LOW TEMPERATURE MOS DEVICE MODELING

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The state of the art in self consistent numerical low temperature MOS modeling is reviewed. The physical assumptions which are required to describe carrier transport at low ambient temperatures are discussed. Particular emphasis is put on the models for space charge (impurity freeze-out), carrier mobility (temperature dependence of scattering mechanisms at a semiconductor-insulator interface) and carrier generation-recombination (impact ionization). The differences with regard to the numerical methods required for the solution of low temperature models compared to room temperature models are explained. Typical results obtained with the simulator MINIMOS 4 are presented. These include comparisons of short channel effects and hot-electron phenomena like energy relaxation and avalanche breakdown at 77K and 300K ambient temperature.

INTRODUCTION

Device Modeling based on the self-consistent solution of fundamental semiconductor equations dates back to the famous work of Gummel in 1964 [31]. However, the first application of this rigorous style of modeling for problems at low ambient temperature (usually liquid nitrogen temperature) has first been carried out by Gaensslen et al. about twelve years later in 1976 [27]. The main reason for this delay cannot only be seen in the lesser demands for low temperature simulation. Today not only supercomputers are made for operation at liquid nitrogen temperature, like the ETA-10, but also microprocessors, cf. [18]. The primary reason for the fairly poor status in fully numerical low temperature device modeling stems from considerably increased difficulties regarding physical assumptions and implementation for the numerical solution.

PHYSICAL ASPECTS

The model for hot carrier transport used in any numerical device simulation is based on the well known fundamental semiconductor equations (1)-(5). There are ongoing arguments in the scientific community whether these equations are adequate to describe transport in submicron devices. Particularly the current relations (4) and (5) which are the most complex equations out of the set of the basic semiconductor device equations undergo strong criticism in view of, for instance, ballistic transport [46]. Their derivation from more fundamental physical principles is indeed not at all straightforward. They appear therefore with all sorts of slight variations in the specialized literature and a vast number of papers has been published where some of their subtleties are dealt with. The interested reader is referred to, e.g., [9], [13], [26], [53]. Anyway, recent investigations on ultra short MOSFET's [47] do not give evidence that it is necessary to waive these well established basic equations.

$$\mathrm{div}(\varepsilon \cdot \mathrm{grad}\,\psi) = -\rho \tag{1}$$

$$\mathrm{div}\,\vec{J}_n - q \cdot \frac{\partial n}{\partial t} = q \cdot R \tag{2}$$

$$\mathrm{div}\,\vec{J}_p + q \cdot \frac{\partial p}{\partial t} = -q \cdot R \tag{3}$$

$$\vec{J}_n = q \cdot \mu_n \cdot n \cdot \left(\vec{E} + \frac{1}{n} \cdot \mathrm{grad}\left(n \cdot \frac{k \cdot T_p}{q}\right)\right) \tag{4}$$

$$\vec{J}_p = q \cdot \mu_p \cdot p \cdot \left(\vec{E} - \frac{1}{p} \cdot \mathrm{grad}\left(p \cdot \frac{k \cdot T_n}{q}\right)\right) \tag{5}$$

These equations include a set of parameters which have to be appropriately modeled in order to describe the various transport phenomena qualitatively and quantitatively correctly. Poisson's equation (1) requires a model for the space charge ρ which makes use of only the dependent variables ψ, n, p and material properties. The well established approach for this model is to sum up the concentrations with the adequate charge sign multiplied with the elementary charge (6).

$$\rho = q \cdot (p - n + N_D^+ - N_A^-) \tag{6}$$

Here the first difference between room temperature and low temperature simulation becomes apparent. The doping concentration $N_D^+ - N_A^-$ is usually assumed to be fully ionized at room temperature which intuitively does not hold for low temperature analysis. The classical way to describe partial ionization is based on the formulae (7).

$$N_D^+ = \frac{N_D}{1 + 2 \cdot \exp\left(\frac{E_{fn} - E_D}{k \cdot T}\right)}, \qquad N_A^- = \frac{N_A}{1 + 4 \cdot \exp\left(\frac{E_A - E_{fp}}{k \cdot T}\right)} \tag{7}$$

