Simulation of High Conversion Efficiency and Open-circuit Voltages Of $\alpha$-si/poly-silicon Solar Cell

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Abstract

The $P^+\alpha$-Si/$N^+$ polycrystalline solar cell is molded using the AMPS-1D device simulator to explore the new high efficiency thin film poly-silicon solar cell. In order to analyze the characteristics of this device, and the thickness of $N^+$ poly-silicon, we consider the impurity concentration in the $N^+$ poly-silicon layer and the work function of transparent conductive oxide (TCO) in front contact in the calculation. The thickness of $N^+$ polycrystalline had little impact on the device when the thickness varied from 20μm to 300μm. The effects of impurity concentration in polycrystalline are analyzed. The conclusion is drawn that the open-circuit voltages ($V_{oc}$) of $P^+\alpha$-Si/$N^+$ polycrystalline solar cell is very high reaching 752 mV, and the conversion efficiency reaches 9.44%. Therefore, based on the above optimum parameters the study on the device formed by $P^+\alpha$-Si/$N^+$ poly-silicon is significant in exploring the high efficiency poly-silicon solar cell.

keywords: $P^+\alpha$-Si/$N^+$ poly-silicon, Solar cell, Photovoltaics, Thin-film polycrystalline-silicon

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1 Introduction

Thin-film polycrystalline-silicon solar cells have offered a promising alternative to standard silicon solar cells. Up to now, however, obtained efficiencies are too low to cut the cost in photovoltaics. Poly-crystalline silicon solar cell modules currently represent between 80% and 90% of the PV world market resulting from the stability, robustness and reliability of this kind of solar cells compared to those of emerging technologies. Thin-film polycrystalline-silicon solar cells are considered to be one of the most promising alternatives to bulk silicon solar cells. Thin films decrease the cost of silicon wafers significantly so that they account for about half of the total cost of standard silicon solar modules. There are many methods for preparing the thin-film polycrystalline-silicon. Both B-doped and n-type polycrystalline silicon thin films were prepared by rapid thermal chemical vapor deposition [1] and chemical vapor deposition (CVD) [2], respectively. In light of these merits, the thin film polycrystalline-silicon solar cells have been studied through many methods. Thin-film solar cells which are fabricated by polycrystalline silicon (poly-Si) films prepared by flash lamp annealing have been fabricated by Yohei Endo et al [3]. They had the open circuit voltage ($V_{oc}$) of 0.21 V and fill factor (FF) of 0.404. Thin-film polycrystalline silicon solar cells on ceramic studied by L. Carnel [4] had the maximum efficiency of 5.3% and Open-circuit voltages ($V_{oc}$) of 520

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mV. S. Gall et al. [5] prepared the polycrystalline silicon thin-film solar cells with high conversion efficiencies on glass using innovative approaches. The studies on polycrystalline silicon thin-film solar cells have obviously focused on photovoltaic industry. Exploring the high conversion efficiency and large open-circuit voltages (Voc) is of importance for the application of polycrystalline silicon thin-film solar cells. However, the high open-circuit voltages and high conversion efficiency cannot be achieved simultaneously for thin-film polycrystalline silicon solar cells. For this reason, we have designed a special polycrystalline silicon solar cell to achieve the required criterion.

