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Improving efficiency of silicon solar cells using europium-doped silicate-phosphor layer by spin-on film coating

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ABSTRACT

This paper reports impressive enhancements in the efficiency of crystalline silicon solar cells through the application of a Eu-doped silicate phosphor luminescent downshifting (LDS) layer controlled by spin-on film technique. Surface morphology was examined using scanning electron microscope (SEM), chemical composition was analyzed using energy dispersive spectroscopy (EDS), and fluorescence emission was characterized using photoluminescence (PL) measurements at room temperature. The optical reflectance, absorbance, and external quantum efficiency (EQE) response of SiO_2-coated cells with and without Eu-doped silicate phosphor were measured and compared. An 18.77% improvement in efficiency was achieved, as determined by photovoltaic current–voltage measurement under one-sun AM 1.5 G illuminations.

1. Introduction

The conversion efficiency of crystalline silicon (C-Si) solar cells at UV-blue wavelengths remains relatively low due to the high reflectance and low responsivity of C-Si within the UV-blue wavelength band. Anti-reflective coatings and textured or structured surfaces are commonly used to reduce surface reflection and improve light trapping in order to promote conversion efficiency. New approaches are still required to enhance the conversion efficiency of C-Si solar cells at shorter wavelengths. There are two principal approaches to achieve a more efficient utilization of short-wavelength part of the solar spectrum. The first is to improve the electronic properties of existing photovoltaic devices using very narrow junction, low doping levels or thin widow layer where exist [1]. The second approach is luminescent down-shifting (LDS) of incident spectrum [1–10]. LDS provides a simple, effective passive method that involves applying a luminescent species in a layer prior to the cells which absorbing light of short wavelengths and re-emitting it at longer wavelengths. Particularly, materials with high photoluminescent quantum yield (PLQY) and large Stokes shift LDS are required to improve the efficiency of C-Si solar cells [11–15]. Using quantum dot-embedded silica film as an LDS layer for crystalline Si solar cells has been demonstrated [16]. Materials with quantum dot LDS possess strong emission characteristics; however, the PLOY tends to be low. In contrast, rare earth phosphors have extremely high PLOYs and very large Stokes shifts. LDS using phosphors doped with rare earth materials to enhance the conversion efficiency of C-Si solar cells have recently reported [4,17–21].

In this work, we investigated 3 wt% europium-doped (Eu-doped) silicate phosphor powder mixed with liquid SiO_2 solution for use as a spin-on film source coating to be applied to a C-Si solar cell surface using spin-on technique. We then investigated the photo-response at short wavelengths. The surface coverage and dimensions of the phosphor particles were examined using scanning electron microscopy (SEM) in conjunction with J-image software. The chemical composition of the Eu-doped phosphors was analyzed using energy dispersive spectroscopy (EDS). The optical properties of the Eu-doped phosphors layer were examined by photoluminescence (PL) and UV–vis–NIR spectrophotometer at room temperature. Measurements of optical reflectance and external quantum efficiency (EQE) response were used to confirm the effectiveness of LDS using Eu-doped phosphors. Finally, we characterized and compared the enhancements in photovoltaic performance of C-Si solar cells with and without phosphor particles according to photovoltaic current–voltage (*I*–*V*) measurement.

2. Experiment

Fig. 1 presents a schematic diagram of a C-Si solar cell coated with a Eu-doped silicate phosphor layer. The 3 wt% of Eu-doped phosphor SiO_2 layer was created by spin-on film coating of 4.8 g of Silicafilm-5000 solution (Emulsitone Company product)

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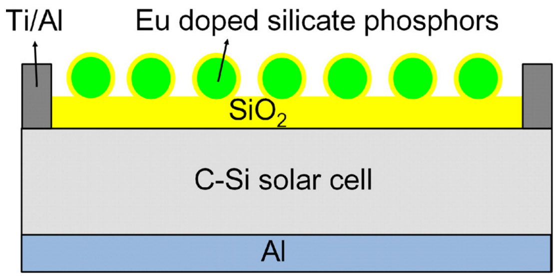

Fig. 1. Schematic diagram showing crystalline silicon (C-Si) solar cell coated with a Eu-doped silicate phosphor layer.

combined with 0.15 g of silicate phosphor powder (InteMatix Company; G2060TM). To determine the optical properties of the Eu-doped phosphor silicate layer, the prepared solution was first spin-coated on clean silicon substrates at 3000 rpm for 40 s before being baked at 150 °C for 1 min under an air atmosphere. As a control, we also produced a 250-nm thick pure SiO_2 layer using the same Silicafilm-5000 solution without phosphor particles. After baking, the surface morphology and chemical composition of the sample with a Eu-doped silicate phosphor layer were examined using SEM and EDS (JEOL JSM-6500F), and the fluorescence emission of the Eu-doped silicate phosphor layer was confirmed by photoluminescence (PL; Ramboss 500i Micro-PL Spectroscopy) measurement at room temperature which can be shown the LDS of the proposed Eu-doped phosphor silicate layer. The reflectance of the silicon substrates (with and without phosphor particles in the SiO_2 layer) was characterized using an UV/vis/NIR spectrophotometer (PerkinElmer LAMBDA 35), which revealed the antireflection and light scattering effects of the SiO_2 layer mixed with phosphor particles.

