Investigation and Modeling of Impact Ionization with Regard to the RF and Noise Behavior of HFET

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***Abstract*—A new small-signal and noise-equivalent circuit for heterostructure field-effect transistors (HFET's), 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 high-frequency (HF) (45 MHz up to 40 GHz) and noise behavior (2 GHz up to 18 GHz) of the InAlAs/InGaAs/InP HFET. Furthermore, based on these results, the bias-dependence of the newly implemented small-signal equivalent elements and the equivalent intrinsic noise sources, are discussed.**

***Index Terms*—Modeling, MODFET's, noise, shot noise.**

I. Introduction

Heterostructure field-effect transistors (HFET's) with a low band-gap channel material, such as the 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 ($V_{\rm DS}$), impact ionization [2] in the channel degrades the dc and, especially, the RF, as well as the noise behavior. This phenomenon leads to high gate-leakage current [3] combined with high output conductances and low breakdown voltages [4], [5]. Up to now, conventional models [6], [7] are not able to describe the influence of these effects on the RF and noise behavior. In this paper, the authors present an extended small-signal and noise-equivalent circuit, which allows an exact modeling and prediction of the RF and noise behavior over a wide frequency range where $1/f$-noise is negligible, including the impact-ionization influence. Bias-dependent experimental investigations as well as the modeling of the RF and noise behavior, with special respect to the intrinsic equivalent noise sources of InAlAs/InGaAs/InP HFET's, clearly demonstrate the reliability and the advantages of the new model.

II. Influence of Impact Ionization on the Gate-Current

At high drain–source voltages ($V_{\rm DS}$), a drastic increase of the gate current $I_{\rm G}$ can be observed [8]. This is caused by impact ionization and the generation of additional electron–hole pairs in the channel of the HFET. Due to the applied electric field, the electrons contribute to the drain-current I_D and the holes are transferred to the gate–electrode corresponding to a tunneling probability T_h. The increase of the gate-leakage current $I_{\rm G}$ at high drain–source voltages $V_{\rm DS}$ (Fig. 1), demonstrates the influence of the additional hole–current $I_{\rm Gh}$.

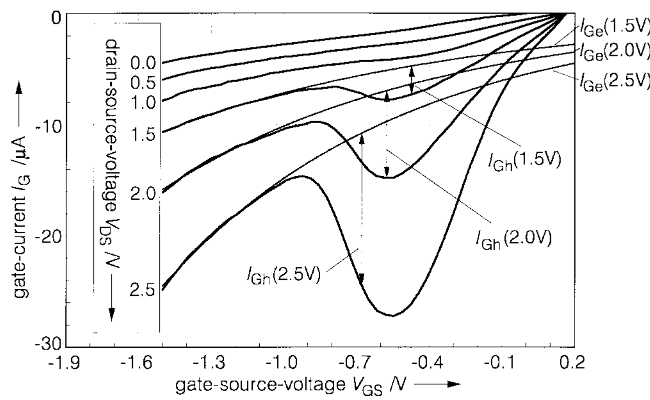

Fig. 1. Typical behavior of a gate-leakage current $I_{\rm g}$ in dependence on the bias conditions and the illustration of superposition of the electron tunneling component $I_{\rm Ge}$ and the hole component $I_{\rm Gh}$. ($L_G = 0.15$ μm, $W_g = 100$ μm, $T = 300$ K).

The total gate current $I_{\rm G}$ can be interpreted as a superposition of an electron tunneling component $I_{\rm Ge}$ through the Schottky barrier [9] and a hole tunneling component $I_{\rm Gh}$, caused by impact ionization. Now, the gate current $I_{\rm G}$ can be described by the following formula:

$$I_{\rm G} = \begin{cases} I_{\rm Ge} + I_{\rm Gh} \\ I_{\rm Ge} + |I_D \cdot \alpha(E) \cdot L_{\rm eff}(E) \cdot T_h(E)|. \end{cases} \tag{1}$$

Here, $\alpha(E)$ is the ionization rate per unit length (impact-ionization coefficient), which is strongly dependent on the lateral electric field in the channel [10], [11]. Significant generation of electron–hole pairs occurs only at the drain end of the gate due to the intrinsic voltage drop $v_{\rm dg}$ over the high-field region, where $L_{\rm eff}$ describes the effective length of this high-field domain.

