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Optimizing Non-Contact Doping and Electrical Defect Metrology for Production of SiC Epitaxial Wafers

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Abstract. The recently introduced corona charge non-contact capacitance-voltage technique, CnCV, is analyzed considering the production needs of epitaxial SiC wafers. The interfering mechanism of charge dissipation on fresh epitaxial 4H-SiC is identified as surface diffusion and is effectively eliminated by optimized ultraviolet pretreatment (UVPT). It is shown that optimized UVPT increases the CnCV dopant measurement voltage range and the depth of profiling. Concurrent UVPT and measurement provides a practical solution for improving throughput for multiple wafers. Electrical defect mapping shows that UVPT reduces the effective defect size. This will be helpful to avoid defects in patterns used for CnCV dopant measurements.

Introduction

Production of epitaxial SiC wafers requires precise control of both dopant concentration and of the density of structural defects. Cost-effective production can benefit from doping and defect metrology that recently became available in commercial corona non-contact capacitance voltage (CnCV) tools [1].

The CnCV technique, designed especially for wide bandgap semiconductors [1,2], uses corona charging as a means of biasing to deep depletion. This is analogous to voltage biasing of a metal Schottky barrier but without the need for metal contacts on the semiconductor surface. Precise incremental charge dosing and non-contact measurement of the surface voltage response with a Kelvin probe are the two key elements in the CnCV measurement of dopant concentration and depth profiling [1,2].

The CnCV tools include QUAD (Quality, Uniformity, and Defect) mapping that combines surface voltage mapping and whole wafer charging to depletion. QUAD maps visualize the electrical activity of defects [3] providing an important supplement to UVPL (ultraviolet photoluminescence) defect imaging [4].

In static type CnCV measurements and QUAD defect mapping, charge stability is an important issue. In this respect, wide bandgap semiconductors have a fundamental advantage over previous corona-Kelvin applications in silicon IC fabrication, which were intended for wafers with dielectrics [5]. The wide bandgap of SiC enables a deep depletion measurement on bare wafers which is important for production monitoring of SiC epitaxial layers.

Theoretically, a depletion layer in a wide bandgap semiconductor, with negligible minority carrier thermal generation, should effectively isolate corona ions, ensuring good charge stability in the dark [2]. Good stability was confirmed with the exception of measurements performed immediatley after epitaxy. In practice, fresh epitaxial 4H-SiC wafers exhibit rapid dissipation of deposited charge. The potential benefit of UV in reducing this effect was suggested by measurements performed after UVPL defect imaging [6]. Accordingly, a UV pretreatment station was introduced in CnCV tools. The goal of the present work was to analyze charge dissipation and to optimize the UV pretreatment for production monitoring of 4H-SiC epi wafers.

Experimental Method and Apparatus

Non-contact C-V measurement of dopant concentration uses corona charge biasing, ΔQ_C, and monitoring of surface voltage, ΔV [1,2]. Differential capacitance ($C = \Delta Q_C/\Delta V$) is calculated and sequential charging-measuring in depletion gives the non-contact Schottky barrier C-V characteristic. The standard $1/C^2$ vs. V method [7] gives dopant concentration, N_D, vs. depletion depth, $W_D = \varepsilon\varepsilon_0/C$.

Illustration of a corona-Kelvin experimental arrangement in a CnCV measurement is given in Fig. 1. The semiconductor wafer is held on a conducting chuck by vacuum suction and the moveable chuck cycles the wafer test site between the corona charging source and the voltage measuring Kelvin probe. The apparatus is enclosed in a black box that also forms a Faraday cage.

Present measurements were performed on 150mm n-type 4H-SiC epitaxial wafers. For dopant measurement, a needle electrode point source corona was used with a nominally 8mm charging spot diameter. A 2mm diameter vibrating electrode was used for Kelvin probe surface voltage measurement. In QUAD mapping, the surface voltage was measured in-flight with the wafer moving under the probe. For whole wafer charging, a wire corona discharge electrode was used.

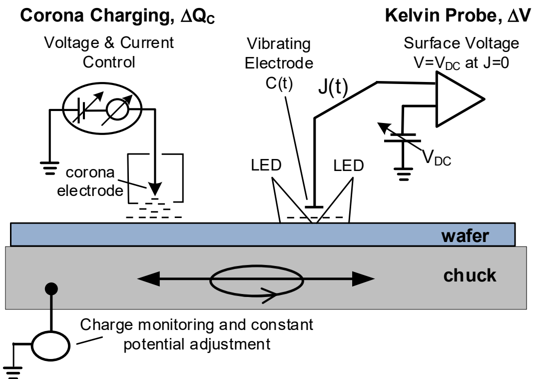

Fig. 1. Illustration of the corona charging and Kelvin probe arrangement in the measurement bay of a CnCV tool.

