A SMALL-SIGNAL AND NOISE MODEL FOR THE PHYSICS-BASED DESIGN AND OPTIMIZATION OF GAAS MESFET'S FOR HYBRID AND MONOLITHIC MIC'S

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ABSTRACT

The paper describes a two-dimensional physical small-signal and noise model for GaAs MESFET's. The model can provide, on the basis of physical and geometrical input parameters only, a complete small-signal and noise performance characterization. The noise model is based on the efficient implementation of the classical impedance-field method for noise analysis within the framework of a frequency-domain numerical drift-diffusion physical model. Attention is devoted to the experimental validation of the model, which is carried out on a realistic case study (a 0.6 μm GMMT MESFET) by testing the DC, the small-signal and noise models against measurements. The role played by the high-field diffusivity in noise simulation is stressed and it is shown how a physics-based model for this parameter allows a good match to be achieved for both the noise figure and the optimum source impedance.

1 INTRODUCTION

The design and optimization of GaAs low-noise MESFET's for hybrid and monolithic MIC's classically requires the repeated iteration of the manufacturing process so as to identify the doping profile and device structure allowing the designer to obtain a satisfactory tradeoff between the device gain and noise performance. The availability of a physics-based CAD tool able to estimate such performances and to suggest trends useful for design optimization would be a promising alternative, particularly for the integrated case.

Although the progress achieved during the last decade in the physics-based 2D or 3D numerical simulation of solid-state devices has provided the technical community with a powerful tool for device design and optimization, a few areas in device performance assessment have been left almost uncovered. In the field of high-frequency devices, a particularly significant example is offered by the physics-based *noise* characterization, which is a fundamental topic in the design of microwave compound semiconductor FET's.

General techniques for the noise analysis of electron devices have been available for years and are based on the *impedance field method* (IFM) [16] and its extensions and generalizations [2, 18]. Although the IFM can be implemented within the framework of a multi-dimensional numerical device model, MESFET physics-based noise models have been traditionally founded on simplified (numerical [4, 3] or analytical [1, 14, 17]) 1D implementations of the IFM. Further simplifications enable to derive from the analytical approach extremely compact expressions for the noise parameters like the Fukui formula for the minimum noise figure [6].

In the present paper a discussion is presented on the results from small-signal and noise simulations carried out by means of a small-signal, frequency-domain 2D numerical drift-diffusion MESFET model [7]. The noise analysis is based on a recently proposed full two-dimensional implementation of the IFM [9, 10] which makes use of an efficient technique to evaluate the scalar impedance field, akin to the so-called adjoint network approach to the noise analysis of electrical networks [15]. The discussion aims at showing that physical parameter models having a somewhat minor relevance for DC and small-signal analysis, play a paramount role in noise simulation. Moreover, with a proper tuning of the physical parameters of the model, the results obtained are in good agreement with measurements.

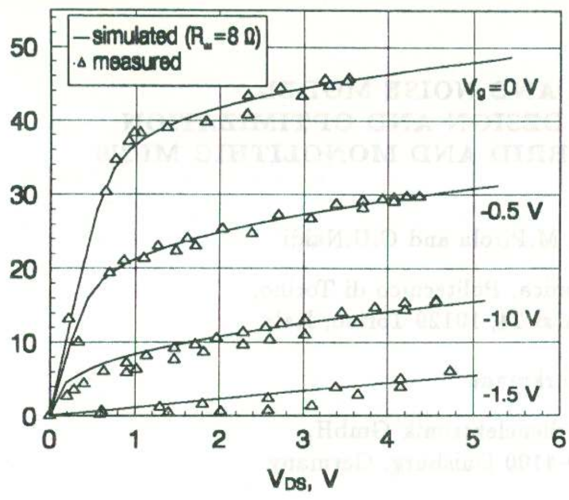

Figure 1: *Measured and simulated DC curves of 0.6 μm GMMT p-buried layer MESFET.*

