von Gastrow, Guillaume; Li, Shuo; Putkonen, Matti; Laitinen, Mikko; Sajavaara, Timo; Savin, Hele

Effect of ozone concentration on silicon surface passivation by atomic layer deposited Al2O3

Published in:
Applied Surface Science

DOI:
10.1016/j.apsusc.2015.09.263

Published: 01/01/2015

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
von Gastrow, G., Li, S., Putkonen, M., Laitinen, M., Sajavaara, T., & Savin, H. (2015). Effect of ozone concentration on silicon surface passivation by atomic layer deposited Al2O3. *Applied Surface Science*, *357, Part B*, 2402 - 2407. https://doi.org/10.1016/j.apsusc.2015.09.263

Effect of ozone concentration on silicon surface passivation by atomic layer deposited Al_2O_3

Guillaume von Gastrow[a*], Shuo Li[a], Matti Putkonen[b], Mikko Laitinen[c], Timo Sajavaara[c], and Hele Savin[a]

[a]Aalto University, Department of Micro- and Nanosciences, Tietotie 3, 02150 Espoo, Finland

[b]VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT, Espoo, Finland and Aalto University School of Chemical Technology, Laboratory of Inorganic Chemistry, FI-00076 Aalto, Espoo, Finland

[c]University of Jyvaskyla, Department of Physics, FIN-40014 University of Jyvaskyla, Finland

[*]Corresponding author: Tel.: +358 50 431 6367. E-mail address: guillaume.von.gastrow@aalto.fi.

We study the impact of ozone-based Al_2O_3 Atomic Layer Deposition (ALD) on the surface passivation quality of crystalline silicon. We show that the passivation quality strongly depends on the ozone concentration: the higher ozone concentration results in lower interface defect density and thereby improved passivation. In contrast to previous studies, our results reveal that too high interface hydrogen content can be detrimental to the passivation. The interface hydrogen concentration can be optimized by the ozone-based process; however, the use of pure ozone increases the harmful carbon concentration in the film. Here we demonstrate that low carbon and optimal hydrogen concentration can be achieved by a single process combining the water- and ozone-based reactions. This process results in an interface defect density of $2 \cdot 10^{11}$ $eV^{-1}cm^{-2}$, and maximum surface recombination velocities of 7.1 cm/s and 10 cm/s, after annealing and after an additional firing at 800 °C, respectively. In addition, our results suggest that the effective oxide charge density can be optimized in a simple way by varying the ozone concentration and by injecting water to the ozone process.

1. INTRODUCTION

Efficient surface passivation is crucial in electronic devices and especially in solar cells, where the generated charge carriers need to diffuse to the contacts before recombining at the surface. Atomic layer deposited (ALD) Al_2O_3 has been intensively studied in the past decade owing to its excellent passivation ability on crystalline silicon (c-Si) surfaces [1-3]. The high passivation quality obtained by Al_2O_3 is associated with low interface defect density values combined with a high negative charge. The interface defect density D_{it} describes recombination activity through midgap defect levels (ideally suppressed by chemical passivation), while the total charge density Q_{tot} is responsible for creating an electric field that prevents minority carriers from reaching the silicon surface (field-effect passivation).

Trimethylaluminum (TMA) and water serve as typical ALD precursors for Al_2O_3 surface passivation studies. However, recent studies have suggested that ozone as an oxidant in the Al_2O_3 process could result in even lower interface defect density and higher total negative charge [4-6] than the conventional water-based process. Nevertheless, the past studies of ozone-based ALD processes often omit the ozone concentration, although this parameter may be of paramount importance for the quality of ALD films. A more systematic study on the effect of ozone concentration on the passivation and its effects on the chemical composition of the Si/Al_2O_3 is thus needed. In particular, the effect of ozone-based Al_2O_3 processes on carbon contamination remains controversial. Carbon atoms are common impurities affecting the passivation quality of Al_2O_3 layers [5,7,8], and are considered harmful for surface passivation. Although ozone possesses a stronger oxidation potential than water, and has potentially beneficial effect on the reduction of impurity concentrations, as shown in previous studies [5,8-10], other studies have also reported relatively high carbon concentration in ozone-based ALD films [11,12]. Despite this possible drawback, ozone-based ALD Al_2O_3 shows promising surface passivation quality [6,13].

In addition to carbon, hydrogen impurities play an important role in the passivation quality. For instance, no passivation is usually provided by as-deposited films, which require a post-anneal treatment to sufficiently reduce the D_{it} values [3,14,15]. This has been explained by hydrogen atoms diffusion from the bulk of the aluminum oxide to the film interface during the anneal, thus providing defect passivation therein [2,15-17]. Similarly, a combined process that consists of the reaction between TMA and a mixture of ozone and water has shown a significant lifetime improvement compared to the pure ozone process [13]. The additional hydrogen content provided by the extra water pulse could thus account for the improved surface passivation, but no experimental evidence has been given so far.

