Recent Developments and Trends in GaN HFETs

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Abstract — **This paper reviews the main challenges and results concerning GaN HFET research and development in Europe. Today several actors are working to allow the emergence of an European source for this technology. The activity sweeps all R&D fields from material growth to circuit realization and reliability.**

I. INTRODUCTION

GaN HFETs open the way to strongly improve the power capability of microwave circuits for military but also telecommunication applications. Power density has been demonstrated above 30 W/mm at 4 and 8 GHz [1]. The about 10 times higher output load impedance will strongly simplify circuit design and allow broadband microwave amplifiers. The robustness will help tolerate overdriving. Low noise performance also challenges GaAs devices. Nevertheless this is a new technology. Therefore success strongly depends on our capability for innovation. Thus, the choice of the best substrate for low defect density growth, easy MMIC process and thermal management is not finalized yet. Processing requires innovative solutions since GaN chemistry is different of the one of arsenides or phosphides. Thermal management is also a great challenge because of the extremely high power densities available. Then circuit design and reliability is to be investigated.

II. STATE OF THE ART

More than 10 years have passed since first AlGaN/GaN HEMTs were published [2]. Since then, considerable progress has been performed as much for frequency as for power performance. Figures 1 and 2 show the evolution of the current gain cut-off frequency F_t versus time and the power density versus frequency. More than 120 GHz F_t has been obtained for a gate length of 0.12 µm [3]. Concerning power, besides the record power density of 30 W/mm demonstrated by CREE at 8 GHz [4], 0.5 W/mm was demonstrated at 60 GHz with 4 dB gain without compression [5]. As the output power was indeed limited by the power source, this gives hope for higher power densities at this frequency but also shows the wide frequency band accessible for this technology. Finally, power amplifiers have been demonstrated such as a 174 W amplifier at 2.1 GHz for W-CDMA base station applications [6].

In Europe, investigations on transistors started a few years after the US. But today many groups are working in this field, covering material growth, process, measurement, circuit design, reliability, ie all fields required to allow the emergence of a European source for this technology. For some of them, their work is now supported by several national and European projects. Table 1 draws the list of the main European players and their main activity in this field.

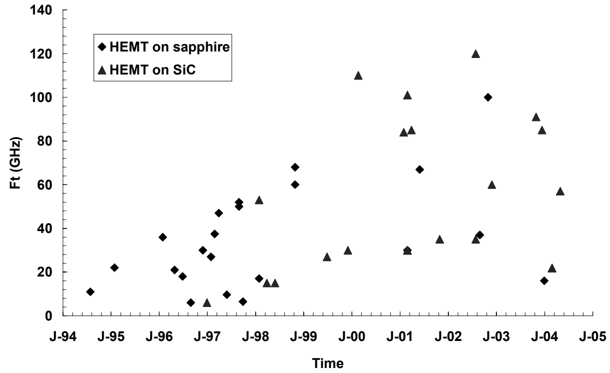

Fig. 1. Evolution of the current gain cut-off frequency F_t of AlGaN/GaN HEMTs with time.

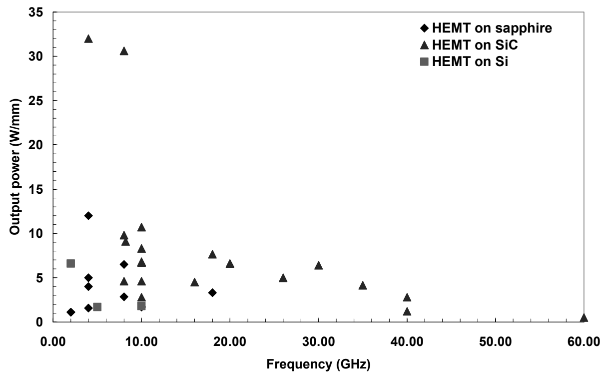

Fig. 2. Evolution of the power density of AlGaN/GaN HEMTs with frequency.

III. MATERIAL.

Among the specific particularities in this field let mention that growth can be performed either by MBE or MOCVD and that several substrates are used (Si, SiC or sapphire). The emergence of doped GaN substrates is on the way. Semi-insulating ones are technically more challenging but will sooner or later appear. A European small company (Lumilog) is targeting this. However this substrate might be very expensive. On the side of low cost, SiCOI could be a relatively cheap alternative to bulk SiC. RWTH Aachen is evaluating this substrate for HEMT structures.

