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Optimized resistivity of p-type Si substrate for HIT solar cell with Al back surface field by computer simulation

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Abstract

For HIT (heterojunction with intrinsic thin-layer) solar cell with Al back surface field on p-type Si substrate, the impacts of substrate resistivity on the solar cell performance were investigated by utilizing AFORS-HET software as a numerical computer simulation tool. The results show that the optimized substrate resistivity (R_{op}) to obtain the maximal solar cell efficiency is relative to the bulk defect density, such as oxygen defect density (D_{od}), in the substrate and the interface defect density (D_{it}) on the interface of amorphous/crystalline Si heterojunction. The larger D_{od} or D_{it} is, the higher R_{op} is. The effect of D_{it} is more obvious. R_{op} is about 0.5 Ω cm for $D_{it} = 1.0 \times 10^{11}/cm^2$, but is higher than 1.0 Ω cm for $D_{it} = 1.0 \times 10^{12}/cm^2$. In order to obtain very excellent solar cell performance, Si substrate, with the resistivity of 0.5 Ω cm, D_{od} lower than $1.0 \times 10^{10}/cm^3$, and D_{it} lower than $1.0 \times 10^{11}/cm^2$, is preferred, which is different to the traditional opinion that 1.0 Ω cm resistivity is the best.

Keywords: HIT solar cell; Substrate resistivity; Simulation

1. Introduction

Silicon heterojunction (SHJ) solar cell called HIT (heterojunction with intrinsic thin-layer), developed by SANYO Ltd. in 1994 (Sawada et al., 1994), is produced by plasma enhanced chemical vapor deposition of thin hydrogenated amorphous silicon (a-Si:H) layers on both sides of a high quality crystalline silicon (c-Si) wafer. Such novel solar cell can simultaneously realize an excellent surface passivation and a p–n junction formation. Its low-temperature processes (<200 °C) can prevent the degradation of bulk quality that possibly happens in high-temperature cycling processes, and compared with conventional diffused cells, a much better temperature coefficient can be obtained with a higher open-circuit voltage (Voc) (Tucci et al., 2004; Voz et al., 2006; Xu et al., 2006). Hence, HIT solar cell has attracted more and more interests all over the world.

While SANYO develops HIT solar cells with a very thin intrinsic a-Si:H(i) layer inserted between p-type a-Si:H and n-type c-Si, most researchers concentrate the exploitation of HIT solar cells on p-type c-Si substrates, since p-type c-Si substrates are more broadly used in current photovoltaic market (Goldbach et al., 2006; Rostan et al., 2006; Veschetti et al., 2006). Si substrates with the resistivity of 1.0 Ω cm were thought as the best choice and were utilized generally in most works (Ok et al., 2007; Schmidt et al., 2007; Tardon et al., 2004). However, as we know, it is difficult for Si wafers, even those sliced from the same ingot, to have the completely consistent resistivity. Thus, as we require Si substrates with 1.0 Ω cm resistivity, the vendors usually provide those wafers with the resistivity in the range of 1.0–10.0 Ω cm or even 1.0–25.0 Ω cm, which may be the reason why 10.0 Ω cm substrates were adopted

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in some references (Gielis et al., 2007; Gudovskikh et al., 2006). These seemed that 10.0 Ω cm resistivity was thought to be acceptable intuitively. The question is whether such a wide range of resistivity has no large impact on the performance of solar cells indeed. There is no evident data to answer this until now.

It has been well known that the density of bulk defects in c-Si substrate, and the density of interface defects (D_{it}) on the heterojunction can influence the solar cell performance greatly (Arafune et al., 2006; Bailey et al., 1996; Kobayashi et al., 2006; Nath et al., 2008). Such defects may take into effect together with the substrate resistivity. However, there are so many kinds of defects that it is difficult to investigate all the specific ones. Since oxygen defect in c-Si is the usual one to injure the solar cell performance (Schmidt, 2004; Zhou et al., 2008), the density of oxygen defects (D_{od}) in c-Si can be adopted as an illustrative one to characterize the quality of c-Si substrate.