Thus, we investigate here the effect of the ozone concentration on the Si/Al_2O_3 interface quality, and aim at a more thorough understanding of the mechanisms responsible for successful surface passivation. In the last part of the paper, we discuss the improvements obtained with the combined process relative to the pure ozone process.

2. EXPERIMENTAL DETAILS

The wafers used in this study were 4'' double-side polished Magnetic Czochralski p-type silicon of resistivity ~ 2.5 Ω·cm, (100)-oriented and (400 ± 10) µm-thick. Double-sided 20 nm -thick Al_2O_3 layers were deposited in a Beneq TFS 500 tool at a temperature of 200 °C after dipping the wafers in a 1 % HF solution for 60 s. Al_2O_3 was deposited using Trimethylaluminum (TMA) from Sigma-Aldrich with a purity of at least 98 %, which is a typical solar-grade precursor for ALD Al_2O_3. Two types of ALD processes were used in this study: the first one from pure ozone as oxygen source, and the second one from a combination of ozone and water during the same half-cycle, water being injected before the ozone pulse (referred to as the “combined process”). The ozone pulse time was optimized and a value of 7 s was chosen in order to reach ALD growth at each ozone concentration used in this study**.** The TMA pulse and purge times were 250 ms and 3 s, respectively, and the ozone purge time was 9 s in both ozone processes. Ozone was produced from O_2 (99.999%) with a Wedeco Ozomatic 4 (TFS 500) generator with a flow of 15 L/h. The ozone concentration was varied in both processes according to Table I. The ozone concentration can be described by the ozone molar ratio, which corresponds to the ratio between the ozone flow and the total gas flow in the travelling-wave deposition chamber. The gas flow during the oxidative precursor pulse consisted of nitrogen carrier gas, oxygen and ozone with nitrogen and oxygen flow rates of 0.4 L/min and 0.25 L/min in standard conditions, respectively.

An anneal in N_2 at 400 °C for 30 min followed the Al_2O_3 deposition, after which the samples were fired in N_2 at 800 °C for 3 s in a rapid thermal annealing (RTA) furnace.

The purpose of the firing anneal is to reproduce the firing step used in industrial production for the screen printed metal contacts, in order to study the stability of passivation quality under high temperature.

The film thickness was measured by a Plasmos SD2300 Ellipsometer at a wavelength of 632.8 nm. The interface charge and defect densities were measured by Semilab SDI PV2000 using the COCOS (Corona oxide characterization of semiconductors) contactless measurement method [18]. In addition, MOS capacitors were fabricated by evaporating aluminum contacts of 100 µm diameter on top of the oxide. They were used in contact-CV measurements to obtain the interface characteristics of the as-deposited samples**,** i.e. of the samples before heat treatments. The minority carrier lifetimes were measured by QSSPC (Quasi-Steady State Photoconductance) with Sinton WCT-120 equipment and the values were taken at an injection level of $5 \cdot 10^{15}$ cm^{-3}. The elemental concentrations were quantified by the time-of-flight elastic recoil detection analysis (ToF-ERDA) tool in the University of Jyväskylä [19] using a 13.6 MeV $^{63}Cu^{7+}$ ion beam. The Al_2O_3 films measured by ToF-ERDA were 100 nm-thick in order to study more accurately the elemental composition at the interface between silicon and aluminium oxide, and were annealed and fired at the temperatures mentioned above before the measurements.

	Ozone concentrations	
Concentration range	low	high
Output O_3 concentration (g/Norm.m^3)	48	162
O_3 dose (g/h)	0.72	2.4
O_3 mole ratio in the reactor* (%)	0.85	2.8

* O_3 mole/(O_3+O_2+N_2)mole x 100

Table 1. Description of the two ozone concentrations in terms of dose and of proportion in the ALD reactor. The concentration of the ozone flow issued by the generator is given in gram per normal cubic meter (g/Norm.m^3), meaning that the concentration is given at a temperature of 0 °C and at a pressure of 1013 hPa.

3. RESULTS

3.1. Passivation quality

In agreement with previous results [6,13], the ozone ALD Al_2O_3 process results in better passivation than the pure water process (Figure 1). The passivation quality was further improved by increasing the ozone concentration both in the case of pure ozone and the combined process. In the latter in particular, increasing the concentration by a factor of 4 improved the post-anneal lifetimes by 33 %, which corresponds to a maximum surface recombination velocity of 7.1 cm/s. In comparison, maximum surface recombination velocities of approximately 2000 cm/s were measured in the as-deposited samples. In comparison, maximum surface recombination velocities over 10 cm/s are usually measured in low resistivity p-type CZ silicon passivated by annealed or fired Al_2O_3, while somewhat lower values are reported with Float-Zone substrates [1,2,4,15,17].

