Enhanced Si Passivation and PERC Solar Cell Efficiency by Atomic Layer Deposited Aluminum Oxide with Two-step Post Annealing

Chia-Hsun Hsu, Yun-Shao Cho, Wan-Yu Wu, Shui-Yang Lien, Xiao-Ying Zhang, Wen-Zhang Zhu, Sam Zhang and Song-Yan Chen

Abstract

In this study, aluminum oxide (Al₂O₃) films were prepared by a spatial atomic layer deposition using deionized water and trimethylaluminum, followed by oxygen (O₂), forming gas (FG), or two-step annealing. Minority carrier lifetime of the samples was measured by Sinton WCT-120. Field-effect passivation and chemical passivation were evaluated by fixed oxide charge (Qₓ) and interface defect density (Dₓ), respectively, using capacitance-voltage measurement. The results show that O₂ annealing gives a high Qₓ of ~3.9 × 10¹² cm⁻², whereas FG annealing leads to excellent Si interface hydrogenation with a low Dₓ of 3.7 × 10¹¹ eV⁻¹ cm⁻². Based on the consideration of the best field-effect passivation brought by oxygen annealing and the best chemical passivation brought by forming gas, the two-step annealing process was optimized. It is verified that the Al₂O₃ film annealed sequentially in oxygen and then in forming gas exhibits a high Qₓ (2.4 × 10¹² cm⁻²) and a low Dₓ (3.1 × 10¹¹ eV⁻¹ cm⁻²), yielding the best minority carrier lifetime of 1097 μs. The SiNx/Al₂O₃ passivation stack with two-step annealing has a lifetime of 2072 μs, close to the intrinsic lifetime limit. Finally, the passivated emitter and rear cell conversion efficiency was improved from 21.61% by using an industry annealing process to 21.97% by using the two-step annealing process.

Keywords: Passivated emitter and rear cell, Aluminum oxide, Atomic layer deposition, Passivation, Two-step annealing

Introduction

Passivated emitter and rear cells (PERCs) have emerged as a promising technology for both high efficiency and competitive cost in recent years. The most difference between the PERC and the traditional full-aluminum back surface field silicon solar cell is rear passivation of wafers. Considerable efforts have been made in order to improve wafer surface passivation. Minority carrier lifetimes of 0.8–8 ms have been reported for p-type floating zone wafers passivated by vacuum [1–4] or spatial atomic layer deposition (ALD) aluminum oxide (Al₂O₃) [5–7]. The passivation quality for p-type Czochralski wafers is lower, in the range of 0.1–2 ms [8, 9]. Spatial ALD Al₂O₃ have been extensively studied and applied to the industry in recent years due to their higher deposition rate (0.03–1.2 nm/s) compared to that of a conventional vacuum-type ALD (< 0.03 nm/s) [10, 11]. Trimethylaluminum (TMA) and H₂O are the most widely used precursors as they are inexpensively volatile liquid and easy to handle. Some research groups use other precursors such as AlCl₃ or O₃ [12–14]. Al₂O₃ is currently considered to be the best passivation material due to its field effect and chemical passivation [15]. It is found that the H₂O-based ALD process mostly leads to a silicon oxide (SiOₓ) layer at the Al₂O₃/Si interface, and this interfacial layer can appear after deposition or annealing [16]. Post annealing for Al₂O₃ films in either nitrogen or forming gas (FG) has been shown to significantly increase the wafer lifetime [12, 17]. Hydrogen in FG or Al₂O₃ cause hydrogenation of Si interface during
annealing. The annealing temperature is typically below 500 °C, beyond which dehydrogenation occurs. However, other annealing processes for further improving passivation quality are rarely reported.

In this study, Al₂O₃ films are prepared on Si by spatial ALD with TMA and H₂O as precursors. Effects of oxygen (O₂) and FG post annealing on passivation of Si wafers are investigated and analyzed. A two-step annealing as a combination of O₂ and FG annealing is proposed and demonstrates a higher wafer lifetime compared to the individual gas annealing process. Finally, photovoltaic performance of PERCs fabricated with industry standard, O₂, FG, and two-step annealing are presented.

