Areal Vertical Transmission Line Model Measurement for Drift Region Characterization in Vertical GaN Based Devices

E. Bahat Treidel*, M. Wolf, F. Brunner, O. Hilt and J. Würfl

*Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Strasse 4 12489 Berlin, Germany. *Corresponding author: email: eldad.bahat-treidel@fbh-berlin.de Tel. +49 30 6392 2780*

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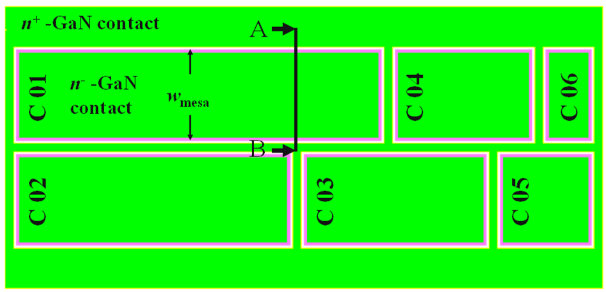
Abstract

In this work we present a process control monitoring (PCM) device for electrical characterization of vertical *n*⁻-GaN drift region layer conduction properties. An areal vertical transmission line model (AV-TLM) like structure with six difference cell surface areas is used for areal specific resistance direct evaluation. The method is used to characterize *n*⁻-GaN drift epitaxial layers with different carrier concentration grown on sapphire substrates. Initially, the resulting areal specific resistance are higher than predicted with large variation within the wafers. The fast feedback to the epitaxy results in a sequential growth run with 3 times improved layer conductivity and with a factor of 60 improved wafer level uniformity for a similar carrier concentration level.

INTRODUCTION

Vertical GaN based power switching devices, diodes and transistors, are particularly desirable due to their reduced die size, in comparison to lateral heterostructures based devices. This results in a reduction of specific ON-state resistance, $R_{DS\_ON} \times A$, by one order of magnitude down to 1.0 mΩ·cm² [1-4]. Also, vertical device concept allows for aggressive device scaling in respect to gate periphery length per area, and enables high current densities per unit area. The targeted blocking capability larger than 1 kV demands the growth of drift layers thicker than 10 µm with low residual background doping. However, the drift region conductivity, in particular for thick n^--GaN drift layers, may be limited by low mobility, low carrier density, background compensating doping, high defect density and built in potential barriers, having a direct impact on the device electrical performance. Therefore, this work has the purpose to provide an evaluation method of the conductivity properties of low carrier density n^--GaN drift regions. For the epitaxy development of vertical GaN based devices, a fast feedback loop to the epitaxy is required in order to reduce the innovation cycle time and speed up the optimization process. Therefore, a simple, direct, reliable and fast characterization method is highly desired. The Areal Vertical Transmission Line Model (AV-TLM) like structure is used as a direct method to measure and assess the drift region contribution to the overall device areal specific resistance, by directly extracting $(R_{ON} \times A)_{\text{drift}}$.



$A_{C\,01} = 1.6 \times 10^{-3}$ cm² $A_{C\,04} = 0.6 \times 10^{-3}$ cm²
$A_{C\,02} = 1.2 \times 10^{-3}$ cm² $A_{C\,05} = 0.4 \times 10^{-3}$ cm²
$A_{C\,03} = 0.8 \times 10^{-3}$ cm² $A_{C\,06} = 0.2 \times 10^{-3}$ cm²

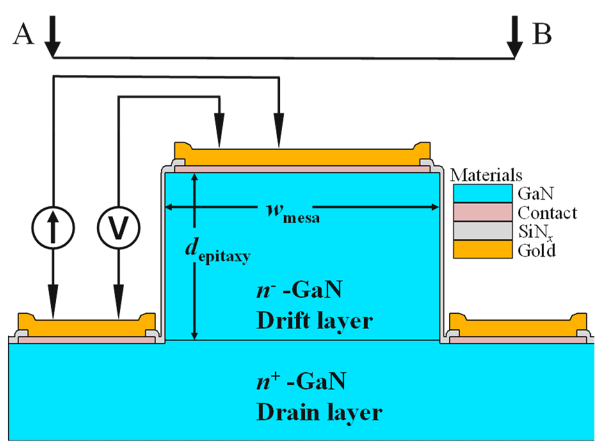


Fig. 1. (top) Schematic layout of an AV-TLM structure (1300 µm × 620 µm) with six cells and their area dimensions. (bottom) AV TLM cell cross section from A to B and the measurement circuit configuration.