III. New Small-Signal and Noise-Equivalent Circuit

Theoretical investigations [cf. (1)] as well as extensive bias-dependent dc and RF measurements, have demonstrated that the phenomenon of the impact ionization in the channel strongly increases with higher drain–source voltage $V_{\rm DS}$ correlated to a higher average lateral-field strength [12], [13]. Fig. 2 shows the typical frequency-dependent s-parameters

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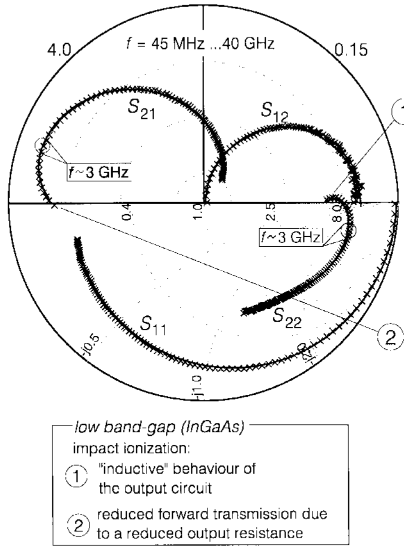

Fig. 2. Measured (×) and modeled (−) scattering parameters versus frequency of an InAlAs/InGaAs/InP HFET at a bias condition where impact ionization occurs. ($T = 300$ K, $V_{\rm DS} = 1.5$ V, $V_{\rm GS} = 0$ V, $L_g = 0.7$ μm, $W_g = 80$ μm).

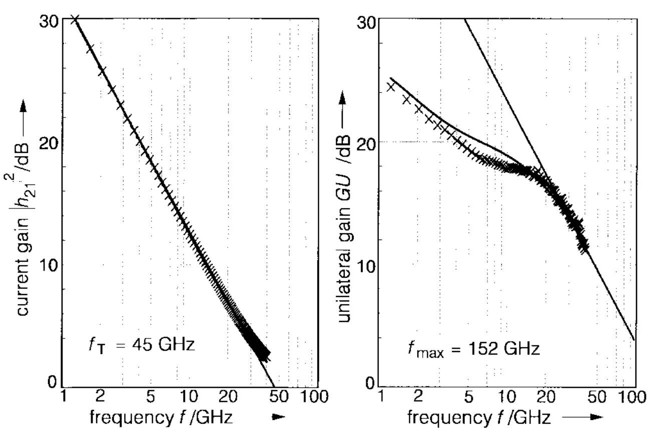

Fig. 3. Measured (×) and modeled (−) current gain $|h_{21}|^2$ and unilateral gain *GU* versus frequency of an InAlAs/InGaAs/InP HFET at a bias condition where impact ionization occurs. ($T = 300$ K, $V_{\rm DS} = 1.5$ V, $V_{\rm GS} = 0$ V, $L_g = 0.7$ μm, $W_g = 80$ μm).