The thin film amorphous silicon which is also applied in solar cell can be obtained at a low temperature by hot-wire chemical vapor deposition [6] or plasma enhanced chemical vapor deposition (PECVD) [7]. We assumed that both Voc and conversion efficiency were improved if the P+ thin film amorphous silicon was deposited on the N+ polycrystalline silicon forming a solar cell. In order to prove our assumption, the frame of P+ thin film amorphous silicon/ N+ poly-silicon was simulated using the AMPS-1D software package [8] which is a very general computer simulation code for analyzing and designing two terminal structures. It can handle devices such as p–n and p–i–n homo- and hetero-junctions, p–i–p and n–i–n structures, multi-junction and Schottky barrier devices. These devices may have poly-crystalline, amorphous or single crystal layers or their combinations. Device operation may be undertaken in dark or under light, and hence it is possible to simulate the behavior of solar cells and photodiodes. This program has been widely used to study device [9], [10], [11]. By simulating P+ α-Si/N+ poly-silicon cell, the maximum Voc of 0.752 V and conversion efficiency of 9.44%, respectively, were obtained on the condition of the optimum doping concentration and proper thickness of N+ polycrystalline silicon. Those values are promising in photovoltaics industry for polycrystalline silicon solar cell. On the other hand, the thin film amorphous silicon and polycrystalline silicon were prepared with a high deposition rate by pulsed plasma and Hot-Wire CVD techniques [12] and hot wire cell method [13] (deposition rates of 1.2 nm/s). That means that the solar cell formed by P+ thin film amorphous silicon and N+ polycrystalline silicon can be fabricated and that the cost will be less than other cells. Therefore, our studies on the solar cell formed by P+ α-Si/N+ poly-silicon are significant for the application of polycrystalline silicon in photovoltaics industry.

This paper contains four sections. In section II, the structure and the parameters of P+ α-Si/N+ poly-silicon solar cell were set. Section III analyzes the calculation results of the model to characterize the P+ α-Si/N+ poly-silicon solar cell.

2 P+ α-Si/N+ poly-silicon solar cell model

To simulate the P+ α-Si/N+ poly-silicon solar cell structure, we build the model like in figure 1. The thin film amorphous silicon covers the polycrystalline silicon with the thickness of 5-20nm. The thickness of polycrystalline silicon is on the order of μm. The P+ thin film amorphous silicon is considered as the emitter layer and the N+ polycrystalline silicon as the absorption layer. The light of the sun travels from the top to the bottom. The first layer viewed as front contact is transparent conductive oxide (TCO) consisting of the Indium tin oxide (ITO) which is the most commonly used material in photovoltaic (PV) devices and light emitting diodes (LED) as high work function transparent electrode. AMPS-1D has two pictures, namely, the Lifetime and DOS pictures. In the DOS picture, the details of recombination traffics, trapping and the charge state of the defects (and the effects of this charge on the electric field variation across a structure) are fully explained. The DOS picture, hence, was employed to simulate the P+ α-Si/N+ poly-silicon solar cell structure. All the parameters are listed in Table 1 and the absorption coefficient for the poly-Si is obtained from a research paper [14]. For P+ α-Si:H, the data is obtained from the compendium of parameters of AMPS-1D, and the absorption coefficient for P+ α-Si:H is the same as for intrinsic α-Si:H [15]. For the simulation under illumination we used the AM 1.5 spectrum normalized to 100 mW/cm².
Table 1: Parameters set for the simulation of the P+ α-Si/N+ poly-silicon solar cell structure with AMPS-1D

| Parameter and units | e, h for electrons and holes respectively | P+ α-Si | N+ poly-silicon |
|---------------------|------------------------------------------|---------|-----------------|
| Thickness (nm)      | 5                                        | var.    |                 |
| Electron affinity (eV) | 3.8                                      | 4.05    |                 |
| Band gap (eV)       | 1.72                                     | 1.12    |                 |
| Effective conduction band density (cm\(^{-3}\)) | 2.5×10\(^{20}\) | 2.8×10\(^{19}\) |         |
| Effective valence band density (cm\(^{-3}\))  | 2.5×10\(^{20}\) | 1.04×10\(^{19}\) |         |
| Electron mobility (cm\(^{-2}\)V\(^{-1}\)s\(^{-1}\)) | 10                                  | 750     |                 |
| Hole mobility (cm\(^{2}\)V\(^{-1}\)s\(^{-1}\))   | 1                                    | 250     |                 |
| Doping concentration of acceptors (cm\(^{-3}\)) | 0                                     | var.    |                 |
| Doping concentration of donors (cm\(^{-3}\))  | 1.0×10\(^{20}\) | 0      |                 |
| Band tail density of states (cm\(^{-3}\)eV\(^{-1}\)) | 2.0×10\(^{21}\) | 1.0×10\(^{16}\) |         |
| Characteristic energy (eV) | 0.06, 0.03                             | 0.01, 0.01 |             |
| donors, acceptors Capture cross section for donor states, e, h, (cm\(^{2}\)) | 1×10\(^{-15}\), 1×10\(^{-17}\) | 1.0×10\(^{-14}\), 1.0×10\(^{-16}\) |         |
| Capture cross section for acceptor states, e, h, (cm\(^{2}\))  | 1×10\(^{-17}\), 1×10\(^{-15}\) | 1.0×10\(^{-14}\), 1.0×10\(^{-16}\) |         |
| Gaussian density of states (cm\(^{-3}\))  | 8×10\(^{17}\), 8×10\(^{20}\) | 1.0×10\(^{-14}\), 1.0×10\(^{-16}\) |         |
| Gaussian peak energy (eV) | 1.22, 0.70                               |         |                 |
| Standard deviation (eV) | 0.23                                   |         |                 |
| donors, acceptors Capture cross section for donor states, e, h, (cm\(^{2}\)) | 1×10\(^{-14}\), 1×10\(^{-15}\) |         |                 |
| Capture cross section for acceptor states, e, h, (cm\(^{2}\))  | 1×10\(^{-15}\), 1×10\(^{-14}\) |         |                 |

