Innovative GaN based engineered substrates for power applications

Eric Guiot[1*], Raphael Caulmilone[1], Yannick Baines[2], Eric Frayssinet[3], Yvon Cordier[3]

*E-mail:eric.guiot@soitec.com
[1] SOITEC S.A., Parc Technologique des Fontaines, 38190 Bernin, France
[2] Univ. Grenoble Alpes, F-38000 Grenoble; CEA, LETI, Minatec Campus, F-38054 Grenoble Cedex 9, France
[3] Université Côte d'Azur, CNRS, CRHEA, rue Bernard Grégory, 06560 Valbonne, France

Keywords: GaN, engineered substrate, layer transfer, power electronics.

Abstract

The use of Smart Cut ™ technology enables the layer transfer of up to 1 µm thick GaN films either from bulk GaN or GaN on sapphire. We have demonstrated up to 3 cycles of reuse of the GaN donor substrate. Different receiver substrates such as Sapphire, Molybdenum and polycrystalline Aluminum Nitride have been evaluated. Through this innovative engineered GaN substrate, we have demonstrated a 13µm GaN epi growth. This breakthrough could enable new vertical GaN devices for high power application such as electric vehicle powertrain. Schottky barrier diodes have been prepared on HEMT structures both on donor and Smart Cut™ transferred GaN layer, showing similar performances on both substrates.

INTRODUCTION

Gallium nitride (GaN) has been recognized as a prime candidate for the next generation of power devices. GaN has the potential for power devices with high breakdown voltages and low on-state resistance. On-state resistance even lower (1mΩ.cm²) than the theoretical one of SiC has been demonstrated at high voltage 1.7kV [1]. GaN can also enable high switching frequencies which reduces the volume of passives.

Most publications on GaN power devices report on lateral devices, namely high electron mobility transistors (HEMT). However, vertical structure GaN power switching devices provide benefits compared to lateral devices including high breakdown voltages, high current densities, reduced footprint and lower sensitivity to surface states. Vertical devices are sensitive to dislocations and low defect density (10^4 to 10^6 dislocations per cm²) is required. This can be achieved through the use of bulk GaN substrate now with diameters demonstrated up to 7 inch. [3]. However such substrates still face challenges including the cost of manufacturing. In addition, the development of vertical devices requires the growth of multi micron thick GaN layers. The significant thermal expansion coefficient (CTE) mismatch between GaN and substrates such as Si foreseen as a solution for large diameter scaling, limits buffer thickness and hence breakdown voltage.

The Smart Cut ™ technology has the potential to lower the cost and improve performances of vertical power devices. This technology is currently used in large scale for SOI manufacturing [2]. By enabling the use of the required high quality bulk GaN substrate, and combining it with the choice of the right receiver substrate, the Smart Cut ™ technology has the potential to meet the requirements of GaN vertical devices. The use of a substrate such as pAlN with better thermal conductivity can enable higher power density and/or die size reduction. In this work, we report preparation and characterization of these substrates. We present also the first tests made on regrown epilayers for power devices.

EXPERIMENTAL

The starting material can be either GaN-on-sapphire template or bulk free standing GaN. In this work, the experimentation was performed using 100 and 150mm GaN/sapphire templates. First, a bonding layer is deposited on the GaN substrate and hydrogen implantation is performed [4]. A first temporary bonding is done on a carrier. As a result, a GaN layer (<1µm) is transferred on the carrier and the starting material can be reused. We have experimentally demonstrated up to 3 full Smart Cut™ cycles and subsequent GaN wafer reuse cycles with no degradation seen at this level. Depending on the targeted surface polarity, a second layer transfer is performed through detachment of the first temporary bonding.

Various receiver substrates have been evaluated. We first started with sapphire (GaNOS: Fig.1a) as a test vehicle. Then we switched to CTE matched substrates such as molybdenum (GaNOMo) and polycrystalline aluminium nitride (GaNopAlN: Fig.1b). In addition pAlN has the benefit of a high thermal conductivity (>200W/m.K).