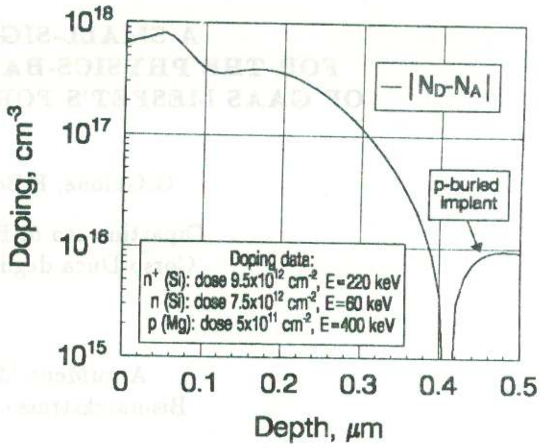

Figure 2: *Doping profile of GMMT MESFET.*

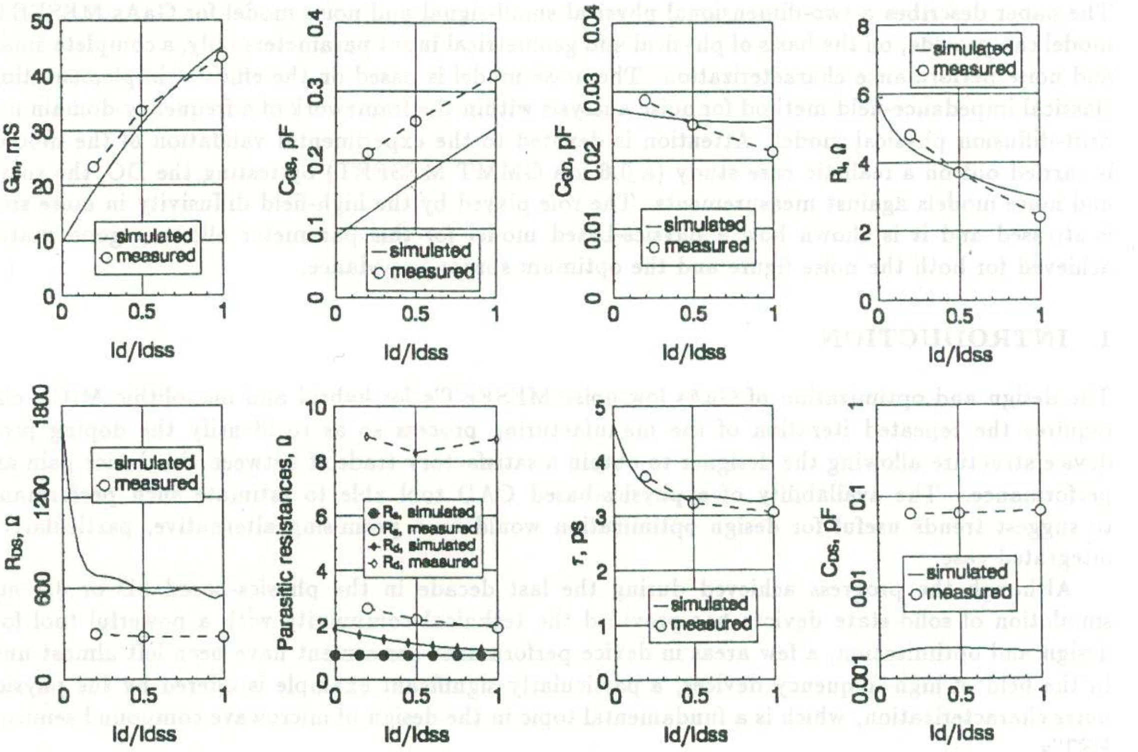

Figure 3: *Measured and simulated small-signal parameters of the intrinsic circuit as a function of gate bias,* $V_{DS} = 5$ *V.*

