Materials Science Forum
ISSN: 1662-9752, Vol. 1193, pp 55-61
doi:10.4028/p-np1tSH
© 2026 The Author(s). Published by Trans Tech Publications Ltd, Switzerland.
Submitted: 2025-09-12
Revised: 2026-01-28
Accepted: 2026-02-26
Online: 2026-05-21

Impact of Ambient Conditions on Oxide Thickness Distribution on 4H-SiC in Thermal Oxidation Furnace

Tamara Fidler[1,a*] and Patrick Schmid[1,b]

[1]Centrotherm International AG, Württemberger Str. 31, 89143 Blaubeuren, Germany

[a*]tamara.fidler@centrotherm.de, [b]patrick.schmid@centrotherm.de

*corresponding author

Keywords: high temperature SiC oxidation, oxide thickness distribution, vertical oxidation furnace, cover wafer effect.

Abstract. 4H-SiC wafers were processed in thermal oxidation furnace and impact of oxidation temperature up to 1500 °C, processing pressure and different gaseous ambient on oxide thickness distribution was investigated. Beside the impact of thermal distribution within oxidation furnace, an additional effect on oxide thickness distribution has been observed, due to promotion of oxidation rate in the center of the wafer. Within this work, we have examined which influence processing parameters have on described effect, specific for SiC oxidation.

Introduction

Vertical furnaces are essential tools for implant anneal as well as thermal oxidation processes in high-performance mass production SiC device manufacturing lines. The thermal distribution in these tools is thoroughly studied by different temperature measuring methods and simulations and specified by manufacturer [1]. Likewise, due to vital role of thermal oxidation and oxide quality in SiC device production, thermal oxidation kinetics and mechanism have been a topic of numerous experimental and theoretical studies [2-4]. However, until now there is no comprehensive study of impact of different ambient and cover wafer conditions on oxide thickness distribution on SiC substrate in thermal oxidation production furnaces.

The design of the furnace for thermal oxidation is the determining factor for oxide thickness distribution. Specifically, the thermal distribution is defined by furnace configuration (the number, dimensions and location of heaters and insulation parts) and its temperature measurement and control system. Also supply and ventilation systems that have impact on ambient distributions inside the process chamber are of importance. The oxidation furnaces used in this work are state-of-the-art production tools. The temperature measurement and control are executed by pyrometers, which are profiled with thermocouple up to the highest oxidation temperature of 1500 °C. The power monitoring ensures processing stability over long time periods. There are different possibilities how temperature distribution inside of a furnace can be determined. Apart from pyrometrical measurements on the surface of the chamber and measurements with thermocouples inside of the processing chamber, one of the conventional methods to determine the thermal distribution of oxidation furnace can be measurement of oxide uniformity on the processed wafer. With known temperature sensitivity, oxide thickness distribution can be converted to temperature distribution. Within this study, another influence on oxide thickness has been observed for thermal SiC oxidation process in conjunction with covered or stacked wafers, which neither matches the thermal distribution pattern nor can it be explained by the consumption or depletion of oxygen and expectations based on published SiC oxidation mechanism [2-4]. Furthermore, influence of different ambient parameters on observed center accentuated distribution has been investigated.

This article is an open access article under the terms and conditions of the Creative Commons Attribution (CC BY) license
(https://creativecommons.org/licenses/by/4.0)

Experimental

Oxides were grown on n-type 150mm or 200 mm SiC wafers with Si-face front surface and C-face rear surface orientation, with 4° miscut angle, using centrotherm's vertical production furnace c.OXIDATOR^{150} or c.OXIDATOR^{200}. After tube evacuation, a process pressure in a range between 100 to 890 mbar is set with defined gas flow of diluted oxidation gas mixture. In this study oxygen, nitrogen monoxide or carbon dioxide were used as oxidation agents. Nitrogen or argon were used for dilution. The wafers were heated to target oxidation temperature. In described experiments temperature range from 1150 °C – 1500 °C was investigated. The ramp rate to target temperature was 10 K/min. At targeted temperature, gas flow was set to tested pure gas or mixture and temperature was maintained for a defined time. Oxidation time was chosen to reach desired oxide thickness in a range up to 60 nm. At the end of the oxidation step, the heating was turned off and the tube was evacuated and refilled with nitrogen. Afterwards wafers were cooled down to 350 °C in free fall cooling.

