Research Article

SiO₂ Antireflection Coatings Fabricated by Electron-Beam Evaporation for Black Monocrystalline Silicon Solar Cells

Minghua Li,¹ Hui Shen,² Lin Zhuang,² Daming Chen,² and Xinghua Liang³

¹ School of Electrical Engineering, Guangdong Mechanical & Electrical College, Guangzhou 510515, China

² Institute for Solar Energy Systems, Guangdong Provincial Key Laboratory of Photovoltaic Technologies, State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-sen University, Guangzhou 510006, China

³ Key Laboratory of Automobile Components and Vehicle Technology in Guangxi, Guangxi University of Science and Technology, Liuzhou 545006, China

Correspondence should be addressed to Hui Shen; shenhui1956@163.com

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In this work we prepared double-layer antireflection coatings (DARC) by using the SiO₂/SiN_x:H heterostructure design. SiO₂ thin films were deposited by electron-beam evaporation on the conventional solar cell with SiN_x:H single-layer antireflection coatings (SARC), while to avoid the coverage of SiO₂ on the front side busbars, a steel mask was utilized as the shelter. The thickness of the SiN_x:H as bottom layer was fixed at 80 nm, and the varied thicknesses of the SiO₂ as top layer were 105 nm and 122 nm. The results show that the SiO₂/SiN_x:H DARC have a much lower reflectance and higher external quantum efficiency (EQE) in short wavelengths compared with the SiN_x:H SARC. A higher energy conversion efficiency of 17.80% was obtained for solar cells with SiO₂ (105 nm)/SiN_x:H (80 nm) DARC, an absolute conversion efficiency increase of 0.32% compared with the conventional single SiN_x:H-coated cells.

1. Introduction

For high-efficiency solar cells, antireflection coating (ARC) is very important for improving the performance of solar cells since it ensures a high photocurrent output by minimizing incident light reflectance on the top surface [1–4]. At present, hydrogen containing silicon nitride (SiN_x:H) thin film deposited by plasma enhanced chemical vapour deposition (PECVD) is widely used as ARC and passivation layer for crystalline silicon solar cells [5, 6]. However, the single-layer antireflection coatings (SARC) used in silicon solar cells still cause considerable optical reflectance loss in a broad range of the solar spectrum. Therefore, double-layer antireflection coatings (DARC) which consist of heterostructure materials such as MgF₂/ZnS [3, 7], MgF₂/BN [8], Al₂O₃/TiO₂ [9–11], and MgF₂/CeO₂ [12] are considered to be a more effective design in decreasing the reflection in a broad wavelength range for the high efficiency solar cells fabrication. These DARC are not common because of process

complexity, which could affect their mass production process. Though SiN_x:H/SiN_x:H [13] shows unique combination of good electronic and optical properties, it has disadvantages of high absorption in the UV region reducing of the short-circuit current of the cell. The SiO₂/SiN_x:H DARC are a promising design to improve solar cells efficiency due to its advantages in both surface passivation and antireflection properties. The simulation on the SiO₂/SiN_x:H DARC was carried out by optimizing their refractive index and film thickness [14]. Kim et al. [15] have investigated the conversion efficiency improvement of monocrystalline silicon solar cell with double layer antireflection coating consisting of SiO₂/SiN_x:H deposited by PECVD. And the solar cells with DARC showed the better efficiency as 17.57% and 17.76%, compared with 17.45% for single SiN_x:H ARC.

In this paper, we present a novel process method that DARC consisting of SiN_x:H and SiO₂ films were deposited via PECVD and an electron-beam evaporation technique, respectively. The thickness of SiN_x:H films as the bottom

FIGURE 1: Schematic of the solar cell with $\text{SiO}_2/\text{SiN}_x\text{:H}$ DARC.

FIGURE 2: FTIR transmission spectra of SiO_2 thin film.

layer is kept at 80 nm, which is optimum for SARC. By simply varying the thickness of the SiO_2 layer as the top layer covering the conventional solar cell, monocrystalline silicon solar cells with different $\text{SiO}_2/\text{SiN}_x\text{:H}$ DARC are fabricated.