AV-TLM DESIGN

The proposed AV-TLM structure consists of six rectangular cells with increased areas well defined by deep mesa etching that electrically insulates their drift regions (see Fig. 1). The AV-TLM cells' size was designed especially to be suitable for characterizing the n^--GaN drift region resistivity with carrier concentrations ranging from

N_D = ~1 × 10^{15} cm^{-3} to ~1.0 × 10^{17} cm^{-3} and thicknesses between ~0.5 µm to ~25 µm [5]. The n^--GaN drift region is directly connected to a top side ohmic contact and to a bottom highly conductive n^+-GaN drain layer with lower-side ohmic contact, forming a serial resistances chain. The drift region resistance should dominate the overall ON-state resistance of well-designed switching devices. Thus, the resistance of the uniform cubical shaped drift region is approximated by: $R_{\text{measured}} = \rho_{\text{drift}} \cdot d_{\text{drift}} \cdot (w_{\text{mesa}} \cdot l_{\text{mesa}})^{-1} = (R_{ON} \times A)_{\text{drift}} \cdot A_{\text{mesa}}^{-1}$ where ρ_{drift} and d_{drift} are the drift region resistivity and thickness, respectively, defined in the epitaxial growth. The drift region cell cross sectional rectangular mesa area, A_{mesa}, is defined by the dimensions of w_{mesa} and l_{mesa}. Thus, the product of $\rho_{\text{drift}} \cdot d_{\text{drift}}$ gives the drift region areal specific resistance $(R_{ON} \times A)_{\text{drift}}$. Although, the transmission line length is constant, since the drift region thickness, d_{drift}, is fixed for all the cells, the periphery length to cell-area ratio decreases as the cell size increases. Therefore, the specific resistivity calculated from the linear fitting to the reciprocal drift region mesa area, A_{mesa}^{-1} exclude all parasitic resistances and edge effects.

Experimental Epitaxy and Manufacturing Process

For demonstration, six different GaN epitaxial layers stacks with different drift region doping concentrations were grown in two sequencing process runs. The epitaxial layers were grown by metalorganic vapor phase epitaxy (MOVPE) on 100 mm diameter *c*-plane sapphire substrates. The epitaxial stack consists of a 1.5 µm un-intentionally doped GaN buffer layer, a 2 µm n^+-GaN:Si (N_D = 3.0 × 10^{18} cm^{-3}) highly conductive layer and a 5 µm n^--GaN:Si drift layer with different doping concentrations from N_D = 4.5 × 10^{15} cm^{-3} to 5.2 × 10^{16} cm^{-3} (see table I). The drift layer doping concentration is confirmed by Electrochemical Capacitance-Voltage (ECV) measurements (see Fig. 2). The main difference between run I and run II consist in a variation of coalescence time and thickness, 2.0 µm, of the undoped GaN buffer. In run II a slightly faster coalescence after nucleation in conjunction with a prolonged growth time of the undoped buffer led to an improved GaN surface morphology. Modifications in epitaxy run II growth conditions are made based on the measurements results from epitaxy run I.

The device manufacturing process sequence starts with top side ohmic contact formation, next the mesa structures are defined by optical lithography and the surrounding GaN layers are etched down by Cl_2-based inductively coupled plasma (ICP) dry etching process down to the lower highly conductive layer. Then, the lower side ohmic contacts are formed on the highly conductive layer and the device is passivated with 200 nm SiN_x. All ohmic contacts are reinforced with 1 µm evaporated Au to form contact pads.

AV-TLM Characterization and Analysis

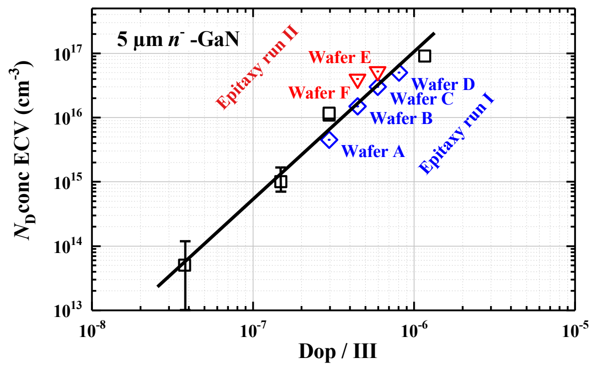


Fig. 2. Carrier concentrations measured by ECV as function of the ratio between the dopants molar flows to the group III precursors on different GaN on sapphire wafers.