Thus even if several actors are growing materials, the multiplicity of techniques and substrates considerably increases the number of possible investigations.

Company/ Institute	Country	Main Focus in GaN HFET R&D
OKMETIC	Sw	Development and production of semi insulating SiC substrates
Linkoping University	Sw	Epitaxial growth and characterisation of nitrides, including AlN, using Hot Wall epitaxy
IMEC	B	Nitrides epitaxial growth, HEMT-like devices process and characterization, thermal management, circuit design and manufacturing, System-in-a-Package
QinetiQ	UK	H-FET epi / Characterisation, H-FET process development, RF test & model extraction, Module fabrication: (Power Amp, LNA, Oscillator)
CRHEA	F	Material and HEMT structure growth, material and basic electrical characterization
Padova University	I	Passivation effects on DC , pulsed and low frequency device characteristics; DC and pulsed hot carrier effects; 2D Modelling of trap related effects (current slump)
Alenia Marconi Systems	I	Process, characterization, circuit design and fabrication
Picogiga	F	Industrial Supplier of GaN HEMT structure & Engineering Material for advanced performances at low cost
Daimler-Chrysler Research Center	G	Process of devices and circuits. Characterization.
RWTH Aachen	G	Nitride MOCVD, characterization, RF power device processing, RF characterization, device / circuit modeling and design
FBH	G	Process of devices and circuits. Characterization.
IAF	G	Multiwafer material and HEMT structure growth, CPW/MSL MMIC process, microwave power/pulsed/ low noise characterization, thermal management, MMIC and hybrid circuit modeling, design, and fabrication, reliability
TNO	NL	Circuit design and fabrication
Chalmers	Sw	HEMT-process development, small&largesignal modeling, circuit design, characterization: I-V, S-par,pulsed, load-pull
IEMN/TIGER	F	HEMT process development, microwave low noise and power characterization, device modelization and physics
Ulm University	G	Process of devices. Characterization
ISOM - Madrid University	Sp	Wafer characterization, electron transport, HEMT processing, MBE growth, surface problems physical-electrical modelling, parasitic analysis
TRT/TIGER	F	Material and HEMT structure growth, process, microwave power characterization, simulation, thermal management, circuit design and fabrication, reliability
IRCOM	F	Microwave characterization
LAAS	F	Low frequency noise characterization and noise sources modelling, physical simulation, low phase noise VCO design
IXL	F	Low frequency noise characterisation in HEMT, LF noise sources location

Table 1 : Main European laboratories in the field of AlGaN/GaN HEMT devices and circuits.

Besides this, Linköping University is developing a specific Hot Wall Epitaxy MOCVD system for nitride growth on SiC. This concept comes from SiC growth research and has allowed to obtain state of the art mobility in 2D electron gases with 1390 cm^2/Vs for a density of 6×10^{12} cm^{-2}.

Due to the lack of GaN substrate the growth of a metamorphic buffer layer is required and strongly determines the quality of the layers. ISOM (Madrid) has also investigated thin strained GaN channels deposited on an AlN/GaN inter layered buffer. The combination of improved material quality and increased polarization results in higher electron densities and mobilities [7]. CHREA (Valbonne) is also working on the buffer optimization for heterostructures with high mobilities.

At TIGER/TRT conventional AlGaN/GaN structures grown by MOCVD on SiC have shown electron densities as high as 1.2×10^{13} cm^{-2} with 1300 cm^2/Vs mobility at 300K. This gives square resistances as low as 400 Ω which is good for decreasing access resistances in HEMTs.

