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Small-signal microwave measurements and modeling of GaN FET devices manufactured by ITME

Abstract. *We present results of small-signal measurements and modeling of GaN FET devices manufactured by Institute of Electronics Materials Technology (ITME). The devices have 500 nm gate length and 100 µm gate width and are grown on 350 µm sapphire substrate. We measured scattering parameters of the devices on-wafer in the frequency range 0.01-15 GHz, and then extracted parameters of their small-signal equivalent circuits. These results show that the devices have repeatable parameters and are capable of delivering at least 14.4 dB of unilateral gain in S-band with f_{max} of at least 23 GHz.*

Streszczenie. *W artykule przedstawiono wyniki małosygnałowych pomiarów w.cz. oraz modelowania tranzystorów GaN FET wyprodukowanych w Instytucie Technologii Materiałów Elektronowych (ITME). Badane tranzystory miały bramkę o długości 500 nm i szerokości 100 µm gate i zostały wyprodukowane na podłożu szafirowym o grubości 350 µm. Parametry rozproszenia tranzystorów zostały zmierzone na stacji ostrzowej w pasmie 0,01-15 GHz, a następnie na ich podstawie zostały wyznaczone parametry małosygnałowego schematu zastępczego. Otrzymane wyniki pokazują, że badane tranzystory mają powtarzalne parametry, uzyskując co najmniej 14,4 dB wzmocnienia unilateralnego w pasmie S oraz maksymalną częstotliwość generacji co najmniej 23 GHz. (**Małosygnałowe pomiary w.cz. i modelowanie tranzystorów GaN FET wyprodukowanych w ITME**).*

Keywords: gallium nitiride FET, small-signal measurements, equivalent-circuit modeling.
Słowa kluczowe: tranzystor FET z azotku galu, pomiary małosygnałowe w.cz., identyfikacja parametrów schematu zastępczego.

Introduction

There in an on-going effort in Polish industry to deliver high-power microwave GaN FET devices. This effort is a part of a world-wide trend to switch to GaN technology in power devices due to their potentially better performance (e.g., higher breakdown voltage, higher per-width power density) as compared to currently used GaAs MESFET or Si LDMOS devices [1].

In this work, we present results of small-signal microwave characterization and modeling of a first batch of GaN FET devices manufactured in the Institute of Electronics and Materials Technology, Warsaw. We start off by briefly reviewing the device technology, and proceed with the description of the measurement results. Following that, we discuss the modeling results, and finally, draw some conclusions.

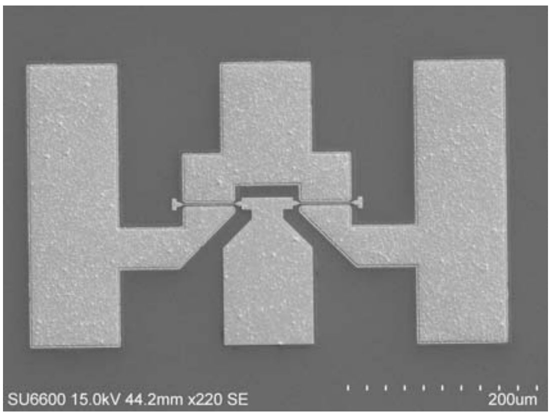


Fig. 1. SEM picture of GaN HEMT device manufactured by ITME

Device fabrication and technology

A picture of a single GaN FET device investigated in this work is shown in Fig. 1. Epitaxial structure was grown on a 350 µm thick sapphire substrate. The stack of epi-layers consisted of AlN buffer, GaN buffer, AlGaN Schottky layer and GaN contact layer. No intentional doping was introduced during epitaxial growth. Transistor geometry was designed to enable on wafer measurement with 200 µm pitch coplanar probes. Drain source distance was 4 µm. Gate length was 500 nm and gate width was 100 µm. Ohmic metal was a stack of Ti/Al/Ni/Au layers and gate metal was Ni/Au system. Device isolation was obtained using ICP RIE in pure chlorine plasma.

Measurements

We performed on-wafer scattering parameter measurements with R&S ZVA50 vector-network-analyzer (VNA). The bias voltages were delivered through a pair of external Picosecond Labs bias-T's. Measurements were done in the frequency range 0.01-15 GHz with the input power of -10 dBm. VNA was calibrated with a set of LRM calibration standards on an alumina substrate. We used the Cascade Summit 9000 on-wafer station.

DC I-V measurements were performed as the first step of the transistors characterization. The drain voltage U_{DS} was swept from 0 to 20 V, while the gate voltage was swept from -1 to -0.5 V with 0.125 V step. The results for one of the devices are shown in Fig. 2. The characteristics are consistent with the ones reported in the literature [4, 6]. In particular, we observe the characteristic "knee" shape at lower U_{DS} voltages and saturation of I_{DS} currents at higher U_{DS} voltages. The DC measurements allowed also to identify the damaged structures.