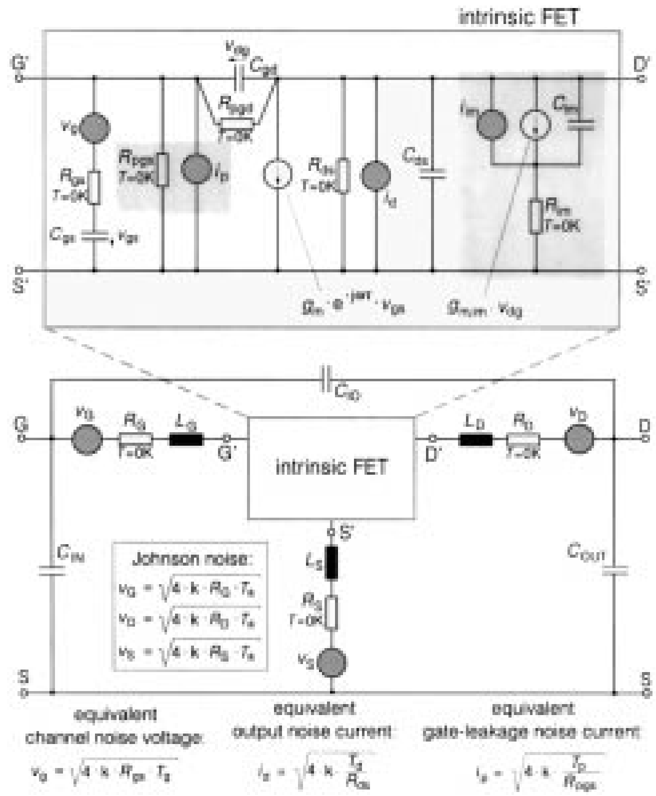

Fig. 4. Intrinsic and extrinsic small-signal and noise-equivalent circuit of HFET including modeling of gate-leakage current and impact ionization on the RF and noise behavior.

of an InAlAs/InGaAs/InP HFET at a bias condition where impact ionization in the channel occurs. Fig. 3 illustrates the corresponding current gain $|h_{21}|$ and unilateral gain (*GU*) in dependence on the frequency and the extracted cutoff frequencies f_T and $f_{\rm max}$, respectively.

In the frequency range from 45 MHz up to about 3 GHz, a strong inductive behavior of the output circuit correlated to the 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 [14] to describe this behavior by an additional series connection of a resistance and an inductance parallel to the output resistance $R_{\rm ds}$, leads to unphysical results which do not allow a realistic interpretation of the impact-ionization phenomenon in the channel. Furthermore, in this paper's model, the electron–hole pair generation due to impact ionization is represented by an additional voltage-controlled current source in the output circuit of the transistor. The investigation of the dc behavior has demonstrated that the current source has to be controlled by the intrinsic drain–gate voltage $v_{\rm dg}$.

The circuit here is based on an extended temperature noise model [15], which takes into account the influence of gate-leakage current on the RF and noise performance. This new equivalent circuit (Fig. 4) now considers the mentioned additional voltage-controlled current source, characterized by $g_{m,\rm im}$, and a *RC*-combination parallel to the output resistance. $g_{m,\rm im}$ represents the current component due to the impact ionization controlled by the drain–gate voltage $v_{\rm dg}$ 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 $R_{\rm im}$ and $C_{\rm im}$. The influence of the impact ionization on noise is considered by the additional white noise source parallel to the $v_{\rm dg}$-controlled current source $g_{\rm m,im}$. Due to the arrangement of the noise source $i_{\rm im}$ and the *RC* combination ($R_{\rm im}$ and $C_{\rm im}$), the external short-circuit noise-current $i_{\rm im,ext}$ differs from the intrinsic impact-ionization noise-current $i_{\rm im}$ and is given by

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

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.

TABLE I
BIAS CONDITION, GEOMETRY DATA, PERFORMANCE DATA, AND THE EXTRACTED SMALL-SIGNAL EQUIVALENT ELEMENTS

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:		
$C_{IN} = 14.2fF$	$C_{IO} = 4fF$	$C_{OUT} = 28.2fF$
$R_G = 3\Omega$	$L_G = 63.1pH$	$C_{gs} = 210.5fF$
$R_S = 8\Omega$	$L_S = 3.8pH$	$L_D = 152pH$
$R_{gs} = 2.8\Omega$	$R_{ds} = 420\Omega$	$R_{pgs} = 12k\Omega$
$R_D = 10\Omega$	$C_{ds} = 8.2fF$	$R_{pgd} = 70.7k\Omega$
$C_{gd} = 9.5fF$	$g_m = 69mS$	$\tau = 0.22ps$
$R_{im} = 38k\Omega$	$C_{im} = 1.42fF$	$g_{m,im} = 4.26mS$

IV. EXPERIMENTAL VERIFICATION

A. RF Behavior

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

The small-signal elements, equivalent noise temperatures (T_p, T_g, and T_d) and equivalent impact-ionization noise-current ($i_{\rm im}$) have been extracted using an optimization algorithm based on the simulated evolution (evolution theory and genetic algorithms) [16]–[18]. The bias-condition, geometry data, performance data, and the extracted small-signal equivalent elements are listed in Table I. Fig. 2 also shows the modeled scattering parameters, while Fig. 3 shows the modeled current gain $| h_{21} |^2$ and unilateral gain *GU* of the investigated InAlAs/InGaAs/InP HFET in the frequency range from 45 MHz up to 40 GHz, respectively. Obviously, the new small-signal equivalent circuit is well suited to model the RF behavior, including the impact-ionization influence.

