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Panchromatic light harvesting by dye- and quantum dot-sensitized solar cells

Jun-Ho Yum [a,*], Jin-Wook Lee [c], Yongjoo Kim [a,b], Robin Humphry-Baker [a], Nam-Gyu Park [c,*], Michael Grätzel [a]

[a] *Laboratory for Photonics and Interfaces, Institute of Chemical Sciences and Engineering, School of Basic Sciences, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*

[b] *R & D Center DSC Team, Dongjin Semichem Co., Ltd., 445-935 Hwasung, South Korea*

[c] *School of Chemical Engineering and Department of Energy Science, Sungkyunkwan University, Suwon 440-746, South Korea*

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Abstract

A PbS:Hg quantum dots-sensitized solar cell (QDSC) combined with a dye-sensitized solar cell (DSC) to harvest panchromatic solar spectrum from the visible light to the near IR is demonstrated. We use the filter to split the solar energy and access the total conversion efficiency. The DSC performing 12.4% under AM1.5G sunlight was able to generate 9.1% with a short-wave pass filter cutting off photons of wavelength longer than 650 nm. On the other hand, QDSC performing 5.58% generated 3.42% with the use of a long-wave pass filter transmitting beyond 630 nm. Calculated on the basis of transmitted light, DSC and QDSC performed 24.0% and 5.90%, leading to almost 13.1% of estimated total power conversion efficiency by harvesting the solar energy from visible light to the NIR.

Keywords: Panchromatic harvesting; Dye-sensitized solar cell; Quantum dot-sensitized solar cell; Solar energy split

1. Introduction

Solar energy is one of the best renewable energy resources as it is a carbon-free, abundant, and ubiquitous. Photovoltaic technology has been currently dominated by conventional p–n junction solid-state solar cell. The demand for low-cost alternative photovoltaic systems though, has driven research into more unconventional technologies. Dye-sensitized solar cells (DSCs) mimicking natural photosynthesis are attractive as they have a great potential to generate low cost energy (O'Regan and Grätzel, 1991; Hardin et al., 2012). The sensitizing dye in a DSC anchored to a wide-bandgap semiconductor absorbs the light to create an excited state in the dye. The photoexcited electron is injected to the conduction band of the semiconductor. The charge flows through the semiconductor to the charge collector and through the external circuit to the counter electrode where it reduces the oxidising component of the redox couple. The redox couple then regenerates the oxidized dye. The record power conversion efficiency, 12.3% at full sun has been obtained with a porphyrin dye in combination with a liquid electrolyte containing a cobalt redox shuttle (Yella et al., 2011). However, DSCs based on commonly used ruthenium

* Corresponding authors. Current address: Thin Film Devices, PV-Center, Centre Suisse d'Electronique et de Microtechnique SA, Switzerland. Tel.: +41 21 695 5772 (J.-H. Yum). Tel.: +82 31 290 7241; fax: +82 31 290 7272 (N.-G. Park).

E-mail addresses: junho.yum@epfl.ch (J.-H. Yum), npark@skku.edu (N.-G. Park).

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complexes or donor-π-acceptor organic dyes still face an issue due to poor response to red and near-infrared (NIR) light. Much effort including panchromatic sensitizers, multiple light absorbers, optical materials engineering, and tandem cells have been investigated to improve the spectral response (Yum et al., 2011). To date, only a tandem cell of a DSC with a CIGS solar cell has shown 15% overall power efficiency that has outperformed a single device (Liska et al., 2006).

In 2009, an elegant concept using a concentrator and a dichroic mirror to split the light into several spectral bands has been reported by (Barnett et al., 2009), where 42.8% of the efficiency with two separate two-junction tandem cell was described. Advantages of the architecture include a broader choice of materials or devices, elimination of ohmic junctions, reduced current matching restraints. The high cost of tandem solar cell has limited their use in commercial applications. In the same year, (Rühle et al., 2009) have proposed another approach without light concentration in this way. A dichroic mirror was used to split the solar spectrum into the visible and the red/NIR components, so that a GaInP cell and a polycrystalline silicon solar cell would harvest the different spectral regions, respectively. They also considered replacing GaInP cell with DSC because GaInP is not ideally a cheap cell but the replacement sacrificed the total conversion efficiency owing to a low open circuit voltage (V_{oc}) generated from DSC. Barber et al. (2011) have reported a hybrid concentrator system using two optical filters to reflect and concentrate NIR light from a DSC to a Si cell and demonstrated feasibility of 20% conversion efficiency. Here, we present a tandem hybrid solar module consisting of a porphyrin sensitized solar cell and PbS:Hg quantum dot solar cell (QDSC) to harvest the solar energy from visible light to NIR (Fig. 1).

