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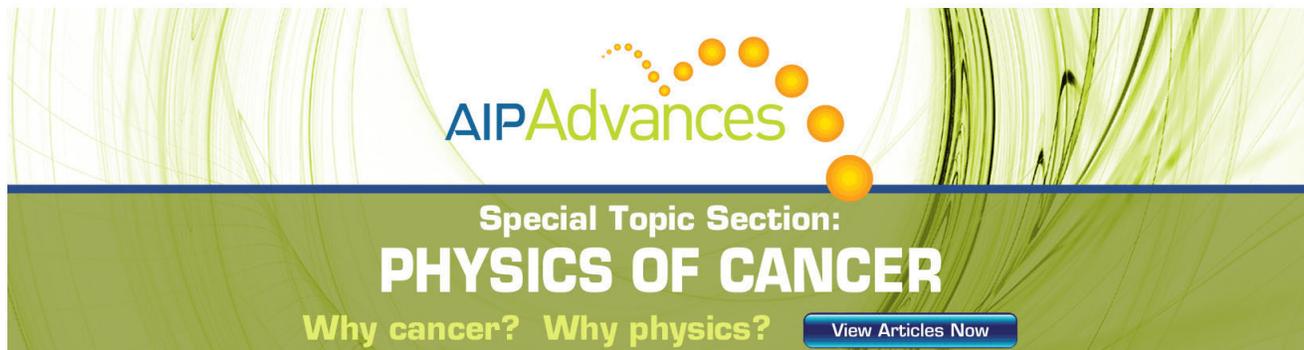
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Oxygen partial pressure dependence of the SiC oxidation process studied by *in-situ* spectroscopic ellipsometry

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The oxygen partial pressure dependence of the Silicon carbide (SiC) oxidation process was investigated using *in-situ* spectroscopic ellipsometry at oxygen partial pressures between 1 and 0.02 atm for 4H-SiC (0001) Si- and (000-1) C-faces. Analyses of the interface structure between the oxide and SiC indicate that the interface layer has a modified SiC-like structure around 1 nm thick accompanied by oxide growth; the structure and thickness do not change after an oxide growth of about 7 nm. The oxide thickness dependence of the growth rate at sub-atmospheric oxygen pressures is similar to that at 1 atm pressure, that is, just after oxidation starts, the growth rate rapidly decreases as the oxidation proceeds. After an oxide growth of about 7 nm thick, the deceleration of the growth rate suddenly changes to a gentle slope. The thickness at which deceleration changes depends slightly on both the oxygen partial pressure and surface polarity of the SiC substrate. The origins of these two deceleration stages, i.e., rapid and gentle decelerations, are discussed from their pressure dependencies based on the SiC oxidation model taking into account the interfacial emission of Si and C atoms. The formation and structures of the interface layers are also discussed in relation to the oxidation mechanisms. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4736801>]

I. INTRODUCTION

Silicon carbide (SiC) is an attractive wide bandgap semiconductor because it has superior physical properties suited for low-loss and high power devices, such as high breakdown field and high thermal conductivity. In addition, Si oxide layers, utilized as insulators in metal-oxide-semiconductor field-effect-transistors (MOSFETs), can be grown on SiC substrate surfaces by thermal oxidation. However, for fabricated SiC-MOSFETs, low on-resistances expected from the material properties of SiC have not been realized.¹ This is considered to be caused by low channel mobility, which is attributed to high trap densities at and/or near the SiO₂-SiC interface.² Therefore, an understanding of the structure of the interface and the formation mechanism of the interface layer are important to realize SiC-MOSFETs with the necessary quality. Moreover, since the reliability of gate oxide thermally grown on SiC has been reported to be lower than that grown on Si, improvement in oxide reliability is also important for the practical use of SiC-MOSFETs. As the creation of interface layers and the characteristics of oxide layers are closely related to the growth mechanism of the oxide, observation of the oxide growth process is believed to be very significant for overcoming these problems.