Fig. 5 shows a typical bias-dependent behavior of the extracted transconductance $g_{\rm m,im}$ at room temperature. The low transconductance $g_{\rm m,im}$ at low drain–source voltages $V_{\rm DS}$ reflects the small influence of impact ionization on the RF performance in this bias range. With increasing drain–source voltage, impact ionization and the inductive behavior of s_{22} occur, correlated to a drastically increased transconductance $g_{\rm m,im}$. The bias-dependence of the transconductance $g_{\rm m,im}$ always exhibits a bell-shaped curve, but due to the bias-dependence of the tunneling probability $T_h(E)$ [cf. (1)] the maxima of the curves are not exactly correlated with the occurring hole current $I_{\rm Gh}$, seen in the input characteristics of the HFET (Fig. 1).

B. Noise Behavior

The measured and modeled noise parameters ($F_{\rm min}$, R_n, g_n, $G_{\rm ass}$, and $\underline{\Gamma}_{\rm opt}$) of the transistor are shown in Fig. 6. Due to the Lorentzian shape of the external short-circuit noise-current $i_{\rm im,ext}$ [cf. (2)] corresponding to an upper frequency-band limitation, especially at low frequencies, a strong impact on the noise performance can be observed. The phenomenon of impact ionization now leads to an increase of the minimum noise figure $F_{\rm min}$. The offset of the minimum noise figure at low frequencies especially reflects the impact-ionization process. In contrast to the influence of a gate-leakage current [15], 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. The inductive behavior of the output path of the HFET also affects the associated gain $G_{\rm ass}$ and leads to an increase of $G_{\rm ass}$ at low frequencies. The three equivalent noise temperatures (T_g, T_p, and T_d) and the equivalent impact-ionization noise-current $i_{\rm im}$ of the modeled extrinsic noise parameters are listed in Table II.

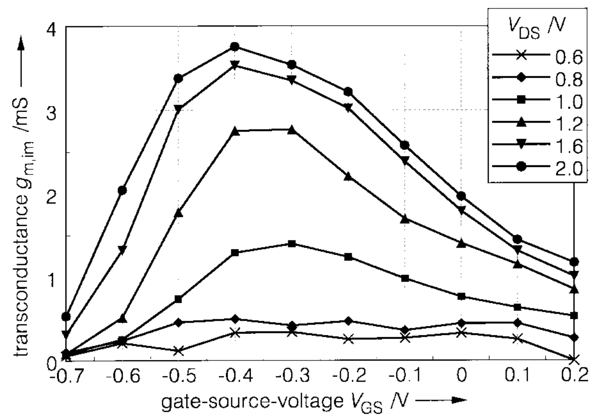

Fig. 5. Impact-ionization transconductance $g_{\rm m,im}$ in dependence on the gate–source voltage $V_{\rm GS}$, with the drain–source voltage $V_{\rm DS}$ as parameter. ($L_g = 0.15$ μm, $W_g = 100$ μm, $T = 300$ K).

V. EQUIVALENT INTRINSIC NOISE SOURCES

The bias-dependent investigations of all equivalent intrinsic noise sources [19] demonstrate the capability of the new model. Fig. 7 shows that the extracted impact-ionization noise-current $i_{\rm im}$ drastically increases with higher drain–source voltages ($V_{\rm DS}$), used as a parameter in Fig. 7. In contrast, at low drain–source voltages $V_{\rm DS} < 0.7$ V, the impact-ionization noise-current $i_{\rm im}$ is negligible. In this bias range, electron energies are smaller than the band-gap and are insufficient to generate electron–hole pairs. With increasing drain–source voltage above $V_{\rm DS} \approx 0.8$ V, impact ionization occurs. This leads to impact-ionization noise-currents which dominate the noise behavior of the transistor and reflects the strong correlation between impact-ionization, bias-condition, and generated noise-current. Due to the fact that the level of the extracted impact-ionization noise-current $i_{\rm im}$ exceeds the equivalent shot-noise drain-current ($= (2 \cdot q \cdot I_D)^{\frac{1}{2}}$) in a wide range of bias-conditions, carrier multiplication [20]–[22] is supposed to occur in the high-field domain leading to the following relation:

