# Estimation of the accuracy of a simplified equivalent circuit for Ku-band GaN HEMTs

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**Research Article**

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# Estimation of the accuracy of a simplified equivalent circuit for Ku-band GaN HEMTs

**Gennadiy Z. Garber**

***Abstract*—We investigate the accuracy of the intrinsic FET's equivalent circuit with only one nonlinear element – the channel current generator given by the Curtice-Ettenberg model. The parameters of this simplified equivalent circuit are assigned using the 2D quasi-hydrodynamic simulation taking into account the electron velocity overshoot. We calculated the power-added efficiency, transducer power gain, and other amplifier parameters as functions of the maximum available power of an 18-GHz input generator by three methods: using the full 2D model for the intrinsic FET and the large-signal equivalent circuit – complete and simplified. Comparison of the functions obtained indicates the suitability of the simplified equivalent circuit for analysis of GaN HEMT power amplifiers of the Ku band. Since this equivalent circuit is implemented in various commercial software packages for analysis and design of RF and microwave devices, our 2D simulation results can be used in these packages.**

***Index Terms*—Channel current generator; Curtice-Ettenberg model; Full 2D model; Input capacitance; Large-signal equivalent circuit; Transfer capacitance.**

## 1. Introduction

Ku-band power amplifiers are used for many satellite communication systems, military radar systems, etc. Typically, these amplifiers are created using commercial software packages for analysis and design of RF and microwave devices. One of such user-friendly packages is Microwave Office, which we use to

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study the simplified equivalent circuit and, in particular, the Curtice-Ettenberg model [1] implemented in the package.

The simulated transistor includes

- 12 nm thickness $Al_{0.3}Ga_{0.7}N$ layer non-doped (Fig. 1);
- 100 nm thickness GaN layer non-doped;
- delta "doping" with a density of $1.3 \cdot 10^{13}$ cm$^{-2}$ above the transistor channel; and
- 100 nm thickness $Si_3N_4$ passivation layer having a negative surface charge with a density of $4 \cdot 10^{12}$ cm$^{-2}$ [2].

The gate width along the $z$-axis, directed perpendicularly to the plane of Fig. 1, is equal to 0.1 mm.

We use the amplifier depicted in Fig. 4 of our article [3]. The IFET unit corresponds to the entire active region ($0 \le x \le x_m$ and $0 \le y \le y_{mm}$). The parasitic elements, as well as inductances and capacitances of the matching networks ($L_1$ = 0.635 nH, $L_g$ = 0.421 nH, $C_1$ = 0.0489 pF, $L_2$ = 1.37 nH, $L_d$ = 1.59 nH, and $C_2$ = 0.0468 pF) are taken from [3]. The gate and drain biases are $U_{GS}$ = -1.5 V and $U_{DS}$ = 35 V, respectively.

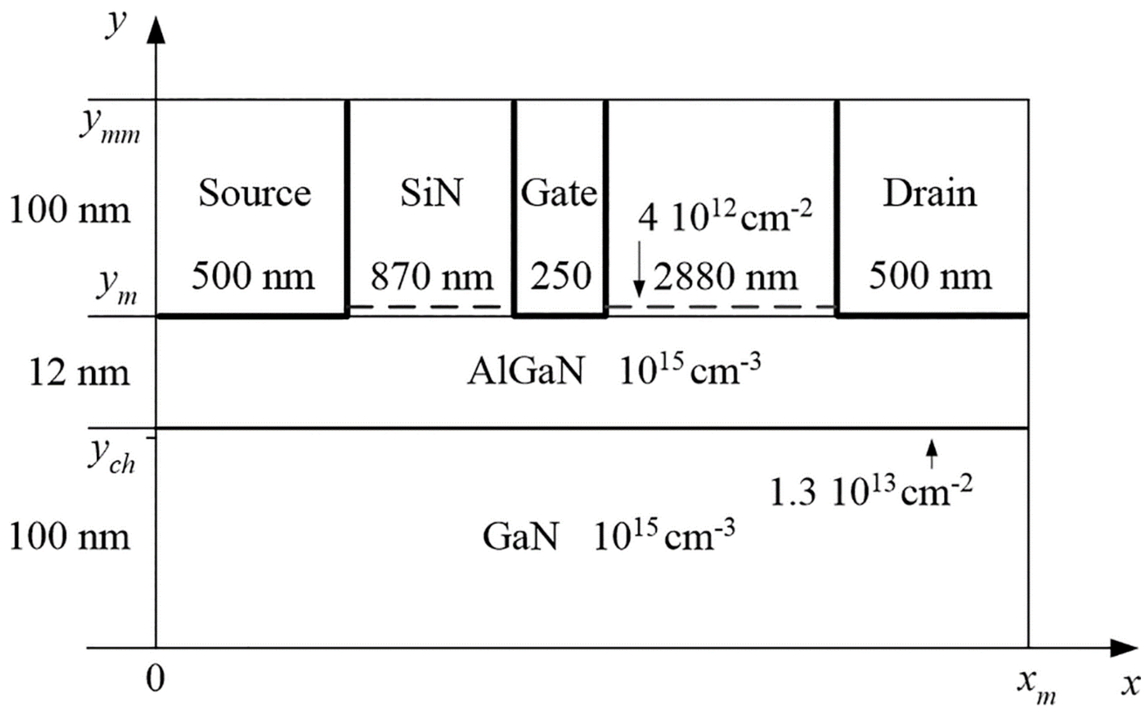


Fig. 1. Active region of the Schottky gate AlGaN/GaN HEMT – a part of the transistor longitudinal section: $y \le y_{ch} = 99$ nm is the channel.