The oxide thickness on Si wafers was determined with laser ellipsometry measurements on a Plasmos SD4000 laser ellipsometer at wavelength of 633 nm. The oxide thickness on SiC wafers was determined with spectral ellipsometry measurements on a Sentech SE800 spectral ellipsometer in a wavelength range of 280 – 370 nm. The angel of incidence was 70°. A two-layer structure was assumed as the analysis model, consisting of SiC/SiO_2.

Results and Discussion

According to the thermal distribution of the furnace, wafer loading position inside of furnace will impact the oxide distribution. During the ramp, steady state and cooldown, the thermal distribution inside of the furnace will change. How much the change of thermal distribution in furnace during one processing run will impact the final oxide thickness distribution, depends on oxide growth rate in each of these stages. For observation of oxide thickness distribution across the wafer and easier comparison which influence various parameters have on the distribution, we have chosen center-to-edge oxide thickness ratio (C/E), described in Eq. 1.

$$\frac{C}{E} = \frac{\mathrm{SiO_2\ thickness\ wafer\ center}}{\mathrm{SiO_2\ thickness\ wafer\ edge}}. \quad (1)$$

By observing C/E ratio, we can easily distinguish if we have center-accentuated e.g. hill distribution (C/E > 1) or edge-accentuated e.g. bowl oxide distribution (C/E < 1) on the wafer.

In figure 1. silicon and silicon carbide oxide distributions processed in different positions inside of the process are presented as illustrated by center-to-edge (C/E) oxide thickness ratios. The tested oxidation condition in this example is 1350 °C processing temperature, in pure oxygen atmosphere with 18 minutes steady state time is identical for silicon and silicon carbide wafers. The oxidation rates of silicon and C-face SiC is faster than the oxidation rate of Si-face SiC. This processing condition grows approximately 50 nm oxide on Si-face SiC e.g. 170 nm on Si or 110 nm on C-face SiC, due to different oxidation rates of these substrates.

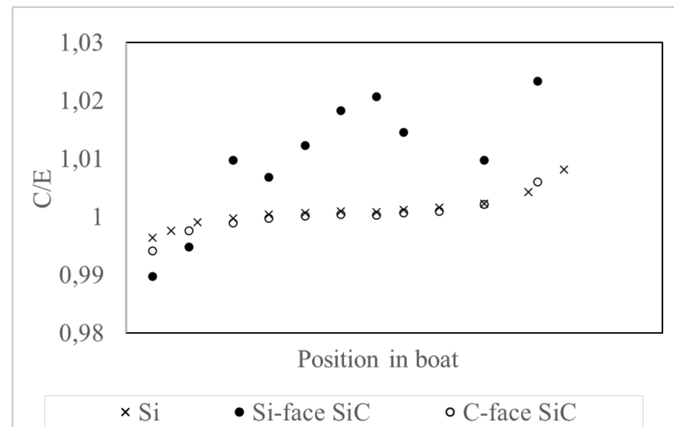

Fig. 1. Ratio of oxide thickness in the center vs. edge of the wafer (C/E) for Si and 4H-SiC substrates.