$$i_{\rm im} \propto f(M(E)) \cdot \sqrt{2 \cdot q \cdot I_D} \quad (3)$$

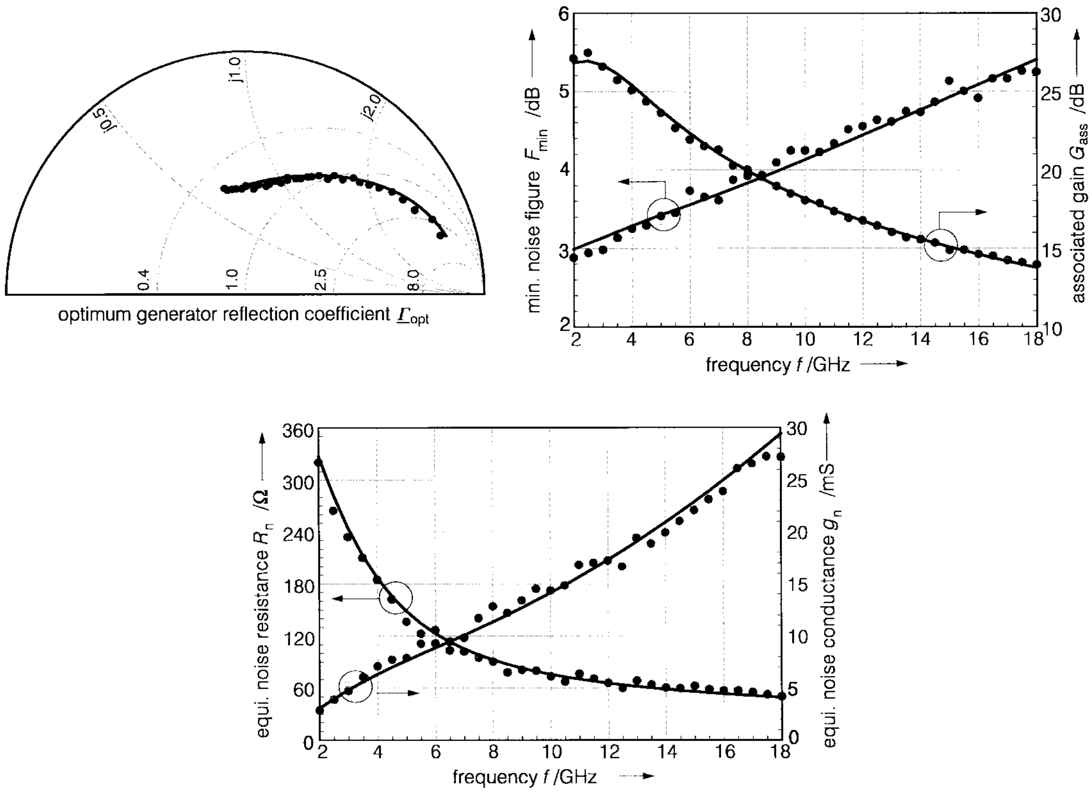

Fig. 6. Measured (•) and modeled (—) noise parameters versus frequency of an InAlAs/InGaAs/InP HFET at a bias condition where impact ionization occurs. ($V_{\rm DS} = 1.5$ V, $V_{\rm GS} = 0$ V, $I_D = 31.8$ mA, $L_g = 0.7\mu$m, $W_g = 80$ μm, $T = T_a = 300$ K).

TABLE II
EXTRACTED EQUIVALENT NOISE TEMPERATURES AND NOISE CURRENT OF THE MODELED HFET ($V_{\rm DS} = 1.5$ V, $V_{\rm GS} = 0$ V, $I_D = 31.8$ mA, $L_g = 0.7$ μm, $W_g = 80\mu$m, $T = T_a = 300$ K)

equivalent channel noise temperature: $T_{\rm g} = 4014.9$K
equivalent output noise temperature: $T_{\rm d} = 18007.84$K
equivalent gate-leakage noise temperature: $T_{\rm p} = 918.65$K
equivalent impact ionization noise current: $i_{\rm im} = 146$pA