## 2. 2D simulations of the active region

Here, the input data for our 2D simulations differ from the corresponding data in [3] only by the field dependence of the electron drift velocity (Fig. 2). We built it on the basis of the theoretical dependences in Fig. 1 from [2] (for a weak electric field) and experimental dependence "HJ with Gate" in Fig. 3 from [4].

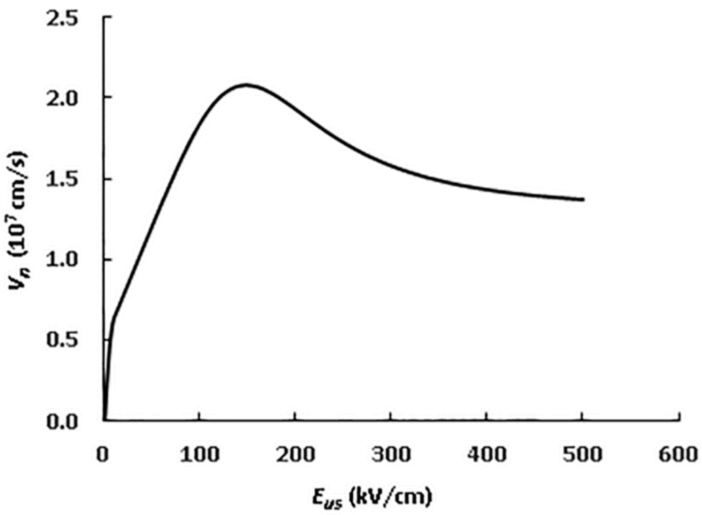



Fig. 2. Field dependence of the electron drift velocity in the transistor channel.

We corrected our 2D models as follows:

- Since the active region has the passivation part (Fig. 1), the electric field intensity, $\vec{E}(x, y, t)$, is calculated using the following equation instead of (7) in [5]:

$$\nabla(\varepsilon \vec{E}) = Q,$$

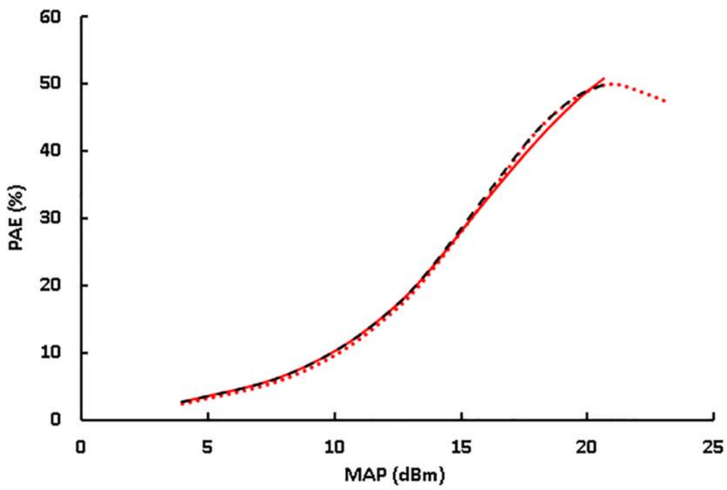
  where $\varepsilon(y)$ is the absolute permittivity of the semiconductor or dielectric. Charge density $Q$ is the fixed function of $y$ in the dielectric and is given by $q(N_d - n + p)$ in the semiconductor.

- Since the AlGaN layer is not doped, we also changed the boundary condition for electrons at the source and drain (at $y = y_m$): $n = \infty$. In practice, we assume $n$ equal to twice the maximum value of $N_d$, i.e., $n = 2.6 \cdot 10^{20}$ cm$^{-3}$ at the source and drain.

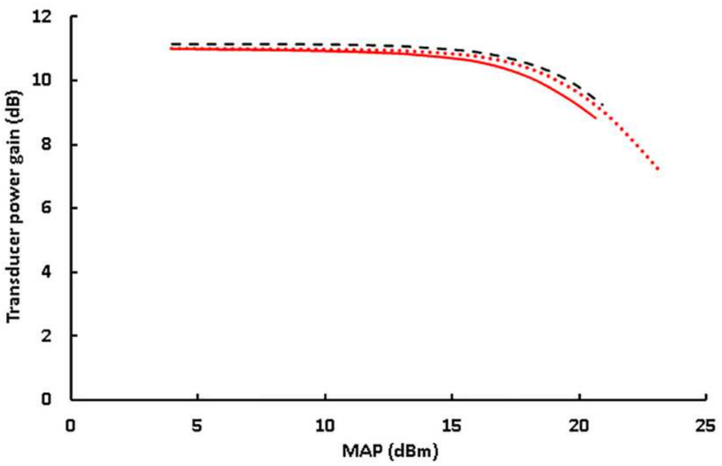
The dotted curves in Fig. 3 show the amplifier's RF and DC parameters as functions of MAP (maximum available power of the input RF generator). We calculated these curves as in [3], using the full 2D model for the IFET.

