Defect and Diffusion Forum *Submitted: 2023-09-26*
ISSN: 1662-9507, Vol. 434, pp 129-134 *Revised: 2024-04-23*
doi:10.4028/p-2btCLo *Accepted: 2024-04-24*
 Online: 2024-08-22

Practical Improvement of Noncontact Production Monitoring of Doping in SiC Wafers with Extended Epilayer Defects

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Keywords: noncontact, corona, CV, doping, SiC, epi.

Abstract. We discuss two defect related practical improvements in the corona noncontact CV metrology, (CnCV) for SiC. The improvements are introduced in response to requests from industrial tool users. The first improvement quantifies mapping of electrically active defects with the QUAD technique (Quality, Uniformity, and Defects). It provides the capability of user selectable die grids directly comparable with Near UV-PL and optical defect mapping. This shall enhance understanding of the device killer defects and help to correlate epilayer defects and device yield. The second improvement introduces auto-remeasurement of outliers appearing in doping measurements on defective sites. This procedure is analogous to that used in the Hg probe technique and it provides a means for correcting defect related distortions in SPC doping monitoring charts.

Introduction

Rapidly growing application of SiC and related wide bandgap material for power electronics are based on epitaxial wafer technology [1]. A necessary element in the technology is characterization of run-to-run and wafer-to-wafer consistency of intrawafer uniformity of key properties. In 2017 the noncontact wide bandgap electrical characterization technique, CnCV (corona noncontact capacitance-voltage) was commercially introduced by Semilab SDI [2]. The technique uses deposition of corona charge, ΔQ, on the surface as an electrical bias. The surface voltage response, ΔV, is measured with a Kelvin probe, giving noncontact capacitance $C=\Delta Q/\Delta V$. As a result, Schottky barrier or MOS like C-V measurements are performed without any fabricated or temporary diodes, or metal contacts. An immediate interest in CnCV was justified by a corresponding reduction of cost and testing feedback time [2]. The expanding usage of CnCV tools resulted in feedback to Semilab SDI that was guiding metrology improvement in accord to wide bandgap technology needs [3]. Increasing CnCV usefulness was manifested in 2022 by annual tool orders matching the previous 5-year total. The CnCV tools include Quality, Uniformity, and Defect mapping (QUAD). In 4H-SiC, this wafer level technique reveals electrically active extended defects [4]. Therefore, improvement of QUAD plays an important role in complementing optical and near UV-PL defect mapping and it shall benefit wafer level device yield diagnostics.

Experimental

CnCV is an adaptation of the charge-based corona-Kelvin noncontact electrical metrology extensively used in Si IC fabrication [5]. The original description of principles, apparatus and applications for wide bandgap semiconductors, including SiC, is given in a 2017 CnCV review paper [6]. The measurements illustrating the present improvements were performed on wafers with n-type epitaxial 4H-SiC on n^+ substrates. Two key experimental elements include 1) negative corona charging of the surface to depletion and 2) the surface voltage response measurement with a Kelvin probe.

The apparatus included whole wafer wire type corona charging for QUAD mapping and a point source needle type corona with a 6mm uniform charging diameter for selected site doping measurements. The latter was performed using a constant surface potential corona charging method with in-situ charge dose monitoring [6]. The negative corona charging presently used involves deposition of negative ions (CO_3^-) [5].

In surface voltage measurements, the Kelvin probe measures the contact potential difference, V_{CPD}, between the wafer and the vibrating reference electrode [5]. A probe pre-calibration is used to subtract the contribution due to the electrode work function. After such a correction, the V_{CPD} is referred to as the surface voltage, V. A 2mm diameter Kelvin probe was used. Whole wafer mapping was performed in about 4min for a 150mm SiC wafer. In practice, a high precision Kelvin probe (0.01%) enabled resolving surface voltage changes in small areas with sub mm dimensions.

In certain high resolution studies in Ref [6,7], a 10μm diameter Kelvin Force Microscopy probe was used to examine small sites with typical SiC extended defect structures and to identify defects by direct comparison with UV photoluminescence images.