2. Experiment

Boron doped monocrystalline wafers, with a thickness of $160\ \mu\text{m}$, a size of $125\ \text{mm} \times 125\ \text{mm}$, and a resistivity in the range of $1\sim 3\ \Omega\text{cm}$, have been used for all experiments. After standard cleaning and alkaline texturization, a standard POCl_3 emitter diffusion in a quartz tube led to a sheet resistivity of $60\ \Omega/\square$. The wafers were coated with a $\text{SiN}_x\text{:H}$ layer in a PECVD (Centrotherm) system. The refractive index of $\text{SiN}_x\text{:H}$ was adjusted by controlling the NH_3/SiH_4 gas flow ratio. The thickness of the $\text{SiN}_x\text{:H}$ layer was 80 nm. After a standard front and back side screen printing process, the contact formation was performed by a firing through process. Then, the solar cells with $\text{SiN}_x\text{:H}$ SARC were performed. To prepare the $\text{SiO}_2/\text{SiN}_x\text{:H}$ DARC, SiO_2 thin films were deposited on the prepared solar cell with $\text{SiN}_x\text{:H}$ SARC by electron-beam evaporation. Considering of the SiO_2 layer on busbars may lead to contact issue in I - V test, we used steel mask on the top of busbars as shelter during e-beam

evaporation. High purity SiO_2 (99.99%) granules were used as the source material for evaporation and the source-to-substrate distance was 50 cm. The substrates temperature was controlled at 200°C . High purity oxygen (99.99%) was introduced into the chamber to maintain a pressure of $3.0 \times 10^{-2}\ \text{Pa}$ and used as reactive gas during the deposition. The deposition rate was controlled using a quartz crystal sensor placed near the substrate, and set as $\sim 2\ \text{\AA/s}$. The thicknesses of the SiO_2 as top layer were 105 nm and 122 nm, respectively. Finally, the solar cells with different $\text{SiO}_2/\text{SiN}_x\text{:H}$ coatings were obtained. The structure of the solar cell with $\text{SiO}_2/\text{SiN}_x\text{:H}$ DARC is schematically shown in Figure 1.

The Fourier transform infrared spectroscopy (FTIR) measurement for the SiO_2 thin film has been made at 25°C using a Thermo Nicolet 6700 FTIR spectrometer. The refractive index of the $\text{SiN}_x\text{:H}$ and SiO_2 films were measured by a n&k analyzer 1200. Spectral reflectance and external quantum efficiency (EQE) measurements were performed by a solar cell spectral response measurement system (PV measurement, QEX7). In addition, the I - V characteristics of the solar cells were measured using a Berger I - V tester on a solar cell production line. All measurements were conducted under the standard test conditions (AM1.5G spectrum, $100\ \text{mW/cm}^2$, 25°C). Prior to the measurements, the simulator was calibrated with a reference monocrystalline silicon solar cell, which was calibrated by the Fraunhofer ISE. All electrical parameters are presented as the average value of ten cells in the study.

3. Results and Discussion

3.1. SiO_2 Thin Film Characterization. XPS was applied to determine the chemical state of the Si and O elements, which can confirm the presence of SiO_2 layer in DARC. XPS analysis for SiO_2 film has been reported in our group [16].

In order to get a qualitative spectra of SiO_2 thin film compositions, we have performed Fourier transform infrared spectroscopy (FTIR) analysis. The samples were prepared on the aluminium thin film with 300 nm thickness on the glass substrate, which deposited by e-beam evaporation. We adopt reflection method to measure the sample. The spectra are presented in Figure 2. The band in the $1040\sim 1150\ \text{cm}^{-1}$ range is assigned to the stretching vibration mode Si-O [17, 18]. For the supplement of oxygen during the SiO_2 deposition, a clear increase of Si-O intensity peak ($1020\ \text{cm}^{-1}$) is observed for the SiO_2 layer, which is related to the high oxygen content in this layer.

3.2. Optical Property. The color of the solar cell depends heavily on thickness of its ARC-layer. Figures 3(a) and 3(b) show the photographs of silicon solar cells with single $\text{SiN}_x\text{:H}$ SARC and SiO_2 (105 nm)/ $\text{SiN}_x\text{:H}$ (80 nm) DARC, respectively. Two kinds of coatings have good uniformity. It is notable that the front surface color of the solar cells changed from dark blue to black, indicating that there was a lower reflectance loss in the DARC, as shown in Figure 3(b).

The reflectance spectrum was measured to characterize the reflectance loss. Figure 4 depicts the reflectance spectra

FIGURE 3: Photographs of monocrystalline silicon solar cells with (a) $\text{SiN}_x\text{:H}$ (80 nm) SARC and (b) SiO_2 (105 nm)/ $\text{SiN}_x\text{:H}$ (80 nm) DARC.

