Materials Science Forum *Submitted: 2022-09-12*
ISSN: 1662-9752, Vol. 1089, pp 51-56 *Revised: 2022-12-07*
doi:10.4028/p-3bn937 *Accepted: 2022-12-07*
 Online: 2023-05-26

Recent Progress in Non-Contact Electrical Characterization for SiC and Related Compounds

A.Savtchouk[1,a], M.Wilson[1,b], D. Marinskiy[1,c], B. Schrayer[1,d], C. Almeida[1,e] and J.Lagowski[1,f]

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

[a]sasha.savtchouk@semilabsdi.com, [b]mwilson@semilabsdi.com, [c]dmitriy@semilabsdi.com, [d]bret.schrayer@semilabsdi.com, [e]carlos.almeida@semilabsdi.com, [f]jacek.lagowski.@semilabsdi.com

Keywords: corona non-contact C-V, CnCV, AlGaN/GaN HEMT on insulating substrate.

Abstract. An increasing interest in the non-contact corona charge-based electrical characterization technique, CnCV, for wide bandgap semiconductors, is justified by the reduction of cost and the reduction of testing feedback time [1]. In addition, the technique expands measurement capabilities. Regarding SiC, recent progress includes expanded dopant concentration range and dopant measurement on fresh epitaxial wafers. The latter is made possible with an ultraviolet wafer pretreatment technique [2]. The novel applications to AlGaN/GaN HEMT on insulating substrates demonstrate the benefits of a noninvasive top side edge contact, TSEC [3], that eliminates the problem of the floating surface potential. This development enables a unique three variable, charge-voltage-capacitance (Q-V-C), characterization of AlGaN/GaN on sapphire and SI-SiC. The quasistatic CnCV measurement, not affected by series resistance, is shown to be suitable for wafer mapping of HEMT parameters. The CnCV version with TSEC can be combined with an eddy current technique enabling non-contact 2DEG mobility measurements vs. electron sheet density.

Introduction

The advancements in wide bandgap semiconductor materials and devices emphasize the importance of cost-effective electrical metrology with rapid feedback to pilot or manufacturing lines.

In this respect, the corona non-contact capacitance-voltage CnCV technique is especially promising since it enables Schottky barrier and MOS-like electrical measurements to be performed without fabrication of metal Schottky barriers or FET test structures [1]. These practical aspects are clearly behind increasing interest in the recently introduced CnCV tools designed especially for wide bandgap semiconductors. In this technique, originally developed for silicon MOS-like characterization [4], an electrical biasing is produced by corona charge deposition on the surface. The response is monitored by measuring the surface voltage with a vibrating probe, such as a Kelvin-probe. Therefore, the technique is often referred to as the corona-Kelvin method. Applications in silicon IC fabrication concentrated on wafers with dielectrics. Without a dielectric, the corona deposited ions on Si are neutralized by capturing of free carriers. In wide bandgap semiconductors, the situation is different. A deep depletion layer can effectively isolate the surface from the bulk. This combined with a negligible minority carrier thermal generation makes corona ions stable on bare surfaces in the dark when the wide bandgap semiconductor is charged to depletion. The CnCV measurements are done in the dark. After measurement short wavelength illumination that generates excess minority carrier is used to photo-neutralize the deposited corona ions and to remove them from the surface [1].

Already demonstrated CnCV applications encompass bare and passivated wafers of materials such as SiC, GaN, AlGaN, Ga_2O_3, and HEMT structures AlGaN/GaN [5]. In this paper, further progress is discussed, including novel applications to AlGaN/GaN HEMT and structures on semi-insulating and insulating substrates. The progress in dopant concentration measurement in epitaxial SiC is discussed in reference [2] that is a companion paper in ICSCRM 2022.

Experimental

A schematic illustration of the CnCV apparatus is shown in Fig. 1. The apparatus includes two standard corona-Kelvin metrology elements i.e., the corona charge source and the Kelvin probe for the surface voltage measurement. In addition, the apparatus includes the top surface edge contact, TSEC, that is a novel element developed for measurement of AlGaN/GaN HEMT layers on insulating substrate wafers [6]. The apparatus elements in Fig. 1 are enclosed in a "black box" (not shown) that prevents photo-neutralization of corona ions that may be caused by stray light reaching the wafer.

