Measurement Of Silicon Carbide Epitaxial Layer Thickness Based on Infrared Interferometry and Fourier Transform Analysis

Yibing Wang *

School of Mathematics, Liaoning Normal University, Dalian, China, 116029

* Corresponding Author Email: 18641634900@163.com

Abstract. To meet the demand for high-accuracy, non-destructive measurement of silicon carbide (SiC) epitaxial layer thickness, this paper presents a progressively refined infrared interferometry methodology. Starting from fundamental physical principles, this approach systematically addresses two major error sources in practical measurements—dynamic refractive index changes and multi-beam interference—by constructing increasingly sophisticated mathematical models. The main innovations of this work are: 1) To overcome the noise sensitivity of traditional extremum-based methods, a robust "Global Interference Order Alignment" algorithm is proposed, which utilizes the entire spectrum to achieve a reliable initial thickness estimation. 2) To resolve the systematic errors caused by multi-beam interference, a high-precision model based on the Fast Fourier Transform (FFT) is further developed. This advanced model extracts the optical path difference from the signal's global frequency characteristics, proving insensitive to non-sinusoidal fringe shape distortions. A Drude-Sellmeier hybrid model is integrated to accurately describe the material's optical properties, accounting for both lattice vibrations and free carriers. Experimental results show that while the initial global alignment algorithm demonstrates strong noise resistance (yielding a thickness of 9.9005 μm), it exhibits a notable discrepancy between measurements at different angles. The advanced FFT model, after confirming the presence of multi-beam interference via kurtosis analysis, effectively eliminates the associated systematic errors. It yields a revised and more accurate thickness of 11.0616 μm for the SiC epitaxial layer, with significantly enhanced consistency and stability across different incident angles. This study not only provides a high-accuracy and highly stable measurement solution for industrial quality control of SiC epitaxial layers but also offers a valuable reference for other spectral metrology fields with its systematic, multi-stage approach to solving complex physical problems.

Keywords: Infrared Interferometry, Drude-Sellmeier Hybrid Model, Fast Fourier Transform, Extremum Point Localization.

1. Introduction

Silicon carbide (SiC) has emerged as a cornerstone wide-bandgap semiconductor, pivotal for the next generation of high-power, high-frequency, and high-temperature electronic devices, owing to its exceptional properties such as a high breakdown electric field, excellent thermal stability, and superior thermal conductivity. Within the architecture of these devices, the thickness of the SiC epitaxial layer is a critical design parameter. It directly governs key performance metrics, including the device's breakdown voltage and on-state resistance. An insufficient thickness can lead to premature device failure under high voltage, while excessive thickness unnecessarily increases material consumption and manufacturing costs. Consequently, the development of a measurement technique that is not only highly accurate and repeatable but also non-destructive is of paramount importance for industrial quality control and process optimization [1].

Among the available characterization methods, infrared interferometry stands out as an ideal non-destructive technique. The method's principle is based on the interference between infrared light reflected from the top surface of the epitaxial layer and the light that traverses the layer and reflects from the layer-substrate interface. This interference arises due to the difference in refractive indices, which is primarily caused by varying dopant concentrations between the lightly doped epitaxial layer and the heavily doped substrate. By analyzing the resulting interference spectrum, the optical path difference, and thus the physical thickness of the layer, can be determined [2].

However, the practical implementation of this technique is fraught with challenges that can significantly compromise measurement accuracy. Firstly, traditional analysis methods often rely on simplified assumptions, such as a constant refractive index, which is physically inaccurate. The refractive index of SiC is a dynamic property, varying with both the wavelength of the incident light (dispersion) and the free carrier concentration (plasma effect). Secondly, conventional models often assume a simple two-beam interference scenario. In reality, especially in high-quality materials with low absorption and significant refractive index contrast at the interfaces, multiple internal reflections can occur. This leads to multi-beam interference, which distorts the sinusoidal shape of the interference fringes, causing a systematic shift in the apparent positions of the interference extrema and thus introducing errors into any calculation based on their location. Finally, methods that rely on identifying adjacent interference fringes are notoriously sensitive to experimental noise and spectral artifacts, which can lead to missed peaks and erroneous thickness calculations.

To overcome these limitations, this paper presents a systematic and progressively refined methodology for high-accuracy thickness measurement. Our research objective is to develop a robust analytical framework that systematically addresses the primary sources of error. The core innovations of this work are twofold: First, to counter the noise sensitivity of traditional extremum-based methods, we propose a "Global Interference Order Alignment" algorithm. This algorithm leverages the entire set of detected interference minima across the spectrum to perform a global optimization, yielding a highly robust initial thickness estimate. Second, to resolve the systematic errors originating from multi-beam interference, we develop an advanced model based on the Fast Fourier Transform (FFT). This approach transforms the spectral data from the wavenumber domain to the optical path difference (OPD) domain, where the thickness information is encoded in a dominant frequency peak. This method is inherently insensitive to the non-sinusoidal fringe shapes caused by multi-beam effects. By validating the presence of these effects through kurtosis analysis and then applying the FFT model, we achieve a significant improvement in measurement accuracy and consistency. This study, therefore, provides a comprehensive solution, progressing from a fundamental physical model to a sophisticated signal processing algorithm, to deliver a reliable and precise measurement tool for the SiC industry.

