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Enhancement of up-conversion efficiency by combining rare earth-doped phosphors with PbS quantum dots

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ABSTRACT

This paper aims to enhance the up-conversion phenomena observed in silicon solar cells by combining a rare earth-doped phosphor with PbS quantum dots. Two different ways of adhering the up-converter and the fluorescent material to a bifacial solar cell are implemented: dissolving the powder in a spin-on oxide and by dissolving it in a silicone gel. Characterization is carried out through photocurrent and photoluminescence measurements. The improvement in photocurrent detected by the combination of the up-converter and the PbS quantum dots is 60% better than without them, demonstrating that the absorption and emission characteristics of the quantum dots embedded both in the oxide or the silicone can be tuned to the desired spectral region.

1. Introduction

Photon converters can enhance the performance of solar cells as they have the ability to condition the solar spectrum, thus suiting the semiconductor bandgap better. In the case of up-conversion (UC), advantage can be taken of the transmitted energy [1]. The implementation and characterization of up-converters (UC) layers on the rear of bifacial silicon solar cells (BSSC) has been reported by several authors [2–4]. Pan et al. [5] attached some commercial phosphors to the BSSC by dissolving them either in a spin-on oxide or a silicone. The performance was characterized through external quantum efficiency (EQE) measurements, demonstrating a gain in photocurrent in the IR wavelength range. This gain is quite small, firstly because response of the UC process is greatly dependent on light intensity, and also because the wavelength range in which it takes place is very narrow, corresponding to a small absorption range of the rare-earth dopant. The use of photoluminescence materials to enhance the UC phenomena has been suggested a number of times for photovoltaic applications [6–8]. The idea is to widen the IR light being used through a material that can absorb it in a range of wavelengths where the UC does not respond, and re-emit it in the wavelengths where it does respond.

The UC used in the experiments reported is called PTIR545/F, made by the company *Phosphor Technology*. PTIR545/F is a very fine pink powder that seems to consist, according to EDX measurements of $ZnSO_4$ doped with ytterbium (Yb) and a small fraction of erbium (Er). This commercial phosphor is typically sold for applications in IR leds, printing inks, credit cards, etc. It can be excited in the 1500 nm range and re-emits it in shorter wavelengths, mainly in the 500 nm range.

PbS quantum dots (QDs) have appropriate absorption and emission properties for combination with the UC and the BSSC [9], and are readily commercially available. There are several requirements of the QDs that have to be fulfilled for this purpose. For instance, Suyver et al. [10] reported that the diameter of the QDs should be below 30 nm to reduce light scattering and for that reason a 5.3 nm diameter PbS QDs made by the company *Evident Technology* were selected and used in this work. These QDs have large quantum efficiency and high indices of refraction compared to the phosphors, which Si devices can take advantage of [11]. The energy transfer will probably occur through radiative emission from the QDs followed by absorption by the UC phosphor.

Fig. 1 details the normalized EQE as a function of wavelength for the BSSC itself, the BSSC with PTIR545/F-UC, and the absorption and emission of the *Evident Technology* PbS QDs. While the EQE for the solar cell is significant in the range 350–1100 nm, the UC layer is able to extend it (although with a very low response) in the 1488–1564 nm range. The PbS QDs have absorption precisely in the range where neither the BSSC itself nor the UC take advantage of the light (1200–1500 nm), and the emission takes place in the range where the UC is active, presenting a possible route to improve the UC efficiency.

In this paper we first present the characterization results for the BSSC with UC, discussing the influence of the light power on the UC efficiency. Second, we combine the UC with PbS QDs characterize the approach through measurements of photocurrent and photoluminescence (PL).

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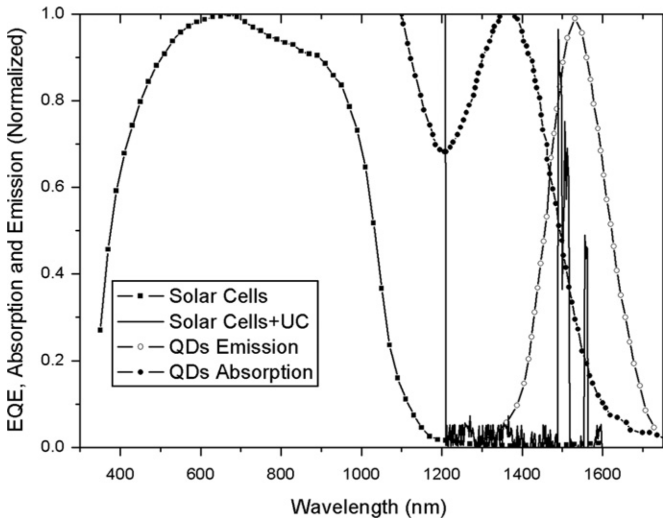

Fig. 1. Experimental results normalized of the EQE for the BSSC with a UC layer, and the emission and absorption reported for the PbS-QDs in arbitrary units.

