High Throughput Wafer Characterization for Manufacturing Needs of SiC and Other WBG Technologies

M. Wilson[1], C. Almeida[1], I. Shekerov[1], B. Schrayer[1], A. Savtchouk[1], B. Wilson[1] and J. Lagowski[1]

[1]Semilab SDI, 12415 Telecom Dr., Tampa, Florida 33637, USA; Email: marshall.wilson@semilabsdi.com; Ph: (813) 977-2244

Keywords: Doping, 4H-SiC, GaN, AlGaN/GaN, HEMT, corona noncontact C-V, CnCV

Abstract

A recently discovered doping characterization technique, Kinetic CV, offers new noncontact monitoring of wide bandgap semiconductor wafers with a production-satisfying throughput of 20 wafers per hour and a precision of 0.2%. Demonstrated on epitaxial n-type 4H-SiC, the technique employs a single corona charging step for biasing the surface to deep depletion. It is followed by a quick millisecond range illumination-induced photoneutralization of the surface corona ions, during which the surface voltage decay is measured with a noncontact Kelvin probe. The time constant, τ_{ph}, of the decay gives the dopant concentration, N_D. In this work, Kinetic CV results are presented for epitaxial SiC, GaN, and AlGAN/GaN HEMTs. The latter case demonstrates a novel rapid determination of the HEMT pinch-off voltage, V_P. Compared to the standard corona noncontact CV method, the V_P throughput is increased 10x for typical 9-point wafer uniformity testing.

INTRODUCTION

Rapidly expanding wide bandgap (WBG) semiconductor technology and corresponding mass production of epitaxial wafers, such as 4H-SiC, GaN, and AlGaN/GaN structures, create special demands for noninvasive wafer level semiconductor characterization. Corresponding measurement techniques must enable precise monitoring of epitaxial properties, including wafer uniformity and run-to-run reproducibility [1].

Our work relates to possibilities opened by a new doping measurement technique [2] that is based on corona charge biasing of WBG semiconductor surfaces to deep depletion followed by photoneutralization of the corona charge by photogenerated minority carriers. A critical aspect for the new doping measurement was the discovery of a direct relationship between the photoneutralization time constant, τ_{ph}, and the semiconductor dopant concentration, N_D [2,3]. The photoneutralization can be a fraction of a second or even in the millisecond range and is adjustable by illumination intensity. This facilitates rapid, noncontact measurement beneficial for high-throughput production monitoring and for practical multisite wafer uniformity testing.

In the standard corona non-contact capacitance voltage (CnCV) technique [4] and in the novel Kinetic mode, charge stability is an important issue. Theoretically, in wide bandgap (WBG) semiconductors in the dark, a deep depletion created by corona charging should be stable due to negligible generation of the minority carriers. In practice however, early applications of CnCV tools in SiC epi-fabrication revealed rapid dissipation of charge deposited on fresh epi surfaces and on freshly etched surfaces. This process involves surface diffusion and dark charge neutralization. It could be effectively eliminated by optimized ultraviolet pretreatment (UVPT) as discussed in Ref. [5]. The potential benefit of UV was suggested by CnCV measurements performed on fresh 4H-SiC wafers after ultraviolet photoluminescence (UVPL) defect imaging [6]. Considering the strictly guarded confidentiality of WBG fabrication, the optimization of UVPT is performed individually at the actual production facilities. In fully automated high throughput tools, UVPT is realized for multiple wafers concurrently with measurements.

EXPERIMENTAL RESULTS AND DISCUSSION

In the experimental configuration, the new technique is implemented into a modified corona noncontact CV (CnCV) tool. The hardware and software arrangement retains all standard CnCV tool capabilities, including UVPT. CnCV results served as a reference and calibration for the new Kinetic mode measurements [2]. The apparatus illustrated in Fig. 1 enables two measurement modes with illumination under the Kelvin probe or at a separate position. The former corresponds to charge photoneutralization with a stationary wafer while the latter involves movement between illumination station and the surface voltage measuring Kelvin probe.

In the example measurement sequence in Fig. 1, the photoneutralization of corona charge deposited on the surface is realized using a train of light pulses. Corona charge ions are neutralized by photogenerated minority carriers drifting to the surface in a strong depletion layer field. Fig. 1 corresponds to n-type SiC with a depletion layer created by negative corona charge. The charge neutralization is caused by photogenerated holes. The measurement of charge neutralization gives time-resolved surface voltage data.