There have been many articles that have reported the oxide thickness as a function of the oxidation time at various oxidation conditions, i.e., various oxidation temperatures and oxygen gas pressures.³⁻⁶ These reports have pointed out that

SiC oxidation can be basically described by the Deal-Grove model, proposed for the explanation of Si oxidation.⁷ Contrary to these previous results, our recent studies using *in-situ* spectroscopic ellipsometry⁸⁻¹⁰ as well as *ex-situ* measurements¹¹ showed that the oxide growth rates in a thin oxide regime are higher than those predicted by the Deal-Grove model, similar to the case of Si oxidation.¹² It is considered that the study of the oxide growth process in the thin oxide regime is very important to understand the formation mechanism and the structure of the oxide-SiC interface layer. Though the oxide growth rate of SiC is much smaller than that of Si, it is still too fast to observe the initial growth process in detail. Therefore, a reduction in the growth rate, for example, by lowering the oxygen partial pressure, is believed to be useful for observation of the initial oxide growth process of SiC more minutely.

To determine the oxygen pressure dependence of the SiC oxidation process, *ex-situ* measurements from 10⁻³ to 4 atm have been carried out.^{4,11} However, both of these studies did not examine the initial oxidation process in detail, partly because *in-situ* real-time observations were not possible. We performed *in-situ* real-time measurements at reduced partial pressures between 0.1 and 1.0 atm, and found the presence of the initial growth rate enhancement to be similar to the case at atmospheric pressure.¹⁰

In this study, we observed the SiC oxidation process under low oxygen partial pressures down to 0.02 atm by performing *in-situ* ellipsometry to examine the initial stage of oxidation in more detail, which is considered to be closely related to the interface layer formation, and to acquire further knowledge about the SiC oxidation mechanism. We discuss

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the oxide growth mechanism in the very thin thickness regime, as well as on the formation mechanisms and structures of interface layers, based on the Si-C emission model that we proposed,¹³ compared to that of Si oxidation.

II. EXPERIMENTS

An *in-situ* spectroscopic ellipsometer consisting of an oxidation furnace combined with the ellipsometer arms was employed in this study. The ellipsometric parameters (Ψ , Δ) in the wavelength region between 295 and 370 nm were obtained using a CCD detector and the angle of incidence was 75.8° .

Epitaxial wafers of 4H-SiC with a 0.5° off-oriented (000-1) C-face and a 8° off-oriented (0001) Si-face, both are *n*-types, having a net donor concentration $N_d - N_a = 3 \times 10^{15}$ and $1 \times 10^{16} \text{ cm}^{-3}$, respectively, were used in this study. All the oxidations were conducted at the oxidation temperature of 1100°C . Prior to the measurements of oxidation, to determine the optical constants of SiC at the oxidation temperature, the ellipsometric parameters (Ψ , Δ) were measured in an argon atmosphere at 1100°C . After acquisition of the optical constants, the argon atmosphere was replaced by a mixed atmosphere of oxygen and argon gases. The oxygen partial pressure was controlled by changing the mixture ratio of oxygen and argon gas flows, and the total flow rate was kept at 1000 sccm. The changes in the ellipsometric parameters (Ψ, Δ) were recorded during oxidation of the samples. The obtained (Ψ, Δ) spectra were analyzed using a three-layer structure model, i.e., SiC/interface layer/SiO₂, because excellent fitting with the observed (Ψ, Δ) spectra has been achieved with this structure, as reported in the references.^{14,15} The optical constants of the interface layers were assumed to follow the modified Sellmeier's dispersion relation taking a weak optical absorption into account,¹⁶ that is,

$$\varepsilon_1 = 1 + \frac{(n_\infty^2 - 1)\lambda^2}{\lambda^2 - \lambda_0^2}, \quad \varepsilon_2 = \frac{C}{\lambda} + \frac{D}{\lambda^3} + \frac{E}{\lambda^5}, \quad (1)$$

where ε_1 and ε_2 are the real and imaginary parts of dielectric constant, respectively, n_∞ and λ_0 are the refractive index at $\lambda = \infty$ and the characteristic oscillation wavelength, respectively, and C , D , and E are the fitting parameters for the optical absorption, so that we could obtain the thickness and optical constants of the interface layer as well as the SiO₂ layer thickness.

