Top Surface Edge Contact for Wafer Level Electrical Characterization of 2DEG in AlGaN/GaN on Semi-insulating Wafers

M. Wilson[1], D. Marinskiy[1], B. Schrayer[1], D. Nguyen[2], M. Benjamin[2] and J. Lagowski[1]

[1]Semilab SDI, 12415 Telecom Dr., Tampa, Florida 33637, USA; Email: marshall.wilson@semilabsdi.com; Ph: (813) 977-2244
[2]Semilab LEI, 208 Memorial Drive, Lehighton, PA 18235

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Abstract

We report the successful development of a noninvasive top surface wafer edge contacting device that eliminates floating surface potential interferences in C-V measurements on AlGaN/GaN HEMT epitaxial layers on semi-insulating or insulating substrates. The present finding of the effectiveness of near-edge contact is supported by the work function pattern revealed by KFM mapping. The contacting device enables the use of corona-charge non-contact C-V (CnCV) metrology for comprehensive characterization of the 2DEG on insulating wafers without costly and time-consuming fabrication of HEMT test structures.

INTRODUCTION

AlGaN/GaN high electron mobility transistors, HEMTs, have been receiving a great deal of fundamental and practical attention. Progress in electrical characterization is an integral part of corresponding R&D and device fabrication. Toward that goal, we have introduced corona-charge non-contact C-V (CnCV) metrology [1]. This metrology uses incremental deposition of charge, ΔQ_C, directly on the surface for electrical biasing instead of conventional gate voltage biasing. Non-contact measurement of the surface voltage, V, is performed with a vibrating Kelvin-probe and the charge and voltage increments give the non-contact capacitance $C=\Delta Q_C/\Delta V$. The method gives a full set of parameters, V, Q and C along with corresponding characteristics, forming a basis for quantification of 2DEG properties. Excellent precision and repeatability have been demonstrated in characterization of the AlGaN/GaN 2DEG on conducting substrates [1]. Extension of this technology to insulating substrates was the goal of the present development.

RESULTS AND DISCUSSION

For HEMT on semi-insulating SiC and insulating sapphire substrates the top layers are electrically floating. This results in a floating electrostatic surface potential susceptible to various static interferences which causes large noise in voltage-based measurements as shown in Fig. 1. Elimination of such interferences requires an excellent quality top surface contacting device. Previous solutions to the problem of electrically floating layers addressed mercury probe ac C-V measurement [2]. They were based on the introduction of a conducting plate topside return contact in proximity to the probe capillary as necessitated by series resistance. Corona-Kelvin C-V is a very low frequency measurement which is less affected by series resistance. Therefore, in our search for a good top surface contact, various contact locations were tested, including the wafer edge region where the top film and layers below could be accessible due to different termination distances from the edge. Testing metal plates with different work functions, the presence in AlGaN/GaN samples of a unique, near-edge zone extending only 0.2 mm to 0.5 mm from the wafer edge was discovered. Within this zone, physical contacting with a thin, flexible, pure Ti cantilever plate produced good electrical contact producing a smooth C-V curve as shown in Fig. 1 [3]. Further away from the wafer edge, good contact could not be made and the C-V curve was noisy as seen in Fig. 1. Searching for the origin of the near-edge difference, work function mapping using Kelvin Force Microscopy (KFM) with a 10 µm resolution was employed.

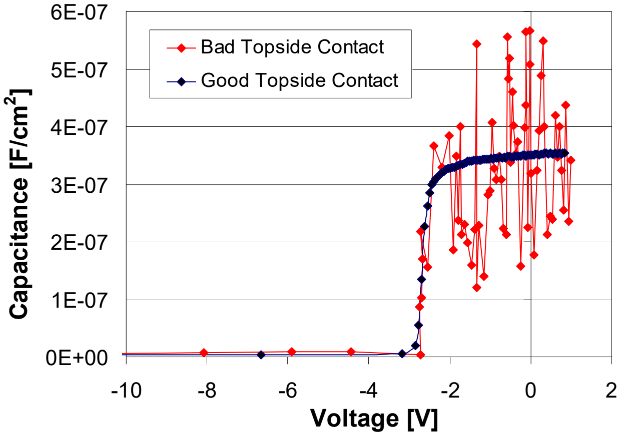

Fig. 1. C-V characteristics of a 5 nm GaN/20nm AlGaN/GaN HEMT on an insulating sapphire substrate representative of measurements with bad and excellent quality topside contact.

The representative result shown in Fig. 2 indeed demonstrates an electrically different near-edge zone that is distinguished by a work function increasing to about 4.7 eV. 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.