Results and Discussion

QUAD mapping of extended defects. QUAD is based on surface voltage mapping wherein the electrical activity of extended defects is spatially resolved as a local change of the surface voltage compared to surrounding areas. In corona charge assisted measurements, the electrical defect activity reflects locally increased depletion layer leakage. Localized surface charge or localized work function variations such as polytype inclusions can be visible in surface voltage without corona charging. In charge assisted QUAD, the wafer inspection includes surface voltage mapping after whole wafer corona charging to deep depletion. The contrast of electrically active defects that cause depletion leakage is enhanced and defects are manifested as spots with reduced depletion voltage magnitude. As confirmed by micro-scale measurements with KFM, SiC extended defects such as triangular, carrot and downfall defects are visible in QUAD [7]. However, comparison with near UV-PL defect mapping has also indicated that only a fraction of the total extended SiC defects are electrically active [4,6,7]. Point defects are not addressed by QUAD. However, one should note that in corona-Kelvin metrology, the time resolved measurement of surface voltage after a charging pulse can be used for defect identification, analogous to isothermal Deep Level Transient Spectroscopy [8].

Answering customer requests, a new development in 2023 introduced in QUAD mapping an additional defect display in the form of a die grid shown in Fig. 1 and Fig. 2. The die grid is similar to that used for near UV-PL images in Lasertec SiCA-88 tools and in Candela CS20 optical surface analyzer defect maps. This shall facilitate direct optical vs. electrical defect comparison and quantification of die yield values, corresponding to a % of the defect free dies. The die yield is treated as an indicator of a percentage of epi wafer useful area [1].

The results in Fig. 1 and Fig. 2 illustrate QUAD defects maps for epitaxial 4H-SiC 150mm wafer with high 237 and low 17 defect counts, respectively. In both figures, the standard QUAD surface voltage maps are shown on the top, while the corresponding displays in a 5mm x 5mm die grid are shown at the bottom. The edge exclusion, the die width and the die height are user selectable. The selected values in Fig.1 and Fig. 2 are all 5mm. The results in Fig. 1 represent an extreme case of a highly defective wafer. Corresponding die yield is 62.4%, unacceptable for device manufacturing. On the other hand, the wafer in Fig. 2 represents state of the art with extremely low defectivity and corresponding die yield of 98%. The QUAD results in Fig. 1 and Fig. 2 represent the corona charge assisted measurement, wherein the electrical defect activity reflects locally increased depletion layer leakage.

The 98% die yield, for electrically active defects on a 150mm diameter 4H-SiC wafer, corresponds to one of the best results in our demo-measurement experience. Generally, the present die yield is closer to 90% for electrically active QUAD defects.