In addition, all ozone-based samples exhibit an improved thermal stability compared to the reference water-based sample. The impact of the firing step was the smallest in the samples deposited using the combined process, where no significant increase of the surface recombination velocity was observed after high temperature treatment.

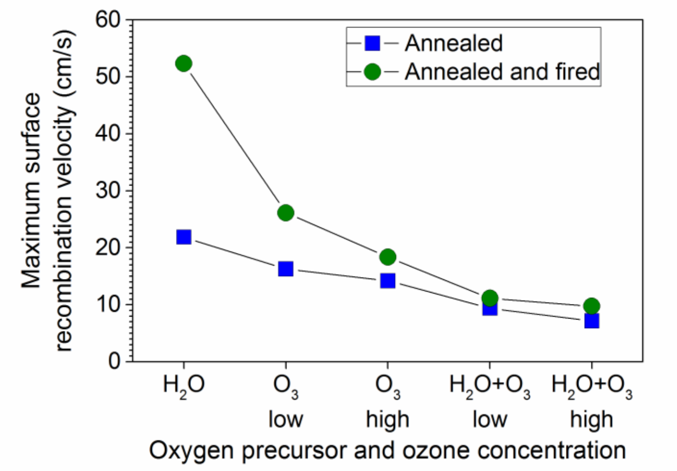

Figure 1: Maximum surface recombination velocities at an injection level of $5\cdot10^{15}$ cm^{-3} as a function of ALD ozone concentration with two different processes: i) ozone ii) water + ozone. The substrates were passivated by 20 nm of Al_2O_3. The terms “low” and “high” refer to ozone concentrations of 48 g/m^3 and 162 g/m^3, respectively (see Table 1). The term “annealed” refers to a post-anneal at 400 °C for 30 min and the term “fired” to a firing anneal at 800 °C for 3 s. The lines are guides to the eye.

3.2. *Electrical properties of the Si/Al_2O_3 interface*

The as-deposited state in Al_2O_3 grown from TMA and water is typically characterized by a low interface charge density and a rather low interface defect density, which are not adequate for efficient passivation. As-deposited films grown by the ozone process do not provide surface passivation either, but on the contrary, they have been reported to provide a high effective charge and a high defect density [6,20]. In our samples, similar results were obtained as a high negative charge over $6\cdot10^{12}$ cm^{-2} was measured in all ozone-based as-deposited samples, regardless of the ozone concentration and of the addition of a water pulse. The poor passivation quality of these samples is explained by high D_{it} of $(7 \pm 2)\cdot10^{12}$ eV^{-1}cm^{-2} .

The interface defect density was greatly improved after annealing and firing, as observed in the Figure 2, which presents the D_{it} variation as a function of the surface band bending for each sample. This improvement after heat treatments explains the low surface recombination velocities obtained in Figure 1. Note that only the midgap defect densities will be considered here, since they are the most decisive for recombination processes. An uncertainty of 25 % is typically found for the midgap D_{it} values [21].

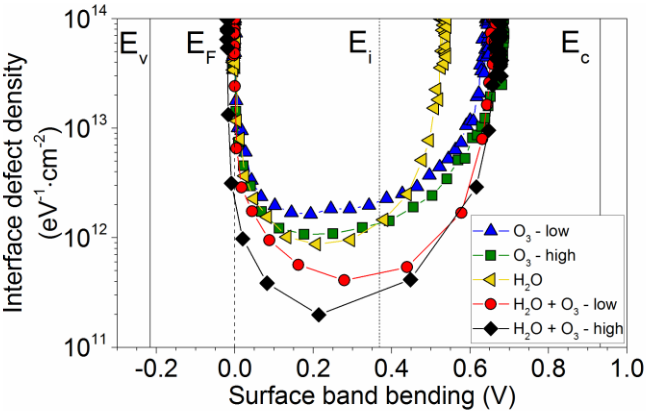

Figure 2: Repartition of the interface defect density over the bandgap for different ozone concentrations after annealing at 400 °C and firing at 800 °C of the 20 nm-thick Al_2O_3 films. The term “low” refers to an ozone concentration of 48 g/m^3 and “high” refers to an ozone concentration of 162 g/m^3.