**Methods**

P-type (100) Czochralski silicon wafers with resistivity of 1 Ω-cm and thickness of 200 μm were used as substrates. The wafers were cleaned using standard RCA process, followed by a 30-s HF dip to remove native oxide on the wafers. The Al₂O₃ thin films with a thickness of 18 nm were deposited using a spatial ALD system, with H₂O and TMA as oxidant and aluminum source, respectively. The gap between gas injection heads and the movable substrate holder was about 1 mm. The detailed deposition parameters are summarized in Table 1. The temperature of the pipes was 70 °C to prevent condensation of precursors. Some of the wafers were passivated with silicon nitride (SiNₓ, 120 nm)/Al₂O₃ (18 nm) stack, where the SiNₓ layer was deposited using a 13.56-MHz inductively coupled plasma vapor deposition at 120 °C with a gas mixture of ammonia (NH₃) and tetramethylsilane (TMS). Other parameters for SiNₓ deposition are listed in Table 2. The oxygen, FG, or two-step annealing process was performed on the samples, and the annealing parameters are listed in Table 3. The lifetime of the samples was measured by Sinton WCT-120. The capacitance-voltage (C-V) measurement was carried out on metal-oxide-semiconductor (MOS) samples by a capacitor meter (HP 4284a) at 1 MHz at room temperature. For MOS fabrication, the wafers were deposited with an 18-nm-thick Al₂O₃ layer and annealed. Aluminum films with a thickness of 500 nm were evaporated on both sides of the samples as electrodes. The area of the MOS samples was 1 mm². The cross-sectional images of the samples were obtained using a transmission electron microscope (TEM). For PERC fabrication, a schematic of the devices is shown in Fig. 1, where the ALD passivation is only on the rear side. The wafers were textured using alkaline solution to generate random pyramids. Emitter was formed by POCl₃ diffusion in a standard tube thermal furnace with a sheet resistance of 100 ohms/square. A SiNₓ of 85 nm thickness was deposited on the front side of the wafer as an antireflective layer by inductively coupled plasma vapor deposition (ICPCVD). The back side of the wafer was polished by KOH solution for 3 min at 70 °C. The Al₂O₃ films of 18 nm in thickness were deposited using spatial ALD. An ICPCVD SiNₓ of 120 nm in thickness was deposited on Al₂O₃. The samples were annealed with different annealing processes. The rear local openings with a diameter of 40 μm and a pitch of 260 μm were created by 532-nm laser scribing. Finally, a silver grid was screen printed on the front and aluminum on the rear dielectric, followed by co-firing at a peak temperature of 850 °C. The current density-voltage (J-V) curves were measured by a dual light source-type solar simulator (Wacom Co., Japan) using both xenon lamp and halogen lamp with a calibrated class A AM 1.5G simulated light spectrum.

**Table 1** Deposition parameters of the ALD Al₂O₃ layer

| Parameter              | Value |
|------------------------|-------|
| Substrate temperature  | 150   |
| TMA bubbler temperature | 17.5  |
| H₂O bubbler temperature | 30    |
| Pressure (Torr)        | 760   |
| TMA flow rate (sccm)   | 200   |
| H₂O flow rate (sccm)   | 500   |
| Thickness (nm)         | 15    |

**Table 2** Deposition parameters of the SiNₓ layer

| Parameter              | Value |
|------------------------|-------|
| Substrate temperature  |       |
| Pressure (Torr)        | 0.005 |
| TMS flow rate (sccm)   | 15    |
| NH₃ flow rate (sccm)   | 45    |
| Power (W)              | 1200  |
| Thickness (nm)         | 120   |

