SIMULATION OF TEMPERATURE DEPENDENCIES USING A NEW AND CAD SUITABLE PHYSICAL GAAS-MESFET MODEL INCLUDING THE ELECTRON PREHEATING EFFECT

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Abstract — **A new physical model for a fast simulation of short channel MESFETs is presented. New analytical approximations for the description of the velocity-overshoot are the basis of a fast physical model named TRISTAN (TRansistor modelling Including bias dependent Saturation velocity, Temperature dependencies and Analysis of Noise). A description of Monte-Carlo results concerning transport and noise properties by means of new analytical formulas also enables an extreme fast access to the material properties. TRISTAN results agree well with experimental data for the noise and small signal equivalent circuit parameters in a wide temperature range down to 27 K. Furthermore it is explained how the electron preheating causes a drastically reduced overshoot effect in some real devices.**

I. Introduction

Because of the increasing capability of computers for the circuit design using CAD programs analytical models drawn from measured data of parameter sets from suppliers, are more and more replaced by physical based approaches. For the physical simulation of FETs different approximations of the stationary relationship between the carrier velocity v_{static} and the electric field E are used in order to get analytically based models for HEMTs [1] or MESFETs like in the 'classical' *Pucel-Haus-Statz* (PHS) model [2]. Such approaches disregard the velocity overshoot occurring in GaAs at gate lengths less than $1\,\mu$m [3, 4]. This paper introduces a new analytical approximation for the velocity overshoot and a new principle of subdividing the channel. One of the results of this approach is a carrier velocity, which depends on both gate length as well as bias. Other short channel effects like the extension of the space charge region towards drain and the electron preheating effect are included. The last effect is influenced by surface states [5, 6]. The material description includes analytical formulas to fit results obtained from Monte-Carlo simulations. There are data sets available for a temperature range from 27 K to 400 K and $10^{16}\,\text{cm}^{-3}$ to $3 \times 10^{18}\,\text{cm}^{-3}$ for the doping level.

II. Material Description: Transport and Noise Properties

A. Stationary Transport

Results of a Monte-Carlo simulation of the stationary behaviour of the electrons in N-GaAs have been fitted using a new analytical relation in order to meet the dependence of the carrier velocity v_{static} on the electric field strength E. Other descriptions exist for the energy $w(E)$, the effective mass $m^*(E)$ and the electron temperature $T_e(E)$. For example the relation for $T_e(E)$ includes 8 parameters, which are all functions of the lattice temperature T and the doping level N_D described by means of simple analytical relations also. For noise considerations the electron temperature T_e is used to define a spectral power density D using

$$D = \frac{kT_e}{m^*}\tau_m \qquad (1)$$

where the momentum (or velocity-) relaxation time τ_m can be deduced using the MC results. The name of this value is 'diffusivity' because in case of low field strength it becomes equal to the diffusion constant. In Fig. 1 the $D(E)$ relation is depicted. One remarkable fact is that for high fields a decreasing temperature T enlarges the spectral noise power density D due to a higher momentum relaxation time[1] τ_m and a high temperature T_e, which is nearly unchangend by T.

B. Nonstationary Transport

For high field conditions, i.e. $E_m > E_c$ the electrons in GaAs are able to reach velocities larger than predictable from the static characteristics [7]. The behaviour of electrons entering a region (at position $x = 0$) with

[1] Due to a reduced number of impacts with phonons.

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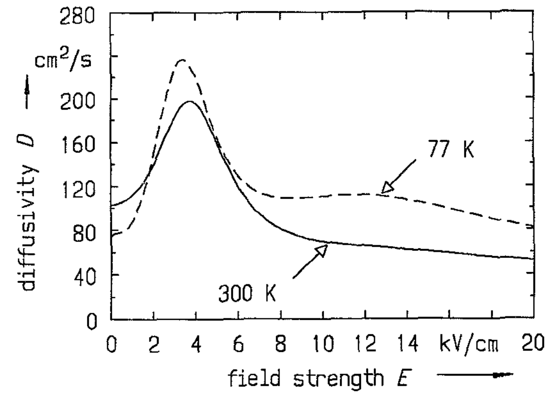

Fig. 1: Diffusivity of GaAs.

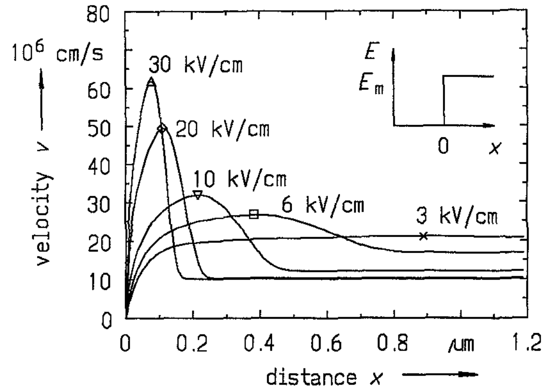

Fig. 2: Velocity overshoot versus distance in GaAs (analytical approximation, see [6]) for different E_{m} values.