On silicon wafer, oxide distribution is mostly flat (C/E close to 1), with slight bowl distribution at bottom positions of the boat and slight hill distribution in upper boat positions. C/E ratio of oxide on C-face follows the same trend and is mainly influenced by thermal distribution inside of the chamber. C/E ratio of oxide grown on Si-face is significantly different to C/E ratio from other two substrates. There is an obvious additional impact that promotes oxide growth in the center of the wafer more than on the edge, which is not in direct correlation with temperature distribution across the wafer nor within the expected ambient distribution in the chamber. We would like to point out that the oxide thickness measurements from Si-face and C-face oxide layers are determined on the same wafer and therefore confirm that temperature distribution is not origin of center-accentuated oxide distribution on Si-face SiC. The gas inlet and outlet are located at the opposite side of the process chamber, and liner tube directs the flow from the bottom towards top of the chamber, with main flow path between liner wall and wafers. Consequently, the gas exchange between wafers is mainly driven by the diffusion and relatively low. Limited ambient exchange could lead to depletion of oxidant species in the center area between wafers. This would result in lower thickness in the middle of the wafer and therefore C/R ratio below 1, because oxidation rate scales with the square root of the oxygen partial pressure [5]. Also, it would be expected that accumulation of carbon monoxide as byproduct of SiC oxidation, would also further dilute the oxygen ambient leading to lower oxidation rate in the wafer center, which is clearly not the case here.

Further evidence that the observed oxide thickness pattern on Si-face is not temperature distribution related is depicted in figure 2, showing the impact of distance between processed wafers in the chamber and the covering wafer material type.

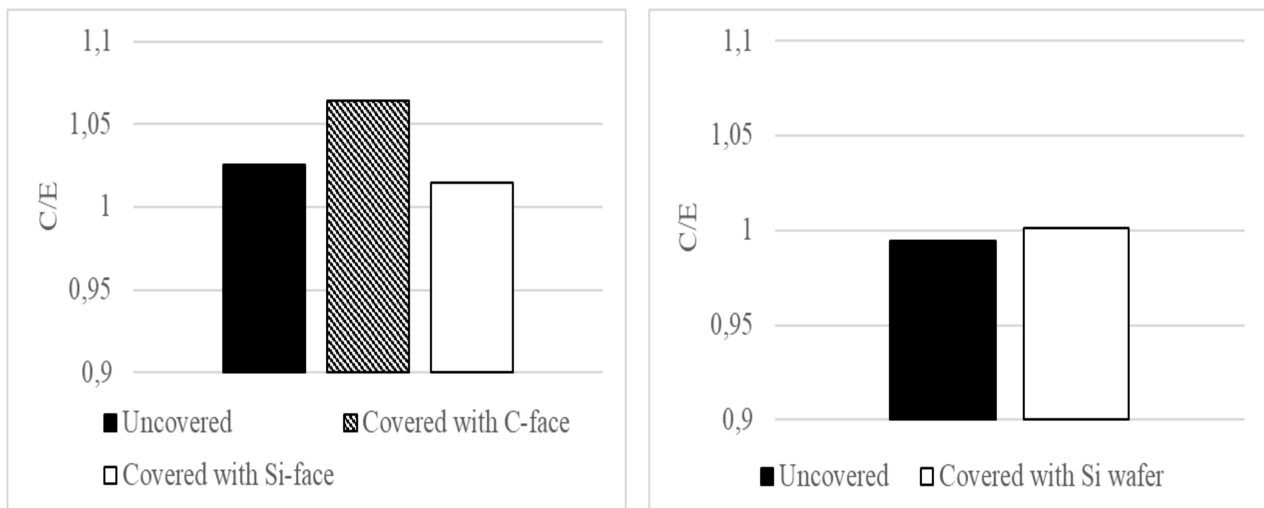

Fig. 2. C/E ratio for 4H-SiC substrates with different wafer coverage.