3 Results and discussion

In order to study the P+ α-Si/N+ poly-silicon solar cell well, we first consider the work function of TCO which plays a great role in silicon hetero-junction solar cell performance [16]. ITO has a low work function compared to the p type silicon material, usually varying from 4.35 eV to 5.1 eV. Figure 2 shows the various values of conversion efficiency at different work functions of ITO. It is apparent that the obtained efficiency increases with the work function of ITO when the value of the work function is smaller than 4.95 eV. But the conversion efficiency is independent of the work function of ITO when the value of the work function is larger than 4.95 eV. So the work function should be controlled above 4.95 eV when the P+ α-Si/N+ poly-silicon solar cell well is fabricated, which is very important for preparing high efficiency solar cell.

In order to find out the best parameters of this P+ α-Si/N+ poly-silicon solar cell, we calculate the thickness of N+ poly-silicon and display its effects on this cell in Figure 3. It is easy to conclude that the N+ poly-silicon layer should be thick enough to absorb light. If the layer is thin, the sun light cannot be absorbed well, leading to a low efficiency. On the other hand, this layer cannot be too thick. If it’s too thick, the carriers cannot arrive at the back.
contact owing to recombination. The best thickness of the N⁺ poly-silicon layer is the value of 20-300 µm.

Figure 4 shows the effects of N⁺ poly-silicon layer doping. It can be seen that the conversion efficiency, fill factor and Voc increase with the doping concentration (N_D) when N_D < 10¹⁹ cm⁻³. But both efficiency and fill factor decrease when N_D > 10¹⁹ cm⁻³. So the conversion efficiency gets up to the maximum value of 9.44% at N_D = 10¹⁹ cm⁻³. The fill factor also has the maximum value of 0.854 at N_D = 10¹⁹ cm⁻³. What’s important is that the Voc can reach the maximum value of 0.752 V at N_D = 10¹⁹ cm⁻³. Although this value is not greater than that of some poly-silicon solar cell which has high efficiency of 14.9% [17], the values of both fill factor and Voc are greater than those of other poly-silicon solar cells, which are usually about 0.5 V [4] for Voc and 0.6 V [18] for fill factor.

In order to account for the effects of N⁺ poly-silicon layer doping on the P⁺ α-Si/N⁺ poly-silicon solar cell, the distribution of electric field is taken into consideration, shown in Figure 5. The electric field works as a function of the position. When the concentration of the N⁺ poly-silicon layer varies from 3.0×10¹⁵ cm⁻³ to 3.0×10¹⁹ cm⁻³, the electric field rises gradually and the area covered by the electric field decreases little. That means the holes produced in a wider area of the absorption layer can be transported through the space charge zone. Although the electrical field increases sharply, the area of the absorption layer becomes narrow, resulting in fewer holes for transport once the concentration reaches 3.0×10²⁰ cm⁻³. The above analysis indicates the best value of concentration of N⁺ poly-silicon layer is 3.0×10¹⁹ cm⁻³ for high conversion efficiency.

