HORIBA

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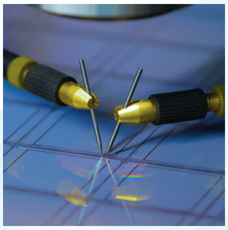
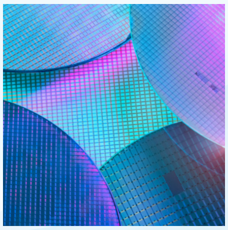
Micro-Photoluminescence Mapping and Identification of Yield-Killing Defects in 4H-SiC





Application Note
Semiconductors
OSD250302

Praveena Manimunda - Applications Scientist II, Piscataway, NJ

Introduction

The 4H polytype of silicon carbide (4H-SiC) is a wide-bandgap semiconductor that has emerged as a critical material for high-performance power electronics, including MOSFETs, Schottky diodes, and high-frequency devices. With a bandgap of approximately 3.26 eV, a high thermal conductivity of 4–4.9 W/cm·K, and a high critical electric field (~3 MV/cm), 4H-SiC enables operation at higher voltages, temperatures, and switching frequencies than conventional silicon. [1] These intrinsic properties allow for thinner drift layers, smaller chip areas, and efficient thermal management, which are key advantages in compact and high-efficiency power devices. However, the exceptional performance of 4H-SiC is strongly dependent on the crystalline quality of the material. Even low densities of structural defects can significantly degrade device performance by introducing leakage paths, lowering carrier lifetime, or affecting threshold voltage stability.

Application Category	Examples
Power Electronics	MOSFETs, Diodes, IGBTs, Power Modules
High-Frequency Devices	RF Amplifiers, Microwave Transistors, Radar Systems
High-Temperature Systems	Aerospace, Automotive Powertrain, Down-hole Drilling
Optoelectronics & Sensors	UV Photodiodes, LEDs, Radiation Sensors
Renewable Energy	Solar Inverters, Wind Turbines, Energy Storage
Industrial & Transportation	EV Chargers, Railway Systems, Smart Grids

Table 1. Summary of 4H-SiC Applications [1,2]

Materials and Methods

Bulk 4H-SiC substrates are typically grown using the physical vapor transport (PVT) method at temperatures exceeding 2200 °C. [3] Schematic representation of the PVT process is shown in Figure 1. In PVT growth, SiC powder sublimes under a high-temperature thermal gradient and the vapor phase condenses onto a seed crystal to form large, single-crystal boules. While PVT can produce high-quality crystals, maintaining uniform stoichiometry and controlling the thermal gradient is challenging, often leading to structural imperfections such as micropipes, threading screw and edge dislocations (TSDs/TEDs), basal plane dislocations (BPDs), and stacking faults. Among these, TSDs and micropipes are especially detrimental, often serving as leakage pathways or reducing breakdown voltage, while BPDs can expand under electrical stress and degrade MOSFET channel mobility. [4] TEDs and certain point defects are typically less harmful, often considered benign, though their presence may still influence uniformity or long-term reliability.

To achieve high-quality device layers, epitaxial growth via chemical vapor deposition (CVD) is employed on PVT-grown substrates. In CVD, precursor gases react on the heated substrate surface to form thin, uniform epitaxial layers (Figure 1). [5] Across all growth stages, yield is a critical concern: defects in bulk substrates, epitaxial layers, or gate oxides can lead to device failure or degraded performance, emphasizing the importance of defect control for cost-effective manufacturing.

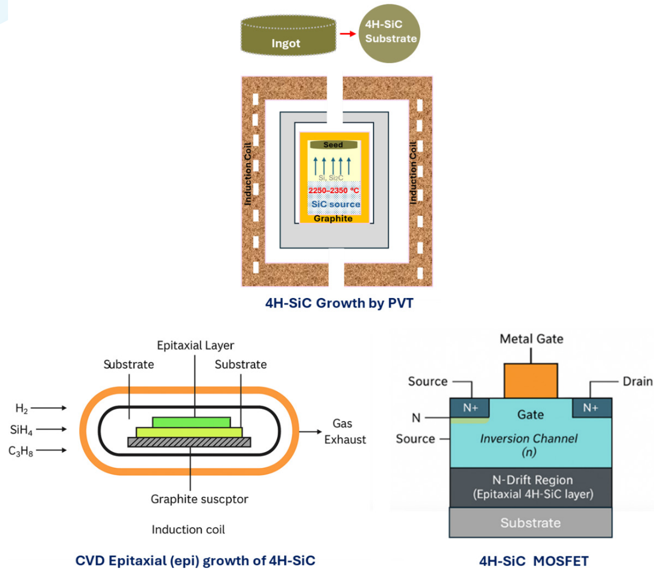


Figure 1. Schematic illustration of PVT growth of 4H-SiC, Epilayer deposition and cross section of 4H-SiC MOSFET

