Materials Science Forum
ISSN: 1662-9752, Vol. 1157, pp 49-56
doi:10.4028/p-qU8rgR

Submitted: 2024-09-10
Revised: 2025-06-03
Accepted: 2025-06-03
Online: 2025-09-05

Recent Advancement in Noncontact Wafer Level Electrical Characterization for WBG Technologies

Marshall Wilson[1,a*], Alexandre Savtchouk[1,b], Liliana Gutierrez[1,c], Carlos Almeida[1d], and Jacek Lagowski[1e]

[1]Semilab SDI, 12415 Telecom Dr., Tampa, FL 33637, USA

[a]marshall.wilson@semilabsdi.com, [b]sasha.savtchouk@semilabsdi.com, [c]liliana.gutierrez@semilabsdi.com, [d]carlos.almeida@semilabsdi.com [e]jacek.lagowski@semilabsdi.com

Keywords: non-contact characterization, corona, doping, SiC, Ga_2O_3, HEMT

Abstract. A breakthrough high throughput WBG semiconductor dopant monitoring method has recently been introduced based on the novel concept of sweeping the electrical bias by near UV illumination-induced photoneutralization of corona charge. As originally discovered for 4H-SiC, the doping determination can be realized using the value of the photoneutralization time constant. In the present work this procedure is tested for β-Ga_2O_3 with a larger energy gap of 4.8eV, using a correspondingly deeper UV range. Such deep UV application to the AlGaN/GaN HEMT structure resulted in the development of a new measurement principle capable of increasing the HEMT wafer measurement throughput 10 times compared to previous corona noncontact C-V metrology. The new principle involves a linear illumination-induced corona charge bias sweep. Combined with surface voltage monitoring, it provides a means for fast and precise determination of the pinch-off voltage, V_P, the AlGaN electrical thickness, and the 2D electron gas density.

Introduction

Wide bandgap (WBG) semiconductor technology is the primary answer to the growing demands of high-power electronic devices. The continually advancing production of WBG epitaxial wafers and structures requires a cost effective, fast feedback metrology, enabling precise wafer level monitoring of epitaxial properties, e.g., dopant concentration, depth profile, uniformity and run to run reproducibility. Our development of such a noninvasive WBG metrology has been based on the adaptation of a Si IC production proven electrical characterization method [1], realized with corona charge, ΔQ_C, biasing of the surface and measuring the surface voltage, V, with a vibrating Kelvin probe. The commercial tool, CnCV (Corona noncontact Capacitance Voltage), initially intended for SiC, was introduced by Semilab SDI in 2017 [2]. With a continuously refined performance, the applicability of the CnCV tool expanded to other WBG semiconductors, including AlGaN/GaN HEMT structures and β-Ga_2O_3 as discussed in this work. The technique can also be applied to other WBG material with a bandgap above ~2eV such as GaN, AlN, BN and diamond.

A noncontact C-V characteristic in CnCV is generated using differential capacitance, $C = \Delta Q/\Delta V$ and the doping is determined from $1/C^2$ vs. V. Rapidly growing mass production of WBG wafers has created a special demand for increasing the throughput in CnCV measurements. In standard CnCV, the multi-step charge deposition and the wafer transfer back and forth for voltage measurement limits the measurement speed and wafer throughput.

New breakthrough improvements of throughput were initiated in 2023 with the discovery of the Kinetic mode [3]. This mode utilizes illumination-induced photoneutralization of the corona-deposited surface charge instead of multi-step deposition. Doping determination using the Kinetic mode is based on the discovery that the photoneutralization time constant, τ_{ph}, provides a measure of the dopant concentration. The τ_{ph} values can be adjusted by illumination intensity to a fraction of a second range, producing a fast dopant measurement and a corresponding enhancement of the monitoring throughput [3]. Both CnCV and Kinetic are considered quasi-static techniques with measurement frequencies in the 1 to 2Hz range. Recent advancements in the noncontact characterization and especially the measurement speed and throughput reported in this work include applications of the Kinetic mode to β-Ga_2O_3 and to a new method for characterization of AlGaN/GaN HEMT structures.