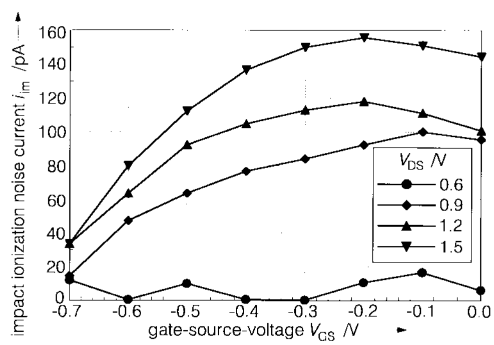

Fig. 7. Extracted equivalent intrinsic impact-ionization noise-current $i_{\rm im}$ in dependence on the gate–source voltage $V_{\rm GS}$ with the drain–source voltage $V_{\rm DS}$ as parameter.

where $f(M(E))$ reflects a function of the electric-field-dependent multiplication factor $M(E)$ [20]. The relation between multiplication factor $M(E)$ and the majority-carrier impact-ionization rate-per-unit length $\alpha(x, E)$ can be described according to [20]

$$M(E) \equiv \exp\left[\int_0^{L_{\rm eff}} \alpha(\xi, E)\, d\xi\right]. \tag{4}$$

Due to the position-dependent electric field, impact-ionization rate, and using the above assumptions, no simple analytical expression can be derived for the relation between bias conditions and generated impact-ionization noise-current $i_{\rm im}$.

The other equivalent intrinsic noise sources show the expected bias dependence [19] and reflects the strong correlation between the equivalent intrinsic noise sources (i_d, i_p, and v_g), and the physical noise sources, such as shot-noise drain-current $i_{\rm sd}$ [cf. (5)] and shot-noise gate current $i_{\rm sg}$ [cf. (6)].

$$i_{\rm sd} = \sqrt{2 \cdot q \cdot I_D} \tag{5}$$

$$i_{\rm sg} = \sqrt{2 \cdot q \cdot I_{\rm G}}. \tag{6}$$

The equivalent output noise-current i_d in dependence on the gate–source voltage $V_{\rm GS}$ and versus the shot-noise drain-current is shown in Fig. 8. It can be seen that the equivalent noise-current i_d is mainly dominated by a reduced shot-noise drain-current [23]. The mathematical interpretation of this correlation is given by

$$i_d = \sqrt{4 \cdot k \cdot \frac{T_d}{R_{\rm ds}}} \cong k_d \cdot \sqrt{2 \cdot q \cdot I_D} + i_{d0} \tag{7}$$

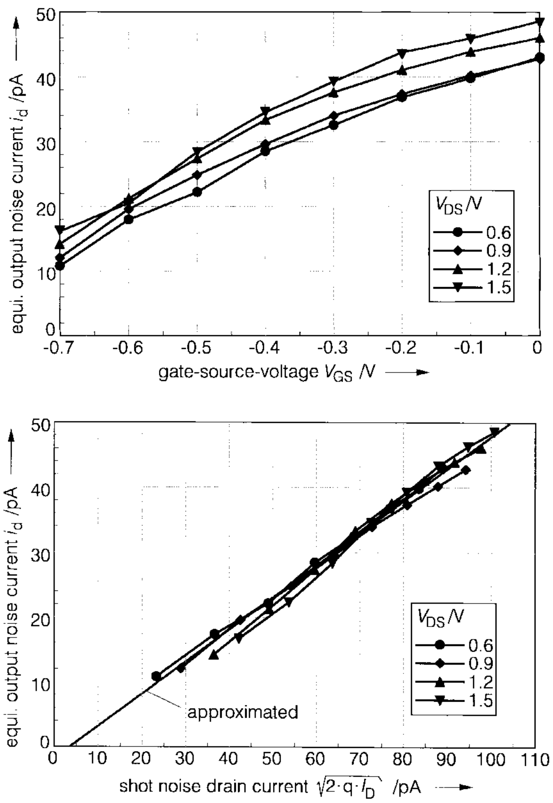

Fig. 8. Extracted equivalent output noise-current i_d in dependence on the gate–source voltage V_{GS} and on the shot-noise drain-current with the drain–source voltage V_{DS} as parameter, respectively.