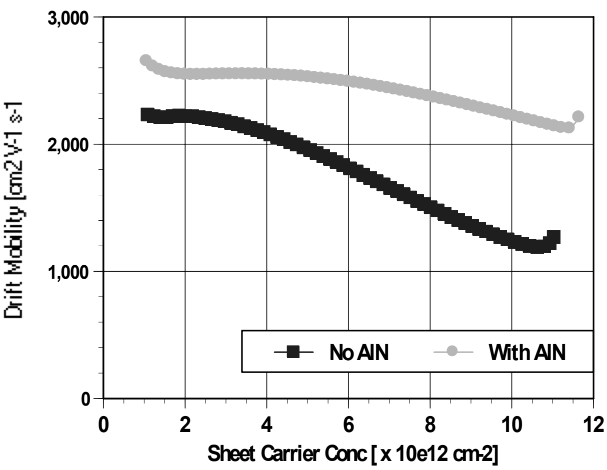

Fig. 3. Drift mobility as a function of carrier density in AlGaN/GaN heterostructures grown on SiC with and without an AlN layer at the interface (300K)

QinetiQ showed and studied the improvements in electron mobility when inserting an AlN layer between AlGaN and GaN in heterostructures deposited on SiC (figure 3).

IMEC Leuven is working on the in situ deposition of a Si_3N_4 passivating layer by MOCVD. This gives a stable surface before process and gives rise to a double current density as compared with an identical unpassivated HEMT heterostructure.

IV. PROCESS.

Considering process a lot of innovative solutions are under investigations.

First, semi-insulating substrates prevent charge flowing during e-beam lithography. This increases the risk for the beam to be deviated by local negative charge. Thus a thin temporary conductive layer must be deposited on the resist surface in order to allow charge removal.

Ohmic contacts technologies are often based on a mixture of Ti, Al, Ni and Au. With this process, ohmic contact resistances as low as 0.15 Ωmm have been obtained on a regular basis at TIGER.

One of the most challenging steps will be the passivation. A large number of papers have shown the improvement brought by passivation [8,9]. Indeed the surface of AlGaN is charged due to spontaneous and piezoelectric polarization. The way for neutralization of this charge may strongly influence the device behavior. Detailed investigation of this aspect may probably determine circuit stability and reliability.

Finally the realization of power transistors requires to handle high temperatures. Therefore SiC substrates are of interest for circuits. First MMIC process steps such as via holes on SiC have been shown.

V. CHARACTERIZATION.

Characterization of GaN HEMTs requires higher voltages than for GaAs or InP devices (at least 10 to 20 V for Id-Vds curves but much higher for breakdown) Current saturation occurs typically at about 3 - 5 V. Concerning current, due to the high electron density, maximum drain current densities are easily above 1 A/mm.

The high current densities and drain voltages lead to high dissipated power. This implies the set up of pulse measurement systems in order to deal with thermal problems. Also set ups able to handle high power at the input and output of the devices will be required to characterize device and circuits under power conditions.

Concerning cut off frequencies, using a 0.15 µm gate technology IAF has achieved 65 GHz Ft (at Vds = 7 V) and 140 GHz Fmax (at Vds = 20 V) on SiC substrates [5] which is not so far from state of the art for this gate length (85 GHz Ft).

On Si substrates state of the art cut off frequencies are lower because this technology is less mature. 46 GHz Ft and 92 GHz Fmax (at Vds = 10 V) have been demonstrated at TIGER [10].

Pulsed or time resolved measurements are also of interest for the investigation of instabilities. They allow to show the trapping effects and the impact of passivation.

The University of Padova is working on the characterization and modeling of instabilities in HEMTs. Figure 4 shows the influence of pulse duration on the device characteristics. This figure shows the strong effect that transient measurements can have on device characteristics in terms of reduction of maximum drain current and increase of knee voltage. These results can be modeled by taking into account surface traps located at 0.35 eV above the valence band.

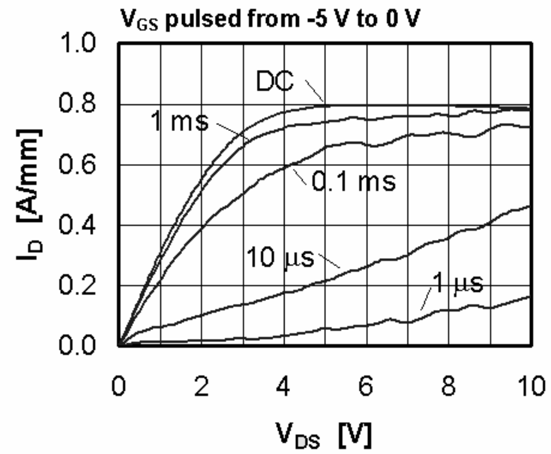

Fig. 4. Evolution of an I_d-V_{ds} characteristics with pulse duration. V_{gs} is pulsed from -5 V to 0 V.