2. Model Development And Methodology

2.1. Fundamental Two Beam Interference Model

We begin by modeling the phenomenon as a classic thin-film interference problem, initially considering only a single reflection at the epitaxial layer-substrate interface. When light with an incident angle Θ_1 enters the epitaxial layer from air $(\mathrm{n}_1 \approx 1)$, it refracts at an angle Θ_2 according to Snell's Law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \tag{1}$$

The optical path difference (OPD) between the beam reflected from the top surface and the beam reflected from the bottom interface is given by:

$$\Delta = 2 n_2 d \cos(\theta_2) \tag{2}$$

where d is the thickness of the epitaxial layer and n_2 is its refractive index. The conditions for destructive and constructive interference, respectively, are:

$$2n^2 d cos(\theta^2) = m\lambda \tag{3}$$

$$2n^2 d cos(\theta^2) = (m + 1/2)\lambda \tag{4}$$

where m is the integer interference order and λ is the wavelength. Rewriting in terms of wavenumber ($\nu = 1/\lambda$), the condition for destructive interference (reflectivity minima) becomes:

$$m = 2n_2 d v cos(\theta_2) \tag{5}$$

To account for the dynamic nature of the refractive index n_2, we employ a Drude-Sellmeier hybrid model, which considers contributions from both lattice vibrations (Sellmeier) and free carriers (Drude) [3]. The complex dielectric function ε is the sum of these contributions, and the refractive index is subsequently derived as $n = Re(\sqrt{\varepsilon})$.

2.2. Algorithm 1: Global Interference Order Alignment

A conventional method for calculating thickness involves using two adjacent interference minima and assuming their orders m are consecutive integers. However, this approach is highly sensitive to noise and missing interference fringes. To overcome this, we developed a more robust "Global Interference Order Alignment" algorithm.

The core idea is to treat the thickness d as an optimization variable [4-6]. For a given d, we can calculate a theoretical (and likely non-integer) interference order $m(\nu_i)$ for each observed reflectivity minimum at wavenumber ν_i using Equation (5). The optimal thickness is the one that minimizes the deviation between these calculated orders and their nearest integer values across the entire spectrum. This is formulated as an unconstrained optimization problem, where the objective function F(d) is:

$$\min F(d) = \sum_{i=1}^{N} \Big(m(v_i) - \mathrm{round}\big(m(v_i)\big)\Big)^2 \tag{6}$$

The algorithm steps are: Data Pre-processing: Apply a Savitzky-Golay (SG) filter to the raw spectral data to smooth noise and facilitate accurate identification of local minima; Extremum Identification: Programmatically locate all local minima in the smoothed reflectivity spectrum to obtain the set of wavenumbers $\{\nu_i\}$; Numerical Optimization: Solve the minimization problem in Equation (6) using a numerical optimizer over a physically reasonable search range for d.

2.3. Algorithm 2: FFT-Based Correction For Multi-Beam Interference

The global alignment algorithm assumes a symmetric, sinusoidal interference pattern typical of two-beam interference [7-9]. However, if the interface reflectivities are high and material absorption is low, multiple internal reflections become significant, leading to multi-beam interference. This results in sharper, asymmetric interference fringes (described by the Airy function), causing a systematic shift between the mathematical extremum and the true phase point. This shift introduces errors into any extremum-based calculation.

To address this, we developed a method based on the Fast Fourier Transform (FFT), which is insensitive to the fringe shape.

2.3.1. Detection Of Multi-Beam Interference

The sharpness of the interference fringes can be quantified by their kurtosis. An ideal sinusoidal (two-beam) signal has a kurtosis of 1.5. A significantly higher value indicates sharp, non-sinusoidal peaks characteristic of multi-beam interference. The kurtosis is calculated on the baseline-corrected oscillatory component of the spectrum [10,11].