2 RESULTS AND DISCUSSION

As a case study, a GMMT 0.6 μm *p*-buried layer F-20 foundry MESFET was considered. The device is a recessed-gate MESFET with a double Si implant and a *p*-type buried layer implant. The measured and simulated DC curves are shown in Fig.1 while the doping profile is presented in Fig.2. If the external parasitics are deembedded from the measurement and added to the simulation, good agreement is found between the measured and simulated scattering parameters; however, a better insight on the model features is provided by a comparison between simulated elements of the lumped small-signal intrinsic equivalent circuit as a function of the drain current and the in-chip measured data (Fig.3). The agreement is fairly good, considering that a large parasitic C_{GS} is present in the real device because of the ground coupling of the gate pads. Large contact resistances also appear in the measured parasitic R_S and R_D (the device is geometrically symmetrical) and the output resistance is overestimated by the model, which

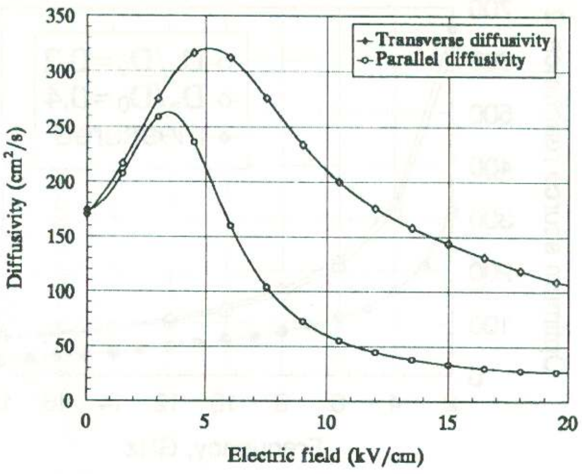

Figure 4: *Diffusivity-field curve of GaAs (from [5]).*

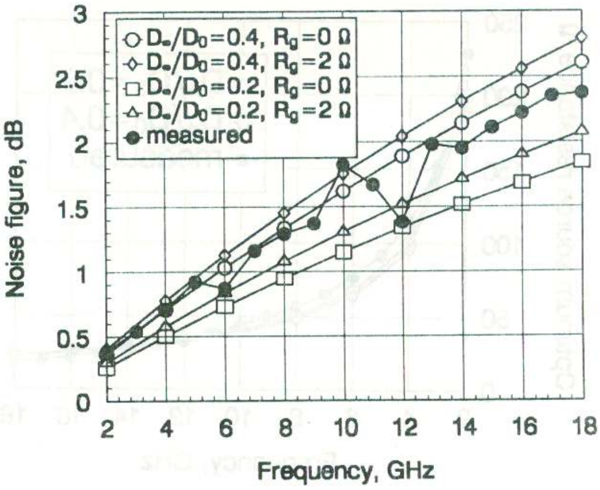

Figure 5: *Simulated and measured minimum noise figure for the low-noise bias point (V_{DS} = 5 V, $I_{DS} \approx$ 10 mA)* versus *the operating frequency.*

does not include low-frequency dispersion effects.

Concerning the noise parameters, a fundamental role is played by the diffusivity-field curve (Fig.4, from [5]). In most discretization schemes for the drift-diffusion model (*e.g.*, the Scharfetter-Gummel scheme with constant electron temperature) the Einstein relationship is enforced at low and high fields; this assumption, however poor it may be at high fields, has a modest impact on the DC and small-signal behaviour. From the standpoint of noise simulation, the use of Einstein relationship at high fields implies that the high-field diffusivity asymptotically behaves like $\mathcal{E}^{-1}$, thereby leading to drastically underestimating the noise originating from the high-field region of the channel. For this reason the noise model makes use of a modified diffusivity-field curve whereby Einstein relation holds up to a critical field $\mathcal{E}_c$ for which $D(\mathcal{E}_c) = D_\infty$; for $\mathcal{E} > \mathcal{E}_c$ the diffusivity is assumed to be constant and equal to the high-field value D_∞. The critical field is typically larger than the threshold field. For vanishing electric field the diffusivity tends to its low-field value $D_0 = (kT/q)\mu_0$. The model is somewhat similar to the one exploited in the analytical model by Statz *et al.* [14]. Notice that the present implementation is not self-consistent, at least in the high-field region of the device.