For HIT solar cell on p-type Si substrate, Al back surface field (BSF) is usually utilized due to its easy fabrication (Tucci et al., 2004; Tucci and de Cesare 2004; Xu et al., 2006). Here, referring to the common HIT solar cell on p-type Si substrate with Al BSF, the impacts of the substrate resistivity on the solar cell performance were investigated with the variation of D_{od} and D_{it} in details by utilizing AFORS-HET software as a numerical computer simulation tool.

2. Solar cell structure and simulation

AFORS-HET has been proven as one convenient and effective means to study the role of various parameters on the performance of HIT solar cells (Froitzheim et al., 2002; Stangl et al., 2003). The simulated solar cell structure is TCO/a-Si:H(n)/a-Si:H(i)/c-Si(p)/Al-BSF/Al as shown in Fig. 1. The gap state densities of a-Si:H were set with the distributions depicted in Fig. 2. Oxygen defects in c-Si were chosen to be located at 0.55 eV above the edge of the valence band, and the capture cross-sections for electrons and holes were both 1.0×10^{-14} cm^2. All these are the default values in AFORS-HET. The front and the back contacts were assumed as flat band ones to neglect the contact potential influence. The surface recombination velocities of electrons and holes were both set as 1.0×10^7 cm/s. The solar AM1.5 radiation was adopted as the illuminating source with the power density of 100 mW/cm^2. The light reflection of front contact and back contact was set to be the reflectance of ZnO/a-Si/c-Si with pyramids texture (one default file in AFORS-HET) and 1.0, respectively.

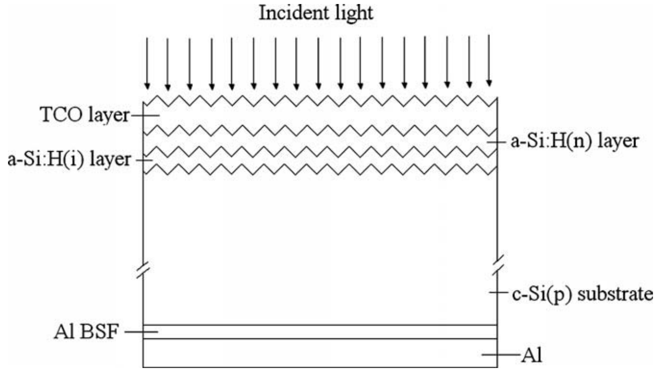

Fig. 1. The schematic structure of HIT solar cell in the simulations.

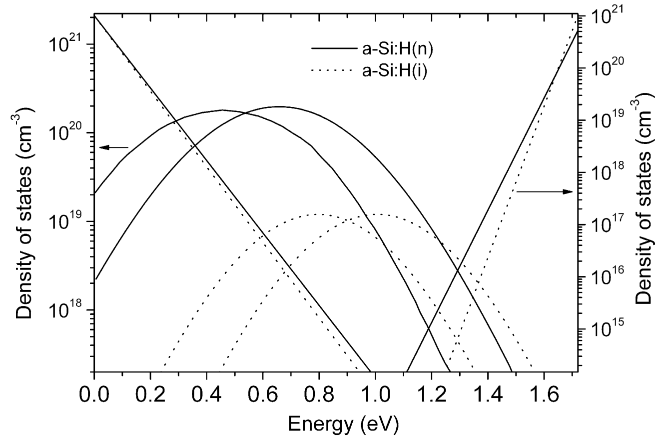

Fig. 2. The gap states distribution of a-Si:H layers in the simulations.

Recombination from the conduction band into the valence band may occur directly (band to band recombination, Auger recombination) and via trap states (Shockley–Read–Hall recombination, SHR). All the three recombination mechanisms were considered during the simulation. Some adopted simulating parameters were given in Table 1. During the simulations, the adopted electron and hole mobilities for c-Si substrates with different resistivities were taken from PC1D, which is a well known simulation tool for crystalline Si solar cells.