Accurate and high-resolution defect characterization plays a key role in mitigating these challenges. Micro-photoluminescence (µ-PL) has emerged as a particularly

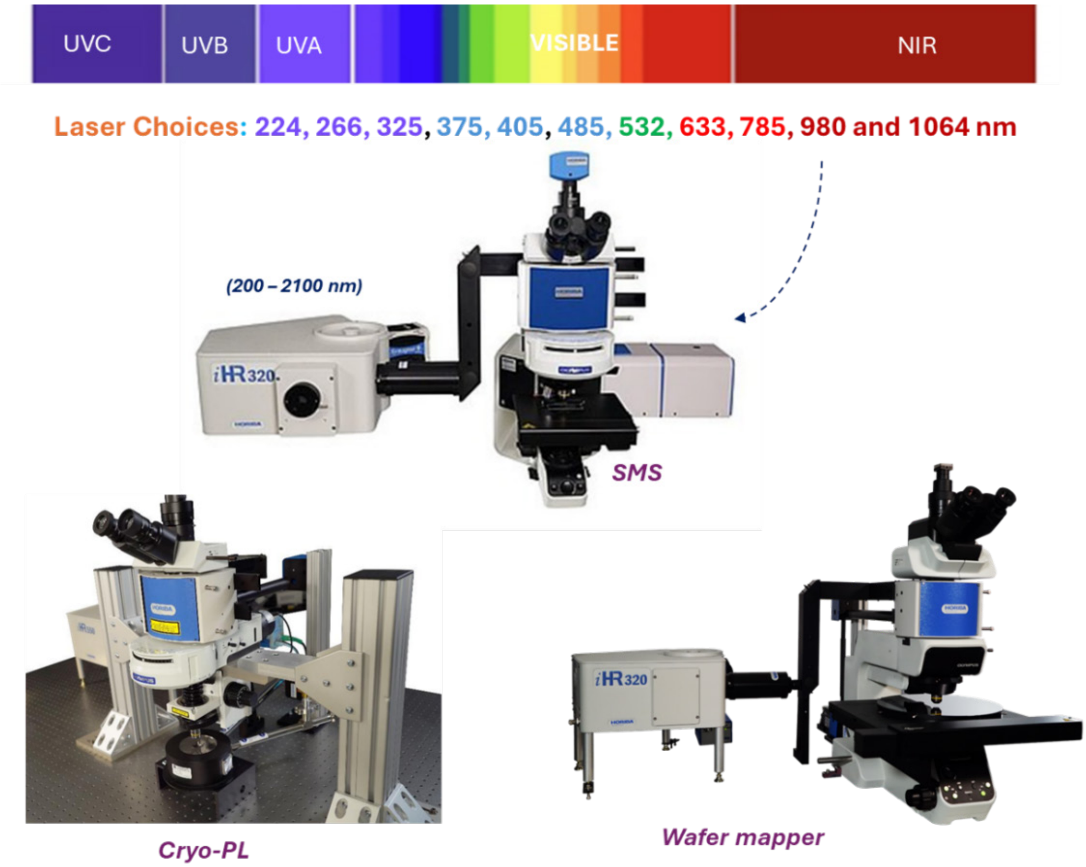


Figure 2. Photographs of modular UV-optimized HORIBA SMS systems

powerful technique for this purpose. Unlike conventional macro-scale PL, which averages emission over a large surface area, μ-PL provides submicron spatial resolution, enabling the detection of individual dislocations, micropipes, stacking faults (SFs) and localized defect clusters. This allows researchers to distinguish between electrically active defects that directly affect device performance and benign point defects, map defect distributions across wafers, and correlate optical signatures with structural features observed via TEM or AFM. The non-destructive nature of μ-PL, combined with its ability to resolve sparse but critical defects, makes it a valuable tool for improving epitaxial growth processes and enhancing yield in high-voltage 4H-SiC devices.