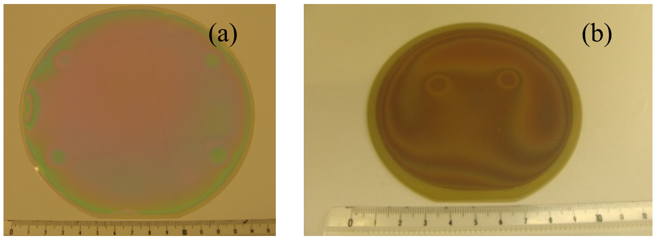

Fig. 1: 150 mm GaNOS (a) and 100mm GaNopAlN (b) wafers following Smart Cut™ technology

The HEMT epilayer stack grown by MOCVD on the GaN donor and on the engineered substrates consists of a 3 to 5 µm thick resistive C-doped GaN layer followed by 0.5 µm undoped GaN, 1nm AlN and 21 nm $Al_{0.27}Ga_{0.73}N$ barrier capped with a 3 nm SiN layer. The stack grown on the GaN donor and engineered substrates is described in Table I.

TABLE I
HEMT LAYERS GROWN on 150mm GaN Smart Cut™ ENGINEERED SUBSTRATE.

Layer description	**Thickness**
SiN Cap	3 nm
$Al_{0.27}Ga_{0.73}N$	21 nm
AlN spacer	1 nm
UID GaN	500 nm
C-doped GaN	3-5 µm

To investigate the electrical quality of GaN epitaxy on layer transferred GaN and evaluate breakdown voltage, Schottky diodes were fabricated. Device patterns were defined by photolithography. The device isolation was achieved by means of a 150 nm deep mesa etch realized by $Cl_2/Ar/CH_4$ reactive ion etching (RIE). To facilitate the ohmic contact formation, a short RIE was performed to remove the SiN cap and partially etch away about the half of the AlGaN barrier layer. Then a Ti/Al/Ni/Au stack was e-beam evaporated using a lift-off process and annealed for 30 s at 750°C by rapid annealing. A Ni/Au bi-layer was deposited to obtain Schottky gate contacts. Finally, an Au layer was evaporated on the ohmic and Schottky contacts to achieve low resistivity access pads. These test devices were not further passivated.

The final device schematic cross section and an optical microscope view of diodes are shown in Fig.2 and in Fig.3 respectively. Van der Pauw devices, linear isolation patterns consisting of 20 interdigitated 100 µm ohmic contacts and circular isolation patterns are shown in Fig.4.

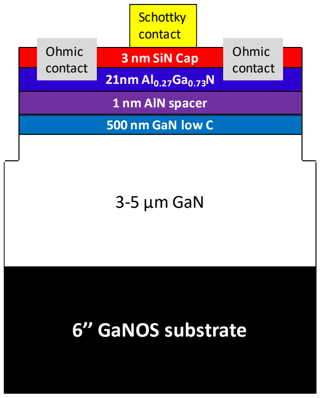

Fig 2: Cross section schematic view of the processed devices.

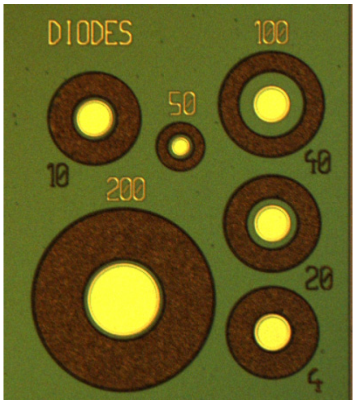

Fig.3: Optical microscope view of round gate transistors and Schottky gate diodes with 50 µm, 100 µm and 200 µm diameter.

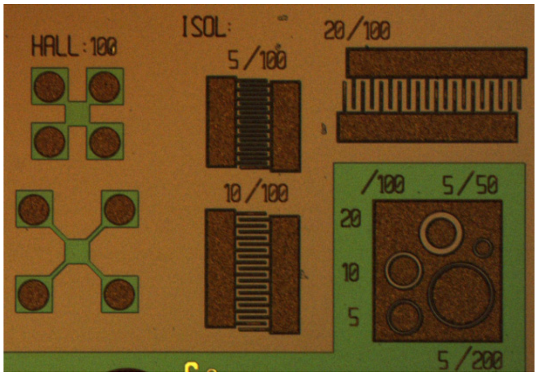

Fig.4: Optical microscope view of van der Pauw devices, linear and circular isolation patterns.

