MINIMOS 3: A MOSFET Simulator that Includes Energy Balance

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Abstract—**We present a model for hot carrier transport which is implemented in the device simulator MINIMOS 3. A brief resume of the model is given. We present various results which were calculated with this new model. We show that the *I-V* characteristics of a MOSFET can be calculated from L_{eff} = 10 μm down to L_{eff} = 0.9 μm with one parameter set. Modifications of carrier and current distributions are presented that show how hot carrier effects tend to smooth these distributions. Implications are discussed how a self-consistent carrier temperature can be used to model impact ionization and oxide injection.**

I. INTRODUCTION

THE CONTINUOUS trend in recent years to miniaturize feature sizes in integrated circuits necessitates a reformulation of the basic semiconductor equations for the purpose of modeling. It was realized long ago that a straightforward extension of the classical semiconductor equations would have to include the energy balance of field-driven carriers [1]. In 1970, Blotekjaer's work appeared in which a suitable set of equations was proposed for modeling [2]. These equations were used in the following years by many groups with more or less encouraging results; see, for instance, [3]–[6]. Surprisingly enough, at present there is no code available that takes heed of the modified physics and is also reliable enough to be used as an engineering tool.

In this work we introduce the MOSFET simulation program MINIMOS 3, which is a development of MINIMOS 2, a well-established tool [7]. Besides a thorough reconsideration of some numerical and device modeling aspects, MINIMOS 3 also provides a hot-carrier model that takes into account the effective carrier heating [8], [9].

Moreover, we will concentrate on Si devices only, being fully aware of the fact that there is a large body of work done on GaAs devices [10]. A more complete discussion of our work in comparison with the earlier work of Blotekjaer [2] is given in [11] and will not be repeated here.

In Section II of this work we will discuss the model, and we show in Section III how this new model alters the internal distributions of the MOSFET. This work closes in Section IV with a brief discussion of our findings and their implications for future device modeling.

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II. THE MODEL

The model for hot-carrier transport that has been implemented in MINIMOS 3 is based on the work of Hänsch and Miura-Mattausch [11]; see also Hänsch [12]. Reference [11] follows very closely the work of Blotekjaer [2] with the distinction that in the first place a different Ansatz for the distribution function was chosen, and secondly, and more importantly, the relaxation time approximation was not used. This provides a closed set of equations for the particle density n, particle current density $\underset{\sim}{j}$, energy density $\langle \epsilon \rangle$, and energy current density $\underset{\sim}{v}_{\langle \epsilon \rangle}$ (compare [12, eqs. (2.7)–(2.11)]).

A self-consistent mobility and energy relaxation time have been derived rigorously (compare [12, eqs. (2.15) and (2.16)]). This very general approach provides a self-consistent formulation concerning the macroscopic variables. It covers particle as well as energy balance in a closed form. Unfortunately it would require the development of a new code to be utilized as a simulation tool. Therefore, Hänsch and Miura-Mattausch presented an approximate solution of these equations that could feasibly be used in conventional codes. Their rationale was based on the observation that, strictly speaking, the classical current equation is rigorously valid in the limit of small fields. High-field effects enter through the saturation of the drift velocity. They are accounted for using a heuristic field-dependent mobility model, which is a local field-dependent function. Following these classical ideas, Hänsch and Miura-Mattansch used a local field dependent model of the mobility μ and thermal voltage U_T to be used in the modified current relationship (compare [12, eq. (2.4)] with $\langle \epsilon \rangle = q \frac{3}{2} U_T n$)

$$\underset{\sim}{j} = q\mu n \underset{\sim}{E} + q\mu \operatorname{grad}(U_T n). \tag{1}$$

To model μ and U_T, however, a local solution of the general equations was performed. To this end they dropped all spatial derivatives so that the complicated system of differential equations turned into a simple algebraic equation for the energy density and in turn the mobility. This rather drastic step is justified by the observation that, in conventional simulation, mobility

models are inferred from drift velocity measurements in constant electric field. The inhomogeneous situation is then accounted for by an appropriate driving force [13]. Assuming infinite bulk material in the first place and replacing the electric field by the driving force F, they obtain for the electron mobility

$$\mu_{LIF} = \frac{2\mu_{LI}}{1 + \left(1 + \left(2\frac{\mu_{Li}}{v_{\text{sat}}}F\right)^{\beta}\right)^{1/\beta}} \tag{2}$$

with $\beta = 2$, and for the thermal voltage

$$U_T = U_{T_0} + \tfrac{2}{3}\tau_\epsilon v_{\text{sat}}^2(1/\mu_{LIF} - 1/\mu_{LI}). \tag{3}$$

