Transfer from MHEMT to GaN HEMT Technology: Devices and Integration

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Abstract

AlGaN/GaN HEMTs are very promising devices for microwave power applications. Using a mask set originally developed for MHEMTs on GaAs and Ge, we have realized GaN-on-sapphire devices exhibiting very good DC and RF performance.

Integration and packaging of these high power density devices necessitate specific attention to thermal management, especially for HEMTs grown on sapphire substrates. The low thermal conductivity of sapphire limits the power performance of these devices. Analogously to earlier work on MHEMTs on germanium substrates, we propose a substrate removal method and MCM-D integration technique for GaN-on-sapphire HEMTs.

INTRODUCTION

Due to superior electron transport properties, GaN-based HEMTs have shown tremendous potential in power generation at microwave frequencies [1]. In this paper, we discuss the technology transfer from MHEMT devices on germanium substrates [2, 3] to GaN-on-sapphire HEMTs at IMEC. Compared to SiC, sapphire substrates are relatively cheap but the low thermal conductivity (σ = 30 W/m.K) is a major disadvantage.

Furthermore, analogously to MHEMTs on Ge, thin-film multi-layer MCM-D technology is used for integration of the GaN devices.

In a first section, we discuss the epitaxial layer structure and device processing. Further, the DC and RF performance of the devices are presented. The last section describes the integration methods.

EPITAXIAL LAYERS AND DEVICE PROCESSING

The epitaxial layer structure for GaN HEMTs has been grown by MOVPE on 2 inch sapphire substrates [4]. The epitaxial layer structure consists of a GaN buffer layer, a very thin AlN spacer layer and an $Al_{0.3}Ga_{0.7}N$ layer. Both the GaN and AlGaN layers are non-intentionally doped.

For small gate periphery devices, i.e., 2 × 50 µm gate width, we have used the mask sets initially developed for MHEMT processing. While the mask levels are identical, the process steps for each level are considerably different for the new material.

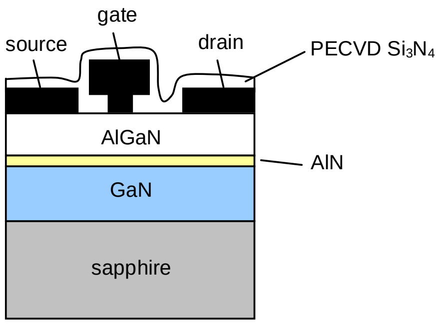


Figure 1: Schematic cross-section of a GaN HEMT on sapphire with T-shaped gate.

Device processing starts with a dry mesa etch based on Cl_2. Then, Ti/Al/Pt/Au ohmic contacts are deposited and alloyed at 850°C in N_2 ambient. TLM measurements reveal a contact resistance of 0.8 Ω.mm. A contact metal is deposited and Ni/Au T-gates with a footprint of 200 nm are fabricated by e-beam lithography. Finally, the devices are passivated by PECVD deposition of Si_3N_4. Figure 1 shows a schematic cross-section of a GaN-on-sapphire HEMT. Table I summarizes and compares the processing steps of MHEMTs on Ge and GaN-on-sapphire HEMTs [2].

TABLE I
COMPARISON: MHEMT AND GAN HEMT TECHNOLOGY

	MHEMT	**GaN HEMT**
Substrate	Germanium or GaAs	Sapphire
Epitaxy	MBE	MOVPE
Doping	2 Si δ-dopings	n.i.d.
Mesa etch	Wet etch (H_3PO_4)	Dry etch (Cl_2)
Ohmic metal	Ni/Au/Ge/Ni/Au	Ti/Al/Pt/Au
Alloy temperature	280°C	850°C
Contact resistance	0.2 Ω.mm	0.8 Ω.mm
Recess etch	Citric acid based	/
T-Gate	0.2 µm; Pt/Ti/Pt/Au	0.2 µm; Ni/Au
Passivation	200 nm PECVD Si_3N_4	200 nm PECVD Si_3N_4

DC AND RF MEASUREMENTS

We have performed DC and RF on-wafer measurements. For devices with gate width of 2×50 µm and a gate length of 200 nm, a maximum drain current (I_{ds}) of about 450 mA/mm and a maximum transconductance (g_m) of 130 mS/mm have been measured. Figure 2 shows the output characteristics of a GaN HEMT before and after passivation. The Si_3N_4 surface passivation layer has a significant effect on the output characteristics. Moreover, a negative V_T shift of about 0.8 V is noticed after passivation. For InP HEMTs (and MHEMTs) we noticed an increase in g_m and positive V_T shift after passivation due to diffusion of Pt into the Schottky layer [5].

