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Planar photonic solar concentrators for building-integrated photovoltaics

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ABSTRACT

Planar photonic concentrators are a promising concept for low-cost building integrated photovoltaic. In this work, they are formed from colloidal photonic crystal layers deposited by the Langmuir–Blodgett technique onto clear polymethylacrylate sheets with a solar cell attached to the edge. Light is scattered into a waveguide mode and guided via total internal reflection to the edge mounted solar cell. Transmission and reflection measurements taken in different geometries strongly indicate an increased scattering of the incident light over a wide range of wavelengths, depending on the size of the beads forming the photonic crystal film. IV measurements on solar cells attached to one side of a sheet with 8 layers of 250 nm beads exhibit a relative increase in efficiency by a factor of up to 3 as compared to the blank PMMA sheet. These concentrators can increase the power output from photovoltaic cells without the need for solar tracking and have the potential of achieving a lifetime matching standard silicon solar cells.

1. Introduction

Building-integrated photovoltaics (BIPV) is a fast growing segment of the solar industry [1]. Solar concentrators designed for BIPV can be mounted on walls, rooftops or be integrated with windows or glass façades. They represent a way of balancing contributions towards natural lighting as well as creating electrically active building elements. We introduce the concept of the planar photonic concentrator (PPC) formed from colloidal photonic crystal layers deposited onto clear polymethylacrylate (PMMA) sheets with solar cells attached to the edges.

To obtain high power generation intensities, solar concentrators have to make optimal use of both the diffuse and direct components of sunlight. They harvest light by trapping the incident photons inside the concentrator material and guiding them to strategically mounted solar cells by total internal reflection (TIR). Due to their wave-guiding characteristics, these concentrators collect the sunlight from a wide range of angles, and do not need expensive sun tracking devices. Such low concentration photovoltaics (PV) technologies are estimated to be able to deliver the same amount of energy as a solar cell without a concentrating device while reducing costs by up to 40% [2]. Examples of such low concentrating systems are luminescent solar concentrators (LSCs) [3] or asymmetric compound parabolic photovoltaic concentrators [2]. LSCs have shown promising results, however, they suffer from degradation problems of the lumophores [3–6]. Using the right sheet material, PPCs can potentially achieve a lifetime similar to standard silicon solar cells.

The colloidal photonic crystals (PhCs) layers cover only one facet of the PPC. Integrated with windows or façade elements, the enhanced scattering would increase the proportion of light that is guided to the edge and thus to the solar cell (see Fig. 1) while visible as an opaque or iridescent layer on the glass itself. As the concentrating mechanism in PPCs is essentially based on scattering and diffraction of layers of spherical silica particles, we do not expect degradation over the lifetime of the sheet material [7].

2. Materials and methods

2.1. Sample preparation

Commercially available clear polymethylmethacrylate (PMMA) sheets with a thickness of 3 mm, cut to a size of 2.4 × 4.5 cm, were used as substrates. After cutting to size, the samples' edges were machine-polished to remove roughness. Prior to deposition, their surface was treated by a silane anchor deposition to improve the adhesion of colloidal particles. Solution A was prepared by mixing 19 parts of Methanol (MeOH) with 1 part of H_2O. The silane bath was prepared fresh in the fume hood by adding 2 ml of the silane anchor (3-aminopropyltrimethoxysilane) to 19.90 ml of solution

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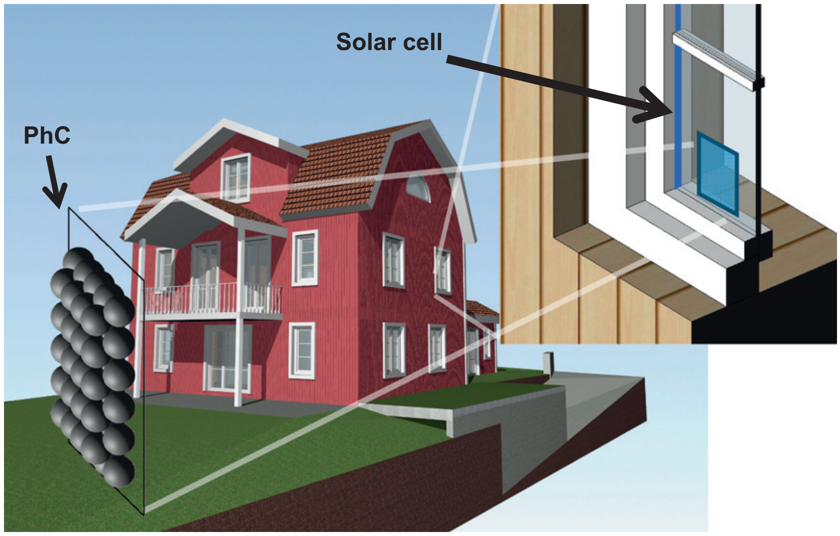

Fig. 1. Schematic of possible building integration of solar concentrators. In this case, the applications are integrated with the windows of a building and represent a way of balancing contributions towards natural lighting as well creating electrically active building elements.