The dashed curves in Fig. 3 are also calculated as in [3], but using the complete large-signal equivalent circuit, the configuration of which is shown in Fig. 1 of [3]. When calculating the characteristics and parameters of this equivalent circuit, here we use the entire active region (in [3] we used a part of it). The dashed lines in Fig. 4 show the current–voltage characteristics of the channel current generator.

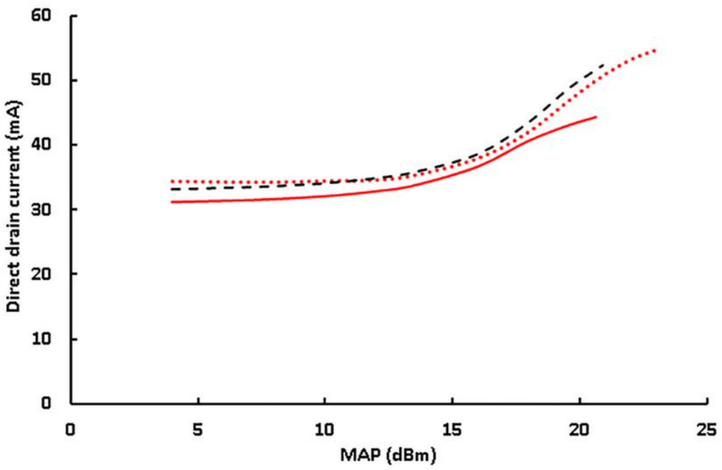
(a)




(b)



(c)




(d)

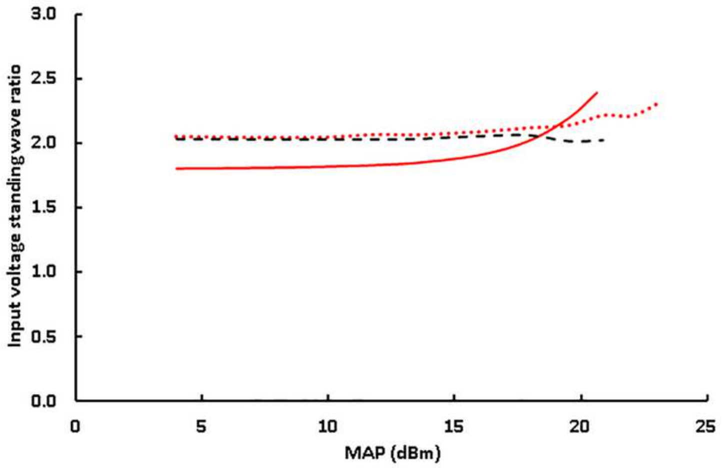



Fig. 3. (a) Power-added efficiency, (b) transducer power gain, (c) direct drain current, and (d) input voltage standing wave ratio as functions of MAP, which are calculated using the full 2D model for the IFET (dotted curves), the complete equivalent circuit (dashed), and the simplified equivalent circuit (continuous).

