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Challenges in Measuring Thin SiO_2 Layers on 4H-SiC via Spectroscopic Ellipsometry

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Abstract. The measurement of thin silicon dioxide (SiO_2) layers on silicon carbide (SiC) substrates is crucial because these layers serve a variety of critical functions in electronic and optoelectronic devices. Silicon carbide's superior electrical and thermal properties make it a preferred material for high-power, high-frequency, and high-temperature applications. When deposited on SiC, thin SiO_2 films act as preconditioning layers, and as gate oxides, precise measurement of these oxide layers is important to ensure both optimal functionality and extended device longevity.

This paper presents the essential considerations that should be addressed when Silicon-Oxide layers on SiC substrate are measured by spectroscopic ellipsometry to avoid backside artifact and enhance sensitivity in their thickness measurements. The methodology demonstrated enables reliable detection of layer thicknesses down to less than 1 nm, with a discrimination of less than ±0.5 nm.

During ellipsometry data evaluation, parametric models are applied to describe the anisotropic backside reflections. Incorporating additional parameters, such as the substrate thickness, can yield deeper insights into the sample. However, this added complexity can render the modeling approach impractical for routine industrial applications, even though it remains scientifically valuable. Overall, this study emphasizes the combined importance of using a microspot system and optimizing the incidence angle to overcome the inherent challenges of measuring thin SiO_2 films on 4H-SiC.

Introduction

The accurate characterization of ultrathin silicon dioxide (SiO_2) layers on silicon carbide (SiC) substrates is essential due to their pivotal role in the performance and reliability of electronic and optoelectronic devices. Owing to its outstanding electrical and thermal characteristics, SiC is widely used in high-power, high-frequency, and high-temperature applications [1]. When thin SiO_2 films are formed on SiC, they function as gate dielectrics or surface conditioning layers, making precise thickness measurement a key factor in ensuring device efficiency and long-term stability.

Previous studies [2] have shown that spectroscopic reflectometry often lacks the necessary sensitivity to accurately measure SiO_2 layers thinner than 50 nm, and especially those below 10 nm. In addition, monitoring the efficiency of SiO_2 hard mask etching is key to checking if the oxide has been totally removed or if there is any (very) thin oxide left because this could hinder a subsequent process step. In contrast, spectroscopic ellipsometry (SE) is a highly sensitive, absolute measurement technique that analyzes changes in the polarization state of light upon reflection from a sample surface. In this study, SE measurements were carried out using the Semilab SE-2000 system [3], and data analysis was performed with the Semilab SEA software.

This study presents the practical consideration to successfully apply Spectroscopic Ellipsometry sensitivity on the measurement of the ultrathin SiO_2 layers on 4H-SiC substrates.

Measurement Principles and Sensitivity Optimization

The results of spectroscopic ellipsometry are typically presented as a pair of spectra: Ψ, which represents the amplitude ratio of the Fresnel reflection coefficients for p- and s-polarized light, and Δ, which denotes the phase difference between these two polarization components.

The Brewster's angle of a bulk material sample is defined as the angle of incidence at which the reflected and refracted light beams are perpendicular to each other. This angle depends on the refractive index of the material and plays a critical role in optical measurements.

When the angle of incidence (AOI) approaches the Brewster's angle of the 4H-SiC substrate, spectroscopic ellipsometry (SE) achieves high sensitivity. At this angle, the p-polarized component of the reflected light is significantly reduced, and ideally, a sharp 180° phase shift (Δ) occurs when the layer thickness is 0 nm. As the layer thickness increases, the slope of the phase change (Δ) gradually flattens (see Fig. 1), enabling precise detection of ultrathin layers. Therefore, selecting an incidence angle close to the Brewster's angle is essential for accurate thin-film thickness measurements.

