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ABSTRACT

Hot-wire chemical vapor deposition (HWCVD) was utilized to develop a fast and high quality a-Si:H thin film fabrication method for poly-Si/SiO_x carrier selective passivating contacts targeting at n-type passivated emitter rear totally diffused crystalline silicon solar cells. The microstructure and hydrogen content of the a-Si:H thin films were analyzed by Fourier-transform infrared spectroscopy in order to understand the influence of film properties on passivation and conductivity. Dense layers were found to be beneficial for good passivation. On the other hand, blistering appeared as a-Si:H layers became more and more dense. However, by adjusting the SiH_4 flow rate and the substrate heater temperature, blistering of a-Si:H could be avoided. A suitable process window was found and firing-stable implied open circuit voltage (iV_{oc}) of up to 738 mV was achieved. In addition to high iV_{oc}, a low contact resistivity of 0.034 Ω cm^2 was also achieved. The deposition rate of the a-Si:H layers was 7 Å/s by using HWCVD, which is one order of magnitude higher than the deposition rate reported using other deposition methods.

Passivating contacts based on poly-Si and ultrathin silicon oxide layer stacks were developed for crystalline silicon solar cells,[1] giving rise to excellent solar cell performances of up to 26.1% energy conversion efficiency.[2] Low pressure chemical vapor deposition (LPCVD)[3–5] and plasma enhanced chemical vapor deposition (PECVD)[6–8] are usually used to deposit the silicon thin films for the passivating contacts. Both of these methods achieved the highest iV_{oc} of 749 mV on 4 Ω cm n-type wafers before firing.[9] Between these deposition methods, LPCVD is a mature fabrication method to grow a-Si layers on both sides of the crystalline silicon wafers simultaneously. Compared with LPCVD, PECVD offers one-side process flexibility.[10] However, a fabrication process for passivating contacts would contain a high temperature annealing or thermal dopant diffusion step to convert the precursor a-Si into poly-Si. Blistering is reported as the a-Si:H layers deposited by PECVD go through these high temperature processes,[11–13] which is explained by hydrogen effusion.[14] Besides, electron beam evaporation[15] and sputtering[16] were also reported to perform one-side deposition for the passivating contact with deposition rates of around 2 Å/s and 0.6 Å/s, respectively. To sum up, an ideal deposition method for the passivating contact should enable one-side deposition to avoid unwanted silicon layers deposited on the other side of the solar cell. At the same time, the deposited silicon layers should remain blistering-free after all high temperature processes and provide both good passivation and good contacts for the solar cells. Last but not least, the deposition rate should be high in order to be attractive for mass production, while the ultrathin SiO_x layer in the interface should not be harmed during the fast deposition.

In this work, hot-wire chemical vapor deposition (HWCVD) was used to develop a one-side a-Si:H fabrication method for passivating contacts which complies with all the requirements stated above. HWCVD was reported to fabricate good quality silicon thin films at a very high deposition rate of over 100 Å/s.[17] Despite the high deposition rate, this deposition method enables good interfaces by avoiding ion damage caused by plasma. Excellent performances have already been reported on silicon thin film solar cells[18] and heterojunction solar cells[19] by using HWCVD. In order to apply HWCVD on the passivating contact, we investigated the microstructure and hydrogen content of the precursor a-Si:H layers to explore the material properties for

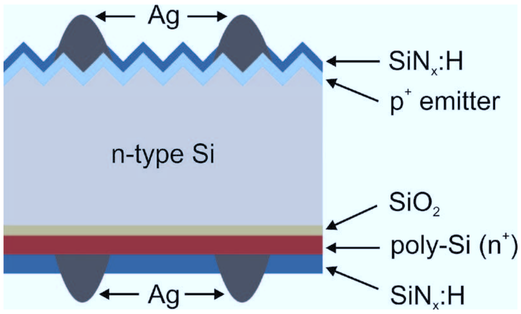

FIG. 1. Targeted n-PERT solar cell structure.

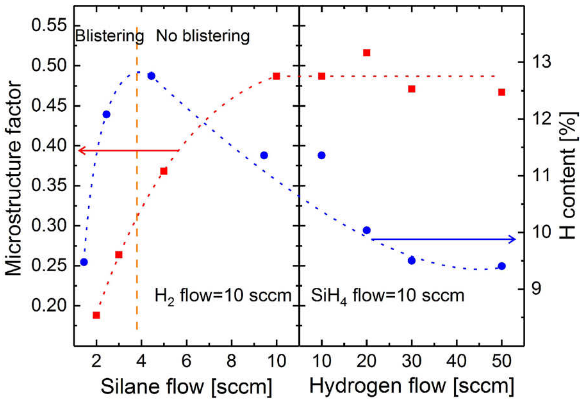

FIG. 3. Microstructure factor and H content of a-Si:H thin films with different gas flow rates; the dashed lines are guides to the eye.

good passivation and good contacts. Dense and blistering-free layers were deposited by optimizing the deposition parameters. Devices with good passivation were fabricated with precursor a-Si:H layers deposited at a high deposition rate of 7 Å/s. We targeted at n-PERT (passivated emitter rear totally diffused) solar cells with the passivating contact on the rear surface, as shown in Fig. 1. To this end, iV_{oc} was measured after a fast firing to test the thermal stability during the formation of the metal contact by glass-fritted Ag paste.[20] A precursor layer thickness of 100 nm was used to provide good lateral conductance.

