# Noncontact Measurement of Doping with Enhanced Throughput and High Precision for Wide Bandgap Wafer Manufacturing

M. Wilson<sup>1</sup>, C. Almeida<sup>1</sup>, I. Shekerov<sup>1</sup>, B. Schrayer<sup>1</sup>, A. Savtchouk<sup>1</sup>, B. Wilson<sup>2</sup> and J. Lagowski<sup>1</sup>

<sup>1</sup>Semilab SDI, 12415 Telecom Dr., Tampa, Florida 33637, USA; Email: <u>marshall.wilson@semilabsdi.com</u>; Ph: (813) 977-2244 <sup>2</sup>University of South Florida, Electrical Engineering Department, Tampa, Florida 33620, USA

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# Abstract

We present a novel approach to noncontact doping monitoring in wide bandgap semiconductors based on a modification of the corona-charge surface voltage CnCV technique. The approach is aimed at acceleration of the measurement and achieving a throughput of 20 wafers per hour in a typical 12 site measurement pattern. Such accelerated measurements (5 times faster compared to current CnCV) are performed with a high precision of 0.1 to 0.2%. The key element for increasing the measurement speed is the development of photo-induced control of the corona-charge bias in deep depletion that is unique for wide bandgap material. The approach is applicable to wide bandgap semiconductors with a bare surface. Specific results demonstrating the novel doping measurement are presented for epitaxial 4H-SiC.

## INTRODUCTION

Increasing demands for wide bandgap semiconductor power and high frequency devices require mass production of epitaxial wafers. Such cost-effective production requires precise, wafer level control of dopant concentration uniformity, and run-to-run reproducibility. The preparationfree, nondestructive doping measurement technique, especially designed for wide bandgap semiconductors, recently became commercially available in the corona noncontact capacitance voltage (CnCV) tools [1,2]. CnCV uses corona charging as means of biasing to deep depletion, analogous to biasing of a metal Schottky barrier, however, realized without metal contacting the semiconductor surface. In the CnCV method, the surface voltage response  $\Delta V$  to charge biasing dose  $\Delta Q_C$  is monitored with a Kelvin probe. A differential capacitance,  $C = \Delta Q_C / \Delta V$  is calculated, and sequential charge-measuring gives a noncontact C-V characteristic. The standard  $1/C^2$  vs. V method gives dopant concentration,  $N_D$ . The CnCV measurement throughput with recent improvements can be from 5 to 12 wafers per hour. In this work, we discuss the charge-voltage method with photoinduced charge sweeping that can significantly increase the doping measurement speed. Considering previous art, one must point out that corona charge photoneutralization is a basic process utilized in electrophotographic and xerographic applications [3]. In CnCV tools this effect has been utilized for removing deposited corona charge and repeating surfaces of wide bangdap measurements on bare semiconductor wafers [2].

#### NOVEL MEASUREMENT PRINCIPLE

The novel approach replaces a sequence of cumulative charge steps with a single large corona charging to deep depletion [4]. Following that, a time resolved photo-induced charge control is realized using near UV illumination generating excess carriers. In this photoneutralization process, illustrated in Fig. 1, the minority carriers photogenerated within the depletion layer are pushed to the surface by the depletion electric field. They are captured by the corona ions, neutralizing the corona charge and reducing the depletion width. The process is monitored with a Kelvin probe time-resolved measurement of the surface voltage.



Fig. 1. Photo-neutralization of corona charge on a n-type wide bandgap semiconductor. The threshold energy,  $h\nu$ , is the energy gap,  $E_g$ .

This corona photoneutralization can be made very fast by increasing the light intensity. This provides a means for fast sweeping of the depletion barrier in a fraction of a second. For novel doping measurements, the most critical aspect is the recently identified direct relationship between the corona charge photoneutralization time constant and the doping concentration. This relationship, originally observed on 4H-SiC was confirmed for other wide bandgap semiconductors and was found valid over a broad range of doping concentration. The enhanced throughput novel doping measurement method is based on this newly identified relationship and the ability to increase the speed of photoneutralization at will by increasing the light intensity.