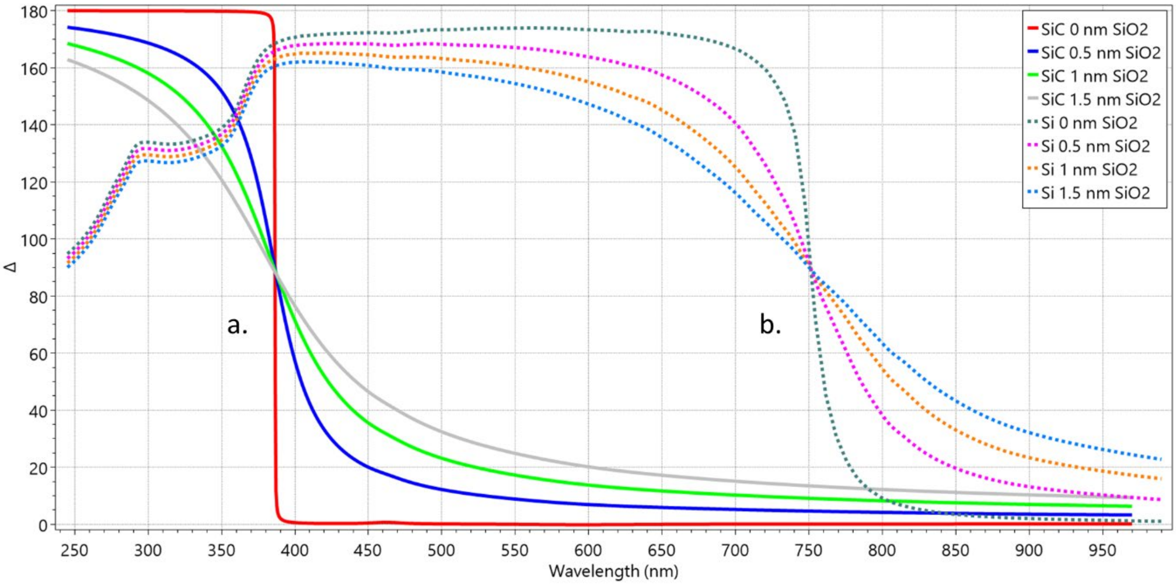

Fig. 1. D sensitivity forSiO_2 layer thickness around Brewster's angle: a. for SiC at 70° AOI, b. for Si at 75° AOI.

Measuring thin SiO_2 films on SiC surfaces becomes more complex due to the anisotropic properties of the substrate [4]. These properties can introduce backside reflections that appear as interference fringes in the spectroscopic data. As an example, a measurement on a 2.9 nm SiO_2 layer on a 4H-SiC substrate measured at 75° angle of incidence is presented. In this case the angle of incidence is not ideal for the measurement as it is further away from the Brewster's angle of 4H-SiC, which is 70° for the refractive index 2.747.

Backside Reflection and Anisotropy Correction

In practice, the spectral interference pattern depends on the difference between the ordinary and extraordinary refractive indices and the thickness of the substrate. As shown in Fig. 2 there are spectral ranges where the interference pattern vanishes due to the peaks in the extinction coefficient (k) spectra which is responsible for light absorption.

The modeling of the ellipsometry spectra affected by anisotropic backside reflection requires the backside reflection correction feature of the SEA software. The optical dispersion for the anisotropic substrate is obtained from the literature [4]. The modeled ellipsometric spectra of anisotropic samples were calculated using the 4×4 Berreman matrix method [5, 6]. Accurate modeling of ellipsometric spectra in the presence of anisotropic backside reflections requires careful consideration of the optical behavior of the substrate. To account for the complex behavior of light within the substrate, including multiple internal reflections and wave interference, advanced modeling techniques are employed. These approaches ensure that both coherent and incoherent contributions to the reflected signal are properly represented, enabling a more precise interpretation of the measured spectra.