The AV-TLM structure cells are electrically characterized by four-point probe arrangement as shown in Fig. 1 (bottom). As an example, for the linear ohmic region, between -1 V to +1 V, current-voltage (IV) characteristics of AV-TLM cells with different mesa areas measured on wafer B are shown in Fig. 3. It is shown that the absolute current and thus the resistance depend on the cell's mesa area. Next, the resistance

TABLE I

Experimental Wafers Epitaxial Structure and Wafer Level Measured Drift Region Areal Specific Resistance

Wafer	Drift	Drain	Buffer	$(R_{ON} \times A)_{\text{drift}}$
	GaN:Si [cm^{-3}]		uid GaN	[Ω·cm^2]
A	5 µm 4.5 × 10^{15}	2 µm 3.0 × 10^{18}	1.5 µm	2.2 ± 0.8 × 10^{-2}
B	5 µm 1.5 × 10^{16}			7.8 ± 3.2× 10^{-3}
C	5 µm 3.5 × 10^{16}			2.6 ± 0.6× 10^{-3}
D	5 µm 5.0 × 10^{16}			1.4 ± 0.6× 10^{-3}
E	5 µm 5.2 × 10^{16}		2.0 µm	4.5 ± 0.1 × 10^{-4}
F	5 µm 4.0 × 10^{16}			5.3 ± 0.1 × 10^{-4}

of each individual cell extracted from the IV curves linear fitting is plotted in Fig. 4 as function of A_{mesa}^{-1}. The slope of the linear fitting corresponds to the drift region areal specific resistance $(R_{ON} \times A)_{\text{drift}}$. Further, a linear fitting example for AV-TLM resistance from each of the tested wafers is shown in Fig. 4. A good agreement with the linear AV-TLM like theory is observed for the wafers from epitaxy run I with a slope that is monotonically decreased with the drift layer carrier concentration measured by ECV. On the other hand, for the wafers from epitaxy run II, cells with small area show

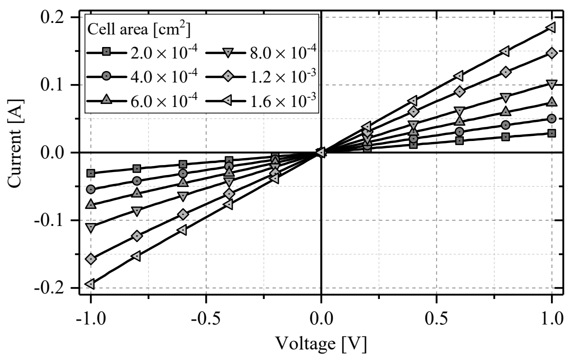


Fig. 3. (top) Example of AV-TLM IV characteristics for cells with different area measured Wafer B.

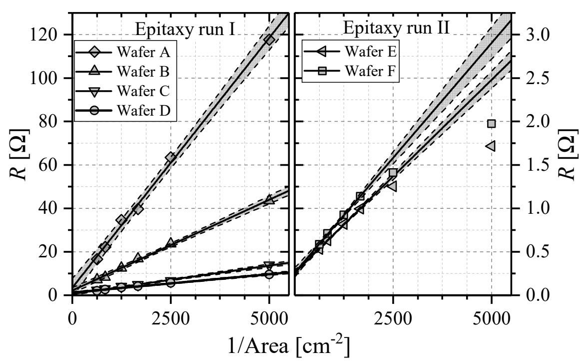


Fig. 4. Resistance as function of A_{mesa}^{-1} for the different examined wafers from the two epitaxy runs and their linear fitting.

lower resistance than predicted. Here, two parallel resistances may be considered; the drift region, R_{drift}, resistance and the edge resistance R_{edge}. Hence, the total cell resistance is $R_{\text{total}} = R_{\text{drift}} \cdot R_{\text{edge}} / \left(R_{\text{drift}} + R_{\text{edge}}\right)$. When the cell area is very large the drift region resistance is much smaller than edge resistance therefore, the total resistance is approximately the drift region resistance. In the smaller cells, as the ratio between the cell area and the cell periphery is smaller, R_{edge} cannot anymore be neglected and as a result the total resistance is smaller than the actual drift resistance. Thus, to evaluate the correct $(R_{ON} \times A)_{\text{drift}}$ the linear fitting should consider only resistances evaluated for larger cell areas (See Fig. 4 (right)).