Experimental

Two measurement applications addressed in the present study include: 1. Dopant concentration, N_D, in epitaxial, n-type β-Ga_2O_3, and 2. Electrical parameters of $Al_XGa_{1-X}N$/GaN HEMT structures with a two-dimensional electron gas, 2DEG.
The measurements were performed in a CnCV tool enabling the standard multi-step corona charging based characterization and the novel Kinetic mode characterization. For the latter one the CnCV tool was modified by the addition of a short wavelength ultra-violet LED light source with a peak wavelength of 255nm (photon energy about 4.9eV), suitable for generation of free electron-hole pairs in Ga_2O_3 and in a $Al_{0.25}Ga_{0.75}N$ barrier layer of the HEMT structure used in this study.
The schematic illustration of the experimental apparatus is shown in Fig. 1. The measured wafer is placed on a moveable stage. The key elements include: (a) the corona charge, Q_C, deposition station, (b) the surface voltage, V, measuring Kelvin probe 2mm in diameter and (c) the LED sources of UV illumination. The illumination can be performed under the probe simultaneously with measuring of V or at a separate location.

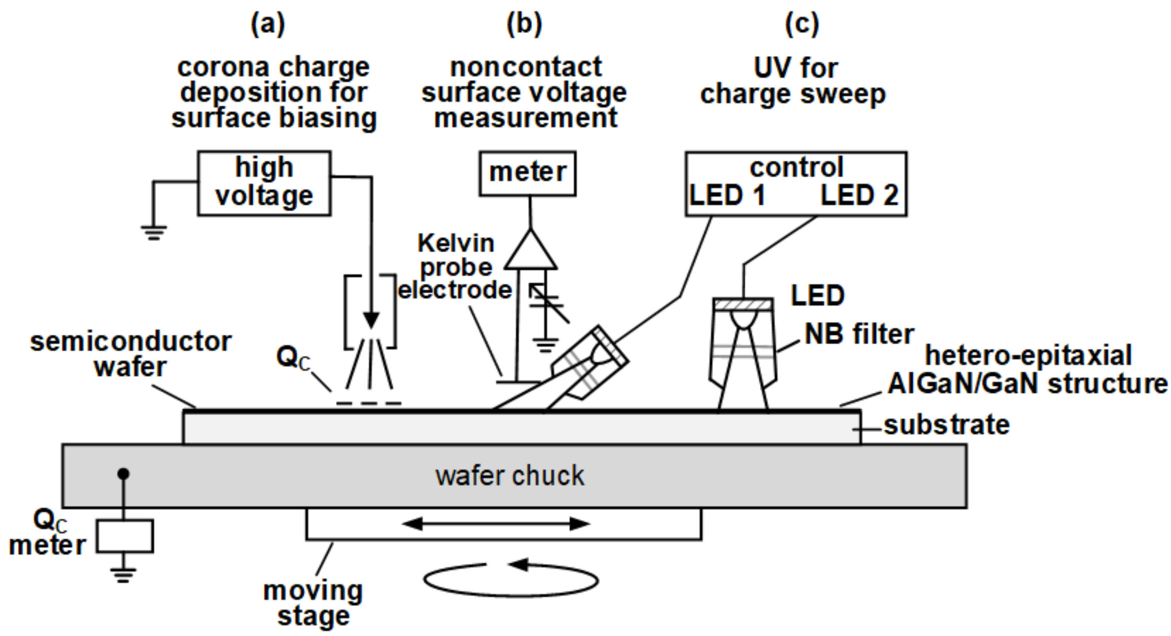

Fig. 1. Schematic illustration of the measurement bay apparatus used for the present study.

In the comparative study performed in this work, the novel measurements with an illumination-induced charge sweep and the standard CnCV measurements were performed on the same wafer locations. Accordingly, the CnCV apparatus included wafer prealigning and robotic handling for precise and repeatable wafer positioning. These elements are not shown in Fig. 1.
An enclosure for the measurement bay is used to prevent stray light from reaching the wafer and interfering with the precise illumination induced corona charge sweep. Further details of the hardware arrangement and the CnCV technique are available in references [1-3].