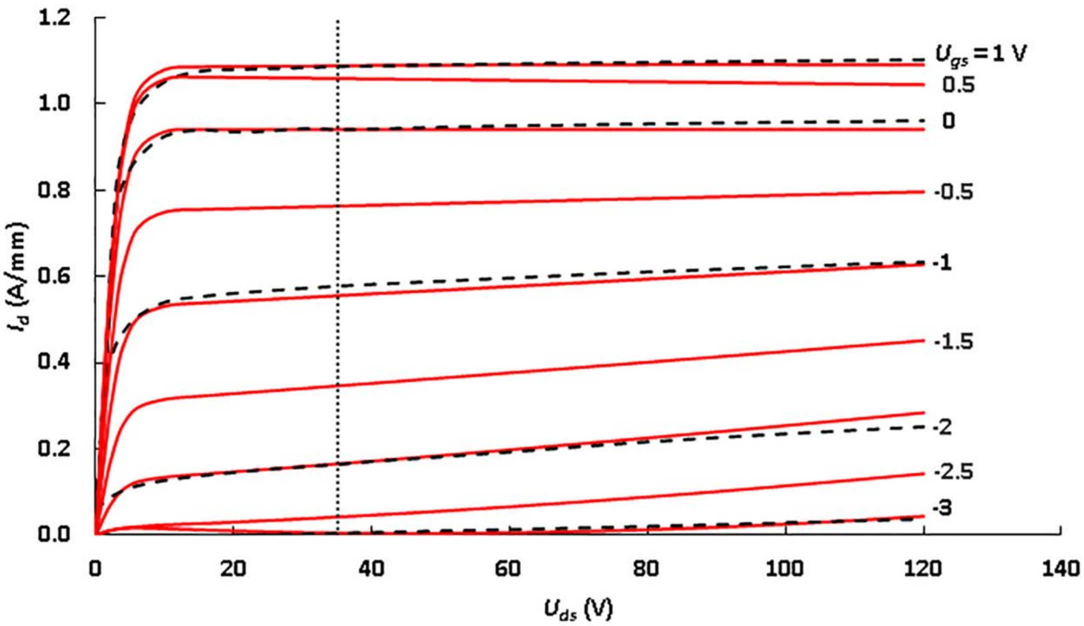



Fig. 4. Current–voltage characteristics of the complete equivalent circuit (dashed lines), and of the Curtice-Ettenberg model (continuous).

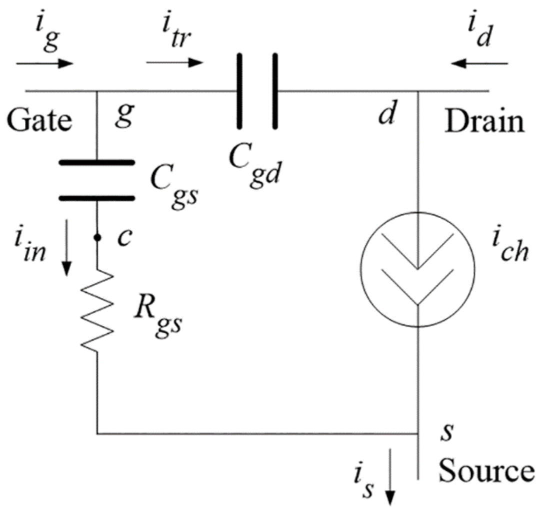



Fig. 5. The simplified large-signal equivalent circuit of the intrinsic FET: $i_{ch}$, channel current generator given by current–voltage relationship of the Curtice-Ettenberg model; $C_{gs} = \text{const}$ and $R_{gs} = 0$, input capacitance and resistance; and $C_{gd}$=const , transfer (feedback) capacitance.

3. Setting parameters of the simplified large-signal equivalent circuit and estimation of its accuracy

Let us construct the simplified equivalent circuit, the configuration of which is shown in Fig. 5. Capacitances used: $C_{gs} = 0.0999\,\text{pF}$ and $C_{gd}$ =0.0045 pF. These values, corresponding to the biases $U_{GS}$ = -1.5 V and $U_{DS}$ = 35 V, are taken from the complete equivalent circuit depicted in Fig. 1 of [3].

The authors of [1] assume that for a fixed drain-to-source voltage, $U_{ds}^0$, the drain current is a cubic function of the gate-to-source voltage. More precisely, the current–voltage relationship is described by the following formulas:

$$I_d = (A_0 + A_1V_1 + A_2V_1^2 + A_3V_1^3) \cdot \tanh(\gamma \cdot U_{ds}),$$

$$V_1 = U_{gs} \cdot [1 + \beta \cdot (U_{ds}^0 - U_{ds})].$$

We set $U_{ds}^0$= 35 V since, as mentioned above, the drain bias is $U_{DS}$ = 35 V. To determine the coefficients $A_0$, $A_1$, $A_2$, and $A_3$, we use the following four linear equations:

$$A_0 + A_1U_{gsi} + A_2U_{gsi}^2 + A_3U_{gsi}^3 = I_{di},$$

where $i$ = 1, 2, 3, 4; $U_{gs1}$ = 1 V; $U_{gs2}$ = 0; $U_{gs3}$ = -2 V; $U_{gs4}$ = -3 V; and $I_{di}$ is the coordinate of the intersection of the dotted vertical line $U_{ds} = U_{ds}^0$ with the corresponding dashed current–voltage characteristic in Fig. 4. These four equations are solved jointly by the Gaussian elimination method [6].

The $\gamma$ parameter is determined from the slope of the first dashed characteristic at $U_{ds} = 0$: $\gamma = 0.3\,\text{V}^{-1}$. The current–voltage relationship of the Curtice-Ettenberg model at $\beta = 2 \cdot 10^{-3}\,\text{V}^{-1}$, shown by continuous lines in Fig. 4, is calculated in Microsoft Office Excel, equipped with macros [6]. Due to this, the image (in Excel) of the current–voltage relationship of the Curtice-Ettenberg model changes instantly when, if necessary, we change the value of $\beta$ and/or the set of $U_{gs1}$, $U_{gs2}$, $U_{gs3}$, and $U_{gs4}$. We used this (and intend to use in the future) to visually approximate the dashed characteristics (etalonic) with the continuous ones. (Excel does not appear in the method for obtaining the parameters of the Curtice-Ettenberg model, used in [7].)

