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Surface Science 552 (2004) 251-259



www.elsevier.com/locate/susc

A comparative photoemission study of polar and nonpolar SiC surfaces oxidized in N₂O

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Received 24 November 2003; accepted for publication 16 January 2004

Abstract

Photoemission studies of oxidized SiC samples grown ex situ in N₂O, at a temperature of 900 °C, on the (0001), (000 $\overline{1}$), (11 $\overline{2}$ 0) and (10 $\overline{1}$ 0) surfaces are reported. Angle resolved data from the Si 1s and Si 2p core levels and the Si KL_{2,3}L_{2,3} Auger transitions are analyzed and compared to data from a sample grown in O₂ on the (0001) surface. The results show oxide growth and no oxy-nitride formation. The growth rate is found to be smallest for the Si-terminated (0001) surface and highest for the nonpolar (10 $\overline{1}$ 0) surface. The presence of two oxidation states, Si⁺⁴ and a suboxide, are required to explain and model recorded Si 1s, Si 2p and Si KLL spectra. The SiO₂ shift is found to be smaller on the (0001) surface than on the other three surfaces, which is attributed to an oxide thickness dependence of the shift.

A layer attenuation model describes satisfactorily the intensity variations observed in the core level components versus electron emission angle when assuming the suboxide at the interface. Estimates made of the thickness of the oxide layers show that the oxidation rate for the $(0\ 0\ 0\ 1)$ surfaces is about half of that for the $(1\ 0\ 1\ 0)$ surface and that the oxidation rate for the $(1\ 0\ 1\ 0)$ surfaces are similar but somewhat smaller than for the $(1\ 0\ 1\ 0)$ surface. The amount of suboxide is found to be smaller on the nonpolar than on the polar surfaces. © 2004 Elsevier B.V. All rights reserved.

Keywords: Silicon carbide; Nitrogen oxides; Oxygen; Oxidation; Angle resolved photoemission

1. Introduction

Since the interface defect density is high for SiO_2/SiC samples grown by standard wet and dry oxidation methods [1] various ways to reduce the defect density have been proposed in both experimental and theoretical work [2–7]. Post-annealing

or growth in different nitrogen containing gases have for example been claimed [2–7] to improve the quality of the interface due to formation of silicon oxy-nitrides. The reason for the high defect density at the SiO₂/SiC interface is still not understood, however. It has been suggested to be due to carbon clusters, or carbon containing byproducts (such as Si₄C₂O₂), at the interface [8–10]. For the Si-terminated (0001) surface we have, however, shown that no carbon clusters, or carbon containing by-products, can be detected by photoemission from SiO₂/SiC samples grown ex situ or in situ [11–14]. The presence of one suboxide

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 (Si^{+1}) , besides the fully developed SiO₂ oxide, was found to be unavoidable on these samples and was therefore instead proposed to be a major reason for the high defect density. Exposures of NO (and NH₃) on the Si-terminated (0001) surface, at a substrate temperature of 800 °C, were found [15] to result in the formation of silicon oxy-nitrides (and Si₃N₄). For the C-terminated $(000\overline{1})$ surface and also for the nonpolar $(10\overline{1}0)$ and $(11\overline{2}0)$ surfaces, on the other hand, the presence of carbon clusters, or carbon containing by-products, at the interface could be detected [13,16] on SiO₂/SiC samples grown in situ in O_2 . Since in that study the maximum oxygen partial pressure during the oxidation was limited to $\leq 10^{-3}$ Torr, it was suggested that a higher oxygen partial pressure probably could be more effective in reducing the interface carbon. For these three surfaces an additional oxidation state (tentatively assigned as Si⁺²) was also revealed [12,16] during initial oxidation.

For the purpose to study the effects of a higher oxygen partial pressure and a nitrogen containing gas, oxide layers were thermally grown ex situ in a N_2O ambient (about 1 atm) via a dry oxidation process at 900 °C on the four different surfaces in the same run. This also allowed a more detailed comparison of the effects induced on the polar and nonpolar surfaces. For reference, one (0001) sample was oxidized in O₂ under the same conditions. Photoemission studies of these samples using a photon energy of 3.0 keV are reported below. Angle resolved photoemission data from the Si 1s and Si 2p core levels and the Si KL_{2,3}L_{2,3} Auger transitions were recorded and analyzed. The data show only oxide formation on all samples, no presence of oxy-nitride formation at the interface of the samples grown in N₂O was observed. This is attributed to the temperature of 900 °C used during the growth which apparently is too low for oxy-nitride formation in N₂O although it is known to be sufficient [15] for oxy-nitride (and nitride) formation in NO (and NH₃). The Si 1s, 2p and KLL spectra reveal differences in the oxide growth rate for the different surfaces and also small differences concerning the amount of suboxide at the interface. For the polar (0001) surface a comparison of the oxides formed after growth in N_2O and O_2 , respectively, is also made. These results are presented and discussed below.