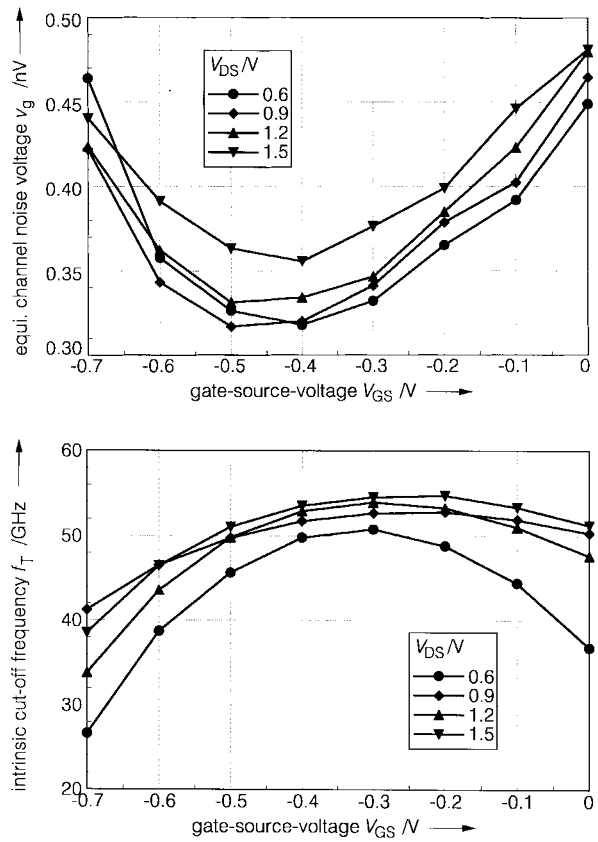

Fig. 9. Equivalent channel-noise voltage v_g and intrinsic current-gain cutoff frequency f_T in dependence on the gate–source voltage V_{GS} with the drain–source voltage V_{DS} as parameter.

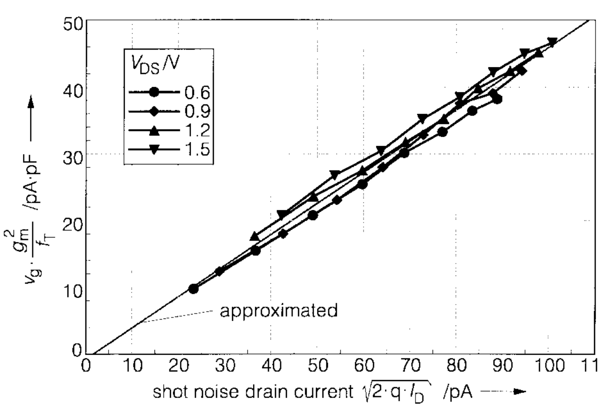

Fig. 10. Extracted transformed equivalent channel-noise voltage in dependence on the shot-noise drain-current with the drain–source voltage V_{DS} as parameter, respectively.

here

$$k_d = 0.49 \text{ and } i_{d0} = -2pA. \tag{8}$$

The behavior of the equivalent channel-noise voltage v_g (Fig. 9) in dependence on the gate–source voltage V_{GS} exhibits an inversely proportional behavior to the intrinsic current-gain cutoff frequency f_T ($f_T = g_m/(2 \cdot \pi \cdot (C_{gs} + C_{gd}))$), which reflects the strong correlation to the intrinsic delay-time behavior of the HFET. A transformation of the equivalent channel-noise voltage v_g, characteristic for the input circuit of the transistor, to a noise measure of the output circuit of the HFET, can be done by multiplying v_g with the ratio of the square of the transconductance g_m and the intrinsic current-gain cutoff frequency f_T. Now, the transformed channel-noise voltage demonstrates a nearly proportional behavior to the shot-noise drain-current (cf. Fig. 10). Using this "transformation" the equivalent channel-noise voltage v_g can be expressed by following the linear approximation:

$$v_g \cdot \frac{g_m^2}{f_T} = \sqrt{4 \cdot k \cdot T_g \cdot R_{gs}} \cdot \frac{g_m^2}{f_T} \cong k_g \cdot \sqrt{2 \cdot q \cdot I_D} + i_{d1} \tag{9}$$

here

$$k_g = 0.47 \,\text{pF} \text{ and } i_{d1} = -1 \,\text{pA} \cdot \text{pF}. \tag{10}$$