Moreover, the ozone concentration increase correlates with a D_{it} reduction. The lowest D_{it} value of $(2.0 \pm 0.5)\cdot10^{11}$ eV^{-1}cm^{-2} is obtained for the highest ozone molar ratio of 2.8, and corresponds to a surface recombination velocity of 10 cm/s after firing. Remarkably, the lowest D_{it} values were systematically obtained with the combined process, which is in agreement with the low recombination velocities measured.

Additionally, the fixed oxide charge remains high in all samples regardless of the O_3 concentration, so that Al_2O_3 still provides adequate field-effect passivation. However, an increase of ozone concentration seems to cause a reduction of the oxide fixed charge, as shown in Figure 3, and the charge can be further reduced by the injection of water during the ozone process. This effect may be related to a thickness variation of the interfacial oxide (SiO_x) between silicon and aluminum oxide that grows during the first cycles of ALD [3,17,22-24]. Recent studies have indeed shown that an increase of the SiO_x interlayer thickness causes a reduction of the negative charge in $Si/SiO_x/Al_2O_3$ stacks, due to the positive bulk charge density in SiO_x and to the low probability of charge tunneling from silicon to Al_2O_3 through thick silicon oxide [25,26]. We thus suspect that higher ozone concentrations and water injection increase the thickness of the SiO_x interlayer.

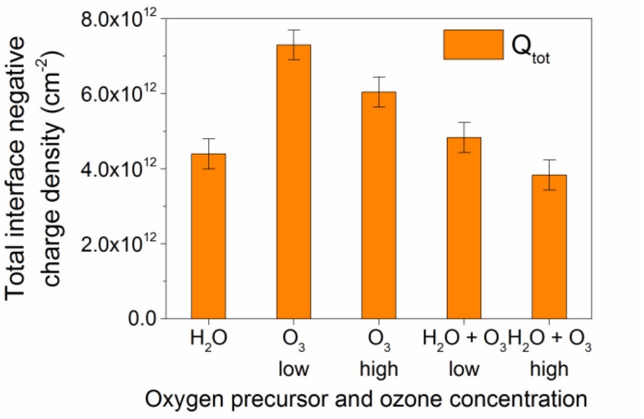

Figure 3: Total negative interface charge density Q_{tot} measured on 20 nm-thick Al_2O_3 films by COCOS after annealing at 400 °C and firing at 800 °C. The term “low” refers to an ozone concentration of 48 g/m^3 and “high” refers to an ozone concentration of 162 g/m^3.

Additionally, it appears that the D_{it} of the pure ozone samples exceeds that of the water reference sample. This drawback is compensated by the significantly larger charge present in the ozone-based Al_2O_3 layers, which explains the lower surface recombination velocities shown in Figure 1.

3.3. Elemental analysis

Elemental characterization of the Al_2O_3 films can reveal further information regarding the origin of the defects at the interface between the film and silicon. As stated in the introduction, carbon impurities constitute typical Al_2O_3 defects that are detrimental for silicon surface passivation, while hydrogen passivates silicon dangling bonds. Those elements are thus investigated in the following section. Note that the absolute values of the measured elemental concentrations may vary depending on the quality of the TMA used.

A reliable characterization of the Si/Al_2O_3 interface by ToF-ERDA requires thicker films; hence 100 nm-thick films were prepared for the study. Despite the difference of Al_2O_3 thickness, those samples exhibit the same trends as the 20 nm-thick Al_2O_3 samples in terms of lifetimes and electrical interface characteristics. The ERDA profiles are presented in Figure 4. The carbon profiles present a surface peak due to contamination from the ambient, which however does not affect the bulk nor the interface concentrations.

As mentioned in the introduction, the effect of hydrogen is the most decisive at the Si/Al_2O_3 interface, where it passivates the silicon surface defects. For this reason, this part focuses specifically on the hydrogen densities at the Si/Al_2O_3 interface and not in the bulk.