E_D and E_A are the ionization energies of the respective donor and acceptor dopant. Typical values for $E_c - E_D$ and $E_A - E_v$ for the most common dopants in silicon are: 0.054eV for arsenic, 0.045eV for phosphorus, 0.039eV for antimony and 0.045eV for boron. A quite complete list can be found in [56]. Note, that only energy differences can be given (E_c and E_v are the conduction band and the valence band energy, respectively). Next the Fermi levels E_{fn} and E_{fp} have to be appropriately related to the dependent variables by making use of Fermi statistics.

$$n = N_c \cdot \frac{2}{\sqrt{\pi}} \cdot F_{1/2}\left(\frac{E_{fn} - E_c}{k \cdot T}\right), \qquad p = N_v \cdot \frac{2}{\sqrt{\pi}} \cdot F_{1/2}\left(\frac{E_v - E_{fp}}{k \cdot T}\right) \tag{8}$$

N_c and N_v are the density of states in the conduction band and the valence band, respectively. The classical formulae for the density of states are given by (9).

$$N_c = 2 \cdot \left(\frac{2 \cdot \pi \cdot k \cdot T \cdot m_n^*}{h^2}\right)^{3/2}, \qquad N_v = 2 \cdot \left(\frac{2 \cdot \pi \cdot k \cdot T \cdot m_p^*}{h^2}\right)^{3/2} \tag{9}$$

$F_{1/2}(x)$ is the Fermi function of order 1/2 which is defined by (10).

$$F_{1/2}(x) = \int_0^\infty \frac{\sqrt{y}}{1 + e^{y-x}} \cdot dy \tag{10}$$

The parameters m_n^* and m_p^* which are the effective masses for electrons and holes have now to be modeled to be able to evaluate the formulae for the density of states (9). The probably most elaborate models which are fits to experimental values date back to Gaensslen et al. [27], [29].

$$m_n^* = m_o \cdot \left(1,045 + 4,5 \cdot 10^{-4} \cdot \left(\frac{T}{\mathrm{K}}\right)\right) \tag{11}$$

$$m_p^* = m_o \cdot \left(0,523 + 1,4 \cdot 10^{-3} \cdot \left(\frac{T}{\mathrm{K}}\right) - 1,48 \cdot 10^{-6} \cdot \left(\frac{T}{\mathrm{K}}\right)^2\right) \tag{12}$$

These fitting expressions are claimed to be valid over the range 50-350K.

It is worthwhile to note that the ratio of the density of states depends only on the ratio of the effective masses.

$$\frac{N_c}{N_v} = \left(\frac{m_n^*}{m_p^*}\right)^{3/2} \tag{13}$$

By means of some simple algebraic manipulation with the expressions for the carrier concentrations (8) we obtain:

$$\frac{E_{fn} - E_D}{k \cdot T} = G_{1/2}\left(\frac{n}{N_c}\right) + \frac{E_c - E_D}{k \cdot T} \tag{14}$$

$$\frac{E_A - E_{fp}}{k \cdot T} = G_{1/2}\left(\frac{p}{N_v}\right) + \frac{E_A - E_v}{k \cdot T} \tag{15}$$

$G_{1/2}(x)$ is the inverse Fermi function of order 1/2 defined with (16).

$$G_{1/2}\left(\frac{2}{\sqrt{\pi}} \cdot F_{1/2}(x)\right) = x \tag{16}$$

It is now possible by evaluating the expressions for the density of states (9) with the fits to the effective masses (11) and (12) to compute numerical values for the ionized impurity concentrations (7) using only the carrier concentrations which are the dependent variables in the basic equations. However, comparisons to experiment indicate that it is better to compute the density of states from relation (13) and a fit to the intrinsic carrier concentration (17).

$$n_i = \sqrt{N_c \cdot N_v} \cdot \exp\left(-\frac{E_g}{2 \cdot k \cdot T}\right) \tag{17}$$

