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High performance and high stability mechanisms of microcrystalline silicon-based thin-film solar cells deposited by laser-assisted plasma-enhancement chemical vapor deposition system

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Abstract

The laser-assisted plasma-enhanced chemical vapor deposition (LAPECVD) system was proposed to deposit high performance and high stability Si-based thin-film solar cells. In the LAPECVD system, the CO_2 laser and plasma were simultaneously utilized to effectively decompose the SiH_4 reaction gas. Consequently, the hydrogen concentration in the i-Si absorption film was reduced with an increase of CO_2 laser power. Furthermore, the microcrystalline i-Si film could be formed due to the formation of more Si nucleation seeds. Si-nanoclusters were formed on the microcrystalline i-Si films deposited in the LAPECVD system. The associated carrier mobility was increased with increasing the CO_2 laser power. The XRD measurements demonstrated that a gradual transformation from amorphous to crystalline as guiding the assisting laser. According to the FTIR measurement, the estimated hydrogen content reduction ratio of the light-soaked i-Si films decreased from 16.5% to 5% as the assisting laser power increased from 0 W to 80 W. The corresponding conversion efficiency degradation ratio of 20.20% and 5.74% was obtained, the high performance and high stability of the resulting Si-based p–i–n thin film solar cells were obtained.

Keywords: Hydrogen concentration; Laser-assisted plasma-enhanced chemical vapor deposition; Light soaking; Microcrystalline silicon

1. Introduction

In view of the serious problems of energy sources and environment, the green renewable energy sources have been attracted and focused, recently. Among the green renewable energy sources being ever utilized, the solar energy source was commonly used. To use solar energy as the green renewable energy source, III–V compound solar cells (Yamaguchi et al., 2008; Tseng and Lee, 2013), organic solar cells (Liang et al., 2010; Lee et al., 2012), and silicon-based solar cells (Tan et al., 2013; Choi et al., 2014) were extensively investigated. In the practical market, the silicon-based (Si-based) solar cells are the dominate commercial market in the solar energy systems. Among the Si-based solar cells, the thin-film-type solar cells have become the most promising structure due to the simple large area fabrication process and low cost. In recent years, several deposition methods of Si-based thin-film including plasma-enhanced chemical vapor deposition (PECVD)

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(Bousbih et al., 2012; Soderstrom et al., 2012), radio-frequency plasma-enhanced chemical vapor deposition (RF-PECVD) (Koch et al., 2001), inductively coupled plasma chemical vapor deposition (ICP-CVD) (Jeong et al., 2010), very high frequency plasma-enhanced chemical vapor deposition (VHF-PECVD) (Takatsuka et al., 2004; Kim et al., 2013), electron beam evaporation (Sontheimer et al., 2012), and hot wire chemical vapor deposition (HWCVD) (Klein et al., 2004; Yoshida et al., 2012) had been explored and reported. However, the conversion efficiency degradation suffered from the Staebler–Wronski effect (SWE) (Bhattacharya and Mahan, 1988; Chen et al., 2010). Furthermore, to further expand the thin-film solar cells on compliant substrates, the thin films must be deposited at low temperature owing to the low glass transition temperature and the low softening temperature of flexible substrates. To improve the conversion efficiency using microcrystalline structure and to circumvent conversion efficiency degradation using a reduction of Si–H bond inclusion, the laser-assisted plasma-enhanced chemical vapor deposition (LAPECVD) system was developed by our laboratory and used to deposit the Si-based thin-film solar cells at low temperature in this work. The LAPECVD system was composed of the conventional PECVD and an assisted dissociation CO_2 laser with a wavelength of 10.6 μm. Since silane (SiH_4) had a higher absorption coefficient at a wavelength of 10.6 μm (Steward and Nielsen, 1935), the CO_2 laser was utilized to assist the dissociation process by a multiphoton vibrational excitation (Chelkowski and Bandrauk, 1993; Bondi et al., 2006). Compared to the heating holder approach of the conventional PECVD, the laser assistance of the LAPECVD system could provide the dissociation energy of reaction gases without heating the substrate by controlling the laser beam path. Consequently, the SiH_4 reaction gas could be easily and efficiently decomposed into Si atoms under the combined action of the plasma and CO_2 laser. To study the improvement mechanisms of the Si-based thin-film solar cells deposited using the LAPECVD system, the same structure was also deposited using a conventional PECVD system.