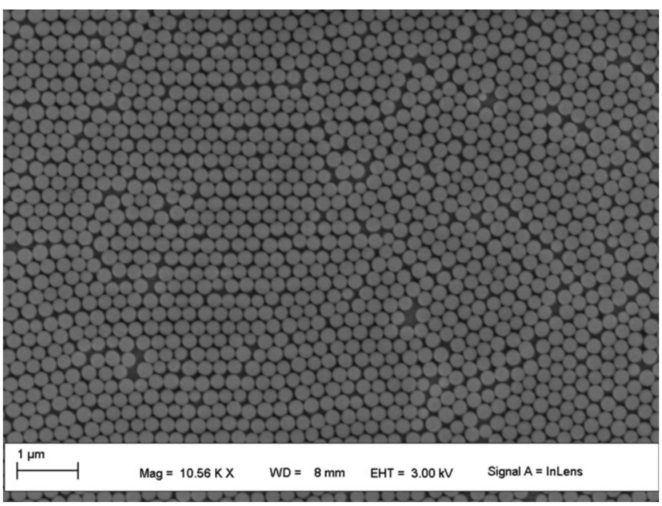

Fig. 2. SEM micrograph of LB layer with 250 nm particles deposited on PMMA substrate.

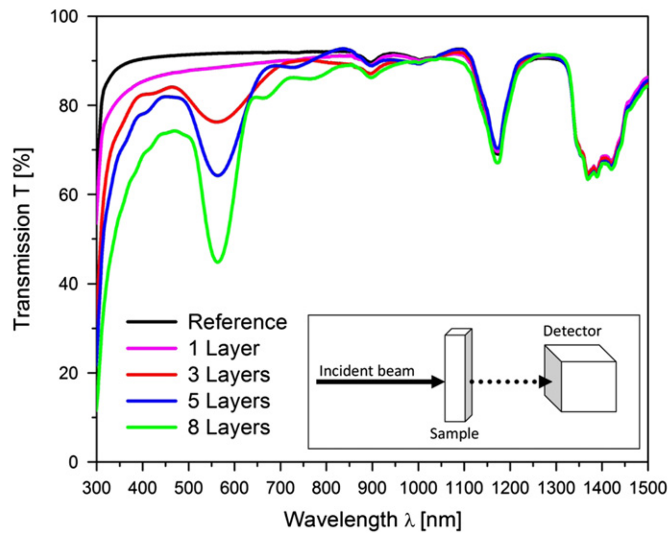

Fig. 3. Transmission spectra of a blank PMMA and samples with LB layers deposited. Generally, the transmission spectra of the samples with LB layers follow closely those of the blank PMMA, except around 560 nm, where the Bragg diffraction minimum appears. Additionally, Fabry–Perot oscillations arise due to the matching condition between layer thickness and wavelength.

A. The substrates were immersed into the silane bath and sonicated for 30 min. They were then washed with MeOH and H_2O and left to dry for 20 min.

The silica colloids were synthesised using the well-known Stöber method [8]. The resulting spherical silica particles with a diameter of 250 nm were used without further surface treatment. The Langmuir–Blodgett (LB) method has been shown to lead to highly ordered PhC thin films via a layer-by-layer deposition of particles assembled at an air/liquid interface [9,10] (see Fig. 2). The LB method is attractive as compared to other methods since it offers the advantage of precise thickness control, the deposition process is relatively fast and it is capable of covering large areas in one fabrication step.

A two-compartment trough with 2 pressure sensors and an alternate dipper mechanism, model 622D2 (NIMA Technology Ltd.) was used as described in [9]. A barrier speed of 6 cm^2/min was used for the monolayer compression. This led to the formation of a 2D hexagonal lattice at the air/water interface, which was transferred onto the PMMA substrate at a pressure of 3 mN/m^2. Subsequent layers (if required) were deposited after a sufficient drying period, and formed what we have previously referred to as a (2+1)D photonic film [11]. In this case, there is order within the planes of particles but a degree of disorder between the planes.

Reflection measurements (see Supplementary Fig. 2) yielded the first Bragg reflection peak at 562 nm in good agreement with calculations for a particle size of 250 nm for LB grown PhCs [10]. The value of $\Delta\lambda/\lambda$ of the reflection peak gives an indication of the crystalline quality of the sample. It was 8% for the thickest samples with 8 layers, which points to a reasonable crystalline quality of the sample [12].

2.2. Transmission measurements

Transmission was measured in two different geometries. In the "straight" geometry, the incident light and the detector were mounted on the same optical axis (see Fig. 3, inset), whereas in the "edge" geometry, the incident light was perpendicular to the