E_g is the band gap $E_c - E_v$ which can be modeled temperature dependent with the fit provided by Gaensslen et al. [27], [29].

$$E_g = \begin{cases} 1,17\text{eV} + 1,059 \cdot 10^{-6}\text{eV} \cdot \left(\frac{T}{\text{K}}\right) - 6,05 \cdot 10^{-7}\text{eV} \cdot \left(\frac{T}{\text{K}}\right)^2 & T \leq 170\text{K} \\ 1,1785\text{eV} - 9,025 \cdot 10^{-5}\text{eV} \cdot \left(\frac{T}{\text{K}}\right) - 3,05 \cdot 10^{-7}\text{eV} \cdot \left(\frac{T}{\text{K}}\right)^2 & T > 170\text{K} \end{cases} \tag{18}$$

The prefactor in (17) can be fitted to experiments by (19).

$$\sqrt{N_c \cdot N_v} = \exp\left(45,13 + 0,75 \cdot \ln\left(\frac{m_n^*}{m_o} \cdot \frac{m_p^*}{m_o} \cdot \left(\frac{T}{300\text{K}}\right)^2\right)\right) \text{cm}^{-3} \tag{19}$$

With (13) and (19) it is now straightforward to compute the numerical values for the density of states. At room temperature we have $N_c = 5,1 \cdot 10^{19}\text{cm}^{-3}$ and $N_v = 2,9 \cdot 10^{19}\text{cm}^{-3}$; at liquid nitrogen temperature we obtain $N_c = 5,8 \cdot 10^{18}\text{cm}^{-3}$ and $N_v = 2,5 \cdot 10^{18}\text{cm}^{-3}$.

It should be noted that (7) are only valid for moderate impurity concentrations. For heavy doping the assumption of a localized ionization energy does definitely not hold. Instead an impurity band is formed which may merge with the respective band edge, e.g. [35], [50]. It is therefore necessary to assume total ionization for concentrations above some threshold value and to account for a suitable functional transition between the classical formulae (7) and total ionization. All concepts to tackle this problem which have come to my attention so far, however,

make use of a very simplistic, not to say alchemical, approach. It should probably be noted that freeze-out is of major importance only for depletion mode devices and devices with a partially compensated channel doping [30].

The next set of physical parameters to be considered carefully for low temperature simulation consists of the carrier mobilities μ_n and μ_p in (4) and (5). The models for the carrier mobilities have to take into account a great variety of scattering mechanisms the most basic one of which is lattice scattering. The lattice mobility in pure silicon can be fitted with simple power laws.

$$\mu_n^L = 1430\frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-2}, \qquad \mu_p^L = 460\frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-2,18} \tag{20}$$

The expressions (20) fit well experimental data of [2], [15] and [42].

The next effect to be considered is ionized impurity scattering. The best established procedure for this task is to take the functional form (21) of the fit provided by Caughey and Thomas [16] and use temperature dependent coefficients.

$$\mu_{n,p}^{LI} = \mu_{n,p}^{min} + \frac{\mu_{n,p}^L - \mu_{n,p}^{min}}{1 + \left(\frac{CI}{C_{n,p}^{ref}}\right)^{\alpha_{n,p}}} \tag{21}$$

$$\mu_n^{min} = \begin{cases} 80\frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-0,45} & T \geq 200\mathrm{K} \\ 80\frac{\mathrm{cm}^2}{\mathrm{Vs}} \left(\frac{200\mathrm{K}}{300\mathrm{K}}\right)^{-0,45} \cdot \left(\frac{T}{200\mathrm{K}}\right)^{-0,15} & T < 200\mathrm{K} \end{cases} \tag{22}$$

$$\mu_p^{min} = \begin{cases} 45\frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-0,45} & T \geq 200\mathrm{K} \\ 45\frac{\mathrm{cm}^2}{\mathrm{Vs}} \left(\frac{200\mathrm{K}}{300\mathrm{K}}\right)^{-0,45} \cdot \left(\frac{T}{200\mathrm{K}}\right)^{-0,15} & T < 200\mathrm{K} \end{cases} \tag{23}$$

$$C_n^{ref} = 1,12 \cdot 10^{17}\mathrm{cm}^{-3} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{3,2}, \qquad C_p^{ref} = 2,23 \cdot 10^{17}\mathrm{cm}^{-3} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{3,2} \tag{24}$$

$$\alpha_{n,p} = 0,72 \cdot \left(\frac{T}{300\mathrm{K}}\right)^{0,065} \tag{25}$$

The fits (22)-(25) are from [34]. Similar data have been provided in [6] and [23].