The HWCVD a-Si:H precursor layers were deposited at a working pressure of 0.01 mbar with a filament temperature of around 1650 °C unless otherwise noted. Tantalum filaments were used in the HWCVD system. For the measurement of iV_{oc} as a determination of passivation quality, 100 mm × 100 mm phosphorus doped n-type silicon wafers [1 Ω cm, (100), as-cut thickness 180 μm] were used as substrates. The wafers were saw-damage etched in NaOH and cleaned. After cleaning, SiO_x layers of about 1.5 nm were fabricated on both sides of the wafers by nitric acid oxidation of the Si (NAOS) method.[21] The wafers were then covered by intrinsic a-Si:H layers deposited by HWCVD. After that, the $POCl_3$ diffusion process was carried out at 825 °C followed by the deposition of SiN_x layers on both sides of the wafers. The devices were completed by firing with a peak temperature of 820 °C to test the temperature stability of the passivation during sintering of the metal contacts.

Infrared absorption[22] was used to analyze the Si-H bonding of the as-deposited thin films. The 2000 cm^{-1} absorption peak is commonly associated with isolated Si-H bonding embedded in rather small cavities in the a-Si bulk, while the 2100 cm^{-1} peak is associated with clustered Si-H_x groups (x = 1 or 2) in larger cavities.[23] Structural analysis was done by calculating the microstructure factor of the a-Si:H thin film, which is expressed as follows:[24]

$$R = \frac{A_{2100}}{A_{2100} + A_{2000}}, \tag{1}$$

where R is the microstructure factor and A_{2100} and A_{2000} are the areas under 2100 cm^{-1} and 2000 cm^{-1} peak modes, respectively. Low R hence indicates a dense a-Si:H layer with less voids.

Figure 2 shows the FTIR spectrum of the intrinsic a-Si:H precursor layers deposited by HWCVD. The 2100 cm^{-1} peak increases with the increase in the SiH_4 flow rate. On the other hand, the 2100 cm^{-1} peak decreases with the increasing substrate heater temperature. The results show that the microstructure factor of a-Si:H thin films decreases with a lower SiH_4 flow rate and higher substrate heater temperature.

In Fig. 3, the microstructure factors as well as H contents[25] with different gas flow rates were extracted from the FTIR spectra. The microstructure factor increases from 0.19 to 0.49 as the SiH_4 flow rate increases from 2 sccm to 10 sccm. On the other hand, increasing the H_2 flow rate from 10 sccm to 50 sccm shows no significant change in the microstructure factor. It is worth noting that blistering appeared when the SiH_4 flow rate was 2 sccm and 3 sccm, i.e., for very low microstructure factors. Microstructure factors and H contents with different substrate heater temperatures are shown in Fig. 4. The

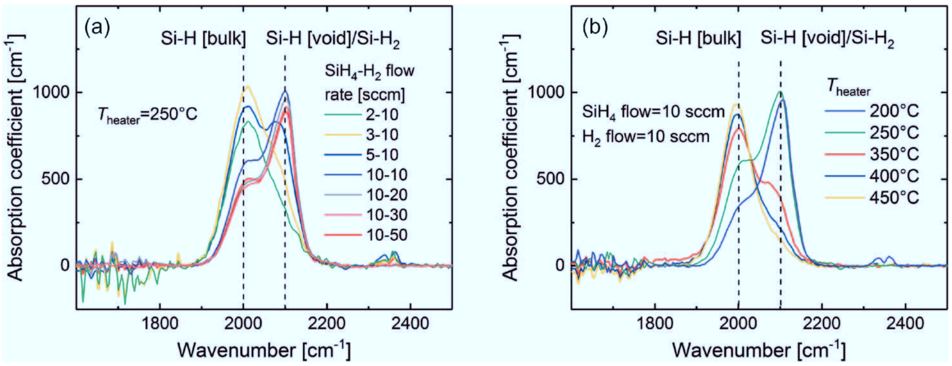

FIG. 2. Fourier-transform infrared spectroscopy (FTIR) spectra of the as-grown a-Si:H thin films with (a) different gas flow rates and (b) different substrate heater temperatures.

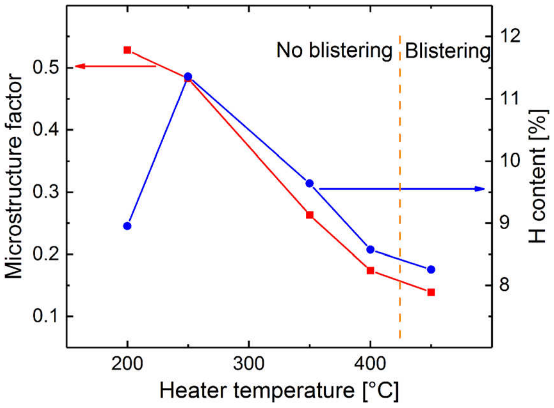

FIG. 4. Microstructure factor and H content of a-Si:H thin films with substrate heater temperature.

microstructure factor decreases from 0.53 to 0.14 when the heater temperature is increased from 200 °C to 450 °C. Blistering also appears when the heater temperature is 450 °C. Both of these results show that blistering appears on the as-deposited a-Si:H layers with a low microstructure factor. However, no clear relationship between blistering and the hydrogen content was observed.