#### EXPERIMENTAL APPARATUS

The experiments demonstrating the method were performed on epitaxial 4H-SiC wafers. A corona chargevoltage characterization apparatus, CnCV, was modified by addition of short wavelength illumination sources as schematically illustrated in Fig. 2. The apparatus was fully automated, and it includes a UV pretreatment chamber, shown in Fig. 3, for stabilizing the fresh epitaxial 4H-SiC wafers. Such wafers, immediately after the epitaxial growth process, exhibit rapid dissipation of deposited corona charge that is caused by surface diffusion [2].

The potential benefit of UV in reducing this effect was suggested by measurements performed after UVPL defect imaging [5]. Accordingly, a UV pretreatment was implemented in CnCV tools. It is performed concurrently with measurements on multiple wafers and thus in practice only affects the measurement time of the first wafer.



Fig. 2. Illustration of the apparatus arrangement in the measurement bay of CnCV tool modified with near UV light sources for charge photoneutralization.

The apparatus in Fig. 2 incorporates two standard CnCV method elements, i.e. (a) the corona charge source for precise charge deposition on the semiconductor surface region, and (b) the Kelvin-probe noncontact surface voltage measurement that is realized with a vibrating electrode at a fraction of mm above the surface. An additional element (c) is the short wavelength near UV illumination for corona charge photoneutralization. It can be realized in two configurations of illumination: i.e. the LED 1 for illumination under the Kelvin probe electrode and the LED 2 for illumination separate from the Kelvin probe. The illumination can be provided by light emitting diodes, LEDs, with a narrow band pass filter. For measurement on 4H-SiC, with an energy gap of 3.3eV, two appropriate light wavelengths were used: 355nm and 325nm corresponding to photon energies of 3.49eV and 3.82eV, respectively.



Fig. 3. Illustration of concurrent UV pretreatment and measurement in CnCV tools.

The point source corona was used in the present work for deposition of the prescribed negative charge density,  $Q_c$ , biasing the surface to deep depletion. The corona charge profile across the charged test site is shown in Fig. 4.



Fig. 4. Corona charge profiles on a 1e16cm<sup>-3</sup> n-type SiC epi sample before and after a UV pulse ( $\lambda$ =355nm) showing charge photoneutralization and no evidence of lateral corona charge spreading.

The charge density was obtained from the measured Kelvin-probe surface voltage scans using the Schottky barrier charge-voltage relation [6]. The result shows the photo-neutralization effect, manifested as a decrease of the charge density after 100ms illumination. In addition, the results show no evidence of lateral charge spreading, confirming very good charge stability achieved with 2min whole wafer UV pretreatment prior to measurement. The absence of surface diffusion is essential for the present work, wherein the detailed time-resolved characteristics of the photo-neutralization are analyzed as a means of a rapid doping measurement.

An example result of a time dependent photoneutralization plot of the surface voltage V(t) is given in Fig. 5A for n-type 4H-SiC with  $N_D$ =3.3e15cm<sup>-3</sup>. These results demonstrate rapid photoneutralization with an effective time constant  $\tau_{ph}$ of about 0.09 seconds at an incident photon flux of 1.2x10<sup>13</sup> photons/cm<sup>2</sup>s. For such a low photon flux, one may expect negligible contribution from photo-ionization of surface states and of deep levels in the bulk SiC, which could potentially interfere with corona-charge based measurements. The initial portion of the voltage transient in the dark shows no evidence of corona charge decay prior to illumination. This dark portion of the transient can be used as an indicator of any charge neutralization due to site defectivity.



Fig. 5A. Depletion voltage decay during 325nm illumination reflecting photoneutralization of the corona charge and a corresponding collapse of the space charge depletion layer.



Fig. 5B. Example of the plot used for determining the photoneutralization time constant corresponding to the illumination induced transient in FIG 5A.

The corona charge decay is quantified using the photoneutralization time constant,  $\tau_{ph}$  that is determined as shown in Fig. 5B. For a constant illumination condition,  $\tau_{ph}$  is found to correlate with the dopant concentration. The correlation plot shown in Fig. 6 was obtained from  $\tau_{ph}$  and  $N_D$  measurements performed on epitaxial 4H-SiC wafers with uniform  $N_D$  depth profiles. The results in Fig. 6 constitute a doping calibration plot for a rapid  $N_D$  determination from the directly measured corona photoneutralization time constant. The doping values in Fig. 6 were obtained on the same wafer sites as  $\tau_{ph}$  using standard noncontact C-V doping measurement capability of the CnCV tool in Fig. 2.