Here, μ_{LI} is the low-field mobility containing lattice and impurity scattering, τ_ϵ is the energy relaxation time, and v_{sat} is the saturation velocity. A mobility of the form of (2) has proposed by Jaggi in 1969 [14]. In a recent publication by Ohno, similar expressions are presented [15]. However, these were not derived but constructed by assuming a convenient dependence of the momentum relaxation time on the thermal voltage.

The expressions for the mobility and thermal voltage as they stand in (2) and (3) are valid for an infinite medium. It is well known, however, that the existence of the surface reduces the channel mobility considerably for high gate voltages [16]. In [11] Hänsch and Miura-Mattansch considered this too. They were able to extend their approach to a semi-infinite medium with a field attracting the carriers toward the surface. This involves not only replacing the low-field mobility

$$\mu_{LI} \to \mu_{LIS} = \frac{\mu_{LI}}{1 + \dfrac{G(x_\perp)}{1 + G^2(x_\perp)}\left(\dfrac{\mu_{LI}}{v_{\text{sat}}}E_\perp\right)^2} \tag{4}$$

but also gives an anisotropy correction

$$\mu = \mu_{LISF}\begin{pmatrix} 1 - \dfrac{1}{1 + G(x_\perp)\dfrac{\mu_{LIS}}{\mu_{LISF}}} & 0 \\ 0 & 1 \end{pmatrix} \tag{5}$$

The function G is exponentially increasing in the direction perpendicular to the interface with a typical length of a few Ångstroms. It is related to the ratio of the strongly localized surface momentum scattering rate with the bulk momentum scattering rate. Modeling $G(x_\perp)$ requires a microscopic theory of surface scattering, with emphasis on its range into the substrate. At present such a theory is not available. However, microscopic calculations of Paasch *et al.* [17] show that surface scattering is indeed of very short range. In the limit $x_\perp \to \infty$, (5) reduces to the isotropic bulk mobility (2). For $x_\perp = 0$ and $E_\perp \to \infty$, μ_{LIS} is independent of the bulk scattering rate. This is a feature that was also obtained by Schrieffer [18], and it means that very close to the surface the mobility is dominated by surface scattering alone. Equation (4) was derived presuming that perpendicular motion of the carriers is more influenced by the surface than parallel motion. This limits (4) to a finite surface scattering or $G \neq 0$ for $x_\perp = 0$.

After including the gate field dependence of the low-field mobility, the thermal voltage U_T becomes

$$U_T = U_{T_0} + \tfrac{2}{3}\tau_\epsilon v_{\text{sat}}^2(1/\mu_{LISF} - 1/\mu_{LIS}). \tag{6}$$

We still have to specify the driving force F. There is some controversy about which one is the most appropriate force in the literature [13]. The problem is that originally the local field-dependent expressions are given with $F = E$. Generalization to the inhomogeneous two-dimensional case is by no means straightforward. There are, however, two limiting cases the driving force has to obey: On the one hand it should give $F = E$ for the homogeneous situation, and on the other hand it has to give a velocity saturation for high-density gradients as well. In this situation carriers do not gain energy from the field, provided it is small, and therefore their mean velocity cannot exceed the thermal velocity, which is not necessarily the same as the high-field saturation velocity v_{sat}. Any physically motivated driving force has to fulfill these requirements. Under the present circumstances a saturation with respect to the gradient of the thermal voltage has to be included too. We have to point out, however, that the saturation velocities for the different extreme situations are not necessarily identical. One appropriate driving force seems to be

$$F = \left|\underset{\sim}{E} + \frac{1}{n}\operatorname{grad}(U_T n)\right|. \tag{7}$$

In the limit $\tau_\epsilon = 0$, this turns into the gradient of the quasi-Fermi level. It can be shown that F itself saturates in the limit $(1/n)\nabla n \to \infty$, which ensures that indeed $E \to \infty$ and $(1/n)\nabla n \to \infty$ give different saturation velocities. However, using parameters appropriate for silicon it can be shown that both are very close, as long as $E \approx 0$ and $T = 300$ K in the second case.

