INVESTIGATION AND MODELING OF IMPACT IONIZATION WITH REGARD TO THE RF- AND NOISE BEHAVIOUR OF HFET

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ABSTRACT

A new small-signal and noise equivalent circuit for **H**eterostructure **F**ield-**E**ffect **T**ransistors (HFET), including the influence of impact ionization and gate-leakage current on the electronic properties, is presented. The capability of the new model is demonstrated by bias-dependent investigations of the RF- and noise behaviour of InAlAs/InGaAs/InP-HFET.

INTRODUCTION

Heterostructure field-effect transistors with a low gap channel material, such as InAlAs/InGaAs/InP-HFET, are well suited for high-speed opto-electronic and microwave communication applications [1]. These transistors have demonstrated excellent RF- and noise performance, but at high drain-source-voltages V_{DS} impact ionization in the channel degrades the DC- and especially the RF- as well as the noise behaviour. This phenomenon causes high gate-leakage current [2] and leads to high output conductance and low breakdown voltages [3], [4]. Up to now conventional models are not able to describe the influence of these effects on the RF- and noise behaviour. In this paper we present an extended small-signal and noise equivalent circuit, which allows an exact modeling and prediction of RF- and noise behaviour in a wide frequency range, including the impact ionization influence. Bias dependent investigations and modeling of the RF- and noise behaviour, and especially of the intrinsic equivalent noise sources of InAlAs/InGaAs/InP-HFET clearly demonstrate the reliability and the advantages of the new model.

NEW SMALL-SIGNAL AND NOISE EQUIVALENT CIRCUIT

Extensive bias dependent RF-measurements have demonstrated that the phenomenon of the impact ionization in the channel strongly increases with higher drain-source-voltage [5].

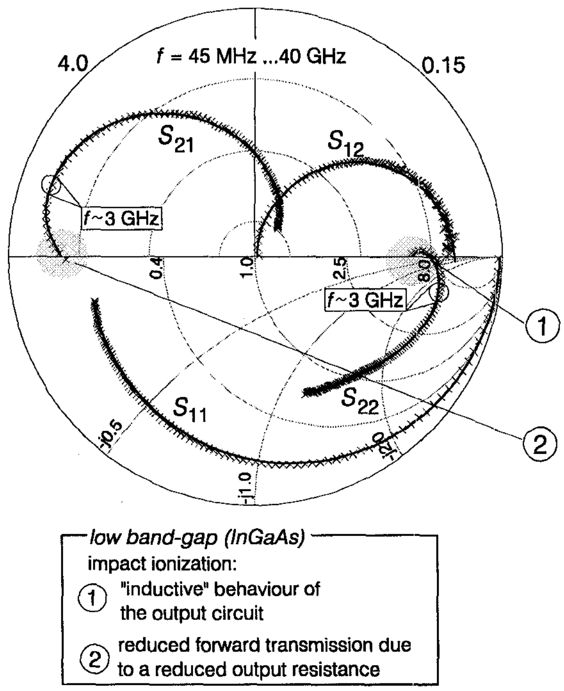

Fig. 1: Measured (×) and modeled (—) scattering parameters versus frequency of an InAlAs/InGaAs/InP-HFET at bias condition with impact ionization (T = 300K, V_{DS} = 1.5V, V_{GS} = 0V).

Fig. 1 shows the typical frequency dependent s-parameters of InAlAs/InGaAs/InP-HFET at a bias condition where impact ionization in the channel occurs. In the frequency range from 45 MHz up to about 3 GHz a strong inductive behaviour of the output circuit correlated to the

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output reflection coefficient s_{22} can be observed. Furthermore, due to a dispersion of the output resistance the forward transmission s_{21} is reduced. The recently published method [6] to describe this behaviour by an additional series-connection of a resistance and an inductance parallel to the output resistance R_{ds} leads to unphysical results which do not allow a realistic interpretation of the impact ionization phenomenon in the channel.

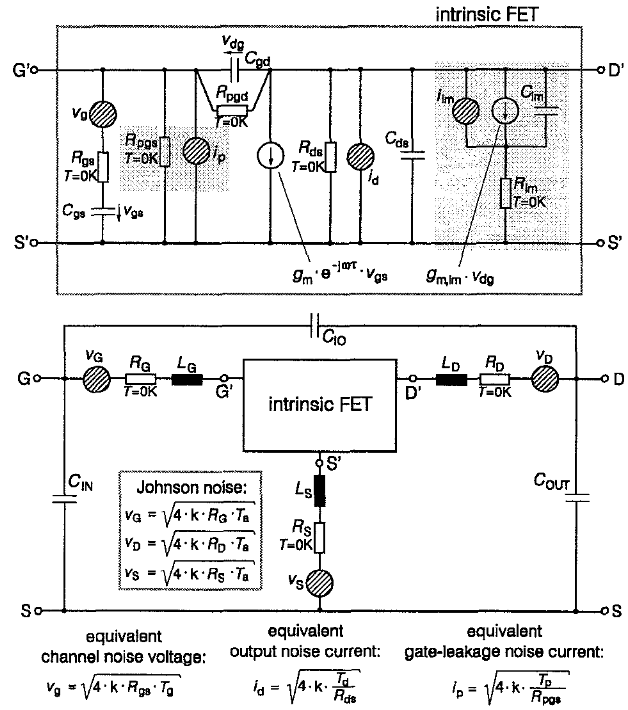

Fig. 2: Small-signal- and noise equivalent circuit of HFET including modeling of gate-leakage current and impact ionization on the RF- and noise behaviour.