This application note demonstrates how deep-UV optimized HORIBA multimodal SMS can be applied to characterize PVT-grown 4H-SiC substrates, as well as epitaxial 4H-SiC structures. The HORIBA SMS320 is an advanced spectroscopy metrology tool designed for high spatial and spectral resolution analysis of semiconductor wafers up to 300 mm in diameter (Figure 2). Its unique capability to perform Photoluminescence (PL), Time-Resolved Photoluminescence (TRPL), Raman, Reflectance, and Transmittance mapping provides a comprehensive characterization platform. With the deep-UV optimized SMS configuration, users can select excitation sources at 224 nm, 266 nm, or 325 nm. Additionally, the system supports an open-frame architecture for cryogenic PL measurements.

In this study, considering the band gap of 4H-SiC (3.26 eV), a 325 nm continuous-wave (CW) laser was chosen as an excitation source. Commercially available 4H-SiC samples were utilized for micro-PL mapping.

Results and Discussion

Figure 3a shows the photoluminescence (PL) spectrum recorded from the 4H-SiC substrate, exhibiting a strong emission peak near 390 nm, which corresponds to excitonic recombination occurring close to the bandgap of 4H-SiC. Large-area PL maps for substrates with low and high defect densities are presented in Figures 3b and 3c. Typical defects in physical vapor transport (PVT)–grown substrates include micro-scratches, inclusions, threading screw dislocations (TSDs), threading edge dislocations (TEDs), and micropipes. These defect regions exhibit variations in PL intensity or distinct emission wavelengths. The high-defect-density sample shows a larger number of micro-scratches, inclusions, and micropipes.

Raman spectroscopy provides complementary information by identifying the composition of defective regions, particularly inclusions, which may arise from growth-induced polytype inclusions or organic/chemical contaminants. Figure 3d presents the Raman spectra, optical image, and Raman map of a localized defect. The most prominent Raman peaks correspond to the transverse optical (E_2, ~776 cm^{-1}) and longitudinal optical (A_1(LO), ~972 cm^{-1}) modes—characteristic signatures of the hexagonal 4H-SiC polytype.

