Procedia Manufacturing
Volume 5, 2016, Pages 734–746
44th Proceedings of the North American Manufacturing Research Institution of SME http://www.sme.org/namrc

Enhancement in Photoconductivity of a-Si Thin Films by Annealing and Texturing Technique with the Third Harmonic Output from a Pulsed Nd^{3+}:YAG Laser

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Abstract
Influence of the third harmonic pulsed Nd^{3+}:YAG laser on the formation of a polycrystalline-silicon (poly-Si) on a-Si thin film with thickness of 1000 nm and 400 nm in water and air ambience was investigated. In order to induce texturing of surface along with annealing, laser beam overlap technique with different percentages of spot overlap was used. Crystalline characteristics and electrical characteristics were studied to confirm the extent of crystallization. The crystalline characteristics of the film obtained with the Gaussian and the flat-top beam profiles were comparable for higher percentage of overlapping. Based on the theoretical modeling, the laser treatment without the ablation with the third output from the Nd^{3+}:YAG laser was limited to the a-Si film thickness up to 800 nm. This was in qualitative agreement with the experimental observations.

Keywords: Laser annealing, amorphous silicon, Texturing, Thin films, Solar cells, Photoconductivity

1 Introduction

Solar photovoltaic technology is one of the most promising technologies to meet the increasing energy demand. Majority of solar cells use silicon as a material due to its efficiency, stability and availability (KL Chopra et al. 2004**)**. However considering material benefit, heterostructure photovoltaic cell with amorphous silicon (a-Si) thin films is attractive as a-Si films possess a larger band gap (1.7 eV) than crystalline silicon (1.1 eV). Hence, cells can also absorb the visible part of the solar spectrum more effectively and offer material saving. However efficiency of a-Si films is limited due to the absence of crystal structure and the presence of dangling bonds which adversely affect the mobility resulting in low photovoltaic efficiency. This less efficient, but cost effective a-Si can be modified into polycrystalline silicon by inducing crystallization through laser annealing (Choi TY et al. 2003). Laser energy is used to heat the a-Si thin film, melting it and changing the microstructure to polycrystalline-Si as it cools. Compared to conventional furnace annealing, this localized laser annealing makes it possible to process thin films without affecting the substrate. Further, as reported

 Selection and peer-review under responsibility of the Scientific Programme Committee of NAMRI/SME

doi:10.1016/j.promfg.2016.08.060

by Palani IA et al.(2008), an increase in absorption of solar radiation on the surface of solar cell is useful in improving the efficiency of the solar cell. Simultaneously inducing texturing during laser annealing may assist in trapping and increase in absorption of solar light.

Laser annealing is a kinetic process where a short high intensity laser pulse is used to heat amorphous-silicon (a-Si) thin film in to a molten layer. The crystallized Si starts to grow as heated a-Si cools (Palani IA et al. 2008). Conventionally, excimer lasers, such as XeCl (308 nm), KrF (248 nm) lasers have been used for annealing of thin film solar cell (Azuma et al. 2002). The advantage of excimer lasers is the strong absorption of UV light in silicon and most of the laser energy is deposited close to the thin film surface (few tens of nm). So the thermal effect on the substrate is lower than that of lasers with longer wavelength. Recently, there has been a growing interest in using XeF (351 nm) for such applications as the photon energy of XeF laser (3.5 eV) is close to the binding energy of the Si-H bond (3.4 eV) as reported by Kuo C et al. (2006). In addition, excimer lasers have certain limitations, such as high operational cost and environmental problems due to its toxic nature. Alternatively, Nd^{3+}:YAG laser with the third (355 nm) harmonics can be considered for the treatment of a-Si films.

Extensive work on laser surface texturing of crystalline silicon had been reported by different groups like Crouch CH et al.(2004), Iyengar VV et al. (2011) and Halbwax M et al.(2008). However, limited work is presented for the simultaneous annealing and texturing of a-Si thin films in different ambience like air and water (Wang H et al. 2012, Palani IA et al. 2008, Nayak BK et al. 2007). Most of the studies concerned utilize femtosecond lasers on silicon wafers or a-Si thin films, but they involve ablation induced surface structuring. There are no studies reported on simultaneous wide-area annealing and texturing of thick (> few hundred nm) a-Si films in water ambience using a Q-switched, nanosecond pulsed Nd^{3+}:YAG laser with a wavelength of 355nm. This laser-assisted melting and re-solidification approach induces the texture formation via capillary action in molten silicon without ablating the material. The laser beam profile used for the laser treatment is also expected to influence the crystalline and electrical characteristics of poly-crystalline thin films. When a Gaussian beam is used, only a part of the energy will be effectively utilized and results in non-uniform annealing. Flat-top profile which has uniform intensity distribution can also be considered (Esther et al. (2015)).

In this paper, the influence of third harmonic (355 nm) of Nd^{3+}:YAG laser on simultaneous annealing and texturing of a-Si thin films in different ambience and beam profiles is studied. Wide area annealing and texturing is achieved by scanning the surface with different percentages of spot overlapping. A two-dimensional thermal model has been used for estimating the rise in thin-film temperature for different fluence values to establish the operational range and the crystallization depth that can be achieved during the process for the wavelength of 355nm.

2 Experimental Details

Figure 1 shows the experimental setup. Simultaneous laser annealing and laser nano- texturing was performed using a solid-state pulsed Nd^{3+}:YAG laser (Brilliant b, Quantel) at third harmonics (355 nm), with a frequency of 1 Hz and a pulse width of 5 ns (FWHM). Two different types of laser-beam profile, namely Gaussian, and flat-top intensity distribution were used. The laser beam was focused to form a spot size of 2 mm diameter on a-Si film by using a lens of focal length 200 mm. Experiments were performed in different ambient conditions, such as in air and under-water to determine appropriate conditions for annealing and texturing of a-Si films. For underwater treatment, the samples were kept under 3 mm depth of deionized water. Samples were scanned by moving the sample with a X-Y stage and the laser position was fixed. A beam shaper (Pi-Shaper 12_12_355_HP, AdlOptica) was used to change the Gaussian output from the laser into a flat-top beam profile. 10 mm × 10 mm samples were scanned using the laser with different percentage of spot overlapping. The speed of X-Y