Results and Discussion

Kinetic mode doping characterization in Ga_2O_3. The measuring sequence used for Ga_2O_3 is similar to previously described measurements on n-type SiC [3]. Accordingly, as the first step, a single negative corona charging to deep depletion V is performed in the dark. Subsequently, the charged

region is positioned under the Kelvin probe and the surface voltage (i.e. the depletion voltage in this case) is briefly measured in the dark as a verification of the deposited charge stability. It is followed by UV illumination with a wavelength of 255nm causing photoneutralization of the corona charge. The illumination is realized in short 10ms pulses with the voltage value monitored after each pulse. The resulting depletion voltage decay is shown in Fig. 2 together with the photoneutralization Kinetic plot $\ln^2(\Delta V/V_0)$ used for determination of the time constant, τ_{ph}.
The process of charge photoneutralization in the deep depletion condition is illustrated in Fig. 3. The effect is caused by photons generating electron-hole pairs within the depletion layer, W_D. The positive holes drift to the surface in the depletion electric field and neutralize the negative corona ions. The depletion layer shrinks during illumination in response to the charge photoneutralization. The shrinking depletion layer decreases the generation of free carriers. It also decreases the depletion layer electric field and affects the drift of photogenerated carriers. As a result, the decay of the depletion voltage V(t) is nonlinear and fitting for the determination of the time constant, τ_{ph}, is performed with the $\ln^2(V/V_0)$ function. The time constant, τ_{ph}, obtained from the inverse slope constitutes a doping index, i.e, a measure of doping in arbitrary units [3]. After calibration is performed for a given illumination condition (wavelength and photon flux), the τ_{ph} value is transformed into the actual dopant concentration as $N_D = \tau_{ph} \cdot f_{cal}$ where f_{cal} is the calibration function [3]. In Fig. 2 the procedure gives $N_D = 2.34 \times 10^{16}$ cm^{-3}.

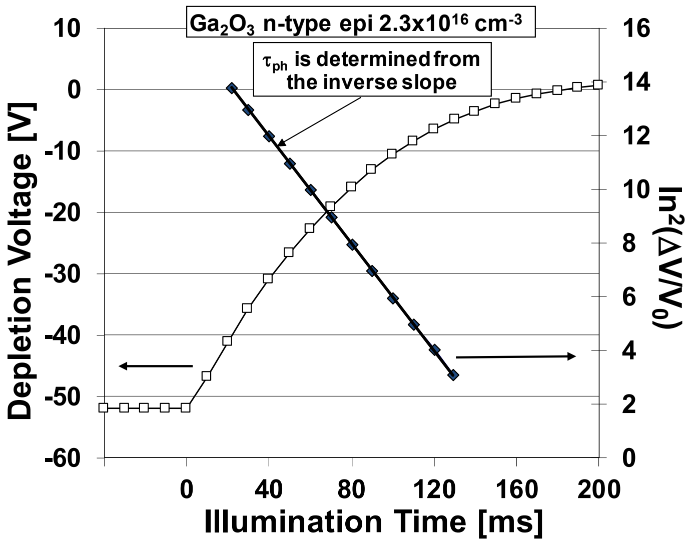

Fig. 2. Kinetic charge photoneutralization characteristic for n-type b-Ga_2O_3 with 10ms light pulses λ= 255 nm.

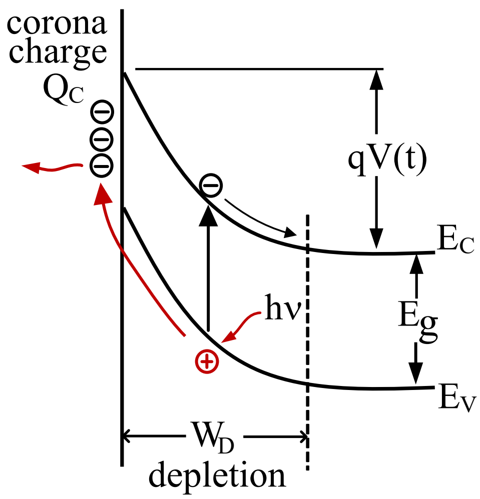

Fig. 3. Illustration of the corona charge photoneutralization.

