Commercial N-polar GaN on SiC HEMT Epitaxial Wafers Manufactured by MOCVD for 5G mm-Wave Applications

Xiang Liu*, Brian Romanczyk, Stacia Keller, Brian Swenson, Ron Birkhahn,
Geetak Gupta, Davide Bisi, Umesh Mishra, Lee McCarthy

Transphorm Inc., 115 Castilian Dr., Goleta, CA 93117, USA
*E-mail: xiang.liu@transphormusa.com, phone: 1-805-456-1800

Keywords: N-polar gallium nitride, silicon carbide, HEMT, MOCVD, 5G, millimeter wave

Abstract

We report the MOCVD manufacturing of N-polar GaN on 100 mm SiC HEMT epitaxial wafers suitable for ultra-high performance 5G mm-wave applications. The wafers exhibit very high 2DEG electron mobility and excellent material characteristics. Pulsed I-V test on processed HEMTs at 25 and 150 ºC showed very little dispersion and charge trapping.

INTRODUCTION

N-polar GaN high electron mobility transistors (HEMT) have emerged as a prime candidate for fifth generation (5G) radio frequency (RF) and millimeter-wave (mm-wave) applications. The reversed internal polarization field in N-polar GaN enables several advantageous device designs over the incumbent Ga-polar GaN [1-3]. Based on a "deep recess" structure, researchers at the University of California at Santa Barbara (UCSB) have demonstrated that a N-polar HEMT can deliver a constant 8 W/mm power density at 10, 30, and 94 GHz with record efficiencies [1], and the 94 GHz data is better than the state-of-the-art Ga-polar devices by more than a factor of 2 [2].

We have previously reported the manufacturing of such a N-polar HEMT on a 100 mm sapphire substrate by metalorganic chemical vapor deposition (MOCVD) [4]. Since mid-2020, N-polar GaN on 100 mm SiC has also entered development and is currently being sampled to several customers in the US.

MATERIALS GROWTH AND CHARACTERIZATION

The production tool is a commercial MOCVD reactor that can handle 100 – 200 mm substrates. The reactor performance and epi characteristics are monitored by various statistical process control (SPC) charts. Real-time growth monitoring includes the wafer temperature, wafer curvature, and growth rate. Post growth material characterizations include wafer bow, epitaxial film thickness, atomic force microscopy (AFM), X-ray diffraction (XRD), Candela surface scan, impurity and dopant concentrations, sheet resistance (R_{sh}), two-dimensional electron gas (2DEG) charge and electron mobility, etc.

Figure 1 (a) and (b) present the schematics of a deep recess HEMT and a conventional planar HEMT, respectively. The thick unintentionally doped (UID) GaN cap within the deep recess HEMT serves to reduce DC-to-RF dispersion and enhance the sheet charge and mobility in the access region [1,2]. Figure 2 (a) shows a typical R_{sh} contour map measured on a deep recess HEMT using a Lehighton eddy current tool, and the mean R_{sh} is 234.3 Ω/sq with a nonuniformity of 2.2%. The typical 2DEG electron mobility measured on a deep recess HEMT using a contactless Lehighton microwave Hall is ~1850 $cm^2/V{\cdot}s$, and the TLM mobility measured along the