**Table 3** Parameters of O₂, FG, and two-step annealing processes

|        | O₂-600 | FG-450 | Two-step       |
|--------|--------|--------|----------------|
|        | Step 1 | Step 2 |                |
| Annealing gas | O₂ | 5% H₂ | 95% N₂ | O₂ | FG |
| Temperature (°C)| 600 | 450   | 600 | 450 |
| Time (min)    | 20   | 20    | 10  | 10  |
Fig. 1 Schematic of PERC solar cells with SiN$_x$/ALD Al$_2$O$_3$ rear passivation

Fig. 2 a Injection-level-dependent minority carrier lifetime. b Lifetime at an injection level of $3 \times 10^{15}$ cm$^{-3}$ for Al$_2$O$_3$/Si/Al$_2$O$_3$ samples with O$_2$, FG, and two-step annealing.
by annealed Al2O3. However, the lifetime values are different in these three annealing conditions, in which oxygen annealing has the lowest curve, FG annealing has the intermediate, and the two-step annealing has the highest. The lifetime values at the injection level of 3 \times 10^{15} \text{cm}^{-3} are extracted as shown in Fig. 2b. The O2-, FG-, and two-step-annealed samples have lifetimes of 818, 934, and 1098 \mu s, respectively. Note that the two-step annealing can obtain the highest lifetime only with the annealing sequence of the first step in O2 and the second step in FG. The reverse sequence results in a lifetime similar to that of the sample with O2 annealing alone. This might be because if FG annealing was performed first, the following O2 annealing might cause dehydrogenation. Niwano et al. reported that for a wafer terminated by Si–H or Si–H2 bonds, exposure to oxygen results in the replacement of the hydrogen bonds with the Si–O bonds [18].

As overall passivation is governed by field effect and chemical passivation, the C-V measurement is helpful to clarify which passivation dominates in the cases of O2, FG, and two-step annealing. Figure 3a shows the normalized C-V curves for the samples without and with different annealing processes. The slope magnitude of the curves in the depletion region can be used as an indicator of interface defect density (Dit), since the existence of interface traps causes C-V curve stretch-out [19]. The two-step annealing gives the largest slope among the others, and thus the lowest Dit is expected. To gain further information, the values of fixed oxide charge density (Qf) and Dit are extracted from the C-V curves as plotted in Fig. 3b. The Qf is helpful for evaluating the field effect passivation and is calculated by [20]

\[ Q_f = \frac{C_{ox}(W_{ms} - V_{fb})}{qA} \]  

where \( C_{ox} \) is the accumulation oxide capacitance, \( W_{ms} \) is the work function difference between semiconductor and electrode (in this case – 0.9 V), \( V_{fb} \) is the flat band voltage, \( q \) is the electron charge, and \( A \) is the area of the MOS devices. The \( Q_f \) is –3.2 \times 10^{-11} \text{cm}^{-2} for the as-deposited sample. \( Q_f \) at this level leads to weak field effect passivation [21]. All the annealed samples elevate \( Q_f \) to the level of 10^{12} \text{cm}^{-2}. It is seen that the O2 annealing gives the highest \( Q_f \) of 3.9 \times 10^{12} \text{cm}^{-2}, the two-step annealing gives the intermediate \( Q_f \) and the