The measurements employ electrical charge bias, with precise in-situ monitored corona charge increments, ΔQ_C, deposited on the surface. The response is monitored as the surface voltage change, ΔV, measured with the Kelvin probe. Static differential capacitance is calculated as $C=\Delta Q/\Delta V$. The method uses three variables (Q-V-C) and corresponding characteristics, for determining electrical parameters of measured semiconductors, heteroepitaxial layer structures, dielectrics and interfaces. An extension to layers on high resistivity substrates required overcoming the issue with the electrically floating top surface and corresponding noise affecting the measured surface voltage, V, and incremental ΔV values used in calculation of differential capacitance. In the present work the floating surface potential noise was eliminated using a novel top surface contact device.

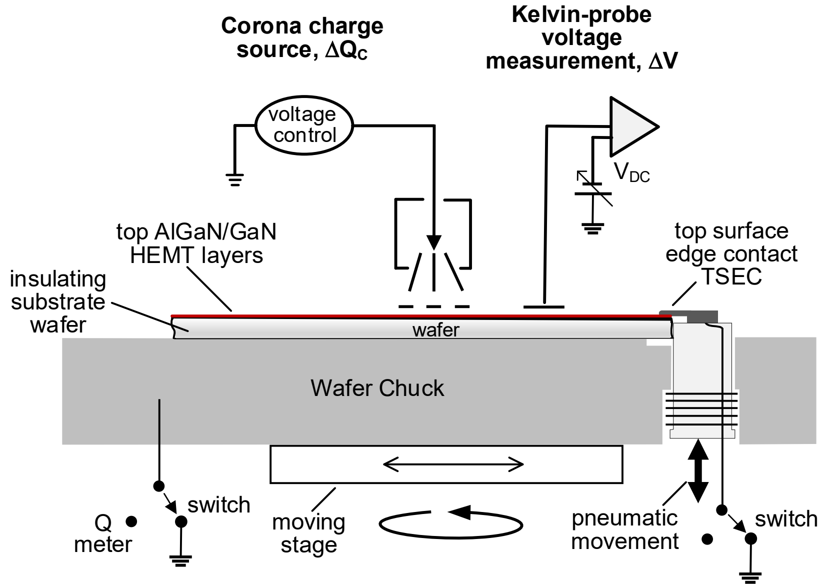

Fig. 1. Illustration of CnCV apparatus incorporating top side edge contact used for AlGaN/GaN HEMT structures on insulating substrates.

Top Surface Edge Contact, TSEC. Previous solutions to the problem were intended for mercury probe ac C-V measurement [7]. They used conducting plate topside return contact in proximity to the probe capillary as necessitated by series resistance. CnCV is equivalent to a very low frequency measurement, not affected by series resistance. Therefore, in a search for a good top surface contact, different contact locations were considered including a near-edge zone extending only 0.2mm from the wafer edge was discovered. It was discovered that within the zone, physical contacting of AlGaN/GaN with a thin, flexible, pure Ti cantilever plate produced good electrical contact. Searching for the origin of good near-edge contact, work function mapping using Kelvin Force Microscopy (KFM) with a 10μm resolution was employed.

The representative result shown in Fig. 2 demonstrates an electrically different near-edge zone that is distinguished by a work function increasing to about 4.7eV. This value is higher than the 4.3 eV work function of pure Ti. Considering the basics of metal-semiconductor contact on n-type semiconductors, such a condition should be helpful for achieving good electrical access to the interfacial 2DEG and the GaN buffer of the AlGaN/GaN HEMT structure.

