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Deep-Ultraviolet Laser-Based Defect Inspection of Single-Crystal 4H-SiC and SmartSiC™ Engineered Substrates for High Volume Manufacturing

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Abstract. Power devices electronics based on silicon carbide (SiC) are emerging as a breakthrough technology for a wide range of applications [1]. SiC engineered substrates provide a solution that fulfills power devices requirements, namely supplying high quality, ultra low resistivity materials. SmartSiC™ substrates, based on Smart Cut™ technology, combine the advantages of high quality single-crystal SiC and innovative pSiC handle material [2]. To achieve high volume manufacturing (HVM) of prime grade SiC engineered substrates, defects monitoring is crucial. This paper explains how a commercially available Deep-Ultraviolet (DUV) laser-based inspection system (KLA Surfscan® SC1) was successfully used for the quality control of SmartSiC™ and single-crystal 4H-SiC in a production environment. Detection of both surface and grown-in defects was investigated, on 150 mm and 200 mm substrates. Statistical data were collected and utilized for driving quality and yield continuous improvement.

Introduction

In the last decade, SiC power devices have emerged as an innovative solution for various applications such as traction inverters for automotive, DC/DC converters, on-board chargers and charging stations. Despite recent advances in the quality and supply of 4H-SiC single-crystal wafers, progress regarding defect density and material performance is still needed and high volume production of prime crystal grade 200 mm 4H-SiC substrates remains a challenge [3-4].

To fulfill the requirements of the SiC industry, the SmartSiC™ substrate proposes to combine the high quality of a single-crystal device layer and the ultra-low resistivity of a handle wafer [5], as illustrated in Fig. 1. In addition, as detailed in [6], Smart Cut™ technology can be scaled to 200 mm wafers to overcome the risk of large size SiC substrates shortage.

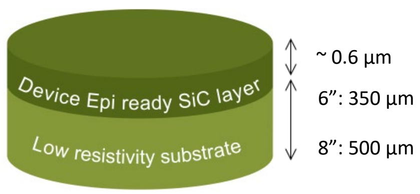

Fig. 1. Typical SmartSiC™ structure

Smart Cut^{TM} for SiC

The Smart Cut^{TM} process (Fig. 2) consists of several steps, including hydrogen implantation of the 4H-SiC starting material (donor material) which enables control of the transferred thickness (typically less than 1 µm). The implanted wafer is bonded to a handler material before splitting (step 5) and proceeding to finishing steps (step 6).

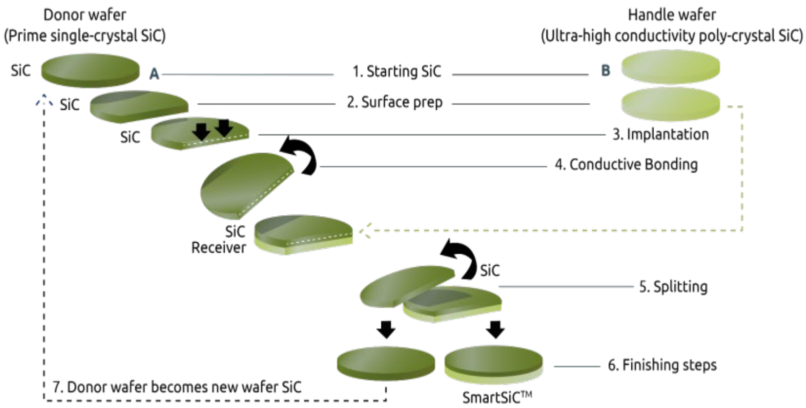

Fig. 2. Smart Cut^{TM} process description, as adapted to SiC

To target high volume manufacturing (HVM) of bonded SiC engineered substrates, inline defect monitoring and final quality control is key to guarantee device epitaxy yield. In this work, we focused on two crucial steps: the automatic defect inspection of the starting single-crystal donor material and the monitoring of the final epi-ready engineered substrate.

Surface Defects Monitoring Based on DUV Laser Light Scattering

As described in [7], a DUV laser-based system can be used to detect scratches and surface defects down to 50 nm on SiC wafers. Using a DUV source limits the noise related to SiC material transparency. When visible and near UV spectral ranges are used, this noise causes sub-surface signal detection and local reflectance variation. In this study, a DUV inspection tool (KLA Surfscan® SC1) was used in a HVM environment for high sensitivity defect inspection of 150 and 200 mm SiC substrates.

