ESA OSIP study

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Study of mm-wave GaN transistors for space applications

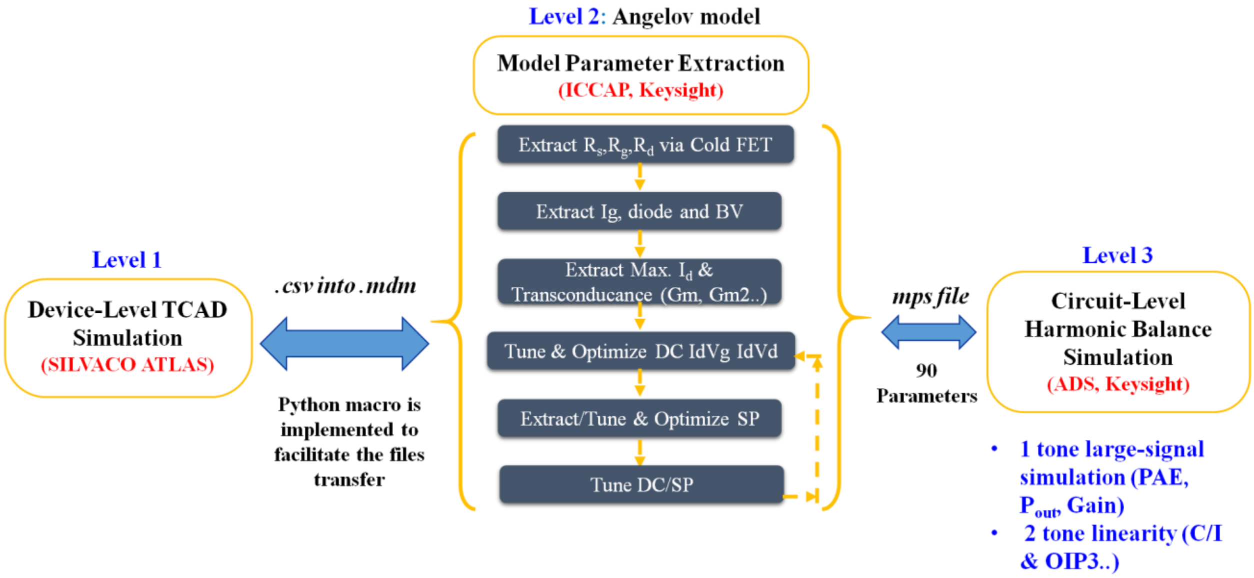
EXECUTIVE SUMMARY

Simulation methodology for Large-signal and linearity performances of mm-wave transistors

CNRS-IEMN

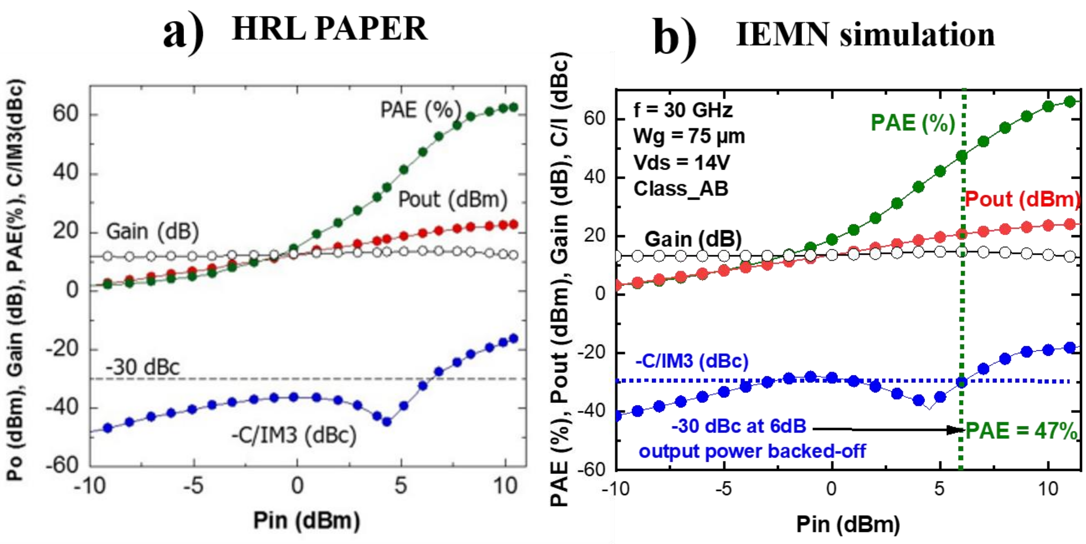
Under ESA contract: Study of mm-wave GaN transistors for space applications

