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Letter

Efficiency enhancement of silicon solar cells with silicon nanocrystals embedded in PECVD silicon nitride matrix

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ABSTRACT

Anti reflection coatings (ARC), comprising of silicon-rich-nitride (SRN) films embedded with down-converting silicon nanocrystals were integrated into monocrystalline silicon solar cells fabricated using standard semiconductor fabrication techniques, and their effects were studied. Two types of ARC layers, one with single layer SRN film and other with double layer SiO_x/SRN were deposited by plasma enhanced chemical vapor deposition (PECVD) during fabrication of silicon solar cells and thermally annealed to precipitate silicon nanocrystals. A relative increase in power conversion efficiency of 15.6% for single layer nanocrystals-embedded-ARC and 22.8% for double layer nanocrystals-embedded-ARC were observed compared to a reference cell.

1. Introduction

Silicon solar cell technology is the leading photovoltaic technology. Silicon based nanostructures are one of the most promising candidates for enhancing the efficiency of silicon solar cells. Among the different loss mechanisms in a solar cell, lattice thermalization of high energy photons ($E_{photon} > E_g$) accounts for 47% loss [1]. This loss can be reduced to some extent using downconversion [2,3] property of silicon nanostructures [4,5]. With a downconverting layer on the top of a conventional solar cell, high energy photons will be absorbed to emit low energy photons. These photons are then absorbed efficiently by the solar cell below, resulting in increased conversion efficiency. While there are other materials and nanomaterials which can exhibit such downconversion behavior [6,7], silicon based nanostructured materials are preferable as its integration with existing manufacturing processes is easier to achieve [4,5,8].

Various studies have reported efficient photoluminescence in silicon based nanomaterials [9–14]. An increase in the internal quantum efficiency (IQE) for photons with wavelengths shorter than 425 nm has been observed in solar cells covered by a spin-on-glass with silicon nanocrystals [15]. Stupca et al [16] has reported a power performance enhancement of ~60% in the range of 254–365 nm with ultrathin films of silicon nanoparticles dispersed over a commercial polycrystalline silicon solar cell. Recently, Yuan et. al. [17] has demonstrated a relative increase of 14% in IQE, by silicon-rich-oxide layer containing silicon nanocrystals, on the top of a conventional silicon solar cell. But this downconverting layer was not optimized for antireflection and hence there was a decrease in power conversion efficiency from 15% on the conventional cell to 9.9% on the cell with SRO layer. As per the authors' knowledge, significant improvement in conversion efficiency using downconverting silicon nanostructures is lacking. This suggests that choice of optimal thicknesses and refractive indices (RI) of these films are crucial to ensure antireflection behavior along with their downconverting property. This motivated us to take-up this study on developing nanostructured PECVD silicon-rich-nitride films and their integration in fabricated monocrystalline silicon solar cells.

2. Experimental procedure

The cross section schematics of the monocrystalline solar cells fabricated and studied are shown in Fig. 1. Solar cells were fabricated using 2″, ⟨100⟩, 300 μm thick, 1–10 Ω-cm resistivity, p-type Czochralski single side polished silicon wafers from Siltronix^{TM}. Three types of solar cells were fabricated with labels A, B and C using standard semiconductor processing steps with three levels of photolithography for selective emitter, contact window and metal patterning.

In the first step, the wafers were selectively textured with optimized KOH based etching process which contained 3 v% of