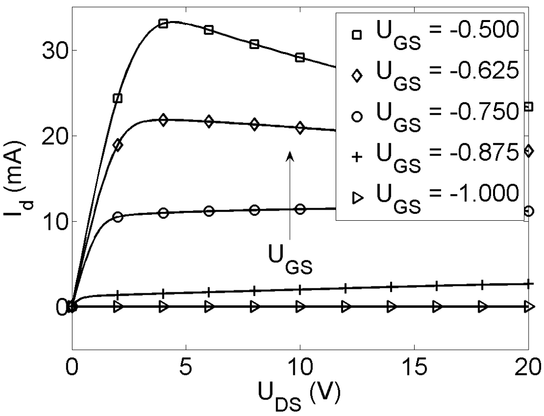
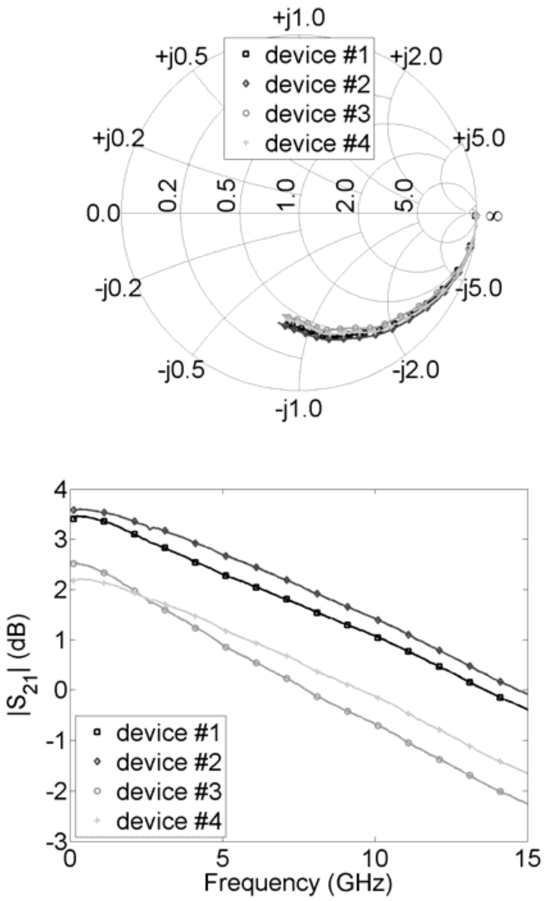


Fig. 2. Drain current as the function of the drain voltage U_{DS} for different gate voltages swept from -1 to -0.5 V with 0.125 V step

After the DC measurements each device was excited by small-signal stimuli in two operating points: a) “hot” with U_{DS}=5 V, I_{DS}=20 mA, b) “cold pinch-off” with U_{DS}=0 V, U_{GS}= -5 V. The additional “cold pinch-off” small-signal measurements were needed to more reliably extract the contact-pad equivalent circuits [2-5].

Table 1. Minimum unilateral gain G_U in S-band and f_{max} of measured devices

Parameter	Device			
	#1	#2	#3	#4
min. G_U [dB]	17.5	18.5	14.4	16.2
f_{max} [GHz]	30.8	29.7	23.7	24.1



(a)

(b)

Fig. 3. Measurement results of S11 (a) and S21 (b) for all the devices for bias point: Uds = 5V, Ids = 20 mA

The measurement results of the S-parameters for all four devices are shown in Fig. 3. First, it can be seen that the characteristics of all of the devices are consistent with the ones for GaN HEMTs reported in the literature [2-5]. All of the structures are amplifying the signals, as can be observed in Fig. 3(b). One has to remember that the devices were measured in a 50 Ohm environment, which means very high mismatch for the capacitive structures such as transistors [see Fig. 3(a)]. Therefore, in order to investigate the device parameters when both input and output are matched, unilateral gain was calculated:

$$G_U = \frac{|S_{21}|^2}{\left(1-|S_{11}|^2\right)\cdot\left(1-|S_{22}|^2\right)}$$

The corresponding results are shown in Fig. 4. Comparing to Fig. 3(b), the rise of gain can be immediately noticed. When matched, all of the transistors are capable of amplifying signals at the frequencies well above 20 GHz.

In order to estimate the maximum oscillation frequencies f_{max} of the transistors, the plots in Fig. 4 were extrapolated using linear regression with least square fitting. The results are collected in Tab. 1. It can be seen that even though the measured devices are the very first prototypes fabricated at ITME, they already show good parameters in the band of interest (S-band: 2-4 GHz).