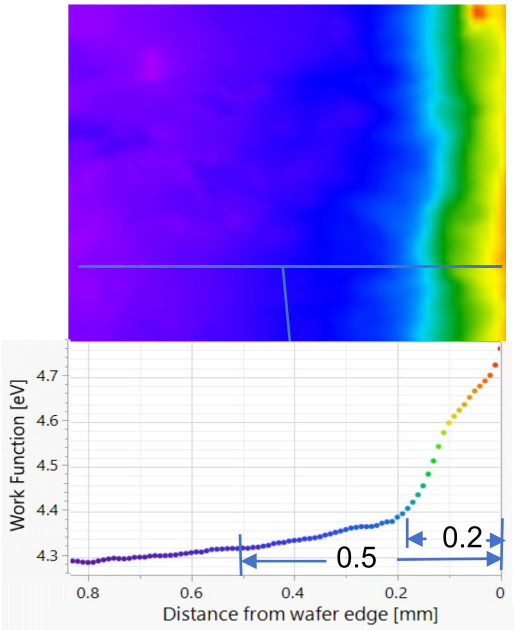

Fig. 2. KFM image of the work function near the wafer edge of AlGaN/GaN HEMT on sapphire. Elevated work function at the edge is beneficial for contact with Ti.

Results and Discussion

Floating surface potential elimination by TSEC. The new results presented in this work are intended to illustrate progress in the CnCV method in HEMT characterization on insulating substrates. Selected results in Fig. 4 to 9 are all based on high stability corona charge biasing with a constant potential corona charging technique [1] that could not be realized on insulating substrates without TSEC. The noise in an AlGaN/GaN measurement caused by floating surface potential and the beneficial effect of TSEC is illustrated with results of a HEMT structure on an insulating sapphire substrate shown in Fig. 3 and Fig. 4, respectively. Compared to the previous publication [3] that used C-V characterization, Fig. 3 shows directly the behavior of incremental surface voltage without TSEC. The smooth C-Q plot in Fig. 4 with TSEC is a consequence of the high stability of both the ΔV and ΔQ_C increments. This stability is essential for using all three variables (Q,V,C) and the corresponding HEMT characteristics.

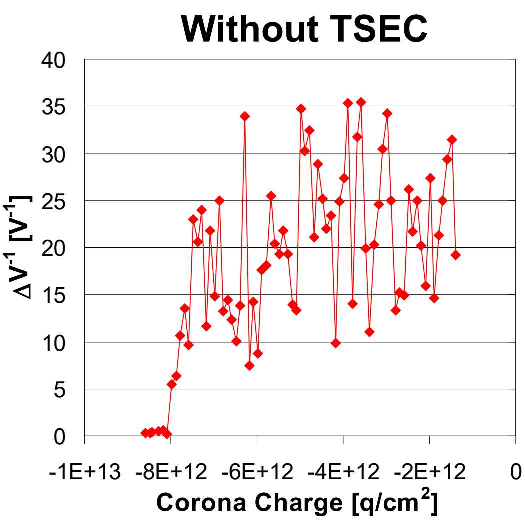

Fig. 3. As measured inverse of incremental surface voltage demonstrates large noise observed without good top side contact. Measurements performed on 5nm GaN/ 20nm AlGaN/GaN on a sapphire substrate.

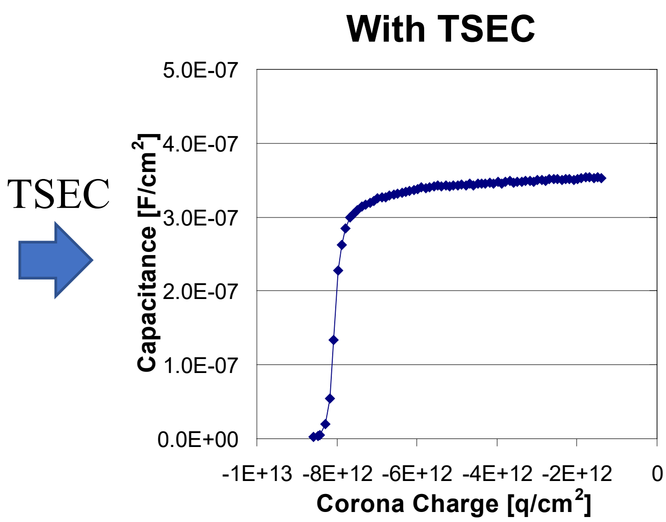

Fig. 4. Smooth C-Q characteristic measured with good TSEC. The capacitance $C=\Delta Q/\Delta V$ plot demonstrates elimination of the noise in surface voltage, ΔV, and stable charge biasing, ΔQ_C.