Because the intrinsic layer in a solar cell is to absorb sun light, we allow changing the thickness to attain the effects of the intrinsic layer on the P⁺ α-Si/N⁺ poly-silicon solar cell. Figures 6 (a)-(d) illustrate the Voc, fill factor, conversation efficiency and short circuit current (Jsc) of the P⁺ α-Si/N⁺ poly-silicon solar cell with the different thickness of the intrinsic layer, respectively. Both open-circuit voltage and fill factor decrease as the thickness of the intrinsic layer is inserted between P⁺ α-Si and N⁺ poly-Si, as shown in Figures 6(a) and (b). Why the intrinsic layer weakens the potential difference between P⁺ α-Si and N⁺ poly-Si is explained, which leads to a smaller value of open-circuit voltage. The thicker the intrinsic layer is, the smaller the opencircuit voltage becomes. Besides, the whole resistance of the cell increases with the thickness of the intrinsic layer, which has a great impact on the fill factor. It is well known that when an intrinsic poly-silicon layer is inserted between the p layer and n layer, the conversation efficiency can be improved dramatically. However, the conversation
Figure 3: The conversion efficiency for different thickness of the N+ poly-silicon layer

Figure 4: Values of efficiency, fill factor and Voc, respectively, are as a function of doping concentration of N⁺ poly-silicon layer
Figure 5: The distribution of the electric field with different doping concentrations of the N$^+$ poly-silicon layer (N$_n$) as a function of position.

Figure 6: (a)-(d) illustrate the $V_{oc}$ (a), fill factor (b), conversation efficiency (c) and short circuit current (Jsc) (d) of the P$^+$ α-Si/N$^+$ poly-silicon solar cell with the different thickness of the intrinsic layer, respectively.
efficiency is not much improved for the P+ α-Si/N+ poly-silicon. Figure 6(c) shows the relation between the conversation efficiency and the thickness of the intrinsic layer. When the intrinsic layer is thin (about 1000 nm), the efficiency decreases sharply with the value of about 8%. While the thickness varies from 1000 nm to 15000 nm, the efficiency increases gradually and reaches up to about 10%. But the efficiency will decrease gradually with the thickness of the intrinsic layer when it is larger than 15000 nm. An in-depth discussion of the relationship between the conversation efficiency and the thickness is made to find out the reason.

There are many defects in P+ α-Si, intrinsic layer and N+ poly-Si resulting in a short lifetime of the carriers. Carriers collection mainly depends on the in-build electric field when the intrinsic layer is thin. But then the intrinsic layer can weaken the electric field leading to a low efficiency. When the intrinsic layer gets thicker, there are many photogenerated carriers. The carriers are collected by the carriers diffusion, which will lead to a higher conversation efficiency and larger short circuit current. Although the carriers diffusion can be enhanced, the in-build electric field is weakened by the thick intrinsic layer. Considering the two factors, the conclusion can be drawn that the efficiency can not be improved sharply when the intrinsic layer with proper thickness is inserted between the P+ α-Si and N+ poly-Si layer. The above discussions lead to the important result that the intrinsic layer can improve efficiency more or less but decrease the open circuit voltage and fill factor.

4 Conclusion

This paper considers the three main effect factors responsible for the outstanding characteristics of such a solar cell. They are the work function of TCO, the thickness of N+ the poly-silicon layer and the doping concentration of N+ poly-silicon layer, respectively. The results suggest that the work function of TCO has little impact on the cell and that the doping concentration of N+ poly-silicon layer is at a magnitude of $10^{19}$ cm$^{-3}$ and that the thickness of N+ polysilicon layer can vary from 20 μm to 300 μm. By simulating the P+ α-Si/N+ polycrystalline solar cell we conclude that this is a prospective solar cell with a high efficiency of 9.44%, high fill factor of 0.845 and high Voc of 0.752 V if the optimization parameters are set. Therefore, our study on the device formed by the P+ α-Si/N+ poly-silicon is very significant in exploring the high efficiency poly-silicon solar cell.

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