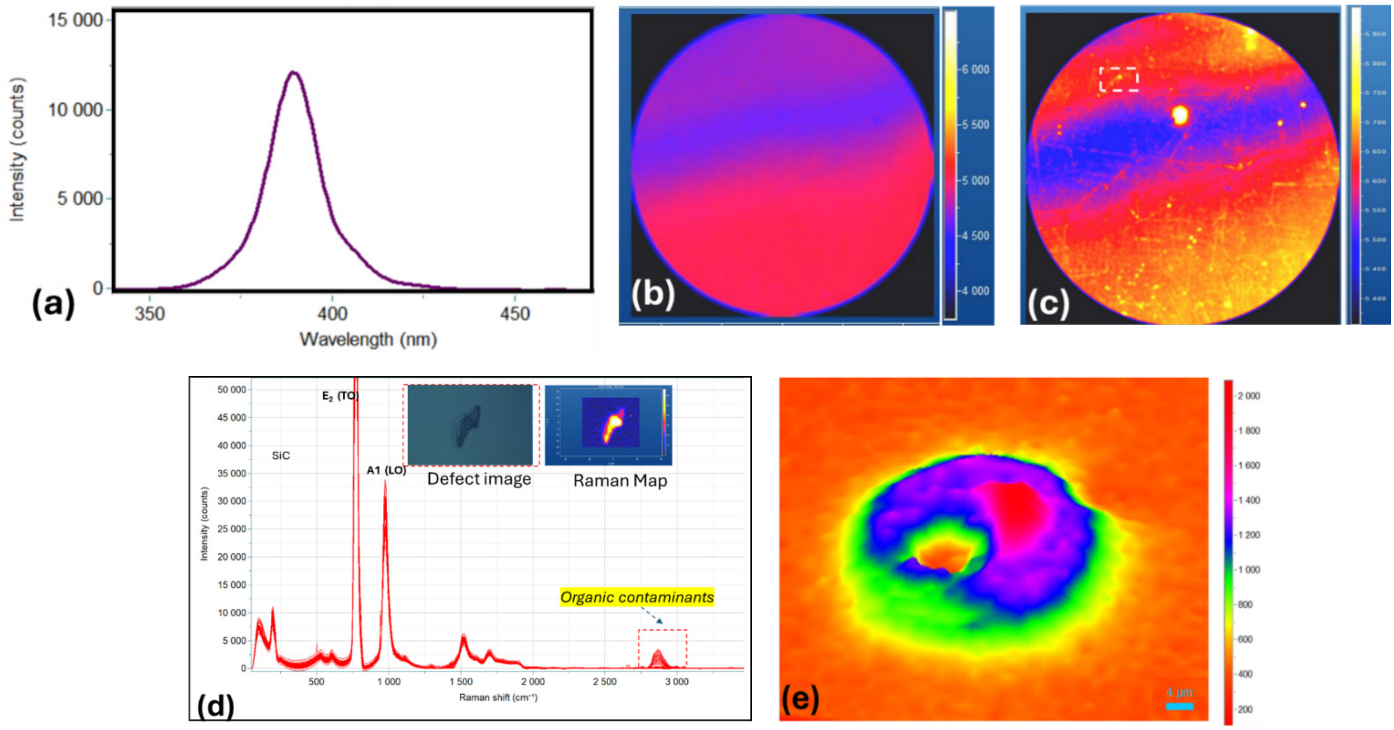


Figure 3. (a) Photoluminescence (PL) spectra from a 4H-SiC substrate; (b) and (c) large-area PL maps corresponding to substrates with low and high defect densities; (d) Raman spectra, optical image, and Raman map of a localized defect; (e) PL map illustrating intensity variation near a micropipe on the 4H-SiC substrate.

In contrast, spectra acquired from the defect region display additional peaks in the 2850–3000 cm^{-1} range, typically associated with C–H stretching vibrations. These features are diagnostic of organic contamination, such as residual hydrocarbons from solvents or processing agents, polymer residues, or carbon-based adsorbates. Figure 3e shows a PL intensity map corresponding to the micropipe defect. Micropipes are hollow-core defects that form along the c-axis during physical vapor transport (PVT) growth of SiC. They are essentially large screw dislocations with a hollow core and a Burgers vector of several lattice units. Micropipes act as non-radiative recombination centers, leading to localized changes in photoluminescence intensity and emission wavelength. In this example the hollow region showed reduced PL intensity, while increased scattering and diffuse PL were observed around the defect. Micropipes are among the most detrimental defects in 4H-SiC, acting as leakage channels, breakdown initiation sites and reliability risks. Their elimination through improved PVT growth and wafer inspection is essential for achieving high-yield, high-voltage SiC device production.

Epitaxial growth of 4H-SiC presents several challenges primarily related to maintaining high crystalline quality and uniformity over large wafer areas. The process, typically carried out by CVD at high temperatures (~1500–1650 °C), must carefully control parameters, such as temperature, precursor flow, and reactor design to minimize defect formation. Common issues include the propagation of substrate defects such as threading dislocations and basal plane dislocations into the epilayer, as well as the formation of new defects like triangular defect and stacking faults. Additionally, the formation of polytype inclusions remains a critical issue, as it can locally alter the electrical and optical properties of the epilayer, thereby degrading device performance. [6,7]

High-resolution micro-photoluminescence mapping was done on an epitaxially grown 4H-SiC sample. Figure 4a, shows micro-PL intensity map of a stacking fault region, while Figure 4b shows variations in PL peak wavelength near the stacking fault and inclusion zone. Stacking faults (SFs) are planar defects formed due to local deviations in the stacking sequence of Si–C bilayers within the hexagonal structure of 4H-SiC. These faults locally create quantum well–like regions with lower bandgaps compared to the surrounding 4H-SiC matrix, resulting in characteristic PL emission bands at longer wavelengths [7,8]. PL spectra recorded at different regions of the stacking faults are shown in Figure 4c. Single Shockley stacking faults show emission near 2.9 eV (430 nm) while double Shockley stacking faults show emission at 2.7 eV (~460 nm). The local 3C-SiC-like region in a stacking fault has a smaller bandgap (~2.3 eV) compared to 4H-SiC (~3.26 eV) with emission around 2.3 eV (~539 nm). Raman spectra acquired from the 3C-SiC inclusion region and the surrounding 4H-SiC substrate are shown in Figure 4d. 3C-SiC region shows a strong peak near 796 cm^{-1}, while the substrate region has peaks corresponding to the E$_2$, ~776 cm^{-1} and A$_1$(LO), ~972 cm^{-1} modes.