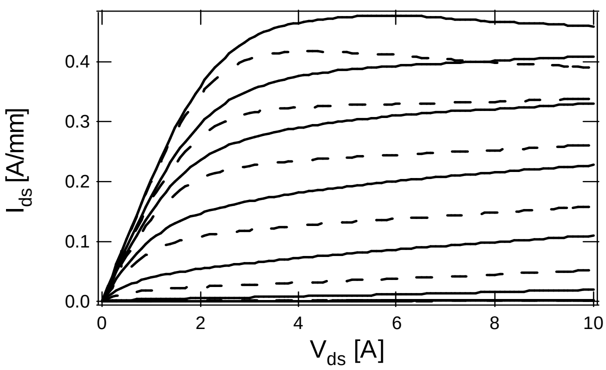
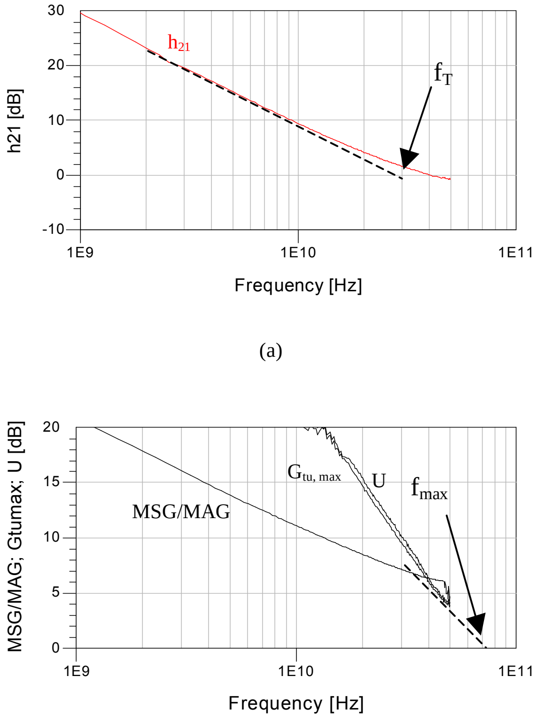


Figure 2: Output characteristics of a GaN-on-sapphire HEMT (0.2×100 µm^2) before (dashed line) and after (solid line) nitride passivation. Bias conditions: V_{gs} ranging from –8 V to 2 V, step 1 V.

S-parameter measurements from 45 MHz up to 50 GHz reveal a current gain cut-off frequency (f_T) and a maximum oscillation frequency (f_{max}) of about 30 and 70 GHz, respectively. Figure 3 (a) shows the current gain and f_T value, figure 3 (b) shows the power gain (MSG/MAG, $G_{tu,max}$ and U) and f_{max} value of a GaN-on-sapphire HEMT.

Table II summarizes and compares the results of an MHEMT on germanium and a GaN-on-sapphire HEMT [2]. The gate length of both types of devices is 200 nm. Identical mask sets have been used. Note however that GaN HEMTs can operate at significantly higher voltages, resulting in a larger output power.

Recently, significantly larger drain currents and transconductance values have been achieved on GaN HEMTs using in-situ Si_3N_4 passivation [4]. In this way, the output power can be further increased.



(a)

(b)

Figure 3: (a) Current gain (h_{21}) and f_T value GaN-on-sapphire HEMT (0.2×100 µm^2); (b) MSG/MAG, $G_{tu\ max}$ and U together with extrapolated f_{max} value GaN-on-sapphire HEMT (0.2×100 µm^2). Bias conditions: V_{gs} at maximum g_m; V_{ds} = 6 V.