Based on an extended temperature noise model [7] which takes into account the influence of gate-leakage current on the RF- and noise performance the new equivalent circuit (Fig. 2) now considers an additional voltage controlled current source, characterized by $g_{m,im}$, and a RC-combination parallel to the output resistance. $g_{m,im}$ represents the current component due to the impact ionization controlled by the drain-gate-voltage v_{dg}, mainly caused by the voltage drop at the high field region at the drain-end of the gate. The frequency dependence is described by the combination of R_{im} and C_{im}. The influence of the impact ionization on noise is considered by the additional white noise source parallel to the v_{dg} controlled current source $g_{m,im}$. Due to the arrangement of the noise source i_{im} and the RC-combination (R_{im} and C_{im}) the external short-circuit noise current $i_{im,ext}$ differs from the intrinsic impact ionization noise current i_{im} and is given by:

$$\sqrt{\overline{i_{im,ext}^2}} = \sqrt{\overline{i_{im}^2}} \cdot \frac{1}{1+\left(\frac{\omega}{\omega_0}\right)^2}, \quad \omega_0 = \frac{1}{R_{im} \cdot C_{im}}. \quad (1)$$

This formula describes the Lorentzian shape of the short-circuit noise current, which reflects the generation of electron-hole pairs due to the impact ionization.

EXPERIMENTAL VERIFICATION

Using a HP8510C network analyzer and a commercial noise parameter measurement set-up (ATN & HP8970B) the influence of impact ionization on the RF- and noise behaviour has been investigated in dependence on the frequency and bias conditions.

bias condition:		gate-geometry:
$V_{DS} = 1.5V$	$V_{GS} = 0V$	$L_g = 0.7\mu m$
$I_D = 31.8mA$	$I_G = -18\mu A$	$W_g = 80\mu m$
cut-off frequencies:		
$f_T = 45GHz$	$f_{max} = 152GHz$	
small-signal equivalent elements:		
$C_{IN} = 14.2fF$	$C_{IO} = 4fF$	$C_{OUT} = 28.2fF$
$R_G = 3\Omega$	$L_G = 63.1pH$	$C_{gs} = 210.5fF$
$R_S = 8\Omega$	$L_S = 3.8pH$	$L_D = 152pH$
$R_{gs} = 2.8\Omega$	$R_{ds} = 420\Omega$	$R_{pgs} = 12k\Omega$
$R_D = 10\Omega$	$C_{ds} = 8.2fF$	$R_{pgd} = 70.7k\Omega$
$C_{gd} = 9.5fF$	$g_m = 69mS$	$\tau = 0.22ps$
$R_{im} = 38k\Omega$	$C_{im} = 1.42fF$	$g_{m,im} = 4.26mS$

Tab. 1: Bias condition, geometry-, performance data and the extracted small-signal equivalent elements.

Likewise, Fig. 1 shows the modeled scattering parameters of the InAlAs/InGaAs/InP HFET in the frequency range from 45 MHz up to 40 GHz. The bias-condition, geometry-, performance data and the achieved small-signal equivalent elements are listed in Tab. 1. Obviously the new small-signal equivalent circuit is well suited to model RF-behaviour including the impact ionization influence.

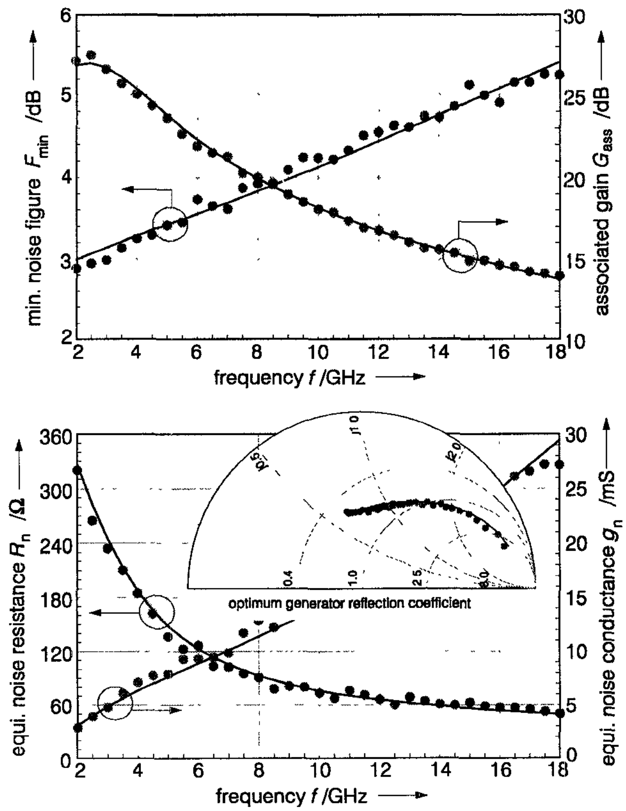

Fig. 3: Measured (●) and modeled (—) noise parameters of an InAlAs/InGaAs/InP-HFET at bias conditionwith impact ionization.