In CnCV tools the calibration of τ_{ph} vs. N_D can be performed using actual dopant concentration measured with the standard $1/C^2$ method. This capability is used in the present application of the Kinetic mode to n-type Ga_2O_3.
The results in Fig. 2, Fig. 4, and Fig. 5 confirm the applicability of the Kinetic mode for doping measurement in Ga_2O_3. The high precision of the measurement is demonstrated by repeatability with a 1σ average of 0.1% obtained in 10 repeats as seen in Fig. 4. In addition, the results in Fig. 5 show a 9pt wafer scan completed with the Kinetic mode in only 3min. This includes wafer loading and unloading and it would correspond to a throughput of about 20 wafers per hour, meeting industry requirements. The Kinetic results in Fig. 5 show agreement with standard CnCV doping measurements with the $1/C^2$ method on the same wafer sites. The standard measurement time of 12 mins corresponds to a throughput of only 5 wafers per hour.

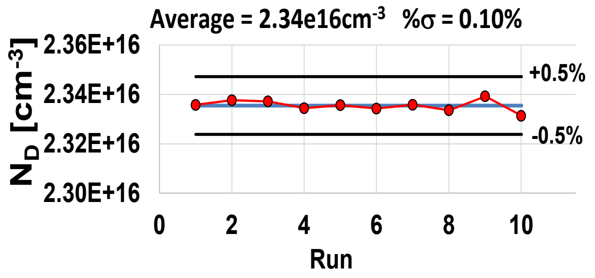

Fig. 4. Kinetic mode repeatability of N_D for n-type b-Ga_2O_3.

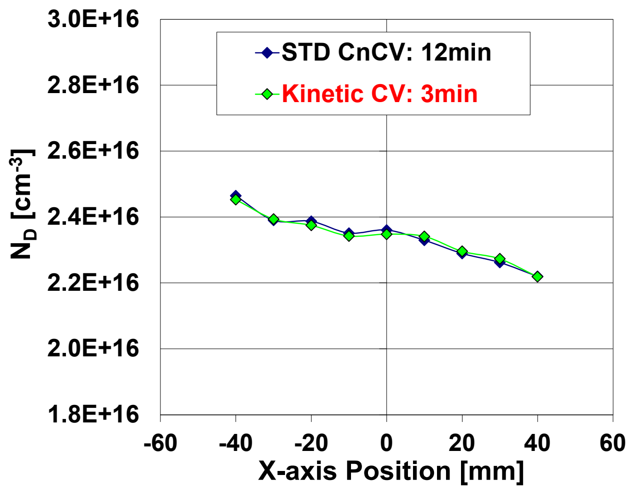

Fig. 5. 9pt scan across the diameter of a n-type b-Ga_2O_3 wafer comparing novel Kinetic mode and standard CnCV results.

Characterization of AlGaN/GaN structure. The $Al_xGa_{1-x}N$/GaN HEMT structure is schematically illustrated in Fig. 6 for the initial state (A) and after negative corona charging (B), respectively. The corresponding energy band diagrams are shown in Fig. 7. The initially populated 2DEG is a consequence of the strong piezoelectric polarization induced by a lattice mismatch between the top $Al_xGa_{1-x}N$ layer and the underlying GaN channel layer [4]. A strong electric field created by polarization directs free electrons from the AlGaN to the 2DEG. The AlGaN barrier layer with a large energy gap, about 4eV, becomes depleted of free carriers and it can retain, very well, the negative corona charge deposited on the surface. The prescribed large dose negative corona deposition on the surface is used to depopulate the 2DEG as illustrated in Fig. 6B and Fig. 7B. This is the first biasing step in the active layer characterization cycle.