Recently Lee et al. (2013) have presented a PbS:Hg QDs solar cell with an encouraging J_{sc} approaching 30 mA/cm^2 under AM 1.5G 1 sun illumination. The power conversion efficiency was 5.6% owing to a poor V_{oc} below 400 mV despite of the noticeable current. We envisaged that a tandem module of PbS:Hg QDs solar cell with DSC based on a zinc porphyrin dye, YD2-*o*-C8 and a co-sensitizer, Y123 in combination with a cobalt based electrolyte (Yella et al., 2011), which can afford to improve further the performance. Based on transmitted power, we estimate that the total power conversion efficiency of 13.1% is attainable and the efficiency could be further improved by QD solar cell development.

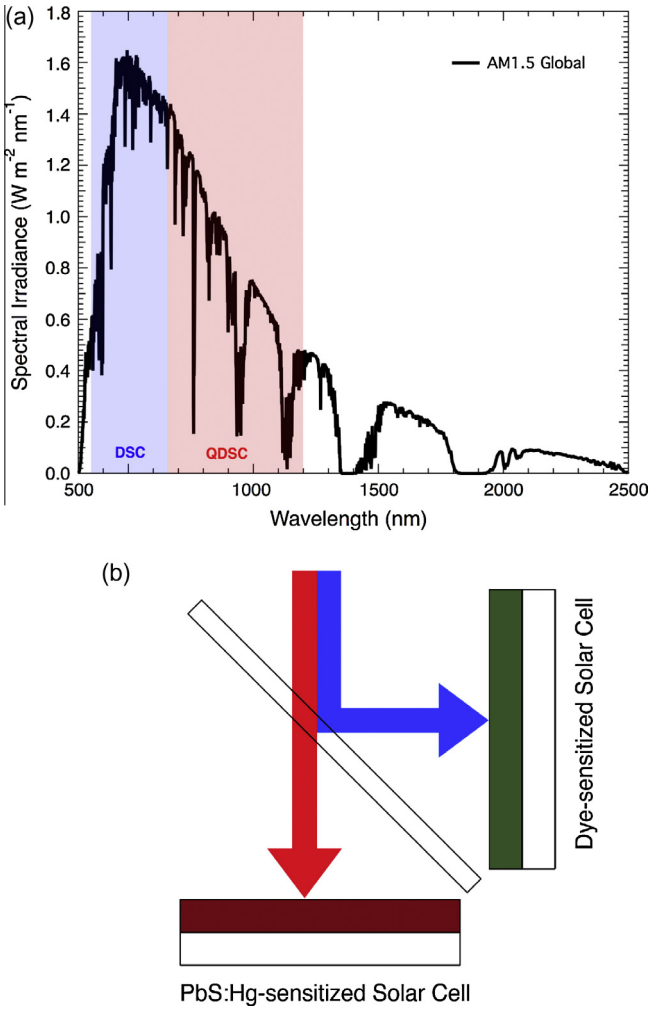

Fig. 1. (a) Reference global AM1.5 solar power spectra with combined spectral responses of DSC and QDSC. (b) Schematic concept of a two-junction solar cell consisting of DSC, QDSC harvesting split light.

2. Materials and methods

2.1. Fabrication of DSC

DSCs were prepared using a previously reported procedure (Yella et al., 2011). In brief, the TiO_2 transparent electrodes are composed of ~20 nm diameter anatase particles. This yields a ~30 nm pore size film on a fluorine doped thin oxide conducting glass (FTO, 4 mm thickness, 10 Ω/sq, Nippon Sheet Glass, Japan) after screen-printing of thickness, e.g. ~4 μm. A ~5 μm scattering layer (400 nm, CCIC, HPW-400) was printed on the top of this transparent layer to effectively increase light path length by scattering. The TiO_2 electrodes were immersed into a 0.2 mM solution of YD2-*o*-C8 with 0.025 mM of Y123 and 0.4 mM of 3α, 7α-dihydroxy-5β-cholic acid (chenodeoxycholic acid) in tetrahydrofuran/ethanol mixture (1:4 v/v) and kept for 4 h at room temperature. As for the counter electrode, a carbonaceous catalyst FTO (TEC 15 Ω/sq, Pilkington) was prepared with graphene nanoplatelets (GNP) (Grade 3, Cheap Tubes, Inc. USA). This carbonaceous type catalyst has been in general known to perform better than Pt owing to the low charge transfer resistance particularly for the cobalt redox system (Sapp et al., 2002; Kavan et al., 2011a,b). The dye-adsorbed TiO_2 electrode and the counter electrode were assembled into a sealed sandwich type cell with a gap of a hot-melt ionomer film, Surlyn (25 μm, Du-Pont). An electrolyte was added containing