Evaluation of GaN Device Structures on 150 mm GaN on Engineered Substrates

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Abstract

GaN-based power switches offer potentially significant performance improvements over Si and SiC devices. However, there is a need for scaling substrate technology to enable cost-effective foundry processing. In this work, GaN films and relevant device structures grown on 150 mm engineered substrates are evaluated for material and electrical quality. Quasi-vertical diodes and HEMT devices are used as demonstration vehicles.

INTRODUCTION

Despite advances in GaN-based power switch technology there are still significant challenges preventing widespread adoption, including the cost of manufacturing on small diameter substrates. The ability to form layered structures on Si substrates is advantageous as the technology can readily be scaled to large diameters compatible with cost-effective foundry processing. Silicon is the obvious substrate choice due to low cost and large diameter. However, there are many growth and processing issues associated with scaling to large diameter wafers. In particular, the significant coefficient of thermal expansion (CTE) mismatch between GaN and Si limits the quality and thickness of GaN films. This becomes a significant issue moving to 200 mm wafers as bow reproducibility is challenging and buffer layer thickness is limited, which ultimately limits breakdown voltage. Yield is also substantially impacted by wafer breakage due to CTE mismatch.

Quora Technlogy Inc. is manufacturing revolutionary engineered substrates designated QST™ (Quora Substrate Technology*). QST™ substrate comprises a core CTE-matched to GaN, a series of thin films encapsulating the core, and an epi-ready Si (111) surface for GaN epi. QST™ substrates are compatible with all MOCVD platforms and CMOS fab facilities. These cost-effective engineered substrates [1, 2] are thermally matched to GaN, and thus enable low-defect density, and thick (from a few µm to tens of µm) epitaxial layers with high crystalline quality and low bow (<20 µm) required for manufacturing. Excellent GaN crystalline quality is advantageous for high-yield and low leakage current devices, and thick GaN enables high blocking voltage.

*The U.S. Navy does not endorse specific companies or products.

EXPERIMENTAL

GaN templates (5 µm) were grown on a 6-inch QST™ substrate by metal organic chemical vapor deposition (MOCVD) and served as the base for more advanced lateral and quasi-vertical GaN structures. Conventional AlGaN/GaN heterojunctions (see Table I) were grown on such templates for HEMT evaluation. Thick (10 µm) GaN layers were grown on GaN templates for evaluating quasi-vertical Schottky-barrier diodes (SBDs). SBDs were also fabricated on 5 µm GaN templates (see Fig. 1). All films were characterized by Raman spectroscopy, atomic force microscopy, x-ray diffraction and electron channeling contrast imaging (ECCI). At the wafer scale substrates were characterized for bow.

Device structures were fabricated on all films. HEMTs on the AlGaN/GaN heterostructure used a conventional mesa, ohmic, Schottky gate, and SiN_x passivation approach with varying gate to drain spacings (5-15 µm). Quasi-vertical SBDs were fabricated by first depositing Ti/Al/Ni/Au ohmic contacts, alloying the ohmic contacts, and then depositing Ni/Au or Pt/Au Schottky barrier contacts. No edge termination was applied. Typical HEMT properties were characterized electrically. Quasi-vertical SBD's were evaluated primarily for breakdown voltage.

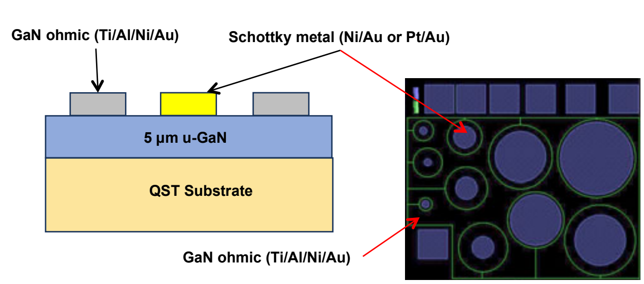

Fig. 1. Schematic cross-section of annular GaN Schottky diodes and the corresponding plan view of the mask.

TABLE I
HEMT LAYERS GROWN ON 150 MM QST™ SUBSTRATES

Layer Description	Thickness
GaN Cap	2 nm
$Al_{20}GaN$	20 nm
UID-GaN	0.1 µm
C-Doped GaN Buffer	6.0 µm

RESULTS & DISCUSSION

Material characterization indicated that the MOCVD GaN epitaxy on QST™ substrates is of high quality. Fig. 2 shows AFM images of a 5 µm thick GaN template on a 150 mm QST™ substrate compared to GaN on a 150 mm Si substrate (albeit a thinner film). A close look at the surface by AFM (Figure 2) shows a smooth surface with clear parallel step edges on GaN on QST™, whereas the GaN on Si steps are not as pronounced.