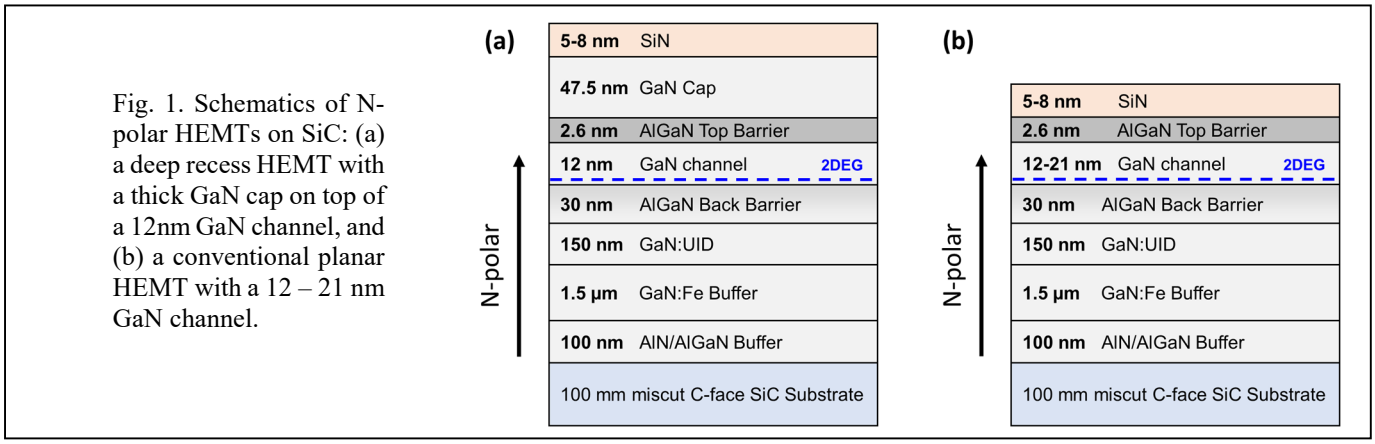

Fig. 1. Schematics of N-polar HEMTs on SiC: (a) a deep recess HEMT with a thick GaN cap on top of a 12nm GaN channel, and (b) a conventional planar HEMT with a 12 – 21 nm GaN channel.

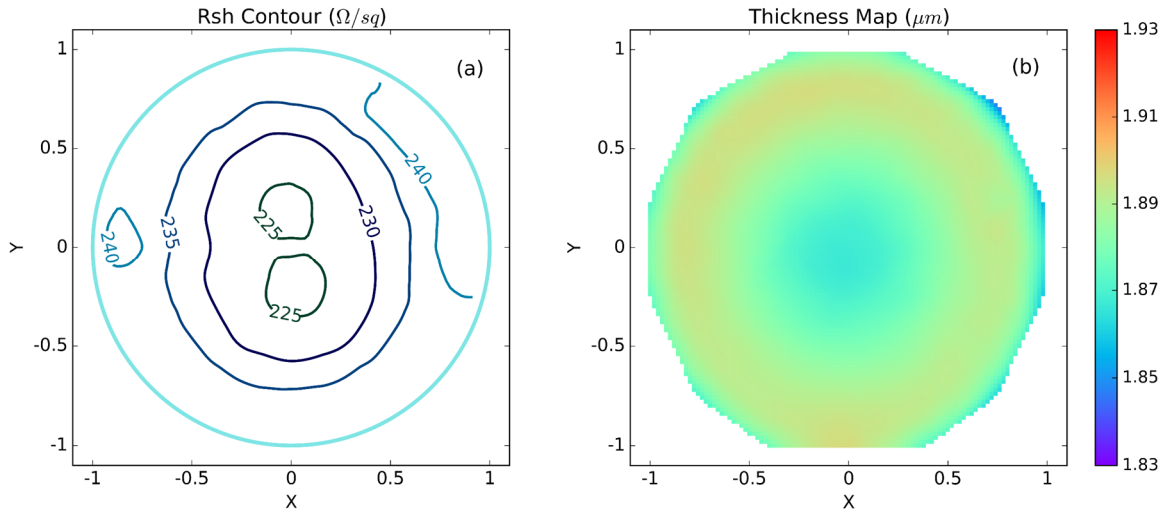

Fig. 2. (a) Typical Lehighton R_{sh} contour map (mean: 234.3 Ω/sq, nonuniformity: 2.2%), and (b) typical thickness map (mean: 1.88 µm, nonuniformity: 0.5%) of a deep recess N-polar GaN HEMT on 100 mm SiC.