2. Experimental

The X-ray wiggler beamline BW2 [17] and the tunable high-energy X-ray photoemission spectrometer (THE-XPS) [18] at HASYLAB were used to perform the angle resolved photoemission studies. This beamline delivers a focused high flux X-ray beam in the keV range monochromatized by a nondispersive Si(111) double crystal monochromator. The end station comprises a hemispherical electron analyzer (Scienta SES-200) with an angular acceptance of about $\pm 6^{\circ}$ and oriented at 45° relative to the incoming beam. A photon energy of 3.0 keV was typically selected with an overall energy resolution of ≤ 0.5 eV for the chosen beamline and analyzer settings. The photon incidence and electron exit angles were varied by rotating the sample relative to the fixed analyzer.

The SiC samples used were n-type 4H crystals. The nonpolar $(11\overline{2}0)$ and $(10\overline{1}0)$ crystals were on-axis samples while the polar (0001) and $(000\overline{1})$ crystals were 8° off cut samples. Oxide layers were thermally grown in a furnace via a dry oxidation process at 900 °C for 6 min. Flowing N₂O gas at a pressure of about 1 atm was utilized and four samples, one of each orientation, were oxidized in the same run. For reference purposes one (0001) sample was oxidized in pure O₂ under the same conditions. These oxide growth parameters were chosen to obtain oxide layers with a total thickness less than \sim 35 A to allows the presence of suboxides near the interface to be detected with good sensitivity. Due to safety regulations N₂O had to be used as the nitrogen containing gas instead of NO as in an earlier reported in situ oxidation study [15].

Angle resolved photoemission measurements were carried out on the load-locked samples at room temperature and at a base pressure of about 2×10^{-10} Torr. An Au foil mounted on the sample holder provided a reference level for the binding energy scale. The core level binding energies obtained from a sample where the oxide layer was

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thermally desorbed in situ were found to agree well with earlier reported values [15]. For the oxidized samples the bulk SiC peaks were aligned to these values since it is the relative binding energies, i.e. the chemical shifts, and intensity ratios of the different oxide related components that are of primary interest. The electron emission angle is measured relative to the surface normal while the photon incidence angle is specified relative to the surface.

3. Results and discussion

Si 1s and 2p core level spectra and Si $KL_{2,3}L_{2,3}$ Auger transitions recorded using a photon energy of 3.0 keV are shown in Fig. 1a–c. The bottom spectrum in each panel (labeled 1) is from a clean SiC(0001) surface, obtained after desorbing the oxide layer from a sample previously oxidized in O₂. The second spectrum (labeled 2) is from the (0001) sample oxidized in O₂. The spectra labeled



Fig. 1. (a) Si 1s (b) Si 2p and (c) Si $KL_{2,3}L_{2,3}$ spectra recorded using a photon energy of 3.0 keV from a clean SiC(0001) surface (#1) and from the oxidized polar and nonpolar SiC surfaces (#2–6). The electron emission angle is 45° in (a) and 70° in (b) and (c).

from 3 to 6 are respectively from the (0001), $(000\bar{1})$, $(11\bar{2}0)$ and $(10\bar{1}0)$ sample oxidized in N₂O under identical conditions (in the same preparation run). The contributions from the SiC bulk (B) and shifted SiO₂ peaks (final state multiplet components for Si KLL) are indicated in the figures and the SiC bulk peak is normalized to a constant peak height in each of the panels. The Si 1s spectra shown in Fig. 1a from the oxidized samples were recorded at an electron emission angle of 45° while the corresponding Si 2p and Si KLL spectra (Fig. 1b and c) were recorded at an emission angle of 70°.

