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Improving Device Efficiency for n-i-p Type Solar Cells with Various Optimized Active Layers

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We investigated n-i-p type single junction hydrogenated amorphous silicon oxide solar cells. These cells were without front surface texture or back reflector. Maximum power point efficiency of these cells showed that an optimized device structure is needed to get the best device output. This depends on the thickness and defect density (N_d) of the active layer. A typical 10% photovoltaic device conversion efficiency was obtained with a $N_d = 8.86\times10^{15}$ cm^{-3} defect density and 630 nm active layer thickness. Our investigation suggests a correlation between defect density and active layer thickness to device efficiency. We found that amorphous silicon solar cell efficiency can be improved to well above 10%.

Keywords: Si thin film solar cell, n-i-p structure, High efficiency, Defect density, Simulation, Optimization

1. INTRODUCTION

The maximum electrical output from a solar cell is determined by its photovoltaic conversion efficiency. This has always been a key criterion for large scale commercialization. It is well known that conversion efficiency depends on various factors [1-5]. While these are easy to understand, it is difficult to improve the performance of a solar cell [6]. In an amorphous silicon solar cell, the energetic electron hole pairs are photo generated in the intrinsic type photo sensitive layer. Therein, the valence and conduction band tail states are exponentially distributed with photon energy. The transmitted light intensity through a layer of thickness d mostly follows Beer Lambert's exponential relation. Therefore, when an AM1.5G like broad band solar spectra falls on such a film, layer thickness is one factor on which the total optical absorption of incident light depends. Increasing the active layer thickness can increase the short circuit current density in a solar cell. It should be noted that the recombination loss of excess carriers opposes carrier generation. SRH (Shockley-Read-Hall) recombination [7] is one of the prominent routes through which the photo generated excess carriers can be lost. Amorphous silicon based semiconductors usually have significant mid gap defects [8] so increasing the active layer thickness may not always give a higher efficiency. Herein we investigate two parameters for solar cell efficiency; thickness and density of the cell's active layer. Since deposition conditions can affect electronic defect density, it is not always possible to reduce density. However, active layer thickness can be controlled as needed. We will show that a suitable combination of these two parameters can result in the best efficiency performance for a device.

2. EXPERIMENTAL DETAILS

Our investigation starts with a baseline n-i-p type solar cell without front surface texture and a back reflector. It was derived from a n-i-p type cell that was fabricated on a textured substrate [9], and we used AFORS-HET [10] simulation to get characteristics of the baseline solar cell (as given in the trace named "simu1" of Fig. 7(a) of reference [9]). The basic cell structure used in this investigation was: p-a-SiO:H (20 nm)/ i-a-Si:H (variable thickness)/ n-a-Si:H(25 nm), where p-a-SiO:H is boron doped hydrogenated amorphous silicon oxide, i-a-Si:H is i-type or intrinsic hydrogenated amorphous silicon, n-a-Si:H is phosphorus doped a-Si:H, with non-textured flat front and back surfaces. The intrinsic layer of this cell had a defect density, $N_d = 8\times10^{17}$ cm^{-3}. Details about this baseline

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reference cell are in reference [9]. The solar cells reported here were simulated from the baseline cell (using AFORS-HET simulation), with varying defect densities (within $N_d = 4\times10^{14}$ cm^{-3} to 8×10^{17} cm^{-3}) and thicknesses (within 25 nm to 3,500 nm) of the active layers.

3. RESULTS AND DISCUSSION

The efficiency of a solar cell is a complicated combination of optical absorption [9,11] and recombination of photo generated carriers [12]. With the help of the Beer-Lambert exponential relation, the optical absorption in the active layer (I_a) is expressed as [9,11]:

$$I_a = I_0[I - \exp(-\alpha d_i)] \tag{1}$$

where I_0 is light intensity at the front surface of the active layer, and α is the absorption coefficient. The SRH (Shockley-Read-Hall) recombination can be expressed as proportional to total trap density (N_t) as [12]:

$$R_{SRH} = k_{SRH} N_t \tag{2}$$

$$k_{SRH} = (np - n_i^2)v_{th}\sigma_t / [p + n + 2n_i \cosh\left(E_i / E_t\right)]$$

where n_i is the intrinsic carrier density, n & p are non-equilibrium carrier concentration in the material, v_{th} is the thermal speed of an electron, and σ_t is the capture cross section.