III. RESULTS

Figures 1(a) and 1(b) show the oxide thickness dependence of the interface layer thickness and those of n_∞ of the interface layers, respectively, on the SiC (000-1) C-face. The values of n_∞ for 4H-SiC and SiO₂ are also shown by dashed lines in Figs. 1(b) and 2(b). Figure 2 shows similar results on the (0001) Si-face. As seen in Figs. 1(a) and 2(a), the interface layer thickness increases with increasing oxide thickness and saturates around 1.5 nm at the oxide thickness of around 7 nm. The figures also show that this saturation thickness depends slightly on the partial pressure. Figures 1(b) and 2(b) show that the values of n_∞ are also saturated around 7 nm in oxide

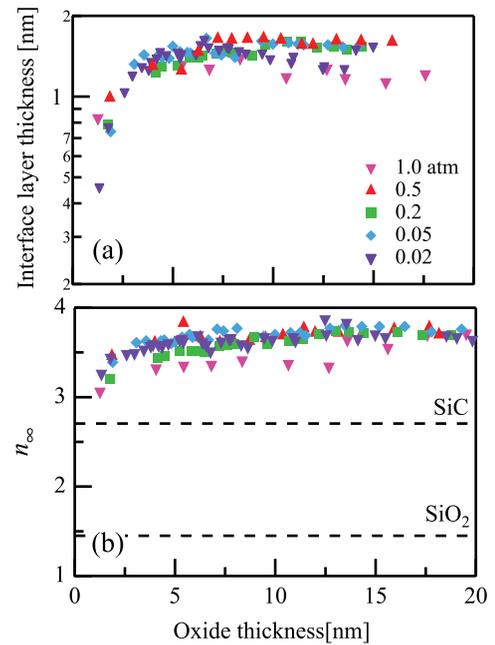


FIG. 1. Oxide thickness dependence at various oxygen partial pressures on the (000-1) C-face: (a) Interface layer thickness and (b) n_∞ (see Eq. (1)).

thickness and the saturated values depend slightly on the partial pressure.

The oxide thickness dependence of the oxide growth rates on the (a) 4H-SiC C-face and (b) Si-face are shown in Fig. 3. As seen in the figure, we could obtain the growth rate data in the extremely thin oxide region down to a few nanometers more precisely by reducing the oxygen partial pressure to less than 0.1 atm, compared with the case of measurements between 0.1 and 1.0 atm.¹⁰ For both faces, the oxide thickness dependence of the growth rate at less than 0.1 atm are basically similar to those of above 0.1 atm even

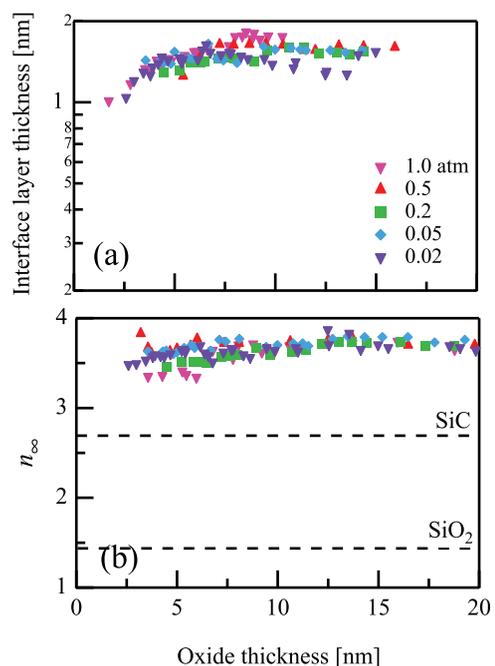


FIG. 2. Oxide thickness dependence at various oxygen partial pressures on the (0001) Si-face: (a) Interface layer thickness and (b) n_∞ (see Eq. (1)).