In conventional production, the wafers are processed in vertical furnace with Si-face pointing up. In this case each Si-face is pointing towards C-face of 4H-SiC wafer. For test in figure 2. (left) two runs were executed with 18 minutes steady state at 1350 °C oxidation temperature. In first run two wafers were placed in the same area of the processing chamber face-to-back and in the second run face-to-face so that Si-face is turned towards Si-face of the adjacent wafer. C/E ratio of the uncovered wafer is additionally shown for comparison. Since the wafers in both runs were processed in a same way with the same number of wafers, loaded in the same boat positions and therefore with thermal mass remaining equal in both runs, the thermal distribution across the wafer is in these two runs is identical and flow pattern of incoming pure oxygen gas is matching as well. Unexpectedly, the thickness in the center is significantly higher, if the processed SiC wafer is covered with C-face, with respect to covering of processed wafer with Si-face SiC. Since there is a clear relation to occurrence of the elevated oxidation rate and covering of the wafer, we can postulate that the observed cover wafer effect is most probably ambient related. In another test, shown in Fig. 2 (right) same processing condition was performed but Si-face of SiC wafer was placed below silicon wafer, which still had slight influence on the oxide thickness in the center of the wafer. Uncovered wafer situation is a reference value for each example, depending on thermal distribution in respective loading position in the processing chamber e.g. boat slot and therefore different in (left) and (right) example.

In the next experiment, shown in figure 3, very big influence of oxidation temperature on cover wafer effect can be observed. Remarkably, if we compare C/R ratio of Si-face 4H-SiC substrate processed at 1150 °C to substrate processed at 1350 °C in pure oxygen, the cover wafer effect is substantially bigger at lower temperature. The experiment with diluted oxygen mixture in figure 3. (right) demonstrates same temperature behavior. Oxidation times for experiments is figure 3. were chosen to grow approx. 50 nm oxide on Si-face of 4H-SiC, therefore oxidation time at lower temperature was longer.

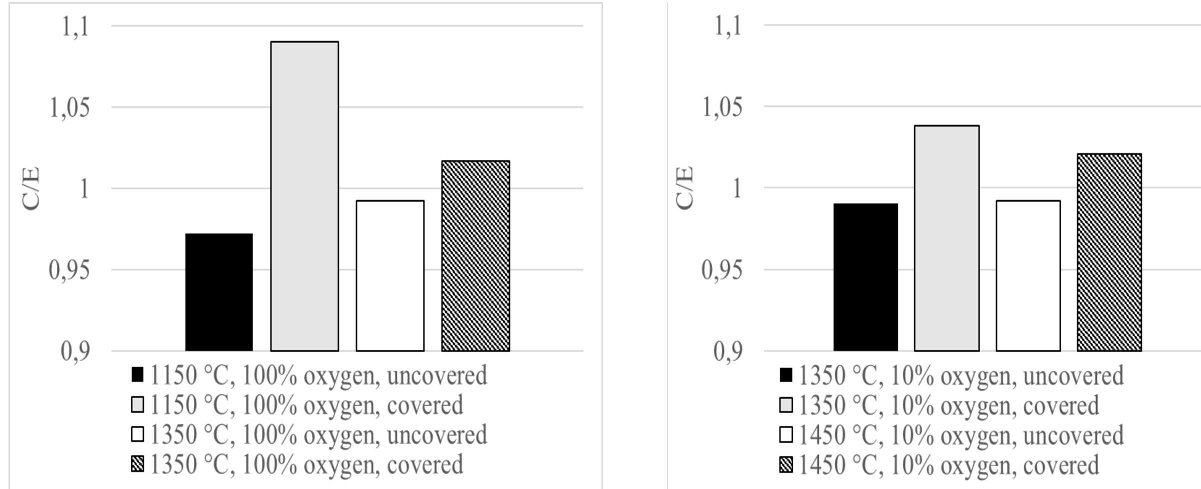

Fig. 3. C/E for Si-face 4H-SiC substrates covered with C-face 4H-SiC or uncovered at different temperatures for pure (left) and diluted oxygen (right).

It must be considered that oxide is partially grown during ramp-up period and with higher oxidation temperature more oxide grows during ramp-up. During ramp-up the wafer edge in a stack of wafers is expected to be colder at the edge of the wafer. Also, in this case we can use uncovered wafer situation as a reference value, which relates better to thermal distribution of different processes to distinguish thermal from ambient related effects, to conclude that effect on higher oxidation rate in the wafer center is clearly higher at lower temperature but not due to thermal distribution.