In order to further explore the relationship between blistering and the microstructure factor, a-Si:H thin films with different microstructure factors were fabricated by applying a set of different gas flow rates, substrate heater temperatures, and deposition pressures. It is observed that the as-deposited a-Si:H thin films blistered when the microstructure factor was too low, as shown in Fig. 5(a). However, the transition points from blistering-free layers to blistering layers depend on the substrate heater temperatures. With higher heater temperature, the transition point shifts to a lower microstructure factor, which means that a more dense material can be achieved without blistering.

The passivation qualities of the a-Si:H layers were investigated by performing quasi-steady-state photo conductance (QSSPC) measurements[26] on symmetric lifetime samples. The after-firing iV_{oc} results are shown in Fig. 5(b). Higher iV_{oc} was achieved when the a-Si:H layer showed a lower microstructure factor, which indicates that a dense a-Si:H thin film is desirable for good passivation. For two samples with the same microstructure factor, the iV_{oc} of a blistering sample was about 30 mV lower than that of a blistering-free one, confirming the detrimental effect of blistering on passivation. However, blistering in a dense thin film could be avoided by using higher substrate heater temperature, as shown in Fig. 5(a). By adjusting the deposition parameters, precursor a-Si:H thin films were deposited with a microstructure factor of lower than 0.3, giving rise to an iV_{oc} value of 738 mV with no blistering after all the high temperature process steps. The champion sample was produced at a high deposition rate of 7 Å/s.

Four-point probe measurement and transmission line measurement were used to measure sheet resistance (R_{sheet}) and contact resistivity (ρ_c) of the passivating layer stacks, respectively. The results are shown in Fig. 5(c). Both R_{sheet} and ρ_c reduced as the microstructure factor decreased. When the microstructure factor was high, some samples were beyond the measurement range. The best R_{sheet} and ρ_c achieved were 280 Ω/□ and 0.034 Ω cm^2, respectively, with an iV_{oc} value of 735 mV. It is reported that the solar cell efficiency is sensitive to ρ_c only when it is over ∼0.1 Ω cm^2, which indicates that the ρ_c result from HWCVD is sufficient for applications in high-efficiency solar cells.[27]

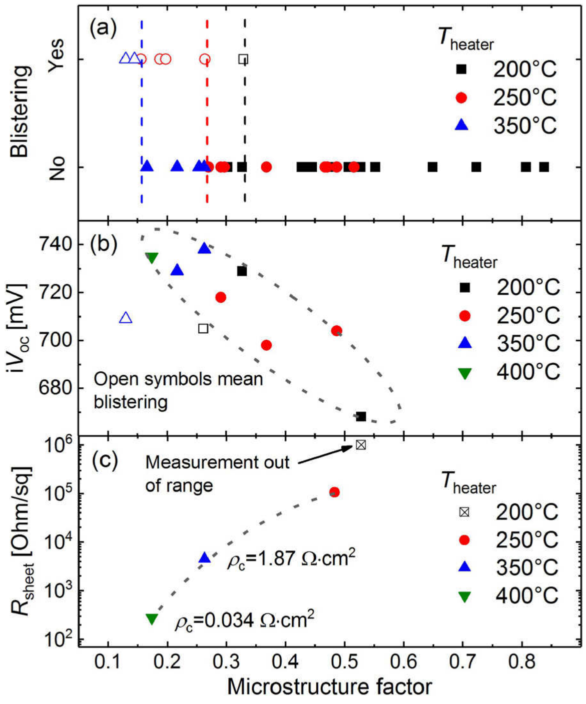

FIG. 5. (a) Blistering, (b) iV_{oc}, and (c) R_{sheet} vs microstructure factor of *ex-situ* doped layers; the dashed lines are guides to the eye.

In conclusion, we developed a one-side a-Si:H thin film fabrication method for poly-Si/SiO$_x$ carrier selective passivating contacts by using HWCVD. With this method, the ultra-thin SiO$_x$ layers were prevented from ion damage caused by plasma. Precursor a-Si:H layers with a low microstructure factor were found to achieve good passivation, and blistering of the silicon layers can be avoided by increasing the substrate heater temperature. After optimization, a dense and blistering-free thin film was deposited at a deposition rate of 7 Å/s, giving rise to the best iV_{oc} of 738 mV after all high temperature processes. Low ρ_c(0.034 Ω cm^2) was also achieved at this high deposition rate (T_{heater} = 400 °C, SiH$_4$ flow rate = 10 sccm, H$_2$ flow rate = 10 sccm, and iV_{oc} = 735 mV) by using HWCVD. We proved that HWCVD is a suitable one-side fabrication method for passivating contacts.

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