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Boron doped nanocrystalline silicon/amorphous silicon hybrid emitter layers used to improve the performance of silicon heterojunction solar cells

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Abstract

Boron doped nanocrystalline silicon/amorphous silicon hybrid thin films were deposited by radio frequency plasma enhanced chemical vapor deposition (RF-PECVD) to improve the performance of silicon heterojunction (SHJ) solar cells. Electrical and optical properties as well as structural and passivation characteristics of these thin films were systematically researched as a function of TMB gas mixture ratio. A high dark conductivity of 6.5×10^{-4} S/cm and minority carrier lifetime (τ_s) of 1740 μs on Czochralski (Cz) Si wafers were obtained with the hybrid p-type Si films. We applied this optimized film as an emitter layer on SHJ solar cells based on Cz silicon wafers; a significant improvement in the solar cell wavelength response at 400 nm and output performance have been achieved.

Keywords: Nanocrystalline silicon; Heterojunction solar cells; Optical properties; Minority carrier lifetime

1. Introduction

SHJ solar cells based on crystalline silicon (c-Si) and hydrogenated amorphous silicon (a-Si:H) is a promising candidate for highly efficient photovoltaic applications (Chen and Zhu, 2012; Dao et al., 2010; Mishima et al., 2011; Wen et al., 2013). Panasonic Corporation has reported that their Heterojunction with Intrinsic Thin-layer (HIT) solar cells based on n-type c-Si, which currently has a 24.7% conversion efficiency, and expected to achieve a 25.5% efficiency in the near future (Taguchi et al., Taguchi et al., 2013). SHJ solar cells obtain a higher open circuit voltage (V_{oc}) than monocrystalline silicon solar cells because of the wider band gap doping Si film acting as the emitter layer. The material quality of the p-type emitter layer is directly related to the conversion efficiency of n-type SHJ solar cells (Deniz Eygi et al., 2013). On one hand, the emitter layer of the high efficiency SHJ solar cell requires a large doping concentration to build up a sufficient internal electric field and adequate contact properties for the indium tin oxide (ITO)/p-type emitter. On the other hand, as the window layer of the SHJ solar cells, the p-type Si film also requires a wide band gap to reduce the parasitic absorption and improve the short wavelength response of the solar cells.

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The Solar energy group of the LG Corporation prepared a p^+/p-a-Si:H emitter layer with multi-step deposition to promote the p/TCO contact properties for SHJ solar cells (Ji et al., 2010). However, because large doping concentrations increase the defects and absorption coefficient of the p-type a-Si:H, the short wavelength response of the solar cells at 400 nm is only ~50%, which deteriorates the short current density (J_{sc}) of SHJ solar cells. To overcome this problem, other research groups (Lien et al., 2012; Ling et al., 2012; Rajagopalan et al., 2003; Wu et al., 2013; Xu et al., 2006) have improved the J_{sc} and fill factor (*FF*) of SHJ solar cells by applying high conductivity and wide band gap nc-Si:H as the emitter layer. The internal quantum efficiency of SHJ solar cells at 400 nm has increased to 87% (Hamashita et al., 2012). However, the p-nc-Si:H/i-a-Si:H structure has a larger band offset than p-a-Si:H/i-a-Si:H, which causes carrier recombination at the i/p Si films interface. In addition, the high temperature and power density processes for preparing nc-Si:H is a detriment to the microstructure of the intrinsic a-Si:H passivation layer hence reducing the V_{oc} of the SHJ solar cells.

Therefore, to improve the optical and electrical properties of the p-type emitter layer for SHJ solar cells without affecting the i-a-Si:H characteristics for c-Si surface passivation, we propose a p-nc-Si:H/p-a-Si:H hybrid structure as the emitter layer. In this paper, the optical and electrical properties as well as the structural and passivation characteristics of p-type films prepared by RF-PECVD at a low temperature were investigated. By incorporating the p-nc-Si:H/p-a-Si:H thin films as the emitter layer, a significant improvement in the performance of SHJ solar cells was achieved.

