A CAD-ORIENTED QUASI-PHYSICAL HEMT NOISE MODEL FOR DEVICE DESIGN AND OPTIMIZATION

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ABSTRACT

The paper describes an analytical, CAD-oriented quasi-2D noise model for AlGaAs-GaAs HEMTs. The model is based on an improved version of the Ando and Itoh approach [2], in which the sheet density of the two-dimensional electron gas (2DEG) as a function of the gate bias is described by a numerical charge control model allowing for deep and shallow donors in the AlGaAs supply layer. The Ando and Itoh's power-law analytical gate control model is then fitted to the numerical charge control model; this yields accurate results in the low-noise operating region of HEMT's. Improved output conductance and low-field mobility models have been implemented to achieve a better agreement with experimental DC data. A critical discussion is presented on the effect of microscopic parameters like the effective thickness of the 2DEG, on the overall noise prediction of the model. Finally, comparisons are presented between the AC and noise model predictions and measurements carried out on a standard 0.5 μm SIEMENS HEMT.

Keywords: HEMT, noise modelling

1 INTRODUCTION

The high-electron mobility field-effect transistor (HEMT, also called MODFET or TEGFET) has become today probably the most significant low-noise component in hybrid and monolithic integrated microwave circuits (MMIC's). HEMT's exhibit superior low-noise performances with respect to MESFET's; in particular, the noise figure as a function of the drain current shows a broader minimum than in MESFET's, thereby enabling low-noise operation also at comparatively high current levels, at which the device has a high associated gain. Indeed, while in MESFET's the optimum low-noise operation is achieved at 10-20 % of the saturation current I_{DSS}, the HEMT noise figure is still near its minimum value at the gate bias point for which maximum transconductance is reached.

The noise modelling of HEMT's has been the object of extensive investigations by means of numerical quasi-2D energy-transport models [4]. These models provide a 1D implementation of the well known *impedance-field method* (IFM) for noise analysis [14]. In the IFM microscopic current density fluctuations are modelled through their correlation spectrum, proportional to the carrier density and carrier diffusivity, and the effect of the microscopic fluctuations on the open-circuit voltage fluctuations at the device terminals is evaluated through a Green's function technique [14, 9].

The basis of analytical noise modelling in GaAs FET's was laid by Statz, Haus and Pucel [15]. The Statz MESFET model is based on the classical two-zone channel approximation; the thermal noise contribution originating from the ohmic part of the channel and the diffusion noise [14] in the saturated part of the channel are separately evaluated by means of an approximate, analytical implementation of the IFM. Apart from the pioneering studies of van der Ziel and Wu [16, 17], in which the noise from the saturated part of the channel was not considered, the Pucel approach was extended to HEMTs by Brookes [3]; Brookes's treatment exploits a very simple, linear charge control model. Significant improvements were later proposed by Ando and Itoh [2], whose model is based on a more refined nonlinear charge control model yielding a better approximation near pinch-off and allows for noise contributions from the ohmic and saturated part of the channel. Brooke's model can be considered as a particular case of Ando and Itoh's model. In both models the charge control does not include the two-dimensional electron gas (2DEG) saturation, which takes place at low gate bias and is included *e.g.* in the Roblin *tanh* 2DEG control model [12].