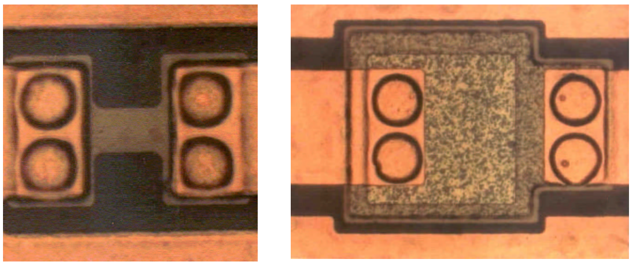
TABLE II
COMPARISON: MHEMT AND GAN HEMT PERFORMANCE

	MHEMT	**GaN HEMT**
drain current (maximum)	600 mA/mm	450 mA/mm
Transconductance (maximum)	700 mS/mm	130 mS/mm
Threshold voltage	-0.7 V	-3 V
Knee voltage	0.5 V	3 V
f_T/f_{max}	70 GHz/120 GHz*	30 GHz/70 GHz

*: after removal of the germanium substrate

INTEGRATION METHODS

Previously, we reported a feedback amplifier in MCM-D technology using MHEMTs grown on Ge substrates [3]. After bonding the device to a glass carrier substrate, the germanium substrate was removed by dry-etching in order to reduce substrate losses. Following a similar scheme, GaN HEMTs are now incorporated in MCM-D circuits. The sapphire substrate, having served its purpose as a low-cost growth platform, can be removed by laser lift-off [6]. Moreover, for its superior thermal conductivity, aluminum nitride (AlN; σ = 180 W/m.K) is now used as carrier substrate and the MCM-D passive component technology has been transferred to this material. Figure 4 shows pictures of a TaN resistor and a MIM capacitor on AlN.



(a) (b)

Figure 4: TaN resistor (a) and MIM capacitor (b) on an AlN substrate in CPW lay-out.

For the first tests of this integration technique we have used standard GaN-on-sapphire HEMTs with a gate length of 3 µm and a gate width of 100 µm. In order to prepare the HEMTs for substrate removal, the devices are diced and glued upside down on an AlN carrier substrate. Figure 5 schematically shows the integration method and substrate removal technique.

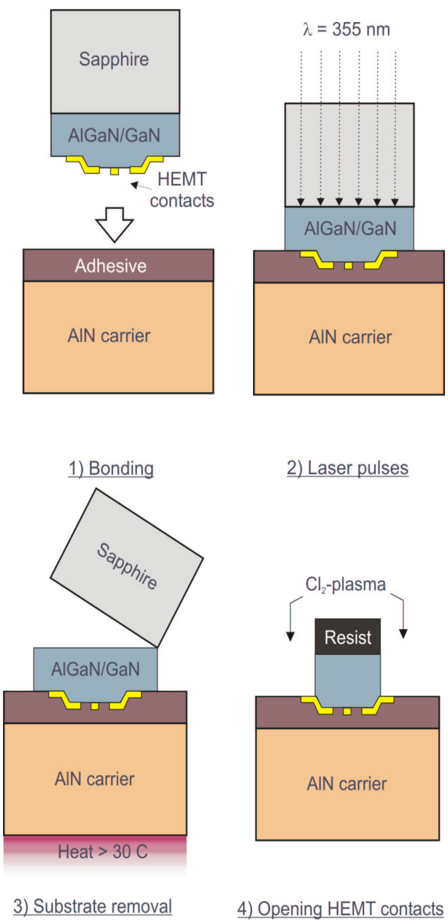


Figure 5: Schematic representation of integration technique and substrate removal method for a GaN-on-sapphire HEMT.

Figure 6 shows a top view micrograph of an embedded MHEMT and GaN HEMT in MCM-D technology.

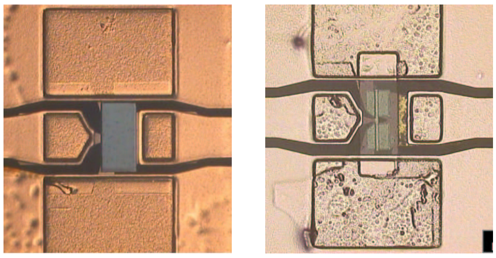


Figure 6: Top view micrograph of an embedded MHEMT (left) and GaN HEMT (right) in MCM-D technology.

Figure 7 shows the output characteristics of a GaN-on-sapphire HEMT before and after substrate removal and MCM-D embedding. For the same device, figure 8 shows I_{ds} and g_m as a function of V_{gs} before and after MCM-D embedding.