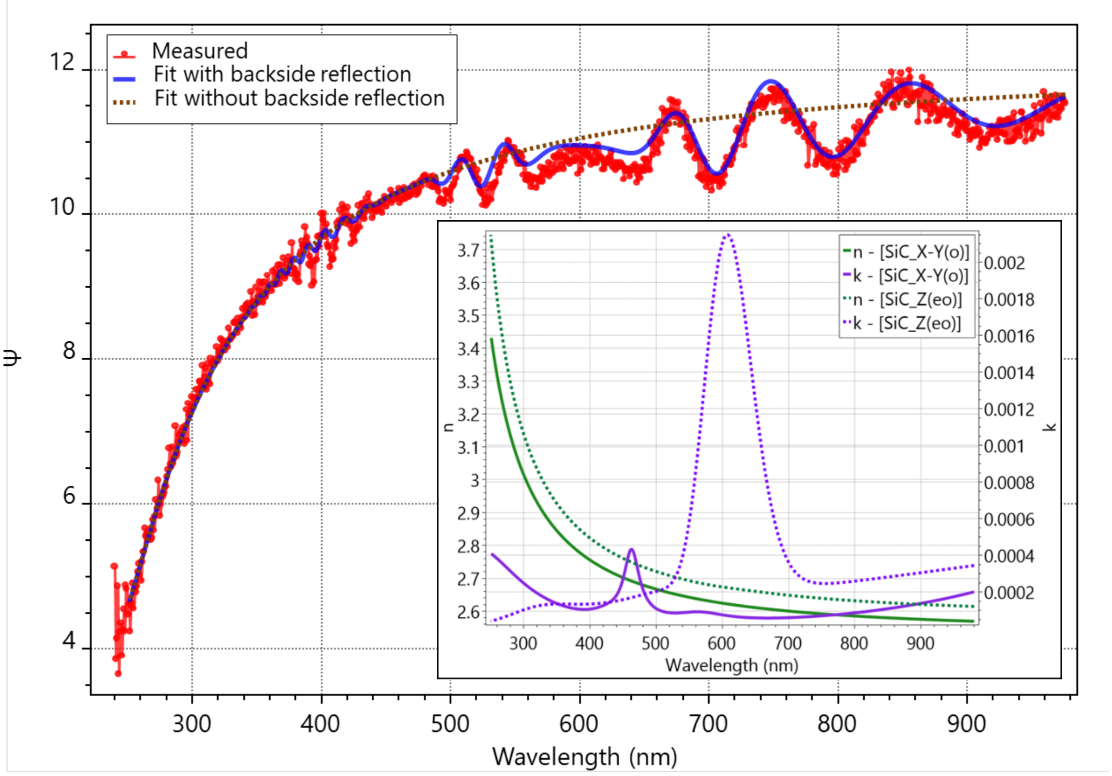

Fig. 2. Y spectrum of a 2.9nm SiO_2 on SiC structure with model fit. The inset shows the ordinary and extraordinary refractive index of 4H-SiC.

Although accounting for anisotropic backside reflection yields scientifically meaningful results for modeling such samples, it is not practical from an industrial perspective. Implementing this correction necessitates incorporating the substrate thickness into the model and fitting it during lateral mapping. This approach not only increases analysis time but may also reduce sensitivity to thin layer thickness due to parameter correlation. Excluding the backside-reflected light from the measured intensity would enable a more robust model with enhanced sensitivity to thin oxide layers.

Microspot System and Instrumental Enhancements

To effectively address this issue, a precisely configured microspot system is essential for reducing or eliminating backside reflections, thereby minimizing spectral interference. The microspot system of the Semilab SE-2000 achieves this by employing the so-called knife-edge method.

The principle of this method is based on the optical separation of frontside, and backside reflected light, ensuring that the backside reflection does not reach the detector. In specific configurations, the system can be adjusted so that only the backside reflected light is detected, while the frontside reflection is excluded.

The implementation of the knife-edge method is based on the SE-2000 microspot system which reduces the measurement spot size by projecting the light source onto the sample, achieving a minification. Using the identical optical configuration in the reverse way at the detection side, it magnifies not only the measurement spot, but also the distance between the frontside reflected light and the virtual position of the backside reflected light. (Fig. 3).

