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Improvement of surface passivation layers for crystalline silicon solar cells

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1. Introduction

Enhancement in the efficiency of crystalline-silicon (c-Si) solar cells is one of great importance in c-Si photovoltaic research. High efficiency solar cells can be obtained only when both loss of photo-generated carriers and loss of sun-light in solar cells are reduced. To reduce the electrical loss due to the surface recombination of photo-generated carriers and the optical loss due to the reflection at air/c-Si interface, the formation of a surface passivation layer with the anti-reflection ability is indispensable.

Recently, silicon-nitride (SiN_x)/amorphous-silicon (a-Si) stacked layers both prepared by catalytic chemical vapor deposition (Cat-CVD), also referred to as hot-wire CVD, are found to have excellent performance as the surface passivation of c-Si. However, since a-Si layer absorbs sun-light, the use of more transparent material is required. Si-rich SiN_x films have higher silicon contents than SiN_x films, and have higher transparency than a-Si films. Thus, in my study, Si-rich SiN_x films were used as an alternative film to a-Si in the stacked structure. The major purpose of my research is to obtain good-transparency films without decrease of passivation quality in c-Si. The use of SiN_x/Si-rich SiN_x stacked layers as passivation films on c-Si wafers results in surface recombination velocity (SRV) of as low as 4.4 cm/s and 30 % improvement of transparency at the wavelength of 400 nm compared with that of SiN_x/a-Si stacked layers. Moreover, after annealing process, the passivation property of the stacked layers was significantly improved to SRV obtained of as low as 3 cm/s.

2. Experimental process

All the SiN_x and Si-rich SiN_x films were prepared by Cat-CVD. The effect of the ratio of silane (SiH_4)-to-ammonia (NH_3) gas flow rates (R= [SiH_4]/[NH_3]) and substrate temperature T_s during deposition of Si-rich SiN_x films on properties of the films was firstly investigated. Then SiN_x/Si-rich SiN_x stacked layers were deposited on both sides of *n*-type c-Si wafers, whose schematic view is shown in Figure 1. Deposition condition of Si-rich SiN_x films and SiN_x films was listed in Table 1. The passivation quality of SiN_x/Si-rich SiN_x stacked layers were evaluated through effective minority carrier lifetime (τ_{eff}) measured by microwave photoconductance decay (μ-PCD) method.

Table 1. Deposition condition of Si-rich SiN_x and SiN_x films.

Film	SiH_4 (sccm)	NH_3 (sccm)	Gas pressure(Pa)	T_s (°C)	T_{cat} (°C)
Si-rich SiN_x	10-20	250	10	90-300	1800
SiN_x	6.9	200	10	250	1800

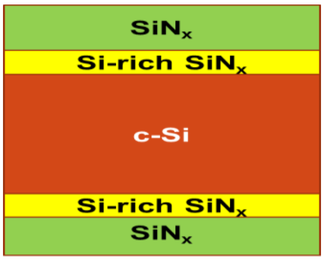

Figure 1. Schematic of cross-sectional view of a c-Si wafer passivated by SiN_x/Si-rich SiN_x stacked layers