In view of partial ionization one should consider neutral impurity scattering [52]. However, in view of the uncertainty of the quantitative values for ionized impurity scattering it seems not to be worthwhile to introduce another scattering mechanism with additional fitting parameters. Furthermore, partial ionization appears to be a second order effect even at liquid nitrogen temperature. It seems therefore justified to include partial ionization only in the space charge model and not in the carrier mobilities.

Surface scattering is modeled with an expression suggested by Seavey [49].

$$\mu_{n,p}^{LIS} = \frac{\mu_{n,p}^{ref} + (\mu_{n,p}^{LI} - \mu_{n,p}^{ref}) \cdot (1 - F(y))}{1 + F(y) \cdot \left(\frac{S_{n,p}}{S_{n,p}^{ref}}\right)^{\alpha_{n,p}}} \tag{26}$$

$$\mu_n^{ref} = 638 \frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-1,19}, \qquad \mu_p^{ref} = 160 \frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-1,09} \tag{27}$$

with:

$$F(y) = \frac{2 \cdot \exp\left(-\left(\frac{y}{y^{ref}}\right)^2\right)}{1 + \exp\left(-2 \cdot \left(\frac{y}{y^{ref}}\right)^2\right)} \tag{28}$$

$$S_n = \max\left(0, \frac{\partial \psi}{\partial y}\right), \qquad S_p = \max\left(0, -\frac{\partial \psi}{\partial y}\right) \tag{29}$$

S_n^{ref} is assumed to be $7 \cdot 10^5 \frac{\mathrm{V}}{\mathrm{cm}}$; S_p^{ref} is $2,7 \cdot 10^5 \frac{\mathrm{V}}{\mathrm{cm}}$ and y^{ref} is 10nm.

The formulae for surface scattering are definitely not the ultimate expressions. They just fit quite reasonably experimental observations. Other approaches with the same claim can be found in, e.g., [7], [36], [44]. A u-shaped mobility behavior as found in [8], [10] has not been synthesized because I believe in a different origin than surface scattering for this experimental observation. It should however be noted that soft turn-on at liquid nitrogen temperature has been successfully simulated with a u-shaped mobility expression [25].

Velocity saturation is modeled with formulae (30). These are again fits to experimental data with, however, a theoretical background considering their functional

form [2], [37], [38].

$$\mu_n^{LISE} = \frac{2 \cdot \mu_n^{LIS}}{1 + \sqrt{1 + \left(\frac{2 \cdot \mu_n^{LIS} \cdot E_n}{v_n^{sat}}\right)^2}}, \qquad \mu_p^{LISE} = \frac{\mu_p^{LIS}}{1 + \frac{\mu_p^{LIS} \cdot E_p}{v_p^{sat}}} \tag{30}$$

E_n and E_p are the effective driving forces given by (31). Their derivation can be found in [32].

$$E_n = |\text{grad } \psi - \frac{1}{n} \cdot \text{grad } (Ut_n \cdot n)|, \qquad E_p = |\text{grad } \psi + \frac{1}{p} \cdot \text{grad } (Ut_p \cdot p)| \tag{31}$$

The saturation velocities are given in the following.

$$v_n^{sat} = 1,45 \cdot 10^7 \frac{\text{cm}}{\text{s}} \cdot \sqrt{\tanh\left(\frac{155\text{K}}{T}\right)}, \qquad v_p^{sat} = 9,05 \cdot 10^6 \frac{\text{cm}}{\text{s}} \cdot \sqrt{\tanh\left(\frac{312\text{K}}{T}\right)} \tag{32}$$

The functional form of these fits is after [2]; the experimental data matched are from [2], [14], [15], [21]. An eventual dependence on the crystallographic orientation which one would deduce from [3], [5], [40] is presently not taken into account.