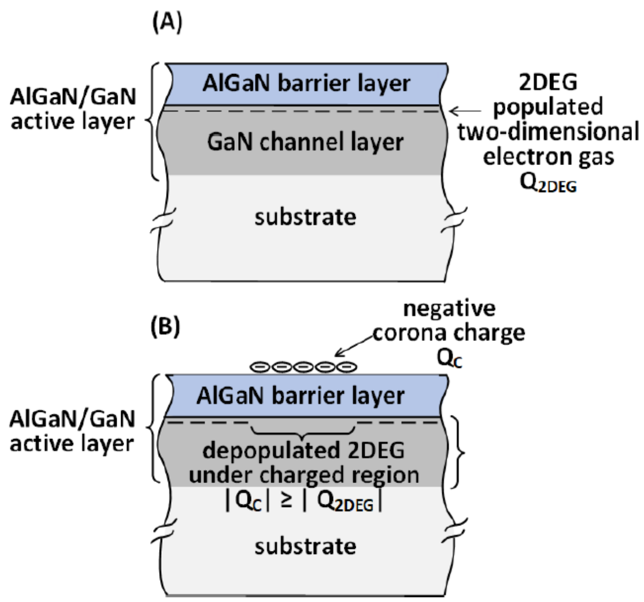

Fig. 6. AlGaN/GaN structure in the initial state (A) and with the 2DEG depopulated by negative corona charge (B).

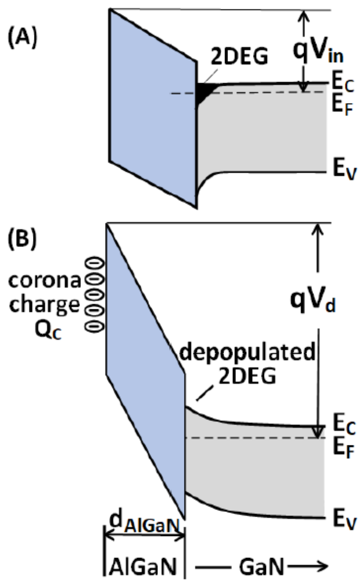

Fig. 7. The energy band diagram of AlGaN/GaN structure corresponding to Fig. 6.

After that, the standard CnCV method uses a positive multi-step corona charging sequence repopulating the 2DEG back to the initial condition. The surface voltage is measured after each charging step. Corona charging cannot be performed under the Kelvin probe. Accordingly, the incremental charging sequence includes wafer transfer to the Kelvin probe and back to the charging position. The resulting AlGaN/GaN characteristic is shown in Fig. 8. It provides a means to determine the active layer parameters. However, it is too slow for industrial needs.
The novel approach replaces the positive charging sequence with a rapid illumination-induced photoneutralization of the negative corona charge. The advantage of illumination is that it can be realized under the probe simultaneously with the surface voltage measurement. The results shown in Fig. 9 are obtained 20 times faster than the standard results in Fig. 8.
The results in Fig. 8 and Fig. 9 show a striking similarity. This demonstrates that for the AlGaN/GaN HEMT structure the time of illumination in the photoneutralization sweep is equivalent to the corona charge density, Q_C, in the multi-step return of the 2DEG to the initially populated condition. This similarity is supported by the modeling of the photoneutralization process illustrated in Fig. 10. A significant difference compared to the deep depletion case in Fig. 3 is that the AlGaN barrier layer thickness is constant during the process, unlike the shrinking depletion width.
In the model in Fig. 10, the photons with 4.9eV energy absorbed in the AlGaN barrier layer with a 4eV energy gap generate electron hole pairs, $h\nu = e^- + h^+$. The positive holes are directed to the surface and neutralize the corona ions $h^+ + Q_C^- \rightarrow Q_C^0$. The free electrons drift to the AlGaN/GaN interface and increase the population of 2D electron gas, $e^- \rightarrow 2DEG$.
The thickness of the depleted AlGaN barrier layer (about 20nm) does not change during the charge sweep. Accordingly, the generation rate of electron-hole pairs in the barrier remains constant. In addition the strong polarization field assures effective carrier drift during the entire process. The above conditions lead to a linear illumination-induced charge sweep unique for the AlGaN/GaN HEMT structure and different than the exponential charge sweep in the surface depletion layer used for the doping measurement.

