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Silicon Carbide Epitaxial Defects and Substrate Defects Analysis by Dynamic Photoluminescence and X-Ray Topography

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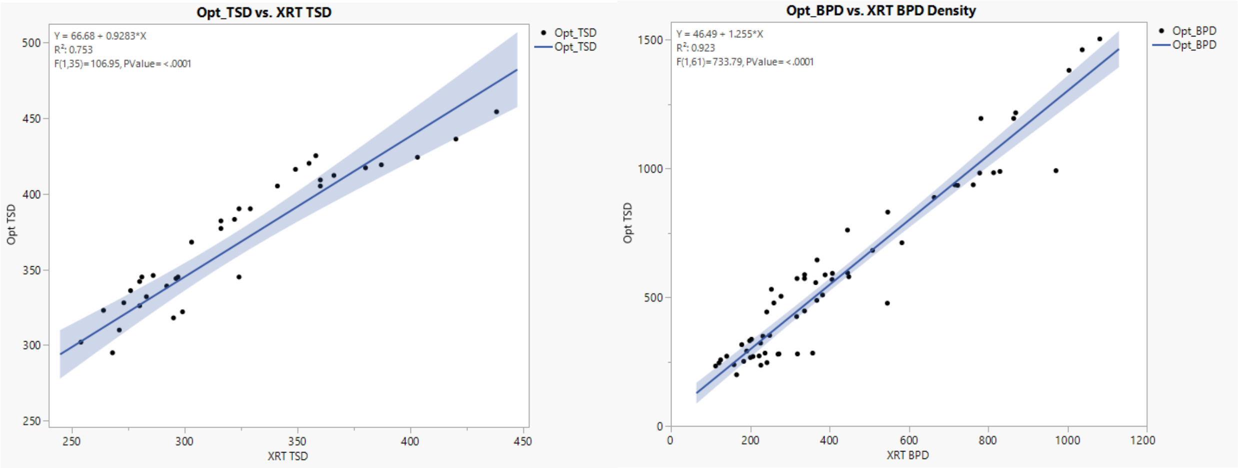
Abstract. The performance and reliability of silicon carbide (SiC) devices are critically dependent on the quality of epitaxial layers which in turn are influenced by substrate properties. The accurate classification of epitaxial defects coming from substrate crystal defects and surface defects is critical since these can adversely affect device performance. In this paper, two new methods of defect characterization in substrates and epitaxial layers are presented utilizing photoluminescence (PL) spectrum and carrier lifetime. These methods can be used to study the evolution of defects from substrates to epi and to better predict Epi yields.

Introduction

4H polytype of silicon carbide (4H-SiC) is a semiconductor material finding increased use in power devices due to its wide bandgap, high breakdown voltage and high thermal conductivity [1]. The performance and reliability of silicon carbide (SiC) devices are critically dependent on the quality of epitaxial layers which in turn are influenced by substrate properties. The accurate classification of the device killer defects in epitaxial layers is critical for predictive capabilities [2]. In general, most epitaxial defects are inspected and classified by confocal differential interference contrast (DIC) microscopy technology. DIC scan images, combined with photoluminescence (PL) intensity, are used to classify defects into different defect bins for both substrates and epi. This study uses dynamic optical reflectance by pump-probe technology to identify dislocations in substrates and PL peak lambda and carrier lifetime based on band edge emission of each defect measured by Time Resolved PL (TRPL, 355nm laser with 30kHZ 600ps pulse) to identify device killer defects in epi layers [3, 4].