Continuous curves in Fig. 3 are calculated in Microwave Office, using the constructed simplified equivalent circuit. Comparison with the dotted curves indicates a fairly high accuracy of this equivalent

circuit in the Ku band. Of course, it is less accurate than the complete equivalent circuit shown in Fig. 1 of [3]. We see this from the comparison of the dashed curves in Fig. 3 with the dotted ones.

As follows from the above, the assumption of constant capacitances is quite acceptable for the Ku band. With an increase in the operating frequency, it is likely that this assumption will have to be abandoned. In this case, to get the dependences $C_{gs}$ and $C_{gd}$ on $U_{gs}$ and $U_{ds}$, we should use the charge–voltage characteristics $Q_g(U_{gs}, U_{ds})$ similar to those in Fig. 10 of [3].

## 4. Conclusion

The complete large-signal equivalent circuit [3] is used in the non-commercial program HIFETA (Harmonics In FET Amplifier). Its use in commercial packages for analysis and design of RF and microwave devices is currently not possible. Therefore, we took the path of its approximation by the simplified equivalent circuit on the base of the Curtice-Ettenberg model [1] used in these packages.

The article describes the approximation method. The important thing is that our method is implemented in Microsoft Office Excel, by developing appropriate macros [6]. Due to this, when we change the parameters of the approximating equivalent circuit, its current–voltage relationship instantly changes on the screen. Comparing the new current–voltage relationship with the unchanged etalonic current–voltage characteristics of the complete equivalent circuit, we can judge how good the parameters of the Curtice-Ettenberg model are, and, if necessary, change them.

Fig. 3 shows that the approximating simplified equivalent circuit is suitable for the Ku band, in particular, the assumption of the constancy of the input and transfer capacitances is acceptable. However, as the operating frequency increases, this assumption will most likely have to be abandoned. To get the dependences $C_{gs}$ and $C_{gd}$ on $U_{gs}$ and $U_{ds}$, we should use the charge–voltage characteristics similar to those in Fig. 10 of [3].

## References


[1] W. R. Curtice, M. Ettenberg, "A nonlinear GaAs FET model for use in the design of output circuits for power amplifiers", *IEEE Transactions on Microwave Theory and Techniques*, vol. 33, pp. 1383–1394, 1985.

[2] S. Vitanov, V. Palankovski, S. Maroldt, R. Quay, S. Murad, T. Rödle, and S. Selberherr, “Physics-based modeling of GaN HEMTs”, *IEEE Transactions on Electron Devices*, vol. 59, pp. 685–693 (2012).

[3] G. Z. Garber, “A novel model of avalanche current generation in the GaN HEMT equivalent circuit”, *Journal of Computational Electronics*, vol. 19, pp. 677–687, 2020.

[4] J. M. Barker, D. K. Ferry, S. M. Goodnick, D. D. Koleske, A. E. Wickenden, and R. L. Henry, “Measurements of the velocity-field characteristic in AlGaN/GaN heterostructures”, *Microelectronic Engineering*, vol. 63, pp. 193–197 (2002).

[5] G. Z. Garber, “Method for simulating efficient RF operation of HEMTs”, *Journal of Computational Electronics*, vol. 17, pp. 419–426, 2018.

[6] G. Z. Garber, *Foundations of Excel VBA Programming and Numerical Methods*. Moscow: PRINTKOM; 2013. https://www.researchgate.net/publication/274891843_Foundations_of_Excel_VBA_Programming_and_Numerical_Methods

[7] A. M. Zubkov, G. Z. Garber, V. D. Krasil’nikov, “Computer-aided design of microwave devices and integrated circuits (in Russian)”, *Electron. Eng. Ser. 2*, 2009, no. 2, pp. 18–32.

**Gennadiy Z. Garber** was born in Moscow, USSR, in 1948. He received the engineer-mathematician degree in applied mathematics from the Moscow Institute of Electronic Machinery in 1972, the PhD in solid-state electronics and integrated circuit design from the Moscow Institute of Radio Engineering, Electronics, and Automatics in 1981, the ScD in solid-state electronics and microelectronics from the Highest Certifying Commission of the USSR in January 1992, and the Professor in computer science from the Highest Certifying Commission of the Russian Federation in 2008.

He develops mathematical models, numerical methods, and computer programs for CAD of IMPATT and limiter diodes and circuits based on them, starting from 1975, and of field effect and bipolar transistors and transistor circuits from 1980. He is the author of 8 books and more than 70 articles.

