

## Influence of Thermal Diffusion on Submicron MOST's

B. Meinerzhagen, W.L. Engl

Institut für Theoretische Elektrotechnik, RWTH Aachen  
Kopernikusstraße 16, D-5100 Aachen, W.-Germany

Limitations of the classical semiconductor equations for Si submicron MOS-devices are being investigated. Special care must be taken if simple extensions of the classical equations are being made because this may lead to artifacts. It will be shown that taking thermal diffusion into account the drain currents remain practically unchanged down to  $L=0.3 \mu\text{m}$ , though substrate current can strongly be influenced.

### I. Introduction

The equations for electron or hole transport used in most of the existing 2D device modeling programs /4/ are based on the so called thermal equilibrium approximation (TEA) /6/. It assumes electron temperatures to be equal to the (constant) lattice temperature. This assumption is apparently wrong if velocity saturation is of noticeable influence on device behaviour.

In the channel region of advanced submicron MOS-transistors the lateral electric fields are often so large that velocity saturation is not only important in a small region near the drain but influences the electron (or hole) transport nearly along the whole channel. Therefore the TEA is invalid within almost the whole channel and it is obviously of major interest to clarify if - or to what extent - the predictive capability of the classical 2D device modeling codes is lost for submicron devices. Only the electron transport in Si devices is considered in the remainder of this paper.

### II. Theory

Dropping the assumption of a thermal equilibrium, thermal diffusion influences electron transport. The simplest expression for the electron current which takes thermal diffusion into account is given by

$$\vec{j} = -q\mu(T)(n\nabla\psi - \nabla(v_T n)), \quad (1)$$

where  $v_T$  is the thermal voltage  $kT/q$  and all other symbols have their usual meaning. The unknown electron temperature can be calculated by equations (2) and (3), where the continuity equation (2) simply expresses the conservation of electron energy.

$$-\nabla \cdot \vec{S} = \vec{j} \cdot \nabla \psi + nB(T) \quad (2)$$

$$\vec{S} = -2.5v_T(\vec{j} + q\mu n \nabla v_T) \quad (3)$$

$B(T)$  is the rate of energy loss to the lattice and  $\vec{S}$  is the energy current density. In 1D-form equations (1)-(3) follow from /6/ if the relaxation time  $\tau$  is assumed to be independent of the microscopic energy  $E$ . Similar equations have also been used in /2/ and /3/. Recently, Hänsch et al. /1/ rederived (1)-(3) using a different approach. Moreover they found for  $B(T)$  and  $\mu(T)$  the following functional forms, where the parameters  $\alpha$  and  $\tau_e$  are independent of  $T$  and  $T_0$  is the lattice temperature.<sup>1)</sup>

$$B = 1.5q(v_T - v_{T0})\tau_e^{-1} \quad (4)$$

$$\mu = \mu_0(1 + \alpha(v_T - v_{T0}))^{-1} \quad (5)$$

- 1) Different results for  $\mu(T)$  are reported in /1/ and /6/, since Stratton yielded a mobility independent of  $T$ , for  $\tau$  independent of  $E$ .

For homogeneous bulk material  $\nabla \cdot \vec{S}$  and  $\nabla(v_T n)$  vanish and equations (1)-(5) can be solved analytically yielding  $v_T$  as a local function of  $E_{\parallel} = -\nabla \psi \cdot \vec{j} / j$  and relating  $\alpha$  to more familiar physical parameters like the maximal drift velocity  $v_d$ :

$$v_T - v_{T0} = \frac{v_d^2 \tau_e}{3\mu_0} \left( \left[ 1 + 4 \left( \frac{\mu_0^2 E_{\parallel}^2}{v_d^2} \right) \right]^{\frac{1}{2}} - 1 \right) \quad (6)$$

$$\alpha = \frac{3\mu_0}{2v_d^2 \tau_e} \quad (7)$$

As an approximation for inhomogeneous material Hänsch et al. /1/ proposed to replace equations (2)-(4) by (6) and to solve Poisson's equation, electron current continuity equation (with  $\vec{j}$  given by (1), (5)) and (6) selfconsistently. They suggested this approach as a first step to include hot electron effects in electronic transport.

By theoretical reasoning formula (6) has a severe disadvantage, since thermodynamics teaches that for operating conditions near thermodynamic equilibrium (TDE) the electron temperature must approach the lattice temperature. Equations (2)-(4) are in agreement with this principle but for inhomogeneous material equation (6) obviously is not.