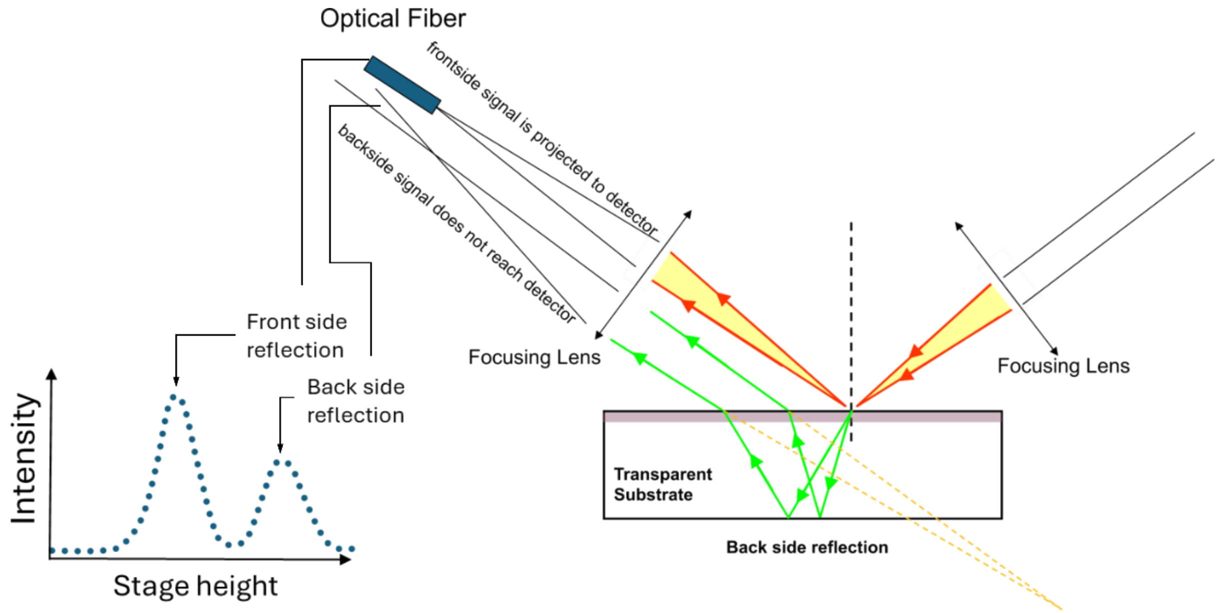

Fig. 3. Schematic drawing shows how the SE-2000 microspot system helps exclude the backside reflection. The layer and substrate thicknesses are not to scale.

The effect of the microspot system on the backside reflection removal could be improved if we further reduce the spot size. In a projection-based system, it could be accomplished either by decreasing the focal length ratio of the focusing objective and the collimation optic or by minimizing the object size. The object size could be reduced by introducing a pinhole in front of the lamp which reduces the area from which the light of the source is used.

Experimental Results and Sensitivity Demonstration

The investigated sample in this study was a native oxide layer on 4H-SiC. The instrument used was an SE-2000 spectroscopic ellipsometer equipped with an automatic goniometer and an Ultra Microspot option. In practice, the Ultra Microspot employs a pinhole in front of the light source to further decrease the measurement spot size and mitigate unwanted reflections.

Fig. 4. shows measurement and fitted spectra of a 1.2 nm thick SiO_2 layer on 4H-SiC along with two simulated spectra using the same model but varying the layer thickness by ±0.5 nm. The measurement in this case applies both the above-mentioned methods for improving the measurement quality. The 70° incidence angle provides sensitivity for even small thickness changes and the microspot system, along with the ultra-microspot pinhole, effectively reduces the backside effect to the noise level.