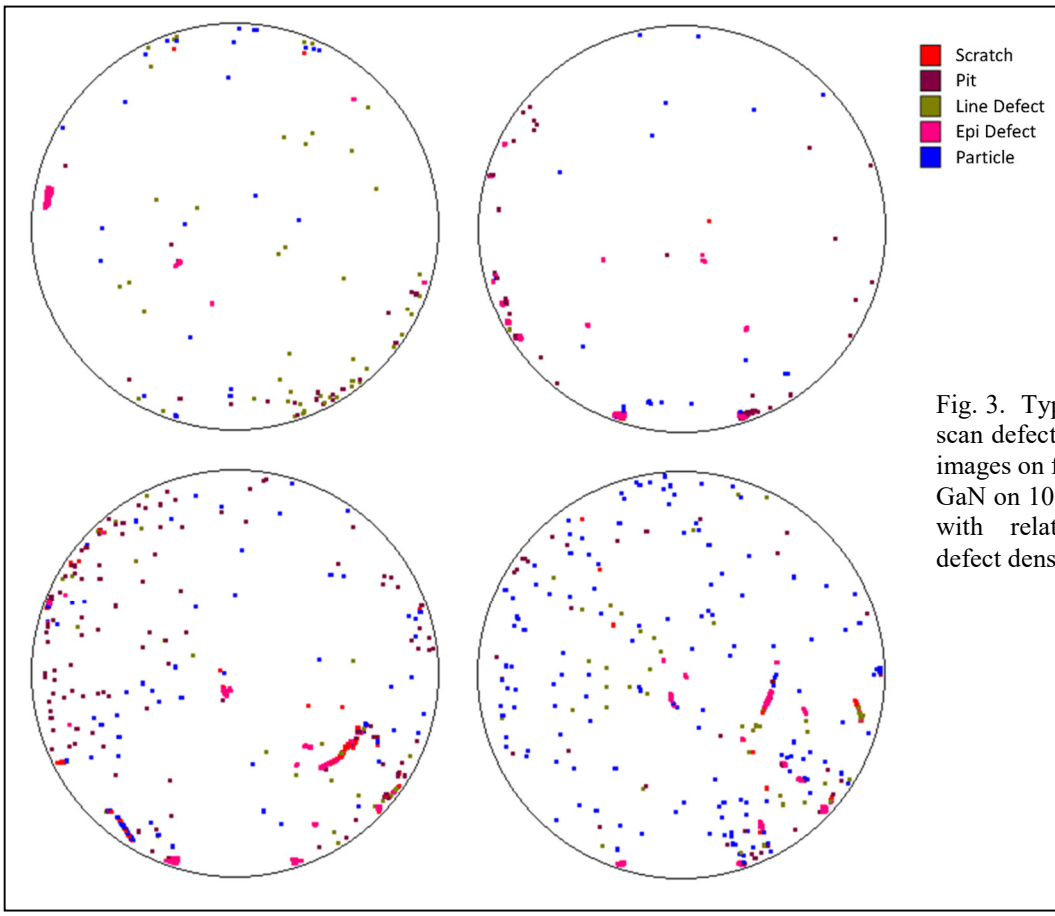

Fig. 3. Typical Candela surface scan defect inspection summary images on four different N-polar GaN on 100 mm SiC epi wafers with relatively low surface defect densities.

surface steps resulting from the SiC miscut is 10-20% higher than the Hall mobility [3]. Figure 2 (b) shows a typical thickness map of N-polar GaN on 100 mm SiC measured by spectroscopic reflectometry. The mean thickness is 1.88 µm with a nonuniformity of 0.5%.

All N-polar GaN on 100 mm SiC epi wafers and the SiC bare substrates pre-epi were scanned using a Candela 8520 system. Figure 3 presents typical defect inspection summary images on four different epi wafers with relatively low surface defect densities. Common defects including scratches, pits, line defects, epi defects, and particles are classified and plotted on the defect wafer maps. Scratches and epi defects have relatively large defect areas and distinct patterns that can be readily identified. Pits and particles can be distinguished based on the defect area ratio between the normal and oblique scatter channels, as well as their different signatures in the topography channel. Line defects are unique to the N-polar GaN epi, which only runs parallel to the surface steps. Further defect classifications are possible by using more sophisticated binning rules [5]. The quality of the C-face miscut SiC substrate is often crucial in achieving good N-polar GaN epi, and we are currently working with the SiC substrate vendors to better understand the correlation.

DEVICE FABRICATION AND CHARACTERIZATION

To assess the performance of the N-polar GaN on SiC epitaxial materials, we have fabricated and tested planar MIS-HEMT devices based on the structure presented in Fig. 1 (b). The fabrication process started with the deposition of source and drain ohmic contacts, which consisted of a n+ GaN regrown by MOCVD and a non-alloyed Ti/Al metal stack. A first 120-nm SiN passivation was deposited by PECVD. The gate-trench was realized by selectively etching the passivation and stopping on the *in-situ* SiN gate dielectric. A Ti/Al metal stack was deposited as the gate contact. The nominal gate length (L_G), source-to-gate distance (L_{SG}), and gate-to-drain distance (L_{GD}) are 0.8, 1.0, and 2.0 µm, respectively. The devices were isolated using mesa isolation. Each transistor comprises of 2x75 µm gate fingers. The finger width is oriented perpendicular to the substrate miscut steps, so that the 2DEG current flows with highest mobility in the direction parallel to the miscut steps. The final device is passivated with 1 µm PECVD SiN to suppress surface charge trapping effect commonly associated with GaN devices, so that the trapping evaluation is on the epi material rather than that induced by the fabrication process.

