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Enhancement of silicon solar cell efficiency by using back surface field in comparison of different antireflective coatings

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Abstract

Back surface field (BSF) (n^+–p–p^+) silicon (Si) solar cells were fabricated with and without TiO_2 or SiO_2 single layer antireflection (SLAR) coatings. The two cell types were obtained with non-texturized surfaces and compared with each other, as well as with an as-grown Si solar cell. The effective aluminium–BSF was fabricated through a simple thermal evaporation and alloying (850 °C, 50 min) technique. The effect of BSF and AR coatings on the performance of the solar cells were characterized through electrical (AM 1.5 G, 100 mW/cm^2), optical, and morphological measurements. The BSF Si solar cells with TiO_2 and SiO_2 AR coatings and without AR coatings demonstrated increased efficiencies of about 168%, 115%, and 50%, respectively, compared with the as-grown Si solar cell. The addition of the TiO_2 (AR) layer initiated 24% improvement in the efficiency of the monocrystalline BSF Si solar cells, compared with 6.9% of the SiO_2 (AR) coated BSF Si solar cell. The results indicate the potential of combining the TiO_2 SLAR coating with BSF in the improved production of high-efficiency, low-cost Si solar cells.

Keywords: Back surface field; Anti reflection coating; Silicon solar cell

1. Introduction

The presence of an electric field at the back surface of an n^+–p silicon (Si) solar cell significantly enhances the collection efficiency of the cell (Tucci and de Cesare, 2004; Plekhanov et al., 2001). A back surface field (BSF) is capable of reducing recombination velocity (S_b) by converting it into an effective recombination velocity (S_{eff}) at the BSF junction edge (Hovel et al., 2010). Combining BSF Si solar cells with antireflective (AR) coating agents significantly improves the solar cell efficiency. Obtaining the minimum reflection of a single wavelength of an incident wave may require a SLAR coating, which must possess (a) a refractive index equal to the square root of the refractive indices of the materials bounding the coating and (b) a thickness equal to one fourth of the wavelength (Lien et al., 2006). To date, different materials have been used as AR coatings in Si solar cells. In the present study, we used titanium dioxide (TiO_2) and silicon dioxide (SiO_2) as SLAR coatings. The TiO_2 has a suitable refractive index, low absorption capacity, low moisture absorption and high chemical stability (Richards et al., 2004). The SiO_2 is also well known in Si processing technology because it is scratch resistant and forms passivated and/or protective layers and chemically stable at elevated temperatures (Li et al., 2013).

Various methods have been used to deposit TiO_2/SiO_2 films, including chemical vapor deposition (CVD) (Hocine et al., 2013), chemical spray pyrolysis (CSP) (Perez-Sanchez et al., 2005), sputtering (Seung, 2013), atomic layer deposition (ALD) (Lee et al., 2012), hydrolysis (Richards, 2003; Saitoh et al., 1991), sol–gel (Morales-Acevedo et al., 2002; San Vicente et al., 2002), pulsed laser deposition (PLD) (Doeswijk et al., 1999) excimer laser sputtering

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(Durand et al., 1995), and screen printing (Szlufcik et al., 1989).

Recently, Hocine et al. (2013) applied CVD method and showed an average reflectance of 15% of single-layer AR coating with an increase of 5.23 mA/cm^2 compared to the reference cell. CSP method adopted by Perez-Sanchez et al. (2005) obtained 11.37% efficiency with 78.9 nm TiO_2 ARC on Silicon Solar Cells. Screen-printed TiO_2 ARC was adopted by Szlufcik et al. (1989) with an improvement of 37% cell efficiency. Another promising technique is the growth of ARCs over porous silicon (PS). Previous studies showed that the reflectivity was reduced to 1% in the 430–720 nm wavelength range using PS double-layer ARC (Martirosyan et al., 2007; Aroutiounian and Soukiassian, 2006) while 7.3% average reflectance in the 400–1150 nm wavelength range was achieved for single AR coating on PS (Strehlke and Levy-Clement, 1999).

In case of thermally grown SiO_2 ARC, Panek et al. (2009) achieved 11.92% efficiency with an effective average reflectance of 20.38%. Spectral Selective Transmission approach adopted by Wang et al. (2013) reported transmissivity of 80.4% within $0.35\ \mu m < \lambda \leqslant 1.1\ \mu m$ wavelength ranges. Tandon and Douglas (1987) introduced a unique way to use TiN film as an excellent metal diffusion barrier and upon controlled heat treatments (up to 600 °C), as a good anti-reflection coating of TiO_2. Wide band wide angle concept of ARC was adopted by Pellicori (1981), and average reflectance was reduced to 3% (550–1000 nm) using two-layer design CeF_3/TiO_2.

