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Letter

Design of asymmetrically textured structure for efficient light trapping in building-integrated photovoltaics

Juhoon Kang [1], Changsoon Cho [1], Jung-Yong Lee *

Graduate School of Energy, Environment, Water, and Sustainability (EEWS), Graphene Research Center (GRC), Korea Advanced Institute of Science and Technology (KAIST), Daejeon 305-701, Republic of Korea

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ABSTRACT

We design a novel light-trapping structure that can be applied to building-integrated photovoltaic systems, which inherently receive incident light asymmetrically during the whole year. The structure is optimized with respect to the asymmetric angular range of the incident light by breaking the structural symmetry. We demonstrate the effectiveness of the designed light-trapping structure for various incident-angle ranges *via* thorough simulation studies and experimental results using organic photovoltaic (OPV) devices. As a result, we achieved an annual energy-production enhancement of 15% in case of OPVs installed on the vertical façade of a building in Daejeon, Korea (latitude = 36.5°).

1. Introduction

The demand of building-integrated photovoltaic (BIPV) systems is sharply emerging due to their effective space utilization in urban areas and reduced distance of energy transmission. The thin-film photovoltaic (PV) cells including organic photovoltaics (OPVs), dye-sensitized solar cells (DSSCs), and quantum-dot photovoltaics (QDPVs) are currently noticed as promising candidates for BIPV applications as their low-cost, light weight, and appearance provide many advantages for building design and construction compared to bulk crystalline silicone (c-Si) PVs [1]. One of the major obstacles for the application of such thin-film PVs is their relatively low light-absorption capacity, which results from their nanometer scale active layer thickness. Although various types of light-trapping schemes have been proposed for enhanced light absorption [2–14], there still remains much room for improvement, in particular since most light-trapping schemes are optimized only for normal incident angle. For BIPV, the annual incident angle strongly deviates from the normal direction and largely depends on installation conditions, such as the local latitude and facing direction. Therefore, new light-trapping schemes surely need to consider the annual angular variation of the incident light for BIPV in order to integrate thin-film PVs into the façade or roof of buildings with effective energy conversion.

For a PV system facing toward the sun, recent research has shown that the PV absorption can be easily improved by just laminating a 1D periodic array of V-groove textured film on the glass substrate [13]. This light-trapping structure enables the reuse of photons by guiding escaping ones back into the active layer. Thus, the optical path length within active layers is increased and, therefore, enhanced light absorption can be achieved. The light-trapping performance of V-groove textured structures is optimized for normal incident angle and sensitive to the cross-sectional angular variation of the incident light [13]. Therefore, the long direction of the 1D V-groove film has to be aligned along the east-to-west direction to minimize the daily incident-angle variation onto the cross-sectional plane and the total system should be tilted at the degree corresponding to the latitude of the installed place (i.e. toward the sun at noon on vernal or autumnal equinox) to ensure the cross-sectional incident-angle variation being within the range of ±23.5° at meridian altitude. Unfortunately, however, tilting the system is typically not allowed for BIPVs because they are installed either horizontally or vertically, and the deviation from the normal direction largely reduces the light-trapping effect of the V-groove textured film. The range of the incident angle θ is determined by the installation condition, as represented in Fig. 1. The variation of the sun height at noon can be limited to 47° and the textured array is aligned along the east-to-west line [13,14]. With such an alignment, the range of θ_i

* Corresponding author.
E-mail address: jungyong.lee@kaist.ac.kr (J.-Y. Lee).

[1] J. Kang and C. Cho contributed equally to this work.

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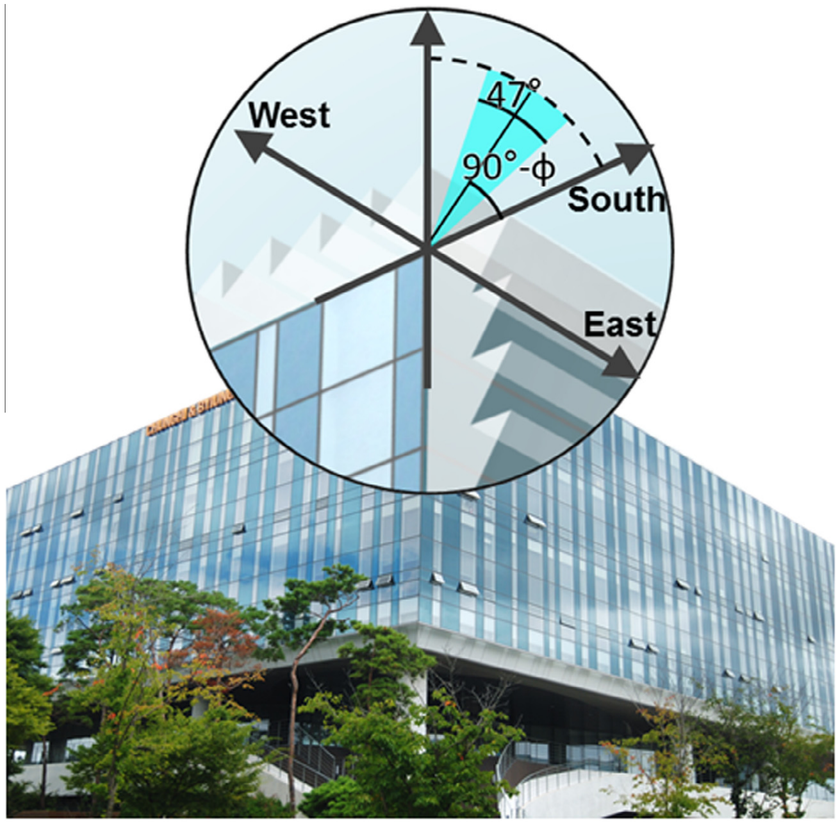

