A Review of SiC Wafers In-Line Detection Method in Power Device Fabrication

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Abstract. Silicon carbide (SiC) has outstanding advantages such as wide band gap, high electron saturation drift speed, high thermal conductivity, high voltage and high temperature resistance. It is particularly suitable for making high-power devices. The in-line detection of wafers in the manufacturing process of SiC devices can reflect the quality of incoming materials and process quality. It is a very important part of the manufacturing process. SiC wafer’s in-line inspections involves characterization of the epilayer thickness, surface defects and contamination, wafer warping, dielectric and metal film thickness, etching morphology, etc. Various test methods are compared and discussed in this paper and suggestions are given on detection method selection.

1. Introduction

Silicon carbide (SiC) is a typical representative of the third-generation semiconductor materials, and it is also one of the most mature and widely used wide band-gap semiconductor materials for crystal growth technology and device manufacturing level at present [1]. After more than 30 years of development, the silicon-based power electronic devices have approached the limit of material and device structure [2]. Compared with silicon based devices, silicon-based power electronic devices have higher voltage resistance and lower loss, which have good application prospects in the fields such as electric automobiles, green energy and smart power grids. Currently, 4H-SiC wafer is generally adopted in the industry to manufacture the SiC power devices. SiC wafer is a semi-transparent semiconductor material, it has a higher hardness than silicon wafer, the price of a single wafer is much higher than that of a silicon wafer, and the in-line test method in its chip manufacturing process also has a certain particularity.

The manufacturing process of SiC chip generally includes incoming material inspection, cleaning, coating, photolithography, etching, injection and other process steps. Among them, the incoming material inspection generally includes the thickness of SiC epitaxial layer, the warping degree of wafer and the defects and contamination of surface, the detection of coating generally includes medium film detection and metal film detection, and the photolithography and etching generally need to detect the cross section morphology after the photolithography and etching. As shown in Figure 1.
Figure 1. Detection Items in the Manufacturing of SiC Power Devices

2. **Incoming Material Inspection**

Silicon carbide devices are generally made on the silicon carbide wafer with a certain thickness of epitaxial thin film, and this kind of silicon carbide wafer is usually termed as silicon carbide epitaxial wafer. When silicon carbide epitaxial wafer is supplied, it is necessary to detect the thickness of wafer, the thickness of epitaxial layer, the warping degree of wafer and the defects and contamination of wafer surface. Because of the high requirements on the cleanliness and quality of epitaxial wafers in the production process of power semiconductor devices, optical method is preferred for the above detection so as to avoid the unnecessary contamination and damage to the wafers.

2.1. **Detection for Wafer Surface Particles and Defects**

The particles and defects on the wafer surface can be detected by emitting laser and collecting its signals [3]. The conventional devices for detecting the surface defects of silicon wafer are also measured by emitting lasers and collecting signals, but there is no noise shielding device at the receiving end. SiC wafer is a kind of semi-transparent material. If it is measured by traditional equipment, the signal receiver will receive the signals from the inside, the back and other positions of the wafer, which will bring about the result that the captured signals are not the correct signals on the surface. The surface defect detection device specially designed for detection SiC and other semi-transparent wafers has added a noise signal shielding device at the signal receiving end to enable it to distinguish the surface and internal defect signals. The result comparison between the traditional surface defect detection system and SiC wafer surface defect detection system is shown in Figure 2. The traditional surface defect detection system also considers the pattern of manipulator at the bottom of wafer as a defect, while the SiC special detection equipment can clearly distinguish the surface and internal defects of wafer.
2.2. Detection of SiC Epitaxial Layer Thickness

The thickness of SiC epitaxial layer is a key parameter in the fabrication of SiC devices, and it directly determines the pressure-proof level of SiC devices. Fourier transform infrared spectrometer or double beam infrared spectrophotometer is generally used to measure this parameter, and the corresponding thickness of the epitaxial layer can be calculated according to the extremum peak of the interference fringe in the reflection spectrum, the optical constant of the sample and the angle of incidence. The test principle is shown in Figure 3, and the thickness of the epitaxial layer is [4]:

$$T_i = \left(P_i - 0.5\right) \frac{0.001 \cdot \lambda_i}{2 \sqrt{n_1^2 - \sin^2 \theta}}$$

(1)

$T_i$ is the corresponding thickness of the epitaxial layer of the $i^{th}$ extremum, and the unit is micron, $P_i$ is the corresponding series of the $i^{th}$ extremum, $\lambda_i$ is the wavelength at the $i^{th}$ extremum, and the unit is nanometer, $n_1$ is the refractive index of the epitaxial layer of 4H silicon carbide, generally 2.55 is taken, $\theta$ is the angle of incidence of incident light, and the unit is degree.