GaN-based devices are becoming a key technology for millimeter-wave applications. Because of outstanding material properties, recent advances in GaN device designs provided a sharp increase in performances including high power, high efficiency, reliability, linearity, and compact size. These capabilities are ideally suited for numerous millimeter-wave power applications such as wireless networks and PAs MMIC for Q-band frequency and beyond. Therefore, GaN will play an important role in advanced RF and millimeter-wave applications including for instance 5G and satellite communications or military oriented applications in harsh environment. However, there is no technology satisfying the whole mm-wave requirement including high DC, RF, large signal, linearity and reliability performances. The aim of this work is to increase the understanding of physical mechanisms involved in mm-wave high performance transistors and their related limitations. In this frame, a literature survey has been carried out followed by extensive device simulations.



For high-frequency beyond 30GHz, Graded AlGaN channel HEMT architectures, is an attractive solution to overcome the trade-off between high linearity and high power-added-efficiency. In-depth understanding requires device simulation as well as device development to reveal its potential. The simulation workflow developed within this project comprises three different levels: a device level simulation, transistor modeling and circuit-level simulation. Our approach uses commercially available software in three levels starting from TCAD (Silvaco), compact transistor modeling (Angelov GaN Model, ICCAP) and circuit level simulation (ADS).

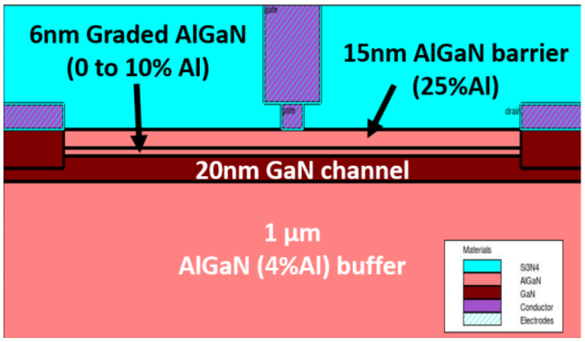
In all three levels, a considerably well quantitative fitting has been achieved between our simulation and the HRL's original data. Such analysis opens several opportunities to further study variations in the epitaxial layers, device geometry and so on, thereby predicting the balance between the power performances and linearity.