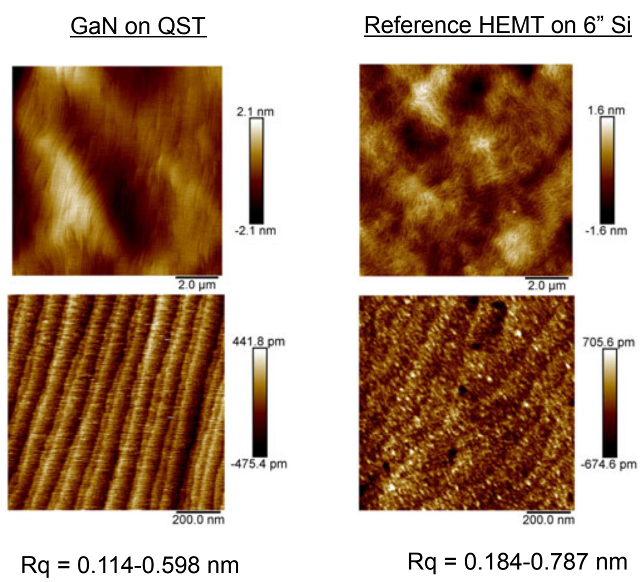

Fig. 2. AFM images comparing GaN on 150 mm QST™ to GaN HEMTs grown on 150 mm Si.

Raman spectroscopy of bulk GaN, GaN on QST™, and GaN HEMT epi on Si was also performed. The E2 peak position and full width at half maximum (FWHM) are shown in Table II. The E2 peak position for GaN on QST™ is closer to that of unstrained GaN [3], indicating less stress in the GaN epitaxy on QST™ than either N^+ doped bulk GaN or GaN-on-Si. The FWHM of the E2 peak is also smaller for GaN on QST™ compared to GaN-on-Si, indicating higher crystalline quality. High resolution X-ray diffraction was employed to characterize thick (~16 µm) GaN films grown by MOCVD on 150 mm QST™ substrates (Table III). The rocking curve FWHM of the asymmetrical (104) reflection was 130 arcsec which is narrower than the symmetrical (004) reflection (165 arcsec), indicating higher crystalline quality near the upper portion of the film and approaching that of free-standing GaN grown by HVPE. The average dislocation density is estimated using the Averbach analysis to be ~$1x10^8$ cm^{-2}. To further probe the crystalline quality of the thick GaN film on 150 mm QST™ substrates, ECCI was employed. Fig. 3 shows a typical electron channeling contrast image of GaN grown on 150 mm QST™ template. Based on this analysis the dislocation density can be estimated at between 1–$3x10^8$ /cm^2. There were also substantially fewer small angle grain boundaries observed as compared to GaN-on-Si. The measured dislocation density is comparable to the best heteroepitaxially grown GaN on 4H-SiC and demonstrates the advantages of engineered substrates to improve GaN crystalline quality.

TABLE II
COMPARISON OF RAMAN SPECTROSCOPY E2 PEAK POSITION AND FWHM OF BULK N^+ GAN, GAN ON QST™, AND GAN HEMT ON 150 MM SI.

	N^+ Bulk GaN (Ammono)	GaN on QST™	GaN HEMT on Si
E2 peak position (cm^{-1})	567.70	567.00	567.41
E2 FWHM (cm^{-1})	3.70	3.97	4.86

TABLE III
HIGH RESOLUTION FWHM OF THE (004) AND (104) X-RAY DIFFRACTION PEAKS FOR THICK (~16 µM) ON GAN ON 150 MM QST™ SUBSTRATE.

	(004) Reflection	(104) Reflection
FWHM (arcsec)	165	129

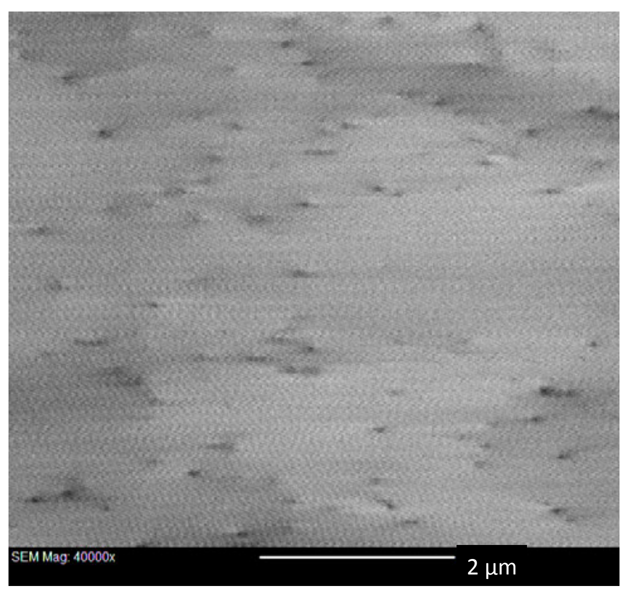

Fig. 3. Example electron channeling contrast image of 16 µm thick GaN grown on 150 mm QST™ substrate by MOCVD.