Fig. 1. Schematic showing the annual incident-angle variation, depending on the type and place of the OPV installation. The figure is not drawn to scale. Actual period of the structure is 500 μm.

is [φ − 23.5°] − [φ + 23.5°] for PV installed on horizontal roofs of buildings, and it is [90° − φ − 23.5°] − [90° − φ + 23.5°] for PV installed on vertical façades of buildings according to the annual variation of the solar altitude, where φ is the latitude of the installation place, as shown in Fig. 1.

Here, a blazed type asymmetric texturing is proposed as alternative light-trapping scheme for BIPVs to account for the asymmetric incident-angle variation. We firstly analyze the angular performance and give a strategy to find the optimal structure for the actual incident-angle range of a given BIPV. Multi-scale optical simulation is used to verify the design and effectiveness of the blazed texturing [13,14]. Then, following the optical study, the realized structure is applied to an OPV device based on PCDTBT:PC_{70}BM active material. The measurements indicate an annual energy-production enhancement of 15% while assuming a BIPV vertically installed in Daejeon, Korea.

2. Results and discussion

2.1. Simple working principles: symmetric vs. asymmetric arrangement

Previous research on symmetrically textured V-groove films focused on the trapping of internal rays approaching the side of the groove that corresponds to the surface through which the incident light is transmitted [13]; the corresponding range (blue) is denoted by R1 in Fig. 2(a). Angles between 100.8° and 112.0° were proven to be the optimal vertex angle in order to secure the trapping of internal rays through R1 for an incident angular range from +23.5° to −23.5°. However, the rays reaching the opposite side of the groove are likely to escape since total internal reflection (TIR) does not occur at that side. The range for the internal rays to escape the system through that side is denoted by R2 (pink) and it should be suppressed for improving the performance of V-groove textured structures. Fig. 2(c) shows the proportion of light that propagates through these ranges for the vertex angle of 100° (i.e., base angles $\theta_1 = \theta_2 = 40°$, as shown in the inset) as a function of the incident angle θ_i as defined in Fig. 2(a), where the incident light comes through the right side of the groove and its path is not disturbed by nearby surfaces. For example, for normal incidence, approximately 40% of the rays at the right side of the V-groove can be trapped by propagating through the R1 region; on the other hand, 60% of the incident rays escape the structure through the opposite plane. The portion of R1 decreases with increasing θ_i and, therefore, a larger amount of internal light escapes the system through R2, implying reduction of the light-trapping effect of the V-groove textured film at increased incident angle. For $\theta_i > 50°$ (dashed vertical line in Fig. 2(c)), R1 almost disappears and a new type of range denoted by R3 appears. R3 indicates the range of internal light that passes through the slanted surface (left) of the groove, but does not escape the system and re-enters the next groove, described by R3 (green) in Fig. 2(a). This range does not exist for small θ_i, but it rapidly widens as θ_i increases and the internal ray propagation becomes more oblique. Therefore, at large incident angles which, in fact, are encountered for BIPV systems, the structure has to be modified to increase the ratio of R3 to R2 rather than to guide the rays through R1. As shown in Fig. 2(b), the steep plane (right surface of the groove) of an asymmetric groove refracts the incident light more obliquely so that the internal rays can reach the lower part of the opposite surface upon reflection at the bottom of the PV and have more chances to re-enter the next groove. Fig. 2(d) and (e) show the changed ratio of R1, R2, and R3 by increasing θ_2 (right base angle) to 60° and 90°, respectively, while θ_1 (left base angle) is fixed at 40°, as shown in the inset. Whereas