![Fig. 3 a Normalized C-V curves. b Dit and Qf for samples with O2, FG, and two-step annealing](image-url)
FG annealing gives the lowest $Q_f$. On the other hand, $D_{it}$ value estimated by the Terman method \[22\] is also shown to evaluate chemical passivation. The as-deposited sample has a $D_{it}$ of more than $10^{13}$ eV$^{-1}$ cm$^{-2}$. It reduces to $5.4 \times 10^{11}$ eV$^{-1}$ cm$^{-2}$ for O$_2$ annealing, $3.7 \times 10^{11}$ eV$^{-1}$ cm$^{-2}$ for FG annealing, and $3.1 \times 10^{11}$ eV$^{-1}$ cm$^{-2}$ for two-step annealing. Thus, by comparing O$_2$ and FG annealing, it is found that O$_2$ annealing has the better field effect passivation, whereas FG has the better chemical passivation. The former might be linked to the interfacial SiO$_x$ growth. Unlike FG annealing which is performed at a relatively low temperature and with lack of oxygen, O$_2$ annealing is expected to have an improved SiO$_x$ interfacial layer growth. This could increase the possibility of Al substitution for Si at the Al$_2$O$_3$/SiO$_2$ interface, which is regarded to be one possible origin of negative fixed charges \[23\]. Considering the two-step annealing, the intermediate $Q_f$ is reasonable as a combination of O$_2$ and FG annealing. However, its $D_{it}$ value is lower than that of the FG annealing. This is explained by the additional contribution by the higher quality of the interfacial oxide layer due to the first-step O$_2$ annealing. Some studies also reported that a denser SiO$_x$ results in a better passivation \[24\]. The lower $D_{it}$ in two-step annealing sample can also be attributed to the hydrogenation improvement of silicon surface induced by the hydrogen in Al$_2$O$_3$ film.

Figure 4 shows the cross-sectional TEM images of the samples without and with different annealing processes. Before annealing, a SiO$_x$ interfacial layer between Si and Al$_2$O$_3$ is observed although the interface is not clear. This might be because H$_2$O was used in the first-half ALD cycle. For O$_2$ annealing, the interfacial layer thickness increases to 5.6 nm, due to annealing at a high temperature (600 °C) and in oxygen ambient. It has been reported that oxygen has a very small diffusion coefficient in Al$_2$O$_3$ ($\sim 10^{-38}$ cm$^{-1}$ at 600 °C) \[25\], and thus, it is unlikely for oxygen to diffuse through the Al$_2$O$_3$ layer to reach the Si interface. Instead, ambient oxygen interchanges with the oxygen in Al$_2$O$_3$, creating a mobile oxygen that can repeat the interchange process in the deeper Al$_2$O$_3$ region until the oxygen reaches the Si interface \[26\]. The sample annealed in FG shows a clearer interface with a very thin SiO$_x$ interfacial layer of

![Fig. 4 Cross-sectional TEM images for samples a without annealing and with b O$_2$, c FG, and d two-step annealing](image-url)
1.4 nm, which is similar to other research groups performing the annealing process in N₂ or FG [16]. This evidences that FG annealing limits the interfacial layer growth. The two-step annealing shows an intermediate SiOₓ interfacial layer thickness of about 4 nm, as a consequence of the reduced time of the O₂ annealing.

Figure 5a shows the injection level-dependent minority carrier lifetime of the SiNₓ/Al₂O₃-passivated wafers without and with different annealing processes. The lifetimes at the injection level of 3 × 10¹⁵ cm⁻³ are 1569, 1579, and 2072 μs for O₂, FG, and two-step annealing, respectively. The improvements are related to that the plasma chemical vapor-deposited SiNₓ films may contain certain amounts of hydrogen depending on the deposition process parameters. During the annealing process, some of the hydrogen would move towards the Si interface, and this enhances the Si interface hydrogenation [27]. As reported in literature [6, 28–30], the lifetime of SiNₓ/Al₂O₃-passivated p-type CZ wafers is in the range of 0.1–2 ms. The optimal temperature of post-deposition annealing either in nitrogen or in FG is around 400–500 °C. In this work, the SiNₓ/Al₂O₃-passivated CZ wafer annealed in FG shows a lifetime of 1579 μs and an optimal annealing temperature of 450 °C, which are in accordance with the reported values. However, this optimal temperature is limited by the hydrogenation of the silicon interface. From the viewpoint of the silicon oxide interfacial layer, this layer might have different optimal temperature as high temperatures generally improve qualities of silicon oxide films. Thus, the two-step annealing could optimize both of the interfacial oxide quality and silicon interface hydrogenation, and leads to a higher lifetime of 2072 μs compared to the case of forming gas single-step annealing. To investigate the reproducibility, 50 samples with two-step annealing were prepared, and their minority carrier lifetime is shown in Fig. 5b. The samples have lifetime values ranging between 1939 and 2224 μs. The average value is 2075 μs, and the error is within ± 7%. The intrinsic lifetime limit of the wafer used in this study is about 2300 μs, calculated by using the Richter parameterization [31]. Thus, the two-step annealing yields a lifetime close to the