Results

The threading dislocation density of the GaN layer reflects that of the starting material. No additional threading dislocations are introduced through Smart-Cut^{TM} with ion implantation or by the regrowth, as confirmed by cathodo-luminescence (6x6µm filed@3kV, Fig.5) after 1µm GaN regrowth: 3.10^{8}/cm² both on the donor GaN-on-sapphire and after Smart Cut^{TM} on the layer transferred GaNOS.

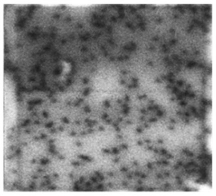

Fig.5: Cathodo-luminescence (6x6µm filed@3kV) after 1µm GaN regrowth.

XRD evaluation was performed for (002) symmetric ω scans (rocking curve) of GaN layers transferred from sapphire substrates. Before and after 3µm (5µm) GaN regrowth following Smart Cut^{TM}, samples showed similar peak width values, 226 and 237 arcsec, respectively. After the regrowth of 3 µm (5 µm) thick GaN, XRD (302) ω scan, which is more sensitive to dislocations, exhibited width values of 422 (391) arcsec respectively (Fig.6).

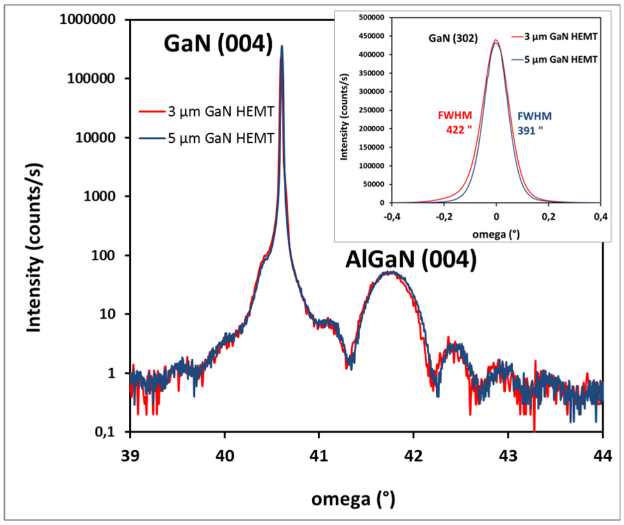

Fig 6: X-ray diffraction 2 theta-omega scans of the 3 µm and 5 µm thick GaN HEMT structures grown on GaNOS. The inset shows the asymmetric (302) GaN omega scans.

Thanks to the use of GaNOMo (GaN layer transferred on molybdenum which is CTE matched to GaN), we have been able to regrow 13 µm thick GaN on top of the engineered substrate. Material characterization indicated that the MOCVD GaN epitaxy on GaNOMo substrates is of high quality. Fig. 7 shows AFM images of a 13 µm thick regrown film on a 150mm substrate: the surface shows clear parallel steps and a low rms roughness around 0.2nm for a 5x5µm field.

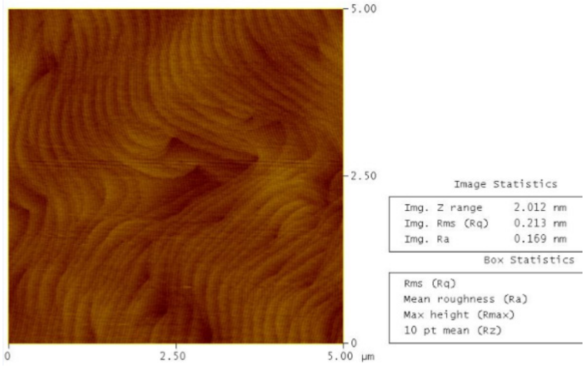

Fig 7: AFM image of the surface of 13µm thick GaN on GaNoMo substrate with 150mm diameter

Diodes fabricated with 100 µm diameter Schottky contacts (with anode to cathode distance of 40µm) have been prepared on top of the HEMT epi stack described above either on the donor GaN-on-sapphire or after Smart Cut^{TM} on the layer transferred GaNOS. Both I-V have been characterized. We clearly see similar characteristics (Fig. 8). In addition, lateral buffer leakage has been measured up to 900V without any breakdown (Fig. 9). Finally, Hall measurements have been carried out (Table II). The same high mobility is measured either for the donor GaN-on-sapphire or after Smart Cut^{TM} on the layer transferred GaNOS with the same level of carrier density.