AFORS-HET simulation was used to generate the J-V characteristic curves for solar cells and estimate efficiency (*Eff*) for each cell at the maximum power point. Figure 1 shows the efficiency of various cells with varying active layer thicknesses and defect densities. Cell efficiency was plotted for various thicknesses while its defect density (N_d) was kept constant, and lines were used to connect the data points for a particular N_d. The variation in efficiency shows that for a particular N_d a maximum efficiency can be achieved for a particular d_i. This implies that an optimized active layer thickness is needed to achieve the best efficiency from a device, and the thickness (d_i) is strongly dependant on the N_d. The maximum possible efficiency for a particular N_d is denoted as open star symbols in Fig. 1. If the stars are connected with a best fit curve (AB), we can divide the first quadrant of the *Eff* vs d_i plot into two regions: one above the AB curve that is dominated by optical generation (equation (1)), the other one below the AB curve is recombination dominated (equation (2)).

Now, collecting some of the cell results for particular di, we plot the efficiency with $Log_{10}(N_d)$, as shown in Fig. 2. It shows that for a particular d_i, the *Eff* always decreases with an increased N_d. This trend matches with the basic concept that when total optical absorption or carrier generation is constant, the maximum cell output power will reduce with increased N_d, or recombination loss of carriers. The accessible solar cell efficiency is limited by the dotted line CD. The upper part of the line CD is inaccessible, while the lower part is accessible. Therefore, CD indicates the limiting device efficiency achievable for a particular combination of thickness d_i and defect density N_d. The open star symbols correspond to the solar cell structures for maximum possible efficiency. These data points are plottedin Fig. 3.

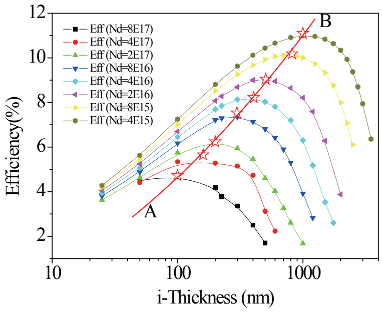

Fig. 1. Solar cell efficiency plot of active layer thickness for various defect densities.

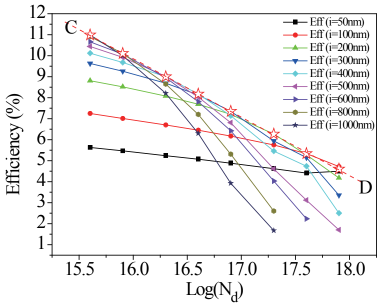

Fig. 2. Solar cell efficiency plot with $Log_{10}(N_d)$ of the active layer, for its various thicknesses.

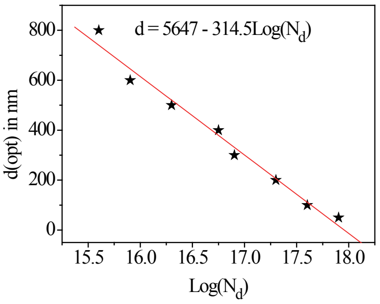

Fig. 3. The relation or plot between optimum active layer thickness, $d(opt)$, with the $Log_{10}(N_d)$. The symbols indicate simulation results, while the straight line is a best fit among the data points.

The best fit line obtained from the Fig. 3 is expressed as

$$d(opt) = d_0 - d_m Log_{10}(N_d) \tag{3}$$

where d_0 = 5,647 nm, d_m = 314.5 nm. Equation (3) outlines a type of relationship that might exist between active layer defect density and thickness for highest achievable device efficiency. In our case, the maximum device efficiency is achievable when $d_i = d(opt)$. In that case the efficiency can be expressed as :

$$Eff = Eff_{\max} - Eff_{factor} Log_{10}(N_d) \tag{4}$$

where $Eff_{\max}$ = 54.35%, Eff_{factor} = 2.781%. Again this is a typical relationship between the solar cell efficiency and defect density. It can also be noted that when the second term of expression (4), the $Eff_{\text{factor}}\ Log_{10}(N_d)$, is close to zero, or the N_d is close to 1 (with $d(opt)$ = 5.6 μm), the $Eff = Eff_{\max}$ = 54.35%. This implies that the ideal limiting efficiency of the amorphous silicon solar cell is 54%. This is much higher than previously predicted. This is a theoretical prediction and may not be achieved practically (because defect density can never be zero or one). However, these results indicate that a very high solar cell efficiency is achievable with amorphous silicon material if active layer defect density and thickness are suitably combined.