Upon inspection of the spectra from the oxidized samples a few things can immediately be noticed. The relative strength of the SiO₂ contribution increases quite considerably from the (0001) surface to the $(10\overline{1}0)$ surface (i.e. from spectrum 2 to 6). This indicates that a considerably thicker SiO₂ layer is formed on the $(10\overline{1}0)$ than on the (0001) surface. For the (0001) surface oxidized in O_2 and N_2O_2 , respectively, the relative strength is very similar (spectrum 2 and 3). This indicates that the oxidation rate in O₂ and N₂O is comparable for the (0001) surface. The SiO₂ chemical shift is larger in the Si 1s level than in the Si 2p level and largest in the Si KLL Auger transitions, which agrees with earlier observations [14]. Moreover, the SiO₂ chemical shift appears to be very similar for the (0001) surface oxidized in O_2 and N_2O , while it is larger for the (0001)and the nonpolar surfaces. This is not interpreted as a different SiO₂ chemistry for these three surfaces compared to the (0001) surface. Instead we attribute this variation to a thickness dependence of the SiO₂ shift, earlier revealed for the (0001) surface [14] and for Si surfaces [19], as further discussed below. Before quantifying these observations, we first discuss the information provided by the C 1s, O 1s and N 1s core level spectra.

No N 1s signal could be detected from any of the oxidized samples. This clearly showed that the selected oxidation temperature of 900 °C was too low to efficiently dissociate N_2O to initiate formation of oxy-nitrides. This was unexpected since for NO and NH₃ formation of oxy-nitrides and nitrides, respectively, is known to occur even at a lower temperature [15]. Post-annealing in a nitrogen containing ambient has been found [1–3] to improve the quality of the SiO₂/SiC interface. However, if N₂O is to be used for such postannealing a higher temperature is required since the present experiment does not reveal any nitrogen incorporation or oxy-nitride formation. O 1s spectra recorded from the oxidized samples and at various electron emission angles were found to be identical. The C 1s spectra measured close to normal emission from the oxidized samples were practically identical, showing only a bulk SiC component (see bottom spectrum in Fig. 2). Differences were observed in more surface sensitive spectra, i.e. at large electron emission angles and also at near glancing incidence of the photon beam. This is illustrated in Fig. 2 by the spectra collected at an emission angle of 70° from the four different surfaces oxidized in N_2O . For the (0001) and $(11\overline{2}0)$ but not for the (0001) and $(10\overline{1}0)$ surfaces a very weak graphite like C 1s component is discernable at $\sim 2 \text{ eV}$ larger binding energy than the SiC bulk peak. Such a component was not observed on the (0001) surface after large oxygen exposures with the substrate at an elevated temperature, as reported earlier [11-14]. Therefore, it



Fig. 2. C 1s spectra recorded using a photon energy of 3.0 keV from four samples oxidized in N_2O . The bottom spectrum was recorded at normal emission from the (0001) sample while the other were recorded at an emission angle of 70°.

is not surprising that it is absent on the (0001)surface after oxidation in N₂O. Its absence also on the $(10\overline{1}0)$ surface, however, is encouraging since for SiO₂/SiC samples grown in situ in O₂, carbon clusters or carbon containing by-products, at the interface have been detected [14,16] for the nonpolar $(10\overline{1}0)$, $(11\overline{2}0)$ and the C-terminated $(000\overline{1})$ surfaces. It was argued that the interfacial carbon was not totally eliminated on these surfaces [16] because the maximum oxygen partial pressure used in the in situ oxidation studies was $\leq 10^{-3}$ Torr. The higher partial pressure of N₂O and O₂ utilized in the present study is clearly more effective in reducing the interface carbon in SiO₂/ SiC. Concerning the weak contribution from graphite like carbon on the $(000\overline{1})$ and $(11\overline{2}0)$ surfaces in the present case it cannot be ruled out that it originates from adsorbed hydrocarbons since the samples were stored in air for several days between growth and measurement. It seems, however, unlikely that hydrocarbon contamination should be observable only on two of the samples since they were all handled and treated the same way. This weak graphite like C 1s signal might therefore originate from carbon clusters or carbon containing by-products at the interface.