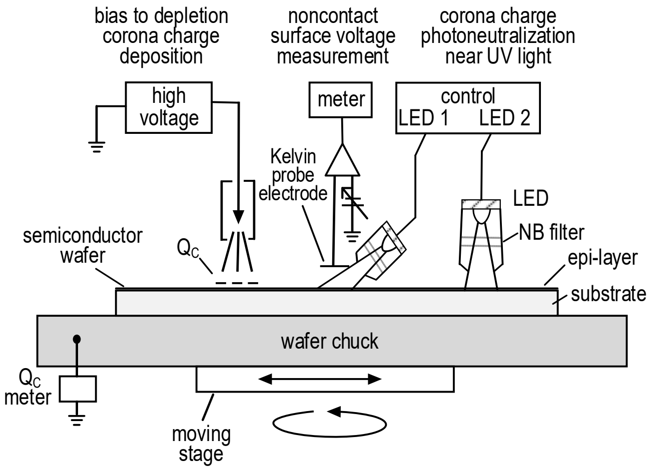

Fig. 1. Illustration of the Kinetic CV apparatus arrangement in the measurement bay of CnCV tool modified with near UV light sources for charge photoneutralization.

A change of the depletion voltage corresponding to decreasing of the depletion width takes place during the illumination pulses. During the dark periods before and after each pulse, the surface voltage remains constant. This proves the absence of dark dissipation of corona charge, as theoretically expected for interface-free deep depletion measurements in WBG semiconductors.

From results in Fig. 2, the Kinetic photoneutralization curve is extracted as V(t) where t is the actual illumination time. Such a Kinetic curve corresponding to Fig. 2 is shown in Fig. 3. Characterization of the semiconductor parameters is based on analysis of the V(t).

The results in Fig. 2 and Fig. 3 correspond to illumination under the Kelvin probe. Other presented results were obtained using a separate illumination station that gives better light spot uniformity and higher precision.

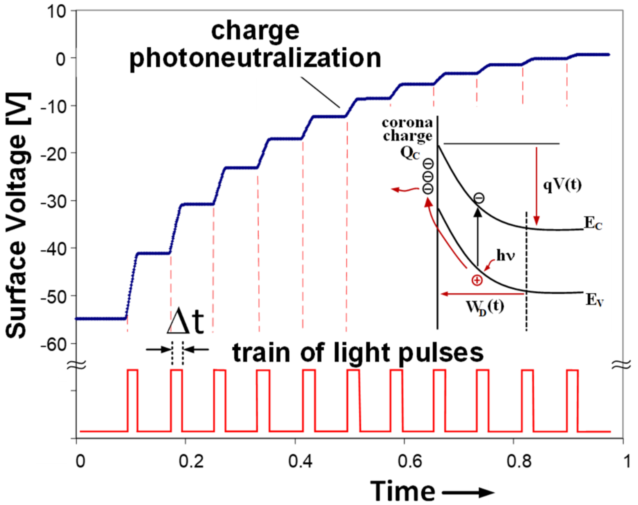

Fig. 2. Photoneutralization of corona charge in n-type 4H-SiC in depletion. Light pulses are 20 ms and wavelength λ = 325nm. Insert shows the photoneutralization process.

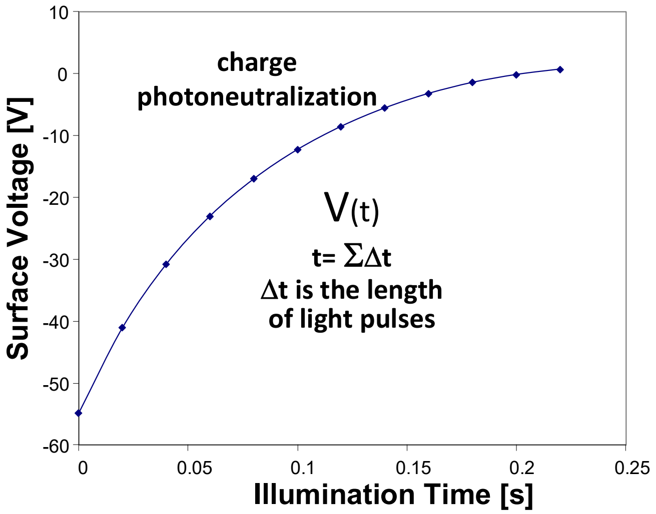

Fig. 3. The depletion voltage decay vs. illumination time calculated from experimental data in Fig. 2.

