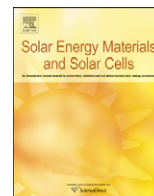




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UV enhancement of silicon solar cells using thin SRO films

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ABSTRACT

A study of comparison of the electrical and optical characteristics of silicon solar cells (SC) with a layer of silicon oxide (SiO₂) deposited by SILOX, and silicon solar cells covered with a silicon rich oxide (SRO) film obtained by LPCVD containing silicon nanoparticles (Si-nps) was made. To increase the density of nanoparticles and thus improve the red photoluminescence, the SRO films were annealed at 1100 °C. Photoluminescence spectra and atomic force microscopy measurements of the silicon rich oxide films are presented and discussed, as well as current–voltage curves and spectral response of the fabricated solar cells. Measurement of the open circuit voltage and short circuit current of the SC under UV light illumination was realized. The results demonstrate that the red luminescence of these films with silicon nanoparticles, produces large enhancement of current and voltage, with improved performance in the UV range.

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1. Introduction

Nowadays, photovoltaic (PV) energy is of the most attractive options for generating electricity using clean [1] and renewable energy. However, PV energy is not yet economical compared to energy obtained through conventional sources. Therefore, it is essential to reduce manufacturing costs of solar cells and photovoltaic modules. This can be achieved by improving the efficiency/cost ratio of solar cells, which constitute the photovoltaic modules [1–2].

The fundamental spectral losses in a single-junction solar cell made of semiconductor material such as silicon can be large. This is a result of the mismatch between the incident solar spectrum and the spectral absorption properties of the material [3]. Large parts of the solar spectrum are not absorbed, because of the existence of a band gap E_g of the material. Photons with energy E_{ph} larger than the band gap are absorbed, but the excess energy $E_{ph}-E_g$ is not used effectively due to thermalization of the electrons, i.e. photons with $E_{ph} < E_g$ are not absorbed. Several routes have been proposed to overcome this intrinsic property of semiconductor solar cells and thereby increasing the power output of solar cells. All these methods or concepts concentrate on a much better use of the solar spectrum and are in general referred to as third generation photovoltaics [4].

One of the aims of this work was to increase the energy conversion efficiency of silicon solar cells by means of silicon rich oxide (SRO) films deposited on the SC surface. These films have the optical property of absorption below ~ 300 nm radiation (UV), so that the absorbed energy by the SRO film is then reemitted as red light (PL). Silicon SC have a greater response [5] in the spectral range from 500 to 1000 nm, so that the redshift of the short wavelengths offers an increase in the energy conversion efficiency of the silicon SC with no significant increase in the cost of fabrication.

In this paper, the electrical and optical parameters of silicon SC with SRO are compared with those for conventional SiO₂-covered silicon solar cells. One important point to mention is that the main interest of this work was just to study the photon-down conversion properties of SRO films, using as a reference a conventional SiO₂-covered silicon solar cell. SRO films were deposited by LPCVD technique. These films were annealed at 1100 °C for increasing the density of Si-nanoparticles and thus to increase the photoluminescence (PL) in the red wavelength range [6]. In previous papers [7–10] we have reported a study on SRO films regarding silicon excess and density as well as Si-nanoparticles size. It was possible to see silicon nanocrystals (Si-nc) in SRO₁₀, SRO₂₀ (silicon excess of 10% and 6.5%, respectively) and amorphous silicon nanoclusters in SRO₃₀ films (silicon excess of 4%) with diameters of approximately 5, 2.5 and 1 nm, respectively. In this work SRO₃₀ films were used. PL spectra and atomic force microscopy (AFM) images corresponding to SRO films are presented and discussed, as well as current–voltage (I – V) curves and spectral response of the solar cells fabricated.

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2. Experiment details

SRO and SiO₂ were deposited on p-type silicon (1 0 0) substrates with resistivity of 9.5 Ω-cm, and 2 in. of diameter. The Si wafers were cleaned with standard cleaning processes RCAI and RCAII and rinsed in deionized water. The native oxide was removed from the Si wafers by a diluted HF dip (5%) for 10 s. The structures of the solar cells designed are similar to the conventional cells with SiO₂; the only difference in this case is the SRO top layer instead of the SiO₂ layer. Before the SRO deposit, the surface of the silicon wafers was textured with potassium hydroxide (KOH) anisotropic attack for 21 min at 85 °C. Fig. 1 shows the image of the textured surface; this is done in order to reduce the light reflection on the surface of the solar cell, which can be up to 30%. Subsequently, the diffusion of phosphorus was realized at 875 °C for 30 min for the formation of the n region and thus obtaining the p–n junction. SRO films were obtained in a