## Figures

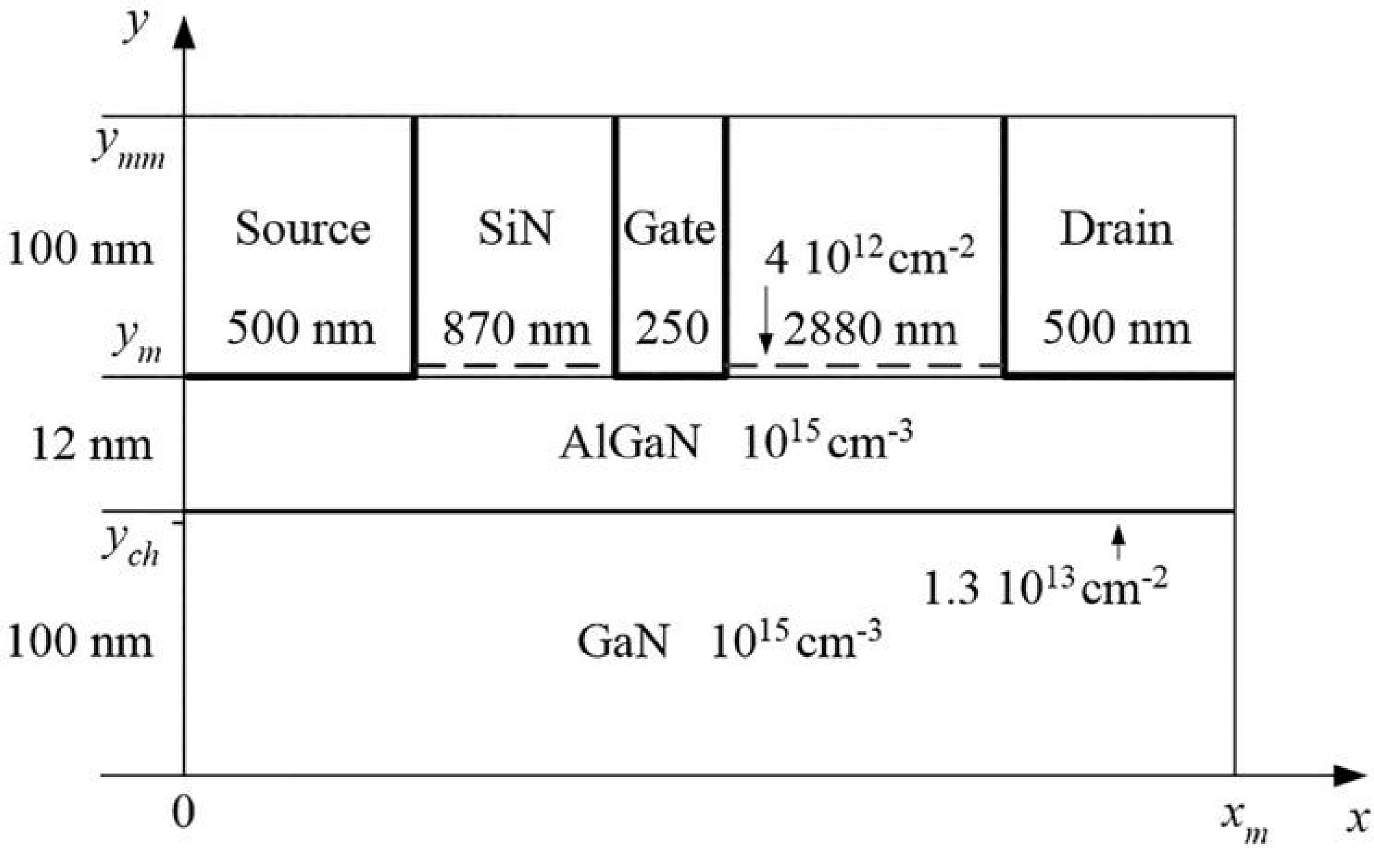



**Figure 1**

Active region of the Schottky gate AlGaN/GaN HEMT – a part of the transistor longitudinal section: nm is the channel.

