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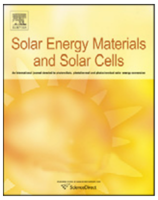

Effect of impurities on performance of hydrogenated nanocrystalline silicon solar cells

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ABSTRACT

We found that for O content as high as $\sim 2\times10^{19}$ at./cm^3, hydrogenated nanocrystalline silicon (nc-Si:H) solar cell having 10.6% efficiency is attainable, when a small amount of B ~ 1–3×10^{16} at./cm^3 is incorporated. Micro-doping compensation is critical for high efficiency nc-Si:H cells absent very low residual impurities. Quantum efficiency (QE) loss in the long wavelength region is observed when O is present, which loss can be eliminated by micro-doping with a compensating element such as B. However, when the B content exceeds a certain compensation level, a QE loss in short wavelength region is observed.

1. Introduction

A hydrogenated nanocrystalline silicon (nc-Si:H) solar cell is a critical component in the fabrication of high efficiency multi-junction thin film solar cells [1,2]. The intrinsic nanocrystalline material of such a component cell has a low bandgap and suffers no light-induced degradation under red light illumination, making it a perfect choice for the bottom cell in hydrogenated amorphous silicon (a-Si:H) and nc-Si:H based multi-junction solar cells [3]. Since the early study of nc-Si:H solar cells by Neuchâtel [4,5], a-Si:H and nc-Si:H based multi-junction solar cell efficiency has now exceeded the record efficiency of a-Si:H and amorphous silicon germanium alloy (a-SiGe:H) based multi-junction solar cells [6,7].

Compared to a-SiGe:H, nc-Si:H has several advantages, such as high photocurrent capability, good stability upon light soaking, and a fabrication process that does not require the use of GeH_4. However, nc-Si:H solar cells also have challenges that need to be addressed before the cells can be incorporated into volume manufacturing. The critical challenges are high rate deposition, large-area uniformity, and high performance as a component cell in multi-junction structures. Efficiency improvement remains one of the most important tasks for the thin film silicon photovoltaic community. One limiting factor for nc-Si:H cell efficiency is the presence of impurities in the nc-Si:H intrinsic layer [8–13]. It has been found that nc-Si:H is more sensitive to O and N impurities than a-Si:H. This is because O and N form weak donors in nc-Si:H materials, which move the Fermi level toward the conduction band edge [13]. nc-Si:H usually shows weak n-type conductivity unless the impurity levels are reduced significantly or compensated by p-type doping. In order to make high efficiency cells, it is generally recommended [2] to get O level below 5×10^{18} at./cm^3. We have improved our deposition reactor and made nc-Si:H materials with O levels in the range of 2–3×10^{18} at./cm^3 [14]. However, it is desirable, from a manufacturing point of view, to improve nc-Si:H solar cell efficiency in an environment more forgiving to the presence of impurity levels, such as the presence of O on the order of 10^{19} at./cm^3. It has recently been shown [13] that the efficiency of cells with an intrinsic layer thickness of 1.2 μm remains unchanged at around 8% till the O level reaches 2×10^{19} at./cm^3. The cell efficiency, however, is much lower when the thickness is $\sim$3 μm, a thickness that is needed to obtain higher efficiency. With that in mind, we explored the highest efficiency attainable using conventional deposition conditions for thicker cells. We studied the B compensation effect on the nc-Si:H solar cell performance, and achieved an initial active-area (0.25 cm^2) solar cell efficiency of 10.6%, in which the O level in the intrinsic layer was 2–3×10^{19} at./cm^3.

2. Experimental Details

We used a multi-chamber reactor with modified very high frequency (MVHF) glow discharge to deposit the nc-Si:H intrinsic (i) layer of the n–i–p structured solar cells on Ag/ZnO back reflector (BR) coated stainless steel substrates, where n and p are the P-doped and B-doped layers, respectively. No extra care was used to minimize impurity levels. The deposition conditions

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and cell structures were optimized, such as by using hydrogen dilution profiling to control the crystallinity along the growth direction and employing an optimized Ag/ZnO BR to enhance photocurrent [6]. In addition, properly optimized n/i and i/p buffer layers and a seed layer with high crystallinity were used to improve the cell performance. The nc-Si:H i layer was deposited at ~5 Å/s with a thickness of ~3 μm. It is well known that the crystalline volume fraction and crystalline preferential orientation affect the cell performance significantly. Our previous studies [15,16] showed that a crystalline volume fraction of ~50% with (220) preferential orientation gives the best cell performance. Although we did not carry out any Raman measurements on the samples used in this study, we believe that the crystalline volume fraction is close to 50% as in the previous best materials.

The impurities in the nc-Si:H i layer were controlled by the deposition procedures. The B contamination was introduced from the depositions of the p-layer even though a multi-chamber system was used. Unless extensive precautions are taken, our standard process results in a small amount of B contamination in the i layer. We verified that the same procedure gave the same B level in the nc-Si:H i layer within measurement uncertainty. The O impurity mostly comes from the degassing of the deposition chamber and the substrate holder. By varying the pre-baking time and condition, we could change the O levels in the nc-Si:H i layer. Also, the same pre-baking condition resulted in the same O impurity within measurement uncertainties.