### III. Numerical method

The device simulation program GALENE /4/ was modified in order to allow a consideration of thermal diffusion. The nonisothermal extensions of Gummel's discretization scheme described in /5/ and /8/ were applied in a slightly modified form to discretize equations (1) and (3) in order to avoid numerical problems stemming from inappropriate discretization schemes. Moreover an extended version of Gummel's nonlinear block relaxation scheme (figure 1) was used to solve selfconsistently Poisson's equation, electron continuity equation (with  $\vec{j}$  given by (1) and excluding impact ionisation) and equation (6) or equations (2)-(4). Since only NMOS-devices under normal operating conditions are considered, TEA is

applied for holes and hole continuity equation is replaced by the usual assumption that p-imref is equal to the substrate bias. After a selfconsistent solution has been achieved, a lucky electron model is used in a postprocessing step to estimate the substrate current due to impact ionisation. A constant value of 0.1ps was chosen for  $\tau_e$ . This choice is in good agreement with the estimate reported in /7/. The low (parallel) field mobility  $\mu_0$  was the same as described in /4/.

### IV. Results

An NMOS transistor with an  $N^+$ -polygate and an effective channel length of  $0.3\mu\text{m}$  has been chosen as a test device. It is characterized by an oxide thickness of 10nm, a source and drain junction depth of  $0.12\mu\text{m}$  and a bulk doping of about  $N=10^{17}\text{cm}^{-3}$ . For threshold adjustment a shallow boron implant was assumed. Since the arsenic source drain profile of this device is very steep, it can be expected that device behaviour is strongly influenced by hot electron effects.

Results labeled classical in the remainder of this paper have been calculated based on the TEA and the field dependent mobility  $\mu(E_{\parallel})$  resulting from (5)-(7):

$$\mu(E_{\parallel}) = \mu_0 \left\{ 0.5 + 0.5 \left[ 1 + 4 \left( \frac{\mu_0^2 E_{\parallel}^2}{v_d^2} \right) \right]^{\frac{1}{2}} \right\}^{-1} \quad (8)$$

#### A) Experience with approximation (6)

Because of severe convergence problems no solution could be obtained for the test device, if approximation (6) was applied, though considerable computational efforts were made and various bias conditions were investigated. These problems are most likely caused by the nonphysical temperature distribution along the source and drain junctions introduced by (6).

Even near TDE sharp temperature peaks exist along the junctions if  $v_T$  is calculated based on (6) and classical  $E_{\parallel}$  distributions. E. g. for a bias of  $V_G=0.6\text{V}$ ,  $V_D=1\text{mV}$ ,  $V_B=0\text{V}$  the resulting maximum electron temperature at the junctions is 1583K. These

temperature distributions are by no means consistent with the classical electron density distributions near TDE, if thermal diffusion is taken into consideration. To show this the solution algorithm (figure 1) is started using classical electron density and electrostatic potential distributions supplemented by the temperature distribution resulting from (6) as starting distributions. The algorithm is stopped after the first step of the first iteration. This gives a selfconsistent solution of Poisson's and electron continuity equation including thermal diffusion with  $v_T$  kept fixed. The resulting electron density distribution differs extremely from the classical one. For the aforementioned bias this difference is so large, that electrons no longer flow from source to drain but enter the device to nearly equal parts at the source and drain electrode and leave at the substrate contact. Compared to the classical results substrate and drain current have opposite sign and increased their absolute value by factors  $10^9$  and 10, respectively. This shows that a selfconsistent solution of the fully coupled system (including thermal diffusion  $v_T$  based on (6)), provided it exists, will largely differ from the classical one. Since the bias point taken into consideration is near equilibrium this indicates a clear violation of basic principles.

Since even for higher drain voltages parts of the device are near equilibrium (e.g. parts of the source junction for  $V_B=0$ ), the same argument holds to some extent even for higher drain voltages. Therefore throughout the rest of the paper  $v_T$  is calculated using (2)-(4) only.

#### B) Influence of thermal diffusion

For six bias points selfconsistent solutions of the total system have been calculated. No convergence problem has been observed during these simulations. The six solutions cover the subthreshold and the "on" region of the  $I_D(V_G)$  characteristic with  $V_B=0$  and  $V_D=3V$ . The resulting drain currents and the lucky electron estimations for the substrate currents are summarized in table 1 and compared with classical results. As can be seen from the table the drain currents remain practically unchanged (max. diff. 1%). This is consistent with the results for 1D-structures reported in /7/ where an even more general system of equations was solved. However the influence of thermal diffusion on the (estimated) substrate current is

much larger. As shown in the table the respective values for e.g.  $V_G=3V$  differ by three orders of magnitude. The reason for this is the redistribution of electrons near the drain. This is demonstrated in figure 2 where a resulting vertical electron density profile for  $V_G=3V$  is compared with the respective classical one. The redistribution of electrons is due to the highly inhomogeneous electron temperature distribution near the drain which is shown in figure 3.