Laser light scattering inspection technology is commonly used to detect surface defects on semiconductor substrates, including engineered substrates [8]. In this work, the Surfscan SC1 inspection system, which leverages a 266 nm laser light source, was utilized to characterize defectivity and surface quality of both SiC single-crystal donor wafers and SmartSiC^{TM} engineered substrates. The optical configuration on the system was selected to gather the entire laser light scattering and spectral range. In this configuration a surface defect can be identified as a location where the scattered intensity is above the scattered signal from the surface, as illustrated in Fig. 3.

Particle (surface defect),
SC1 patch image, 0.5 mm FOV

Collected signal (a.u.)

Fig. 3. Signal processing used to identify surface defects based on laser light scattering

As the laser light scattering of surface defects is strongly dependent on substrate's optical properties, when using the laser light scattering configuration, it is important to calibrate the scattered intensity to estimate the size of the detected defects. For this experiment, calibrated Polystyrene Latex Spheres (PSL) were deposited both on single-crystal SiC and SmartSiC^{TM} stack and the scattered intensity was correlated to defects size as illustrated in Fig. 4 and Fig. 5.

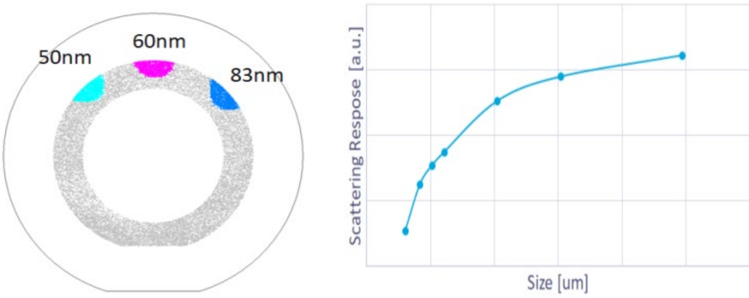

Fig. 4. PSL spheres deposited on a single-crystal 4H-SiC (left) and scattering response calibration (right)

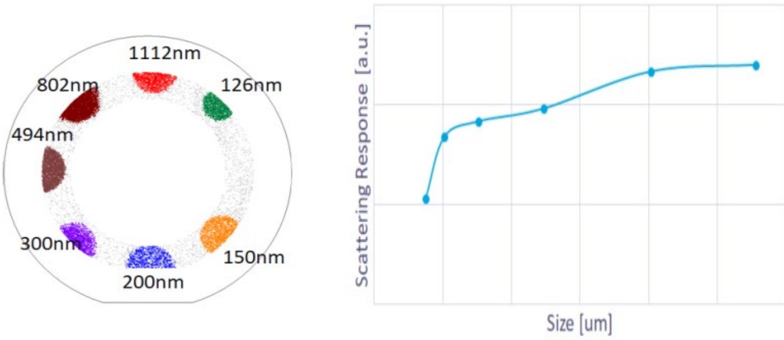

Fig. 5. PSL spheres deposited on a SmartSiC^{TM} substrate (left) and scattering response calibration (right)

This procedure allowed us to collect statistical and comparable data in a production environment both for donor wafers (single-crystal SiC) and for SmartSiC^{TM} engineered substrates. Fig. 6 shows the statistical data for both populations at 300 nm minimum threshold.