3. Results and discussion

3.1. *The effect of R and T_s on the properties of Si-rich SiN_x films*

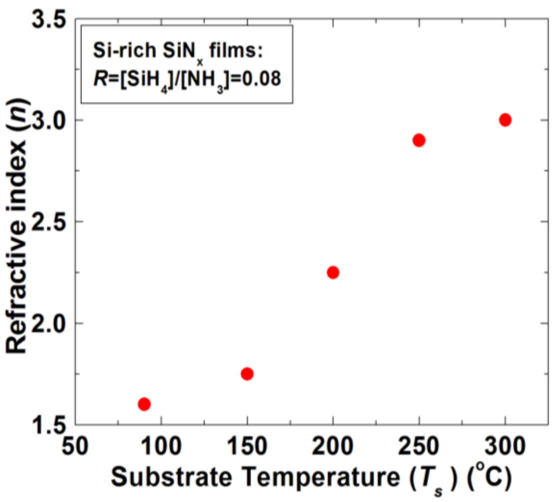

Figure 2. *n* at 630 nm of of Si-rich SiN_x films deposited at various T_s

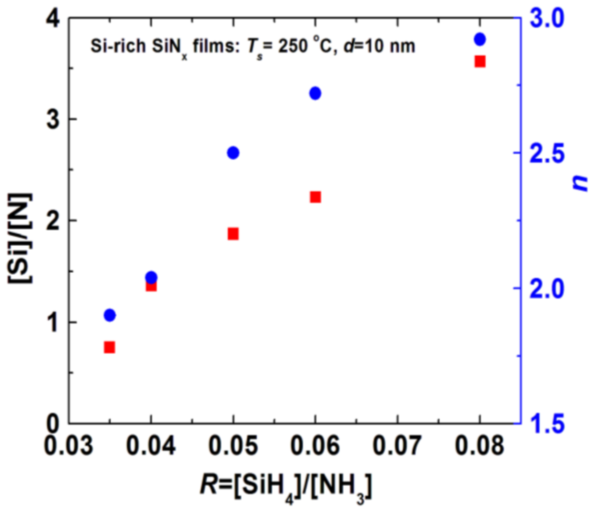

Figure 3. Atomic composition [Si]/[N] and n of 10-nm-thick Si-rich SiN_x films as a function of *R* at T_s of 250 °C

Figure 2 shows refractive index (*n*) at 630 nm of Si-rich SiN_x films at *R* of 0.08 as a function of T_s. *n* becomes higher with increase in T_s. This variation of *n* may be due to the change of atomic ratio of silicon/nitrogen (Si/N) shown in Figure 3. Figure 3 shows the atomic composition and *n* at 630 nm of 10-nm-thick Si-rich SiN_x films deposited at various *R*. Si content in the films increases as *R* increases. The excess Si content in the films induces the increase in mass density of the films, which may contribute to increase of *n*.

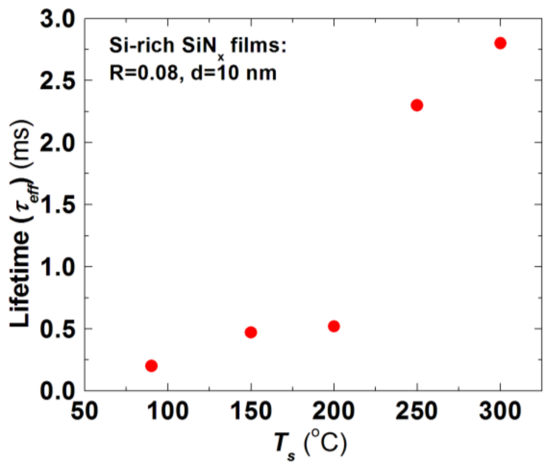

Figure 4. τ_{eff} of c-Si wafers passivated by SiN_x/Si-rich SiN_x stacked layers as a function of T_s

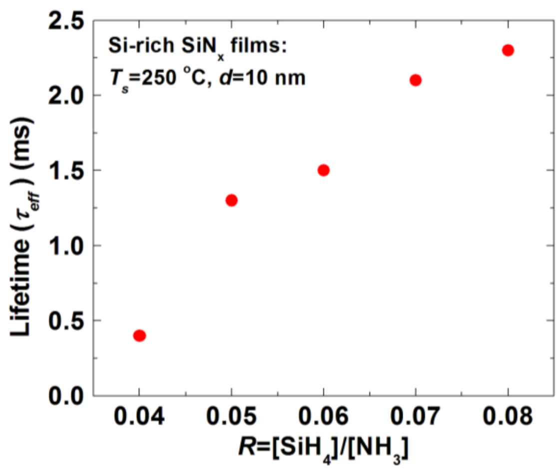

Figure 5. τ_{eff} of c-Si wafers passivated by SiN_x/Si-rich SiN_x stacked layers as a function of *R*