The Kinetic CV mode for doping characterization was initially demonstrated on n-type epitaxial 4H-SiC wafers [2,3] and is illustrated in Fig. 4. In this method, a single negative corona charge to deep depletion (-55 V) is performed in the dark. It is followed by near UV illumination with a wavelength λ = 325 nm and photon flux in range of 10^{13} photons/cm^2-s, generating the excess carriers. The insert in Fig. 2 illustrates the photoneutralization of negative corona charge by photogenerated holes drifting to the surface in a strong depletion field.

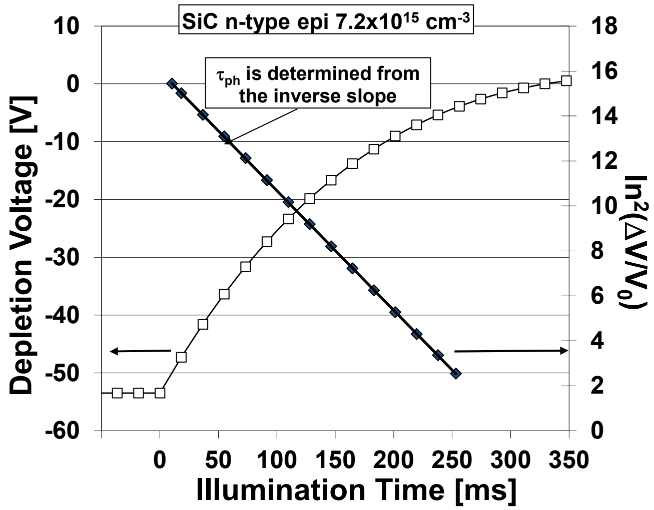

Fig. 4. Kinetic CV photoneutralization characteristic for n-type 4H-SiC.

The depletion width, W_D, and the voltage, V, decrease with illumination time, t. The Kelvin probe measurement gives V(t), shown in Fig. 4 together with the corresponding photo-neutralization kinetic plot $\ln^2(\Delta V/V_0)$ vs t. The photo-neutralization is quantified using the time constant, τ_{ph}, obtained from the inverse slope of the kinetic plot. After calibration, the τ_{ph} value for given illumination condition (wavelength and photon flux), is used to determine the dopant concentration. In Fig. 4 τ_{ph} = 75.2 ms and N_D = 7.21×10^{15} cm^{-3}.

In CnCV tools the calibration of τ_{ph} vs. N_D can be performed using actual N_D measured with the standard capacitance based $1/C^2$ method. This capability is used in SiC and the new application of the Kinetic mode to n-type GaN.

The GaN corona charge photoneutralization characteristics in Fig. 5, were measured using illumination with λ = 255 nm and a photon flux of ϕ_{eff} = 1.96×10^{13} photons/cm^2-s.

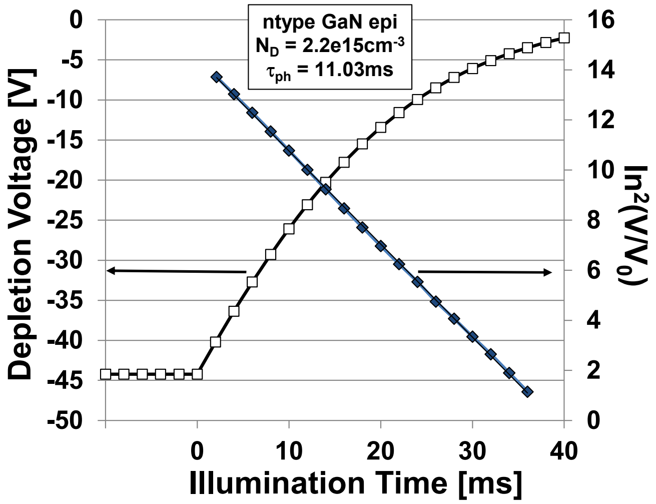

Fig. 5. Kinetic CV photoneutralization characteristics for n-type GaN. Measurements with 2 ms light pulses λ = 255 nm.

The results illustrate fast photoneutralization in 40 ms with a time constant of τ_{ph} = 11.03 ms, giving a dopant concentration, N_D = 2.22×10^{15} cm^{-3}. The precision of the measurement was verified by the repeatability results shown in Fig. 6, and the std. deviation σ = 0.12% over 10 runs.