Experiments

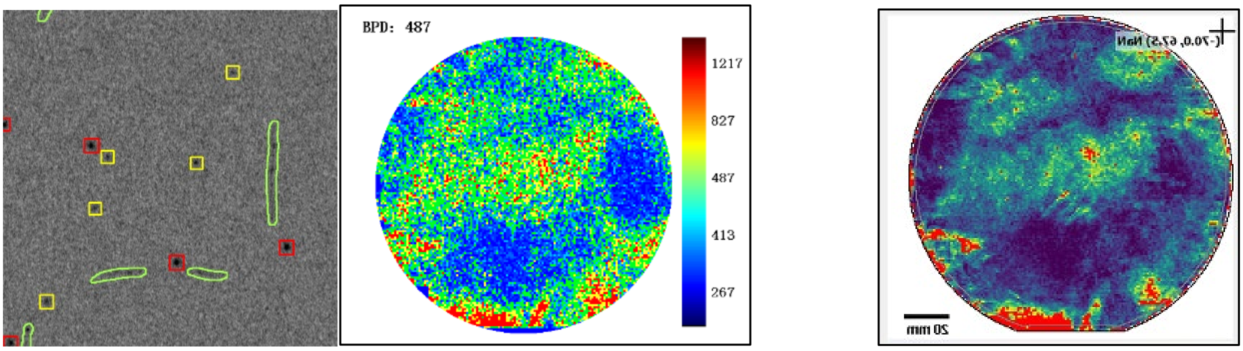
4H-SiC substrates were scanned initially by standard Lasertec SICA88 to identify crystal and surface defects. Conventional method for dislocation detection and classification in SiC uses KOH based etching chemistries followed by etch pit classification. This method is destructive and can show variability due to different chemistries and the need to control etching conditions carefully. Non-destructive methods of dislocation detection can avoid the disadvantages of etching and are more conducive to correlation with post-Epi defects. Previously, non-destructive detection and classification of dislocations have been studied using Lasertec SICA PL images [5]. In the present study, threading screw dislocations (TSD), threading edge dislocations (TED) and basal plane dislocations (BPD) are identified using a new dynamic optical reflectance technique that employs pump-probe technology (similar to photo-reflectance). Results from a beta version of this tool were correlated with the X-ray topography (XRT) measurements. A large dataset of wafers was used for this study and tool reproducibility, and repeatability was verified. The optical approach is also faster compared to XRT and can detect TEDs as well. XRT data was collected using Rigaku's XRT micron system. Fig. 1 (a) and (b) shows the correlation between the two different measurements for TSD and BPD. The R^2 factors are close to 0.753 for TSD and 0.923 for BPD. The optical method shows higher values for TSD due to some TED and TMD being identified as TSD. XRT BPD measures a volume density which is converted to a surface density whereas the dynamical optical measurement measures the BPD signal at the surface which can also lead to discrepancy between the two measurements. The exact number of BPD on the surface is also affected by the accuracy of BPD counting in areas where there are high density clusters.



(a) (b)

Fig. 1. Dynamic pump-probe optical measurement and XRT TSD (a) and BPD (b) measurements show linear correlation.

Fig. 2 (a) shows TSD, TED and BPD identification from the optical measurement scan image. Map images were processed using computer vision for improved classification and counts. Fig. 2 (b) is the optical measurement BPD map and Fig. 2 (c) shows the XRT BPD map on the same wafer. The BPD defect distribution on the wafer is similar between the two techniques.



(a) (b) (c)

Fig. 2. The scan image of the dynamic pump-probe optical measurement for TSD, TED, and BPD (a), and BPD map distribution by the dynamic optical measurement (b) and the corresponding BPD map distribution of XRT scan on the same wafer (c). The two different measurements show similar trends

Epitaxial films were grown on these substrates using multi-wafer chemical vapor deposition (CVD). These wafers were scanned using Lasertec SICA again to identify epitaxial defects. The epitaxial wafers were also scanned and analyzed using EtaMax MiPLATO-SiC for PL spectrum and carrier lifetime of epitaxial defects. First, substrate defects and epitaxial defects were compared to correlate and detect propagation of defects from the substrate surface to epitaxial layers. However, it was found that SFs (stacking faults) were not easy to trace down to substrate defects. Most substrate BPD were converted into TEDs and could not be identified through standard characterization methods.

Lasertec SICA is the standard technique used to characterize epitaxial defects. Epi defects are mostly classified by DIC images, and the majority of defects are stacking faults based on DIC images and PL intensity. Some SF defects overlap in DIC and PL images. However, it is difficult to identify specific killer defects as shown in Fig. 3. Epi BPD counts are minimal and quite different from substrate BPD distribution (not shown here). Poly type inclusions are identified through DIC images.