![Fig. 5](image-url)
lifetime limitation and demonstrates excellent interface passivation. For other ALD, a silicon oxide interfacial layer between Al₂O₃/Si is also found, and the two-step annealing should be able to improve the passivation quality of Si wafers. AlOₓ/SiNx is necessary as the silicon nitride not only enhances passivation but also increases rear reflectance and protects AlOₓ from a high-temperature cofiring process for PERC fabrication.

Figure 6 shows the implied open-circuit voltage (V_{oc}) for the SiNₓ/Al₂O₃-passivated samples with different annealing processes. For p-type wafers and long diffusion lengths, the implied V_{oc} can be written as

\[
\text{implied } V_{oc} = \frac{kT}{q} \ln \left( \frac{\Delta n (N_A + \Delta n)}{n_i^2} \right)
\]

where \( k \) is the Boltzmann constant, \( T \) is the absolute temperature, \( n_i \) is the intrinsic carrier concentration, \( N_A \) is the acceptor concentration, and \( \Delta n \) is the excess carrier concentration measured at one-sun light intensity by the WCT-120 Sinton lifetime tester. It can be seen that the O₂- and FG-annealed samples have similar implied V_{oc} values, which are 696 and 697 mV, respectively. The two-step annealing has an implied V_{oc} of 706 mV.

Figure 7 shows the J-V characteristics and photovoltaic parameters such as V_{oc}, short-circuit current density (J_{sc}), fill factor (FF), and conversion efficiency (\( \eta \)) of the fabricated PERCs with different annealing processes. The performance of an industrial PERC is also shown for the purpose of comparison. The industry PERC was fabricated under identical conditions but no additional annealing process was used, since the Al₂O₃ layer was annealed during the SiNₓ deposition at 400 °C. Note that in this study, during the annealing processes, the front side was placed downward and made contact to a wafer holder. The front SiNₓ layer was not exposed to the annealing gases, and thus, the influence of the front SiNₓ layer might be insignificant. The industry PERC shows the lowest V_{oc} of 665.4 mV among the others. This could be attributed to its lower wafer lifetime of 797 μs at the injection level of 3 × 10^{15} cm⁻³. The V_{oc} value improves to 671.3 mV for O₂ annealing and 672.3 mV for FG annealing. The two-step annealing further increases V_{oc} to 675.5 mV, which is an improvement by about 0.6% compared to one-step annealing, or by 1.5% compared to the industry one. There is no much difference in J_{sc} and FF between the PERCs. The two-step annealing exhibits the best conversion efficiencies of 21.97%, which is 0.36%abs higher than industry PERC. Finally, five PERCs were fabricated for each annealing process. The mean value and distribution range of V_{oc} and FF are shown in Fig. 8a and b, respectively. The PERCs with the two-step annealing show V_{oc} of 675–677.5 mV with a mean value of 676 mV, and FF of 0.813–0.819 with a mean value of 0.816.