The number of different oxidation states present on SiC(0001) surfaces oxidized in O_2 has caused some controversy. The latest results [13,14] show the presence of only one suboxide, Si⁺¹, besides Si^{+4} (SiO₂) for both ex situ and in situ oxidized samples. If SiC(0001) surfaces are prepared in situ by Si deposition and annealing, resulting in a 3×3 reconstructed surface, additional oxidation states have been identified [10,20,21] upon initial oxidation. The 3×3 reconstructed surface is Si rich and is terminated by at least three top layers of Si. The presence of the additional oxidation states has been revealed [11,20,21] for O₂ exposures not large enough to completely oxidize these top Si layers. For the ex situ oxidized (0001) surface in the present study, the presence of only Si⁺⁴ and Si⁺¹ oxidation states are expected. This is confirmed by the detailed analysis of the spectra applying a peak fit procedure, see below. For the nonpolar $(11\overline{2}0)$ and $(10\overline{1}0)$ surfaces, one additional oxidation state, tentatively assigned as Si⁺², was earlier revealed [16] in initial oxidation studies. For the Cterminated $(000\overline{1})$ surface this Si⁺² oxidation state was the only suboxide observed after initial oxidation [13]. Its presence was suggested related to



Fig. 3. (a) Si 1s and (b) Si $KL_{2,3}L_{2,3}$ difference spectra obtained from data collected at emission angles of 70° and 0° for the different oxidized samples (#2–6). The uppermost curve shows the Si 1s (Si KLL) spectrum from sample 6 at an emission angle of 70°. The SiO₂ peak (main SiO₂ KLL multiplet component) has been aligned and normalized to the same peak height for all samples, i.e only relative energies and intensities for each sample are displayed.

remaining carbon containing by-products at the interface. The C 1s spectra (Fig. 2) show that the high partial pressure of N₂O utilized in the present study was clearly more effective in reducing the interface carbon than the lower partial pressure of O₂ used in earlier in situ oxidation studies [13,16]. Only for the C-terminated (0001) and the nonpolar (1120) surfaces was a very weak C 1s signal detected which might be associated with remaining carbon containing by-products at the interface, as discussed above. It is therefore uncertain if the additional (Si⁺²) oxidation state also exists on these ex situ oxidized (0001) and nonpolar surfaces.

Difference spectra, obtained from data collected at an emission angle of 70° and normal emission, are shown in Fig. 3a and b for Si 1s and Si KLL, respectively. For comparison the Si 1s and KLL spectra collected from the oxidized $(10\overline{1}0)$ sample (#6) at an emission angle of 70° are also shown. For the Si-terminated (0001) surface oxidized in O_2 (sample #2) only Si⁺⁴ (SiO₂) and Si^{+1} oxidation states are expected [13,14]. In the Si 1s (Si KLL) difference spectrum from this sample the presence of only one additional component is observable on the low binding (high kinetic) energy side of the SiO_2 peak. Note that the KLL difference spectrum also contains several strong multiplet components, indicated by arrows. It should be pointed out that the SiO₂ peak has been aligned in this figure and normalized to the same peak height for all samples so only relative energies and intensities for each sample are displayed. The difference spectra for sample 3 are very similar to those of sample 2, indicating the presence of only one suboxide also for the (0001)sample oxidized in NO2. For the C-terminated and the nonpolar surfaces, samples 4-6, the additional structures in the difference spectra, besides SiO₂, are considerably weaker and give no indication for the presence of an additional suboxide. Their relative intensity is smaller because the SiO₂ layer is thicker on these surfaces than on the Si-terminated (0001), as noted in Fig. 1. A suboxide component is expected to have a width not very different from that of the dominant SiO₂ peak. Therefore the shapes of the difference spectra indicate that only one suboxide component is required to model the spectra for all oxidized samples. Difference spectra obtained for the Si 2p level yield the same conclusion, although the results are not as clear because the relative Si 2p chemical shifts are smaller.

A peak fit procedure [22] was applied to model the spectra and extract the intensities of the oxide components. The line shape parameters for the bulk SiC peak were determined from the clean SiC sample, and for the SiO₂ peak from the three samples having the thickest oxides, samples 4–6. Therefore only the number of additional suboxide



Fig. 4. (a) Si 1s and (b) Si 2p spectra collected at three different emission angles from the oxidized $(10\overline{1}0)$ sample (#6). Included in the figure are the fitted results. For the normal emission spectra (bottom curve) the fit results are also shown, indicating two oxide related shifted components.