The measured and modeled noise parameters (F_{min}, R_n, g_n, G_{ass} and $\underline{G}_{opt}$) of the transistor are shown in Fig. 3. The impact ionization causes a decrease of the signal-to-noise ratio, especially at low frequencies a strong impact on the noise performance, due to the Lorentzian shape of the external short-circuit noise current, can be observed.The achieved noise parameters are listed in Tab. 2. In contrast to the influence of a gate-current, impact ionization leads to higher optimum generator impedances and causes a strong increase of the equivalent noise resistance R_n at low frequencies, as well.

equivalent channel noise temperature: $T_g = 4014.9\text{K}$
equivalent output noise temperature: $T_d = 18007.84\text{K}$
equivalent gate-leakage noise temperature: $T_p = 918.65\text{K}$
equivalent impact ionization noise current: $i_{im} = 166\text{pA}$

Tab. 2: Extracted noise parameters of the modeled HFET; ($V_{DS} = 1.5\text{V}$, $I_D = 31.8\text{mA}$, $T_a = 300\text{K}$).

Furthermore the additional noise source (i_{im}) in combination with R_{im} and C_{im} drastically increases the minimum noise figure F_{min} and affects the associated gain G_{ass}. The investigation of the bias dependent behaviour of all equivalent intrinsic noise sources [8] is a powerful tool to verify the capability of the new model.

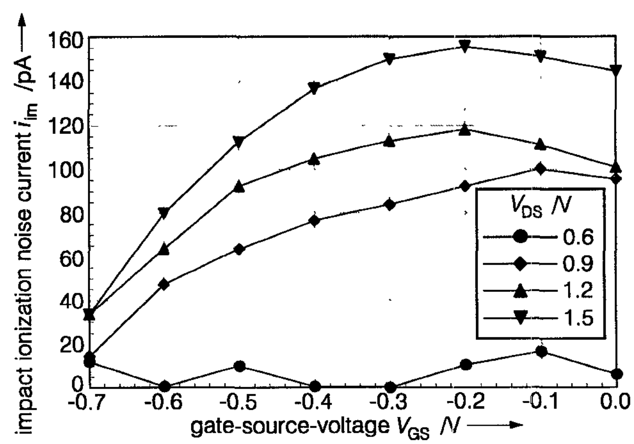

Fig. 4: Extracted equivalent intrinsic impact ionization noise current i_{im} in dependence on the gate-source-voltage V_{GS} with the drain-source-voltage V_{DS} as parameter.

Fig. 4 shows that the impact ionization noise current i_{im} drastically increases with higher drain-source-voltages V_{DS} used as a parameter in Fig. 4. In contrast, at low drain-source-voltages $V_{DS} < 0.7$ V, corresponding to electron energies lower than the band-gap energy of the channel material, the impact ionization noise current i_{im} is negligible. With increasing drain-source-voltage above $V_{DS} \approx 0.8$ V impact ionization occurs. This leads to impact ionization noise currents which dominate the noise behaviour of the transistor and reflects the strong correlation between impact ionization, bias-condition and generated noise current. The other equivalent intrinsic noise sources show a bias dependence as expected [8]:

- the equivalent gate-leakage noise current i_p is propotional to the shot noise gate-current,
- the equivalent output noise current i_d is strongly correlated to a reduced shot noise drain-current, and
- the equivalent channel noise voltage v_g shows an inverse proportional behaviour to the intrinsic current gain cut-off frequency f_T.

These dependencies demonstrate the capability to separate the intrinsic noise sources and the correlation to physical noise processes by the presented noise model.

CONCLUSION

S-parameter (45 MHz up to 40 GHz) and noise parameter measurements (2 GHz up to 18 GHz) on InAlAs/InGaAs/InP-HFET have shown that impact ionization strongly influences the RF- and noise behaviour. A new small-signal- and noise equivalent circuit is presented, which allows an exact modeling of s-parameters and of all noise parameters in a wide frequency range. In contrast to conventional RF- and noise models, the agreement between measured and modeled scattering and noise parameters is excellent. Furthermore, the investigation of the bias-dependence of the small-signal elements and of the intrinsic equivalent noise sources demonstrates the capability of the presented model to give a physical interpretation of different circuit elements.

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