An automated measuring setup system is deployed for fast wafer level characterization. Fig. 5 depicts a drift region areal specific resistance wafer distribution mapping example for wafer F with a drift region carrier concentration of $N_D = 4.0 \times 10^{16}$ cm^{-3}. Comparison of measured $(R_{ON} \times A)_{\text{drift}}$ values for all examined wafers from both epitaxy runs is depicted in Fig. 6 and summarized in Table I, showing for each epitaxial run monotonically relation to the drift region carrier concentration. For epitaxial run I, the measured

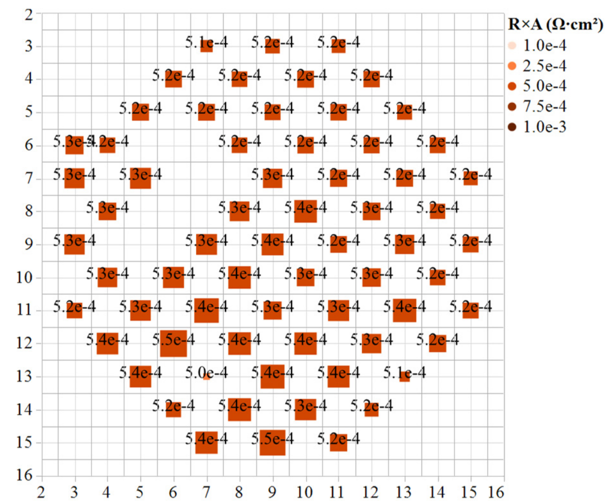


Fig. 5. Example of areal specific resistance $(R_{ON} \times A)_{\text{drift}}$ 100 mm wafer map evaluated for wafer F.

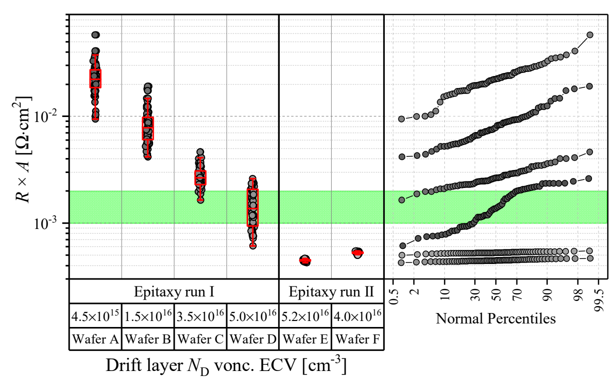


Fig. 6. Wafer-to-wafer areal specific resistance $(R_{ON} \times A)_{\text{drift}}$comparison. The green band indicate the drift region specific resistance target.

$(R_{\text{ON}} \times A)_{\text{drift}}$ shows to be about one order of magnitude higher than the predicted theoretical values [5] with large distribution over the wafer for all wafers. Epitaxy run II AV-TLM measurements show improved conductivity of the grown drift region. The measured $(R_{\text{ON}} \times A)_{\text{drift}}$ from epitaxy run II is by factor of ~3 smaller with more than 1.5 orders of magnitude lower wafer level distribution.

Conclusions

We may conclude that the proposed AV-TLM is a fast and direct measurement PCM structure to characterize the conduction properties of epitaxial layers in GaN-based vertical devices. It provides to the epitaxial grower an essential and valuable information about one of the most sensitive layers to be grown, the drift region layer. Properties including the relation between the doping and the specific conductivity, growth uniformity across the wafer, and wafer to wafer variations can be easily extracted. In addition, the AV-TLM measurement may give treasured / valuable information on the presence of undesired compensation doping and build in potential barriers that hinder the expected device ON-state conductivity.

As a result of the AV-TLM analysis in initial epitaxy growth run, the origin of the discrepancy between the measured and theoretical values of the drift region $(R_{\mathrm{ON}} \times A)_{\mathrm{drift}}$ could be pin-pointed to the drift region only. Thus, as consequence of fast feedback improved epitaxial layers could be developed. Further complimentary investigations regarding defect structure and impurity incorporation during epitaxy may give additional insight. The improvement in the $(R_{\mathrm{ON}} \times A)_{\mathrm{drift}}$ for the epitaxy run II demonstrate the capability to increase the drift region thickness and reduce the drift region doping concentration while still meeting the desired 1.0 mΩ·cm^2 specified target.

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ACRONYMS

TLM: Transmission line method
PCM: Process control monitoring
MOVPE: metalorganic vapor phase epitaxy
ECV: Electrochemical Capacitance-Voltage
uid: un intentional doping
ICP: Inductively Coupled Plasma