The electrical quality of GaN epitaxy on QST™ substrates was investigated by evaluating the properties of SBDs fabricated on thin and thick GaN epilayers. HEMTs fabricated on AlGaN/GaN heterostructures were also evaluated. To investigate the electrical quality of GaN epitaxy on QST™ and evaluate breakdown voltage, quasi-vertical Schottky diodes were fabricated using Ni/Au and Pt/Au Schottky metal and Ti/Al/Ni/Au ohmic metal as described above. The I-V characteristics are shown in Figure 4. The diode turn-on characteristics were consistent with the expected barrier height for metal-GaN contacts, and the ideality factor was <1.5. The breakdown voltage of ~150V was demonstrated on 5 µm GaN templates with ~$1x10^{17}cm^{-3}$ doping concentration. By increasing the GaN thickness to ~16 um by growing additional UID GaN on the GaN templates the breakdown voltage increased to over 800 V without a termination scheme though measured in a high vacuum probe station (see Fig. 5).

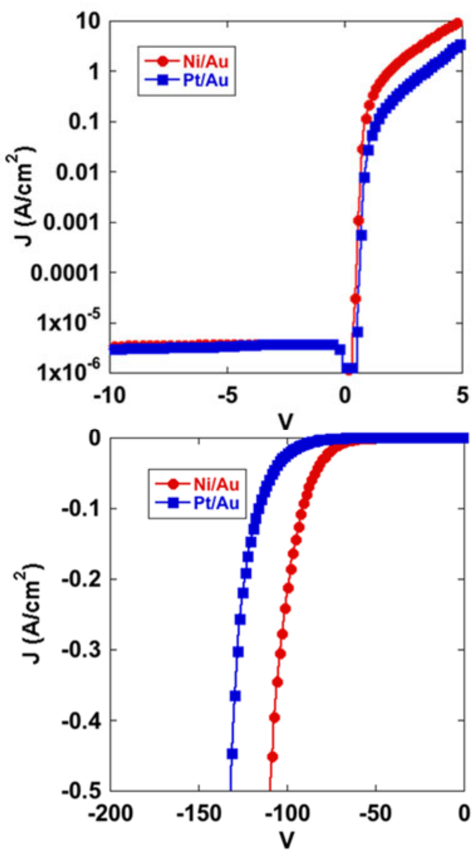

Fig. 4. Quasi-vertical Schottky barrier diode I-V characteristics of 5 µm GaN templates on 6-inch QST™.

The electrical characteristics of AlGaN/GaN HEMTs grown on 150 mm QST™ substrate were evaluated. Fig. 6 shows several curves: transfer, transconductance, pulsed and

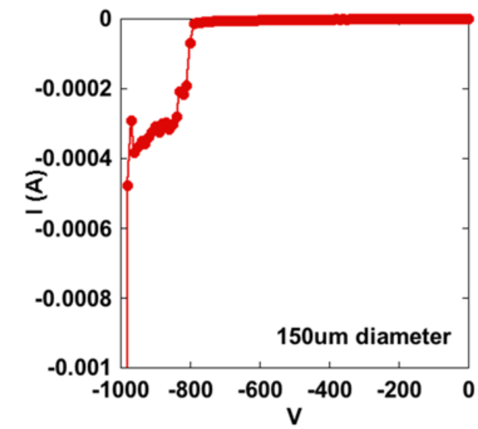

Fig. 5. Reverse breakdown of Schottky barrier diode on thick (~16 µm) GaN on 150 mm QST™ substrate.

static current-voltage, and dynamic on-resistance. HEMT properties are listed in Table IV. The large difference between static and dynamic IV characteristics which is also show in the dynamic R_{ON} plot indicates significant carrier trapping. The origin could be the passivation, barrier or channel/buffer regions. These particular devices were processed alongside HEMTs that received an optimized bi-layer SiNx passivation [4-6] where the latter showed minimal current collapse. The current collapse is likely due to the unoptimized thick buffer intended to support approximately 600V. Indeed as shown in Fig. 7, HEMTs without source- or gate-connected field plates support nearly 600 V in the off-state.