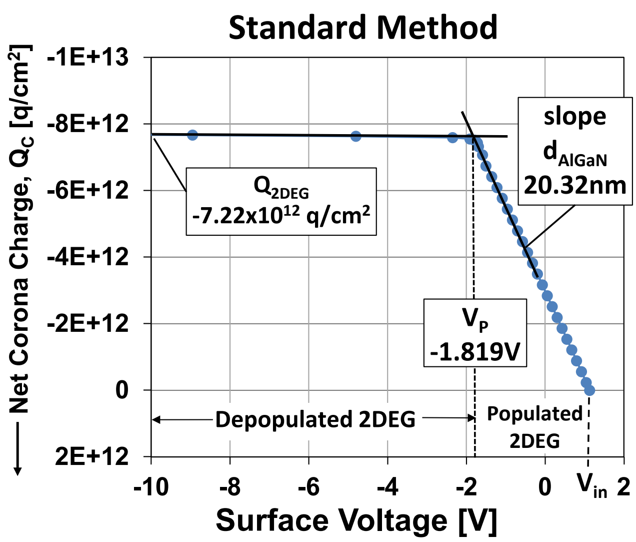

Fig. 8. Standard CnCV sequential corona charging results illustrating the extraction of AlGaN/GaN HEMT parameters.

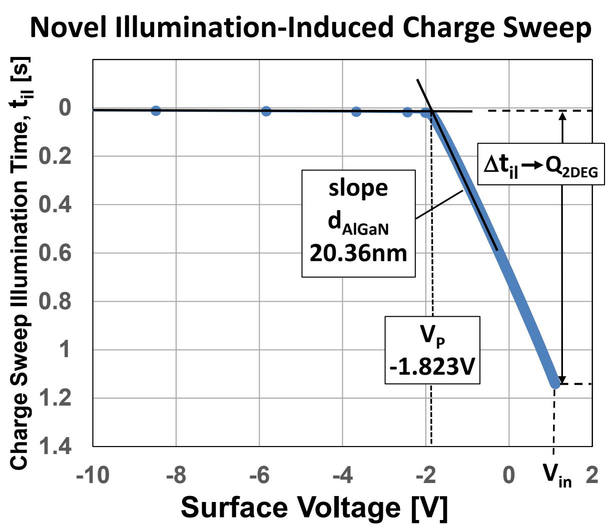

Fig. 9. Novel charge sweep results illustrating the extraction of AlGaN/GaN HEMT structure parameters.

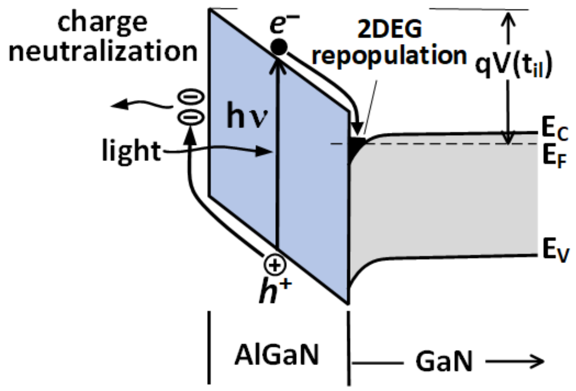

Fig. 10. Illumination-induced neutralization of corona charge on the AlGaN/GaN surface and corresponding repopulation of the 2DEG.

The much shorter measurement time in Fig. 9 is a consequence of the rapid illumination-induced charge sweep, about 20 times faster than the charge-transfer-measure sequence in Fig. 8. In both techniques the pinch-off voltage is determined as the intercept voltage between the different slope lines and the results are very similar. The low slope line corresponds to the depleted 2DEG while the high slope corresponds to the populated 2DEG, respectively. This procedure for determining the pinch-off voltage is adopted from the $Al_xGa_{1-x}N$/GaN HEMT characterization with mercury probe CV described by E. Tucker et al. [5]. The determination of the AlGaN layer thickness using the slope value of the charge-voltage line, (i.e. the structure capacitance, C_{HEMT}) in the range where the 2DEG is populated is also adopted from ref [5]. The capacitance of the AlGaN layer, C_{AlGaN}, and that of the 2DEG, C_{2DEG}, are connected in series. For a sufficiently large 2DEG population, $C_{2DEG} >> C_{AlGaN}$, the C_{AlGaN} dominates the total capacitance which becomes a measure of the AlGaN thickness.