To evaluate the dynamic behavior and lack of charge trapping effects, we measured pulsed I-V output characteristics on planar MIS-HEMTs structures at chuck temperatures of 25 and 150 °C. The measurements were acquired using a commercial system with separate pulse heads to simultaneously pulse the gate and drain. The pulsed current was measured by averaging a 200-ns window within a 650-ns bias pulse-width with a 1-ms delay between pulses.

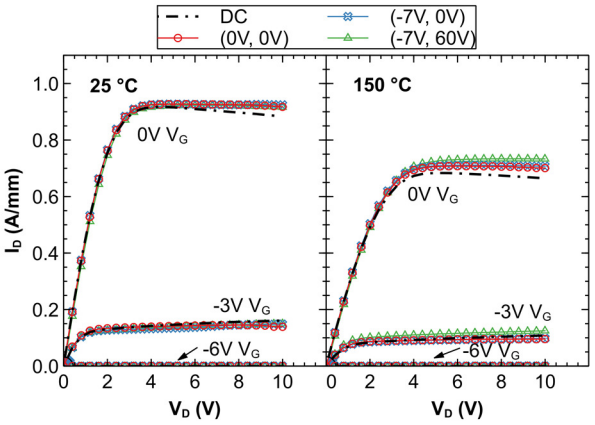

Fig. 4. DC and pulsed IV measurements acquired at probe chuck temperatures of 25 °C (left) and 150 °C (right). The pulsed measurements are taking at 25 °C there is effectively no deviation in the current characteristics with 60 V V_{DQ} and the gate pinched off at -7 V V_{GQ}. Similarly, at 150 °C the pulsed currents are all within 4% of each other indicating no significant charge trapping effects are observed.

Initially, the pulsed I-V curves were acquired with a gate and drain quiescent bias point (V_{GQ}; V_{DQ}) of (0 V; 0 V) to examine the device behavior under no stress and no charge trapping. Subsequently, pulsed I-V curves were acquired at multiple off-state quiescent bias points to assess the dynamic behavior under stress conditions similar to those found in real applications. The quiescent gate voltage (V_{GQ}) was held with the channel pinched off at -7 V and the quiescent drain-bias (V_{DQ}) was increased from 0 V to 60 V. The results from a representative device are shown in Fig. 4. At 25 °C The saturation drain-current measured at the knee voltage is > 0.9 A/mm and is effectively unchanged when the drain quiescent bias is increased to 60 V. Similarly, at 150 °C, while the increased temperature reduces the knee current and increases the knee voltage due to the heating of the channel, the dynamic behavior is nearly unchanged, with the knee current at (-7 V; 60 V) within 4% of the current from the 150 °C (0 V; 0 V) quiescent bias point. These results indicate that no major charge trapping effects are present in the device structure, therefore indicating the good quality of the N-polar GaN epitaxial material developed at Transphorm.

CONCLUSIONS

We report the MOCVD manufacturing of N-polar GaN on 100 mm SiC HEMT epitaxial wafers suitable for ultra-high performance 5G mm-wave applications. The wafers exhibit very high 2DEG electron mobility, excellent R_{sh} and thickness uniformities, and very low Candela defect densities. Pulsed I-V test on processed HEMTs at 25 and 150 °C showed very little dispersion and charge trapping, indicating good epitaxial material quality.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Defense (DoD) Office of Naval Research (ONR) under contract No. N6833519C0107, monitored by Dr. Paul A. Maki.

REFERENCES

[1] B. Romanczyk *et al*., IEEE Trans. Electron Devices **65**, 45, 2018.
[2] B. Romanczyk *et al*., IEEE Electron Device Lett. **41**, 1633, 2020.
[3] S. Keller *et al*., Semicond. Sci. Technol. **29**, 113001, 2014.
[4] X. Liu *et al*., 2020 CS MANTECH Digest, pp. 29 - 32, May 2020.
[5] V. Gupta *et al*., 2020 CS MANTECH Digest, pp. 37 - 40, May 2020.

ACRONYMS

GaN: Gallium nitride
SiC: Silicon carbide
HEMT: High electron mobility transistor
MIS: Metal-insulator-semiconductor
5G: Fifth generation
RF: Radio frequency
mm-wave: Millimeter-wave
MOCVD: Metalorganic chemical vapor deposition
SPC: Statistical process control
2DEG: Two-dimensional electron gas
R_{sh}: Sheet resistance
UID: Unintentionally doped