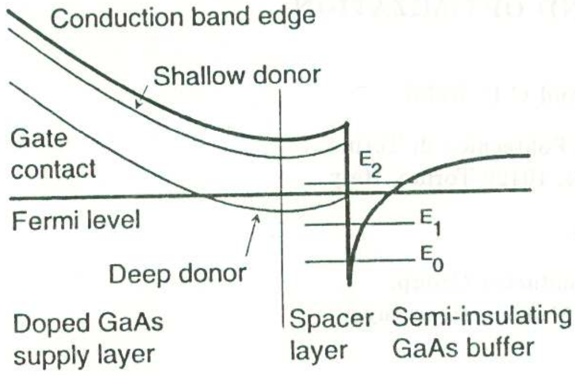

Figure 1: *Band structure of HEMT under the gate contact.*

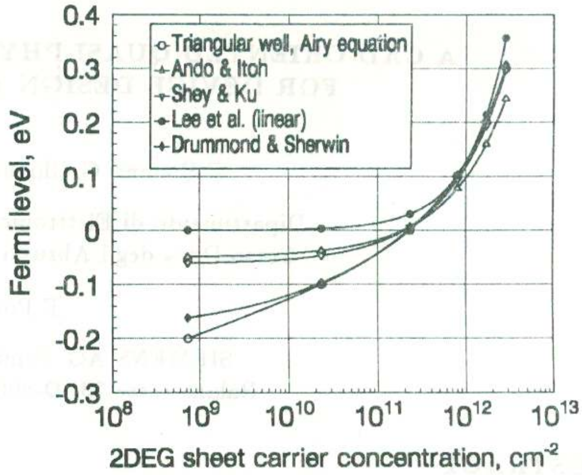

Figure 2: *Comparison between several control models $n_s(E_F)$ for the two-dimensional electron gas.*

The Ando and Itoh model is fraught with a significant limitation - the gate charge control model is based on a simple depletion approximation of the AlGaAs layer, in which only fully ionized shallow donors are considered. In the present work, this limitation is overcome by exploiting a completely numerical charge control model, similar to the one in [11], which accounts for the incomplete ionization of deep and shallow levels in the supply layer and allows for Fermi electron statistics. The analytical power-law charge control of Ando and Itoh is then fitted to the control curve derived from the numerical charge control model. Among the additional features of the model, a position-dependent initial mobility coupled to a two-piece velocity-field curve was introduced, which gives closer agreement to the VI characteristics in the linear region. On the other hand, the analytical model does not include, at least in its present version, the gain compression at low gate bias due to the saturation of the 2D electron gas, nor does it include the so-called parasitic MESFET, since those phenomena are not particularly relevant to the low-noise device operation, which takes place near the optimum gain point. Finally, the output resistance is modelled through the Pavlidis approach [10, 8].

The paper is structured as follows. Section 2 is devoted to a brief description of the model implemented, while Sec. 2.1 presents a critical discussion on the effect of the charge control law on the simulated noise figure. Finally, in Sec. 3 some results are presented concerning comparisons with experimental data on a 0.5 μm SIEMENS device.

2 THE ANALYTICAL MODEL

The analytical HEMT DC and AC model is based on the two-piece linear approximation for the velocity-field relation, which allows the channel to be divided into two regions. For region I, Ohm's law and a charge-control analytical model are valid, while in region II the electrons travel at their saturation velocity. The charge control model of the HEMT makes use of two models: a quantum charge control model, whereby the sheet carrier density n_s of the 2DEG is given as a function of the Fermi level E_F within the potential well (see Fig.1); a gate control model, which relates the electric field in the well, and therefore at the interface between the buffer layer and the spacer layer, with the potential profile in the supply layer and therefore at the gate contact. Following Ando and Itoh [2], the analytical charge-control model is based on the Shey and Ku [13] non-linear approximation of the $E_F(n_s)$ relation, rigorously obtained from a self-consistent analysis of Poisson's and Schrödinger's equations in the triangular quantum well.

The Shey and Ku formula is a polinomial approximation of the $E_F(n_s)$ relation derived numerically from a self-consistent solution:

$$E_F = \gamma_f n_s^{2/3} - E_{F0}, \tag{1}$$

where $\gamma_f = 0.0315 \times 10^{-22/3}$ eV $\cdot$ cm$^{4/3}$ and $E_{F0} = 50$ meV for an AlGaAs/GaAs modulation doped structure.