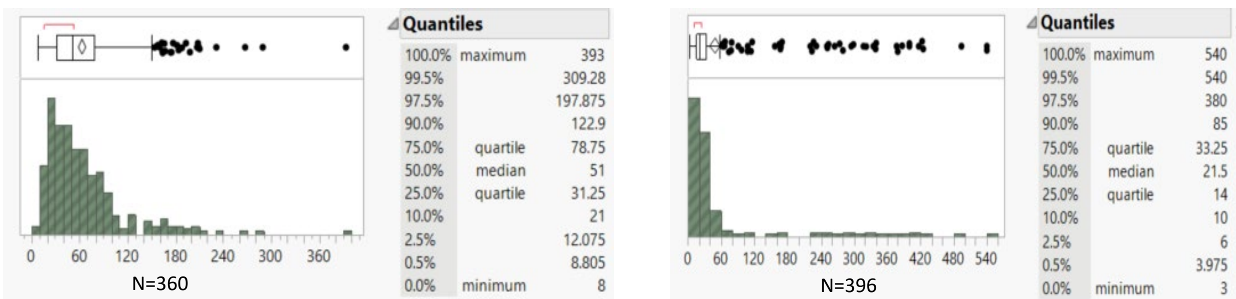

Fig. 6. Statistical distribution of surface defect counts for 4H-SiC prime donor wafers (360 wafers, left) and SmartSiC^{TM} engineered substrates (396 wafers, right) (Surfscan SC1 scan, PSL threshold 300 nm)

On this sample, SiC engineered substrates surface defect density is comparable to single-crystal bulk substrates used as donors down to 300 nm inspection threshold. This performance is achieved thanks to specific surface finishing process, allowed by thin transferred layer surface treatment used for SmartSiC™ manufacturing.

Crystal originated defects monitoring based on PL intensity mapping

A crucial step of the Smart Cut™ process consists of splitting a thin monocrystalline SiC layer from a donor (refer to Fig. 2, step 1): the defectivity of the starting material has an impact on the total usable area of SmartSiC™ wafers. Depending on its quality, the donor substrate can show different grown-in defect types, like micro-pipes and inclusions [9-10]. As detailed in [11] and illustrated in Fig. 7, donor material defects may cause the generation of crystal originated defects (COD) on bonded engineered substrates. For this reason the HVM of SiC engineered substrates needs a fast and sensitive detection for this failure mode.

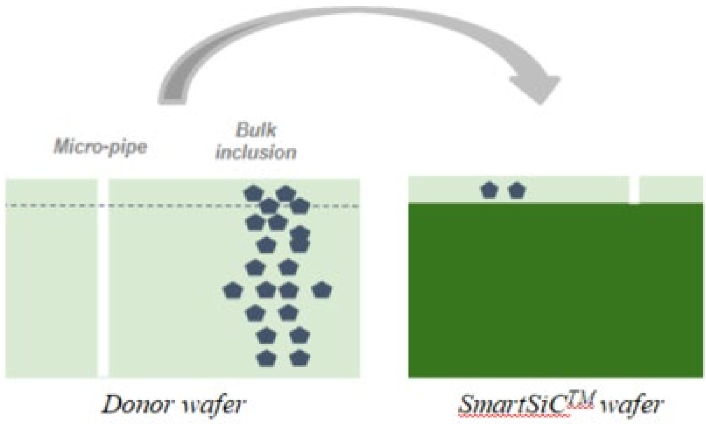

Fig. 7. Crystal Originated Defect generation on engineered substrates from a 4H-SiC donor

SiC photoluminescence (PL) imaging has been used for decades to characterize SiC crystal defects [12]: for this application the photon energy of the excitation source must be larger than the bandgap of the material, therefore an ultraviolet lamp or laser showing a wavelength shorter than 370 nm should be used. For this experiment, the Surfscan SC1 system, including a 266 nm laser and a PMT sensor, was utilized to characterize both SiC single-crystal donor wafers and SmartSiC™ engineered substrates. Because active defects affect carrier recombination, PL measurements provide a method to detect extended defects: PL intensity is locally reduced in defective areas, as defects act as nonradiative recombination centers. In this study, the optical configuration of the system was selected to avoid the collection of the scattered signal, by defining a defect as a location where the captured intensity is lower than the signal gathered from the surface, as illustrated in Fig. 8. The usage of a negative threshold algorithm allowed us to flag material grown-in defects in contrast to pure crystal.

Bar stacking fault (crystal defect), SC1 patch image, 0.5 mm FOV

Collected signal (a.u.)

Fig. 8. Signal processing used to identify crystal defects based on PL intensity mapping

A high resolution optical bench including a 266 nm excitation source and a CCD camera was used to image the defects identified thanks to negative threshold algorithm, as illustrated in Fig. 9.