3. Results and discussion

Fig. 3 gives the dependence of the solar cell efficiency on the substrate resistivity with different D_{od} and D_{it}, where the substrate thickness is 300 μm. It can be seen that the solar cell can obtain excellent efficiency with a mediate substrate resistivity, called the optimized resistivity (R_{op}) here. When the resistivity is lower than R_{op}, the efficiency decreases rapidly. When the resistivity is higher than R_{op}, the efficiency decreases in another relative low rate. And R_{op} is dependent on D_{od} and D_{it}. When D_{od} or D_{it} increases, R_{op} intends to increase.

In order to understand this clearly, Fig. 4 further gives out the changes of *Voc*, the short-circuit current density (*Jsc*) and the fill factor (*FF*) as functions of the substrate resistivity. D_{it} can lower *Voc* greatly. D_{od} mainly reduces *Jsc*. The internal quantum efficiency (IQE) curves of HIT solar cells in Fig. 5 illuminate that such *Jsc* reduction results from the decreased light response at longer wavelengths induced by D_{od}. The reduced *Jsc* can also lower *Voc*, which is obvious only when D_{it} is low, because when D_{it} is high, the interface recombination plays the dominant

Table 1
Some parameter values adopted for HIT solar cells in the simulations.

Parameters	c-Si(p)	Al-BSF	a-Si:H(n)	a-Si:H(i)
Layer thickness (nm)	3×10^5	5×10^3	10	3
Dielectric constant	11.9	11.9	11.9	11.9
Electron affinity (eV)	4.05	4.05	3.9	3.9
Band gap (eV)	1.12	1.12	1.74	1.72
Optical band gap (eV)	1.12	1.12	1.74	1.72
Effective conduction band density (cm^{-3})	2.8×10^{19}	2.8×10^{19}	1×10^{20}	1×10^{20}
Effective valence band density (cm^{-3})	1.04×10^{19}	1.04×10^{19}	1×10^{20}	1×10^{20}
Electron mobility ($cm^2\,V^{-1}\,s^{-1}$)	Variable	202.4	5	5
Hole mobility ($cm^2\,V^{-1}\,s^{-1}$)	Variable	77.15	1	1
Doping concentration of acceptors (cm^{-3})	Variable	1×10^{19}	0	0
Doping concentration of donators (cm^{-3})	0	0	1×10^{20}	0
Thermal velocity of electrons ($cm\,s^{-1}$)	1×10^7	1×10^7	1×10^7	1×10^7
Thermal velocity of hole ($cm\,s^{-1}$)	1×10^7	1×10^7	1×10^7	1×10^7
Layer density ($g\,cm^{-3}$)	2.328	2.328	2.328	2.328
Auger recombination coefficient for electron ($cm^6\,s^{-1}$)	2.2×10^{-31}	2.2×10^{-31}	0	0
Auger recombination coefficient for hole ($cm^6\,s^{-1}$)	9.9×10^{-32}	9.9×10^{-32}	0	0
Direct band to band recombination coefficient ($cm^3\,s^{-1}$)	1.1×10^{-14}	1.1×10^{-14}	0	0
Position of oxygen defects (eV)	Ev + 0.5	Ev + 0.5	–	–
Capture cross-section for electrons (cm^2)	1.0×10^{-14}	1.0×10^{-14}		
Capture cross-section for holes (cm^2)	1.0×10^{-14}	1.0×10^{-14}		

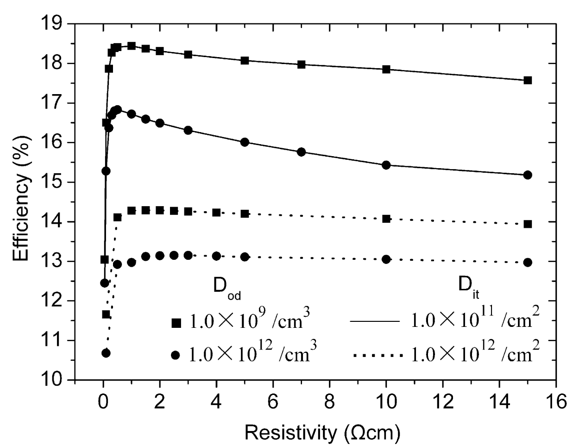

Fig. 3. The HIT solar cell efficiency dependence on the resistivity of c-Si(p) substrate.

