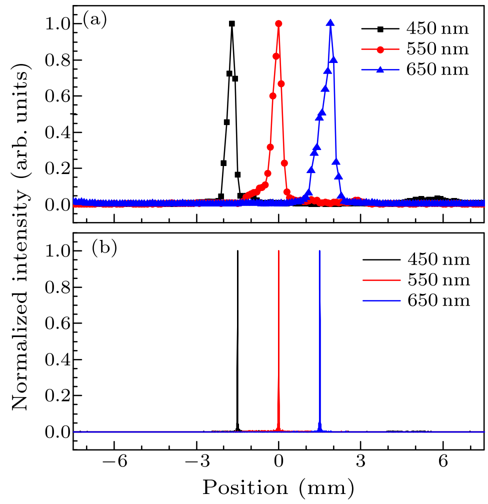

Fig. 3. (a) Experimental and (b) simulative normalized intensity of characteristic wavelengths 450 nm (black), 550 nm (red) and 650 nm (blue) on the focal plane.

As the diffractive light is ultimately utilized by the solar cells placed on the focal plane, the optical efficiencies of the whole solar cells at the three designed wavelengths are considered. The detect window matches with all three solar cells and the width is 5.28 mm. The incident light is fixed and the width of input window keeps 21.22 mm. Without the DOE, the optical efficiencies of all the whole solar cells at each designed wavelength are the same as 24.9% only (solar light intensity is uniform in the X-direction, the efficiency η of light utilized by all solar cells can be calculated to be 5.28 mm/21.22 mm). After the modulation of DOE, the light concentrates on the solar cells and the light intensity changes. The optical efficiencies of three wavelengths are measured, as listed in Table 1. The average optical efficiency of three wavelengths is 60.07% and is strongly enhanced in comparison with the result without the DOE. Obviously, with the aid of the DOE, more optical energy has been utilized by the same solar cells.

Table 1. The optical efficiencies of three designed wavelengths, η, of all the solar cells with and without the DOE.

	450 nm	550 nm	650 nm	Average
Without DOE	24.9%	24.9%	24.9%	24.9%
With DOE	49.01%	64.80%	66.41%	60.07%

Among the present three-bandgap DOE designs and fabrications,[16,17] the concentration factor (12×) of our DOE is high. The high concentration factor not only improves the efficiencies of the PV cells by promoting the short-circuit current but also reduces the cost of PV materials. Moreover, our optical efficiency (60.07%) is quite similar to the other three-bandgap designs, indicating that solar energy can be effectively utilized. Furthermore, as the DOE in our fabrication is made of quartz, it is easily preserved and duplicated in large production. The cost of the system is more economic and the solar energy utilization is higher.

In summary, an SSBC DOE for lateral three-junction photovoltaic has been designed and fabricated by the five-circle micro-fabrication process. The solar light is efficiently split by the as-fabricated DOE into three sub-spectrum ranges and strongly concentrated on the focal plane. The system concentration factor is 12×. Meanwhile, the average optical efficiency of all three solar cells over the three designed wavelengths (450 nm, 550 nm, 650 nm) reaches 60.07%. The DOE with high concentration factor and high optical efficiency helps to increase the solar energy utilization and to reduce PV materials cost. Thus the SSBC DOE is a feasible approach to achieve the better efficiency-to-cost ratios.

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