Secondary Ion Mass Spectroscopy (SIMS, measured by the Evans Analytic Group) was carried out on n–i–p nc-Si:H solar cells on the area with no ITO coverage to analyze the impurity profiles. The solar cell current density versus voltage (*J*–*V*) was measured under an AM1.5 solar simulator at 25 °C. Quantum efficiency (QE) was measured under short-circuit conditions and under a -5 V electrical bias. We use the integral of QE and AM1.5 spectrum to calculate the current density, and define the relative difference of photocurrent densities measured under zero bias and -5 V bias normalized by the photocurrent at -5 V as QE loss. The same integral in the wavelength region >610 nm is defined as the long wavelength loss.

3. Results and discussion

Fig. 1 illustrates the effect of doping on QE curves, where three solar cells were studied. We used similar B concentration in the three solar cells, but with different O impurity levels achieved by varying the conditions of the deposition reactor. The SIMS profiles of O and B are plotted in Fig. 2 for the three samples in Fig. 1. Sample A has the highest O level and its QE shows the largest long wavelength loss. Table 1 lists the *J*–*V* characteristic parameters for the three solar cells with different QE losses. From previous studies [5–8], it is known that O is a weak dopant in nc-Si:H solar cells and causes long wavelength QE losses that could be effectively compensated by a small amount of B. However, if the amount of B exceeds the proper compensation value, it would make the nc-Si:H to become slightly p-type resulting in a short wavelength QE loss. We believe that if the B content is extremely low, the cell performance would improve significantly by reducing the O content. However, as shown in Fig. 3c and Table 1, the cell has the worst performance when O content is reduced to the lowest level showing a short wavelength loss. Therefore, we speculate that the nc-Si:H i layer in this study might be slightly p type caused by the small amount of B contamination, which reduces the built-in electrical field in the area close to p–i interface, and results in a short wavelength QE loss. A proper compensation occurs at middle level of O concentration, in which QE shows minimal loss for both short and long wavelengths as shown in Fig. 3b. Under this optimum compensated condition, we achieved an initial active-area efficiency of 10.6% in a nc-Si:H single-junction solar cell. For this cell, the O impurity level is 2–3×10^{19} at./cm^3 and the B micro-doping content is 1–3×10^{16} at./cm^3 in the i layer. It is noteworthy that the cell performance depends both on O and B concentration. For the level of residual B concentration presented in this study, reducing O concentration below 2×10^{19} at./cm^3 makes the cell performance poorer (sample 21916).

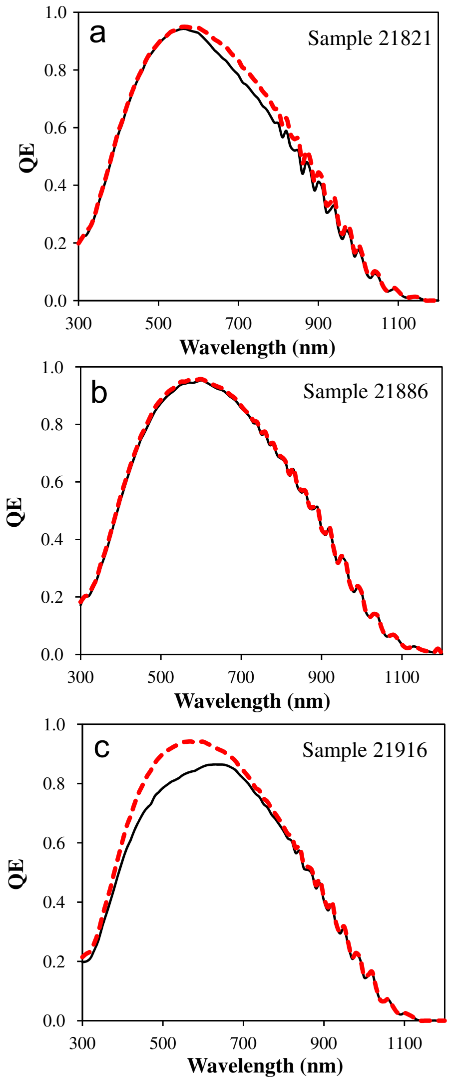

Fig. 1. Quantum efficiency (QE) measured under -5 V (thick dotted lines) and short-circuit condition (thin solid lines) for three samples with different QE losses, where Sample 21821 has a long wavelength QE loss (a) Sample 21886 has a minimal QE loss and (b) Sample 21916 has a short wavelength QE loss.

The concentrations of other elements, such as, N, C, P, H, and Ge from SIMS measurements were also obtained. The concentration of these elements is either the same or very small in the three samples, and should not affect our results. For example, the N concentration is $\sim5\times10^{16}$ at./cm^3 in the three samples; it is lower than the level that could cause deterioration of performance in the nc-Si:H solar cells [13].

Fig. 3 shows the *J*–*V* curves of the high efficiency nc-Si:H solar cell. This efficiency is one of the highest for nc-Si:H single-junction solar cells and indicates that in principle, one can attain high nc-Si:H solar cell efficiencies, while being less stringent about impurity levels; provided that a small amount of B