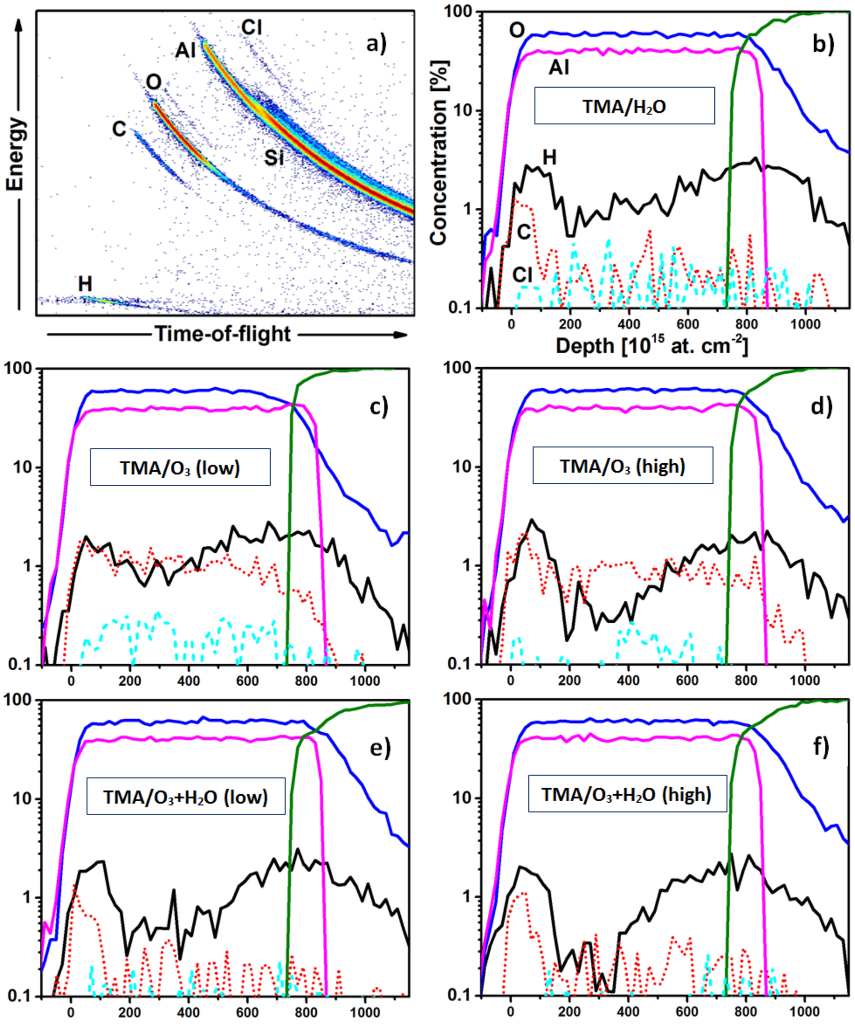

Figure 4: Typical raw TOF-energy histogram of an Al_2O_3 film (a) and concentration depth profiles of the five films grown with different oxygen sources (b, c, d, e, f). The Al_2O_3 layers had a thickness of 100 nm and were annealed at 400 °C for 30 min and fired at 800 °C for 3 s.

Figure 5 presents the average carbon concentrations in the 100 nm aluminum oxide layers as well as the interface hydrogen concentrations. The values of carbon concentration in Figure 5a are consistent with the values usually reported in the literature for TMA-based Al_2O_3 deposited at 200 °C with either water or ozone, in the order of magnitude of 1 at.% [23,27,28]. According to our results, the values measured in the pure ozone samples exceed notably the carbon concentration measured in the water-based reference sample – (0.20 ± 0.05) at. %. The carbon atomic percentage in the pure ozone samples was not clearly affected by the ozone concentration, with values of 1.1 at.% and 0.9 at.% at low and high ozone concentration, respectively. It should however be noted that the difference in the ozone concentrations studied here might be insufficient to significantly affect the carbon content in the layers. Moreover, extremely low carbon concentrations of approximately 0.2 at % were achieved with the combined process, most probably due to the addition of water. The same densities were indeed already obtained with the pure water process, and as a result, the ozone concentration showed no effect on the carbon densities due to their low initial level. In summary, the relatively low carbon concentrations measured in all samples correlate well with the low D_{it} values obtained. The lower carbon content in the combined process can partly explain the lower D_{it} [29], and thus the lifetime improvement compared to the samples deposited using ozone as sole oxygen source.

The hydrogen interface concentrations in the five samples are shown in Figure 5b. Ozone appears to reduce the hydrogen concentration at the interface of both pure ozone and combined samples in comparison to the reference water sample. In addition, it seems that the interfacial hydrogen density is slightly higher in the combined process. The hydrogen reduction in the ozone-based samples could consequently be related to the ozone reaction mechanism, while the combined process may provide extra hydrogen from water molecules. Interestingly, the addition of water to the ozone process does not allow hydrogen recovery to the level observed in the pure water process. The higher reactivity of ozone could lead to a more efficient removal of the adsorbed hydroxyl groups, thus preventing excessive hydrogen inclusion.