Although the high-field diffusivity [12] is not easily estimated in doped materials from first principles [11], its value can be exploited as a technology-dependent tuning factor. As a matter of fact, the closest agreement is achieved by ratios $D_\infty/D_0 \approx 0.3$, as suggested by theoretical considerations. An example of measured and simulated frequency behaviour of the noise figure, optimum source resistance and reactance in the low-noise bias point are shown in Fig.5, Fig.6 and Fig.7, respectively. For the noise figure also the effect of the gate resistance was investigated (the experimental result is around 2.8 Ω). Notice that the simulated and measured optimum reactance ($X_o \approx 1/\omega C_{GS}$) differ since the external parasitic gate-source capacitance has not been added to the simulation. Both reactances turn out to be consistent with the simulated and measured small-signal parameters.

In order to gain a deeper insight into the behaviour of the noise parameters as a function of the bias point, the frequency-dependent noise parameters (NF, Z_o, and noise resistance R_n) were measured for V_{DS} = 1, 2, 3, 4 and 5 V for several values of the drain current. From these, the spectra $S_{i_D}(f)$, $S_{i_G}(f)$ and the (normalized) correlation spectrum $C_{i_D i_G}(f) = S_{i_D i_G}(f)/\sqrt{S_{i_D}(f) S_{i_G}(f)}$ were obtained. The frequency behaviour of the three spectra is shown in Figs.8. The error bars refer to the standard deviation resulting from an average measurement uncertainty of ±7.5% on Z_o and R_n and of ±10% on NF (in dB) and has been numerically generated through Monte Carlo simulation. The uncertainty on the measured scattering parameters has been assumed as negligible; notice that beyond 10 GHz the nominal accuracy of the measurement equipment is slightly degraded.

From the measured data it may be concluded that the spectrum of the short-circuit drain current fluctuations is virtually white, while the correlation spectrum is almost white in magnitude, at least up to 10 GHz, and has linear phase. The behaviour of the spectrum of gate short-circuit current fluctuations approximately follows the theoretical ω^2 slope, at least under 10 GHz. It may be appreciated from the

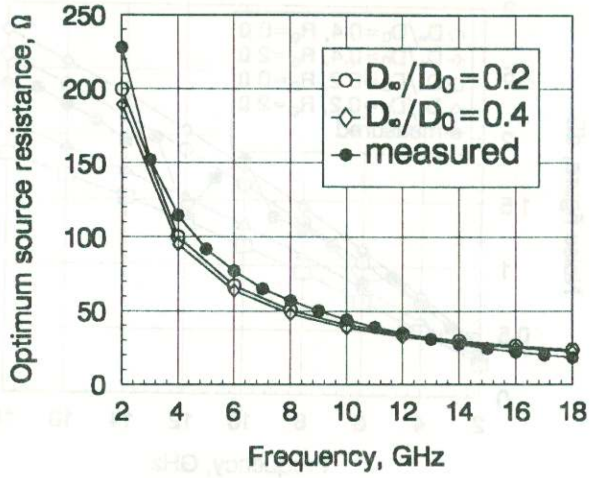

Figure 6: *Simulated and measured optimum input resistance as a function of frequency for the low-noise bias point.*

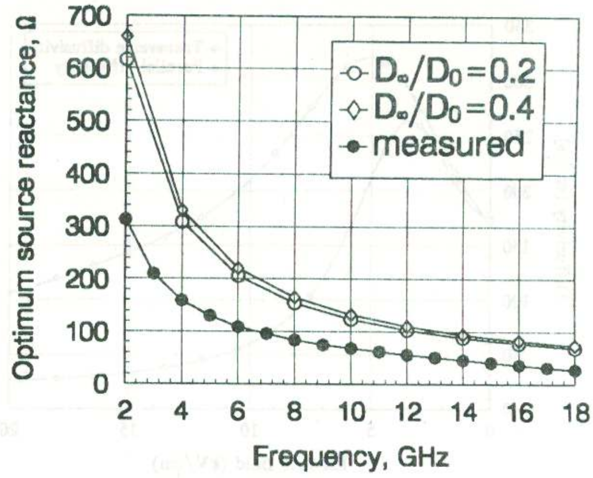

Figure 7: *Simulated and measured optimum input reactance as a function of frequency for the low-noise bias point.*