2. Experiment

2.1. Preparation of p-type Si films

P-type Si films were prepared in a multi-chamber cluster PECVD system at 180 °C with gaseous mixtures of SiH_4, Trimethylboron (TMB), and H_2. The vacuum pressure of the deposition chamber was 10^{-6} Pa, and the deposition pressure was kept constant at 2 Torr. P-type Si films were deposited simultaneously on Eagle XG glass substrates to investigate the properties of the films. The thickness of all the samples was set to 20 nm by controlling the deposition duration. The electrical properties of p-type Si films were measured with co-planar conductivity using a Keithley 617 programmable electrometer. Raman spectroscopy was performed using a He–Cd laser with a wavelength of 532 nm. Atomic Force Microscope (AFM) was taken by a NanoNavi SPV400 to characterize the surface morphology of the Si films. The optical band gap of thin p-type Si films was calculated through Tauc's plot (Tauc, 1974) from the reflectance-transmittance results. Reflectance–transmittance measurements were applied by a Varian-Cary 5000. Samples used to evaluate the passivation effect were deposited on n-type double-side polished 250 μm thick 1–3 Ω cm Cz silicon wafers. Sinton WCT-120 was used to measure the minority carrier lifetime of the passivation samples.

2.2. SHJ solar cells fabrication

SHJ solar cells were fabricated on n-type NaOH textured 280 μm thick Cz silicon wafers. The structure is Ag grid/ITO/hybrid p-type emitter layer/i-a-Si:H/n-c-Si/i-a-Si:H/n-a-Si:H/Al back contact, as illustrated in Fig. 1. The intrinsic a-Si:H was deposition at a separate chamber with gaseous mixtures of SiH_4 and H_2; the deposition pressure and temperature was kept constant at 1 Torr and 140 °C respectively. The Ag grid (thickness ~600 nm), Al back contact (thickness ~600 nm) and ITO layers (thickness ~80 nm) were prepared using physical vapor deposition (PVD), and patterned into the 0.64 cm^2 pad area. The *J–V* characteristics of solar cells were measured at 25 °C under 1-sun (AM1.5, 100 mW/cm^2) simulator radiation. External quantum efficiency (EQE) measurements were also performed to evaluate the spectral response of the fabricated solar cells.

3. Results and discussion

3.1. Properties of the p-type Si films

Two categories of p-type Si films were deposited by varying the power density (P_d) and hydrogen dilution ratio (R_H) with a different TMB concentrations. The R_H is defined as $[SiH_4]/[H_2]$, and the TMB concentration is defined as $[TMB]/[SiH_4]$. The dark conductivity and band gap of the p-type Si films are shown in Fig. 2. For the case of the samples deposited under low power density and hydrogen dilution conditions ($P_d = 41$ mW/cm^2, $R_H = 1{:}120$), the dark conductivity continuously increases with the concentration of TMB, which can be attributed to the increase of TMB concentration in the as-deposited Si films (Gracin et al., 2008; Rath and Schropp, 1998).

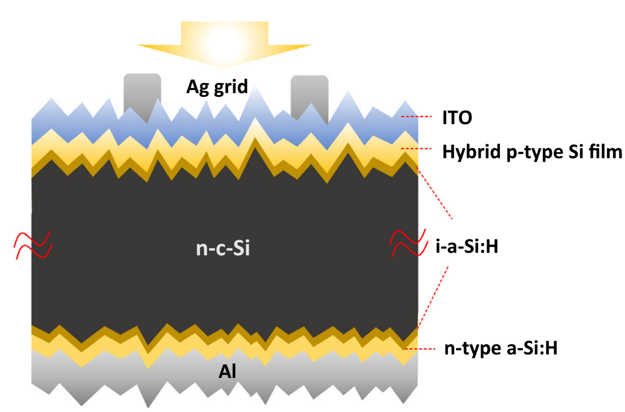

Fig. 1. Sketch of a SHJ solar cell with hybrid p-nc-Si/a-Si:H. The arrow indicates the direction of the incident light.