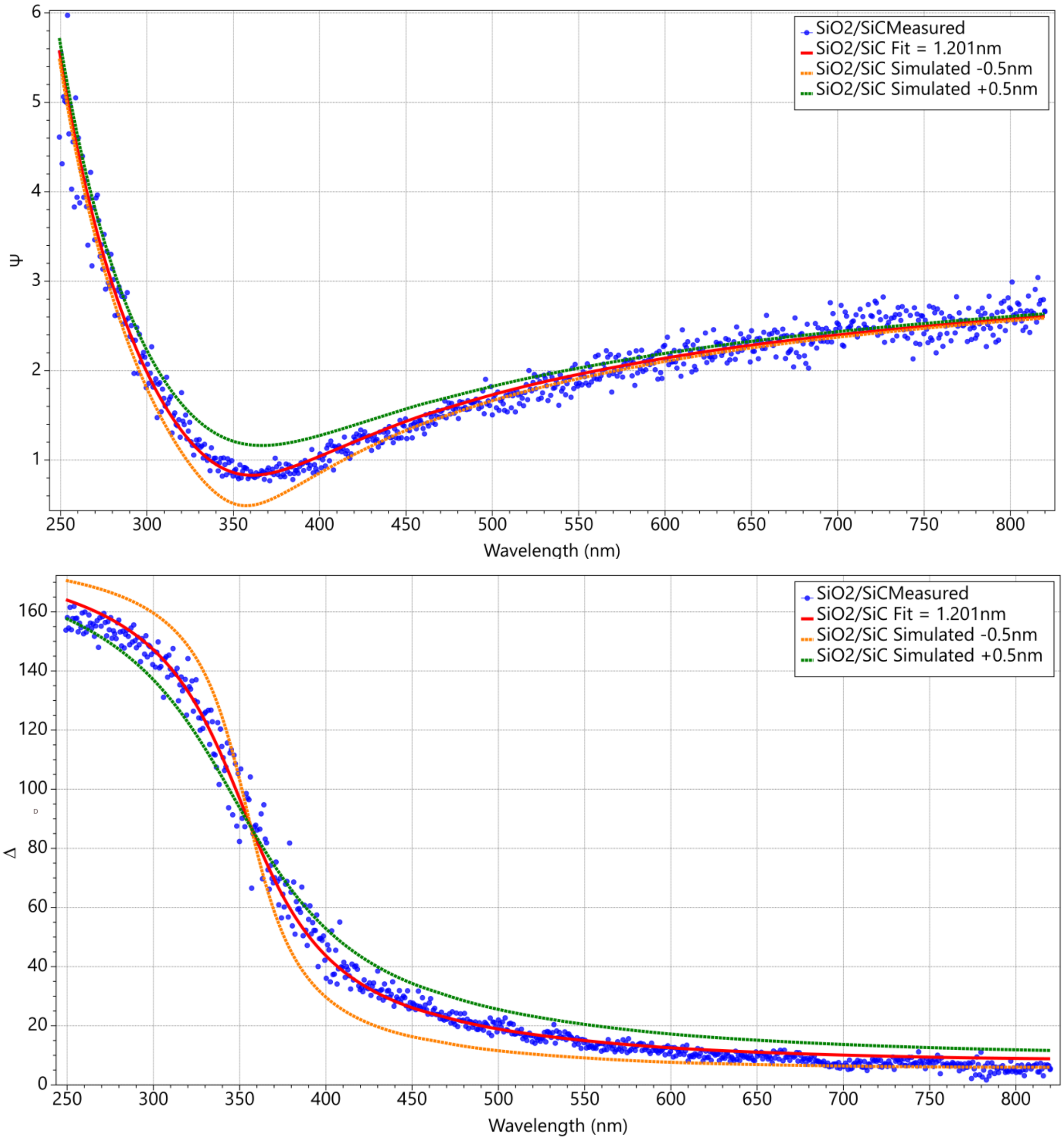

Fig. 4. Measured native oxide layer on 4H-SiC surface with fitted thickness of d=1.201 nm and simulated curves for layers with d±0.5 nm. The dashed and dotted curves apparently present the sensitivity of the Brewster's angle conditions for small changes in thickness

Conclusion

This study demonstrates that spectroscopic ellipsometry enables highly sensitive measurement of ultrathin oxide layers on 4H-SiC substrates. However, due to the material's high transparency, elevated refractive index, and the limited thickness of the substrate, specific methodological enhancements are required to ensure measurement robustness. These include the suppression of anisotropic backside reflections and the optimization of measurement geometry—particularly by aligning the incidence angle near the Brewster's angle of the sample. With these improvements, spectroscopic ellipsometry holds strong potential to become a standard process control technique for wide-bandgap materials, even in applications where precise monitoring of thin oxide layers is critical.

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