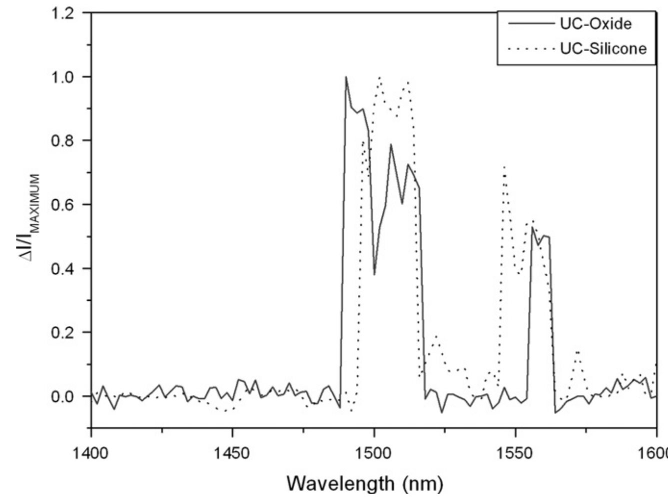

Fig. 2. Normalized photocurrent for the two ways of attaching the PTIR545/F-UC to the BSSC dissolved in an oxide or silicone for the QTH incandescent lamp.

2. Characterization of up-conversion effect under IR LED illumination

As reported in previous deliverables and publications [4] we have manufactured BSSC and attached the UC to the rear using two different methods: either by dissolving it in a spin-on oxide, or by doing so in a silicone gel. Characterization is made through EQE measurements adapted to the IR range, the light source being a quartz–tungsten–halogen (QTH) incandescent lamp (200 W). Fig. 2 shows a comparison of the gain in photocurrent experienced for the two approaches. It demonstrates that the photon conversion phenomenon takes place, although the gain in photocurrent is rather small.

By translating the increase in photocurrent to EQE, we can compare the performance of the PTIR545/F for the two alternative binders, the oxide and silicone, with that of others reported in the literature for silicon solar cells. In Table 1 this comparison is detailed.

The response of the PTIR545/F phosphor is much lower than for the others, and this is not only related to the kind of phosphor, but also to the fact that the incident power light is much lower. The up-conversion process for Erbium-doped compounds is based on the energy transfer up-conversion (ETU) mechanism, which has a quadratic dependence on light intensity [10].

In our EQE system we are restricted to low power intensities in the IR region because our light source is optimized for the visible energy range. So, in order to increase the detectivity of the UC effect we have replaced the halogen lamp with two LEDs sources. Some of their characteristics are shown in Table 2. Although the power for the LEDs is 20 times higher than that of the QTH lamp for the wavelengths of interest, it experiences a big reduction when passing through the monochromator, so for the following measurements the monochromator has not been used. That changes the interpretation of the measurements because we lose the spectral resolution, but nevertheless gives valuable information on the enhancement of photocurrent (or not) resulting from photon conversion. Fig. 3 compares the results for the characterization with the QTH lamp and with the LEDs, showing some correspondence.

The increase in photocurrent when illuminating with the LEDs is higher than for the QTH lamp, showing the influence of the incident power. In addition, having two LEDs centered in two different wavelengths (1450 and 1550 nm), one is able to distinguish the two peaks that this UC has in this range when illuminated with each of

Table 1
Comparative EQE results with different up-converters materials.

Material	Peak wavelength (nm)	Incident light power (mW)	Increase of the EQE (%)
$NaYF_4:Er^{3+}$ [2]	1523	6	3.4
$BaCl_2:Er^{3+}$ [3]	1535	3	3.6×10^{-4}
PTIR545/F-oxide	1488–1518	0.1	4.0×10^{-7}
PTIR545/F-silicone	1494–1516	0.1	5.9×10^{-6}

Table 2
Characteristics of the IR LED lamp used in the experiments provided by the company *Roithner Lasertechnik*.

LED name	Peak wavelength (nm)	Half width (nm)	Maximum radiated power (mW)
1450-03	1450	100	2.0
1550-525	1550	100	2.0

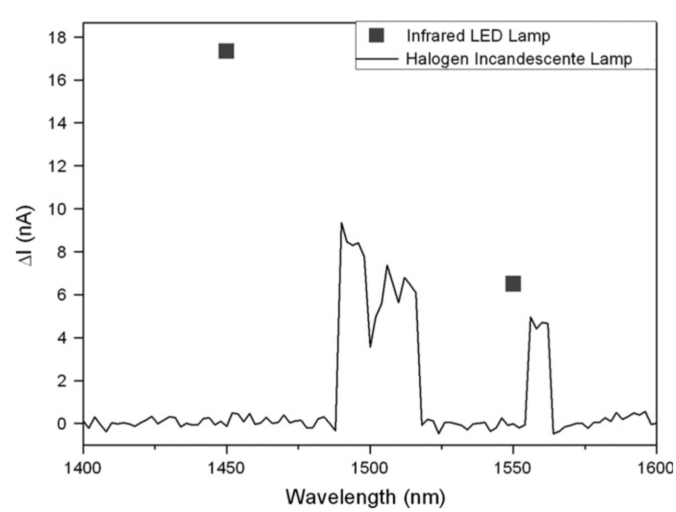

Fig. 3. Increase in photocurrent versus wavelength for the PTIR545/F up-converter embedded in the spin-on oxide layer, for the different source lamps. The dots correspond to the LED sources, which are not just the response in the indicated wavelength, but in the range of the LED width shown in Table 2.