The negative corona charging that creates depletion in n-type SiC deposits thermalized CO_3^- ions on the surface. The deposited charge is removed from the surface using short wavelength illumination that generates free minority carriers in the surface depletion region [2].

UV Pretreatment. The fully automated CnCV tool utilized in this study incorporates an ultraviolet pretreatment station for charge stabilization on fresh epitaxial SiC. The arrangement illustrated in Figure 2 is designed for concurrent UVPT and CnCV measurement with optimized throughput for measuring multiple wafers. The UVPT uses 360nm wavelength LEDs to provide uniform illumination for wafers up to 200mm diameter with the wafer rotating under the LEDs. The UVPT time is adjustable and, in an optimized measurement, typically ranges between 2 and 8 mins.

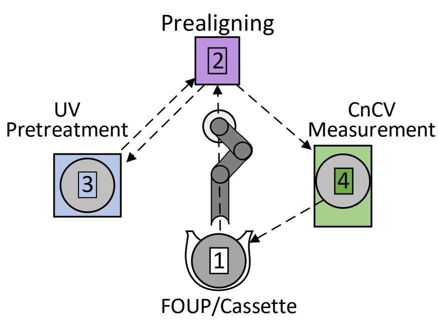

Fig. 2. Illustration of concurrent UV pretreatment and measurement in CnCV tools.

Results and Discussion

Charge dissipation and effect of UVPT. The mechanism of charge dissipation was analyzed based on the time dependence of the charge density and the lateral charge density profiles. Two surface charge dissipation effects in the surface depletion condition include 1) Charge neutralization caused by electric field enhanced generation of minority carriers and 2) Charge spreading from the deposition site caused by surface diffusion. The results for corona spot charging on fresh epitaxial 4H-SiC are shown in Fig. 3 and Fig. 4. The charge density was obtained from the measured surface voltage using the Schottky barrier charge-voltage relation [7].

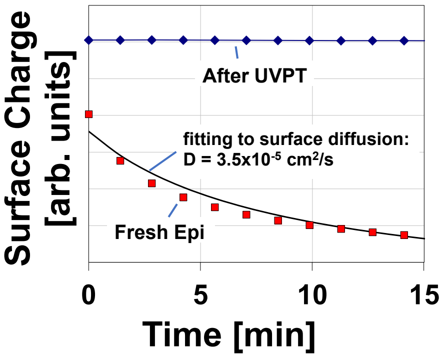

Fig 3. Time dependence of corona charge showing a decay consistent with surface diffusion on fresh epi and a stable charge after optimized UVPT. Fitting considered 2D diffusion from the initially circular spot.

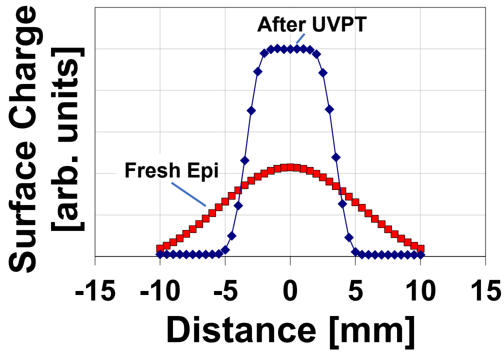

Fig 4. Profiles of deposited corona charge density showing lateral spreading consistent with surface diffusion and elimination of spreading achieved with optimized UVPT.

The results imply the dominant role of a surface diffusion mechanism in decreasing the charge density in the deposited spot. 2-D integration of charge profiles showed a constant total charge indicating an insignificant contribution from the charge neutralization effect. The measurement after optimized ultraviolet pretreatment, UVPT, demonstrates effective elimination of the charge dissipation effect.

The surface voltage results in Fig. 5 and Fig. 6 enable visualization of the corona charge spreading effect decreasing the voltage magnitude and enlarging the charged spot size in Fig. 5 compared to the nominal 50V magnitude and 8mm spot size after UVPT in Fig. 6.

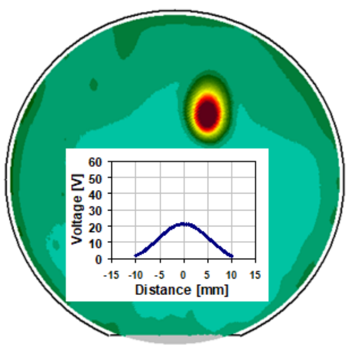

Fig. 5. Corona charge spot map and profile on as received SiC n-type epi before UVPT.