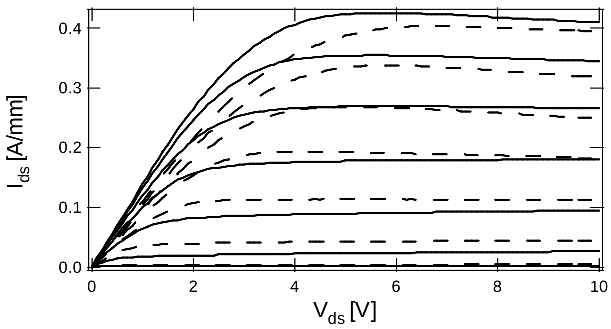


Figure 7: Output characteristics of a GaN-on-sapphire HEMT (solid line) and a GaN HEMT after substrate removal and embedding in MCM-D technology (dashed line). The gate periphery is 3 × 100 µm^2. Bias conditions: V_{gs} ranging from –8 V to 1 V, step = 1 V.

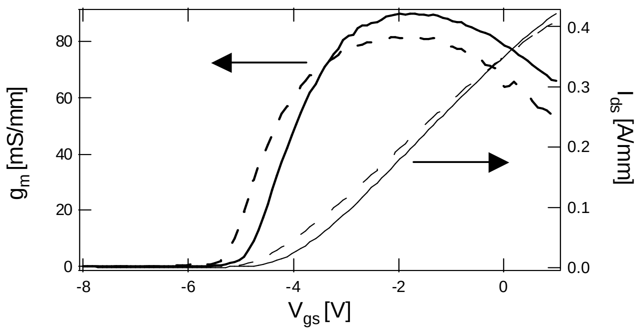


Figure 8: Transconductance (thick) and drain current (thin) of a GaN-on-sapphire HEMT (gate periphery: 3 × 100 µm^2) before (solid line) and after (dashed line) removal of the sapphire substrate and MCM-D embedding. Bias condition: V_{ds} = 6 V.

After substrate removal and embedding, the threshold voltage has changed from –5 V to –5.2 V together with a small drop in maximum I_{ds} and a decrease in g_m by about 15% [6]. The origin of these effects is not yet completely clear. Possible causes are changes in stress in the heterostructure, electron traps at the front or back surface of the device, and/or an increased self-heating of the HEMT after substrate removal. It is expected however that by adding an appropriate surface passivation layer and additional heat removal layers a significant improvement in HEMT performance is achieved.

Furthermore, also the high frequency performance has been compared before and after substrate removal. A slight decrease (~ 10%) in f_T and f_{max} has been noticed. Note however that the high frequency performance of these large gate length (3 µm) devices is very low.

Recently, new masks are being used for processing of GaN HEMTs. The source-to-drain spacing is increased to optimize the breakdown voltage and output power. Devices with multiple gate fingers are also included. Extra processing steps for air bridge technology have to be included. After PECVD passivation, a 5-µm-thick BCB layer is spin coated. This layer serves as an “underfill” for the air bridges. Further, Au air bridges are deposited by electroplating in order to connect the different source areas. Figure 9 shows a top view micrograph of a six-finger GaN-on-sapphire HEMT.

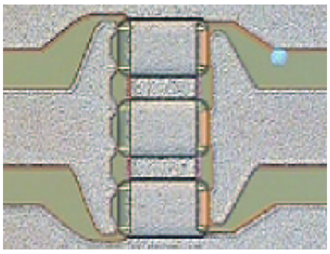


Figure 9: Top view micrograph of a six-finger transistor with air bridges.

More mainstream interconnection methods such as wire bond or flip chip (using Au studs or Sn bumps) technologies are also being investigated. Currently, thermal 3D simulations of the different integration methods are being performed and the first demonstrator circuits are in the development phase.

CONCLUSIONS

In this paper, GaN-on-sapphire HEMT technology has been presented. Although the mask levels are based on GaAs technology, very different processing steps have been used. Excellent DC and RF performance results have been achieved. Analogously to MHEMTs on germanium, we have shown that the sapphire substrate of HEMT devices can be removed using a laser lift-off technique. This is an important step towards a system-in-a-package integration of HEMTs for microwave applications.

ACKNOWLEDGEMENTS

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ACRONYMS

CPW: Coplanar Waveguide
$G_{tu,max}$: Maximum Unilateral Transducer Gain
HEMT: High Electron Mobility Transistor
MAG: Maximum Available Gain
MBE: Molecular Beam Epitaxy
MCM-D: Multi-Chip Module-Deposition (of thin layers)
MHEMT: Metamorphic HEMT
MIM: Metal-Insulator-Metal
MOVPE: Metal-Organic Vapor Phase Epitaxy
MSG: Maximum Stable Gain
TLM: Transfer Length Method
U: Mason’s Gain