The Shey and Ku approximation of the relationship $E_F(n_s)$ can be considered as an improvement with respect to the simple linear approximation initially proposed by Delagebeaudeuf and Linh [5] and

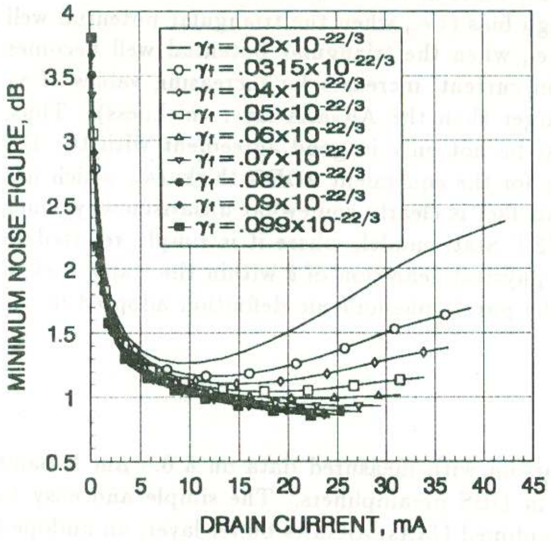

Figure 3: *Behaviour of minimum noise figure as a function of gate bias for several values of the charge control parameter γ_f.*

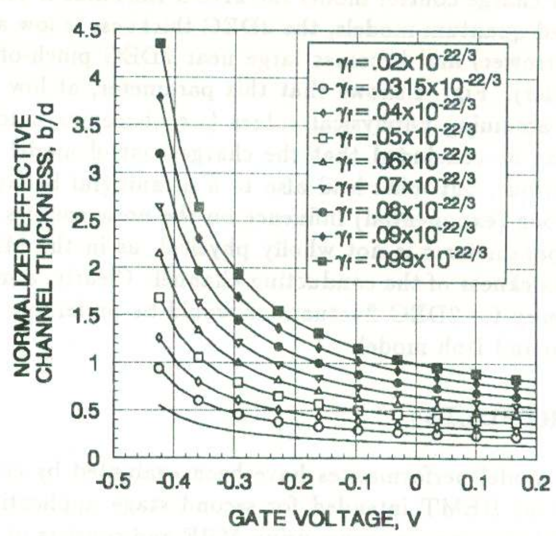

Figure 4: *Behaviour of normalized effective thickness of two-dimensional electron gas as a function of gate bias for several values of the charge control parameter γ_f; d is the thickness of the AlGaAs layer (supply layer and spacer).*

adopted in the Lee and Morkoç model [7]. Although better fitting formulae can be found, see *e.g.* [6] and references therein, the Shey and Ku relation is a reasonable compromise between accuracy and complexity. Examples of several approximations to the 2DEG sheet density as a function of the Fermi level are shown in Fig.2; the curve labelled "triangular well" is a numerical solution obtained by modelling the energy spectrum by means of the asymptotic eigenvalues of the Airy equation.

In order to lead to a fully analytical treatment, the Ando and Itoh model makes use of the *depletion approximation* in the doped AlGaAs layer to solve the one-dimensional Poisson's equation perpendicular to the gate direction.

The Ando [2] DC and AC model has been improved by the Pavlidis [10] substrate resistance and a gate voltage dependent initial mobility. These new features improve, respectively, the output resistance and the transcharacteristic of the modelled device. However, it should be noted that the effect of the substrate resistance path on the channel noise source turns out to be negligible and can therefore be discarded.

2.1 Effect of the charge control model on the noise parameters

Charge control models are usually meant to provide an accurate approximation to the DC curves of the device. Their effect on the noise performances is less trivial, and will be discussed here in detail. As already recalled, the present charge control model is based on the numerical solution of the Poisson equation perpendicular to the gate direction. In order to allow the analytical treatment required by the noise model to be carried out, the coefficients γ_f and E_{F0} of Eq. (1) of the Shey and Ku model, also exploited by Ando and Itoh, are estimated by means of a least squares fitting between numerical and analytical [2] charge-control models. Since the analytical charge-control model is unable to account for the saturation of the 2D electron gas at low gate bias, gain compression at low gate bias cannot be simulated. Thus, the fitting of the analytical model is confined to the region below the maximum g_m bias, which is, on the other hand, the common low-noise operating range.