TIGER has set up a pulse measurement system for DC and S parameters. Figure 5 shows the effect of passivation on pulsed characteristics using a quiescent bias point at V_{ds0} = 15 V and V_{gs0} at threshold voltage. This point enhances the trapping effects and demonstrates the beneficial effect of passivation.

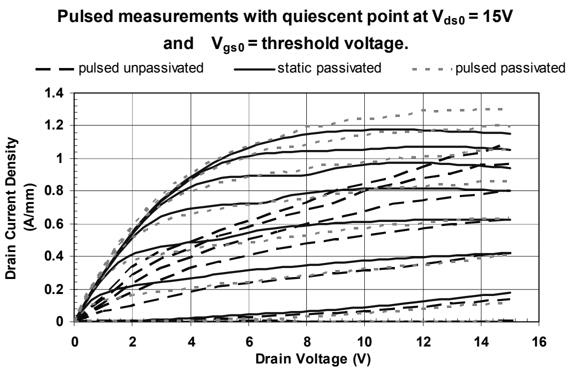

Fig. 5. Static and pulsed I-V characteristics of GaN/AlGaN/GaN HEMT before and after passivation (static : passivated only).

Concerning power measurements, state of the art power results depend on the substrate used. For instance on Si, Daimler-Chrysler Research Centre established 6.6 W/mm at 2 GHz with 49 % P.A.E. [11].

Noise measurements at 10 GHz on Si substrates have given 1.1 dB with 12 dB of associated gain [10]. This also demonstrates state of the art technology on Si substrates in Europe.

Low frequency noise measurements are carried out at LAAS and IXL for comparison of different technologies and different substrates. IXL found that performance can be as good as GaAs based HEMTs. These measurements are also used to get some information on fluctuation localization and to feedback for process improvement [12].

VI. Circuits.

One of the advantages of AlGaN/GaN technology is that output matching could be much easier because the output impedance of large development devices will be less far from 50 Ω as compared to Si or other III-V technology.

Thus, recently IAF has demonstrated a CPW MMIC on SiC substrate showing 1.8 W CW at 18 GHz with a 0.15 µm process (figure 6). Daimler has published a 10 GHz CPW MMIC delivering 3.7W P_{max} with 26 % P.A.E. [13]

Nevertheless thermal dissipation will be strongly determining the capability of circuits. This aspect will be taken into account in circuit design.

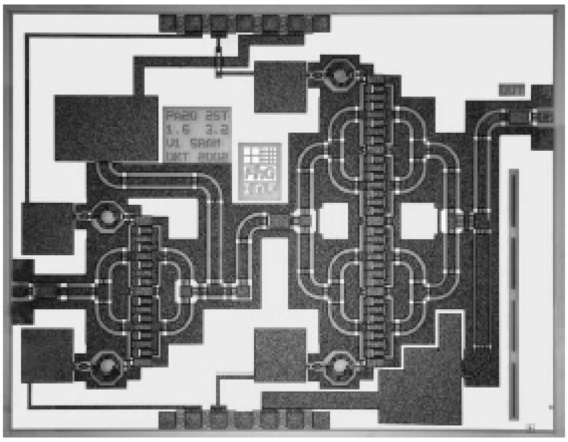

Fig. 6. 20 GHz CPW MMIC on S.I. SiC substrates.

VI. Conclusion and Perspectives.

Today, a lot of centers in Europe are contributing to the research and development on AlGaN/GaN HEMTs and circuits. Although they started later than the US, they paved the way to succeed. However we also have to look at the future where there is still a lot to do. In particular, nitrides are semiconductors of interest because they allow the fabrication of a lot of different materials such as BGaN. Investigating the growth of those materials is already engaged. But the physical properties need further studies. Just as an example, InN band gap is still controversial. Of course material studies will allow process and device investigations. This could lead to enhance the capabilities of nitride based technology in the future.

Acknowledgement

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