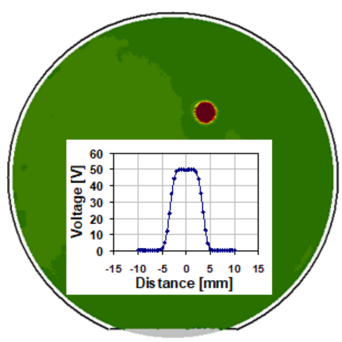

Fig. 6. Corona charge spot map and profile on as received SiC n-type epi after UVPT optimization.

UVPT effect on dopant measurement. In the CnCV method, the doping measurement is performed using a conventional slope analysis of the $1/C^2$ vs. V characteristics [7]. The effect of charge dissipation is most visible in wafers with a constant dopant depth profile wherein the actual characteristic will be linear. The goal of optimized UVPT is to achieve good quality characteristics extending over a large voltage range. Results illustrating the beneficial effect of UVPT on the $1/C^2$ characteristics are shown in Fig. 7. Increasing UVPT time increases the linear $1/C^2$ range. A full linear range up to 50V corresponding to a deposited charge density of $1.8\mathrm{x}10^{12}$ q/cm^2 is reached after 4 minutes of UVPT. Dopant concentration results measured under such optimization show uniform doping with N_D=7.24 x10^{15} cm^{-3} and 1σ/average of 0.24% for the entire depth range up to 2.5µm beneath the epi surface. In actual CnCV dopant depth profiling, the depletion layer probing depth, W(V), at a given voltage, V, is determined from the corresponding capacitance value, C(V) as $W_D(V) = \varepsilon\varepsilon_o/C(V)$, where ε_0 and ε are the permittivity of free space and sample, respectively.

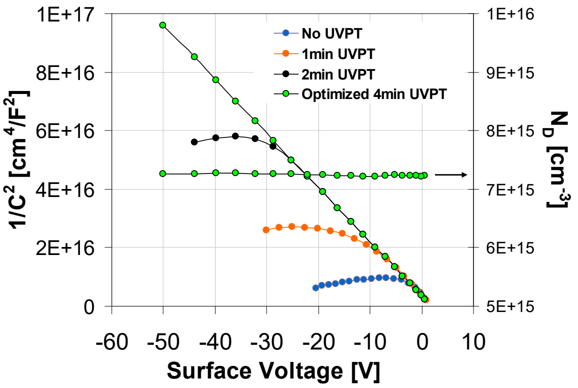

Fig. 7. CnCV measurement on fresh epi before and after UVPT.

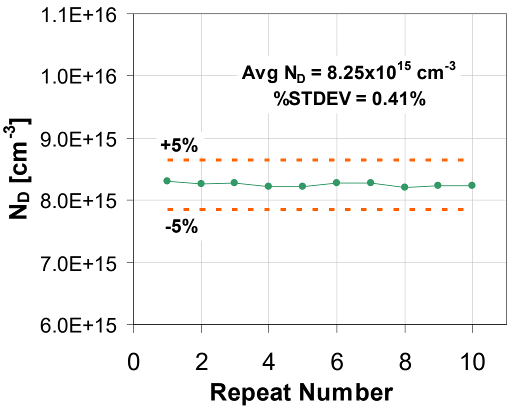

Fig. 8. Good dopant concentration repeatabillity in CnCV measured after UVPT.

Good repeatability of dopant concentration measurement after optimized UVPT is illustrated by the results in Fig. 8. For this wafer, N_D=8.25x10^{15}cm^{-3} is within the target N_D=8.5x10^{15} ± 5% cm^{-3}. The data points represent a 9 site wafer average of 10 repeats after initial UV pretreatment. Before each repeat, the pre-charging condition was restored using low illumination intensity corona charge photoneutralization [2].

Optimization of CnCV for production monitoring must include consideration of throughput. A practical solution favors concurrent C-V measurement which, for a multiple wafer set, would improve overall throughput. In such an arrangement as shown in Fig. 2, the next wafer from the set is being UV treated while the previous one is being measured.

QUAD defect mapping. Optimized UVPT that reduces surface diffusion is also beneficial for electrical defect mapping with the QUAD technique. This finding is illustrated in Fig. 9 by results of QUAD mapping on a fresh epitaxial SiC wafer before and after UVPT. In these measurements, uniform whole wafer corona charging was used, minimizing the charge gradient outside of the defects. Electrical defects, however, neutralize charge and create localized gradients, activating surface diffusion in the vicinity of the defect. Supply of charge from the surrounding area enlarges the QUAD defect image size seen in Fig. 9 before UVPT. After UVPT, suppressed surface diffusion eliminates this effect and results in about 3x smaller defect image diameter.

A comparison between electrically active QUAD defects and UV photoluminescence images is shown in Fig. 10. Such a comparison is important for understanding defect properties and should benefit from optimized UVPT that provides better QUAD defect resolution and contrast in mapping of fresh wafers in a production cycle of SiC epitaxial wafers.