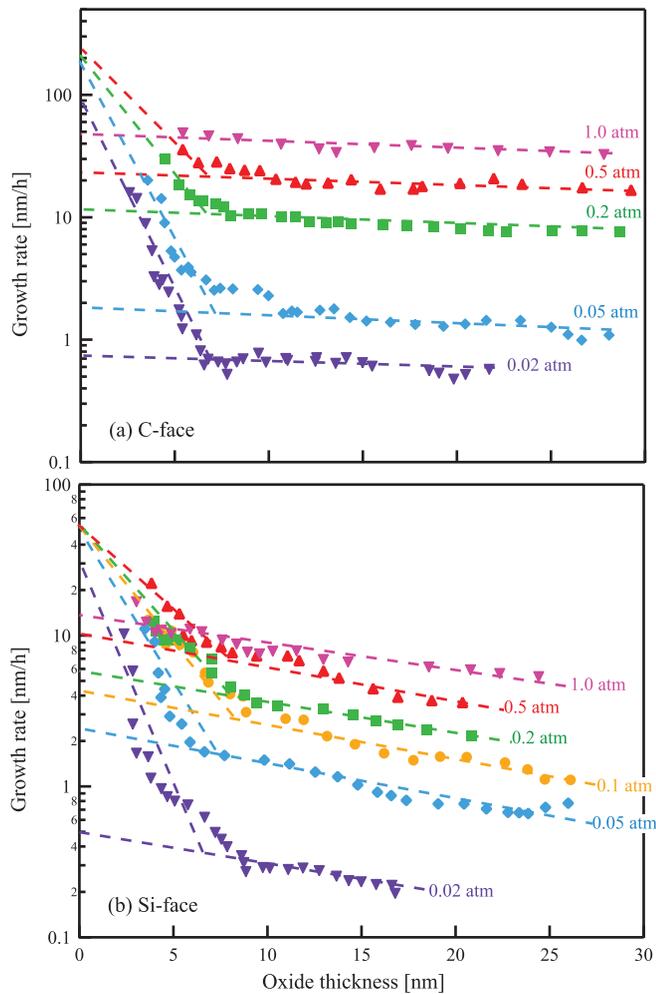


FIG. 3. Oxide growth rates as a function of oxide thickness at various oxygen partial pressures on (a) the (000-1) C-face and (b) the (0001) Si-face. Dotted lines are fitted to the experimental data using exponential functions.

if the partial pressure is lowered to 0.02 atm. Namely, just after the oxidation starts, the oxide growth rates rapidly decrease and the deceleration rate changes to a gentle one at around 7 nm in oxide thickness (hereafter the two oxidation stages are denoted as the rapid and gentle deceleration stage, respectively).

We fitted the experimental data at each partial pressure with two straight lines, as shown by the dotted lines in Fig. 3, and derived the initial growth rate of the two deceleration stages, R_0 and R_1 , by extrapolating the straight line to $X=0$ (X : oxide thickness) in the rapid and gentle deceleration stages, respectively. The figures show that the thickness at which the deceleration rate changes from a rapid to a gentle one (termed “deceleration-rate-change thickness X_c ”), i.e., the cross point of the two decay lines, is almost constant around 7 nm regardless of the oxygen partial pressure or surface polarity.

Figure 4 shows the oxygen partial pressure dependence of R_0 and R_1 , denoted by unfilled and filled symbols, respectively, on the C- and Si-faces (circles and triangles, respectively). Since oxide growth in the thin region was too fast to follow spectroscopic ellipsometry measurements in the case of 1 atm pressure on the C-face, we could not obtain the

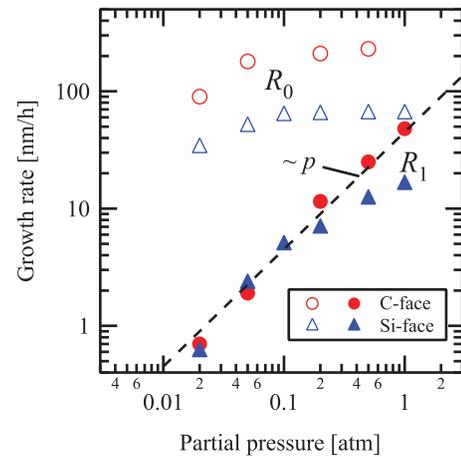


FIG. 4. Oxygen partial pressure dependence of the initial growth rate, R_0 (unfilled symbols), and the gentle deceleration growth rate, R_1 (filled symbols), on the C-face (circles) and Si-face (triangles).