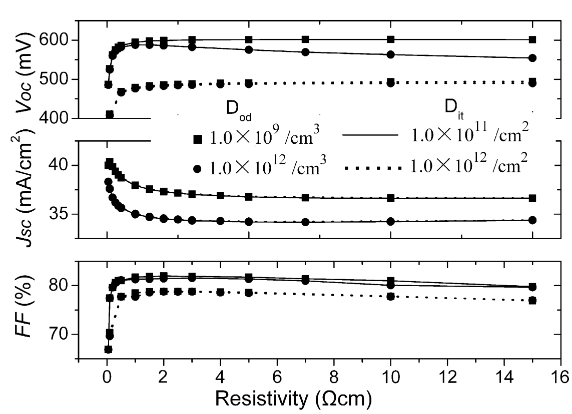

Fig. 4. The *Voc*, *Jsc* and *FF* of HIT solar cell as functions of the resistivity of c-Si(p) substrate.

role and becomes the determinant factor to *Voc*. When the substrate resistivity is lower than R_{op}, the decrease of the

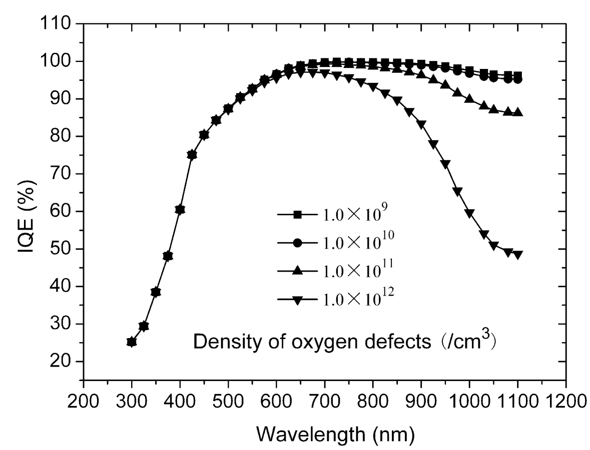

Fig. 5. The IQE curves of HIT solar cells with different oxygen defect densities in c-Si(p) substrates. $D_{it} = 1.0 \times 10^{11}/cm^2$.

solar cell efficiency is attributed to the low *Voc* and *FF*, although *Jsc* has a relative higher value.

The increase of *Jsc* indicates that SHR recombination is still the dominant bulk recombination mechanism in the simulated cases. Band to band recombination and Auger recombination has little possibility to occur. The internal quantum efficiency (IQE) results in Fig. 6 show that as the substrate resistivity decreases, the increase of *Jsc* can be attributed to the increased response in the range of 400–600 nm. While the resistivity decreases, the current response at the longer wavelength decreases due to the reduced effective diffusion length (L_{eff}). At the same time, the electric field strength in the space charge region (SCR) enhances, the width of SCR decreases in the c-Si base, but increases in the a-Si:H emitter. Light with the wavelength in the range of 300–400 nm is mainly absorbed by the a-Si:H side of SCR, and light in the range of 400–

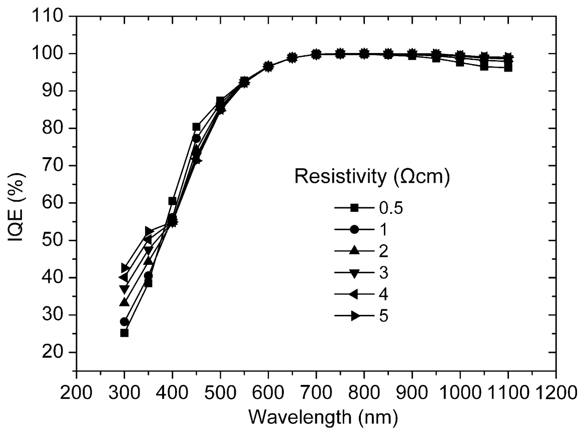

Fig. 6. The IQE curves of HIT solar cells on the substrates with different resistivities. $D_{it} = 1.0 \times 10^{11}/cm^2$, $D_{od} = 1.0 \times 10^9/cm^3$.