Surprisingly, it appears that better lifetimes correlate with lower interfacial hydrogen levels, although high hydrogen levels are traditionally associated with effective surface passivation. In fact, Tsetseris et al. have shown by first principles calculations that hydrogen may be detrimental for passivation after high temperature treatments, because it can dissociate Si-Si bonds, thus creating more defects in the form of Si-H bonds [30]. Consequently, high hydrogen levels combined with high temperature treatments, such as firing at 800 °C, could impair the passivation quality – the inserted hydrogen atoms contributing to the final hydrogen content without participating to the passivation. By lowering the hydrogen content in the aluminum oxide, ozone could thus prevent the formation of such defects after high temperature treatments. The high hydrogen concentration measured in the water sample also sustains this hypothesis, since the corresponding D_{it} is higher than in the combined samples despite similar carbon concentrations.

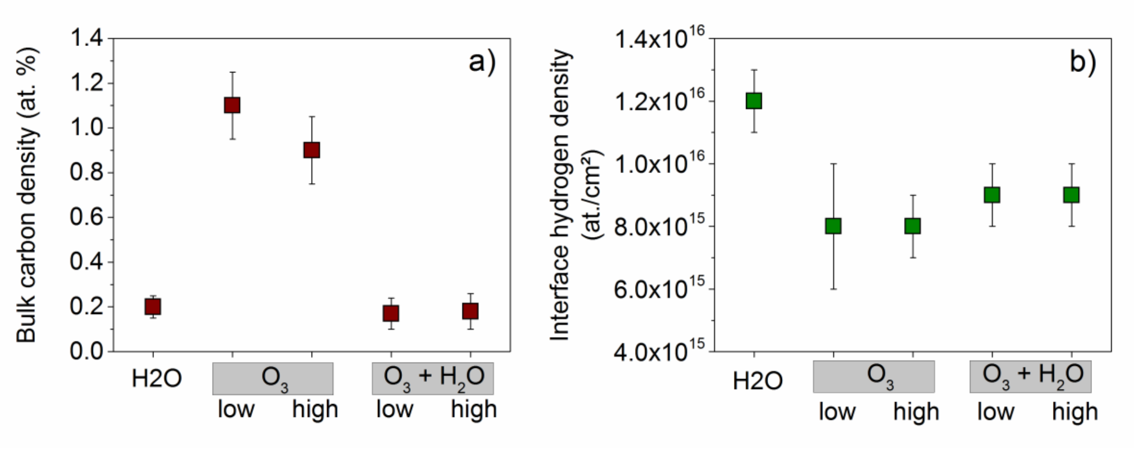

Figure 5: a) Carbon concentrations in the bulk of a 100 nm-thick aluminum oxide layer and b) hydrogen concentrations at the Si/Al_2O_3 interface in the five types of studied. The terms "low" and "high" refer to ozone concentrations of 48 g/m^3 and 162 g/m^3, respectively.

4. CONCLUSIONS

We have studied the effect of the ozone concentration on the ALD Al_2O_3 passivation quality. An increase of ozone concentration causes a clear reduction of defect density at the interface between Al_2O_3 and silicon, which correlates well with the minority carrier lifetime improvement. The negative charge present in Al_2O_3 also seems to be affected by an increasing ozone concentration. We have shown that ozone is beneficial to the passivation, but a too low ozone concentration might be detrimental for the quality of the interface, and could lead in particular to a higher carbon density in comparison to the pure water process. We suggest that the D_{it} can be improved using higher ozone concentration and adding water to the ozone process, which seems to be related to a reduction of both carbon and hydrogen in the ALD film. Our results imply that too high hydrogen concentrations can be detrimental after high temperature treatment. Using a process combining water and ozone, a maximum surface recombination velocity of 10 cm/s was obtained after high-temperature firing, owing to excellent interface characteristics.

To conclude, we have suggested a simple way to modify the interface properties of $Si/SiO_x/Al_2O_3$ stacks, such as interface charge density and interface defect density, by varying the ozone concentration and by injecting water during the ozone process.

ACKNOWLEDGMENTS

This work was funded by Beneq Oy, Okmetic Oyj, Aalto University, Tekes and the Academy of Finland. This research was undertaken at the Micronova Nanofabrication Centre, supported by Aalto University. The authors would like to thank Dr. Alexander Perros for assistance with ALD and the Fraunhofer Institute for Solar Energy Systems for the COCOS measurements.

References

[1] G. Agostinelli, A. Delabie, P. Vitanov, Z. Alexieva, H.F.W. Dekkers, S. De Wolf, G. Beaucarne, Very low surface recombination velocities on p-type silicon wafers passivated with a dielectric with fixed negative charge, Sol. Energ. Mat. Sol. Cells. 90 (2006) 3438-3443. doi:10.1016/j.solmat.2006.04.014.