To describe carrier heating properly one has to account for local carrier temperatures $T_{n,p}$ in the current relations (4) and (5). This can be achieved by either solving enery conservation equations selfconsistently with the basic transport equations, or by using a model obtained by series expansions of the solutions to the energy conservation equations [32]. I believe that the latter is sufficient for silicon devices. For the electronic voltages we have (33) as an approximation. Confirming theoretical investigations can be found in [1].

$$Ut_{n,p} = \frac{k \cdot T_{n,p}}{q} = Ut_o + \frac{2}{3} \cdot \tau_{n,p}^{\epsilon} \cdot \left(v_{n,p}^{sat}\right)^2 \cdot \left(\frac{1}{\mu_{n,p}^{LISE}} - \frac{1}{\mu_{n,p}^{LIS}}\right) \tag{33}$$

The $\tau_{n,p}^{\epsilon}$ are in the order of $0,5$picoseconds and just weakly temperature dependent [11].

A quick comment should be made on the model for the impact ionization rate which has to be supplied for the continuity equations (2) and (3). It still seems, though under heavy dispute of the scientific community, that the old Chynoweth formulation (34) of impact ionization can be used quite satisfactorily for device simulation.

$$R^{II} = -\alpha_n \cdot \frac{|\vec{J}_n|}{q} - \alpha_p \cdot \frac{|\vec{J}_p|}{q} \tag{34}$$

with:

$$\alpha_{n,p} = \alpha_{n,p}^{\infty} \cdot \exp\left(-\frac{\beta_{n,p}}{E}\right) \tag{35}$$

The coefficients of (35) can be modeled temperature dependent by (36) and (37) to fit experimental data [19], [22], [45]. It should be noted that there is some lack of data for liquid nitrogen temperature, cf. [55]. However it seems that this impact ionization model is somewhat too pessimistic for a proper quantitative prediction of substrate currents as already stated in [41].

$$\begin{aligned} \alpha_n^{\infty} &= 7 \cdot 10^5 \mathrm{cm}^{-1} \cdot \left(0,57 + 0,43 \cdot \left(\frac{T}{300\mathrm{K}}\right)^2\right) \\ \alpha_p^{\infty} &= 1,58 \cdot 10^6 \mathrm{cm}^{-1} \cdot \left(0,58 + 0,42 \cdot \left(\frac{T}{300\mathrm{K}}\right)^2\right) \end{aligned} \tag{36}$$

$$\begin{aligned} \beta_n &= 1,23 \cdot 10^6 \frac{\mathrm{V}}{\mathrm{cm}} \cdot \left(0,625 + 0,375 \cdot \left(\frac{T}{300\mathrm{K}}\right)\right) \\ \beta_p &= 2,04 \cdot 10^6 \frac{\mathrm{V}}{\mathrm{cm}} \cdot \left(0,67 + 0,33 \cdot \left(\frac{T}{300\mathrm{K}}\right)\right) \end{aligned} \tag{37}$$

The Auger coefficients for the model of Auger recombination (37) can also be made weakly temperature dependent with (38). The fit has been made to the data of [24].

$$R^{AU} = (C_{cn} \cdot n + C_{cp} \cdot p) \cdot (n \cdot p - n_i^2) \tag{38}$$

$$C_{cn} = 2,8 \cdot 10^{-31} \frac{\mathrm{cm}^6}{\mathrm{s}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{0,14}, \qquad C_{cp} = 9,9 \cdot 10^{-32} \frac{\mathrm{cm}^6}{\mathrm{s}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{0,2} \tag{39}$$