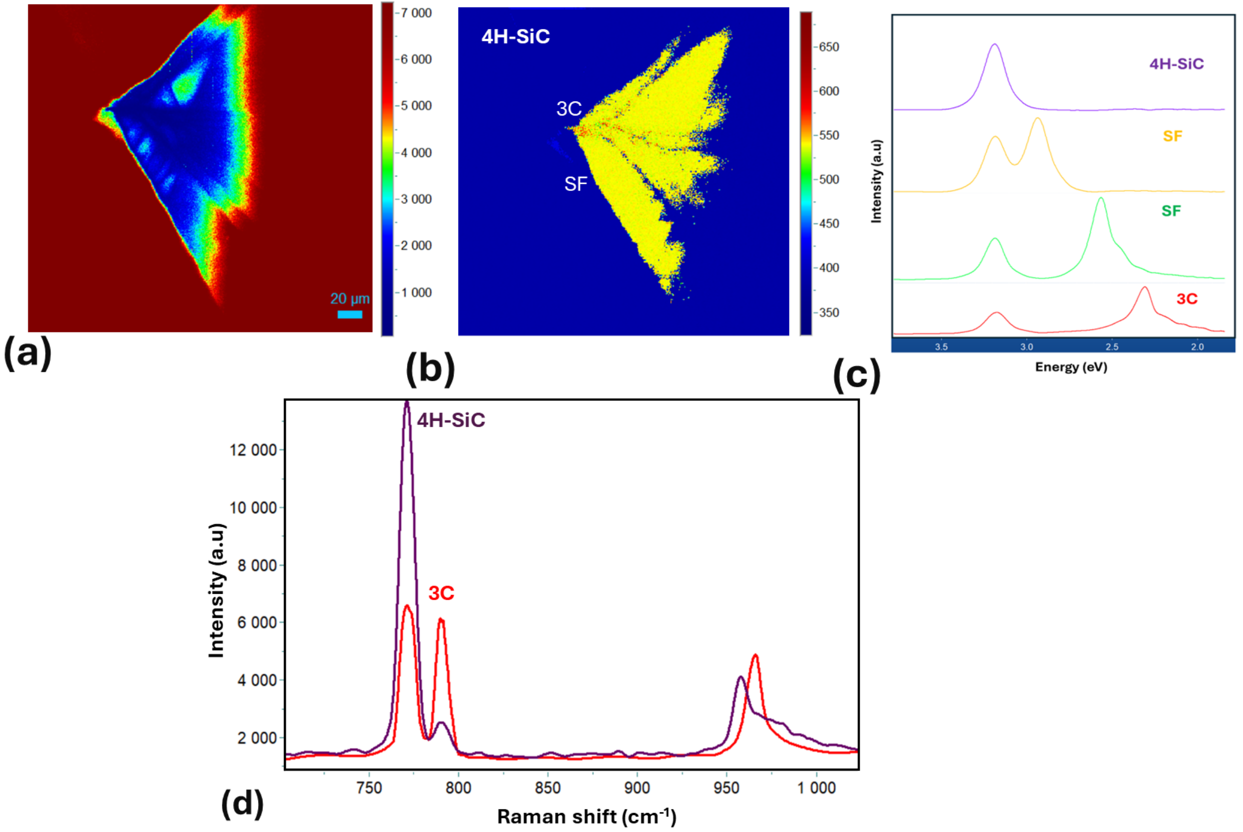


Figure 4. (a) micro-PL intensity map highlighting a stacking fault on an epitaxially grown 4H-SiC substrate; (b) PL peak wavelength map showing emission variations near the stacking fault and inclusion zone; (c) PL spectra recorded from different regions of the stacking fault; (d) Raman spectra acquired from the 3C-SiC inclusion region and the surrounding 4H-SiC substrate.

Summary

Overall, photoluminescence mapping identified structural and external defects, polytype inclusions and PL emission variations within the stacking fault structures. Raman spectroscopy helped in identifying the composition of the inclusions. In summary, the integration of photoluminescence and Raman spectroscopy within a single multi-modal platform, such as the HORIBA SMS system, enables correlative analysis without sample transfer between instruments. This approach minimizes characterization cost, reduces contamination risk, and improves defect identification accuracy, ultimately enhancing substrate yield and quality. Furthermore, additional modalities such as time-resolved photoluminescence (TRPL), photocurrent, electroluminescence, reflectance/transmittance and darkfield imaging spectroscopy can be added to extend its spectroscopic capabilities.

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info.sci@horiba.com **www.horiba.com/osd**

USA:	+1 732 494 8660	**France:**	+33 (0)1 69 74 72 00	**Germany:**	+49 (0) 6172 1396 0
UK:	+44 (0)1604 542 500	**Italy:**	+39 06 51 59 22 1	**Japan:**	+81(75)313-8121
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Taiwan:	+886 3 5600606	**Brazil:**	+55 (0)11 2923 5400	**Other:**	+33 (0)1 69 74 72 00