All the previous expressions are equally valid for electrons and holes. There is one difference, however. Equation (2) has been derived in the effective mass approximation, which restricts the carriers to one band. This is not valid for the holes. Here we have the light hole and the heavy hole band with a mutual interaction between them. Therefore, they cannot be superposed independently. It can be shown that if an energy exchange between these two bands is properly taken account of [19], the hole mobility is given by (2) with $\beta = 1$, which is in good agreement with empirical data [13].

The low-field mobility μ_{LI} is modeled by using the expressions of Arora *et al.* [20]. The energy relaxation time is a constant within the approach used in [11]. This is also confirmed by Monte Carlo calculations at room temperature [21]. Its value as extracted from fitting I–V characteristics of n- and p-channel MOSFET gives a reasonable agreement with the corresponding Monte Carlo

values, which are of the order of 0.1 ps. For further numerical details concerning the implementation of the above model in MINIMOS 3, we refer to [8].

III. Results

Preliminary results were published in [9]. Since then we have gained a lot more experience with the MINIMOS 3 program. In particular, the automatic grid generator is now optimized. We tried MINIMOS 3 on various types of MOSFET's with different technologies. Our special attention was focused on modifications due to hot-electron effects. We also did a comparison of MINIMOS 3 and MINIMOS 2.9, which is the most advanced MINIMOS 2 version.

As a first example, we present a conventional p-channel MOSFET with 25-nm oxide thickness, 0.8-μm junction depth, and a compensation doping with surface concentration 3.5×10^{16} cm^{-3} on 2.2×10^{14} cm^{-3} bulk material. We compared data for an effective channel length from $L_{\text{eff}} = 10$ μm down to $L_{\text{eff}} = 0.9$ μm. The mobility model for MINIMOS 3 was adjusted for the longest channel length $L_{\text{eff}} = 10$ μm, to give the best fit. Here, hot-electron effects are not important, and the classical formulation is sufficient. The energy relaxation for the holes was determined by fitting the measured I–V characteristics to the simulation. This gives $\tau_\epsilon = 0.25$ ps, which is independent of the channel length. It is striking how good a fit to the measured data is accomplished by including hot-electron effects (open circles in Fig. 1) with only one parameter set. For comparison we show a simulation based on the conventional semiconductor equations that was performed with MINIMOS 2.9 (crosses in Fig. 1). Here, we adjusted the mobility model to fit the species with $L_{\text{eff}} = 1.5$ μm best. A deviation of simulation and experiment is observed for both the long-channel and the short-channel devices. To get comparable results with MINIMOS 3, one parameter set is not sufficient. If we set $\tau_\epsilon = 0$, MINIMOS 3 gives very poor results for the short-channel device; the drain current decreases by 50 percent. This is a very strong indication that indeed hot-electron effects will modify conventional carrier transport in submicrometer devices. The very same results hold true for comparable n-channel devices.

As a second example, we show in Fig. 2 the minority-carrier distributions of a p-channel device of $L_{\text{eff}} = 0.7$ μm under stress bias conditions $U_G = -2$ V and $U_D = -8$ V. This is a conventional device with a boron source-drain, an oxide thickness of 17.5 nm, and a compensation doping with a surface concentration of 3.7×10^{16} cm^{-3} on 2×10^{16} cm^{-3} bulk material. We see very clearly that classical simulation gives a very pronounced pinchoff while the new hot-electron model is somewhat smoother. The fields are only slightly affected. This can be understood by the observation that modifications are most pronounced where the carrier concentration is already lower than the doping level, and therefore doping alone determines the solution of Poisson's equation. In Fig. 3, we compare the current distributions at the drain side of the

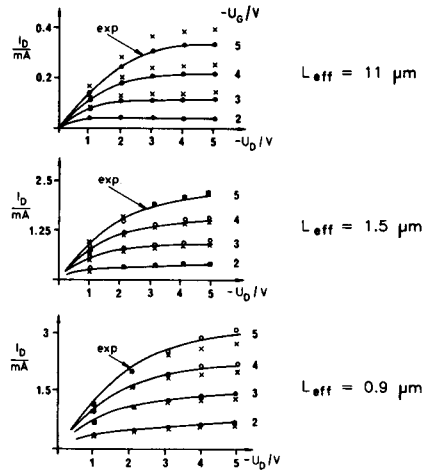

Fig. 1. I–V characteristics of a p-channel MOSFET device. For specifications, see text. Experiment: solid lines; simulation with hot-carrier model of MINIMOS 3: open circles; simulation with conventional equations of MINIMOS 2.9: crosses.