![Figure 3](image_url)  
**Figure 3.** A schematic diagram of the principle of SiC epi layer thickness measurement by Fourier transform infrared spectrometer

Recently, some researchers also choose to use infrared ellipsometer (IRSE) to measure the epitaxial thickness of SiC. The result shows that the fitting degree of the measured spectrum and optical model can reach above 0.996, as shown in Table 1 [5].
Table 1. Test Results of SiC Epilayer Thickness by IRSE

| Layer Type | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 |
|------------|----------|----------|----------|----------|----------|
| Thickness of the Substrate | 350 μm | 350 μm | 350 μm | 350 μm | 500 μm |
| Expected Thickness of Epitaxial Layer | 100 μm | 100 μm | 100 μm | 100 μm | 100 μm |
| The 1st Layer: 1 μm | 41.27 μm | 12.71 μm | 180 μm | 180 μm | 180 μm |
| The 2nd Layer: 0.5 μm | 41.86 μm | 12.94 μm | 181.81 μm | 179.36 μm | 179.36 μm |
| Test Results of Epitaxial Thickness | 0.9979 | 0.9967 | 0.9988 | 0.9975 | 0.9994 |
| Degree of Fitting (R²) | 0.9979 | 0.9967 | 0.9988 | 0.9975 | 0.9994 |

2.3. Detection of the Wafer Surface Evenness
The warping degree test of silicon carbide wafer is also an important detection item for the incoming material inspection. When manufacturing the low-pressure silicon carbide devices, as the thickness of the epitaxial layer is relatively thin, the surface stress and warping degree of the wafer are generally not too large, which will not affect the subsequent process; when manufacturing the high pressure silicon carbide devices on a large-size wafer, as the thickness of the epitaxial layer is very thick, and the surface stress is often highlighted after the processes such as high-temperature ion implantation and high-temperature annealing, which makes the wafer produce obvious warping. In the subsequent process, the risk of debris will be increased, and the wafer with a high warping degree is not easy to be grabbed by the manipulator, which will seriously affect the production efficiency. Oblique incidence laser interferometry can be used to measure the flatness parameters of SiC wafer, such as bow, warp, SORI, TTV, and TIR, etc. From the flatness parameters, the surface stress of the wafer can be calculated. This method can be adopted to select the wafer whose flatness does not meet the requirements when the wafer is supplied. In this way, it can avoid the waste of manpower, material resources and time due to the insufficient stress of wafer that cannot be issued to lower levels in the process of manufacturing. The aggregate thickness of wafer can also be measured by adopting the method of oblique incidence laser interferometry.

3. Film Thickness Measurement and Quality Assessment
In the manufacturing process of SiC devices, the film thickness shall be measured and the film quality shall be evaluated to monitor the film process and provide data reference for the subsequent processes such as etching.

3.1. Film Thickness Measurement
The film thickness gauge based on the principle of reflection is widely used in the measurement of dielectric films in the manufacturing process of silicon-based devices. However, when the film thickness gauge is used to measure the film on the translucent SiC wafer, the intensity of reflected light will be much lower than that on the opaque SiC wafer. Therefore, the accuracy of using the film thickness gauge to measure the film on the SiC wafer is poor. However, the adoption of ellipsometer to measure the thin film on SiC wafer is a good choice. The ellipsometer polarizes the light so that it has P light and S light components perpendicular to the light path. According to the difference of the ratios and differences of the two components, the ellipsometer signal collecting end will obtain more abundant information and the measured film thickness will be more reliable. The test principle of the ellipsometer is shown in Figure 3, according to the known polarization state of the incident light, the polarization state of the reflected light can be measured. Based on the optical model, the parameters such as film thickness of the tested structure can be calculated.
3.2. Film Quality Evaluation