Investigations on the noise figure resulting from the Ando and Itoh model have pointed out a strong dependence of the behaviour of minimum noise figure *versus* the gate bias from the γ_f coefficient of Eq. (1). This effect is shown in Fig. 3, where the minimum noise figure of the 0.5 μm SIEMENS HEMT (further data are reported in the next section) is plotted as a fuction of the drain current for different values of the γ_f parameter, with $E_{F0} = 0.1469$ eV and at $V_{DS} = 2$ V. It can be seen that the typical "U" shape of the minimum noise figure of microwave FETs is obtained for a γ_f value as close as possible to the one actually suggested by Ando [1], *i.e.*, $0.0315 \times 10^{-22/3}$ eV $\cdot$ cm$^{4/3}$. The physical reason of this behaviour can be traced back to the fact that the charge control model is connected to the capacitance of the 2DEG and therefore, according to the definition in [5], to the *effective 2DEG thickness b*. In the linear charge control model the 2DEG thickness is constant, while in the Shey and Ku model, as in more refined quantum models, the 2DEG thickness is low at high bias (*i.e.*, when the triangular potential well is narrower) and becomes large near 2DEG pinch-off (*i.e.*, when the triangular potential well becomes broader). Fig. 4 shows that this parameter, at low drain current, increases for increasing values of γ_f thus assuming unphysical values (*i.e.*, becomes much larger than the AlGaAs layer thickness). Thus, it may be concluded that the charge control model must be not only in good agreement with the DC behaviour, but must lead also to a meaningful behaviour for the equivalent 2DEG thickness, which has a strong (exponential) influence on the noise sources. This fact is clearly somewhat unsatisfactory, since the parameter b is not wholly physical, as in the MESFET Statz model, where it is simply referred to the thickness of the conducting channel. Clearly, a more physical definition of b within the framework of a theory for 2DEG fluctuations would be preferable to the purely phenomenic definition adopted in the Ando and Itoh model.

3 RESULTS

The model performances have been evaluated by comparison with measured data on a 0.5 μm X-band Siemens HEMT intended for second stage applications in DBS preamplifiers. The simple and easy to model structure is grown using MBE and consists of an undoped GaAs/AlGaAs buffer layer, an undoped AlGaAs spacer layer, a homogeneously doped supply layer and a highly doped cap layer. By proper adjustment of the physical supply layer thickness around its nominal value, and the introduction of the Pavlidis model for the output resistance, good agreement was found on the DC curves (Fig.5) and on the g_m curve (Fig. 6). As already recalled, gain saturation is not included in the present version of the model.

AC measurements of scattering parameters, minimum noise figure and associated gain were carried out on a packaged device. The package parasitics were then deembedded from the scattering parameters and chip S-parameters were derived. For the low-noise bias point a lumped small-signal equivalent circuit was then extracted (Fig. 9); the chip S-parameters and the lumped parameter fitting are show in Fig.7 and Fig.8. For the physical simulation of the noise figure and associated gain of the device a simple equivalent circuit was adopted for the intrinsic device [15, 2] on the basis of the small-signal parameters derived from the analytical model, and the remaining elements were estimated according to the measured equivalent circuit. In agreement with the discussion in [15, 2] the capacitive feedback between gate and drain plays a far larger role on the associated gain than on the noise figure. In Fig.10 a comparison is presented between the in-package measured noise figure and the simulation, as a function of the drain current; the operating frequency is 12 GHz. The effect of package parasitics, which have not been added to the simulation, can be estimated to lead to a decrease of the noise figure of about 0.1 dB. Also in this case, the agreement between measurement and simulation can be considered as satisfactory. Similar remarks also apply to the associated gain, shown in Fig.11. In order to obtain a good agreement between the U-shaped behaviour of the simulated and measured noise figure, a proper choice of the charge control parameter γ_f was needed, as already discussed in the previous sections. Further investigations will be performed in the future on more sophisticated HEMT structures.

4 CONCLUSIONS

An analytical HEMT noise model has been developed within the framework of Ando and Itoh's theory [2]. With proper modifications, the model shows good agreement with experimental data measured on a 0.5 μm standard SIEMENS HEMT. The effect of the charge control model on the noise figure through the equivalent 2DEG thickness has been stressed. Further investigations will concern the development of a noise model based on an improved charge control model allowing for 2DEG saturation, and a better physical understanding of the role played by the 2DEG thickness.