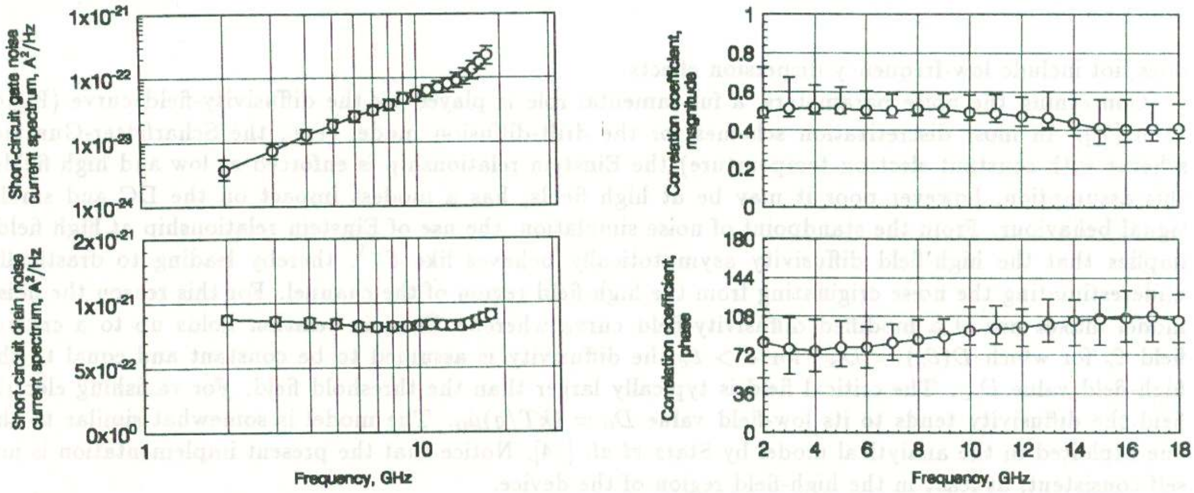

Figure 8: *Frequency behaviour of measured short-circuit drain and gate current fluctuations spectrum, and of the normalized correlation spectrum. The working point is $I_D = 20$ mA, $V_{DS} = 3$ V. For the meaning of the error bars see text.*

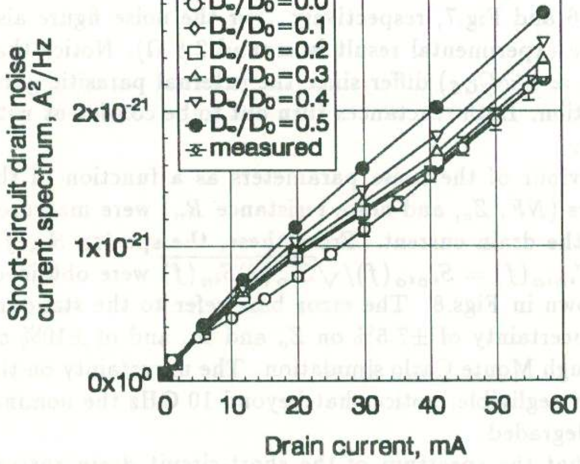

Figure 9: *Measured and simulated spectra of drain current short-circuit fluctuations versus the drain current at the onset of saturation (V_{DS}=1 V). The frequency is f = 5 GHz.*