3.2. *Passivation quality of SiN_x/Si-rich SiN_x stacked layers on c-Si wafers*

Figure 4 shows τ_{eff} of c-Si wafers passivated by SiN_x/Si-rich SiN_x stacked layers as function of T_s. τ_{eff} improves with increase in T_s, and increases up to more than 2000 µs, particularly at T_s of 250 ºC or more. The reason is not clear at the moment. It may be due to more effective termination of unbonded Si atoms at the Si-rich SiN_x/c-Si interface and Si-rich SiN_x films at higher T_s. Figure 5 shows τ_{eff} of c-Si wafers passivated by SiN_x/Si-rich SiN_x stacked layers as function of *R*. τ_{eff} also increases with increase of *R*. One possible explanation for this tendency is that the increase of SiH_4 gas flow rate can provide more hydrogen atoms passivating Si wafers during Si-rich SiN_x films deposition process. Figure 6 shows τ_{eff} of c-Si wafers passivated by SiN_x/Si-rich SiN_x stacked layers as a function of Si-rich SiN_x film thickness. Without Si-rich SiN_x insertion, τ_{eff} is quite low. The obtained τ_{eff} of c-Si wafers passivated by 100 nm SiN_x films is 500 μs, corresponding to SRV of 29 cm/s. When Si-rich SiN_x films are inserted, τ_{eff} is significantly improved, and reaches maximum value of 3300 μs, corresponding to SRV of 4.4 cm/s when 8-nm-thick Si-rich SiN_x films are inserted. Figure 7 shows the dependence of τ_{eff} on annealing temperature (T_a). τ_{eff} increases when T_a increases and reaches highest value at T_a of 350 ^{o}C, and it drops drastically at T_a of 500 ^{o}C. Figure 8 shows transmission spectra of Si-rich SiN_x films at various R before and after annealing. The spectrum of a 10-nm-thick a-Si film is also shown for comparison. Transmission of Si-rich SiN_x films decreases with increase of R. However, at higher R which shows good passivation effect, transmission

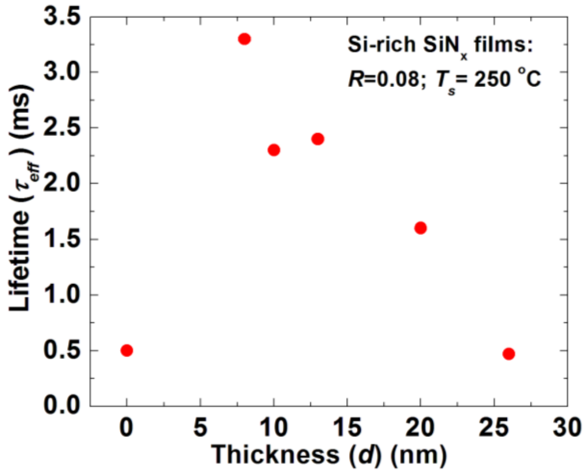

Figure 6. τ_{eff} of c-Si wafers passivated by SiN_x/Si-rich SiN_x stacked layers as a function of thickness of Si-rich SiN_x films.

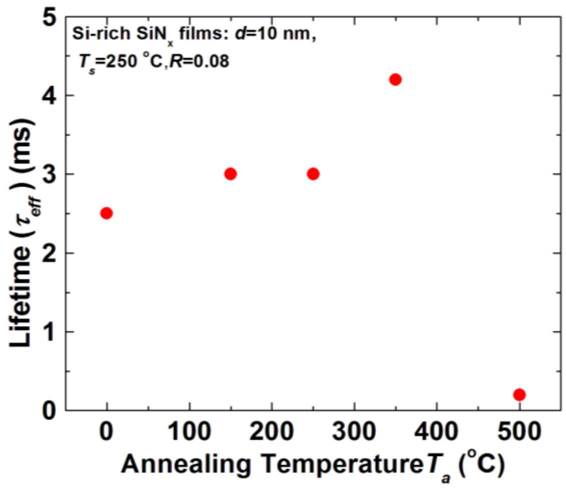

Figure 7. τ_{eff} of c-Si wafers passivated by SiN_x/Si-rich SiN_x stacked layer as a function of T_a.