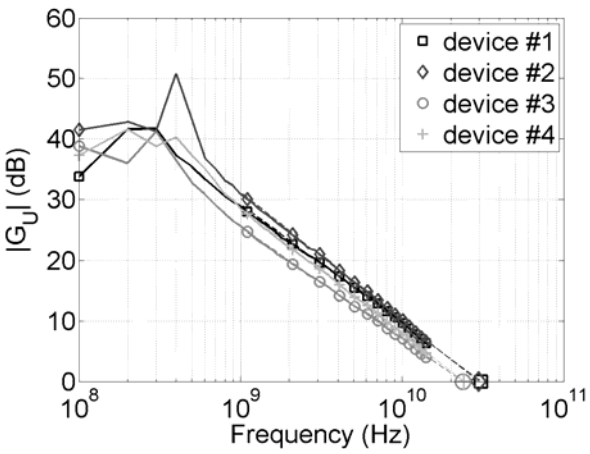


Fig. 4. Unilateral gain of the devices as the function of the frequency for the bias point: Uds = 5 V, Ids = 20 mA. Dashed line denotes linear extrapolation used to determine maximum oscillation frequency f_{max}

Last but not least, it should be noticed that the device parameters are consistent within pairs #1,#2 and #3,#4. The number of investigated samples was not large enough to assess the repeatability of the ITME process. However, the initial consistency is promising.

Modeling results

The modeling process is crucial for every fabrication technology. On the one hand, it allows to better understand the ongoing phenomena. On the other hand, the models are necessary for the designers, which will use the transistors. Since the prototype devices will not be used in any designs, a very simple equivalent circuit presented in Fig. 5 was considered.

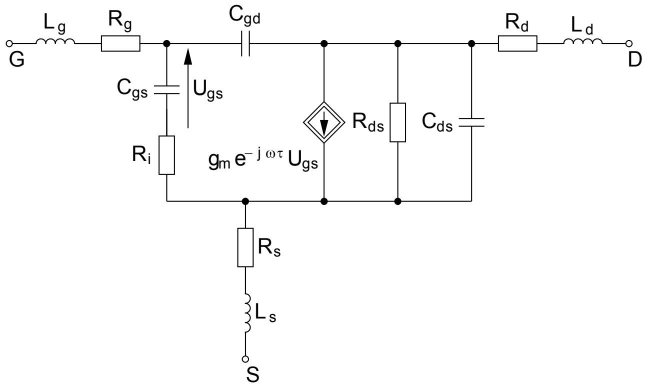


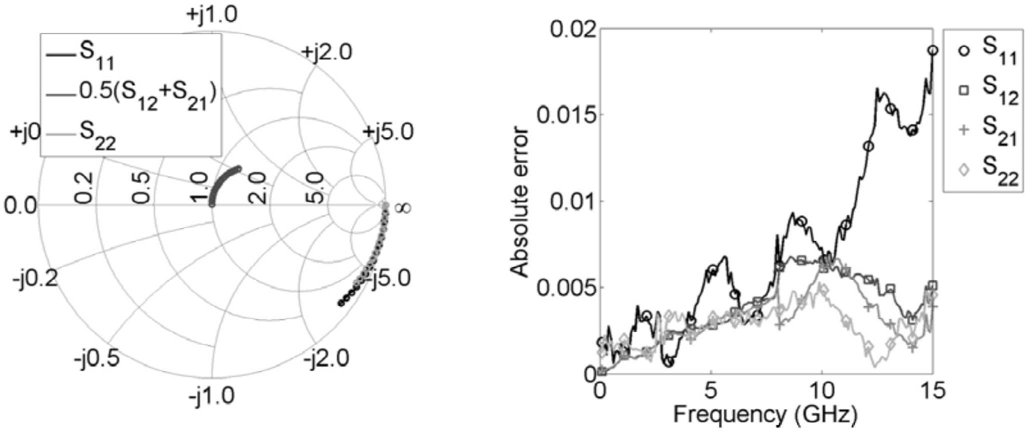
Fig. 5. GaN FET small-signal equivalent circuit

The model extraction procedure consists of two steps. In the first one, the parasitic components (L_g, L_d, L_s, R_g, R_d, R_s) have been determined from the transistor measurements at the “cold pinch-off” [2-5]. In this state, both the gate junction and the channel can be perceived as open circuits. Therefore, the equivalent circuit simplifies, and the elements R_{ds}, g_m and R_i can be neglected leaving purely capacitive core. In this step, the intrinsic capacitances have been also calculated in order to fit the measurement data. However, contrary to the series R and L components, their values depend on the voltages and cannot be directly used for modeling at different bias points.

The fitting results of "cold pinch-off" measurements for device no. 1 are shown in Fig. 6. Similar results were obtained for the other devices. Very good fit has been obtained. The modeling error has not exceeded 0.04 for all the devices for all the scattering parameters. Additionally, it can be reduced even further by considering more complex networks of the parasitic components [3]. Such investigations are planned to be conducted for the next generations of ITME devices.