**Conclusion**

The Al₂O₃ films are prepared using atomic layer deposition, followed by O₂, FG, or two-step annealing. Comparing O₂ annealing with FG annealing, the former yields a thicker SiOₓ interfacial layer and the higher Qₓ density of 3.9 × 10^{12} cm⁻², indicating a superior field effect passivation. The FG annealing shows the lower Dₓ of 3.7 × 10^{11} eV⁻¹ cm⁻² resulting from the hydrogenation of the Si interface. The two-step annealing combines the advantages of these two annealing processes and has an
Fig. 7 Current density-voltage curves and photovoltaic performance of PERCs with industry standard fabrication, O₂ annealing, FG annealing, and two-step annealing.

| Process    | V_{oc} (mV) | J_{sc} (mA/cm²) | FF  | η (%) |
|------------|-------------|-----------------|-----|-------|
| Industry   | 665.4       | 39.6            | 0.82| 21.61 |
| O₂-600     | 671.3       | 39.7            | 0.82| 21.85 |
| FG-450     | 672.3       | 39.7            | 0.82| 21.88 |
| Two-step   | 675.5       | 39.7            | 0.82| 21.97 |

Fig. 8 Mean value and distribution range of a \( V_{oc} \) and b FF for PERCs with different annealing processes.
intermediate $Q_i$ and the lowest $D_{it}$ of $3.1 \times 10^{11}$ eV$^{-1}$ cm$^2$. The SiN$_x$/Al$_2$O$_3$-passivated samples with the two-step annealing demonstrate a minority carrier lifetime of 2072 $\mu$s, close to the intrinsic lifetime limit. For the PERC fabricated with the two-step annealing, $V_{oc}$ of 675.5 mV and conversion efficiency of 21.97% can be obtained, which respectively have increases of 10 mV and 0.36% as compared to those of the industry PERC.

Abbreviations

Al$_2$O$_3$: Aluminum oxide; ALD: Atomic layer deposition; C-V: Capacitance-voltage; DoD: Interface defect density; FF: Fill factor; FG: Forming gas; J$_{sc}$: Short-circuit current density; J-V: Current-density/voltage; MOS: Metal-oxide-semiconductor; NH$_3$: Ammonia; O$_3$: Oxygen; PERC: Passivated emitter and rear cell; Q$_i$: Fixed oxide charge; SiN$_x$: Silicon nitride; SiO$_x$: Silicon oxide; TEM: Transmission electron microscope; TMA: Trimethylaluminum; TMS: Tetramethylsilane; $V_{oc}$: Open-circuit voltage; $\eta$: Conversion efficiency

Funding

This work is sponsored by the Ministry of Science and Technology of Taiwan (nos. 104-2632-E-212-002-, 104-2622-E-212-005-CC3, 104-2221-E-212-002-MY3). This work is also supported by the National Natural Science Foundation of China (nos. 61474081, 61534005 and 61507115), the Science Technology Innovation project of Xiamen (nos. 35022201730404) and the Fundamental Research Funds for the Central Universities (nos. 20720150028).

Availability of Data and Materials

All data supporting the conclusions of this article are included within the article.

Authors’ Contributions

CHH and SYL designed and performed the experiments. YSC and XYZ finalized the manuscript. All authors read and approved the final manuscript. CHH and SYL designed and performed the experiments. YSC and XYZ finalized the manuscript. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

Publisher’s Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Author details

1School of Opto-electronic and Communication Engineering, Xiamen University of Technology, Xiamen, China. 2Department of Materials Science and Engineering, Da-Yeh University, Changhua, Taiwan. 3Faculty of Materials and Energy, Southwest University, Chongqing, China. 4Department of Physics, OSUED, Xiamen University, Xiamen 361005, China.