The quality of the oxide layer of wafer is an important parameter in the production of MOSFET. The traditional method is to make a capacitor structure and test its C-V characteristics. The C-V curve shall be compared with the ideal high frequency C-V curve, and the parameters such as the density of interfacial states $D_{it}$ can be calculated therefrom to characterize the quality of the oxide layer [6]. The smaller the $D_{it}$, the higher the quality of the interface between the oxide layer and the SiC substrate, and the calculation method of $D_{it}$ is:

$$D_{it} = \frac{C_{ox}}{q} \left( \frac{dV_g}{d\phi_s} - 1 \right) - \frac{C_s}{q}$$  \hspace{1cm} (2)

Among them, $C_{ox}$ is the capacitance of the oxide layer, $V_g$ is the gate voltage and $\phi_s$ is the surface potential.

In recent years, a contactless Corona Kelvin measurement method has appeared. This contactless electrical characteristic description method can test the C-V characteristics between the oxide layer and the substrate without making a capacitor structure, which is more economical for the production of semiconductor and less polluting for the in-line use [7-9]. The test principle is shown in Figure 5, Corona probe will spray the electric charge onto the sample within the 6mm diameter range, and the point at which an electric charge is applied to the sample will be quickly transferred under the Kelvin probe to measure the change of the surface voltage along with the time. Test once respectively under the conditions of light and non-light to determine the flat band status. The density of the interfacial states can be calculated according to Formula (3).
\[ D_a = \frac{\Delta Q_{a}}{\Delta V_{sb}} \]  

(3)

4. Etching Morphology Test

Deep groove etching morphology is also a parameter worth paying attention to. In the manufacturing process of grooved silicon carbide devices, the groove structure with high aspect ratio is often adopted. It is of great importance to conduct the in-line and non-destructive precise detection for the structures in the manufacturing process. Scanning electron microscope (SEM) can be used to check the critical size of the cross section, but sectioning is required for each test, which is not conducive to large-scale production.

Figure 6. Schematic illustration of SEM measurement

Figure 7. MBIR test diagram of etching morphology
Model-based infrared reflection technique (MBIR) can be used to test the key parameters such as the top plate, bottom plate and over-etching of the deep groove. It can be easily used to monitor the deep-groove etching morphology during the process of in-line manufacturing [10, 11]. Before the first test, it is necessary to slice the test structure and measure the key dimensions with SEM, and then model the tested structure in the MBIR tester. In the subsequent test, the wafer is only need to be placed under the MBIR tester for non-contact test, the spectrogram of the measured reflectivity and wavelength shall be compared with the model, and the key dimension parameters such as top, middle, bottom and over-etching can be obtained by calculation. The schematic diagram of the modeling and testing process is shown in Figure 7.

5. Other Measurements
In order to monitor some key processes, such as the changes of the wafer surface before and after the high-temperature ion implantation and annealing processes, it is necessary to measure the roughness of the wafer surface before and after the processes. Generally, the surface roughness can be measured either by adopting the atomic force microscope (AFM) or the white light interferometry. Step height test is generally carried out by a step profiler, and white light interferometry can also be adopted for the steps formed by the opaque or translucent films. As for the metal film uniformity test, the four-probe method can be used to measure its square resistance. These measurements are essentially the same as those used in the manufacturing process of conventional silicon-based devices.

6. Conclusion
SiC materials are more and more popular in the high-voltage and high-power electronic devices and application fields because of its unique advantages. Currently, the cost of SiC wafer is still at a higher level than that of Si wafer. In order to further control the production cost, it is necessary to give special consideration to non-destructive and non-stained detections in various detections during the production of SiC devices. By adopting the non-contact optical method, considering the translucent characteristics of SiC wafer and the special processing of optical signals, the surface defects, flatness, thickness of epitaxial layer, thickness and quality of thin film, step height and even section morphology of SiC wafer can be well measured. The in-line measurement of the above parameters is of great significance for the quality control in the manufacturing process of SiC devices.

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