oxide growth rates in the rapid deceleration stage accurately. Thus, the value of R_0 for the C-face at 1 atm is not shown in this figure. The dashed line in Fig. 4 shows the data proportional to the oxygen partial pressure and fitted to the R_1 data for the C-face. For both polar faces, the data points of R_1 are almost on the line, suggesting that R_1 is proportional to the partial pressure, though, for the Si-face, R_1 becomes slightly smaller as seen from the linear relation approaching 1 atm. It should be noted that the rates are almost equal for the C- and Si-faces at low pressures, which is different from the fact that the oxide growth rates for the C-face are about eight times larger than those for the Si-face in the several 10 nm thickness region at atmospheric oxygen pressure.^{3,5,10,11}

Looking carefully at the growth rate data in the rapid deceleration stage in Fig. 3, we note the changes in the gradients of the growth rate data between 4 and 5 nm in oxide thickness. These *kinks* are seen on the C- and Si-faces and, in addition, the thicknesses of the *kinks* are almost the same. In such an extremely thin oxide region, various factors, such as the flatness of the substrate surfaces used, the difference in growth mode, i.e., the layer by layer or three-dimensional growth mode, and the interfacial roughness,¹⁷ might influence the oxide growth rate. However, the experiments in this study do not have sufficient accuracy to distinguish these effects from each other. Further studies such as an *in-situ* monitoring of oxidation using a well-defined substrate are thought to be necessary to clarify the origin of the fine structures observed. It should be noted that, since the C-face substrates used in these experiments are decimally off-orientated, the influence of the off-orientation of the surfaces might be quite small.

IV. DISCUSSION

A. Si-C emission model

Here, we briefly state the essence of the Si and C emission model that we proposed for a description of the SiC oxidation process.¹³ Figure 5 shows a schematic of this model. During oxidation, Si and C interstitials are emitted from the SiC-oxide interface, and a decrease in the interfacial

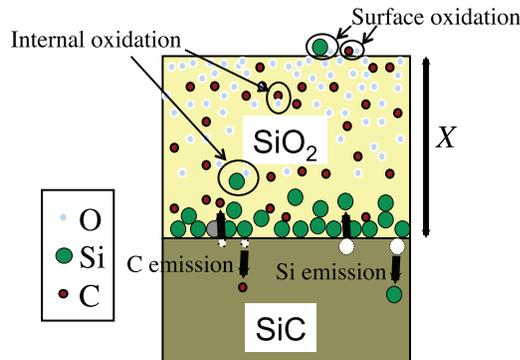


FIG. 5. Schematic illustration of the Si-C emission model.¹³ It is to be noted that Si and C atoms are emitted into not only to the SiO₂-side, but also the SiC-side.

reaction rate, k , as expressed by the following function, occurs as the interstitials accumulate inside the oxide near the interface accompanying progress in oxidation:

$$k = k_0 \left(1 - \frac{C_{\text{Si}}^{\text{I}}}{C_{\text{Si}}^{\text{O}}}\right) \left(1 - \frac{C_{\text{C}}^{\text{I}}}{C_{\text{C}}^{\text{O}}}\right), \quad (2)$$

where C^{I} and C^{O} are the concentration at the interface and the solubility limit in the oxide, respectively, of the corresponding interstitial atoms and k_0 is the initial interfacial oxidation rate. If the oxide grows only at the interface, the oxide growth rate dX/dt is represented by the equation,¹³

$$N_0 \frac{dX}{dt} = kC_{\text{O}}^{\text{I}}, \quad (3)$$

where N_0 is the molecular density of SiO₂. As seen from this equation, a decrease in k corresponds to a decrease in dX/dt . It should be noted that if the value of k is constant regardless of the oxide thickness, this oxidation model is equivalent to the Deal-Grove model.⁷

B. Formation and structures of the interface layers

We have reported that^{15,18} the photon energy dependence of the optical constants n and k derived from the complex dielectric constants between 2 and 6 eV, covering the direct interband transition energy E_0 of 4H-SiC of 5.65 eV, is similar to that of bulk 4H-SiC, though the absolute values of n are about 1 larger than those of SiC, which were again confirmed in this study. The similarity in the energy dispersion of the optical constants of the interface layers suggests that the interface layer is not a transition layer between SiC and SiO₂, such as SiO_x or SiC_xO_y. Rather, it is a layer having a modified structure and/or composition compared to SiC, such as a stressed or interstitials-incorporated SiC layer, locating not on the SiO₂ side but the SiC side of the SiC-oxide interface.