In the novel method, a calibration quantifying the time of the linear sweep vs. corona charge is used in the determination of the capacitance and the corresponding AlGaN thickness. The new measurement of the pinch-off voltage, V_P, is calibration free.

The results of repeated Kinetic mode measurements of the pinch-off voltage are given in Fig. 11. These results indicate a relative 1σ value of 0.11% in ten repeats. This can be treated as an indication of the good precision of the measurement.

In the actual Kinetic mode measurement cycle, the calibration can be performed using the precise in-situ measured value of the negative corona charge, Q_{CD}, in the first 2DEG depopulating step. The calibration factor $F_{cal} = Q_{CD}/\Delta t_{il}$ where Δt_{il} is the sweep time interval required to return the 2DEG to the initial precharging condition. This initial condition in the method is defined by the initially measured surface voltage value, V_{in}.

The calibration factor F_{cal} depends on the specific illumination condition, the photon flux and the wavelength. In the novel characterization approach, increasing the photon flux provides a practical means for increasing the speed of the measurement and the wafer measurement throughput.

The enhanced speed of the measurement is especially beneficial for whole wafer uniformity testing, such as the 49pt V_P map shown in Fig. 12. This map can be obtained in 20 minutes compared to the 3.5 hours required in the previous standard CnCV testing of the AlGaN/GaN wafer uniformity.

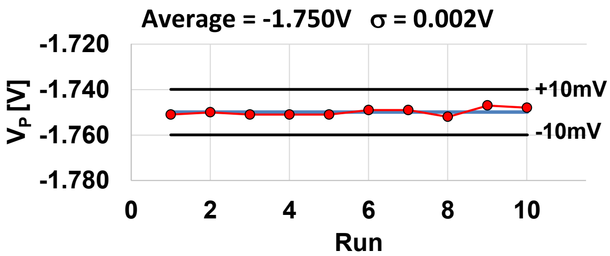

Fig. 11. Kinetic mode V_P measurement repeatability for AlGaN/GaN HEMT structure.

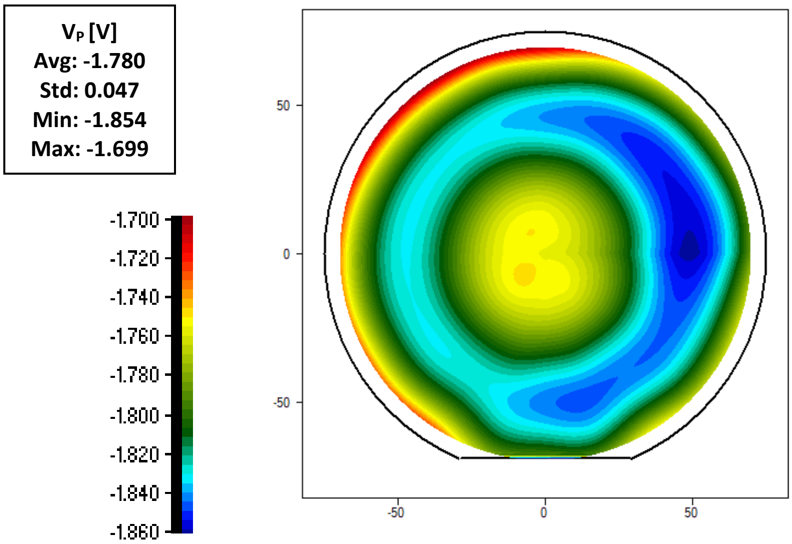

Fig. 12. 49pt Kinetic mode pinch-off voltage, V_P, map for AlGaN/GaN HEMT. There is an order of magnitude improvement in throughput for the Kinetic mode compared to standard CnCV.