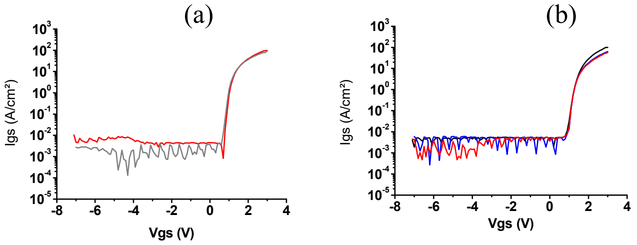

Fig. 8: I-V characteristics of diodes fabricated with 100 µm diameter Schottky contacts on GaN-on sapphire donor (a) and GaN Smart Cut ^{TM} (b).

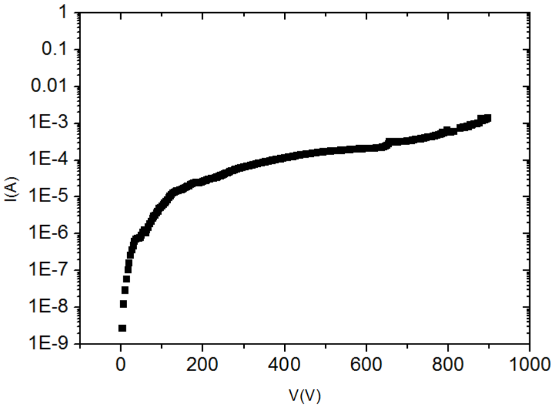

Fig. 9: Lateral buffer leakage between ohmic contacts on GaN grown on GaN Smart Cut^{TM} (GaNOS) with 20µm spacing.

TABLE II

MOBILITY AND CARRIER DENSITIES MEASURED ON DONOR AND GANOS SUBSTRATES

Sample	**Sheet resistance (Ω)**	**µ (cm²/Vs)**	**Ns (cm^{-2})**
GaN donor	339	2000	9.2×10^{12}
GaNOS	361	2250	7.6×10^{12}

In addition, 100mm diameter GaNopAlN wafers have been prepared (fig 1b) and are under evaluation for multi micron thick GaN epitaxy. Data will be shared during the conference.

CONCLUSIONS

We have developed a Smart Cut™ technology for GaN wafers enabling large scale and cost effective use of any GaN starting material: either epi wafer or bulk wafers. We have demonstrated a 13µm GaN epi growth on GaN layer transferred on Mo, and a highly thermal conductive and CTE matched GaN engineered substrate. Equivalent materials properties are obtained on both starting material and GaN engineered substrates. 3 and 5 µm GaN layers have been grown on top of GaNOS engineered substrates leading to equivalent electrical properties as on the starting material.

ACKNOWLEDGEMENTS

This research was supported by ENIAC through project AGATE ("Development of Advanced GaN substrates & Technologies')-Grand Agreement n° 325630 and by "Programme d'Investissement d'Avenir" France FSN AAP Nanoélectronique N°P3642-367657 and GaNeX (ANR-11-LABX-0014).

The authors would like to thank François Levy and Pierre Ferret from CEA-Leti, and Farid Medjdoub from IEMN Lille for their contributions.

REFERENCES

[1] D. Shibata et al., IEDM2016 Technical Digest, 10.1(2016).

[2] W. Schwarzenbach et al., 2017 IEEE International Conference on IC Design and Technology (ICICDT)

[3] Hajime Fujikura et al., Gallium Nitride Materials and Devices XII, Proc. of SPIE Vol. 10104, 1010403 (2017)

[4] A. Tauzin et al., "Transfer of two inch GaN film by the Smart CutTM technology", ECS proceedings, Vol. 06, pp 119-127, 200