[2] G. Dingemans, P. Engelhart, R. Seguin, F. Einsele, B. Hoex, M.C.M.v.d. Sanden, W.M.M. Kessels, Stability of Al2O3 and Al2O3/a-SiNx:H stacks for surface passivation of crystalline silicon, J. Appl. Phys. 106 (2009) 114907. doi:10.1063/1.3264572.

[3] B. Hoex, J.J.H. Gielis, M.C.M. van de Sanden, W.M.M. Kessels, On the c-Si surface passivation mechanism by the negative-charge-dielectric Al2O3, J. Appl. Phys. 104 (2008) 113703. doi:10.1063/1.3021091.

[4] P. Repo, H. Talvitie, S. Li, J. Skarp, H. Savin, Silicon Surface Passivation by Al2O3: Effect of ALD Reactants, Energy Procedia. 8 (2011) 681. doi:10.1016/j.egypro.2011.06.201".

[5] J.B. Kim, D.R. Kwon, K. Chakrabarti, C. Lee, K.Y. Oh, J.H. Lee, Improvement in Al2O3 dielectric behavior by using ozone as an oxidant for the atomic layer deposition technique, J. Appl. Phys. 92 (2002) 6739-6742. doi:10.1063/1.1515951.

[6] Z. Xia, J. Dong, X. Li, C. Ren, R. Sidhu, W. Song, L. Tao, Z. Yangj, B. Zhang, G. Xing, Comparison between passivation properties of thermal ald Al2O3 deposited with TMA+ O3 and TMA+ H2O, 38th IEEE Photovoltaic Specialists Conference (PVSC). (2012) 001163-001165.

[7] V.R. Rai, V. Vandalon, S. Agarwal, Influence of Surface Temperature on the Mechanism of Atomic Layer Deposition of Aluminum Oxide Using an Oxygen Plasma and Ozone, Langmuir. 28 (2012) 350-357. doi:10.1021/la201136k.

[8] S. Jakschik, U. Schroeder, T. Hecht, D. Krueger, G. Dollinger, A. Bergmaier, C. Luhmann, J.W. Bartha, Physical characterization of thin ALD-Al2O3 films, Appl. Surf. Sci. 211 (2003) 352. doi:http://dx.doi.org/10.1016/S0169-4332(03)00264-2".

[9] S.K. Kim, C.S. Hwang, Atomic-layer-deposited Al2O3 thin films with thin SiO2 layers grown by in situO3 oxidation, J. Appl. Phys. 96 (2004) 2323-2329. doi:http://dx.doi.org/10.1063/1.1769090.

[10] Sang-In Lee, J.S. Owyang, Y. Senzaki, A. Helms Jr., K. Kapkin, ALD Hf-based oxides, Solid State Technol. 46 (2003) 45.

[11] V. Miikkulainen, O. Nilsen, H. Li, S.W. King, M. Laitinen, T. Sajavaara, H. Fjellvåg, Atomic layer deposited lithium aluminum oxide: (In)dependency of film properties from pulsing sequence, Journal of Vacuum Science & Technology A. 33 (2015). doi:http://dx.doi.org/10.1116/1.4890006.

[12] S.K. Kim, S.W. Lee, C.S. Hwang, Y. Min, J.Y. Won, J. Jeong, Low Temperature (<100 °C) Deposition of Aluminum Oxide Thin Films by ALD with O3 as Oxidant, J. Electrochem. Soc. 153 (2006) F69-F76. doi:10.1149/1.2177047.

[13] G. von Gastrow, S. Li, P. Repo, Y. Bao, M. Putkonen, H. Savin, Ozone-based Batch Atomic Layer Deposited Al2O3 for Effective Surface Passivation, Energy Procedia. 38 (2013) 890-894. doi:http://dx.doi.org/10.1016/j.egypro.2013.07.361.

[14] G. Dingemans, P. Engelhart, R. Seguin, B. Hoex, M.C.M. Van de Sanden, W.M.M. Kessels, Firing stability of atomic layer deposited Al2O3 for c-Si surface passivation, Photovoltaic Specialists Conference (PVSC), 2009 34th IEEE. (2009) 000705-000708. doi:10.1109/PVSC.2009.5411187.

[15] G. Dingemans, M.C.M. van de Sanden, W.M.M. Kessels, Influence of the Deposition Temperature on the c-Si Surface Passivation by Al2O3 Films Synthesized by ALD and PECVD, Electrochem. Solid State Lett. 13 (2010) H76-H79. doi:10.1149/1.3276040.

[16] G. Dingemans, W. Beyer, M.C.M. van de Sanden, W.M.M. Kessels, Hydrogen induced passivation of Si interfaces by Al2O3 films and SiO2/Al2O3 stacks, Appl. Phys. Lett. 97 (2010). doi:http://dx.doi.org/10.1063/1.3497014.