Charge-voltage Q-V Characteristic of HEMT structure illustrated in Fig. 5 enables direct determination of HEMT parameters, such as: the pinch-off voltage, V_P, the charge to full 2DEG depletion, Q_C^{FD}; the 2DEG sheet charge density, $N_S = -\frac{1}{q}Q_C^{FD}$, and the HEMT structure top layer thickness, t. Such direct determination of AlGaN/GaN HEMT parameters is a unique feature of the CnCV metrology, based on charge biasing in which the charge is the independent variable. Unlike in procedures based on ac-CV measurements on test FET capacitors or Hg probe CV, this is done in CnCV without integration of capacitance voltage and without differentiation. Introduction of TSEC enabled the realization of complete Q-V characterization for structures on insulating substrates.

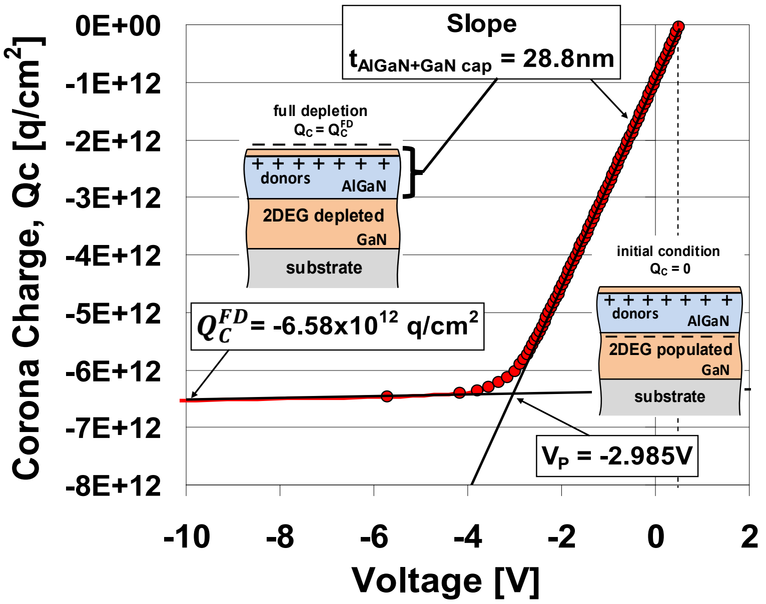

Fig 5. Q-V characteristic illustrating determination of the AlGaN+GaN cap thickness, the pinch off voltage (V_P) and the charge to full 2DEG depletion, Q_C^{FD}. Results are for a HEMT structure on semi-insulating SiC substrate.

Positioning of the top side contact at the wafer edge leaves practically the entire wafer surface available for the CnCV measurement, providing that the corona charge dosing and the measurement of surface voltage are indeed independent of the distance between the measured site and the contact.

Such behavior, theoretically expected based on the static character of CnCV was shown in C-V characteristics in ref [3]. Presently it is also evident in Fig. 6, where identical capacitance-charge, CQ, characteristics are obtained for the same site positioned 10mm and 80mm from the TSEC.

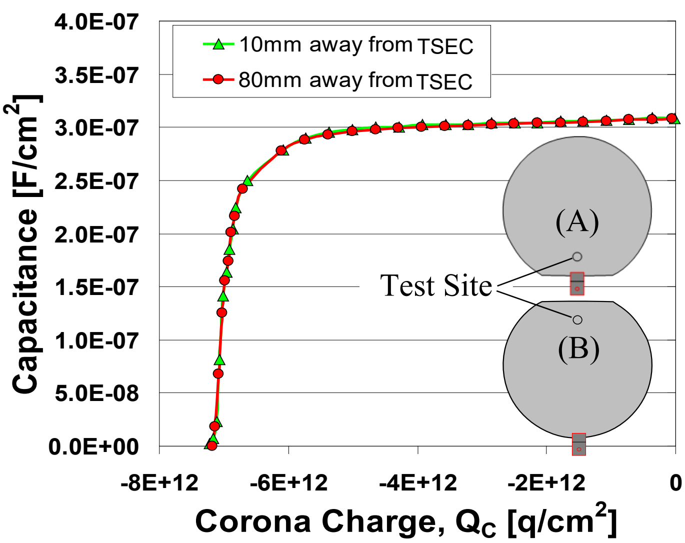

Fig 6. C-Q characteristic for a 5nm GaN/ 25nm AlGaN/GaN HEMT on a SI SiC substrate illustrating insensitivity of the method to the distance between the measured site and the TSEC.