2.3.2. FFT-Based Thickness Calculation

From Equation (5), the interference order m is approximately linear with the wavenumber ν. This means the reflectivity spectrum, as a function of wavenumber, is a quasi-periodic signal. The "frequency" of this oscillation is directly proportional to the optical path difference (OPD). The FFT transforms the signal from the wavenumber domain to its conjugate domain, the OPD domain. The location of the dominant peak in the resulting power spectrum corresponds to the average OPD.

$$OPD_{avg} = 2d\sqrt{\bar{n}^2 - \sin^2(\theta_1)} \tag{7}$$

where n is the average refractive index over the measured spectral range. The thickness d can then be directly calculated:

$$d = \frac{OPD_{peak}}{2\sqrt{\bar{n}^2 - \sin^2(\theta_1)}} \tag{8}$$

The FFT-based algorithm steps are: Resampling: Interpolate the non-uniformly spaced spectral data onto a uniform wavenumber grid, as required by the FFT algorithm; Baseline Correction: Estimate and subtract the slowly varying baseline from the signal to isolate the purely oscillatory interference component; FFT and Peak Detection: Apply the FFT to the corrected signal and identify the position of the primary peak (OPD_peak) in the resulting power spectrum; Thickness Calculation: Calculate the thickness using Equation (8).

3. Results And Discussion

3.1. SiC Thickness Calculation Using Global Alignment Algorithm

The global alignment algorithm was applied to the SiC wafer spectral data [12].

Table 1. SiC Thickness Results using Global Alignment Algorithm

Incident Angle	Calculated Thickness (μm)	Mean Thickness (μm)	Relative Difference (%)
10°	10.0383	9.9005	2.63
15°	9.7703	9.9005	2.63

As shown in Table 1, the algorithm successfully identified 18 interference minima for both datasets. The calculated thicknesses show a relative difference of 2.63%. This discrepancy, while small, suggests underlying systematic errors not accounted for by the two-beam model. The average thickness is estimated to be 9.9005 μm.

3.2. Analysis Of Multi-Beam Interference In Si And SiC Wafers

To investigate the effect of multi-beam interference, we first analyzed the Si wafer data, which is known to exhibit this phenomenon strongly. Kurtosis analysis was performed on the baseline-corrected signals.

(1) Si Wafer (10°): Calculated kurtosis = 5895.07.
(2) Si Wafer (15°): Calculated kurtosis = 5847.79.

These values are over 3000 times greater than the 1.5 baseline for two-beam interference, confirming the presence of strong multi-beam interference.

Next, the same analysis was performed on the SiC wafer data:

(1) SiC Wafer (10°): Calculated kurtosis = 16.96.
(2) SiC Wafer (15°): Calculated kurtosis = 12.17.

While significantly lower than for the Si wafer, these kurtosis values are still substantially higher than 1.5, confirming that weak but non-negligible multi-beam interference is present in the SiC sample. This justifies the application of the FFT-based correction model.

3.3. Refined Thickness Measurement Using FFT Model

The FFT-based algorithm was applied to both the Si and SiC datasets. For the SiC wafer, the results are shown in Table 2.

Table 2. SiC Thickness Results using FFT-Based Model

Incident Angle	Calculated Thickness (μm)	Mean Thickness (μm)	Relative Difference (%)
10°	10.9751	11.0616	1.56
15°	11.1480	11.0616	1.56

The FFT method yields thickness values of 10.9751 μm and 11.1480 μm for the two angles. These results are highly consistent, with a relative difference of only 1.56%. This marked improvement in consistency demonstrates the FFT method's ability to effectively eliminate the systematic errors caused by the asymmetric fringe shapes of multi-beam interference. The refined and more accurate average thickness for the SiC epitaxial layer is determined to be 11.0616 μm.

4. Conclusion

This study successfully developed and validated a progressively sophisticated methodology for measuring the thickness of SiC epitaxial layers using infrared interferometry. The journey began with a fundamental two-beam interference model incorporating a dynamic Drude-Sellmeier refractive index. To enhance robustness against experimental noise, a novel global interference order alignment algorithm was proposed, which provided a solid initial thickness estimate.

Recognizing the limitations of extremum-based methods in the presence of multi-beam interference, a superior FFT-based model was developed. Quantitative analysis using kurtosis confirmed the presence of weak multi-beam effects in the SiC data. The application of the FFT model, which analyzes the global frequency characteristics of the interference signal, successfully mitigated the systematic errors associated with fringe shape distortion. This resulted in a significant improvement in measurement consistency across different incident angles and yielded a final, high-accuracy thickness of 11.0616 μm for the SiC epitaxial layer. This work demonstrates a powerful, multi-stage approach to extracting precise physical parameters from complex spectral data, achieving a leap from idealized models to real-world accuracy.

Looking ahead, the FFT-based analysis model proposed in this research demonstrates high feasibility for practical applications. It can be integrated into an automated, rapid, and non-destructive online or offline inspection system for quality control in SiC epitaxial wafer production, thereby improving device performance uniformity and reducing costs. Future development directions could include: 1) Combining this technique with microscopy to develop Micro-FTIR measurements, enabling 2D mapping of the epitaxial layer thickness distribution; 2) Extending the algorithm to simultaneously resolve the thickness and optical constants of multi-layer structures, such as SiC-on-GaN; and 3) Utilizing machine learning algorithms to further optimize baseline correction and peak detection, enhancing the automation and accuracy of the algorithm in more complex or low signal-to-noise ratio scenarios.

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