Received: 3 January 2019 Accepted: 1 April 2019

Published online: 18 April 2019

References

1. Werner F, Veith B, Tibas V, Poold T, Roozeboom F, Brendel R et al (2010) Very low surface recombination velocities on p- and n-type c-Si by ultrafast spatial atomic layer deposition of aluminum oxide. Appl Phys Lett 97: 162103. https://doi.org/10.1063/1.3505311
2. Richter A, Benick J, Hermle M, Glunz SW (2011) Excellent silicon surface passivation with 5 Å thin ALD Al$_2$O$_3$ layers: influence of different thermal post-deposition treatments. Phys status solidi – Rapid Res Lett 5:5–6. https://doi.org/10.1002/pssr.201001988
3. Reichel C, Reush M, Kotula S, Granek F, Richter A, Hermle M et al (2018) Insulating and passivating plasma-enhanced atomic layer deposited aluminum oxide thin films for silicon solar cells. Thin Solid Films 655:53–60. https://doi.org/10.1016/j.tsf.2018.04.030
4. Simon DK, Jordan PM, Dinntorfer I, Benfer R, Richter C, Mikolajick T (2014) Symmetrical Al$_2$O$_3$-passivated based passivation layers for p- and n-type silicon. Sol Energy Mater Sol Cells 131:72–76. https://doi.org/10.1016/j.solmat.2014.06.005
5. Agostinelli G, Delabie A, Vitaro P, Alexieva Z, Dekkers HFW, Wolf SD et al (2006) Very low surface recombination velocities on p-type silicon wafers passivated with a dielectric with fixed negative charge. Sol Energy Mater Sol Cells 90:3438–3443. https://doi.org/10.1016/j.solmat.2006.04.014
6. Poold T, Tibas V, Werner F, Schmidt J, Vermeer A, Roozeboom F (2011) Ultrafast atomic layer deposition of alumina layers for solar cell passivation. J Electrochem Soc 158:H937–H940. https://doi.org/10.1149/1.3160994
7. Granneman EHA, Kuznetsov VI, Vermont P (2014) Spatial ALD. Deposition of Al$_2$O$_3$ films at throughputs exceeding 3000 wafers per hour. ECS Trans 61:3–16
8. Bao Y, Huang H, Zhu Z, Lv J, Savin H (2016) Silicon surface passivation by mixed aluminum precursors in Al$_2$O$_3$ atomic layer deposition. Energy Procedia 92:304–308. https://doi.org/10.1016/j.egypro.2016.07.085
9. Decker, J., Cornagliotti, E., Debucquoy, M., Gordon, I., Mertens, R., Poortmans, J. (2014) Aluminum oxide-aluminum stacks for contact passivation in silicon solar cells. Energy Procedia 55:656–664. https://doi.org/10.1016/j.egypro.2014.08.041
10. Schmidt, J., Werner, F., Veith, B., Zieke, D., Bock, R., Tibas V et al (2010) Industrially relevant Al$_2$O$_3$ deposition techniques for the surface passivation of Si solar cells. In: 25th European Photovoltaic Solar Energy Conference and Exhibition, p.1130.
11. Poold T, Lankhorst A, Roozeboom F, Spee K, Maas D, Vermeer A (2010) High-speed spatial atomic-layer deposition of aluminum oxide layers for solar cell passivation. Adv Mater 22:3564–3567. https://doi.org/10.1002/adma.201000766
12. Dingemans G, Terlinden NM, Pierreux D, Profijt HB, van de Sanden MCM, Kessels WMM (2011) Influence of the oxidant on the chemical and field-effect passivation of Si by ALD Al$_2$O$_3$. Electrochem Solid State Lett 14:HI–14. https://doi.org/10.1149/1.3509707
13. Elliott SD, Scare G, Wiemer F, Cappelli E, Pavia G (2006) Ozone-based atomic layer deposition of alumina from TMA: Growth, morphology, and retention mechanism. Chem Mater 18:3764–3773
14. Dueñas S, Castán H, García H, de Castro A, Ballón L, Kühl K, Aida A et al (2006) Influence of single and double deposition temperatures on the interface quality of atomic layer deposited Al$_2$O$_3$ dielectric thin films on silicon. J Appl Phys 99:054902. https://doi.org/10.1063/1.2177383
15. Dingemans G, Kessels WMM (2012) Status and prospects of Al$_2$O$_3$-based surface passivation schemes for silicon solar cells. J Vac Sci Technol A Vacuum, Surfaces, Films 30:4082–4080. https://doi.org/10.1116/1.4728205
16. Hoxe B, Heil SB, Langereis E, van de Sanden MC, Kessels WM (2006) Ultrafast surface recombination of c-Si substrates passivated by plasma-assisted atomic layer deposited Al$_2$O$_3$. Appl Phys Lett 89:042112. https://doi.org/10.1063/1.2240736
17. Li M, Shin HS, Jeong KS, Oh SK, Lee H, Han K et al (2014) Blistering induced degradation of thermal stability Al$_2$O$_3$ passivation layer in silicon solar cells. J Semicond Technol Sci 14:53–60
18. Nivano M, Kageyama JI, Kurita K, Kinashi T, Takahashi I, Miyamoto N (1999) Infrared spectroscopy study of initial stages of oxidation of hydrogen-terminated Si surfaces stored in air. J Appl Phys 87:2157–2163. https://doi.org/10.1063/1.357627
19. Engel-Herbert R, Hwang Y, Stremmer S (2010) Comparison of methods to quantify interface trap densities at dielectric/III-V semiconductor interfaces. J Appl Phys 108:124101. https://doi.org/10.1063/1.3520431
20. Werner F, Schmidt J (2014) Manipulating the negative fixed charge density at the c-Si/Al$_2$O$_3$ interface. Appl Phys Lett 104:090104. https://doi.org/10.1063/1.4867652
21. Glunz SW, Biro D, Rein S, Warta W (1999) Field-effect passivation of the SO$_2$/Si interface. J Appl Phys 86:683–691. https://doi.org/10.1063/1.370784
22. Terman LM (1962) An investigation of surface states at a silicon/silicon oxide interface employing metal-oxide-silicon diodes. Solid State Electron 5: 285–299. https://doi.org/10.1016/0038-1101(62)90111-9
23. Johnson RS, Lucovsky G, Baumvol I (2001) Physical and electrical properties of noncrystalline Al$_2$O$_3$ prepared by remote plasma-assisted atomic layer deposition. J Electrochem Soc 148:H937–H940. https://doi.org/10.1149/1.1379316
24. Nakada K, Miyajima S, Konagai M (2013) Passivation effect of amorphous silicon oxide thin films studied by hydrogen evolution. In: 2013 International Conference on Solid State Devices and Materials, pp 1160–1161
25. Heuer A (2008) Oxygen and aluminum diffusion in α-Al2O3: how much do we really understand? J Eur Ceramic Soc 28:1495. https://doi.org/10.1016/j.jeurceramsoc.2007.12.020