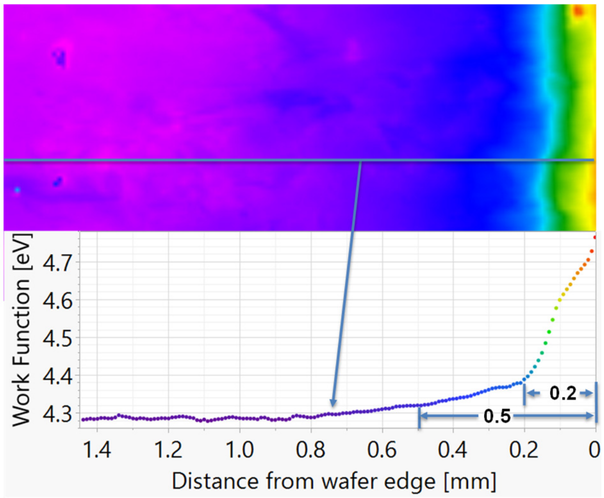

Fig. 2. KFM image of the work function near the wafer edge of AlGaN/GaN HEMT on sapphire.

In an automated contacting apparatus, the flexible Ti cantilever plate contacts the wafer at the edge zone. The plate connection is switched between ground and a coulombmeter for measurement of the surface voltage, V, and the charge increments, ΔQ_C, respectively.

The results in Fig. 3 confirm the excellent quality of the C-V measurement with the top surface edge contact as evidenced by the low noise, accurate and repeatable capacitance values. Practically identical results are seen in measurements with the edge contact positioned 10mm and 80 mm from the same test site. This indicates the insensitivity to series resistance as expected for the low frequency corona-Kelvin technique. Series resistance increases with the increasing distance between the top surface edge contact and the measurement site and in the case of high frequency, small signal alternating current (ac) C-V, the measured capacitance will be reduced by the term, $1+(\omega r_s C)^2$, where $\omega = 2\pi f$ is the angular frequency, r_s is the series resistance and C is the true capacitance [4]. However, in the quasistatic, low frequency case of the corona-Kelvin technique (f ~0.5Hz), ω becomes small and the effect of series resistance on the measured capacitance vanishes as observed in the result in Fig. 3. This insensitivity to the contact to measurement site distance is very beneficial for the corona-Kelvin technique with one small contact at the wafer edge allowing full wafer mapping of important HEMT parameters. The study reported here was performed on a 100 mm diameter HEMT structure on a SI SiC substrate but this contact to measurement site distance insensitivity was also confirmed on a 150 mm diameter HEMT sample on a SI SiC substrate with a maximum contact to measurement site distance of ~147 mm.

Negative corona charge results in removal of electrons from the 2DEG creating a fully depleted 2DEG condition. The corresponding decrease of 2DEG capacitance is evidenced by the steep drop in capacitance in the C-Q plots in Fig.4. The fully depleted 2DEG condition is illustrated in the insert in Fig. 4 that is based on the prevailing model that considers a polarization induced supply of electrons to the 2DEG from surface donors. Negative bias charge compensates the donors and results in a fully depleted 2DEG. The charge to full depletion, Q_{2DEG}, enables direct evaluation of the initial 2DEG electron sheet density, N_{2DEG}. The results of such measurements are compared in Fig. 5 with the sheet electron density, N_{HALL}, measured with a non-contact microwave Hall technique. Good correlation is seen with average $N_{2DEG} = 1.06\ N_{HALL}$. This indicates a Hall factor of r=1.06, in agreement with literature [5].

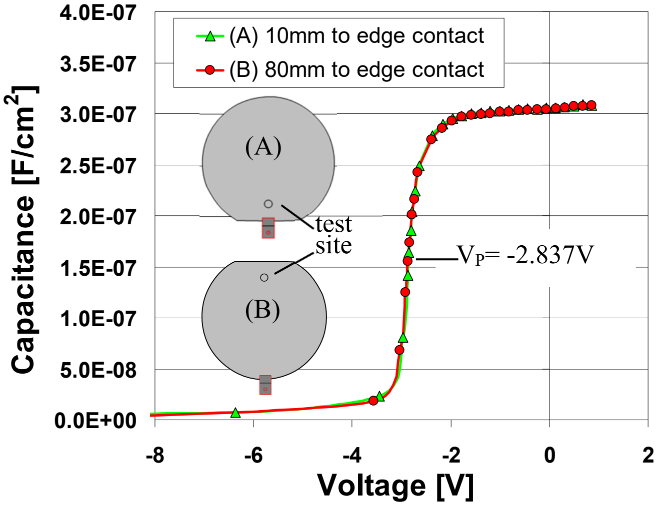

Fig. 3. C-V curves for a 5 nm GaN/25 nm AlGaN/GaN HEMT on a SI SiC substrate measured on the same test site with edge contact positions 10 mm and 80 mm from the site.