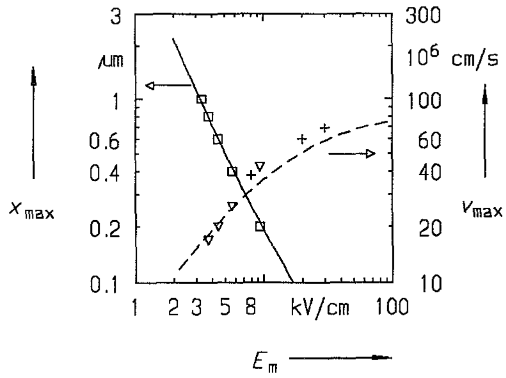

Fig. 3: Comparison of the velocity maximum and its position for a field step situation. Monte-Carlo results: symbols ([3]: ▽, □ and [8]: +), TRISTAN: ——— and – – – .

a high electric field strength E_{m} is illustrated in Fig. 2 and described by *Teitel* [4] in detail. As illustrated in this figure, the essences are an increasing maximum velocity v_{max} and a decreasing x_{max} with increasing field steps, where x_{max} is the position of v_{max} indicated by the symbols in Fig. 2.

The main feature of TRISTAN is the usage of the following equations in order to take into account this effect:

$$v_{\mathrm{max}} = \frac{\mu_{\mathrm{eff}} E_{\mathrm{m}}}{1 + \frac{\mu_{\mathrm{eff}} E_{\mathrm{m}}}{v_\infty}} \qquad (2)$$

and

$$x_{\mathrm{max}} = \frac{w_{\mathrm{c}} - w_0}{\mathrm{e} E_{\mathrm{m}}} \left(1 + \frac{E_1}{E_{\mathrm{m}}}\right). \qquad (3)$$

Because of the simple form of these relations the analysis of one bias point reduces to the evaluation of one quadratic equation. Anyway the analytically calculated values of v_{max} and x_{max} agree well with corresponding Monte-Carlo results of field step simulations as shown in Fig. 3. In this way the usage of the critical energy $w_0 = 0.17\,\mathrm{eV}$ as a fixed parameter replaces the usage of the critical field strength in the old PHS model in order to account for the velocity overhshoot. The other parameter was found to be $v_\infty = 8.56 \times 10^7\,\mathrm{cm/s}$.

III. SIMULATION PRINCIPLE

The proposed method uses the concept of subdividing the FET channel into two regions, following the PHS model [2]. In order to describe the high-field region, the analytical solution of the two-dimensional Poisson equation given in [9] is adopted. As depicted in Fig. 4 a field step occurs in the low field region and may cause a velocity overshoot. The basic idea in TRISTAN is to set the border between the high field region and the low field region equal to the position which is accompanied with the maximum carrier velocity in the channel and with the critical energy w_{c}: $\ell_1 = x_{max}$. That is reasonable because at larger values of x when the velocity decreases due to an enhanced scattering into higher valleys (because of the high electron energy), the carrier density has to become larger resulting in a strong increasing electric field.

One of the important features of TRISTAN is to take into account that in case of a high surface charge density especially in the recess region near the gate edge of the source side a lower channel cross section yields a higher field strength. Like indicated in Fig. 4 a high field strength for $x < 0$ causes a higher energy w_0 of the

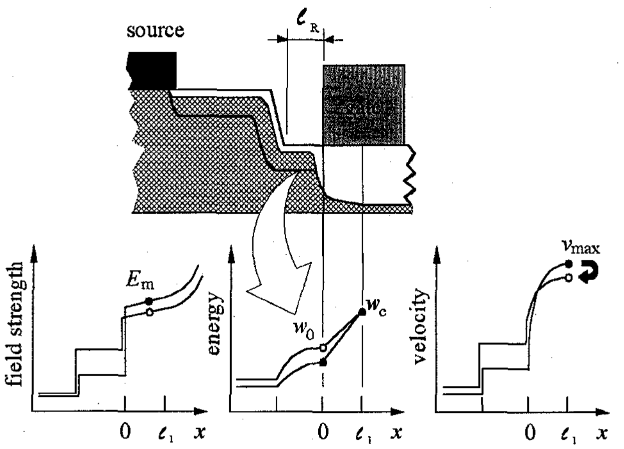

Fig. 4: The result of the electron preheating in the region below the recess at the source side gate edge.