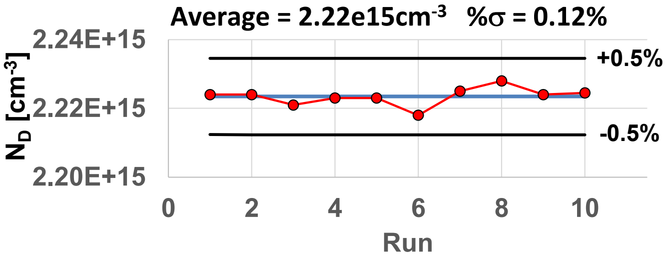

Fig. 6. Kinetic mode CV repeatability of N_D for n-type GaN.

The Kinetic mode application to GaN demonstrated doping measurement capability with high precision and a throughput of about 20 wafers per hour for 12 sites per wafer testing, similar to that in SiC [3].

Characterization of AlGaN/GaN HEMT structures with the novel Kinetic mode uses negative corona charging to fully deplete the initially populated 2DEG at the AlGaN/GaN heterointerface. As illustrated in the energy band diagram in Fig. 7, this is reversed by illumination causing corona charge photoneutralization. The resulting voltage decay during illumination V(t), shown in Fig. 8 reflects 2DEG recovery to the initial condition, achieved in a fraction of a second. Two slopes distinguish the rapid decay of the deep depletion voltage and slow voltage change when the 2DEG is populated. The demarcation point defined by intercept of 2 lines corresponds to the HEMT pinch-off voltage, V_P.

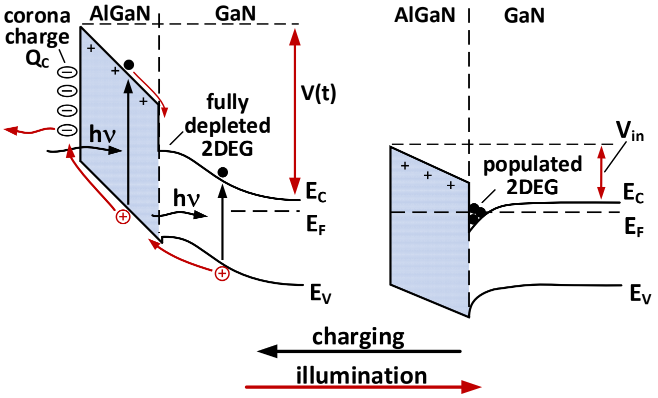

Fig. 7. Corona charge effect and illumination induced charge photoneutralization for AlGaN/GaN HEMT with 2DEG.

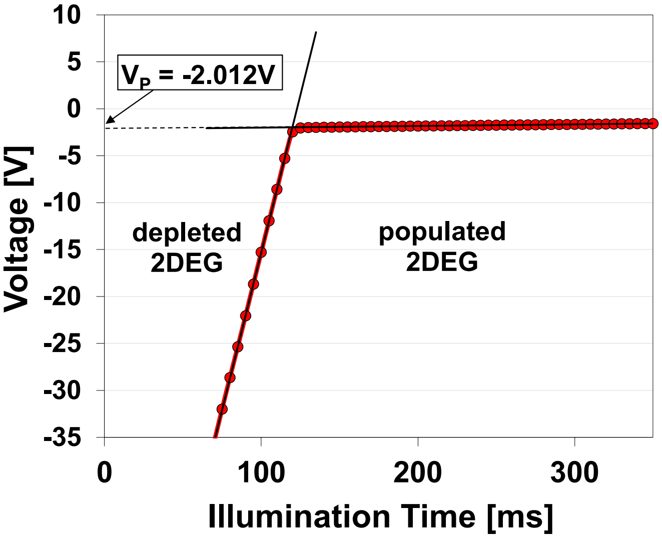

Fig. 8. Kinetic mode pinch-off voltage, V_P, measurement on AlGaN/GaN HEMT.

The Kinetic mode pinch-off voltage determination does not require any calibration and the measurement can be performed at different illumination conditions, optimized for a given AlGaN/GaN structure regarding speed and precision.