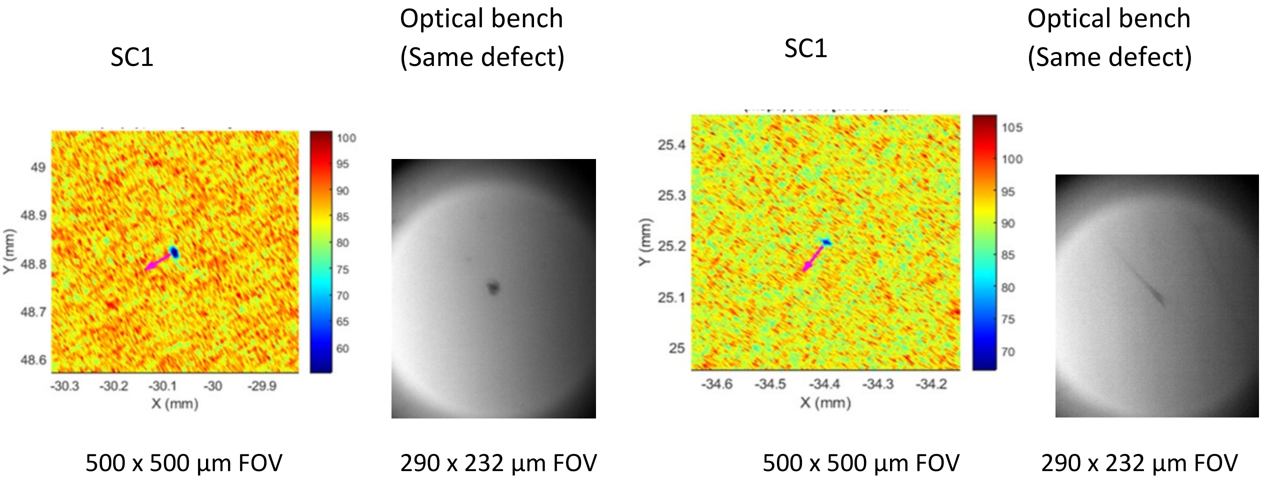

Fig. 9. Examples of PL defects on 4H-SiC as imaged by SC1 (left image) and using an optical bench (right image)

PL signal intensity was mapped on a full wafer, on a broadband including visible and UV spectrum. To enhance the selectivity versus scattered signal the 266 nm peak was filtered. As illustrated in Fig. 10, this characterization revealed both crystal extended defects (such as species inclusions and micro-pipes) on incoming single-crystal donors and crystal originated defects on SmartSiC^{TM} substrates.

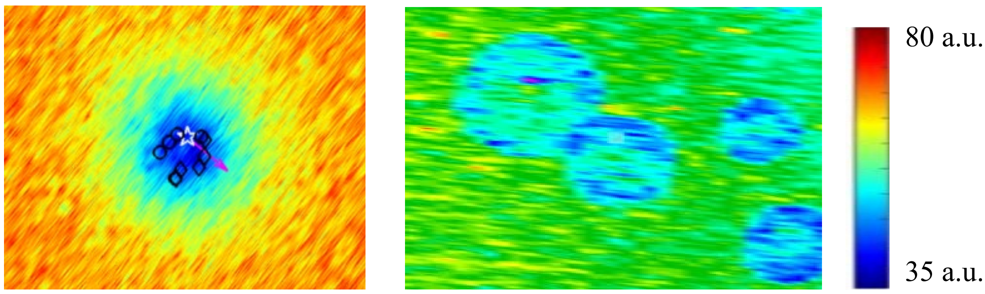

Fig. 10. Surfscan SC1 PL intensity mapping of a donor grown-in defect (species inclusion) (left) and SmartSiC^{TM} crystal originated defects (right), 0.5 mm field of view, 266 nm source

Summary

This work showed that a DUV laser-based inspection system, the Surfscan SC1, can be used in a production environment for inline defect monitoring for manufacturing high-quality SmartSiC^{TM} engineered substrates, at both 150 mm and 200 mm wafer sizes.

Both surface and extended crystal defects should be monitored to allow quality continuous improvement. In this study, surface defects were captured using the laser light scattered signal, while grown-in defects were revealed by PL intensity mapping. Statistical data collected showed that SiC engineered substrates surface defect density is comparable to single-crystal bulk substrates used as donors down to 300 nm inspection threshold.

Acknowledgements

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