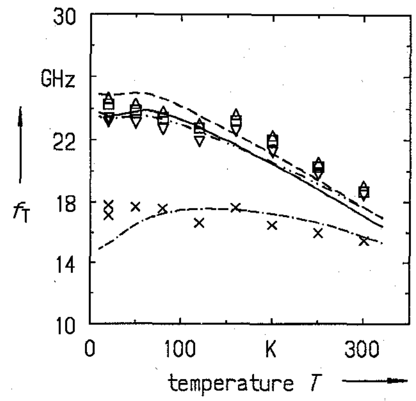

Fig. 5: Temperature dependence of the transit frequency (conditions and symbol meaning see Fig. 6).

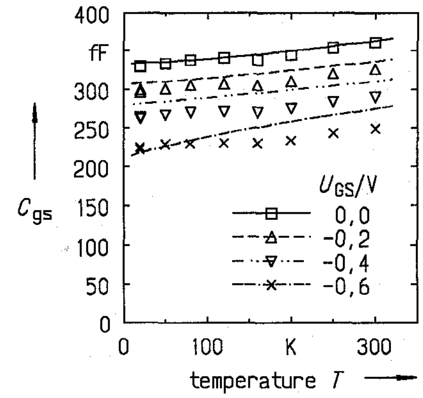

Fig. 6: Temperature dependence of the gate-source capacitance at different gate-source voltages U_{GS}. The symbols represent measurements and the lines indicate TRISTAN results.

electrons at $x = 0$, i.e. preheated, hot electrons enter the active region. The theory points out that the energy difference $w_c - w_0$ is responsible for the intensity of the velocity overshoot. Because of a nearly constant (device voltage controlled) x_{max}, Eq. (3) predicts for lower channel cross sections (due to a higher surface charge density) a lower field step height E_m and so a reduced overshoot effect. In that way it can be deduced a drastically reduced velocity overshoot[2] effect in case of realistic values for a rest recess length of $\ell_R \approx 0.1\,\mu$m. That seems to be the main reason for the (nearly) absence of velocity overshoot in some real devices.

The small signal parameters are evaluated numerically by varying the terminal voltages. The noise sources are determined using the 'impedance field method' similar to [10, 11]. Temperature dependencies have been introduced by the usage of temperature dependent parameters in the description of the transport and noise relations.

IV. Results and Discussion

In this section is reported a comparison of measured results (symbols) with TRISTAN (lines) for a $0.5\,\mu$m gate length GaAs MESFET. From the temperature dependence of the transit frequency f_T given in Fig. 5 at fixed gate-source voltages U_{GS} a temperature shift of the threshold voltage of $dU_t/dT = -0,6\,$mV/K was deduced. The temperature dependence of C_{gs} given in Fig. 6 is influenced by U_t and the ε_r variation with T. Due to the higher carrier velocities the transit frequency becomes higher at lower temperatures.

One interesting feature revealed by our study is that there can be found as well in theory as in the measured data a local noise figure minimum (Fig. 7). The reason for this behaviour is as follows. With decreasing temperature a higher carrier velocity in the channel causes a higher transconductance, gain and transit frequency and gives an improved (suppressed) noise figure. At the other hand lower temperatures enlarge the inherent spectral noise power density D of GaAs (see D for high fields in Fig. 1) and yield a higher noise figure. In case of devices with high parasitics (e.g. high source resistance) corresponding to [12] a monotonous drop of the noise figure with decreasing temperature can be found.

[2] Compared to theoretical values up to $v_\infty = 8 \times 10^7$ cm/s.

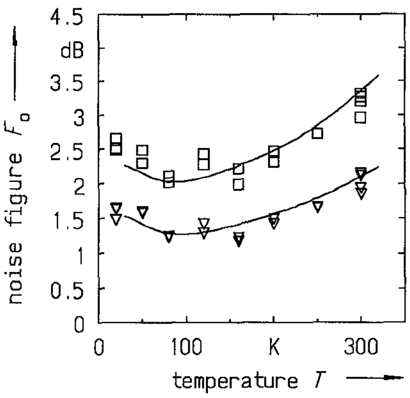

Fig. 7: Temperature dependence of the noise figure at $U_{GS} = 0\,V$ and $U_{GS} = -0.5\,V$ (minimum noise figure condition) at 12 GHz.

V. Conclusion

A new physical MESFET model named TRISTAN has been developed which enables the user to consider short channel devices at different temperatures. The simulation method is based on the usage of the critical electron energy and can be extended to other FETs such as JFETs or HFETs. Due to the use of implicit but analytical formulas the model is fast enough to become suitable for CAD-applications. By means of TRISTAN it is possible to explain that the electron preheating suppresses the appearance of the velocity overshoot. Furthermore, it was shown that the relative minimum of the noise figure with respect to the ambient temperature is caused by the increasing inherent spectral noise power density in GaAs for lower temperatures.

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