The experimental results also indicated that the thickness at which the interface layer thickness and the value of n_{∞} become constant (i.e., 7 nm) is determined not from the surface polarity or oxygen partial pressure but from the oxide thickness. The Si-C emission model describes this behavior by considering that Si and C atoms are emitted into both

directions of the SiC-oxide interface accompanying oxidation at the interface, i.e., into not only the oxide layer but also the SiC layer, and accumulation of interstitial Si and/or C atoms emitted into the SiC substrate may form a layer having similar optical properties as SiC but larger refractive indices compared to SiC. Since accumulation of interstitials is linked to the growth of the oxide, it is considered that growth of the interface layer is saturated at some intrinsic oxide thickness even if the oxygen pressure is changed. We will discuss the behavior of the interface layer as well as that of X_c , later.

C. Oxide thickness dependence of oxide growth rate

As mentioned above, there are two oxidation stages in the oxide growth rate curves, i.e., first rapid deceleration and second gentle deceleration. Since the growth rates at each deceleration stage are seen as a straight line in a semi-log plot (shown by dotted lines in Fig. 3) in the respective stage, the oxide thickness dependence of the oxide growth rate can be approximated by the sum of two exponential functions,¹⁹ as

$$\frac{dX}{dt} = R_0 \exp(-X/L_0) + R_1 \exp(-X/L_1), \quad (4)$$

where R_0 and R_1 ($R_0 \gg R_1$) have the same meaning as in Fig. 4 (i.e., pre-exponential constants), and L_0 and L_1 ($L_0 < L_1$) are the characteristic lengths for the deceleration of oxide growth rate in each oxidation stage, respectively. Equation (4) means that in the thin oxide regime, oxide growth occurs by two ways and they proceed not in series but in parallel because the growth rate is given by the sum of two terms and is chiefly determined by the faster one in each stage. Obviously, the L_0 and L_1 values correspond to the gradients of the fitted line in the rapid and gentle deceleration stage, respectively. As shown in Fig. 3, the L_0 value decreases with decreasing partial pressure, which corresponds to the more remarkable rapid deceleration. In contrast, the L_1 value is almost constant regardless of the partial pressure. This suggests that the oxidation process is different between the rapid and gentle deceleration stages. We will discuss these two deceleration stages relevant to the oxide growth mechanism.

D. Discussion of the two decelerating stages in terms of SiC and Si oxidation mechanisms

The existence of a rapid deceleration stage in the oxide growth rate just after oxidation starts ($X < 10$ nm) has also been observed for Si oxidation.^{12,20} However, in investigations on Si oxidation mechanisms, the cause of the rapid deceleration has not yet been clarified. That is, the Deal-Grove model cannot fully account for the initial rapid deceleration.⁷ An empirical equation, i.e., the D-G term plus an exponential term, proposed by Massoud *et al.*¹² can only reproduce the observed growth rates numerically, but does not provide a physical meaning. The interfacial Si emission model²¹ is now believed to be the model that can reproduce the observed oxide growth rate quantitatively very well.

However, the model also cannot reproduce the remarkable rapid deceleration at sub-atmospheric oxygen pressures, as pointed out by Farjas and Roura.²⁰ For SiC oxidation, Yamamoto *et al.* tried to reproduce the observed data using Masoud's empirical equation.^{8–10} Here, we discuss the reasons why two deceleration stages exist in the thickness dependence of oxide growth rate, based on the Si-C emission model.