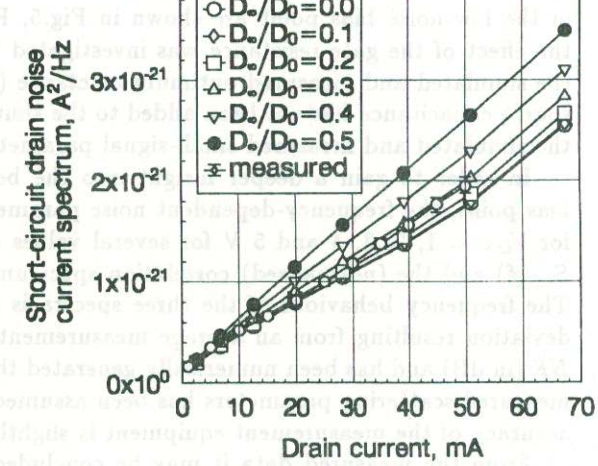

Figure 10: *Measured and simulated spectra of drain current short-circuit fluctuations versus the drain current in full saturation (V_{DS}=5 V). The frequency is f = 5 GHz.*

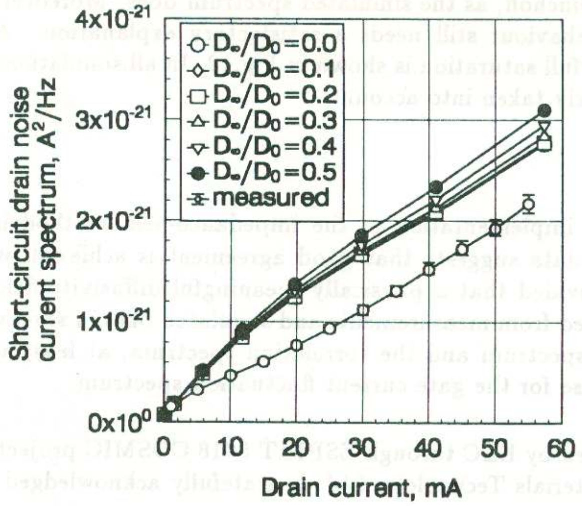

Figure 11: *Measured and simulated spectra of drain current short-circuit fluctuations versus the drain current at the onset of saturation (V_{DS}=1 V) with a modified diffusivity model $D = D(\underline{\mathcal{E}} \cdot \underline{J}/J)$. The frequency is f = 5 GHz.*

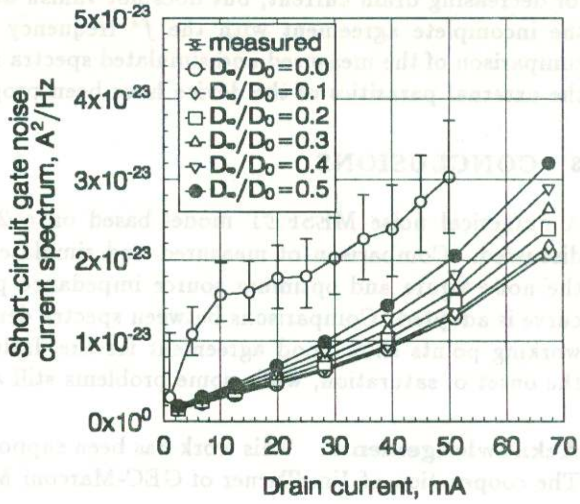

Figure 12: *Measured and simulated spectra of gate current short-circuit fluctuations versus the drain current in full saturation (V_{DS}=5 V). The frequency is f = 5 GHz.*