The increase of the photoneutralization time constant,  $\tau_{ph}$ , with increasing of dopant concentration,  $N_D$ , is a consequence of a smaller surface depletion width  $W_D = Q_C/qN_D$ . This results in smaller photogeneration of holes within depletion. As depicted in Fig. 1, free holes,  $h^+$ , generated in depletion are active in photoneutralization. They are directed to the surface by the depletion electric field. At the surface, negative corona ions capture holes,  $Q^- + h^+ \rightarrow Q^+$  and neutralized corona species detach from the surface.



Fig. 6. Experimental results illustrating the photoneutralization time constant,  $\tau_{ph}$ , dependence on doping concentration,  $N_D$ , measured on n-type SiC over a range of 6e14 to 1.2e16 cm<sup>-3</sup>.

At increased doping, smaller hole generation caused by the reduced depletion width can be overcome by increasing the incident photon flux,  $\phi_{eff}$ . Indeed, as shown in Fig. 7,  $\tau_{ph}$  is inversely proportional to the incident photon flux. Accordingly, a rapid measurement can be realized at higher  $N_D$  by increasing the incident photon flux.

Quantitative determination of the doping concentration from the calibrated  $\tau_{ph}$  vs  $N_D$  uses the inverse function  $N_D$  vs  $\tau_{ph}$  that is denoted  $f_{cal}$ . The measurements are performed at the same wavelength as the one used for calibration, for example  $\lambda$ =325nm in Fig. 6 and 7. The actually used photon flux,  $\phi_{eff}$ , is typically different than  $\phi_{cal}$ , since it is adjusted considering the speed of measurement requirement. The measured  $\tau_{ph}$  is normalized based on the inverse dependence on the incident photon flux. The normalized value  $\tau_{ph}^* = \tau_{ph}(\phi_{eff}/\phi_{cal})$  is then used in the inverse function to calculate doping concentration as  $N_D = f_{cal}(\tau_{ph}^*)$ . In the present case, the  $\tau_{ph}$  calibration in Fig. 6 was performed at  $\phi_{cal} = 1.2e13$  photons/cm<sup>2</sup>s. It is recommended that the novel method be coupled with standard CnCV in order to account for variations in illumination conditions.



Fig. 7. Results illustrating the photoneutralization time constant dependence on the incident photon flux.

Accuracy, precision, and speed of the novel doping measurements are demonstrated by the results in Fig. 8. The scan across the wafer diameter in Fig. 8A demonstrates matching with standard CnCV N<sub>D</sub> to within  $\pm 1\%$  for all sites.



Fig. 8. Results of a 13pt line scan across the diameter of a 100mm n-type SiC wafer (A), illustrate agreement between standard CnCV and the novel approach. (B) shows repeatability of  $0.19\% 1\sigma$  over 15runs demonstrated with the novel approach.

The standard CnCV results are consistent with mercury C-V results and can be considered as accepted values, therefore matching illustrates  $\pm 1\%$  accuracy. The measuring time for 13 sites using the novel method is reduced to 2.2 min, compared to 12 min for standard CnCV. The corresponding increase of the measurement speed results in increasing the throughput to about 20 wafers per hour. Figure 8B shows the precision of the novel method illustrated by a wafer average  $1\sigma$  of 0.19% for 15 repeats.

High measurement speed in this novel approach shall benefit wafer manufacturing, making full wafer mapping practical in a reduced time of 8 min compared to 40 min for standard CnCV. Such a 49-site map is shown in Fig. 9.



Fig. 9. 49-site  $N_D$  map measured in 8.2min with the novel  $\tau_{ph}$  approach which is ~5x faster than standard CnCV measurements.

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## ACRONYMS

CnCV : Corona non-contact Capacitance Voltage C-V: Capacitance-Voltage UV: Ultraviolet UVPL: Ultraviolet Photoluminescence LED : Light Emitting Diode NB : Narrow Bandpass