2. Experiments

The designed LAPECVD system equipped with three chambers in a conventional PECVD system as shown in Fig. 1 for depositing p-Si films, i-Si films and n-Si films, respectively. In the LAPECVD system, three external CO_2 lasers with a wavelength of 10.6 μm were respectively guided into the three chambers of the conventional PECVD system through ZnSe window. To avoid substrates were heated by the incident CO_2 laser, the incident laser beam was controlled to be almost parallel to the surface of substrates. Fig. 2 shows the schematic configuration of the Si-based thin-film solar cells studied in this work. The 25-nm-thick p-Si, the 200-nm-thick i-Si and the 20-nm-thick n-Si thin films were sequentially deposited on fluorine-doped tin oxide (FTO)-coated glass substrates using the LAPECVD system. A 150-nm-thick Al film was then deposited as the back contact electrode using an electron beam evaporator. Reactant gas of 95% hydrogen-diluted silane (SiH_4) was used as the material source of the Si-based films. The diborane (B_2H_6) and the 99% hydrogen-diluted phosphine (PH_3) were used as the acceptor dopant and the donor dopant of the p-Si films and the n-Si films, respectively. The laser beam of CO_2 laser was guided into the chamber of the designed LAPECVD system to assist the decomposition of SiH_4. Therefore, because both the plasma and CO_2 laser could be simultaneously utilized to effectively decompose the SiH_4 reactant gas in the LAPECVD system, it was expected that more resulted silicon atoms could be formed as nuclear seeds for depositing microcrystalline silicon films with embedded Si-nanoclusters. Furthermore, compared with the conventional PECVD system in which only plasma was used to decompose the SiH_4 reactant gas, the Si–H bonds in the deposited Si films were significantly reduced owing to the more complete decomposition of SiH_4 reactant gas in the LAPECVD system.

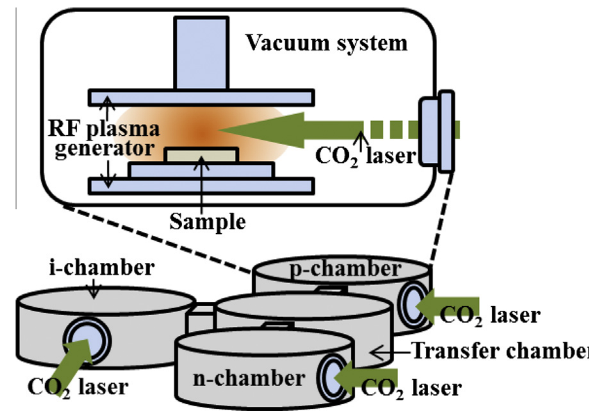

Fig. 1. Schematic diagram of LAPECVD system equipped with three chambers and CO_2 lasers.

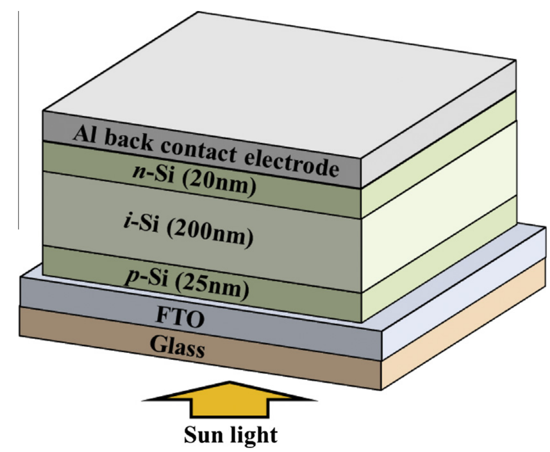

Fig. 2. Schematic configuration of Si-based p–i–n thin-film solar cells.

To study the performances of the i-Si absorption film of the Si-based p–i–n thin film solar cells as shown in Fig. 2, i-Si films were respectively deposited using the conventional