It is to be noted that the term $Eff_{\max}$ in equation (4) implicitly contains the effect of parasitic optical absorption, although it was not included in this parameter explicitly. One parasitic effect can be described as the following. With increased thickness of the

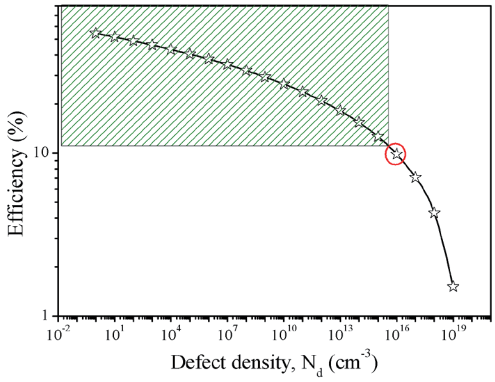

Fig. 4. Variation in device efficiency with defect density, as obtained from Equation (4). The red circle indicates the point corresponding to 10% solar cell efficiency. The shaded area is arbitrarily selected to give an idea of the region of the curve that is difficult to achieve, because it requires a lower active layer defect density. Since the defect density of most of the amorphous silicon active layers is higher, so most of the optimized cell efficiency may fall on the curve outside the shaded region.

p-a-SiO:H layer, its optical absorption will increase and hence the light available to the active layer for absorption also reduces. Experimental results indicate an increase in short circuit current density and the fill factor is expected while a reduction in open circuit voltage may take place with reduced thickness of the p-type layer [15]. Based on the results of [15], the device efficiency increases from 6.61% to 7.06% and reaches near saturation when the thickness of the p-type layer decreases from 20 nm to 12 nm which is an increase by a factor of 0.0681. Therefore the Eff_{max} is expected to be higher by a similar factor if thickness of the p-type layer is decreased, and vice versa. A similar effect of parasitic optical absorption of the n-type layer can come into effect if back reflection of unabsorbed light is considered. Additionally, parasitic electrical resistance of the individual layers can also influence the Eff_{max}.

Furthermore, relationship (4) indicates that a 10% device efficiency can be achieved with $N_d = 8.86\times10^{15}$ cm^{-3} and d(opt) = 630 nm. A graphical representation of equation (4) is given in Fig. 4. Here, the curve in the shaded region is considered to be difficult to achieve because the required defect density of the active layer is low. The curve outside the shaded area is achievable with the existing state of the art semiconductor device fabrication technology. Intrinsic amorphous silicon alloy can exhibit a defect density close to 10^{16} cm^{-3}, and intrinsic hydrogenated amorphous silicon oxide materials [13,14] can be one of them. A further improvement in material preparation is expected to provide an active layer with reduced defect density.

This investigation is based on n-i-p type solar cells, so light trapping can be easily introduced. With suitable pyramidal or prismatic light trapping, at least 1.26 times enhancement in device efficiency is achievable [9]. Therefore, the efficiency, expressed in equation (4) can be suitably modified to obtain approximate the efficiency of a device with light trapping.

This investigation is limited to the structure of the device used in the study. Here opto-electronic characteristics of the doped p-type and n-type layers were not varied. We also did not investigate possible variations in opto-electronic characteristics of the active layer that may be associated with practical variation in defect density of the i-type layer. Although our investigation has limitations, it showed that the efficiency of amorphous silicon solar cells can be enhanced significantly if a proper optimized active layer thickness is used. Our investigation shows that an optimized active layer thickness depends upon its defect density.

4. CONCLUSION

An optimized device structure is needed to get the best possible photovoltaic conversion efficiency from n-i-p type amorphous silicon solar cells. To achieve optimization, the two most important parameters are the defect density of the active layer and its thickness. Thicker cells tend to have more recombination loss while thinner cells have less than optimal photo generated carriers. Optimizing these parameters will give the best device structure with the highest efficiency. Our investigation showed a new theoretical efficiency limit of 54.35% for an amorphous silicon solar cell device under ideal conditions. Different plasma deposition systems have different degrees of purity for the deposited intrinsic layer. Therefore, achieving the best device efficiency requires specific optimization for both defect density and thickness of the active layer.

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