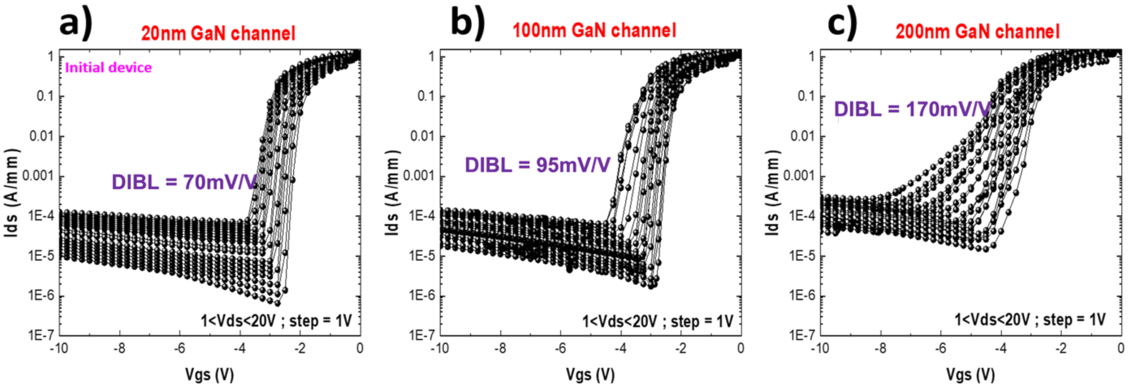

a) HRL PAPER

b) IEMN simulation

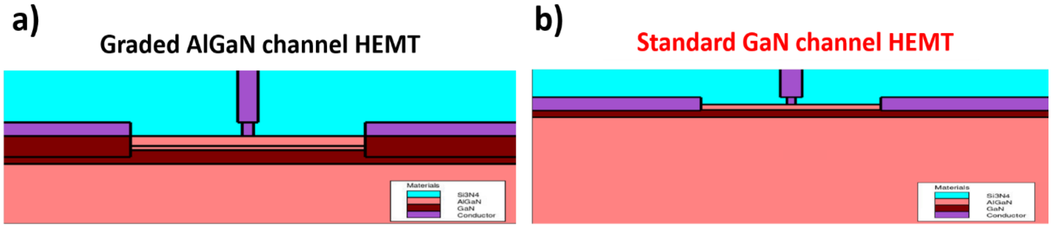
As an input to the TCAD simulation, the epitaxial structure and physical parameters mentioned in the HRL's publication has been considered. For instance, AlGaN graded composition, thickness, mobility, carrier concentration and so on. By using the GaAs like transport model and field dependent mobility models, the shape of HRL's experimental transconductance has been reproduced by simulation. Similarly, the RF small signal figure of merits such as Unilateral gain, Ft and Fmax are also found to be very close. The quantitative fitting of both simulated DC and RF characteristics to the HRL's original data reveals that our TCAD simulation is calibrated and can be extended to simulate power and linearity performances at 30GHz. Thus, large-signal and linearity performances of HRL's device architecture have been reproduced by hybrid simulation method that involves physical-empirical models and harmonic balance simulation. Once the HRL device has been satisfactory calibrated, some epitaxial variations have been investigated on the reference structure to better understand the impact of the graded channel. It can be pointed out that the comparison between the various configurations has been carried out up to the circuit level providing large signal and linearity performances.

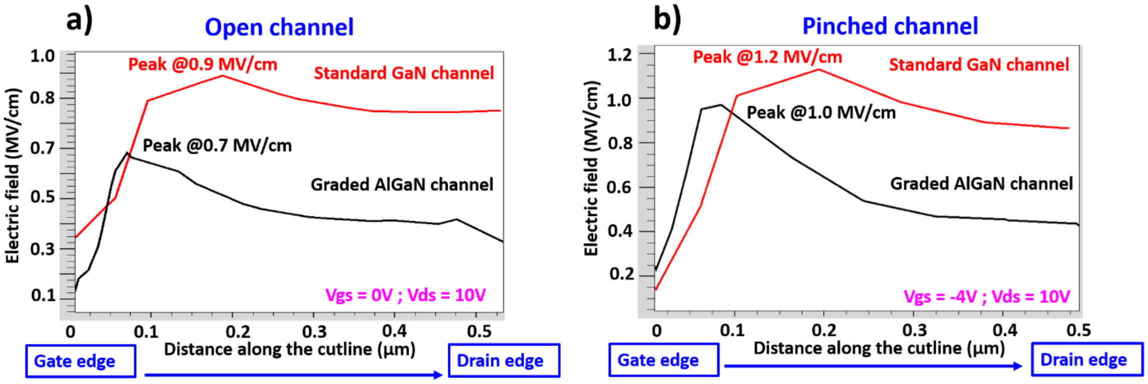
The TCAD simulated data is then quantitatively fitted to Angelov GaN Model, which consists of RLC lumped elements equivalent circuit. As Angelov model utilizes nearly 90 parameters, fitting becomes challenging and can be inaccurate particularly, for capacitances (Cgs, Cgd and Cds) extracted from S-parameters in the frequency range 100 MHz – 20 GHz. However, the most contributing inter-modulation parameters such as Gm1, Gm2 and Gm3, fit considerably well. The fitting is also verified along the load line from the knee region to the saturation region at high Vds and low current. This FET model is being used for simulation of non-linear characteristics, i.e., linearity figure of merits and load pull characteristics at 30GHz.