The distance independence of corona charge bias enables full wafer mapping of the HEMT structure parameters extracted from Q_C-V. This mapping capability is illustrated in Fig. 7 for the top layer thickness and in Fig. 8 for the 2DEG sheet charge density. These mapping results indicate an inverse pattern of the 2DEG density and the top layer thickness.

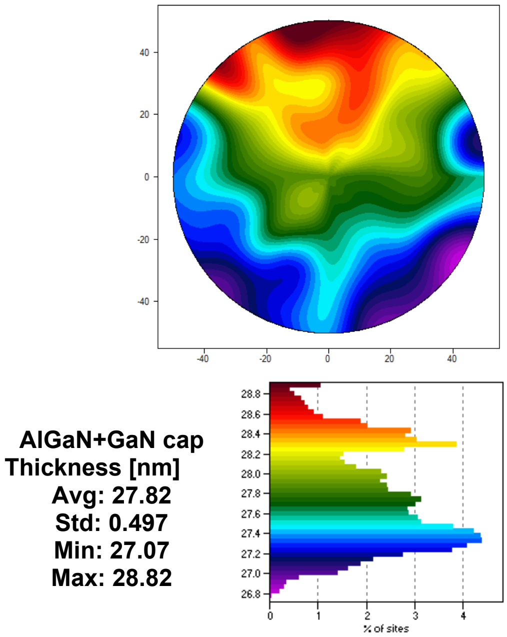

Fig 7. CnCV measured AlGaN+GaN cap thickness map for a 3nm GaN/ 25nm AlGaN/GaN HEMT on a SI SiC substrate.

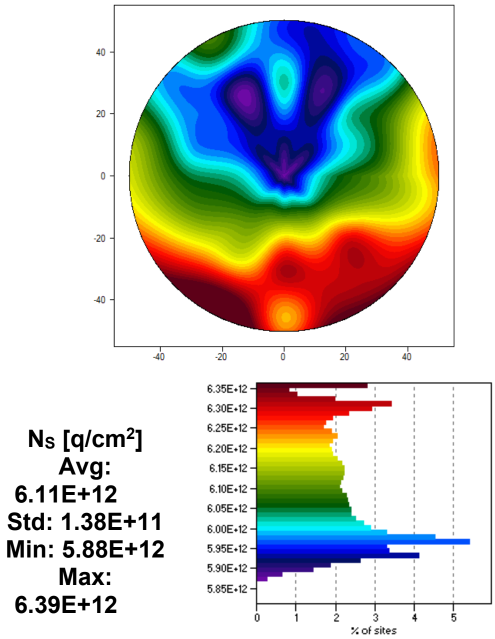

Fig 8. CnCV measured 2DEG sheet charge density (N_S) map for a 3nm GaN/25nm AlGaN/GaN HEMT on a SI SiC substrate

According to literature data [8], the 2DEG density (N_S) increases with Al fraction, x, in $Al_xGa_{1-x}N$ for a constant AlGaN thickness, and it also increases with thickness for a constant Al fraction, x. The CnCV measured maps for a 3nm GaN/ 25nm AlGaN/GaN HEMT on SI SiC sample in Fig. 7 and Fig. 8 show a reversed pattern of N_S and the AlGaN+GaN thickness. This result may be a consequence of the opposite spatial variation of the thickness and the Al content in the actual epitaxial deposition of the HEMT structure, i.e., lower N_S measured in sites with larger thickness may be an indication of low Al content in these sites with the later dominating the N_S magnitude.