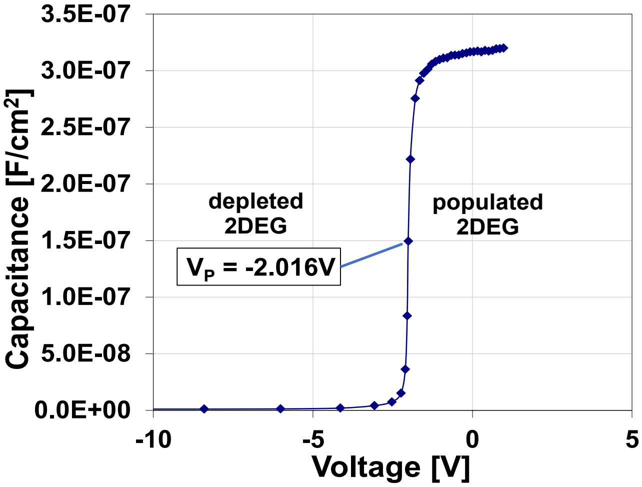

Fig. 9. Standard CnCV pinch-off voltage, V_P, measurement on AlGaN/GaN HEMT.

Compared to V_P measurement in the standard CnCV mode in Fig. 9, the Kinetic mode offers about an order of magnitude faster measurement. The CnCV measurement is based on differential capacitance characteristics, C-V, illustrated in Fig. 9. The technique requires a large number of time-consuming, sequential steps involving corona charge deposition, ΔQ, and voltage change measurements, ΔV [4]. The differential capacitance C=ΔQ/ΔV vs. the cumulative voltage, V, gives the noncontact C-V characteristic from which the pinch off voltage is determined by the onset of 2DEG full depletion.

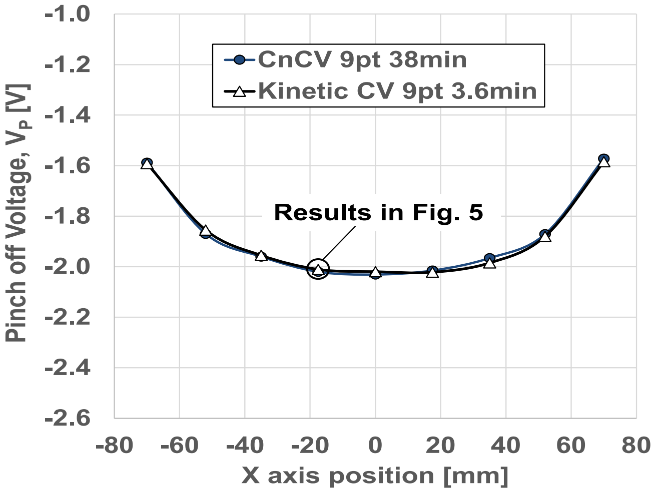

Fig. 10. 9pt scan across the diameter of an AlGaN/GaN HEMT wafer comparing novel Kinetic mode and standard V_P results.

The V_P scans across the AlGaN/GaN wafer diameter in Fig. 10 demonstrate matching of the new Kinetic mode and the standard CnCV results within 1% for all 9 sites. Such agreement with the results of an established C-V technique illustrates the good accuracy of the Kinetic mode. In addition, the measurement time for 9 sites using the novel Kinetic mode is reduced to 3.6 minutes compared to 38 minutes for standard C-V measurement. The precision of the novel V_P method was evaluated by a wafer average 1σ of 0.5% in 10 repeated measurements, similar to that in standard CnCV.

CONCLUSIONS

The novel, noncontact Kinetic CV method has been proven to be an attractive, mercury-free alternative technique for high throughput monitoring of SiC epi layer dopant concentration. Present results demonstrate the application of the Kinetic CV method for monitoring the critical properties of other wide bandgap semiconductor structures. For AlGaN/GaN HEMT structures, Kinetic CV offers an order of magnitude increase in the throughput of V_P measurements compared to standard CnCV. Kinetic CV will benefit wafer uniformity testing, making full wafer mapping of critical properties such as dopant concentration in SiC and GaN epi layers and V_P in AlGaN/GaN structures practical in development and manufacturing applications.

REFERENCES

[1] A.A. Burk, M. O'Loughlin, Denis Tsvetkov, and S. Ustin, "Industrial Perspective of SiC Epitaxy" in Wide Bandgap Semiconductors for Power Electronics; v.1 p.75; 2022, Wiley-VCH.

[2] M. Wilson, et al., Semiconductor Doping Characterization Method Using Photoneutralization Time Constant of Corona Surface Charge, Patent pending.

[3] M. Wilson, et al., "Noncontact Measurement of Doping with Enhanced Throughput and High Precision for Wide Bandgap Wafer Manufacturing", CSMantech 2023 proceedings.

[4] M. Wilson, et al., ECS Journal of Solid State Science and Technology, 6(11) S3129 (2017).

[5] V. Pushkarev, et al., Solid State Phenomena 342 99 (2023).

[6] Bernd Thomas, private communication.