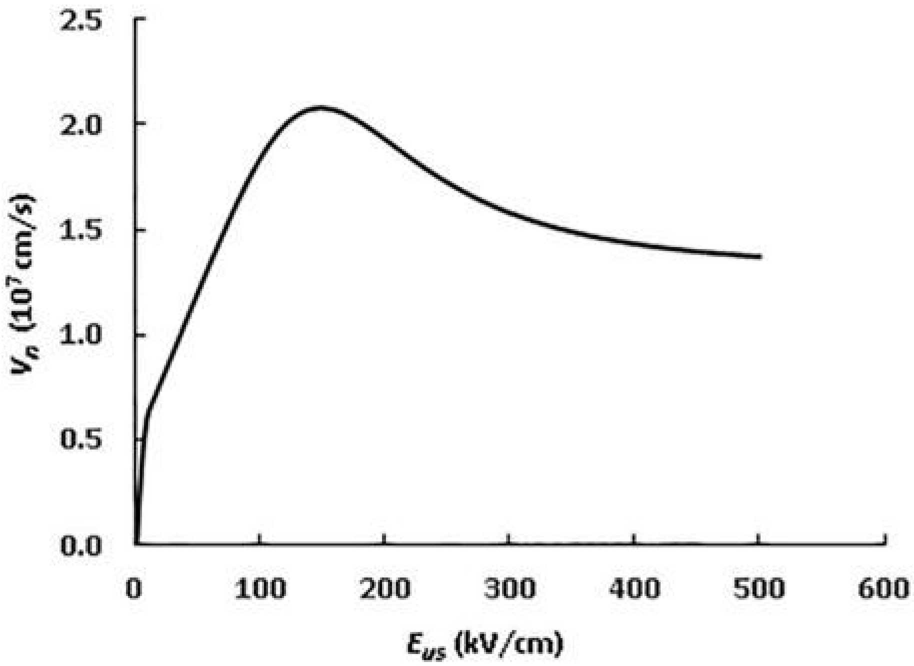
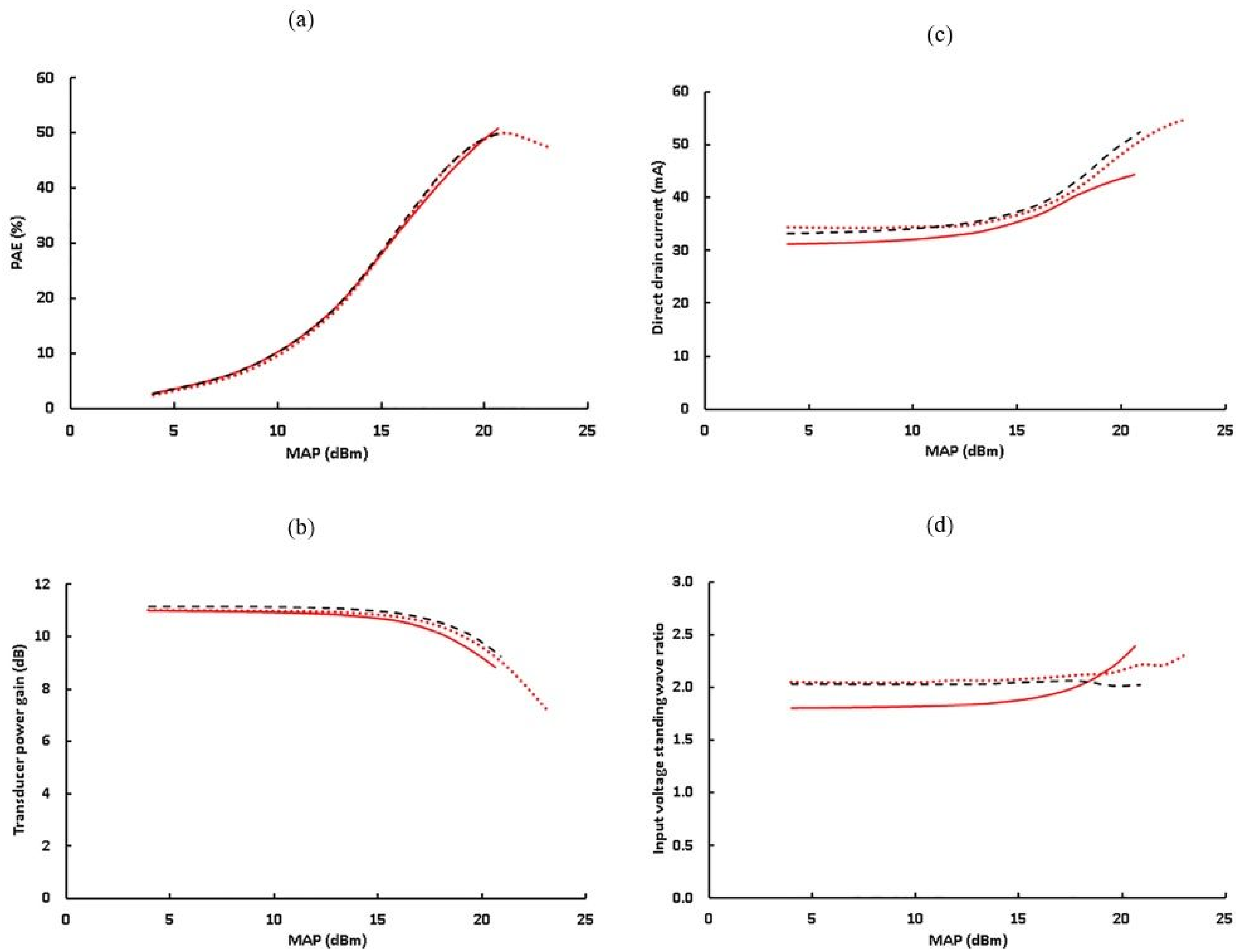



**Figure 2**

Field dependence of the electron drift velocity in the transistor channel.




## Figure 3

(a) Power-added efficiency, (b) transducer power gain, (c) direct drain current, and (d) input voltage standing wave ratio as functions of MAP, which are calculated using the full 2D model for the IFET (dotted curves), the complete equivalent circuit (dashed), and the simplified equivalent circuit (continuous).