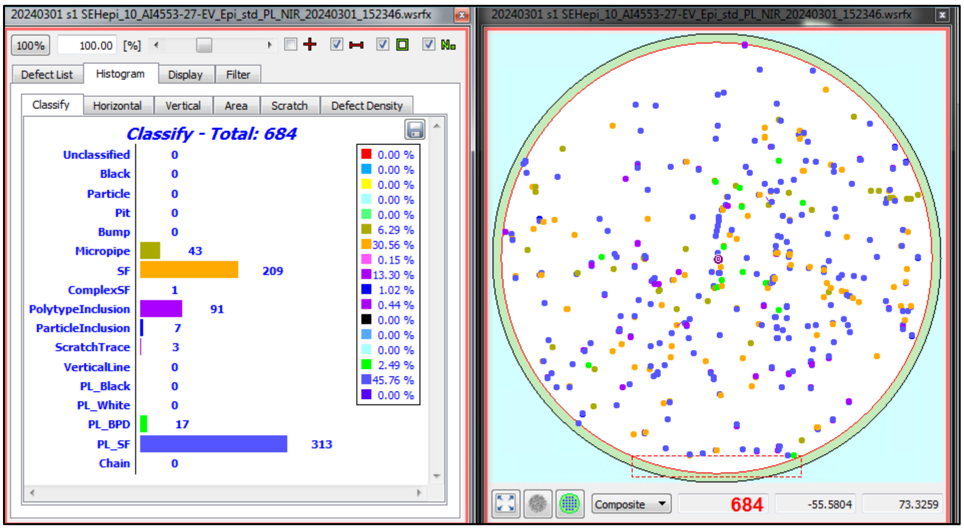


Fig. 3. Lasertec SICA scan on an epi wafer shows various defects and needs to filter out as needed.

This wafer was scanned again using EtaMax MiPLATO. Figure 4 shows the scanned data with classified SFs and polytype inclusions, associated spectrum and carrier lifetime. Analysis of epi defects with a peak lambda of 540nm in the PL spectrum can reveal additional 3C poly type inclusions, which do not appear in DIC images. Polytype and some SF defects show a peak at 540nm. The ratio of polytype inclusion from DIC detection to 3C defect using the 540nm peak lambda ranges from 95/109 to 90/122. This implies that DIC based classification may miss some 3C poly type defects. Thus, defect classification based on peak lambda can result in improved killer defects identification for correlation with device performance. In addition, the 424nm peak lambda in the PL spectra reveals all 1SSF. Most poly type inclusions and major defects are relatively well matched between SICA and MiPLATO-SiC as shown in Fig. 3 and 4.

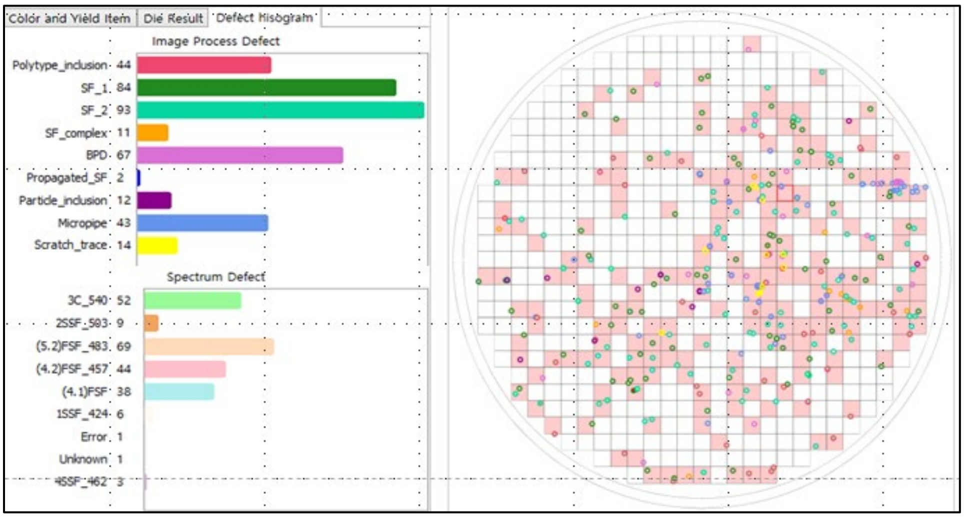


Fig. 4. EtaMax MiPLATO-SiC scan on an epi wafer shows various defects and classification based on PL peak lambda.

Individual defects were analyzed using 5um spatial resolution for TRPL carrier lifetime as shown in Fig. 5. The area surrounding the defects has abrupt changes in spectrum and carrier lifetime. The carrier lifetime of normal epi area is longer than 70 ns and the carrier lifetime of most SF defect areas is about 20-60 ns. 3C polytype inclusion related defect spots have the shortest lifetime as 20-40 ns. The carrier lifetime of substrate defects is shorter than 15 ns. These different carrier lifetimes of defects and materials enable dynamic PL to be more efficient in filtering out crystal defects than static PL imaging. Depending on epi structure and growth mechanism, band-edge carrier lifetime has some differences. Relatively thicker structure has usually longer lifetime. These initial results show the potential advantage of utilizing carrier lifetime measurement to gain further insight into substrate and epi defects.