The interfacial reaction rate (k in Eq. (2)) is unlikely to depend on the oxygen partial pressure, p , because it corresponds to the rate at which one SiC molecule is changed to one SiO₂ molecule, which should not depend on p . In the thin oxide regime discussed here, the interface oxygen concentration C_{O}^{I} can be expressed as $C_{\text{O}}^{\text{I}} \sim pC_{\text{O}}^0$ by Henry's law, where C_{O}^0 is the solubility limit of oxygen in SiO₂. Therefore, the growth rate in the thin oxide regime, R , should be proportional to p , which is in good agreement with the experimental results in the gentle deceleration stage, i.e., R_1 .

According to the Si-C emission model,¹³ as the number of accumulated atoms increases with oxidation, and is thus proportional to the quantity of oxidized molecules, i.e., the thickness of the oxide X , the variation in k may be approximately given as an exponential function of X in the form of $C \exp(-X/L)$, where C and L are the pre-exponential term and characteristic length, respectively, related to the accumulation of Si and C interstitials at the interface. From these considerations, as well as the fact that R_1 is proportional to p , the gentle deceleration of the oxide growth rate can be attributed to the accumulation of Si and C interstitials near the interface, and given approximately as $dX/dt \sim R_1 \exp(-X/L_1)$, which is coincident with the second term in Eq. (4).

If the initial growth rate R_0 in the rapid deceleration stage is also followed by Eq. (3), it can be expressed as $R_0 \sim k_0' C_{\text{O}}^{\text{I}} / N_0$, where k_0' is the interfacial reaction rate when oxidation starts. As the value of k_0' is also unlikely to depend on the oxygen partial pressure, R_0 should be proportional to the oxygen pressure. As seen in Fig. 4, while R_0 is not proportional to p , it decreases with decreasing p in the low p region. This suggests that R_0 , i.e., the rapid deceleration, is not related to the interfacial oxide growth. In the case of Si oxidation, the experimental data show almost no dependence of R_0 with respect to p .¹²

We next consider the reason why R_0 is not proportional to but rather is almost independent of the oxygen partial pressure, both for Si and SiC oxidations. It has been considered that oxide growth occurs only or mainly at the Si-oxide (SiC-oxide) interface. However, according to the Si emission model²¹ for Si oxidation and the Si and C emission model¹³ for SiC oxidation, Si atoms (Si and C atoms) are emitted into the oxide layer, some of which encounter the oxidant inside the oxide to form SiO₂. When the oxide is very thin, some of the emitted Si atoms can go through the oxide layer and reach the oxide surface, and are instantly oxidized, resulting in the formation of an SiO₂ layer on the oxide surface. Therefore, there are two oxide growth processes other than the interfacial oxide growth, i.e., oxide formation due to oxidation of Si interstitials inside the oxide and on the oxide surface. The total growth rate is given by the sum of these three oxidation processes. In the case of oxidation inside the oxide,

the probability of the emitted Si interstitials meeting the oxidant inside the oxide should be proportional to the oxygen concentration in the oxide. Therefore, this oxidation process should be proportional to p like R_1 , and thus can be excluded as a candidate of the origin of R_0 .

In contrast, in the case of oxidation on the oxide surface, the amount of oxygen is thought to be sufficient to oxidize all the Si atoms emitted and appearing on the surface, because the number of oxygen molecules impinging onto the surface from the gaseous atmosphere is several orders larger than the number of emitted Si atoms transmitted through the oxide even if the oxygen pressure is as low as 0.02 atm.²² Therefore, the oxide growth rate for oxidation on the oxide surface should be independent of the oxygen partial pressure, which is in good agreement with the behavior of R_0 . Besides, the possibility that Si interstitials go through the oxide and reach the oxide surface is considered to decrease rapidly with increasing oxide thickness, and can be given the form $\exp(-X/L_0)$, where L_0 ($< L_1$) is the escape depth of Si atoms from the oxide layer. From these considerations, the rapid deceleration stage of oxide growth rate observed just after oxidation starts is thought to be due to oxidation of Si interstitials on the oxide surface. Therefore, the value of X_c obtained from the experiments of 7 nm indicates that the escape depth of Si atoms from the oxide is estimated to be several nanometers at 1100 °C. Since the behavior of Si interstitials other than at the interface should be the same for the C- and Si-faces, it is reasonable that the value of X_c does not depend on the polarity of the SiC faces. Moreover, the fact that the growth rates in the thin regime at low pressures are not very different for the C- and Si-faces can be explained by considering that surface oxide growth is dominant over oxide growth in this stage and oxidation on the oxide surface may proceed independent of the surface polarity.

