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Effects of seeding methods on the fabrication of microcrystalline silicon solar cells using radio frequency plasma enhanced chemical vapor deposition

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Abstract

Single junction *p-i-n* μc-Si:H solar cells were prepared in a low-cost, large-area single chamber radio frequency plasma enhanced chemical vapor deposition system. The effects of seeding processes on the growth of μc-Si:H *i*-layers and performance of μc-Si:H solar cells were investigated. Seeding processes, usually featured by highly hydrogen rich plasma, are effective in inducing the growth of μc-Si:H *i*-layers. It has been demonstrated that *p*-layer seeding methods are preferable to *i*-layer seeding. While performance of μc-Si:H solar cells produced by *i*-layer seeding methods was usually limited by very low fill factors, μc-Si:H solar cells with good initial and stabilized conversion efficiencies were obtained by *p*-layer seeding.

Keywords: Solar cells; Silicon; Chemical vapor deposition; Nucleation

1. Introduction

Over the past decade, advances have been made in the fabrication of solar cells with hydrogenated microcrystalline silicon (μc-Si:H) intrinsic (*i*-) layers. High quality μc-Si:H is usually deposited by plasma enhanced chemical vapor deposition (PECVD). Early success in fabricating μc-Si:H solar cells was achieved by *very high frequency PECVD* [1]. Recently, studies on the fabrication of μc-Si:H solar cells using conventional radio frequency (RF-) PECVD have attracted extensive attention due to its compatibility with the existing large-scale manufacturing technology of amorphous silicon (α-Si:H) photovoltaic (PV) modules. In most laboratory scale research, sophisticated, multi-chamber, load-locked deposition systems, expensive laboratory substrates, as well as highly effective back reflector or transparent interlayer were routinely used to obtain high efficiency μc-Si:H solar cells [2–4]. However, the true potential of μc-Si:H solar cells can only be evaluated under conditions of cost-competitive manufacturing of large-area PV modules. Industrial production of 8 Ft^2 α-Si:H PV modules by a massively-parallel batch process in single chamber RF-PECVD systems has been successfully developed [5]. A realistic approach based on this proven technology has been taken to study the manufacturing of μc-Si:H solar cells on a low-cost, large-area basis [6]. Generally, glow discharge of highly hydrogen diluted silane is used as the standard PECVD approach for μc-Si:H deposition. Although the microscopic mechanism of μc-Si:H growth has yet to be better understood, it is generally believed that the initial nucleation of μc-Si:H crystallites on α-Si:H, α-SiC:H or other under-layers is critical to obtaining high quality μc-Si:H films. In this study, therefore, a wide variety of seeding processes were systematically explored and the effects of seeding schemes on the growth of μc-Si:H and device performance of μc-Si:H solar cells were investigated.

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2. Experimental details

Single junction *p-i-n* solar cells with μc-Si:H *i*-layers (absorbers) were fabricated on commercial grade SnO_2 superstrates by RF-PECVD method (13.56 MHz), using silane highly diluted by hydrogen as feed gas mixtures. Substrate temperature was usually kept near 200 °C. This single chamber deposition system, without load-lock, was routinely exposed to air for unloading and loading the substrates. The advantages of this low-cost PECVD system include a large electrode utilization ratio (a single 12 in.×15 in. powered electrode was used to simultaneously coat four substrates equal to its size), high gas utilization, a controllable contamination profile, ease of operation, and low maintenance. The doped *p*-layers and *n*-layers, as well as *i*-layers, were deposited in the same reactor without any movement of the substrates and/or the reactor. A thin α-SiC:H *p*-layer was first deposited on the SnO_2 superstrate. Then, a seeding step was applied to induce crystallization for the Si:H *i*-layer followed by the deposition of bulk *i*-layer. Finally, an α-Si:H *n*-layer was grown. Sputtered Al, without any rear reflection enhancement schemes, was used as the standard back contact.