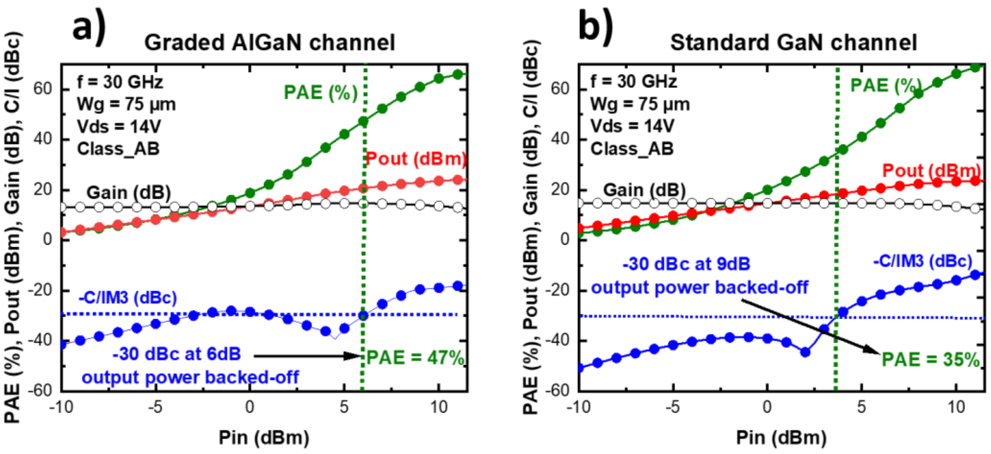




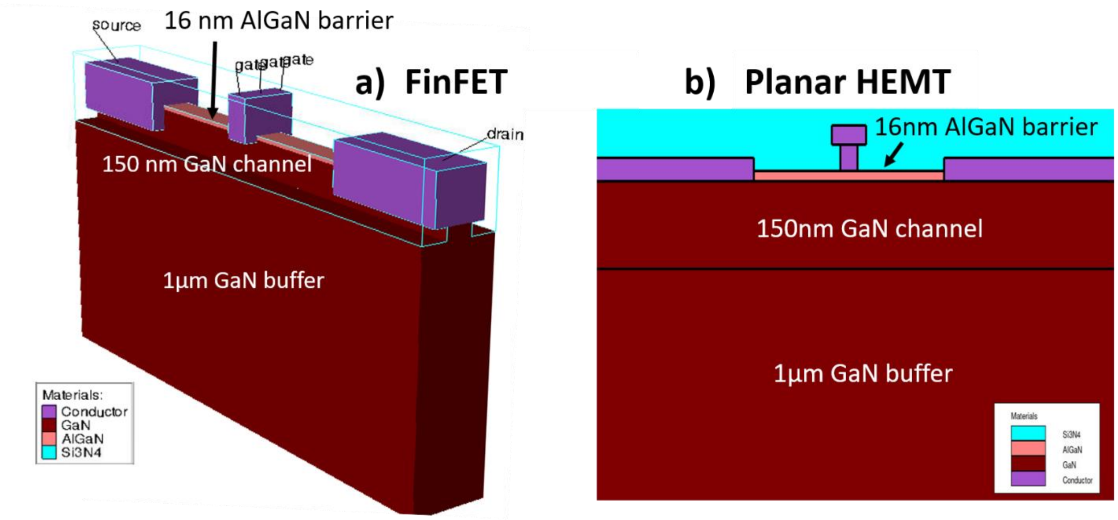
In a second step, TCAD variations on a reference HRL structure has been performed. We varied the gate length from 40nm to 90nm. As expected, the RF performances increase when the gate length decreases at the expense of the breakdown voltage. DC and small signal parameters were also studied by varying the gate-drain distance. A GaN channel thickness variation was also shown. We observed that from a thickness of 100nm, the electron confinement in the 2DEG is degraded (punch-trough effect). The choice of HRL for a sub-100nm thin channel is therefore a good compromise with respect to the electron confinement. Finally, the %Al in the graded channel has been tuned. With a fixed barrier thickness and composition, it has been shown that increasing the %Al in the graded channel is not a viable solution because it causes a decrease of the Ns and thus impacts the performances (Gm drop).