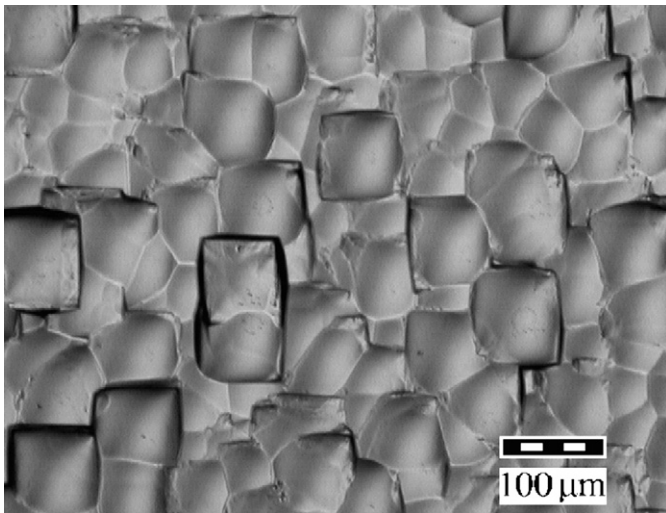


Fig. 1. Photograph of the silicon surface textured by anisotropic KOH attack.

Table 1
Solar cells with different annealing time and thickness of SRO and SiO₂.

| | P1 | P2 | P3 | P4 | P5 | P6 |
|--------------------------------|-----|----|----|----|----|----|
| SRO (nm) | 80 | X | X | | | |
| | 500 | | X | X | | |
| Time annealed at 1100 °C (min) | 90 | X | X | | X | |
| | 180 | X | | X | | X |
| SiO ₂ (nm) | 500 | | | | X | |
| | 400 | | | | | X |

horizontal LPCVD hot-wall reactor using SiH₄ (silane) and N₂O (nitrous oxide) as reactive gases at 715 °C. The gas flow ratio, $Ro = [N_2O]/[SiH_4]$, was used to control the amount of silicon excess in the SRO films. The surface of one group of solar cells (P1, P2, P3, P4) was passivated using SRO with two different thicknesses. Two other cells (P5, P6) were covered with thermal SiO₂ deposited by SILOX; then, an annealing at 1100 °C for two different times was applied to all the samples, as indicated in Table 1.

The annealing at 1100 °C is performed with two purposes, one is the formation of silicon nanoparticles embedded in the oxide matrix (SRO) and the other is the phosphorus redistribution and thus to obtain an optimum junction depth in the SC. Finally, Aluminum grids were patterned on the SRO surface by evaporation and standard photo-lithography. The surface Al grid electrodes have several fingers on all samples. It is important to remark that the zones between fingers are covered by the SRO films.

The surface morphology of SRO films was studied using a Nanosurf EasyScan atomic force microscopy (AFM) system version 2.3 operated in noncontact mode. A scanned area of $4 \times 4 \mu\text{m}^2$ was used for each topographic image. Four different scans were done for each sample, showing good reproducibility. AFM images were analyzed using scanning probe image processor (SPIP) software [11]. Room temperature PL of the SRO films was measured using a spectrofluorometer Horiba Jobin Yvon FluoroMax 3 model with a xenon source of 150 mW and a monochromator. The samples were excited using 290 nm radiation, and the emission signal was collected from 400 to 950 nm with a resolution of 0.3 nm.

Characteristic current–voltage (*I*–*V*) curves of the SC were obtained using a solar simulator and a curve tracer under AM1.5 conditions. Also, we obtained the current versus wavelengths (*I*–*W*) characteristic curves of the SC. Short circuit current and open circuit voltage of the SC were measured under illumination of a lamp FL15GER with a wide range in the UV.

3. Results

Fig. 2 shows the 3-D surface morphology of SRO films. The annealing time strongly influences the size and density of grains so that a longer time of thermal treatment provoked more roughness and higher grains on the SRO surface. Fig. 3 depicts results of the roughness analysis. It is clearly noted that with thermal treatment the roughness and diameter of the grains increases in both SRO and SiO₂ films. The results obtained by SPIP software corresponding to grain diameter are listed in Table 2. The average roughness $\langle S_a \rangle$ is defined in [12].

The red photoluminescence of the SRO films was used for increasing the number of photons reaching the active region of the SC with appropriate energy to be trapped. PL spectra of the

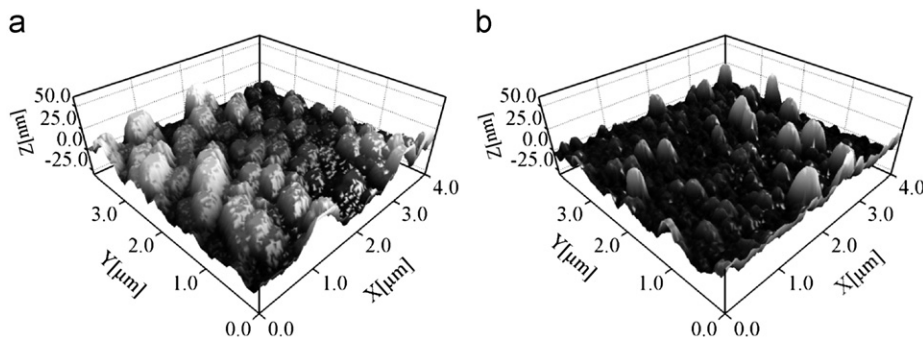


Fig. 2. 3-D image of SRO films annealed at 1100 °C for (a) 90 min and (b) 180 min.

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