In the second step, after extracting the series parasitic components, the remaining values of the equivalent circuit shown in Fig. 5 were determined at "hot" bias condition (U_{ds}=5 V, I_{ds}=20 mA). The models have been extracted using a combination of random and gradient optimizers in Agilent's ADS v. 2013.06. The initial values for the nonlinear capacitances were taken from the previous step. S_{12} was excluded from the optimization goals, as transistors are barely used in reverse direction. The modeling results are shown in Fig. 7. It can be seen that a very good fit has been achieved despite the use of a very simple equivalent circuit. Similar error levels were observed for the other devices, and the maximum error is below 0.08 for all the transistors and all the quantities. The model parameters for all the devices were collected in Tab. 2. It can be seen that, again, the parameters are pair-wise consistent, especially the transconductance g_m. The obtained values agree with the ones reported in the literature to within an order of magnitude [4, 6]. Their optimization will be of interest in the future realizations of the ITME devices.

It has to be noticed that the extracted model is not sufficient for the design purposes, as it mimics the transistor at only a single bias point. More comprehensive description requires multi-bias measurements, and in the most general case - large signal measurements [5]. Such measurements followed by the extraction of the nonlinear analytical models will be the next step of our research.

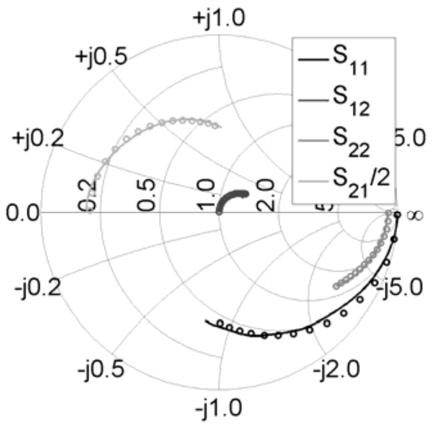


(a) (b)

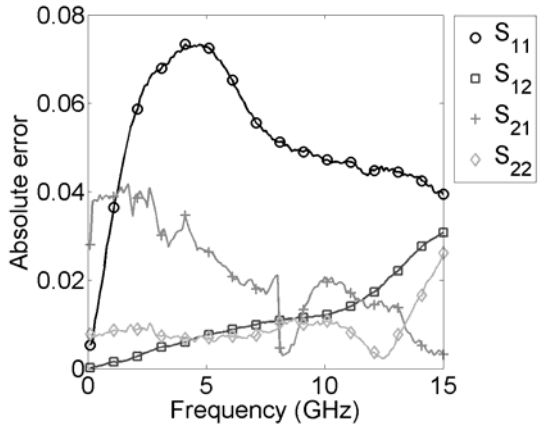
Fig. 6. Modeling results of the device no. 1 at the "cold pinch-off" condition U_{DS}=0 V, U_{GS}=-5 V. (a) – model fitting results – markers denotes modeled values and solid lines measurement results; (b) – absolute error between the model and the measurement results as a function of frequency

Table 2. Equivalent circuit values for the extracted models of the measured devices

Device	R_g [Ω]	R_d [Ω]	R_s [Ω]	L_g [pH]	L_d [pH]	L_s [pH]	
#1	5.7	5.7	2.0	46.3	270.1	1.5	
#2	4.8	4.6	0.6	67.0	130.0	4.9	
#3	5.7	3.9	1.2	40.0	290.0	4.0	
#4	4.9	4.3	0.8	86.0	90.8	1.8	
Device	C_{gs} [fF]	C_{ds} [fF]	C_{gd} [fF]	R_i [Ω]	R_{ds} [kΩ]	g_m [mS]	τ [fs]
#1	171.7	20.0	31.8	23.4	1.7	15.4	222
#2	171.0	17.7	34.8	13.5	2.0	16.0	306
#3	198.0	12.4	34.8	28.5	1.7	13.4	342
#4	167.0	10.2	40.8	23.9	1.7	13.2	360



(a)



(b)

Fig. 7. Modeling results of the device no. 1 at the „hot" condition U_{ds}=5 V, I_{ds}=20 mA. (a) – model fitting results – markers denotes modeled values and solid lines measurement results; (b) – absolute error between the model and the measurement results as a function of frequency

Conclusions

In this paper, small-signal measurement results of a first batch of GaN HEMTs manufactured by ITME have been presented. The measurement results clearly prove that the fabricated transistors are functional, and they can amplify signals even up to 30 GHz. At the same time the unilateral gain was not lower than 14 dB in the frequency band of interest (S-band). The results are consistent with the ones reported in the literature. Based on the measurement data equivalent-circuit models have been extracted. Very small fitting error is achieved, even though a simplistic model has been proposed. Again, good consistency with the literature results is reported.

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