Sample		Oxide shift (eV)						Oxide thickness (Å)		
		Si 2p		Si 1s		Si KLL				
		+4	+1	+4	+1	+4	+1	d_4	d_1	$d_{\rm tot}$
2	$(0001) + O_2$	2.21	0.5	2.77	0.6	-5.20	-0.8	9.5	2.4	11.9
3	$(0001) + N_2O$	2.19	0.5	2.74	0.6	-5.19	-0.7	10.0	2.5	12.5
4	$(000\bar{1}) + N_2O$	2.35	0.5	2.87	0.7	-5.30	-0.7	16.0	2.6	18.6
5	$(11\bar{2}0) + N_2O$	2.61	0.6	3.13	1.1	-5.56	-1.1	17.5	1.9	19.4
6	$(10\bar{1}0) + N_2O$	2.57	0.6	3.12	1.0	-5.60	-1.1	19.5	1.6	21.1

Table 1 The shift in Si core level binding energy, KLL kinetic energy and oxide thickness determined for the different samples

The uncertainty (spread) in the shift (average values) was ± 0.05 eV for the +4 component and ± 0.10 eV for the weaker +1 component.

components had to be varied in the fit procedure. For the Si-terminated (0001) surface one suboxide component produced the best fits in agreement with earlier findings [12–14]. For the oxidized Cterminated and nonpolar surfaces, attempts to utilize more than one suboxide component were unsuccessful (no numerical stability could be obtained). Therefore, also these spectra were modeled assuming one suboxide component which appeared reasonable in view of the difference spectra shown above. The additional suboxide component earlier revealed on these surfaces [13,16] after smaller oxygen exposures has been related to remaining carbon containing by-products at the interface. In the present case, only a very weak graphite like C 1s signal, possibly originating from carbon containing by-products. was observed at the interface of the oxidized $(000\overline{1})$ and $(11\overline{2}0)$ surfaces. It is therefore reasonable to assume only one suboxide component also for the carbon terminated and nonpolar surfaces.

Si 1s and 2p spectra measured at three different electron emission angles from the oxidized $(1 \ 0 \ \overline{1} \ 0)$ sample are shown in Fig. 4. Also shown in the figure are the fit results for the normal emission spectra. The curve through the data points shows the result of the fit, the individual components are shown by the curves underneath. The shifts of the oxide components are larger in the Si 1s than in the Si 2p spectrum, as expected [14]. The suboxide component, assigned as Si⁺¹, has a small relative intensity for this sample, which was noticed also in the difference spectra shown in Fig. 3. The same fit procedure was applied to all spectra using the same peak parameter values² and produced fits of the quality illustrated in Fig. 4. The binding energy shifts determined (average values) for the oxide components for the different samples are summarized in Table 1, where also the kinetic energy shifts obtained from the Si KLL spectra are included. The SiO₂ chemical shift is smallest in the Si 2p level, somewhat larger in the Si 1s level and largest in the Si KLL Auger transitions, in agreement with earlier findings [14]. For the (0001) surface oxidized in O₂ and N₂O, respectively (sample 2 and 3), the SiO_2 chemical shift is very similar but becomes gradually larger for the $(000\overline{1})$ and the nonpolar surfaces. The latter is attributed to the earlier reported [14,19] oxide thickness dependence of the SiO₂ shift.

An estimate of the oxide thickness can be obtained by evaluating the oxide to bulk peak areas as a function of electron emission angle using a simple attenuation model. The area ratios, obtained for sample 6, are plotted versus electron emission angle in Fig. 5. The SiC bulk peak is denoted B and the SiO₂ and suboxide peaks +4 and +1, respectively. The peak area ratios shown in Fig. 5 are SiO₂/SiC (filled circles), suboxide/SiC

² The parameters chosen for the Si 1s level were a Lorentzian width of 0.45 and an asymmetry parameter value of zero. Gaussian widths of about 1.35, 1.05 and 0.75 eV were found to produce best fits to the Si⁺⁴, Si⁺¹ and B components, respectively. The parameters used for the Si 2p levels were a spin orbit splitting of 0.61 eV, a branching ratio of 0.50, a Lorentzian width of 0.07 and an asymmetry parameter value of zero. Gaussian widths of about 1.35, 0.85 and 0.75 eV were found to produce best fits to the Si⁺⁴, Si⁺¹ and B components, respectively.



Fig. 5. Peak area ratios SiO₂/SiC (filled circles), suboxide/SiC (open circles) and SiO₂/suboxide (filled squares) obtained versus electron emission angle from (a) Si 1s and (b) Si 2p spectra from sample 6. The solid curves show the results predicted by the layer attenuation model for SiO₂ and suboxide layer thicknesses of 19.5 and 1.6 Å. See text for further details.