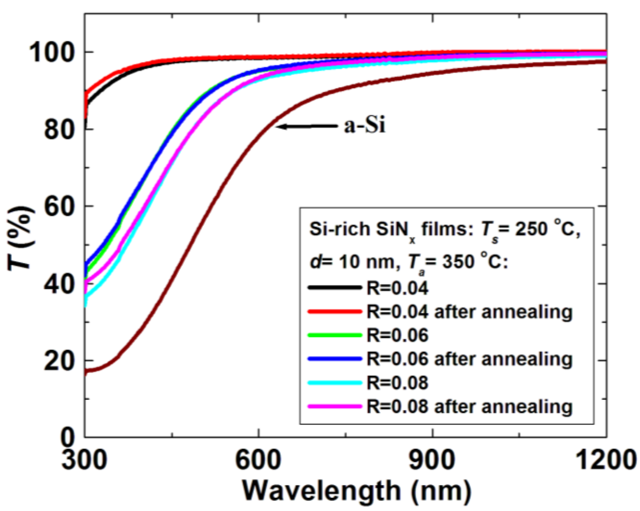

Figure 8. Transmission spectra of Si-rich SiN_x films at various R before and after annealing (The spectrum of a 10-nm-thick a-Si film is also shown for comparison).

of the films is higher than that of an a-Si film. Transmission of Si-rich SiN_x films does not change after annealing process. Figure 9 shows at wavelength (λ) of 400 nm of Si-rich SiN_x films deposited at various R and τ_{eff} before and after annealing. Transmission at a wavelength of 400 nm of Si-rich SiN_x films was used for evaluation. Transmission tends to decrease when R increases, while τ_{eff} tends to increase with R. At the highest τ_{eff} of 4.8 ms after annealing at 350 ^oC, transmission of Si-rich SiN_x film is 60 %. Compared to an a-Si film, the transmission of the films is improved by 30 %. SRV of 3 cm/s for SiN_x/Si-rich SiN_x stacked films is a little bit worse than that of 1.5 cm/s for a SiN_x/a-Si structure. However, this difference of SRV will decrease the open-circuit voltage of solar cells only by 0.015 V. On the contrary, the improvement in transparency in short wavelength region from 300 nm to 1200 nm may improve short-circuit currents by about 10 %.

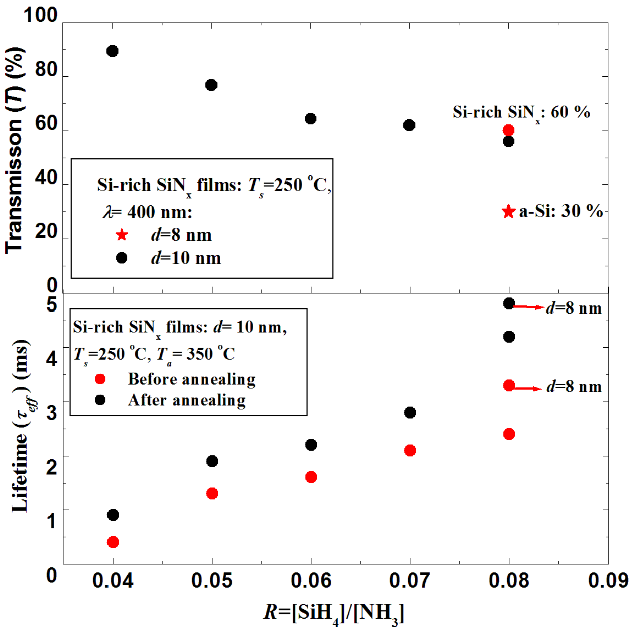

Figure 9. Transmission at wavelength (λ) of 400 nm of Si-rich SiN_x films deposited at various R and τ_{eff} before and after annealing at T_a of 350 ^oC.

4. Conclusion

SiN_x/Si-rich SiN_x stacked layers formed by Cat-CVD system show good passivation on *n*-type c-Si wafers with resistivity of 2.5 Ω cm, which are available for solar cell fabrication. Passivation quality of this structure increases with increase in T_s and R during the deposition of Si-rich SiN_x films. The best τ_{eff} obtained before annealing is 3.3 ms, corresponding to SRV of 4.4 cm/s and SRV reduces from 4.4 cm/s to 3 cm/s. After annealing process, τ_{eff} is enhanced greatly from 3.3 ms to 4.8 ms, at which transparency is improved by 30 % in comparison with a-Si films. The results indicate that the use of Cat-CVD SiN_x/Si-rich SiN_x stacked layers can enhance c-Si solar cell efficiency due to high transparency and good passivation quality of Si-rich SiN_x films.