



## Fabrication of thin film nanocrystalline silicon solar cell with low light-induced degradation

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### ABSTRACT

Nanocrystalline silicon thin films have been deposited at different total gas flow rates and plasma excitation frequencies and samples with similar crystalline volume fraction have been compared. In hydrogenated nanocrystalline silicon solar cells, amorphous component is not necessarily the only determining factor for light-induced degradation. Smaller grain size less than 3 nm diameter and intermediate range order provide a better stability in the i-layer near the p/i interface, thus improving the overall stability of the solar cell. Light-induced degradation (LID) of efficiency of the cell mainly depends on the light-induced degradation of short-circuit current density and light-induced degradation of fill factor (FF). Degradation of open-circuit voltage is less than 1%. Minimum degradation of efficiency obtained in this work is 2%.

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### 1. Introduction

In order to make photovoltaic technology cost effective and competitive with other technologies, we need to improve the efficiency and minimize the light-induced degradation. Hydrogenated nanocrystalline silicon (nc-Si:H) has attracted remarkable attention due to its ability to absorb long wavelength photons and its better stability under prolonged light soaking. Recent results in nanocrystalline silicon solar cells have shown that best efficiencies have been achieved using materials close to the transition from nanocrystalline to amorphous growth using Plasma Enhanced Chemical Vapour Deposition (PECVD) [1]. This material has a large amount of amorphous fraction, which can turn out to enhance the degradation of the device when exposed to long time illumination. It has been reported previously that no light-induced degradation (LID) was observed in nc-Si:H solar cells [2,3]. Some recent results show that nc-Si:H single-junction cells degrade in the range 3–15% [4,5]. In order to improve nc-Si:H cell performance and stability at the same time, a better understanding of the factors determining the stability is essential. It is well known that metastable defect generation leads to degradation in hydrogenated amorphous silicon (a-Si:H)-based material quality and solar cell performance. The defects can be induced by prolonged illumination, [6,7] charge accumulation, [3] or carrier injection [8,9]. It is believed that the defect creation is caused by recombination of the excess electron-hole pairs

generated by photo excitation or forward-bias current injection. Stability in hydrogenated nanocrystalline silicon is very complex. nc-Si:H represents a wide range of materials comprising grains with different sizes and different crystalline volume fractions. Meillaud et al. [10] found that the defect density and the stability of nc-Si:H cells made by a very-high-frequency glow discharge method are related to the crystalline volume fraction. Although the degradation decreases with increasing crystalline volume fraction, the defect density has a minimum value for the cells deposited in the nanocrystalline/amorphous transition region. Smirnov et al. [11] showed that light-induced degradation in nc-Si:H films is associated with a large density of metastable light-induced defects. Silane concentration is known to determine the grain size in nc-Si:H films, and the best material with a compact structure is grown at a concentration just above the transition from amorphous to nanocrystalline.

In this paper, we report a systematic study of the stability of nc-Si solar cells made with various silane concentrations and correlate the result to the material structural properties. We have optimized the material structure and improved the cell performance and stability.

### 2. Experimental details

Nanocrystalline silicon films were deposited using 54.24 MHz (MHF) and 13.56 MHz (RF) plasma excitation frequencies ( $f_{ex}$ ) in a multichamber PECVD system. Three sets of samples M100, M200 and M300 were deposited using MHF (M-series) and total gas flow rates ( $T_{fl}$ ) of 100, 200 and 300 SCCM, respectively. For the

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above-mentioned films, silane concentration  $[Y = (\text{SiH}_4/(\text{SiH}_4 + \text{H}_2))100]$  was varied from 1.5% to 4%. The fourth set of samples (RF series), RF200, was deposited using RF frequency and a  $T_{\text{fl}}$  of 200 SCCM where  $Y$  was varied from 5% to 6.5%. The crystalline volume fractions of the films were investigated by Raman spectroscopy and X-ray diffraction (XRD). The Raman spectra were taken using 514.5 nm Ar laser light. Raman spectra of each film in the range  $400\text{--}560\text{ cm}^{-1}$  were deconvoluted into three Gaussian peaks corresponding to crystalline silicon peak ( $\sim 520\text{ cm}^{-1}$ ), intermediate peak ( $\sim 510\text{ cm}^{-1}$ ) and amorphous peak ( $\sim 480\text{ cm}^{-1}$ ). The crystalline volume fraction was calculated from  $X_c = (I_c + I_{\text{in}})/(I_c + I_{\text{in}} + I_a)100\%$ , where,  $I_c$ ,  $I_{\text{in}}$  and  $I_a$  are the integrated intensities of crystalline, intermediate and amorphous components, respectively [12]. The fractions of intermediate Raman component and crystalline Raman components were given by  $F_{\text{in}} = I_{\text{in}}/(I_c + I_{\text{in}} + I_a)100\%$  and  $F_c = I_c/(I_c + I_{\text{in}} + I_a)100\%$ , respectively. X-ray diffraction studies were done using  $\text{CuK}\alpha$  radiation. The grain sizes of the films were calculated from the FWHM of  $\langle 220 \rangle$  peaks using Scherrer's formula. For the fabrication of single junction p–i–n solar cells, these nanocrystalline films of about  $1.5\ \mu\text{m}$  thickness were used as the absorber layer (i-layer). The solar cells were deposited on TCO-coated glass substrate and aluminium was used as back contact. The  $I\text{--}V$  characteristics of the solar cells were measured under AM 1.5 illumination at  $28^\circ\text{C}$ . Light-induced degradation of photoconductivity ( $\sigma_{\text{ph}}$ ) of all these films and the solar cells were investigated under white light of intensity  $100\text{ mW/cm}^2$  for 1000 and 500 h of light soaking, respectively at  $28^\circ\text{C}$ . Percentage of degradations ( $\Delta$ ) for conductivity and solar cell performance parameters is defined as  $\Delta = \{[(\text{initial value}) - (\text{final value})]/(\text{initial value})\}100\%$ .