Most of these techniques require a type of heat treatment (200–450 °C) for the substrates during or after the deposition (Hocine et al., 2013; Doeswijk et al., 1999; Szlufcik et al., 1989). While in some cases, the samples are sintered up to a temperature of 1050 °C for a long period of time (1–6 h). Although sol–gel is cost efficient technique but thickness is not precisely controlled (Seung, 2013). On the other hand, necessity of high vacuum in CVD makes this method unsuitable for mass production of silicon solar cells (Hocine et al., 2013). Thermal treatments applied in the solar cell processing may change the intended compositional distribution and also introduce defects that act as recombination centres for charge carriers in the solar cell device (Ariza et al., 2003, 2001).

This work aims to investigate the effect of TiO_2 and SiO_2 AR coatings on BSF c-Si solar cells prepared by sputtering and thermal oxidation, respectively. The sputtering technique used in this work employed a remarkably sophisticated and efficient heat treatment process. The prepared solar cells were compared with each other, as well as with a BSF Si cell without an AR coating and an as-grown Si solar cell. The results are promising as they show the simplicity, lower cost, low deposition temperature, suitability for mass production and to investigate the effect of AR coatings on electrical and optical properties of silicon solar cells. The results indicate the potential of combining the TiO_2 SLAR coating with BSF in the improved production of high-efficiency, low-cost Si solar cells.

2. Experimental

Flow chart of the BSF process for the crystalline solar cells with and without AR coating and the as-grown Si solar cell is shown in Fig. 1. Table 1 tabulates the sputtering/ and oxidation parameters and deposition results of the TiO_2 and SiO_2 films. The solar cells were fabricated using 0.01–1.5 Ω cm boron-doped c-Si wafers, with one side polished. Before the diffusion process, the Si substrates were cleaned following the standard Radio Corporation of America method to remove surface contamination. After a deionized water (DI) rinse ($\rho > 18.2$ MΩ cm) and an N_2 blow, the emitter region was fabricated by performing thermal diffusion of the phosphorous atoms in a quartz tube furnace at 1000 °C. Phosphosilicate glass (PSG) formed in the diffusion process was then removed by using 1:50 HF: H_2O oxide etches followed by DI rinse.

After the samples were thermally evaporated at 3×10^{-5} Torr in an oil vacuum pump system, a 3 μm thick layer of high-purity Al (99.999%) was constructed on the entire back surface and annealed at 850 °C to form the effective BSF. The thickness of the Al layer was measured using a gravimetric technique; thus, the weights of the samples were measured before and after the evaporation process. The TiO_2 and SiO_2 AR coatings were deposited on the front of the solar cells by sputtering and oxidation, respectively. After the baking processes, the refractive index, thickness, and reflectance of the films was measured using an optical reflectometer (Filmetrics F20) employing white light with a frequency range of 3×10^{14} Hz–7.5×10^{14} Hz. In this regard, light with a combination of differ-

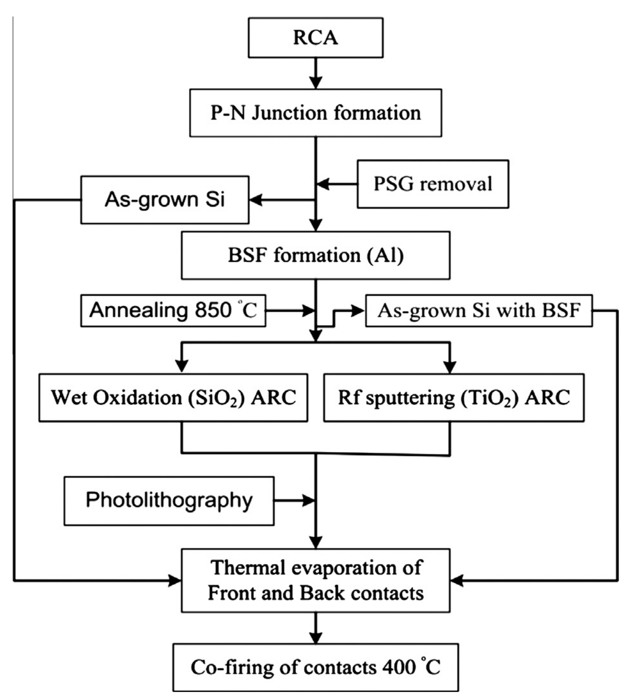

Fig. 1. Flow chart of BSF process for crystalline solar cells with/without antireflection coatings and as-grown silicon solar cell.