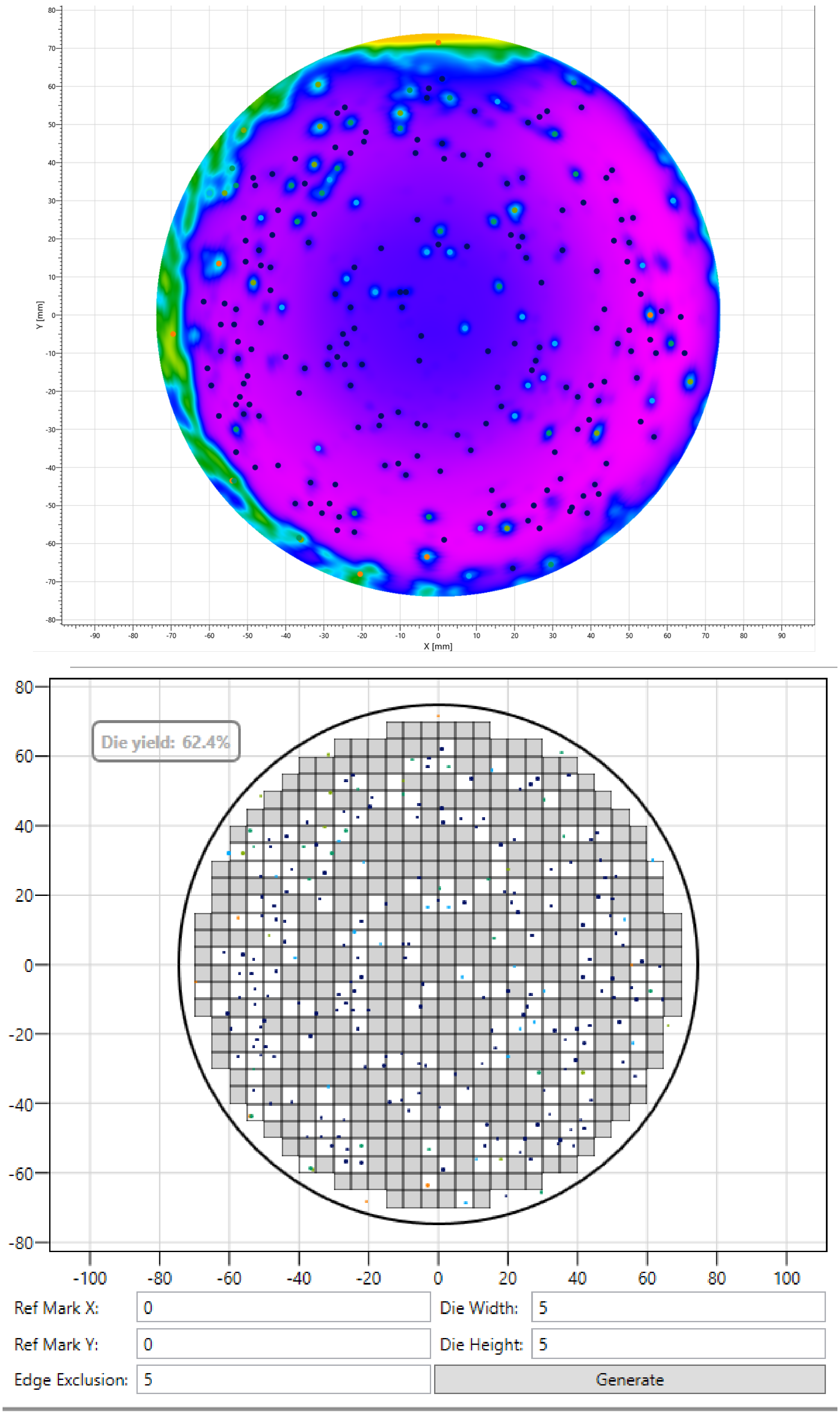

Fig. 1. QUAD defect map displays for highly defective 4H-SiC epitaxial wafers. Standard map is on the top, novel die grid map is at the bottom. The 62% die yield quantifies defect related problem.