(open circles) and SiO₂/suboxide (filled squares). The values are scaled with the factors indicated in the figure. Assuming a SiO₂ layer with a thickness of d_4 on top of a Si₂O suboxide layer with a thickness of d_1 , the layer attenuation model predicts the following ratios:

$$I(+4/\text{Bulk}) = \frac{c_{\text{SiO}_2}}{c_{\text{SiC}}} e^{\frac{d_1}{\lambda\cos\theta}} (e^{\frac{d_4}{\lambda\cos\theta}} - 1)$$

$$I(+1/\text{Bulk}) = \frac{c_{\text{Si}_2\text{O}}}{c_{\text{SiC}}} (e^{\frac{d_1}{\lambda\cos\theta}} - 1)$$

where λ is the electron attenuation length and θ the electron emission angle. Values of $c_{\text{SiO}_2} = 1/3$, $c_{\text{SiC}} = 1/2$ and $c_{\text{Si}_2\text{O}} = 2/3$ (the suboxide) were assumed to approximate the atomic concentration ratios. Using an electron attenuation length λ [23] of 23 and 50 Å for Si 1s and Si 2p, respectively, the ratios shown by the solid curves are obtained for oxide layer thickness values of $d_4 = 19.5$ Å and $d_1 = 1.6$ Å. This model for the chemical composition describes reasonably well the relative intensity variations observed versus emission angle and shows that the suboxide is located at the interface. This modeling was performed for all samples and the oxide thickness values obtained are summarized in Table 1.

Concerning the thickness values one should be aware of the approximations made and sources of error [14,24]. However, despite the simplicity of the model and the approximations that introduce additional uncertainty, the obtained difference in oxide thickness can be expected to reflect the variation in oxidation rate between the different samples. Samples 3–6 were oxidized in N_2O under identical conditions while sample 2 was oxidized in O_2 in a separate run, but at the same pressure and for the same time. The total thickness values, see Table 1, show that the oxidation rate is considerably lower for the Si-terminated (0001) surface than for the other surfaces. The oxidation rate is higher for the $(10\overline{1}0)$ surface than for the $(11\overline{2}0)$ and C-terminated $(000\overline{1})$ surfaces. For the latter two it is very similar. The total oxide thickness obtained for the Si-terminated (0001) surface oxidized in N₂O and O_2 (samples 3 and 2) is very similar indicating a comparable oxidation rate for these two gases. The thickness of the suboxide is around 2.5 Å for the polar surfaces while it is less than 2 Å for the nonpolar surfaces. While the suboxide is present on all surfaces, it forms a thinner layer on the nonpolar surfaces. The same suboxide thickness is obtained on the (0001) surface after oxidation in N₂O and O_2 , respectively. For the $(10\overline{1}0)$ surface the suboxide thickness is significantly smaller although the thickness of the SiO_2 layer is about twice as large as on the (0001) surface. A recent theoretical work suggests [25] that the nonpolar surfaces, unlike the polar surface, can be completely passivated by a single SiO₂ layer. Our results show that a suboxide is formed after dry oxidation also on the nonpolar surfaces. The amount of suboxide is however smaller on the nonpolar surfaces than on the polar surfaces. This may be of importance for obtaining a lower defect density at the SiO₂/SiC interface.

4. Summary

The results of X-ray photoemission studies of oxidized SiC samples grown ex situ in N₂O on the $(0\ 0\ 0\ 1), (0\ 0\ 0\ 1), (1\ 1\ 2\ 0)$ and $(1\ 0\ 1\ 0)$ surfaces have been reported. Angle resolved data from the Si 1s and 2p core levels and the Si KL_{2,3}L_{2,3} Auger transitions were analyzed and compared to data from a sample grown in O₂ on the $(0\ 0\ 0\ 1)$ surface. The results showed oxide growth on all samples and no oxy-nitride formation. The presence of one suboxide, besides SiO₂, was required to explain and model the Si 1s, 2p and KLL spectra. The shift of the SiO₂ component was found to be smaller on the $(0\ 0\ 0\ 1)$ surface than on the other surfaces. This is attributed to the thickness dependence of the SiO₂ shift earlier observed on SiC and Si surfaces.

A layer attenuation model described satisfactorily the intensity variations observed in the core level components versus electron emission angle, assuming the suboxide at the interface. Estimates of the thickness of the oxide layers showed that the oxidation rate for the (0001) surfaces was about half of that for the (10 $\overline{1}$ 0) surface. For the (11 $\overline{2}$ 0) and (000 $\overline{1}$) surfaces it was similar but somewhat smaller than for the (10 $\overline{1}$ 0) surface.