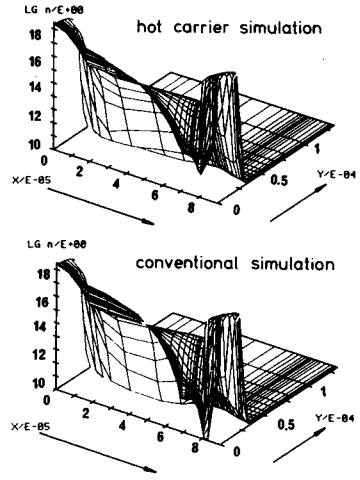

Fig. 2. Minority-carrier distribution of a p-channel MOSFET. For specifications, see text. The device is seen from the gate with the drain at the lower right side; all units are in centimeters and reciprocal cubic centimeters, respectively.

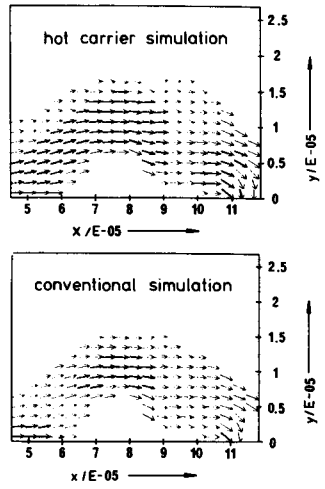

Fig. 3. Minority-carrier current density distribution. Specifications are as in Fig. 2. The plot shows the drain side of the device with the drain contact at the lower right-hand side.

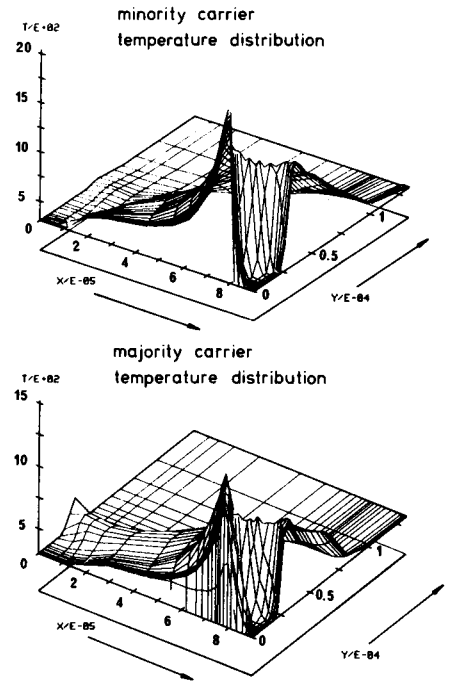

Fig. 4. Carrier temperature distribution in a p-channel device. Specifications are as in Fig. 2. The distribution is seen from the gate with the drain at the lower right side; the temperature is given in units of T_L, where T_L = 300 K is the lattice temperature.

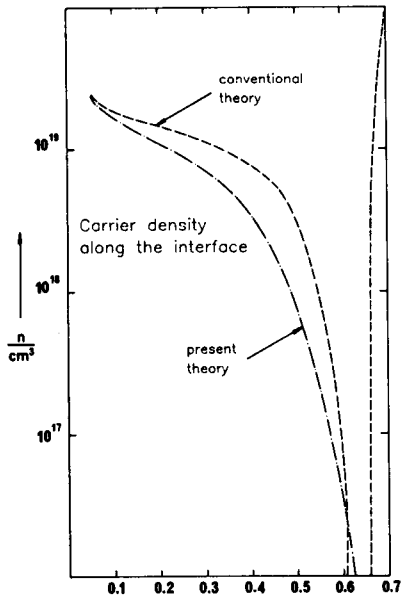

Fig. 5. Carrier density along the interface of an n-channel MOSFET. For specifications, see text. The x-scale covers the gate length with the source side at x = 0. Hot-carrier analysis: dash-dot curve; conventional analysis: dashed curve.