TABLE IV
SUMMARY OF ALGAN/GAN HEMTS PROPERTIES GROWN ON 150 MM QST™ SUBSTRATES

$I_{D,MAX}$ (A/mm)	0.376
$g_{m,MAX}$ (mS/mm)	155
V_T (V)	-1.79
R_{ON} (ohm-mm)	9.82
I_D @ V_G = -10V (A/mm)	$4.46x10^{-5}$
I_G @ V_G = -10V (A)	$5.99x10^{-6}$
$R_{ON,DYN}$ @ $V_{D,Q}$ = 20V (%)	99.1
V_{BR} (V)	570
Hall Mobility (cm^2/Vs)	1859
Sheet Density, $N_{s,2DEG}$ (cm^{-2})	$5.3x10^{12}$
Sheet Resistance, Ω/□	633

CONCLUSIONS

Engineered QST™ substrates have been characterized and several device structures were fabricated to evaluate the efficacy of these new and highly scaled GaN substrates. The material properties are commensurate with GaN-on-SiC however the excellent thermal match between GaN and QST™ allows for much thicker device layers leading to a new paradigm in GaN materials technology.

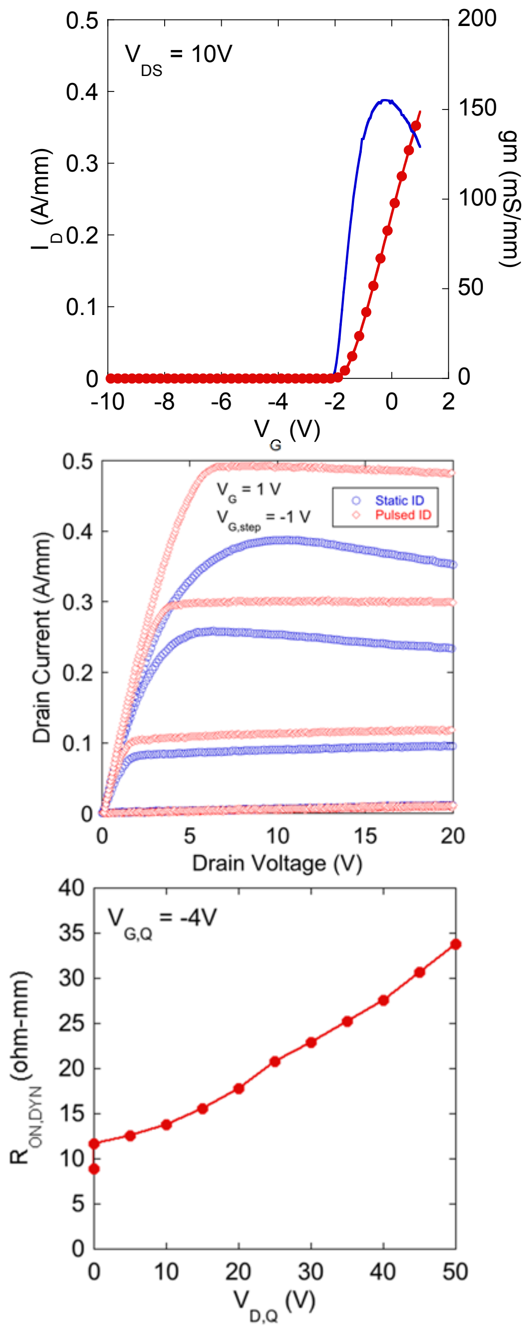

Fig. 6. HEMT transfer, transconductance, pulsed (quiescent point: $V_{G,Q}$ = 0 V, $V_{D,Q}$ = 0 V, which represents the lowest point on the $R_{ON,DYN}$ vs. $V_{D,Q}$ curve at $V_{D,Q}$ = 0) and static current-voltage, and dynamic on-resistance curves.

ACKNOWLEDGEMENTS

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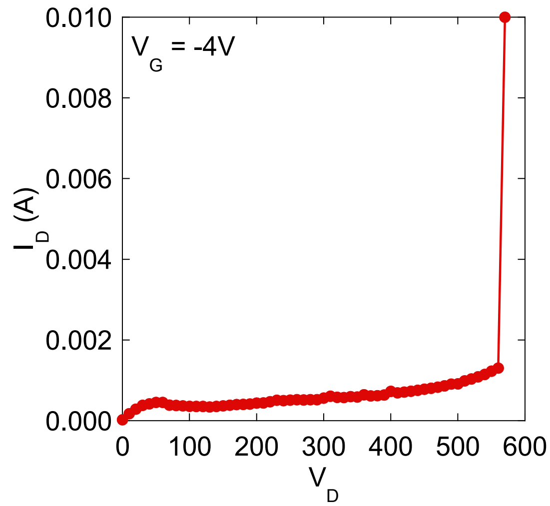

Fig. 7. AlGaN/GaN HEMT on 150 mm QST™ substrate blocking characteristic.

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ACRONYMS

HVPE: Hydride Vapor Phase Epitaxy
ECCI: Electron Channeling Contrast Imaging
AFM: Atomic Force Microscopy
HEMT: High Electron Mobility Transistor
QST™: Quora Substrate Technology