A bare-type Si solar cell using a p-type, CZ, (100), 5 Ω cm, and 525-μm-thick crystalline Si wafer was also fabricated for a further comparison of performance. After standard cleaning processes, an n^+-Si emitter layer was formed by spin-on film processing using a liquid phosphorous (P) source and treated in rapid thermal annealing (RTA) chamber at 800 °C for 5 min under ambient N_2. Following the formation of the diffuse n^+-Si layer, the remaining phosphorous oxide on the sample surface was removed using a buffered oxide etchant. E-beam evaporation and lift-off processing were used to deposit an Al film (300 nm in thickness) on the back-side as an electrode as well as an Al/Ti film (20 nm/300 nm) on the front-side as finger-electrodes. Finally, bare-type solar cells were obtained after annealing at 450 °C for 10 min under ambient N_2.

Improvements in the efficiency of the Eu-doped silicate phosphor layer were characterized by coating the bare solar cells with Silica film solution mixed with 3 wt% of phosphor powder. Photovoltaic *I–V* measurements under one-sun AM 1.5 G illumination as well as the external quantum efficiency (EQE) response from 300 to 1200 nm wavelengths were used to confirm the enhanced contribution from the LDS Eu-doped silicate phosphor layer.

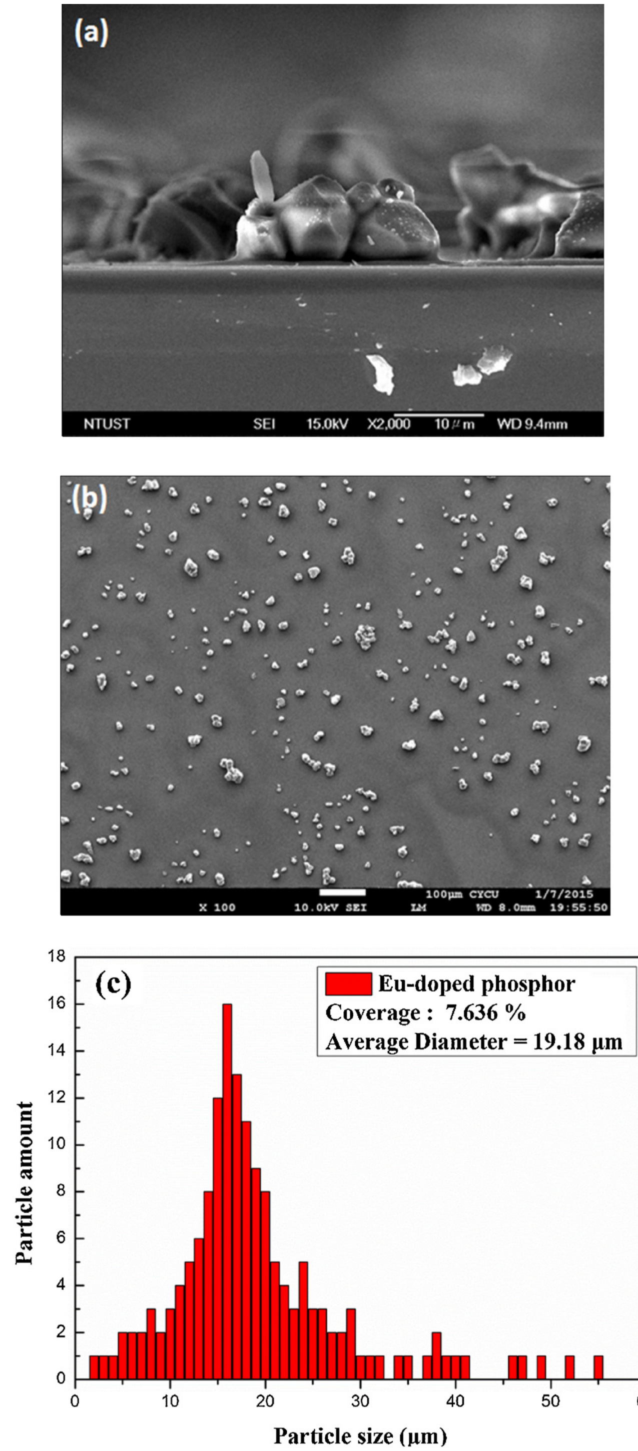

Fig. 2. SEM images: (a) cross section-view, (b) top view, and (c) size distribution of phosphor particles distributed across surface of Si-substrates.

3. Results and discussion

Fig. 2(a) and (b) presents cross-section and top-view SEM images of the Eu-doped phosphor SiO_2 layer profile on the Si-substrates. The thickness of the SiO_2 layer was approximately 250 nm. The phosphor particles were approximately 10–15 μm in diameter and the coverage of the phosphor particles was approximately 7.636%. The size distribution and the coverage of the phosphor particles were calculated using Image-J software, as shown in Fig. 2(c). Some of the phosphor particles were not distributed uniformly across the surface; therefore, the incident light was shaded and reflected from these areas of dense particle aggregation, as shown in Fig. 2(b). This had the effect of lowering the conversion efficiency of the solar cell. A cross-section view obtained by SEM also shows that the morphology of the phosphor particles was not spherical. This combined to give the incident light greater opportunity to scatter from the surface into the active region of the solar cells.

The EDS spectrum of Eu-doped silicate phosphor (G2060TM) was shown in Fig. 3 EDS is an analytical technique used for the elemental composition analysis or chemical composition characterization of a sample. Energy peaks correspond to the various