600 nm is mainly absorbed by the c-Si side of SCR. Since the recombination in SCR is high due to the high interface defect density, the above change of SCR can reduce the response in the range of 300–400 nm, and enhance the response in the range of 400–600 nm. Obviously, the enhancement can overcompensate the reduction in the shorter and the longer wavelength range, so *Jsc* increases. The results show that the recombination in SCR plays an important role here. The similar results were also observed in the reference (Yang et al., 2008).

From Fig. 4, the increase of D_{it} can lower *Voc* greatly, which means *Voc* is determined by the interface recombination. The *Voc* limit imposed by interface recombination reads as: $Voc = \frac{\Phi_B}{q} - \frac{nkT}{q}\ln(\frac{qN_V S_{it}}{Jsc})$. Here, Φ_B is the effect barrier, q denotes the elementary charge, kT is the thermal energy, N_V is the effective densities of states in the valence band, S_{it} is the interface recombination velocity (Jensen et al., 2002). D_{it} can reduce Φ_B, increase S_{it}, and thus reduce *Voc*. While the substrate resistivity decreases from above 10 Ω cm, Φ_B and *Jsc* can increase gradually, which can result in a little increase of *Voc* while S_{it} is relative low. But when the substrate resistivity is low enough, the SCR will be very thin and the negative effect of D_{it} becomes severer. At the same time, the possibility of tunneling recombination increases. Thus, *Voc* will decrease greatly. So R_{op} exits to obtain the maximal efficiency for the solar cell. The larger D_{it} or D_{od} is, the easier the above transition can occur. Hence, R_{op} is about 0.5 Ω cm for $D_{it} = 1.0 \times 10^{11}/cm^2$, but is higher than 1.0 Ω cm for $D_{it} = 1.0\times10^{12}/cm^2$, as obtained in Fig. 3.

According to the results in Figs. 3–6, in order to obtain very excellent solar cell performance, Si substrate, with the resistivity of 0.5 Ω cm, D_{od} lower than $1.0 \times 10^{10}/cm^3$, and D_{it} lower than $1.0 \times 10^{11}/cm^2$, is preferred, which is different to the traditional opinion that 1.0 Ω cm resistivity is the best. In fact, high *Voc* has been obtained on p-type FZ silicon with the doping concentration of acceptors of 4.6×10^{16} cm^{-3} (Jensen et al., 2002), which is corresponding to the substrate resistivity of 0.37 Ω cm (from PC1D).

4. Conclusion

In summary, for HIT solar cell on p-type Si substrate with Al back surface field, the impacts of substrate resistivity on the solar cell performance were investigated by utilizing AFORS-HET software as a numerical computer simulation tool. The results show that the optimized substrate resistivity (R_{op}) to obtain the maximal solar cell efficiency is relative to the bulk defect density, such as oxygen defect density (D_{od}), in the substrate and the interface defect density (D_{it}) on the interface of amorphous/crystalline Si heterojunction. The larger D_{od} or D_{it} is, the higher R_{op} is. The effect of D_{it} is more obvious. R_{op} is about 0.5 Ω cm for $D_{it} = 1.0 \times 10^{11}/cm^2$, but is higher than 1.0 Ω cm for $D_{it} = 1.0 \times 10^{12}/cm^2$. In order to obtain very excellent solar cell performance, Si substrate, with the resistivity of 0.5 Ω cm, D_{od} lower than $1.0 \times 10^{10}/cm^3$, and D_{it} lower than $1.0 \times 10^{11}/cm^2$, is preferred, which is different to the traditional opinion that 1.0 Ω cm resistivity is the best.

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