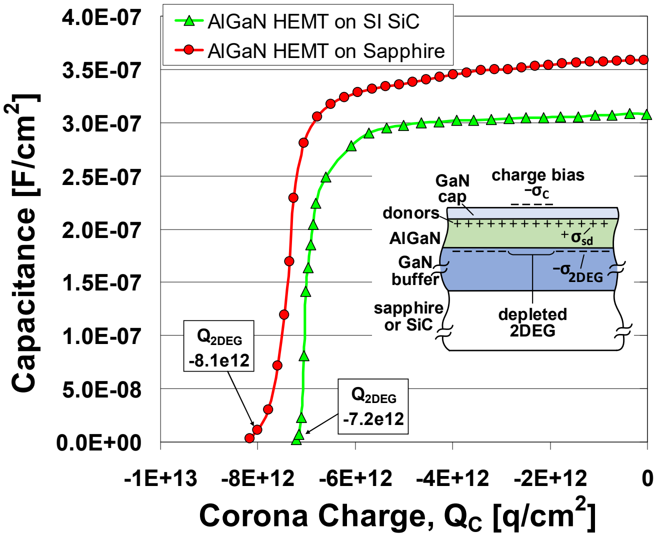

Fig. 4. C-Q characteristics of AlGaN/GaN HEMTs on insulating sapphire and semi-insulating SiC substrates.

Results in Fig. 5 were obtained on a series of wafers provided as a courtesy by commercial manufacturers. All heteroepitaxial layers represented a “normally on” HEMT configuration with two-dimensional gas 2DEG on GaN side, below the $Al_xGa_{1-x}N$ layer. For structures on semi-insulating SiC substrates, the Al content was x=0.24, while for one wafer with sapphire substrate x=0.20. A range of the AlGaN thickness plus the thickness of GaN capping layer was sufficient for demonstration of consistent measurements of capacitance-voltage C-V and the charge-voltage, Q-V available in the corona-Kelvin method.

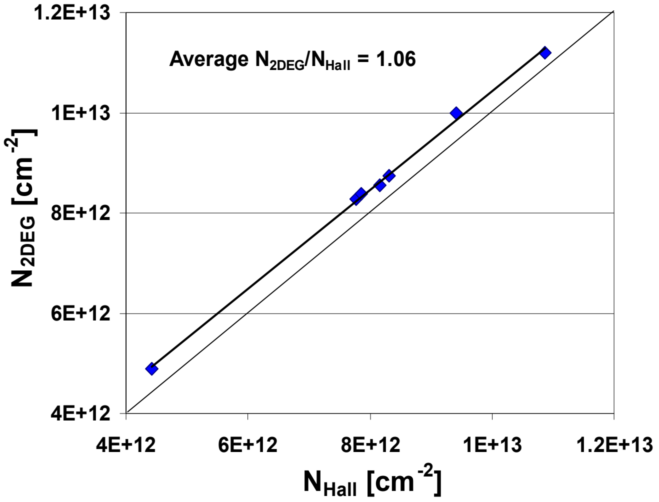

Fig. 5. Hall effect and charge based 2DEG electron density correlation.

As discussed in ref. 6, conventional ac C-V measurements of 2DEG use integration of the C-V for evaluation of the sheet charge density, $qN_s = \int CdV$. The slope of qN_s vs. V in the linear range gives the thickness of AlGaN plus GaN capping layer. The capacitance integrated from the full depletion condition to the initial condition, corresponding to zero applied charge bias, gives the initial 2DEG electron sheet charge density, qN_{2DEG}.

We applied this method for the present corona-Kelvin C-V results. However, in the corona-Kelvin method, the 2DEG parameters can also be determined from the directly measured Q-V characteristic without integration [7].

We compared results of the C-V integration method and direct Q-V method for 5 wafers. The thickness results are shown in Fig. 6. The results are close to 1:1 with $R^2 = 0.9998$, demonstrating very good agreement. The results of the integrated 2DEG electron sheet charge density, qN_{2DEG}, are compared in Fig. 7 with directly Q-V measured charge to full 2DEG depletion, Q_{2DEG}. Results show 1:1 correlation with $R^2 = 0.9989$. The data in Fig. 6 and Fig. 7 can be considered as a proof of the reliable measurement of HEMT structures on insulating substrates, achieved with the top side edge contact.