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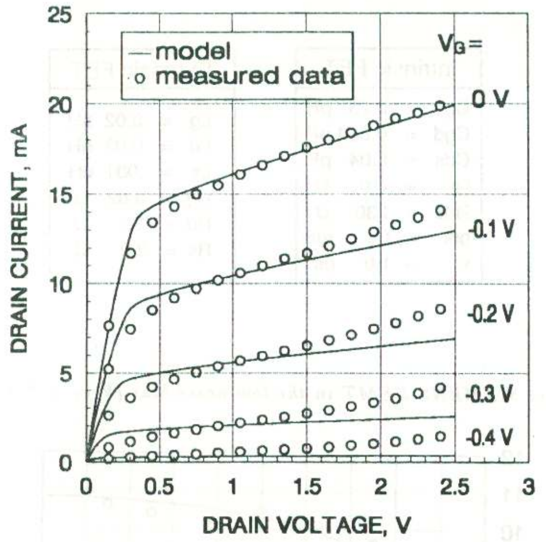

Figure 5: *Measured and simulated DC curves of standard 0.5 μm SIEMENS HEMT.*

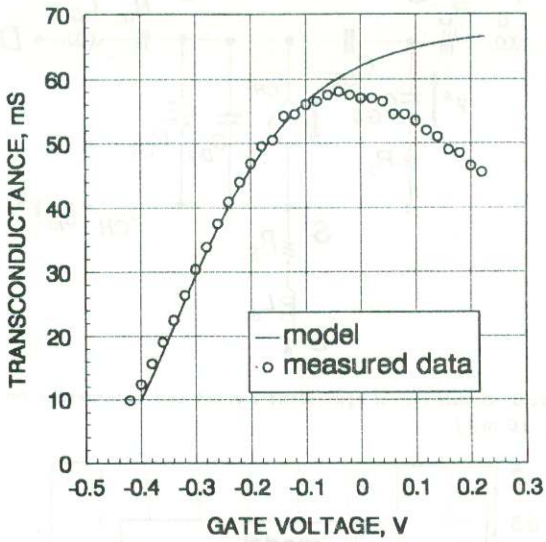

Figure 6: *Measured and simulated transconductance of standard 0.5 μm SIEMENS HEMT in saturation (V_{DS} = 2 V).*

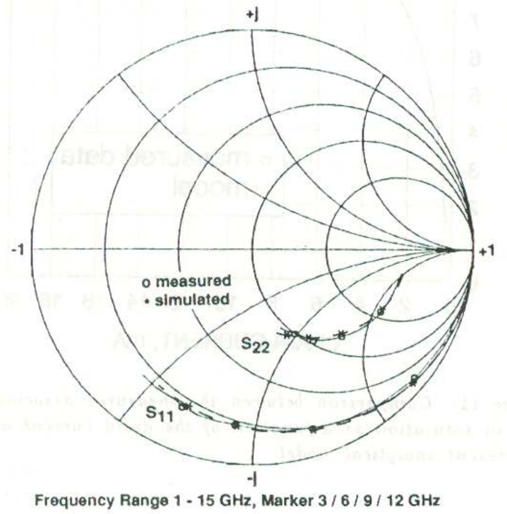

Figure 7: *Scattering parameters S_{11} and S_{22} in the low-noise bias point (V_{DS} = 2 V, I_D = 10 mA): comparison between measurements and the lumped equivalent circuit in Fig.9.*

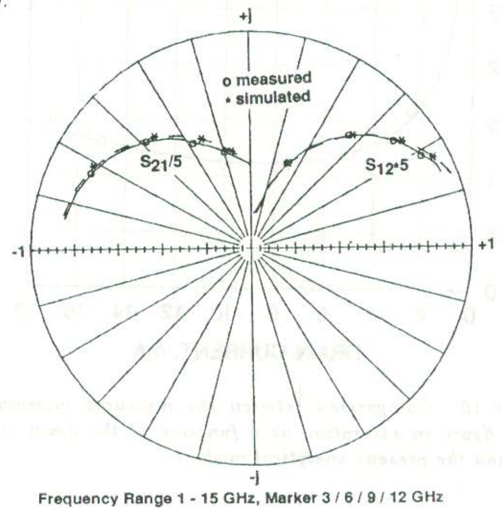

Figure 8: *Scattering parameters S_{12} and S_{21} in the low-noise bias point (V_{DS} = 2 V, I_D = 10 mA): comparison between measurements and the lumped equivalent circuit in Fig.9.*