The strong dependency of elevated oxidation rates in the middle of the wafer to temperature as well as strong effect from covering of wafer with C-face lead to assumption that might be explained by the higher amount of generated oxidation byproducts, due to much higher oxidation rate of C-face in relation to Si-face at 1150 °C [5, 6], are causing observed effect. It's unclear if presence of CO_x

byproduct of C-face SiC oxidation is catalyzing SiC oxidation on Si-face of neighboring wafer or if elevated oxidation rates are caused by improved diffusion of oxidant through oxide. In both cases, concentration of oxidation byproducts is center accentuated under tested pressure and flow conditions and contributes to observed center to edge thickness distribution.

Change of the oxide thickness across the wafer length is exemplary illustrated for 1200 °C oxidation temperature for covered and uncovered sample in figure 4. As has been explained above, at 1200 °C covering effect is more pronounced, hence it is convenient for observation of oxidation time and thickness influence on spatial distribution. Oxide thickness distribution across the uncovered wafer (full symbols) is similar for different wafer thicknesses and is mainly impacted by temperature distribution during steady state at 1200 °C and placement in the central position of the boat. On the contrary, oxide distribution across the covered wafer (empty symbols) is center accentuated and is getting more pronounced with higher thickness.

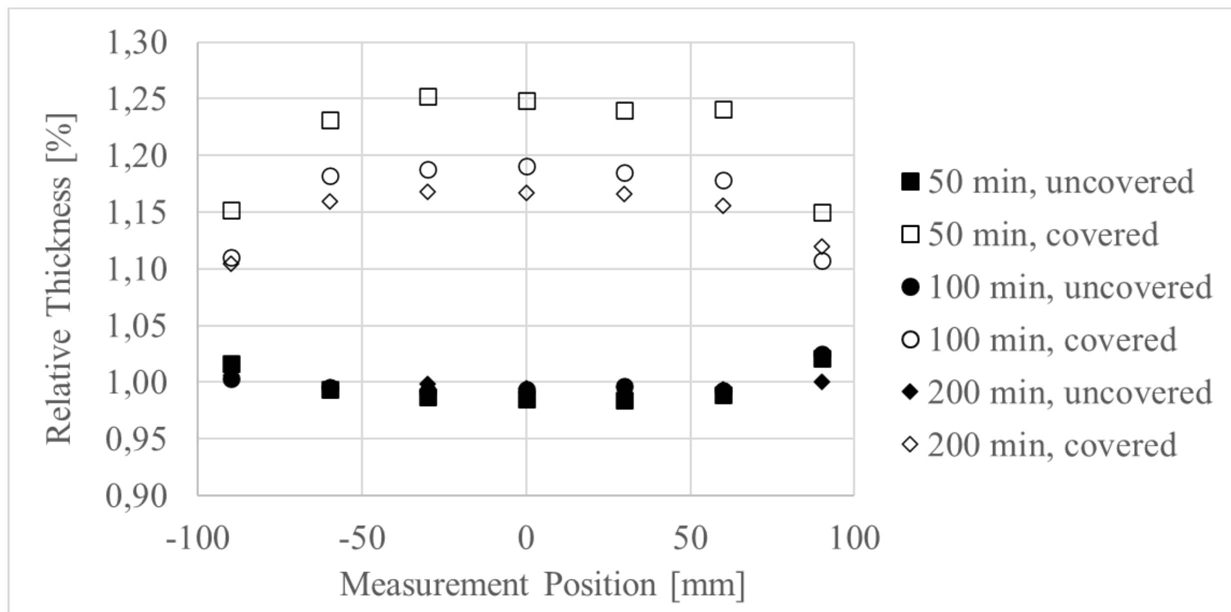

Fig. 4. Spatial oxide thickness distribution across the covered (empty symbols) vs. uncovered wafer (full symbols) for different oxidation times of Si-face 4H-SiC oxidation at 1200 °C in pure oxygen illustrated as oxide thickness at measured position on the wafer relative to mean oxide thickness of covered wafer.