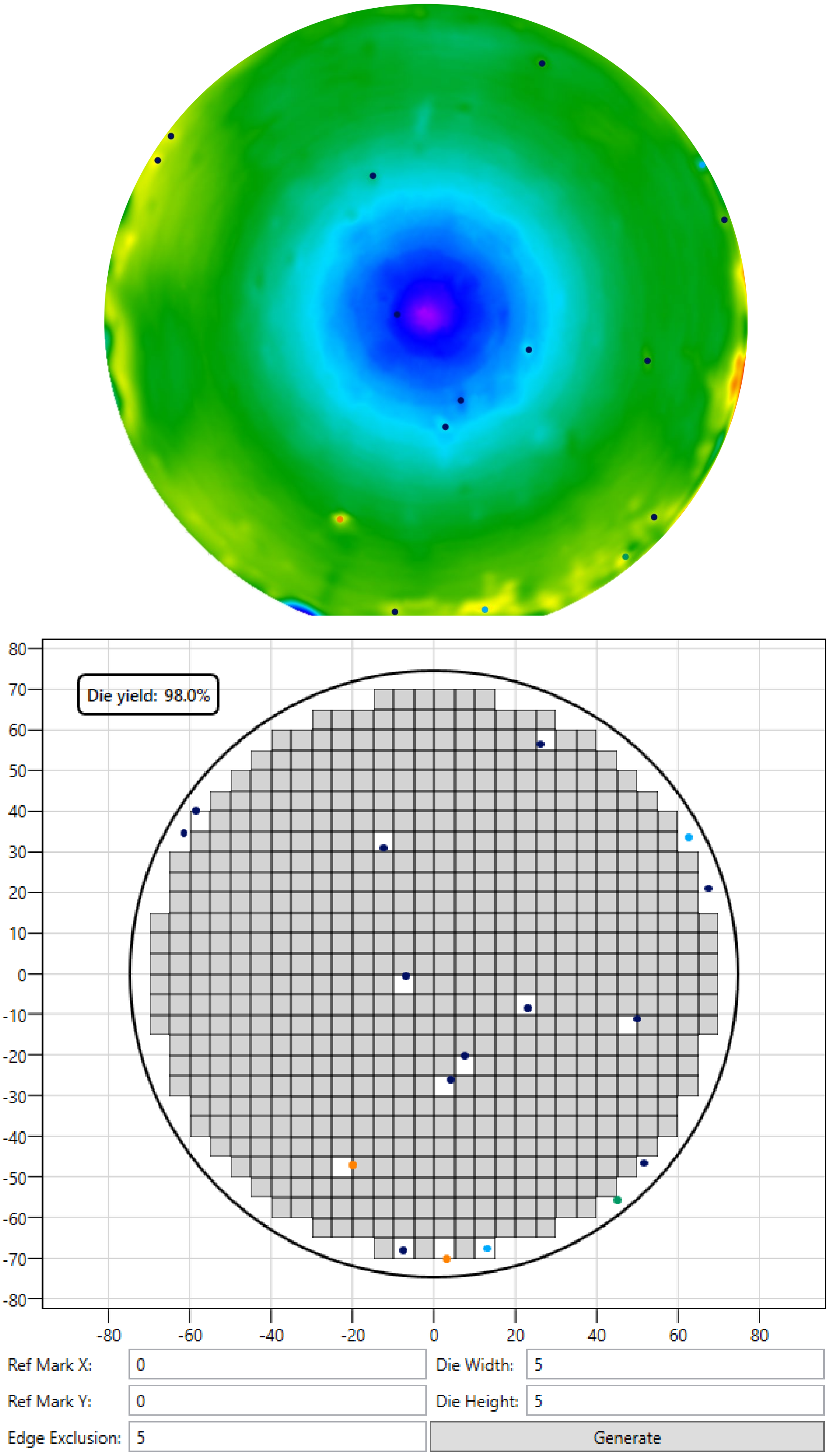

Fig. 2. QUAD defect map displays low defectivity for 4H-SiC epitaxial wafer. Standard map is on the top, novel die grid map is at the bottom. The % die yield is one of the best results.

Doping Auto-remeasure. Increased depletion layer leakage, and reduced surface voltage that make electrically active defects visible in QUAD mapping may cause distortion in C-V characteristics measured at defective spots. The corresponding doping concentration determined from such a distorted $1/C^2$ plot becomes artificially increased in defect spots. As a result of the presence of electrically active epi-layer defects, the multisite scanning in production monitoring of intrawafer doping may contain outliers. In wafers with a QUAD die yield above 90%, the outlier probability for a 12-site measurement is rather low, such as 1 or less outlier per 5 wafers. However, even infrequent outliers can affect the σ/mean value used as a measure of the intrawafer uniformity. To eliminate this problem, an improved 2023 CnCV version introduces an auto-remeasurement similar to outlier handling used in Mercury Probe C-V. In this new CnCV version, the remeasurement position is shifted, typically by 2mm from the identified outlier and doping is remeasured at this spot, free of distortion caused by the defect as shown in Fig. 3.