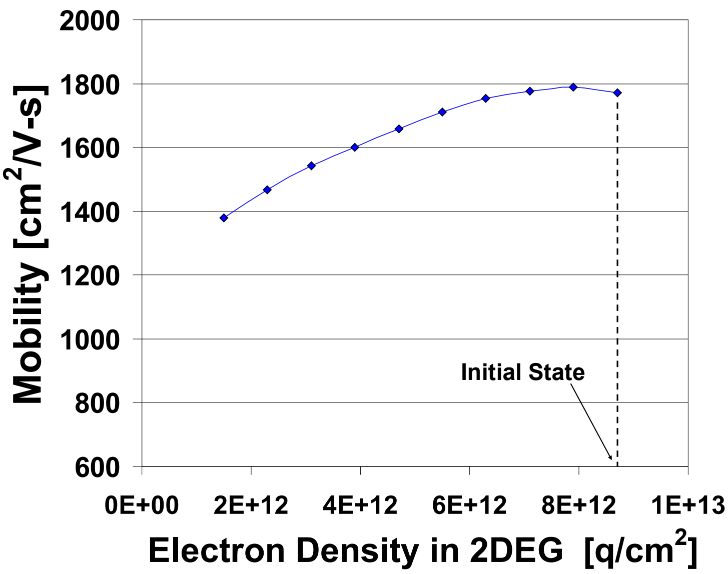

Fig. 9. The effective 2DEG mobility vs. the sheet charge density measured on a HEMT structure on a semi-insulating SiC substrate. Measurements performed with CnCV and eddy current.

2DEG Mobility Determination. A recent application of corona charge biasing, illustrated by the results in Fig. 9, is related to non-contact 2DEG mobility determination [9]. The development takes advantage of the wafer-level, non-invasive character of CnCV that is combined with non-contact eddy current sheet resistance measurement. The mobility is determined from the sheet conductance and the 2DEG electron density, giving the mobility characteristics shown in Fig. 9. The presently measured maximum mobility of about 1800 cm^2/V-s is comparable to the best room temperature AlGaN/GaN 2DEG mobilities measured in ref [9] and also to values reported in the literature.

Conclusion

Novel results on charge based (Q-V-C) measurements demonstrate the progress in corona non-contact C-V achieved with top surface edge contact. Selected results focus on the extension of the applicability of the metrology to wafer level characterization of AlGaN HEMT structures on high resistivity substrates, such as insulating sapphire or semi-insulating silicon carbide. The TSEC eliminates noise caused by floating surface potential and allows for high stability corona charge biasing which provides a means for high precision CnCV determination of HEMT electrical parameters. Multiple-parameter wafer mapping capabilities are demonstrated with results of 2DEG sheet charge and AlGaN+GaN cap thickness mapping. It is believed that such mapping shall enhance the fundamental understanding and practical control of HEMT wafer properties and uniformity. A determination of the 2DEG mobility is demonstrated using 2DEG sheet electron density measured with CnCV and the sheet conductance measured with an eddy current probe.

New results confirm the unique CnCV capability of comprehensive noncontact characterization of 2DEG properties on insulating substrates that does not require costly and time-consuming fabrication of test structures.

References

[1] M. Wilson et al., ECS Journal of Solid State Science and Technology, 6(11) S3129-S3140 (2017).

[2] V. Pushkarev, T. Rana, M. Gave, E. Sanchez, A. Savtchouk, M. Wilson, D. Marinskiy and J. Lagowski, companion paper in 19th Int. Conf. on SiC and Related Mat., Davos, CH 2022.

[3] M. Wilson, D. Marinskiy, B. Schrayer, D. Nguyen, M. Benjamin, and J. Lagowski, in the 2022 CSMantech Conference Proceedings.

[4] D.K. Schroder in, Semiconductor materials and Device Characterization, 3rd ed., Chapter 9, pp. 523, Wiley-Interscience, Hoboken, New Jersey (2006).

[5] M. Wilson, Compound Semiconductor, 25-6 (2019), pp. 20-26.

[6] M. Wilson et al., US Patent Application US 2022/0381816 A1, December 1, 2022.

[7] Mazur et al., US Patent 5,036,271 Jul. 30, 1991.

[8] I.P. Smorchkova et al., J. Appl. Phys., Vol. 86, No. 8, 4520 (1999).

[9] M. Wilson, D. Marinskiy, J. Lagowski, C. Almeida, A. Savtchouk, D. Nguyen, and M. Benjamin, Jpn. J. Appl. Phys. 61, 020903 (2022).