NUMERICAL ASPECTS

Almost none of the many device simulation programs which have proven their usefulness for room temperature simulations can be directly applied to low temperature applications. The primary reason for this is the scaling of carrier concentrations with all thereby induced consequences. Briefly sketched: De Mari recommended in an early paper [20] to scale the intrinsic carrier concentration to unity, which contributes to change the basic semiconductor equations into a dimensionless form very convenient for computer implementation. Due to the

fact that the intrinsic carrier concentration at liquid nitrogen temperature is in the order of 10^{-20}cm^{-3}, it is obviously not applicable for scaling in this case, since for instance an impurity concentration of 10^{20}cm^{-3} would then be scaled to 10^{40}. To scale the maximum impurity concentration to unity as recommended in the elaborate mathematical book of Markowich [43] is also not feasible, since the scaled intrinsic concentration would be in the order of 10^{-40}. A way out of this dilemma to use the concentration C_s defined by (40) for scaling.

$$C_s = \sqrt{4,8 \cdot 10^{22}\text{cm}^{-3} \cdot n_i} \tag{40}$$

The magic concentration in (40) is the number of silicon atoms per cubic centimeter. It serves as an absolute upper limit for the maximum possible concentration of any type. At 300K temperature $C_s = 2,58 \cdot 10^{16}\text{cm}^{-3}$, at 77K temperature $C_s = 3,51 \cdot 10^{1}\text{cm}^{-3}$. This scaling equilibrates the relevant concentrations and thus is optimal for avoiding fatal floating point underflow or overflow exceptions.

A further detail to be considered for numerical implementation is the appropriate approximation of the inverse Fermi function $G_{1/2}(x)$. A convenient fit is given by (41).

$$G_{1/2}(x) = \frac{\ln(x)}{1-x^2} + \frac{\left(\frac{3 \cdot \sqrt{\pi} \cdot x}{4}\right)^{2/3}}{1 + \frac{1}{\left(0,24 + 1,08 \cdot \left(\frac{3 \cdot \sqrt{\pi} \cdot x}{4}\right)^{2/3}\right)^2}} \tag{41}$$

The first term in (41) has to be replaced by a truncated series expansion if the argument x is in the vicinity of 1.

$$\frac{\ln(x)}{1-x^2} = \frac{x-2}{2} + O((x-1)^2) \tag{42}$$

A review about approximations to Fermi functions and their inverse functions can be found in [12], [17].

A GLIMPSE OF RESULTS

I have investigated submicron n-channel enhancement mode MOSFET's at room and liquid nitrogen ambient temperature. A lightly doped drain technology for 3/4 micron operation has been analyzed where the geometric channel length has been shrunk to 0.5 micron thus giving a metallurgical channel length of about

0.3 micron. The gate oxide thickness is 15nm and the work function of the donor doped gate polysilicon is -470mV. A window of the critical drain profile corner is depicted in Fig.1.

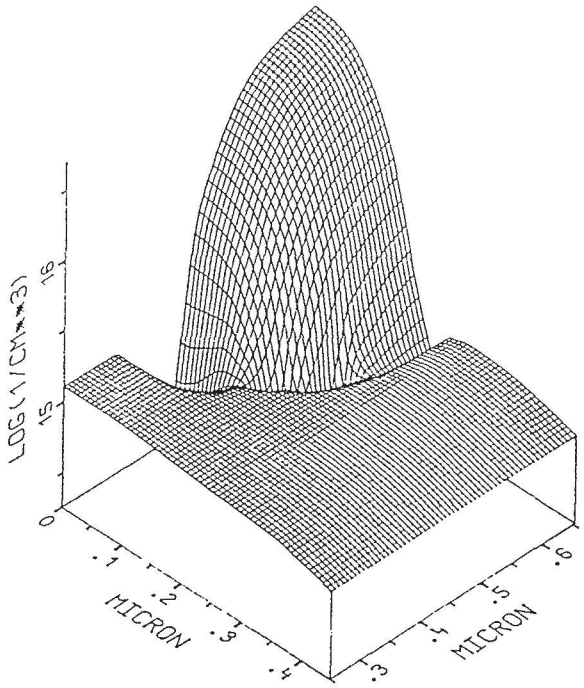


Fig.1: Detail of Net Impurity Profile

The actual analysis has been carried out with MINIMOS 4 which is a further development of the MINIMOS program [32], [48], [51] to include also quantitative capabilities for low temperature simulation.