It is a quite unique feature of the new technique that the capacitance-voltage characteristic in arbitrary units can be generated by differentiation of the (t_{il}, V) data set as $C_{arb} = dt_{il}/dV$. Using the calibration factor F_{Cal}, the C_{arb} is converted to the actual capacitance, $C = F_{cal} \cdot C_{arb}$, enabling a direct quantitative comparison with standard C-V measurement results. Such a comparison presented in Fig. 13 demonstrates excellent agreement between the novel and standard method and confirms the validity of the novel high throughput AlGaN/GaN structure characterization. According to recent studies, this technique of capacitance determination can be extended to doping measurements on other wide bandgap material such as SiC including multilayer epi structures [6].

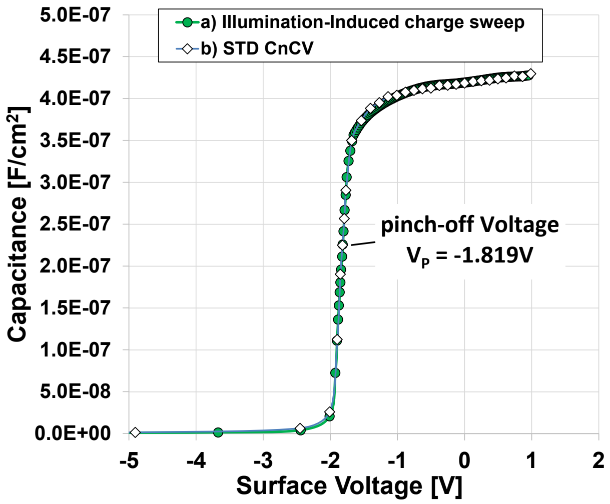

Fig. 13. CV characteristics from both the a) Standard CnCV and b) novel illumination-induced charge sweep methods for the AlGaN/GaN HEMT structure Q-V and t_{il}-V results in Figs. 8 and 9.

Conclusion

A high throughput noncontact electrical characterization technique based on sweeping of the electrical charge bias by UV illumination is found applicable for high precision doping measurement of large energy gap b-Ga_2O_3. The most recent advancement of the technique is demonstrated for AlGaN/GaN HEMT structures wherein the time of the UV illumination-induced charge sweep, t_{il}, is found to constitute a unique charge index and together with the surface voltage gives the derivative capacitance of the active layer as dt_{il}/dV. Upon in-situ calibration these quantities and corresponding voltage characteristics provide a novel means for determination of the critical active layer parameters such as V_P, AlGaN thickness and Q_{2DEG} with wafer testing throughput as high as 20 wafers per hour.

References

[1] D.K. Schroder, Chapter 9: Charge-based and Probe Characterization, in: Semiconductor Material and Device Characteristics, Wiley-Interscience, Hoboken, New Jersey, 2006, p. 523.

[2] M. Wilson, A. Findlay, A. Savtchouk, J. D'Amico, R. Hillard, F. Horikiri and J. Lagowski, "Review—Recent Advancement in Charge- and Photo-Assisted Non-Contact Electrical Characterization of SiC, GaN, and AlGaN/GaN HEMT," ECS Journal of Solid State Science and Technology, 6(11) S3129 (2017).

[3] M. Wilson, J. Lagowski, C. Almeida, B. Schrayer, and A. Savtchouk, "Semiconductor doping characterization method using photoneutralization time constant of corona surface charge", US Patent Granted US12027430B1, Publication Date July 2, 2024.

[4] H. Umeda, Chapter 19.2: GaN Epitaxy on Si Substrate, in: Wide Bandgap Semiconductors for Power Electronics vol. 2, Wiley-VCH GmbH, Weinheim, Germany, 2022, p. 563.

[5] E. Tucker, F. Ramos, S. Frey, R. Hillard, P. Horváth, G. Zsákai, and A. Márton, "Characterization of $Al_xGa_{1-x}N$/GaN High Electron Mobility Transistor Structures with Mercury Probe Capacitance–Voltage and Current–Voltage," Phys. Status Solidi A, 2100416 (2022).

[6] M. Wilson, J. Lagowski, I. Shekerov, C. Almeida, B. Schrayer, L. Gutierrez and A. Wincukiewicz, "Wide Bandgap Semiconductor Characterization Based on Capacitance Characteristics Acquired Using Corona Surface Charge Neutralization by UV Radiation Pulses," US Patent Pending 02695-0058001, submitted May 2025.