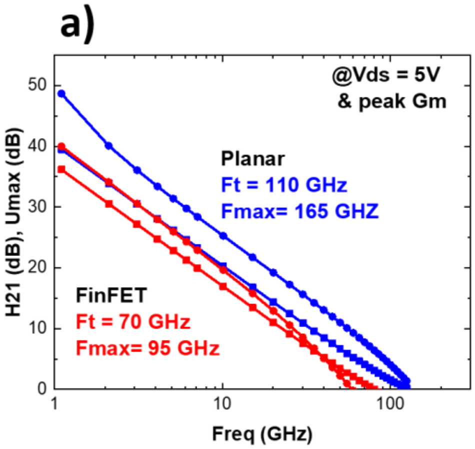




In a third step, the power performance and linearity of the graded AlGaN channel transistors were compared to a standard GaN channel. TCAD DC and small signal characteristics were assessed. The electric field under different conditions were extracted for the graded AlGaN channel and the standard GaN channel. We observed that the insertion of a graded channel decreases the electric field peak at the gate edge. In turn, the formation of a 3DEG enables to spread the electric field (similar to a field plate but without the parasitic capacitance increase drawback) and achieve flat gm and a good linearity. Then, we used the full workflow to simulate the performance of the standard GaN channel. Under the same simulation conditions that were used (TCAD, ICCAP fitting...), it was shown that the standard GaN channel can reach a higher PAE, but its linearity is degraded.



Finally, a preliminary TCAD study on FinFETs was carried out to understand the pros and cons of this technology in terms of high frequency performances. We compared a FinFET and a planar device using the same structure and 2DEG properties. The FinFET delivers a flatter gm. An improvement of the linearity (as seen from gm, gm2 and gm3) is then possible with this technology. Nevertheless, a severe penalty has been observed on the small signal performances. Indeed, this Fin architecture induces additional parasitic capacitances leading to a strong drop of RF performances. Thus, this technology is certainly useful to enhance the high frequency linearity performances but at the expense of the frequency of operation.