#### V. Conclusions

Though thermal diffusion was taken into account only in a simplified manner, if compared to Blotekjaers theory /3/, it is believed that three conclusions can be drawn from the above results:

- 1) Thermal diffusion has no significant influence on the drain current even for very short channel devices.
- 2) For modeling substrate current or hot carrier injection into the oxide the consideration of thermal diffusion may become important.
- 3) An oversimplified consideration of thermal diffusion can lead to both nonphysical results and convergence problems.

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VG/V	CLASSICAL		WITH TH. DIFF.	
	ID/A cm <sup>-1</sup>	IB/A cm <sup>-1</sup>	ID/A cm <sup>-1</sup>	IB/A cm <sup>-1</sup>
.4	1.89 · 10 <sup>-6</sup>	1.27 · 10 <sup>-7</sup>	1.90 · 10 <sup>-6</sup>	1.71 · 10 <sup>-7</sup>
.6	2.15 · 10 <sup>-4</sup>	7.70 · 10 <sup>-6</sup>	2.14 · 10 <sup>-4</sup>	1.56 · 10 <sup>-5</sup>
.8	1.25 · 10 <sup>-2</sup>	4.07 · 10 <sup>-4</sup>	1.23 · 10 <sup>-2</sup>	6.73 · 10 <sup>-4</sup>
1.	9.00 · 10 <sup>-2</sup>	3.66 · 10 <sup>-3</sup>	8.87 · 10 <sup>-2</sup>	4.67 · 10 <sup>-3</sup>
2.	1.18	5.42 · 10 <sup>-4</sup>	1.18	1.03 · 10 <sup>-2</sup>
3.	2.72	1.45 · 10 <sup>-6</sup>	2.73	3.57 · 10 <sup>-3</sup>

Table 1: Comparison of terminal currents for an  $I_D(V_G)$  characteristic with  $V_D=3V$  and  $V_B=0V$ .

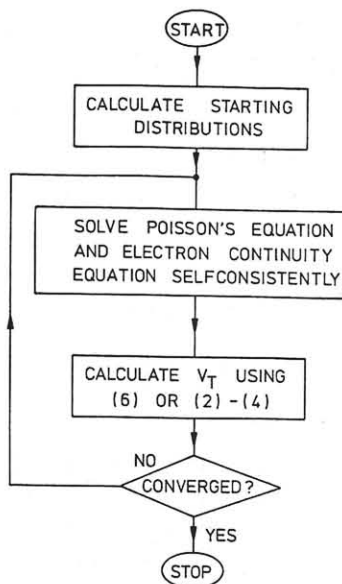


Figure 1: Solution algorithm for nonisothermal simulations.

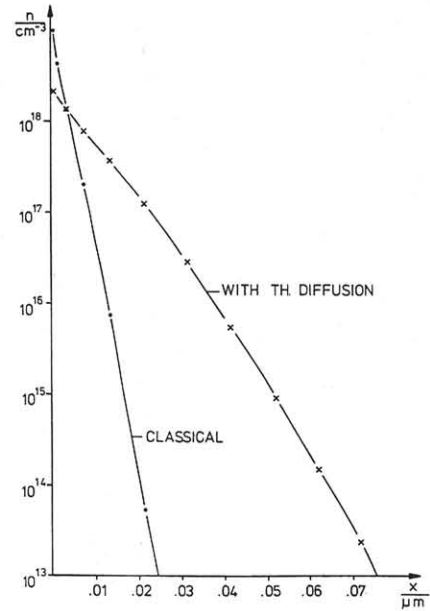


Figure 2: Comparison of vertical electron density profiles for  $V_G=V_D=3V$  and  $V_B=0V$ . The profiles were evaluated within the channel in direct neighborhood of the drain junction.

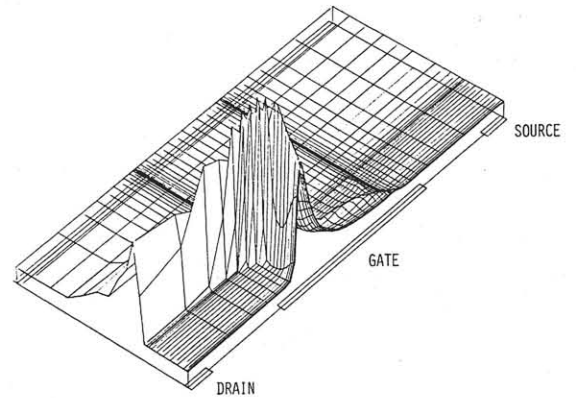


Figure 3: Electron temperature distribution in linear scale for  $V_G=V_D=3V$  and  $V_B=0V$ . The maximum temperature is 3197 K.