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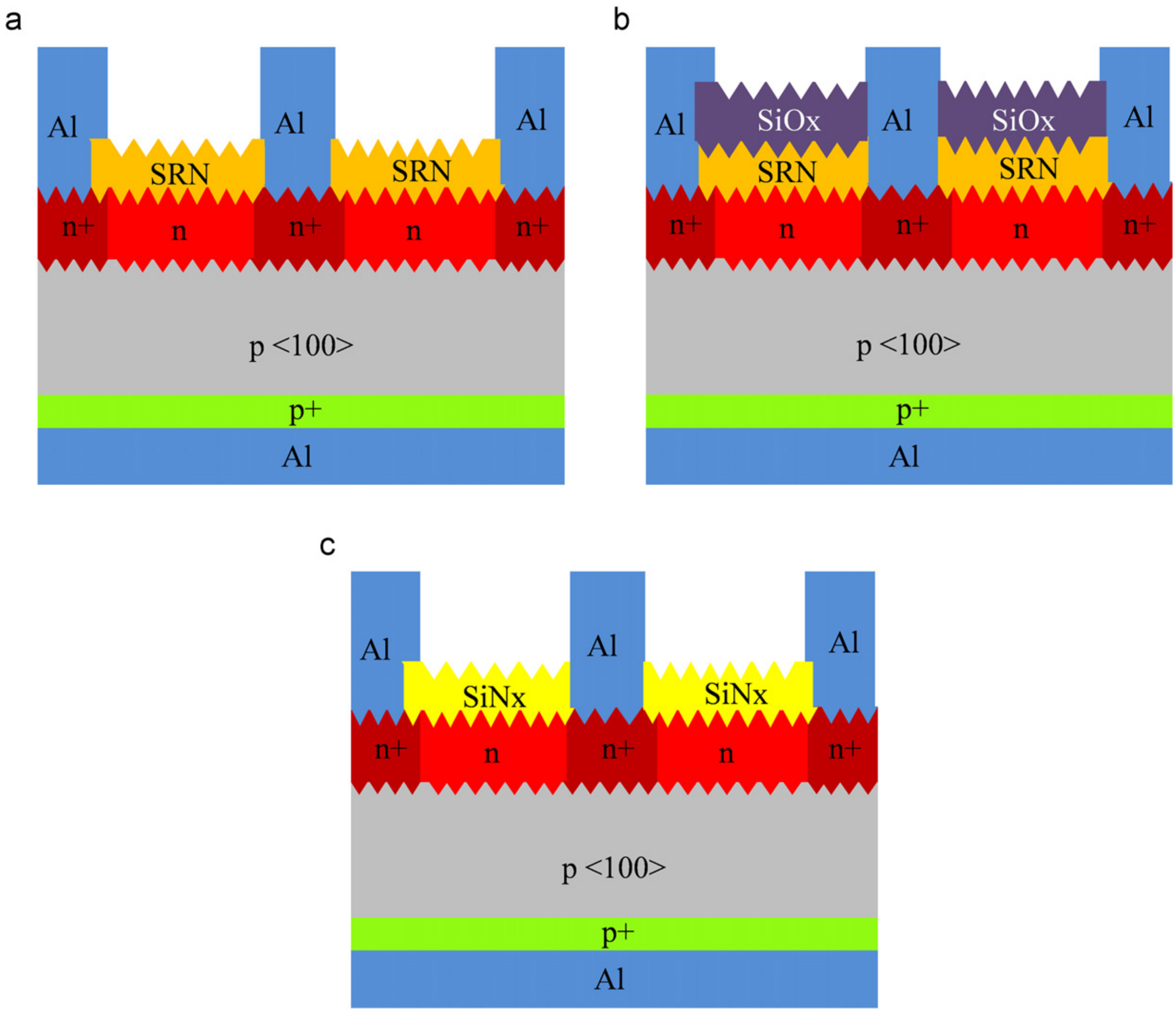

Fig. 1. Schematics of the solar cells (a) Cell A is with SRN ARC with embedded silicon nanocrystals (b) Cell B is with SiO_x/SRN (with embedded silicon nanocrystals) double layer ARC (c) Reference cell C is with normal PECVD SiN_x ARC.

45% KOH and 10 v% IPA. The top emitter was realized by phosphorus diffusion at 850 °C resulting in emitter sheet resistance of 75 Ω/square. Boron diffusion was done for back surface field. Second phosphorus diffusion step was carried out at 1000 °C for selective emitters. PECVD SRN, SiN_x, SiO_x based antireflection coatings were deposited on these cells. The films' thicknesses and refractive indices were optimized using transfer matrix method (TMM) as discussed in Section 3.

Solar cell C is the reference cell with normal SiN_x ARC of refractive index 1.83 and thickness 83 nm. Solar cell A has a single Layer ARC of SRN with refractive index 2.00 and thickness 76 nm. Solar cell B has a double layer ARC with bottom layer comprising of SRN of refractive index 2.2 and thickness 62 nm and top layer comprising of normal PECVD SiO_x of refractive index 1.46 and thickness 93 nm. Film thicknesses were measured using Talystep™ surface profiler and refractive indices were measured using Metricon2010™ Prism Coupler and single wavelength laser ellipsometer both at wavelength 632.8 nm. The increased refractive indices of SiN_x in samples A and B are achieved by increasing the $[SiH_4]/[NH_3]$ ratio during PECVD deposition process thus making it silicon-rich. The deposited SRN films (cells A and B) were annealed at 700 °C for 30 minutes in N_2 ambient, leading to precipitation of silicon nanocrystals [9,18]. Aluminum was deposited on both sides for contact formation by RF sputtering. The top side aluminum films were patterned by photolithography followed by chemical etching to define contact fingers. The backside of the cell is completely covered with aluminum. The size of the each cell is 3.00 cm × 3.00 cm with active area of 2.85 cm × 2.85 cm. The fabricated solar cells are shown in Fig. 2.

Efficiency measurements were performed in a solar simulator under 100 mW/cm^2, corresponding to AM1.5 G insolation. Before measurement, the intensity of the source was calibrated using a standard calibrated solar cell. Current density-voltage (J-V) characteristics were measured with a source measure unit using a 4 point probe technique. The temperature of the solar cells was maintained at 25 ± 1 °C during the measurements. Spectral response and external quantum efficiency (EQE) measurements were done on solar cell spectral response measurement system (Model: Bunkoh-Keiki Co. CEP-45 HS-40 SR) owing to IEC60904 standard. The short circuit current densities obtained from J-V measurements and spectral response are matching well within ± 3%. Fig. 3 shows the J-V characteristics of the three solar cells. Short circuit current density J_{sc}, open circuit voltage V_{oc}, fill factor FF and efficiency η extracted from the J-V characteristics are given in Table 1.

3. Downconversion mechanisms and optimization of ARC

Two mechanisms of downconversion are possible with silicon nanocrystals [4]: (1) Photo- luminescence (PL) and (2) Photon splitting via MEG (Multiple Exciton Generation) also called as