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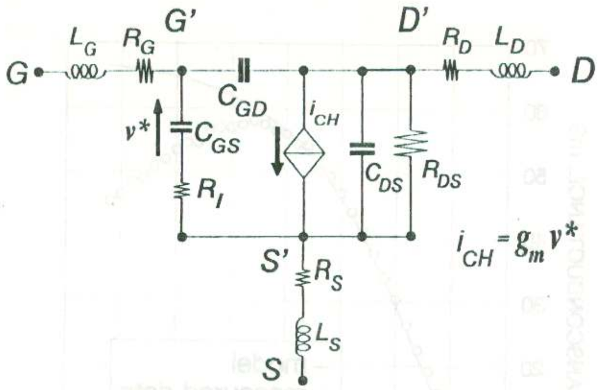

Intrinsic FET			
Cgs	=	0.23	pF
Cgd	=	0.054	pF
Cds	=	0.04	pF
Ri	=	4.0	Ω
Rds	=	230	Ω
gm	=	63	mS
τ	=	1.0	ps

Extrinsic FET			
Lg	=	0.02	nH
Ld	=	0.03	nH
Ls	=	.001	nH
Rg	=	0.82	Ω
Rd	=	3.5	Ω
Rs	=	3.2	Ω

Figure 9: *Small-signal equivalent circuit and parameters for 0.5 μm SIEMENS HEMT in the low-noise bias (V_{DS} = 2 V, I_D = 10 mA).*

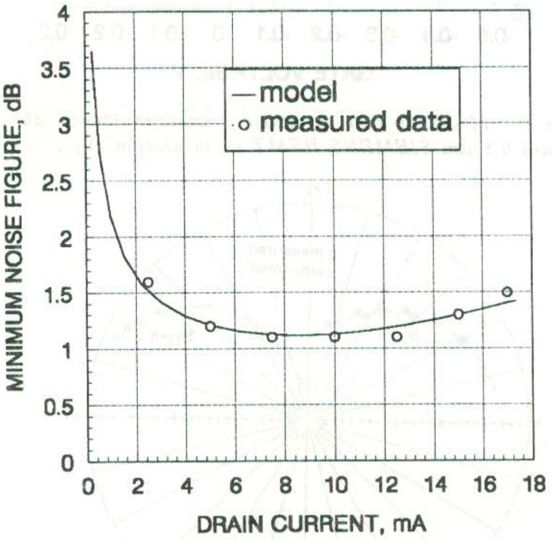

Figure 10: *Comparison between the measured minimum noise figure in saturation as a function of the drain current and the present analytical model.*

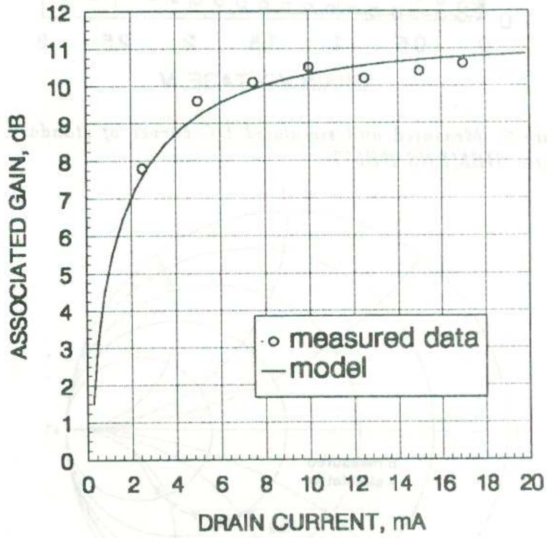

Figure 11: *Comparison between the measured associated gain in saturation as a function of the drain current and the present analytical model.*

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