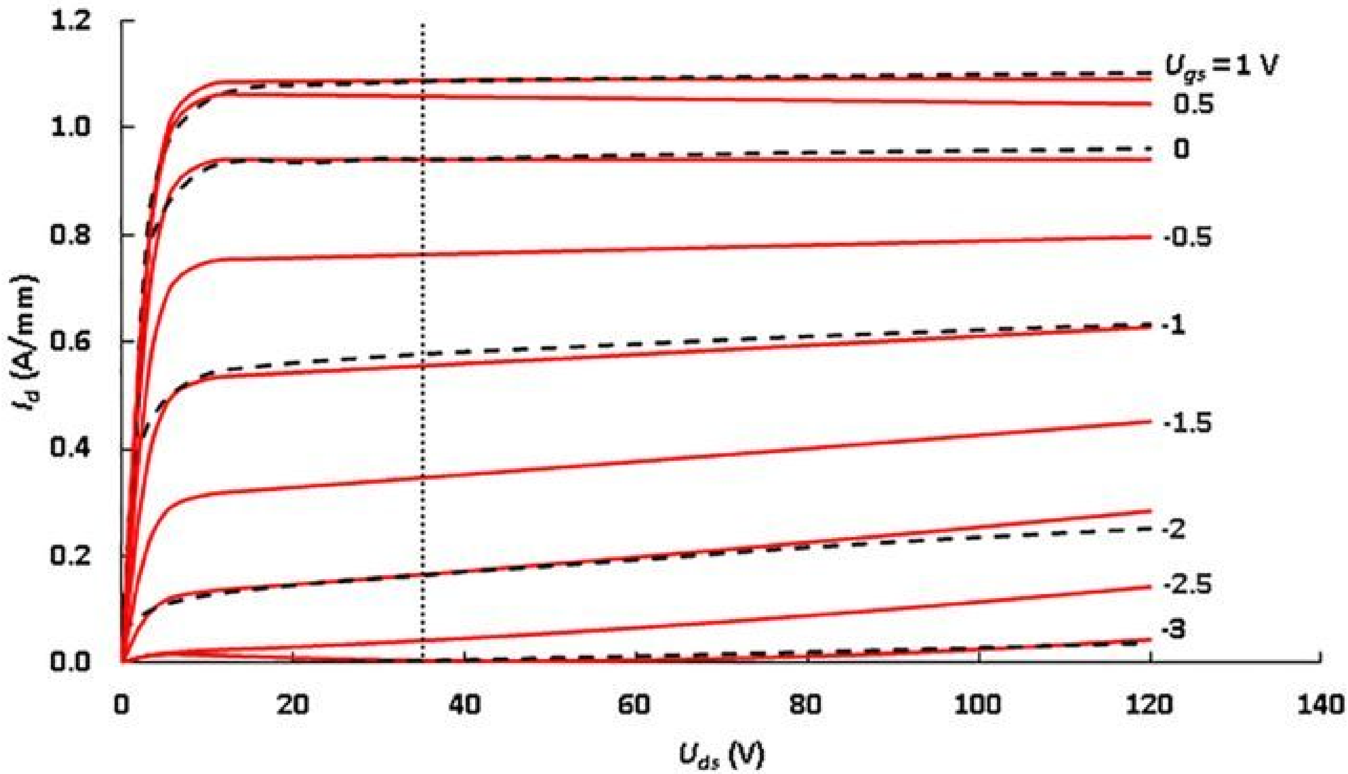
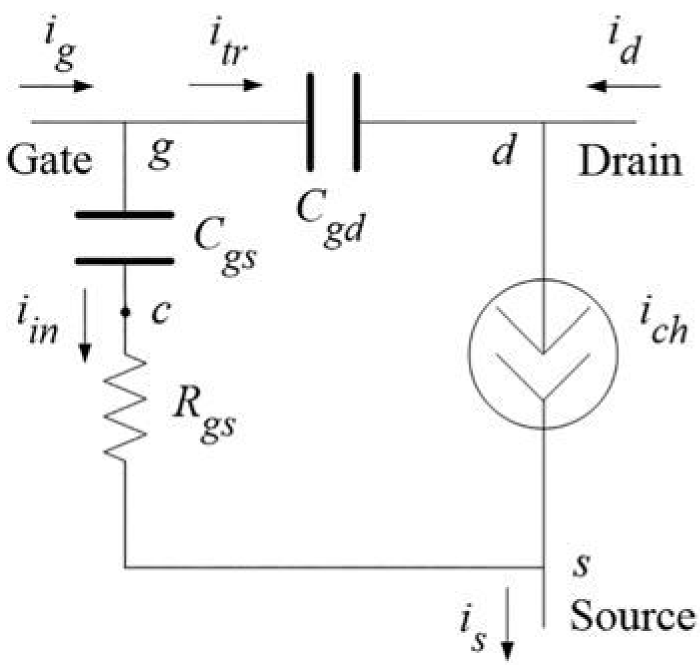



**Figure 4**

Current–voltage characteristics of the complete equivalent circuit (dashed lines), and of the Curtice-Ettenberg model (continuous).



## Figure 5

The simplified large-signal equivalent circuit of the intrinsic FET: $i_{ch}$ , channel current generator given by current–voltage relationship of the Curtice-Ettenberg model; $C_{gs}$ = const and $R_{gs}$ = 0, input capacitance and resistance; and $C_{gd}$ = const , transfer (feedback) capacitance.