[17] B. Hoex, S.B.S. Heil, E. Langereis, M.C.M. van de Sanden, W.M.M. Kessels, Ultralow surface recombination of c-Si substrates passivated by plasma-assisted atomic layer deposited Al2O3, Appl. Phys. Lett. 89 (2006). doi:http://dx.doi.org/10.1063/1.2240736.

[18] D.K. Schroder, Contactless surface charge semiconductor characterization, Materials Science and Engineering: B. 91–92 (2002) 196-210. doi:http://dx.doi.org/10.1016/S0921-5107(01)00993-X.

[19] M. Laitinen, M. Rossi, J. Julin, T. Sajavaara, Time-of-flight – Energy spectrometer for elemental depth profiling – Jyväskylä design, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 337 (2014) 55-61. doi:http://dx.doi.org/10.1016/j.nimb.2014.07.001.

[20] G. Dingemans, N.M. Terlinden, D. Pierreux, H.B. Profijt, M.C.M. van de Sanden, W.M.M. Kessels, Influence of the Oxidant on the Chemical and Field-Effect Passivation of Si by ALD Al2O3, Electrochemical and Solid-State Letters. 14 (2011) H1-H4. doi:10.1149/1.3501970.

[21] D. Schuldis, A. Richter, J. Benick, P. Saint-Cast, M. Hermle, S.W. Glunz, Properties of the c-Si/Al2O3 interface of ultrathin atomic layer deposited Al2O3 layers capped by SiNx for c-Si surface passivation, Appl. Phys. Lett. 105 (2014). doi:http://dx.doi.org/10.1063/1.4903483.

[22] S. Ha, E. Choi, S. Kim, J. Sung Roh, Influence of oxidant source on the property of atomic layer deposited Al2O3 on hydrogen-terminated Si substrate, Thin Solid Films. 476 (2005) 252-257. doi:http://dx.doi.org/10.1016/j.tsf.2004.09.035.

[23] H. Lee, T. Tachibana, N. Ikeno, H. Hashiguchi, K. Arafune, H. Yoshida, S. Satoh, T. Chikyow, A. Ogura, Interface engineering for the passivation of c-Si with O3-based atomic layer deposited AlOx for solar cell application, Appl. Phys. Lett. 100 (2012) 143901. doi:10.1063/1.3701280.

[24] G. Dingemans, W.M.M. Kessels, Status and prospects of Al2O3-based surface passivation schemes for silicon solar cells, Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films. 30 (2012) 040802. doi:10.1116/1.4728205.

[25] G. Dingemans, N.M. Terlinden, M.A. Verheijen, M.C.M.v.d. Sanden, W.M.M. Kessels, Controlling the fixed charge and passivation properties of Si(100)/Al2O3 interfaces using ultrathin SiO2 interlayers synthesized by atomic layer deposition, J. Appl. Phys. 110 (2011) 093715. doi:10.1063/1.3658246.

[26] N.M. Terlinden, G. Dingemans, V. Vandalon, R.H.E.C. Bosch, W.M.M. Kessels, Influence of the SiO2 interlayer thickness on the density and polarity of charges in Si/SiO2/Al2O3 stacks as studied by optical second-harmonic generation, J. Appl. Phys. 115 (2014). doi:http://dx.doi.org/10.1063/1.4857075.

[27] J. Kim, K. Chakrabarti, J. Lee, K. Oh, C. Lee, Effects of ozone as an oxygen source on the properties of the Al2O3 thin films prepared by atomic layer deposition, Mater. Chem. Phys. 78 (2003) 733. doi:http://dx.doi.org/10.1016/S0254-0584(02)00375-9".

[28] L.G. Gosset, J.-. Damlencourt, O. Renault, D. Rouchon, P. Holliger, A. Ermolieff, I. Trimaille, J.-. Ganem, F. Martin, M.-. Séméria, Interface and material characterization of thin Al2O3 layers deposited by ALD using TMA/H2O, J. Non Cryst. Solids. 303 (2002) 17. doi:http://dx.doi.org/10.1016/S0022-3093(02)00958-4".

[29] S.Y. No, D. Eom, C.S. Hwang, H.J. Kim, Property Changes of Aluminum Oxide Thin Films Deposited by Atomic Layer Deposition under Photon Radiation, Journal of The Electrochemical Society. 153 (2006) F87-F93. doi:10.1149/1.2186179.

[30] L. Tsetseris, S.T. Pantelides, Migration, incorporation, and passivation reactions of molecular hydrogen at the Si-SiO2 interface, Phys.Rev.B. 70 (2004) 245320. doi:10.1103/PhysRevB.70.245320.