FIGURE 4: Reflectance curve for the single-layer ARC and double-layer ARC samples.

of solar cells with $\text{SiO}_2/\text{SiN}_x\text{:H}$ DARC and $\text{SiN}_x\text{:H}$ SARC, respectively. Compared with the $\text{SiN}_x\text{:H}$ SARC, $\text{SiO}_2/\text{SiN}_x\text{:H}$ layer stacks show lower reflectance in the range 300–450 nm. The amorphous SiO_2 coating is transparent in the measured wavelength range. It is obvious that the reflectance of the $\text{SiN}_x\text{:H}$ layer stack is dependent on the thickness of the SiO_2 coatings. With the thickness of SiO_2 in the $\text{SiO}_2/\text{SiN}_x\text{:H}$ stack increasing, the reflectance changes correspondingly. A similar simulation trend was also reported by Aguilar et al. [19]. In our work, the lowest reflectance was obtained while the thickness of SiO_2 was 105 nm in the $\text{SiO}_2/\text{SiN}_x\text{:H}$ stack, which is nearly consistent with previous simulation results. The value of calculated weighted reflectance is 1.72%.

It is acknowledged that a reduction in light of around 30% resulted from the reflectance at the Si and air interface [20]. ARC means an optically thin dielectric layer designed

TABLE 1: Summary of the average electrical parameters of the different ARC stacks compared with $\text{SiN}_x\text{:H}$ SARC solar cells (AM1.5G, 100 mW/cm^2 , 25°C).

Samples	Efficiency (%)	FF (%)	J_{sc} (mA/cm^2)	V_{oc} (mV)
$\text{SiN}_x\text{:H}$ (80 nm)	17.48	76.82	36.74	621.6
SiO_2 (105 nm)/ $\text{SiN}_x\text{:H}$ (80 nm)	17.80	77.58	37.77	621.3
SiO_2 (122 nm)/ $\text{SiN}_x\text{:H}$ (80 nm)	17.55	76.64	37.29	620.8

to suppress reflection by interference effects. By using DARC with $\lambda/4$ design, with growing indices from air to silicon, the minimum in reflection is broader in wavelength range. The measured refractive indices of $\text{SiN}_x\text{:H}$ and SiO_2 were 2.1 and 1.46 at 633 nm wavelength, respectively. Thus, the optimal thickness for each layer in term of their refractive indices can be obtained.

EQE data was collected for wavelengths in the range of 300–1100 nm to determine the spectral response of the solar cells, as shown in Figure 5(a); no significant differences in the infrared wavelength range were observed among these cells. On the other hand, the EQE of cells with DARC is higher than that with $\text{SiN}_x\text{:H}$ SARC in the range 300–450 nm wavelength. It was also shown that SiO_2 (105 nm)/ $\text{SiN}_x\text{:H}$ (80 nm) stack coatings has the highest improvement in short wavelength. IQE data was collected for wavelengths in the range of 300–1100 nm, as shown in Figure 5(b); EQE and IQE curves have the similar trends.

3.3. Solar Cell Results. The solar cells fabricated with novel $\text{SiO}_2/\text{SiN}_x\text{:H}$ stacks were tested and compared to conventional solar cells with $\text{SiN}_x\text{:H}$ SARC, as shown in Table 1. All data in Table 1 are the average values of ten samples. With the thickness of SiO_2 thin films varied, the conversion efficiency of the cells changed. Table 1 shows the conversion efficiency of the cells with SiO_2 (105 nm)/ $\text{SiN}_x\text{:H}$ (80 nm) DARC reached 17.80%, which was 0.32% (absolute) higher than solar cells

FIGURE 5: EQE and IQE of the single layer ARC and double layer ARC solar cells.

Area = 154.83 cm² FF = 77.58%
 V_{oc} = 621.3 mV Efficiency = 17.80%
 J_{sc} = 37.77 mA/cm²

FIGURE 6: J - V characteristics of the solar cell with SiO₂ (105 nm)/SiN_x:H (80 nm) DARC (AM1.5 G, 100 mW/cm², 25°C).

with SiN_x:H SARC. The fill factor of each group is nearly the same, while the V_{oc} shows small degradation for solar cells, which probably caused by the surface damages during the e-beam evaporation.

Correspondingly, the highest short-circuit current density (J_{sc}) was also obtained. It is demonstrated that the conversion efficiency of cells with DARC is dependent on the thickness of SiO₂ coatings, the same as the dependence of reflectance and EQE. Figure 6 shows the J - V characteristic of the solar cell with SiO₂ (105 nm)/SiN_x:H (80 nm) DARC.

4. Conclusions

In this work, SiO₂/SiN_x:H DARC were deposited on monocrystalline silicon solar cells. The results show that the SiO₂/SiN_x:H DARC have a lower reflectance compared with the SiN_x:H SARC. Accordingly, solar cells with SiO₂/SiN_x:H DARC exhibit a higher EQE and IQE in the short wavelengths of 300–450 nm. Due to current density improvement, the conversion efficiency of 17.80% was obtained for solar cells with DARC, 0.32% (absolute) higher than that of cells with single SiN_x:H coatings.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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