Reduction of the effective defect size will be also helpful for avoiding defective spots in CnCV dopant measurement.

Before UVPT **After UVPT**

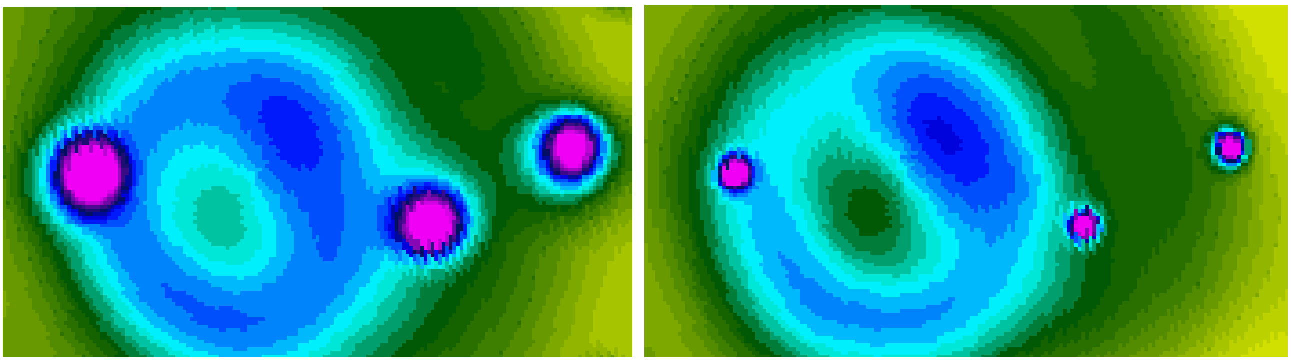

Fig. 9. QUAD defect maps of the same area on a fresh epi wafer before and after UVPT, showing enlarged and reduced effective defect sizes, respectively.

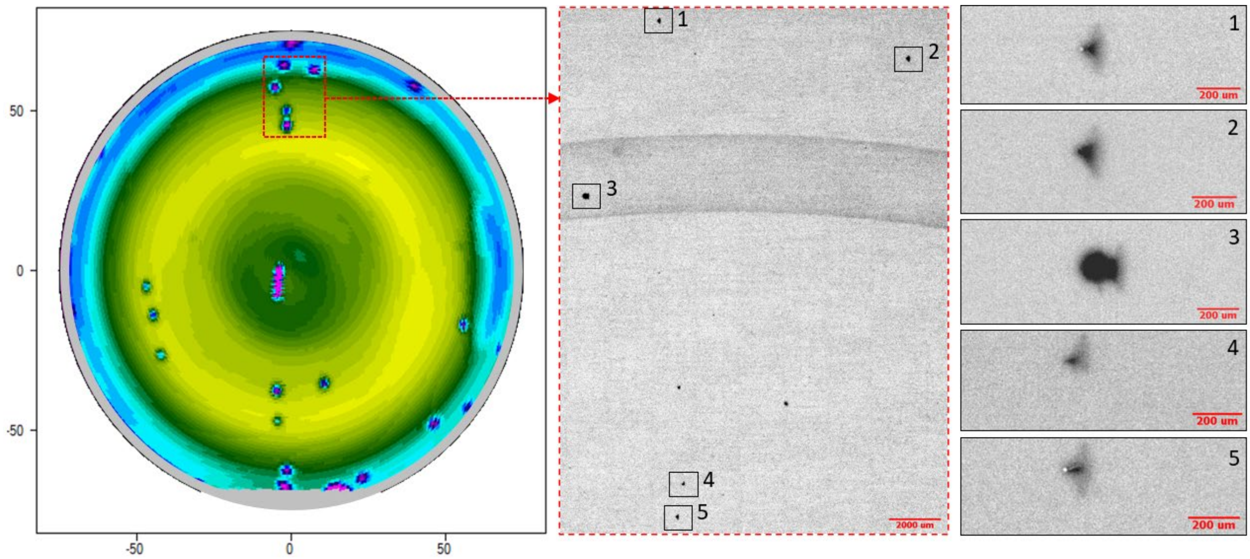

Fig. 10. QUAD defect map showing defective sites correlating with confocal UVPL images.

Conclusion

Results of this work demonstrate an improvement in corona non-contact C-V measurements on fresh epitaxial wafers that can be beneficial for application of the metrology in production of SiC epitaxial wafers. The results clarify the surface diffusion mechanism of corona charge dissipation observed on recently deposited epitaxial wafers. It is shown that elimination of this effect can be achieved with an optimized UV pretreatment of fresh epi-wafers. Effective elimination of surface diffusion benefits the dopant concentration measurement, as well as QUAD mapping of the electrically active structural defects.

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