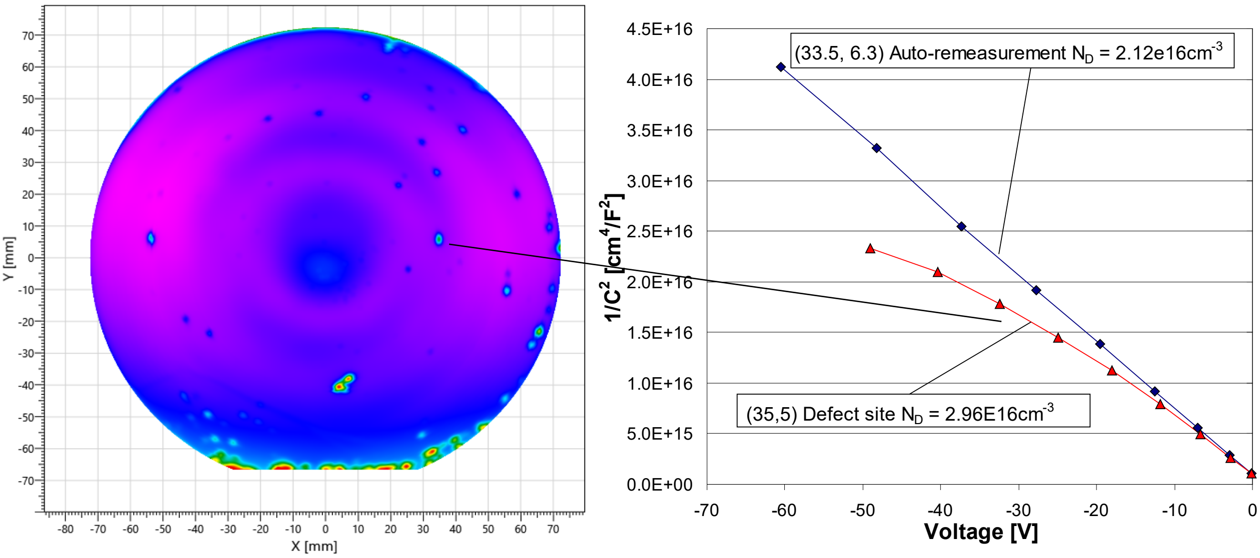

Fig. 3. The results of CnCV measurements on n-type epitaxial 4H-SiC wafer that illustrates the auto-remeasurement. The QUAD surface voltage defect map is shown on the left of the figure and $1/C^2$ vs. V characteristics used in auto-remeasurement procedure are shown on the right.

For a defective site at location (35, 5), defect enhanced depletion leakage causes a distortion of the $1/C^2$ vs. V characteristic that is shown in Fig. 3 on the right. This gives artificially higher doping of N_D=2.96 E16 cm^{-3} extracted from the average slope. Auto-remeasurement is performed at defect free location, shifted by about 2mm to the site (33.5, 6.3). The shift is comparable to a diameter of the Kelvin surface voltage measuring probe. Considering submillimeter defect sizes in silicon carbide, this is found sufficient to give a correct linear $1/C^2$ and lower N_D=2.12 E16 cm^{-3} value consistent with other intrawafer values.

The remeasurement produces reliable $1/C^2$ - V characteristics, re-establishing the value of doping concentration not affected by outliers and provides a more accurate record of the actual epitaxial process as illustrated by results in Fig. 4. For run-to-run, and wafer-to-wafer epitaxial doping monitoring the new CnCV ability to eliminate defect related outliers is an important practical improvement.

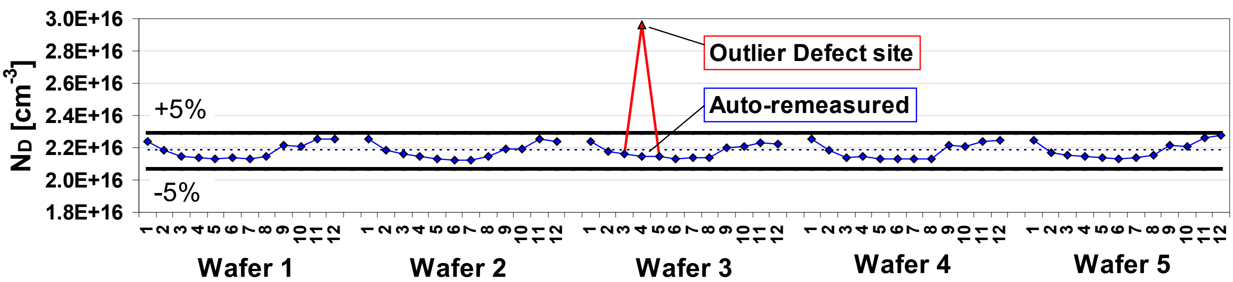

Fig. 4. SPC chart of CnCV measured N_D showing 1 outlier over 5 wafer runs with 12 measurement sites. With auto-remeasurement mode activated, doping is remeasured in an adjacent defect free location shifted by about 2mm and the result replaces the outlier value in the SPC chart.

Conclusion

Recent improvements in CnCV metrology address questions of electrically active defects in 4H-SiC. The monitoring of defect shall benefit from quantification of the unique QUAD mapping technique that is realized by addition of used selectable die grid, similar to die grid commonly used in optical and near UV-PL mapping. Other improvements introduce auto-remeasurement procedure correcting the CnCV outliers appearing at defect location. The CnCV auto-remeasurements shall benefit monitoring of the intrawafer doping uniformity in mass production of epitaxial wafer.

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