Device fabrication and performance testing, including current–voltage curve (*I–V*), spectral response (QE), and light soaking, were routinely conducted at Energy Photovoltaics, Inc. (EPV). Parameters obtained from performance testing, such as conversion efficiency, open circuit voltage (Voc), short circuit current density (Jsc), fill factor (FF), and red-light spectral response (QE at 800 nm or longer), were also used to deduce the microstructural properties of μc-Si:H solar cells. In particular, low Voc and high red-light response were used as the signatures of μc-Si:H *i*-layers. Raman Spectroscopy of actual solar cells, performed at New Jersey Institute of Technology (NJIT), was used to study the micro-crystallinity of μc-Si:H solar cells. Due to the contribution from substrates and vary optical properties of Si:H *i*-layers, the micro-crystallinity was presented in terms of the ratio of peak intensities (Ic/Ia) of Raman shift corresponding to μc-Si:H (Ic) and α-Si:H (Ia), respectively.

3. Results and discussion

3.1. Seeding methods for μc-Si:H i-layer deposition

The performance of μc-Si:H solar cells depends on many processing details, chief among which are the seeding steps and the growth conditions for the bulk *i*-layers. Throughout this study, it has been established that, for a fixed set of *i*-layer plasma conditions capable of sustaining μc-Si:H growth, the seeding or incubation procedure (which may comprise several individual steps) largely determines the properties of Si:H absorber, and strongly influences the device performance. Under the same *i*-layer growth conditions, amorphous, mixed-phase, or micro-crystalline (nano-crystalline) Si:H absorbers can be obtained, respectively, depending on the seeding method.

The seeding methods we have explored can be classified into two categories: (i) *p*-layer seeding, which refers to all seeding methods involving boron doped *p*-layer, and (ii) *i*-layer seeding referring to the nucleation methods inside the 'intrinsic' Si:H layer. To grow μc-Si:H on an α-Si:H or α-SiC:H under-layer, a defective transition layer may exist at or near the *p*/*i* interface which may severely affect device performance. Thus, its thickness should be limited. Highly hydrogen rich plasma conditions are usually applied during seeding steps to induce initial μc-Si:H nucleation followed by growth of bulk μc-Si:H *i*-layer under relatively softer plasma conditions. However, the hydrogen rich plasma used in seeding processes could do severe damages to the microstructure and performance of μc-Si:H solar cells. Thus, the *p*-layer seeding approaches take the advantage of limiting the damages associated with energetic seeding plasma within the PV non-active *p*-layer and consequently lead to better overall carrier collection. Conceptually, *i*-layer seeding methods take the advantages of minimized optical loss associated with the thicker, defective *p*-layers resulting from *p*-layer seeding approaches and higher Voc due to the wider band gap of the non-microcrystalline *i*-layer near the *p*/*i* interface. Presumably, the disadvantage of this type seeding methods is the unavoidable defects near the *p*/*i* interface (*i*-layer side) created by the hydrogen rich plasma used to create nucleation sites, which might lead to poor carrier collection.

The *i*-layer seeding processes usually consist of the deposition of a thin α-Si:H buffer layer, an incubation layer deposited by pure hydrogen etching on the buffer layer or seeding using very high hydrogen dilution ratio, and a silane grading step leading to the growth of bulk μc-Si:H *i*-layer. The *p*-layer seeding processes consist of similar approaches with μc-Si:H nucleation occurs within doped *p*-layer.

3.2. Effects of seeding methods on the growth of μc-Si:H

High hydrogen to silane dilution ratio has been widely recognized as the most important factor to induce and sustain the growth of μc-Si:H. Therefore, hydrogen to silane dilution ratio, R=[H_2]/[SiH_4], was used as the major parameter in analyzing the seeding processes. In the relatively large area RF-PECVD system, it has been demonstrated that the seeding schemes so far explored, such as pure hydrogen etching on α-SiC:H or α-Si:H buffer layer and seeding by very high hydrogen dilution ratio, are effective in inducing the formation of μc-Si:H. Without special seeding methods, high hydrogen dilution ratio is necessary for the growth of bulk μc-Si:H *i*-layers.