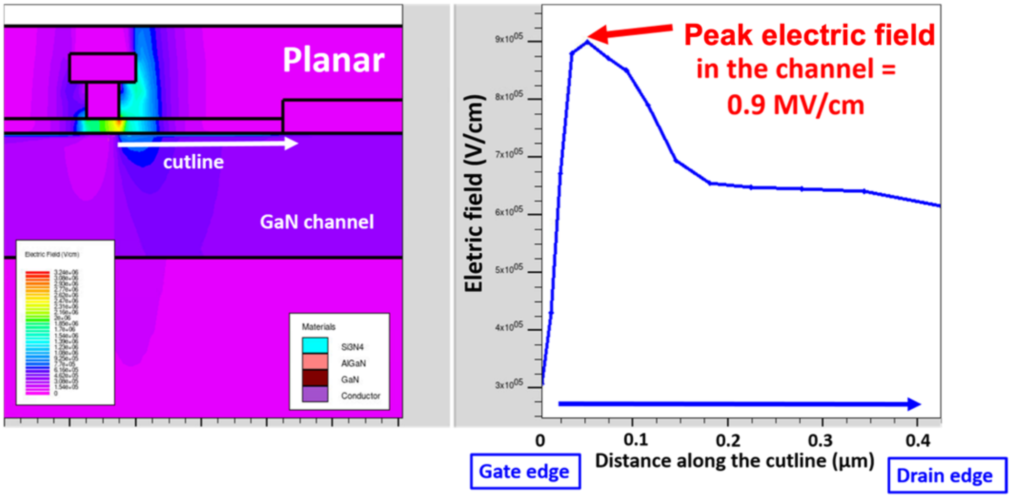


b)

Capacitances (fF/mm)	Planar	FinFET
Cgs	425	645
Cgd	150	205
Cds	255	375

Cgs, Cg & Cds are extracted @1GHz, Vds = 5V & peak Gm a)

Open channel Vgs = 0V, Vds 10V



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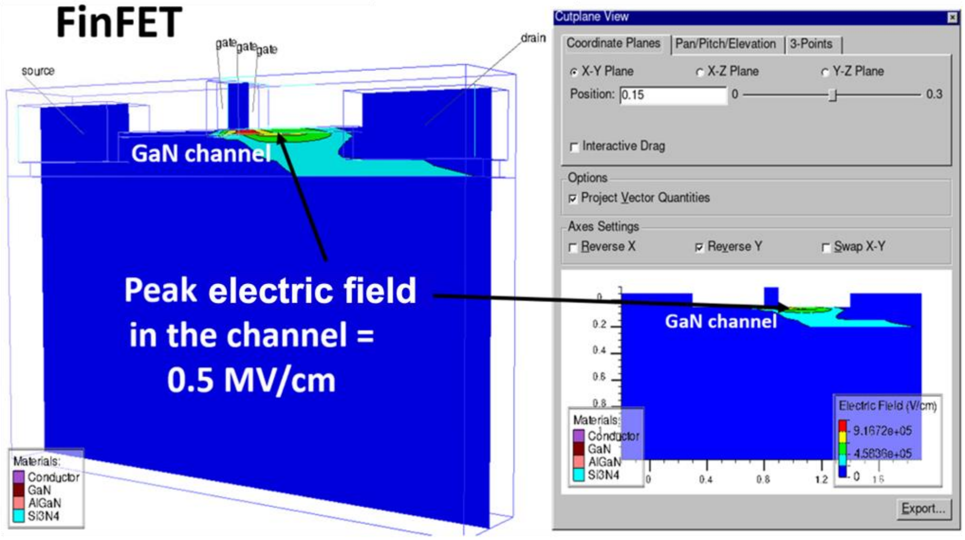

● X-Y Plane ○ X-Z Plane ○ Y-Z Plane

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☐ Interactive Drag

Options

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Axes Settings

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As final recommendations, it is advised to support short to mid-term solutions such as more traditional HEMTs including aggressive transistor dimensions such as shorter gate lengths, ultrathin barriers combined with specific channel and buffer engineering that seem to be the most promising technology to satisfy the whole requirement (linearity, power efficiency, reliability) within the next years. As shown in this work, a positive point is that TCAD can now efficiently support the understanding of such a complex development involving multidisciplinary research.

Several groups in Europe including both academics and industrials have made progress in mm-wave GaN devices. In order to reach the stretch performance for future space applications, it is therefore recommended to ESA 1) to identify the research groups and key industrial players that have already experience in this field; 2) to support the technology development of most promising approaches based on more traditional HEMTs (avoiding long-term purely academic technology) in order to maximize the chance of a reliable technology emergence in short / mid-term (3 to 5 years); 3) to systematically implement TCAD simulations for better device physics understanding and guidance in technological choices.