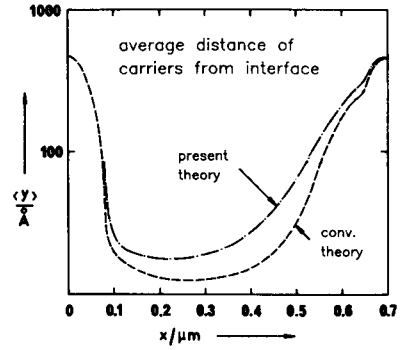

Fig. 6. Average distance of carriers from interface. Specifications as in Fig. 5. Hot-carrier analysis: dash-dot curve; conventional analysis: dashed curve.

device. The far left side is located in the middle of the channel (gate) and shows that hot-electron effects tend to broaden the channel. A pronounced redistribution of the carrier flow is observed in the high-field region. This gives a different overlap of high current levels with high-field regions, which is essential for determining such effects as impact ionization and oxide injection. As a rule of thumb our experience so far shows that

$$I_{sub}/I_{drain}/I_{hot} < I_{sub}/I_{drain}/I_{convent}$$

if we keep the parameters in the impact ionization model constant. Finally, we show in Fig. 4 the carrier temperature distributions for majority and minority carriers. It is surprising that for the same field strength the maximum hole temperature is larger than that of the electrons. It is also interesting that the maximum temperature of the majority carriers is located somewhat away from the surface while the minority carriers exhibit their temperature maximum directly at the Si–SiO_2 interface. These observations are interesting in context with recently observed degradation of submicrometer p-channel devices [22].

As a third example, we show a typical submicrometer n-channel MOSFET with 25-nm oxide thickness and effective channel length L_{eff} = 0.5 μm. This device has a phosphorus source–drain with a junction depth of 0.25 μm. The surface concentration is 7.2 × 10^{16} cm^{-3}. In Fig. 5 we show the minority-carrier concentration along the Si–SiO_2 interface from source to drain. In Fig. 6 the average distance of channel electrons with respect to interface is presented. As mentioned earlier, we observe that hot-electron effects tend to spread the channel at the cost of a decreasing surface density. The physical reason for this is in the enhanced diffusion constant in the hot-electron model.

IV. Discussion

In the previous sections we introduced a model for hot-electron transport in MOSFET devices and showed several examples utilizing this model. The results are intuitively acceptable and were partly proposed earlier [23]. We do not find a reduction of the maximum electric field strength as was suggested in a simple one-dimensional model [24].

The model is based on a local solution of a more general set of equations. This excludes overshoot effects [11], which are presumably not important in silicon devices. It is expected, however, that, for devices with less than 0.5-μm channel length, this local approximation might fail and a rigorous treatment of the general equations is required. So far we were only concerned with hot-carrier

effects that are related to certain averages of the microscopic distribution function. These averages are insensitive to the actual shape of that function. This is no longer true for the hot-electron phenomena that are related to the high energetic carriers in their distribution. These carriers cause impact ionization and oxide injection. Input data for modeling these effects require the field and current distributions in the device. As we have seen, these are modified due to hot-electron transport phenomena. Certainly a code like MINIMOS 3 gives more rigorous results on which the models can be built. With MINIMOS 3 a self-consistent carrier temperature is provided that can be used in constructing the high-energy tail of the distribution function. The central goal in the near future must be a consistent model that describes gate and substrate currents on the same footing. For this end a physical modeling of oxide injection and impact ionization is required, although it is only part of the solution [25]. However, we hope that, with the hot-carrier transport as provided by MINIMOS 3, we have a good starting point toward this goal.

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Note added in proof: Since submitting the manuscript a more fundamental understanding concerning the nature of the driving force F, in (7), has been developed. In particular one can show that this form of the driving force is a result of an asymptotic solution of the complete equations presented in [11]. In a forthcoming publication we will address this point more precisely.
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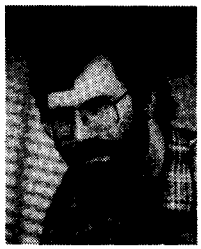

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