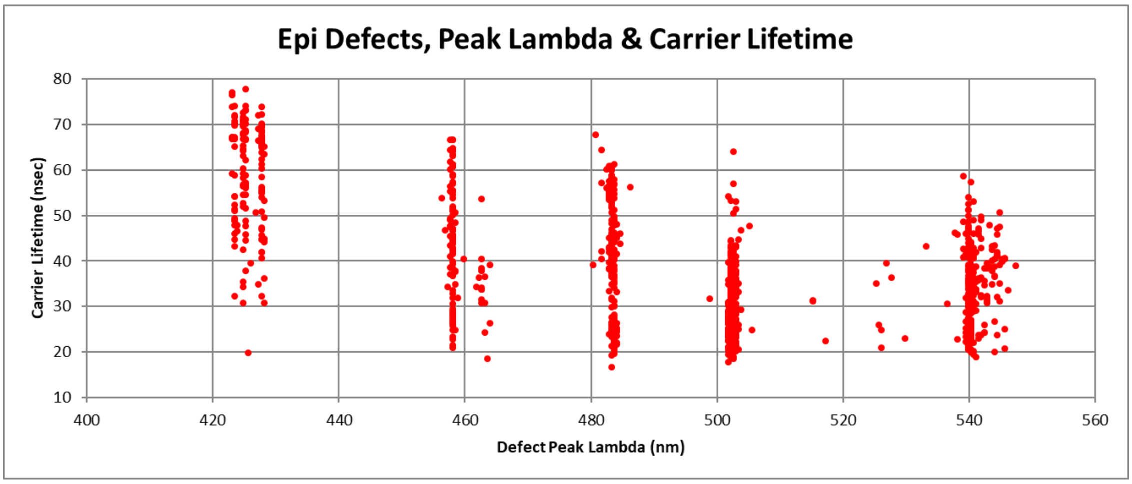


Fig. 5. Time resolved photo luminescence (TRPL) shows the carrier lifetimes on defect areas with different peak lambda as shorter than the carrier lifetime of the defect free area.

Discussion

Lasertech SICA reveals typical SiC substrate defects and most of the epi defects. While Epi killer defects can be identified, it is not easy to correlate these killer defects to substrate defects. New metrology using pump- probe technology (TimeTech Spectra) and XRT (Rigaku) provide nondestructive mapping characterization of TSD, TED, and BPD on substrates. Spectroscopic PL characterization by Horiba's MiPLATO-SiC identifies all epi killer defects on various epi wafers, which can be correlated relatively well with substrate defects from SICA defects, TSD, TED, and BPD.

XRT section topography can be employed for detailed analysis by dissecting epitaxial wafers and tracing the origin of killer defects back to the substrate, as shown in Fig. 6. While this approach provides valuable insight, it is limited in capturing all killer defects across the wafer. Therefore, it serves best as a complementary, non-destructive technique for analyzing selected defects identified through XRT mapping.

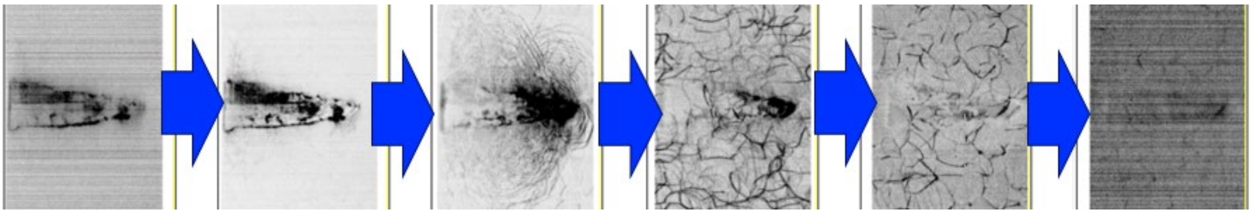


Fig. 6. XRT section topography tracks the killer defect from the top of thick epi film to the origin of substrate defect. The first three images are from Epi film and the next three images from substrate (proportional to propagational depths). This propagation indicates this defect as IGSF (In-Grown Stacking Faults), which originated from substrate and formed in the buffer layer during epi growth.

A combination of multiple characterization techniques enables more accurate detection and classification of killer defects. Using TRPL, the carrier lifetime of substrate and epi will be evaluated to confirm the formation and evolution of killer defects, like single Shockley SF (1SSF) from BPD. The evolution of defects from substrate to Epi is challenging and a subject of continued study.

Summary

This study employs advanced metrology techniques for analyzing defects in both SiC substrates and epitaxial layers. We present results from a non-destructive optical method that accurately detects and classifies BPD, TSD, and TED in substrates. Additionally, PL spectroscopy and TRPL measurements demonstrate enhanced capability to distinguish among various types of epitaxial defects. Together, these techniques enable more effective correlation between substrate and epitaxial defects, supporting improvements in material quality and yield.

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