The oxide thickness growth of uncovered Si-face wafers as well as covered and uncovered C-face 4H-SiC at 1200 °C fits well with the model for SiC oxidation based on Deal-Grove model with Massoud's empirical corrections for thin oxides, implemented in the process simulator Sentaurus Process [5], as shown in figure 5. Oxidation rate of covered Si-face 4H-SiC wafers is higher than values predicted by the model in examined thickness range.

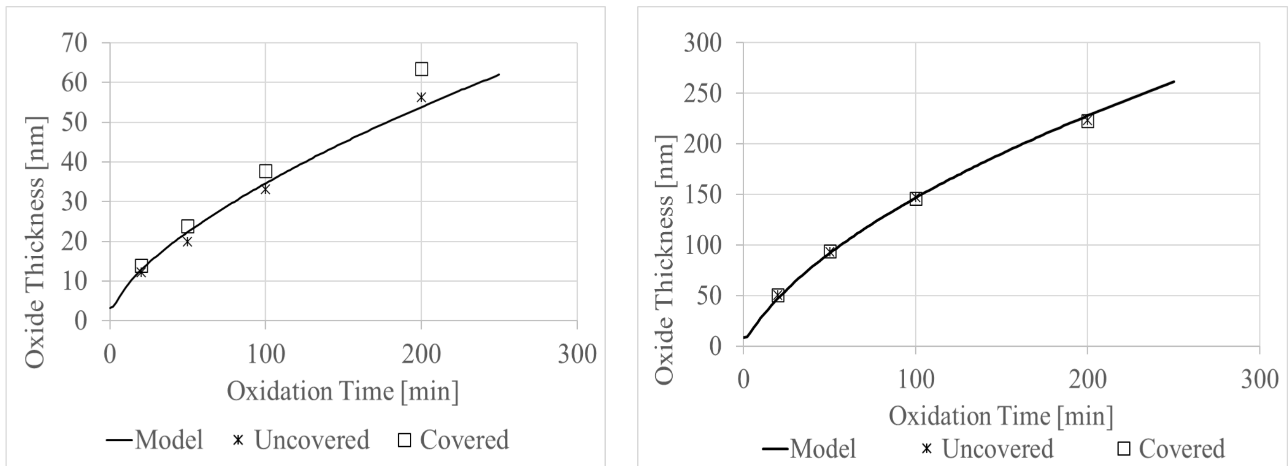

Fig. 5. Oxide thickness as a function of time for Si-face (left) and C-face (right) 4H-SiC oxidation at 1200 °C in pure oxygen. Experimental data for covered and uncovered substrates, indicated by symbols, are compared to data obtained by SiC oxidation process model published by Zechner et al. [5], indicated by full line.

Furthermore, we have investigated influence of different gaseous ambient, on described enhanced growth in the center of the wafer, as demonstrated in figure 6. On the left side we see example of oxide distribution in different ambientes for thin oxides around 5 nm, which are thinner in the middle of the wafer and example for growing 50 nm thick oxide in carbon dioxide on the right side. With change of ambient due to altered oxidation mechanism [7, 8] and absence of species essential for oxidation rate enhancement, we have influenced the growth in the middle of the wafer.