Our results showed that a suboxide was formed after dry oxidation on all four surfaces. The amount of suboxide was however smaller on the nonpolar surfaces than on the polar surfaces. This may be of importance for obtaining a SiO_2/SiC interface with a low defect density.

Acknowledgements

Support from the Swedish Research Council is gratefully acknowledged. This work was sup-

ported by the European Commission, as project I-02-069.

References

- See H. Kobayashi, T. Sakurai, M. Takahashi, Phys. Rev. B 67 (2003) 115305, and references therein.
- [2] K. McDonald, M.B. Huang, R.A. Weller, L.C. Feldman, J.R. Williams, F.C. Stedile, I.J.R. Baumvol, C. Radtke, Appl. Phys. Lett. 76 (2000) 568.
- [3] G.Y. Chung, C.C. Tin, J.R. Williams, K. McDonald, M. DiVentra, S. Pantelides, L.C. Feldman, R.A. Weller, Appl. Phys. Lett. 76 (2000) 1713.
- [4] F. Amy, L. Douillard, V.Yu. Aristov, P. Soukiassian, J. Vac. Sci. Technol. A 17 (1999) 2629.
- [5] H.F. Li, S. Dimitrijev, D. Sweatman, H.B. Harrison, P. Tanner, B. Feil, J. Appl. Phys. 86 (1999) 4316.
- [6] P.T. Lai, S. Chakraborty, C.L. Chan, Y.C. Cheng, Appl. Phys. Lett. 76 (2000) 3744.
- [7] Y.D. Chung, J.W. Kim, C.N. Whang, H.W. Yeom, Phys. Rev. B. 65 (2002) 155310.
- [8] V.V. Afanasev, M. Bassler, G. Pensel, M. Schultz, Phys. Status Solidi A 162 (1997) 321.
- [9] K.C. Chang, N.T. Nuhfer, L.M. Porter, Q. Wahab, Appl. Phys. Lett. 77 (2000) 2186.
- [10] F. Amy, P. Soukiassian, Y.K. Hwu, C. Brylinski, Phys. Rev. B 65 (2002) 165323.
- [11] C. Virojanadara, P.-A. Glans, L.I. Johansson, Th. Eickhoff, W. Drube, Appl. Surf. Sci. 172 (2001) 253.
- [12] C. Virojanadara, L.I. Johansson, Surf. Sci. 472 (2001) L145.
- [13] C. Virojanadara, L.I. Johansson, Surf. Sci. 505 (2002) 358.
- [14] L.I. Johansson, C. Virojanadara, Th. Eickhoff, W. Drube, Surf. Sci. 529 (2003) 515.
- [15] C. Virojanadara, L.I. Johansson, Surf. Sci. 530 (2003) 17.
- [16] C. Virojanadara, L.I. Johansson, Phys. Rev. B 68 (2003) 125314.
- [17] W. Drube, H. Schulte-Schrepping, H.-G. Schmidt, R. Treusch, G. Materlik, Rev. Sci. Instrum. 66 (1995) 1668.
- [18] W. Drube, T.M. Grehk, R. Treusch, G. Materlik, J. Electron Spectrosc. Relat. Phenom. 88–89 (1998) 683.
- [19] S. Iwata, A. Ishizaka, J. Appl. Phys. 79 (1996) 6653, and references therein.
- [20] F. Amy, P. Soukiassian, Y.-K. Hwu, C. Brylinski, Appl. Phys. Lett. 75 (1999) 3360.
- [21] F. Amy, H. Enriquez, P. Soukiassian, P.-F. Storino, Y.J. Chabal, A.J. Mayne, G. Dujardin, Y.K. Hwu, C. Brylinski, Phys. Rev. Lett. 86 (2001) 4342.
- [22] P.H. Mahowald, D.J. Friedman, G.P. Carey, K.A. Bertness, J.J. Yeah, J. Vac. Sci. Technol. A 5 (1987) 2982.
- [23] P.J. Cumpson, M.P. Seah, Surf. Interface Anal. 25 (1997) 430.
- [24] D.-A. Luth, T. Miller, T.-C. Chiang, Phys. Rev. Lett. 79 (1997) 3014.
- [25] E. Rauls, Z. Hajnal, P. Deak, Th. Frauenheim, Phys. Rev. B 64 (2001) 245323.