### 3. Results

#### 3.1. Structural studies of absorber layer

Deposition rate and properties of four sets of films deposited under different conditions are shown in Table 1. For all the sets, deposition rate increases as silane concentration increases. Higher deposition rates are obtained for films deposited at a lower  $f_{\text{ex}}$  of 13.56 MHz compared to 54.24 MHz. This is because the films were deposited at high-power–high-pressure regime using 13.56 MHz.

In this work, films of different sets with same crystallinity will be compared.

The amount of crystalline volume fraction in the films was estimated from the Raman scattering study [12]. Tables 1 and 2 show the results of the Raman scattering study of films deposited at different total gas flow rates, silane concentrations, powers, pressures and plasma excitation frequencies. Maximum  $X_c$  of 80% is obtained for films deposited at RF. For each of the four sets of films,  $X_c$  increases as silane concentration decreases. This may be due to higher etching by atomic hydrogen at lower silane concentrations. Nanocrystalline silicon has a peak at around  $510\text{ cm}^{-1}$  and it is called intermediate component. Mavi et al. [13] and He et al. [14] associated this intermediate component in the Raman spectra to the thermodynamically stable nanocrystalline grains of size below 3 nm. In this work it is found that  $F_{\text{in}}$  does not vary much with increase in silane concentration (Table 2). The crystalline component  $F_c$  significantly increases as silane concentration decreases. At lower silane concentrations small grains merge to form bigger grains. It is observed that films M100-1 and M200-2 have a similar value of  $F_c$  around 32%, whereas their  $F_{\text{in}}$  decreases with increase in total gas flow rate from 100 to 200 SCCM. Further increase in  $T_{\text{fl}}$  does not decrease  $F_{\text{in}}$ . It is also observed that the film RF200-2 has higher fraction of intermediate component than the M-series films.

Nature of crystallinity and grain sizes of the films were investigated using the X-ray diffraction method. Fig. 1 shows the X-ray spectra of films deposited under different conditions. At low silane concentration, three orientations i.e.  $\langle 111 \rangle$ ,  $\langle 220 \rangle$  and  $\langle 311 \rangle$  of crystalline silicon are observed for MHF-deposited films. As the silane concentration is increased, only a single  $\langle 220 \rangle$  orientation evolves. Shah et al. [15] found similar results when they decreased  $Y$  below 1.25%. Grain sizes of the films calculated from  $\langle 220 \rangle$  orientation are shown in Table 1. Maximum grain size of 13.2 nm is obtained for films deposited at MHF. Minimum average grain size of 5 nm is obtained for films deposited at RF. It is observed that grain sizes and peak heights increase as silane concentration decreases from 4% to 1.5% for samples deposited at MHF. This can be corroborated to increase in crystalline volume fraction as observed from Raman scattering studies. It is observed that for films deposited at MHF, grain sizes do not vary much with variation in total gas flow rate.

**Table 1**  
Properties of nc-Si:H films deposited under different conditions.

Absorber layer	Silane concentration (%)	Power ( $\text{W/cm}^2$ )	Deposition rate ( $\text{\AA/s}$ )	Grain size (nm)	$X_c$ (%)	% of degradation
M100-1	4	0.5	6.7	6.2	49.6	61
M100-2	3		6.1	9.7	60.7	52
M100-3	2		5.1	12.2	72.1	23
M200-1	4	0.5	6.8	–	31.5	49
M200-2	3		6.3	9.1	45.2	44
M200-3	2		5.8	11.4	58.3	29
M200-4	1.5		4.5	12.9	79.3	21
M300-1	4	0.7	7.5	–	32.9	81
M300-2	3		6.95	9.8	48.2	68
M300-3	2		6.2	12.2	59.1	53
M300-4	1.5		4.8	13.2	78.5	42
RF200-1	6.5	0.4	12.8	–	20.2	96
RF200-2	6		12	5	65	68
RF200-3	5.5		11.1	5	71	37
RF200-4	5		10.6	6.7	80	18

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