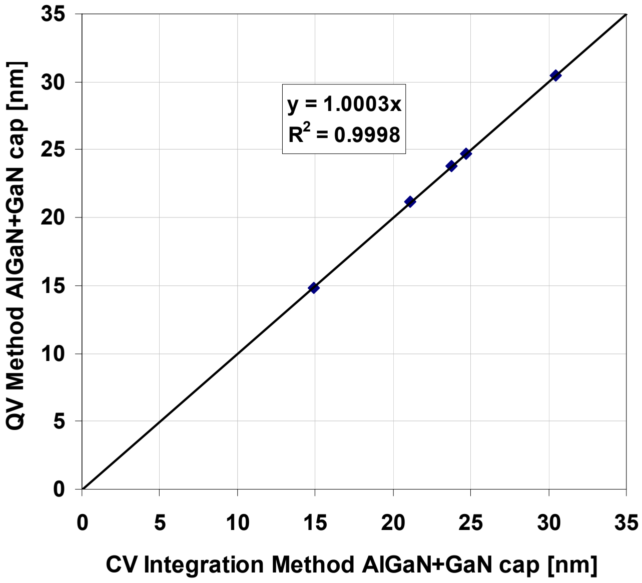

Fig. 6. Thickness of AlGaN layer plus GaN cap for HEMT structures on semi-insulating SiC and insulating sapphire.

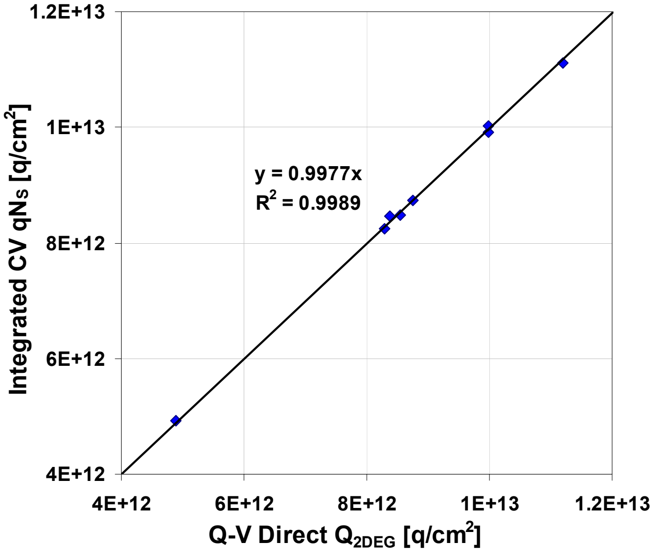

Fig. 7. HEMT structure 2DEG sheet charge density for wafers on semi-insulating SiC and insulating sapphire.

Wafer mapping in the corona-Kelvin metrology provides a means for 2DEG uniformity testing and optimizing device fabrication, improving device yield. The quasi-static corona-Kelvin technique is not sensitive to the distance between the measured site and the topside edge contact. Along with a very small contact area this enables mapping of almost the entire wafer surface. An example map of Q_{2DEG} is shown in Fig. 8 for AlGaN/GaN HEMT on a semi-insulating SiC substrate.

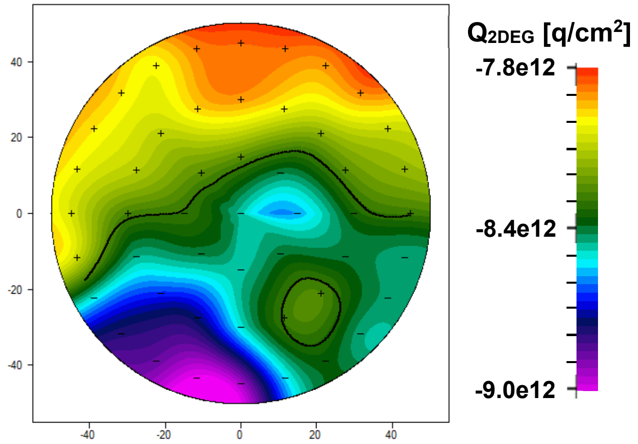

Fig. 8. Map of the charge to 2DEG depletion, Q_{2DEG}, for an AlGaN/GaN HEMT on semi-insulating SiC 100mm wafer.

CONCLUSION

This work demonstrates an extension of the corona-charge Kelvin metrology to wafer level electrical characterization of the 2DEG in AlGaN/GaN HEMT structures on semi-insulating substrates. The noninvasive, temporary contact-device enabling the measurements is realized with a thin, flexible Ti cantilever contacting the wafer in a narrow zone at the wafer edge. Experimental results illustrate corresponding 2DEG characterization achieved with the edge contact.

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