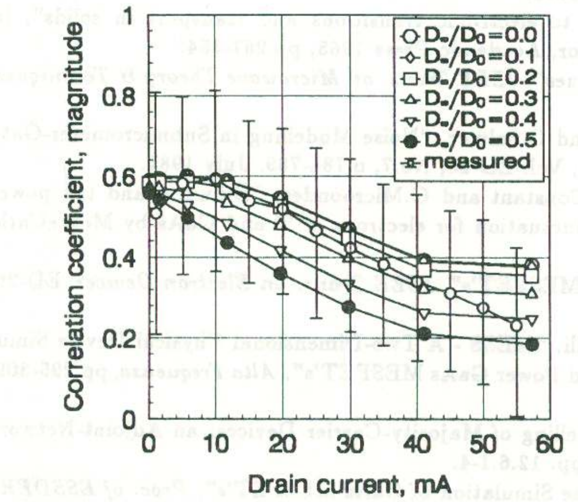

Figure 13: *Measured and simulated correlation of current short-circuit fluctuations versus the drain current at the onset of saturation (V_{DS}=1 V). The frequency is f = 5 GHz.*

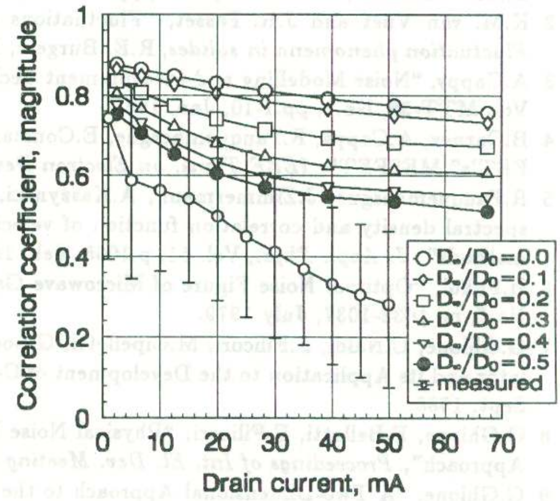

Figure 14: *Measured and simulated correlation of current short-circuit fluctuations versus the drain current in full saturation (V_{DS}=5 V). The frequency is f = 5 GHz.*

error bars that the drain spectrum is less affected by uncertainty, while this is larger for the correlation and gate spectrum. The frequency behaviour of the measured spectra suggests that the frequency-dependent noise parameters can be deduced (*cfr.* [13]) for each bias point from four parameters: $S_{i_D}(f)$ = const., $S_{i_G}(f)/f^2 \approx$ const., $|C_{i_D i_G}(f)| \approx$ const. and $\angle C_{i_D i_G}(f)| \propto f$. The same conclusions can be derived from simulated noise parameters [10].

The behaviour of measured and simulated data *versus* the bias point in now discussed. The drain current spectrum is almost linear in the drain current and does not greatly depends on V_{DS} after the onset of saturation. The same behaviour is found in the simulation, as shown in Fig.9 and Fig.10. The best agreement with measured data is again obtained for ratios of D_∞/D_0 around 0.3. Further investigations were carried out with a diffusivity model depending on the electric field component along the current density; this overestimates the drain current fluctuation spectrum, as shown in Fig.11. The correlation coefficient decreases for increasing drain current; however, a certain discrepancy exists between the measurements and the simulation, at least in the saturated region, as shown in Fig.13 and Fig.14. Contrarily to theoretical estimates, the measured correlation coefficient does not increase with increasing drain voltage; thus, the agreement with the model is better at the onset of saturation. Finally, the spectrum of the gate current fluctuations still poses some problems. The measured spectrum decreases for decreasing drain current, but does not vanish at pinchoff, as the simulated spectrum does. Moreover, the incomplete agreement with the f^2 frequency behaviour still needs a satisfactory explanation. A comparison of the measured and simulated spectra in full saturation is shown in Fig.12. In all simulations the external parasitics of the device have been properly taken into account.

3 CONCLUSIONS

A numerical noise MESFET model based on a 2D implementation of the impedance-field method is discussed. Comparison of measured and simulated data suggests that good agreement is achieved on the noise figure and optimum source impedance provided that a physically meaningful diffusivity-field curve is adopted. Comparisons between spectra derived from measurements and simulated ones in several working points show good agreement for the drain spectrum and the correlation spectrum, at least at the onset of saturation, while some problems still arise for the gate current fluctuation spectrum.

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