Theoretical calculations of the growth rates reported so far have not taken into account the surface oxide growth for both Si and SiC oxidations. However, in the extremely thin oxide thickness range and especially at low oxygen partial pressures, the contribution from surface oxide growth as well as those from the interface and internal oxide growth should be taken into account. However, to confirm the argument derived from the experimental results in this study, it is necessary to perform numerical calculations of the oxide growth rates within the framework of the Si-C emission model, taking into account the contribution from oxidation on the surface. In the case of Si oxidation, the interfacial Si emission model²¹ cannot reproduce the growth rate in the thin oxide region at sub-atmospheric pressures, as pointed out by Farjas and Roura,²⁰ where the introduction of the contribution from the surface oxide growth may dissolve the disagreement between the calculated and observed oxide growth rates.

As mentioned above, the X_c value is almost constant around 7 nm regardless of the oxygen partial pressure, though the rapid deceleration stage can be observed more remarkably at lower partial pressures. In the case of Si oxidation, a rapid deceleration stage has also been observed just after oxidation starts, and the thickness corresponding to X_c is also almost independent of the oxygen partial pressure, though the growth rates at X_c depend on the oxygen partial

pressure.^{12,20} Therefore, it can be stated that X_c is determined only by the thickness of the oxide layer for both the Si and SiC oxidation cases. It is to be noted that the value of X_c is very close to the thickness at which the interface structures become constant as revealed above. In addition, the pressure dependence of the oxide thickness when the interface layer becomes unchanged also exhibits the same behavior, i.e., they are almost independent of pressure. These results suggest that an interface layer gradually grows during the surface oxide growth and, after transforming to the interfacial and internal oxide growth, the interface layer stops growing. It is considered that the interface layer located on the SiC side of the interface may be oxidized to form SiO₂ and a new interface layer may form on the SiC side, which results in movement of the position of the interface layer in the direction of the SiC substrate with progress in oxidation. Therefore, the brake for the interface layer growth is considered to be responsible for the abrupt change in growth rate at X_c . Otherwise, during the surface oxide growth fewer interstitials emit into the SiC-side because the concentration of interstitials in the oxide is quite low, in turn, the emission into the SiC-side increases with accumulation of interstitials in the oxide and then the accumulation of interstitials is saturated when it balances with the progress in oxidation front.

V. SUMMARY

We have studied the oxygen partial pressure dependence of the SiC oxidation process using an *in-situ* spectroscopic ellipsometer at oxygen partial pressures ranging from 0.02 to 1.0 atm both for the (0001) Si- and (000-1) C-faces of 4H-SiC. It was found that regardless of the surface polarity as well as the oxygen partial pressure, an interface layer having modified SiC structures is formed accompanied by oxidation just below the SiC-oxide interface in the same manner, i.e., the thickness and refractive indices of the interface layer increase with an increase in the oxide thickness, the interface layer thickness reaches about 1.5 nm at an oxide thickness of around 7 nm, and then the thickness and structure of the interface layer do not change anymore with further increase in oxide thickness. The oxide thickness dependence of the growth rate at sub-atmospheric oxygen partial pressures down to 0.02 atm is similar to those at 1 atm. Namely, just after oxidation starts, the oxide growth rate rapidly decreases and the deceleration-rate changes to a gentle mode at around 7 nm in oxide thickness, which is almost the same thickness at which the thickness and the structure of the interface layers become constant. We have shown that the Si-C emission model can explain the cause for the change in deceleration rate of the oxide growth rate from the oxygen partial pressure dependence and found that the oxide growth due to

oxidation of Si interstitials on the oxide surface plays a dominant role in the extremely thin thickness region, less than several nanometers. We have tried to explain the formation mechanism and the structures of the interface layers in the frame of the Si-C emission model.

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