Fig. 11 shows the equivalent gate-leakage noise-current i_p in dependence on the gate–source voltage V_{GS} and versus the shot-noise gate current. The equivalent gate-leakage noise-current i_p is nearly proportional to the shot-noise gate current. This clearly depicts that a gate-tunneling current causes pure shot noise [cf. (6)] [19], [24], [25]. The described behavior leads to

$$i_p = \sqrt{4 \cdot k \cdot \frac{T_p}{R_{pgs}}} \cong \sqrt{2 \cdot q \cdot I_G}. \tag{11}$$

These presented dependencies demonstrate the capability to separate the intrinsic noise sources and the correlation to

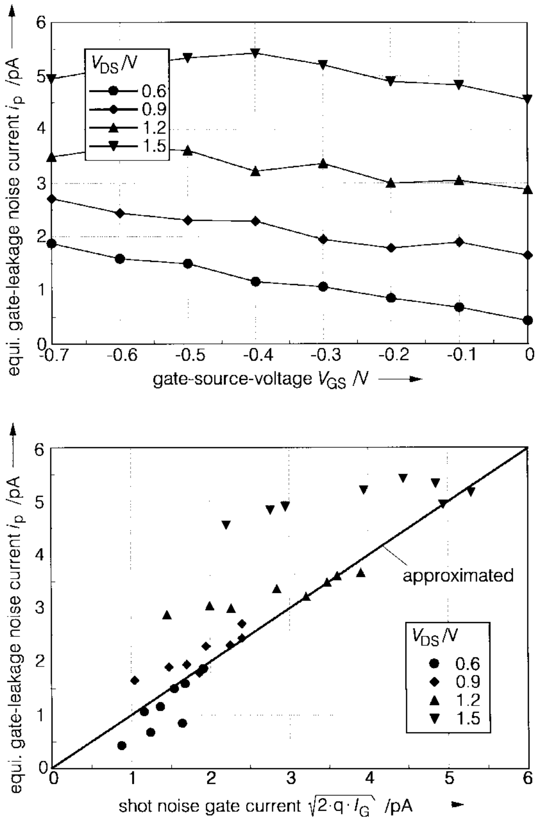

Fig. 11. Extracted equivalent gate-leakage noise-current i_p in dependence on the gate–source voltage $V_{\rm GS}$ and on shot–noise gate current with the drain–source voltage $V_{\rm DS}$ as parameter.

physical noise processes by the presented noise model. Furthermore, two independent noise-parameter measurements are sufficient to extract the unknown parameters (k_g, k_d, i_{d0}, i_{d1}) in (7)–(11). With the extracted bias-dependence of the small-signal equivalent elements and of (7)–(11), the behavior of the channel-noise voltage v_g, output noise-current i_d, and equivalent gate-leakage noise-current i_p of the HFET can be predicted for any bias condition at any frequency where 1/f-noise is negligible.

VI. Conclusion

A new small-signal- and noise-equivalent circuit is presented, which allows an exact modeling of s-parameters and all noise parameters over a wide frequency range. In contrast to conventional RF and noise models, the agreement between measured and modeled scattering and noise parameters is excellent, which allows the successful prediction and modeling of small-signal and all noise parameters of various monolithic microwave integrated circuits (MMIC's) [26], [27]. 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, allowing a physical interpretation of various circuit elements. 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 behavior. The output reflection coefficient s_{22} shows a strongly inductive behavior where the minimum noise figure $F_{\rm min}$ and the equivalent noise resistance R_n drastically increases at low frequencies.

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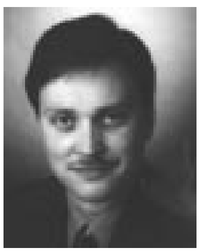

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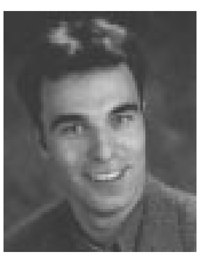

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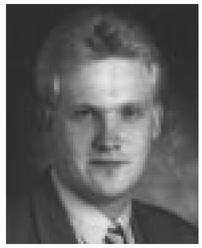

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