26. DaRosa EBO, Baumvol IJR, Morais J, de Almeida RMC, Papaléo RM, Stedile FC (2002) Diffusion reaction of oxygen in aluminum oxide films on silicon. Phys Rev B Condens Matter Mater Phys 65:1–4. https://doi.org/10.1103/PhysRevB.65.121303

27. Schmidt J, Veith B, Brendel R (2009) Effective surface passivation of crystalline silicon using ultrathin Al2O3 films and Al2O3/SiNx stacks. Phys Status Solidi RRL. 289(9):287–289. https://doi.org/10.1002/pssr.200903272

28. Schmidt J, Veith-wolf B, Werner F Silicon surface passivation by ultrathin Al2O3 films and Al2O3/SiNx stacks. In: IEEE Photovoltaic Specialists Conference 2010. https://doi.org/10.1109/PVSC.2010.5614132

29. Richter A, Benick J, Hermle M, Glunz SW (2012) Thermal stability of spatial ALD deposited Al2O3 capped by PECVD SiNx for the passivation of lowly- and highly-doped p-type silicon surfaces. In: EUPVSEC Frankfurt, Germany, pp 24–28. https://doi.org/10.4229/27thEUPVSEC2012-2AV.5.25.

30. Richter A, Glunz SW, Werner F, Schmidt J, Cuevas A (2012) Improved quantitative description of Auger recombination in crystalline silicon. Phys Rev B Condens Matter Mater Phys 86:1–14. https://doi.org/10.1103/PhysRevB.86.165202