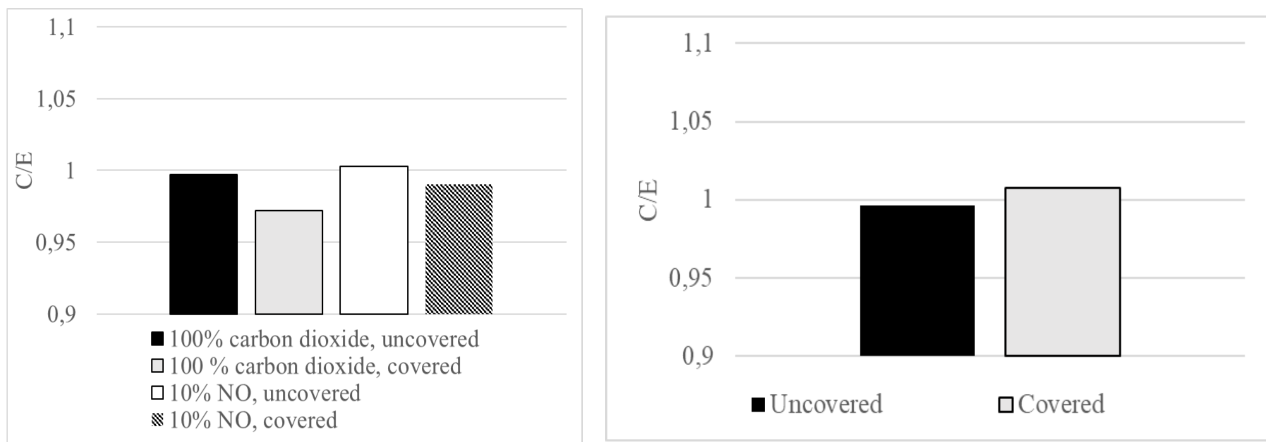

Fig. 6. C/E ratio comparison for covered and uncovered wafers processed in different gaseous ambient at 1400 °C for oxide thickness around 5 nm (left). C/E ratio comparison for wafer covered and uncovered wafers processed in pure carbon dioxide at 1450 °C for oxide thickness around 50 nm (right).

Since changing oxidation parameters (temperature, pressure, oxidant species or concentration) may impact quality of oxide and increasing space between wafers would impact the throughput of the tool, another approach is recommended to improve oxide uniformity in SiC oxidation process. Diminishing CO_x byproduct concentration with preventing or reducing oxidation rate on C-face by protective layer is a viable approach in a case when higher oxidation temperature or ambient change are not possible. Deposition of silicon nitride, silicon dioxide or poly silicon can be considered as possible options.

Summary

In conclusion, we have presented empirical oxide thickness data for crucial ambient parameters that have to be considered for optimization of oxide uniformity of thermal oxidation furnace for SiC substrates. We have reported unexpected, elevated oxidation rates, which are in contradiction with low oxidant concentration between wafers expected for described flow pattern in the furnace. Based on observed temperature dependence and wafer coverage dependence we have proposed explanation for observed behavior as well as preventing measures against it.

References

[1] P. Schmid, ECSCRM 2020-2021, Industrial Session: c.ACTIVATOR^{200} & c.OXIDATOR^{200} (2021).

[2] V. Šimonka, A. Hössinger, J. Weinbub, S. Selberherr, J. Appl. Phys. 120 (2016) 135705.

[3] D. Goto, Y. Hijikata, J. Phys. D: Appl. Phys. 49 (2016) 225103.

[4] N. S. Jacobson, D. L. Myers, Oxid. Met. 75 (2011) 1.

[5] C. Zechner, A. Johnsson, T. Fidler, P. Schmid, Phys. Status Solidi A 217 (2024) 2400234.

[6] D. Goto, Y. Hijikata, S. Yagi, H. Yaguchi, J. Appl. Phys. 117 (2015) 095306.

[7] R. Deguchi, T. Hosoi, ICSCRM 2023, Thermal oxidation of 4H-SiC(0001) surface in a pure CO_2 ambient (2023).

[8] S. A. Corrêa, C. Radtke, G. V. Soares, L. Miotti, I. J. R. Baumvol, S. Dimitrije, J. Han, L. Hold, F. Kong, F. C. Stedile, Appl. Phys. Lett. 94 (2009) 251909.