Fig.2 shows the simulated subthreshold characteristics for two different drain biases (UD=0,1V, UD=5V, UB=0V) at room and liquid nitrogen temperature. The subthreshold slope is obviously much steeper at liquid nitrogen temperature with about 28mV/decade compared to 100mV/decade at room temperature. It is interesting that the improvement of the slope is not as good as 3,9 the ratio of 300K/77K. Furthermore, the shift of the subthreshold characteristics between low and high drain bias which should be primarily due to drain induced surface barrier lowering is about 20mV larger at 77K temperature compared to the room temperature shift (75mV). To have a larger influence of drain induced barrier lowering at lower temperature is in contradiction with the sound results of [58]. The observed phenomenon must therefore be of different origin. My investigations have brought up several interacting causes. One is partial freeze-out of acceptors in the bulk below the channel which leads to an increase of built-in potential

and thus to increasing depletion widths with decreasing temperature [39], [57]. This reasoning is partially confirmed in [28]. The second and dominantly seeming cause is the formation of a sort of parasitic channel by impact ionization which can also be seen in Fig.3. This phenomenon has already been reported in [48].

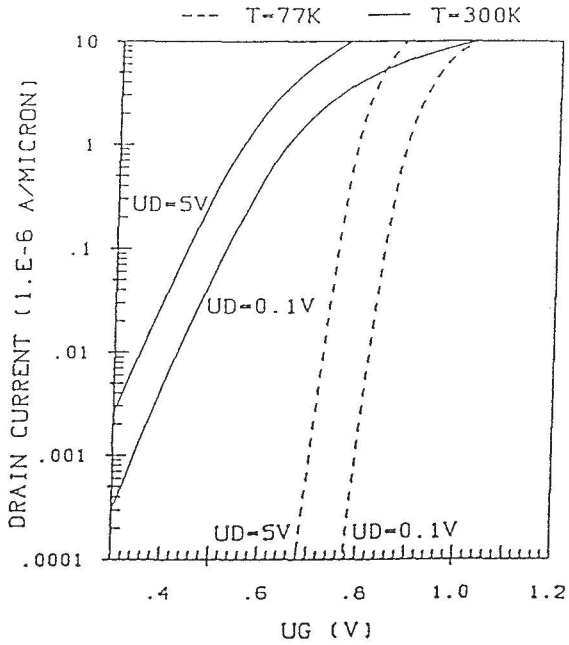


Fig.2: Subthreshold Characteristics

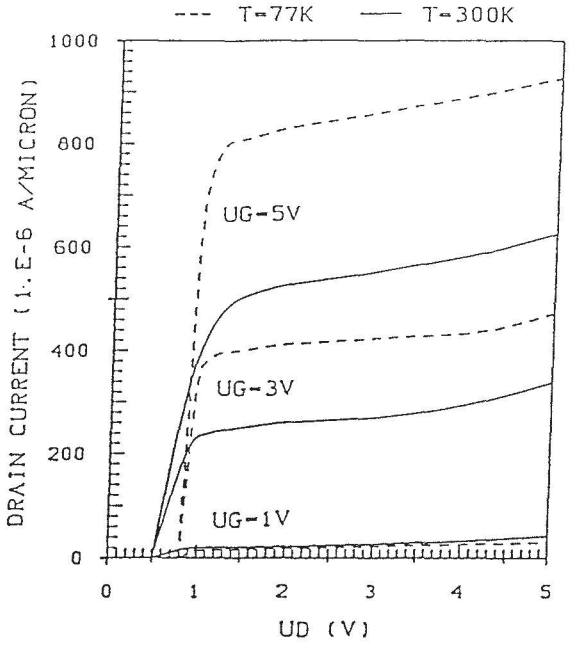
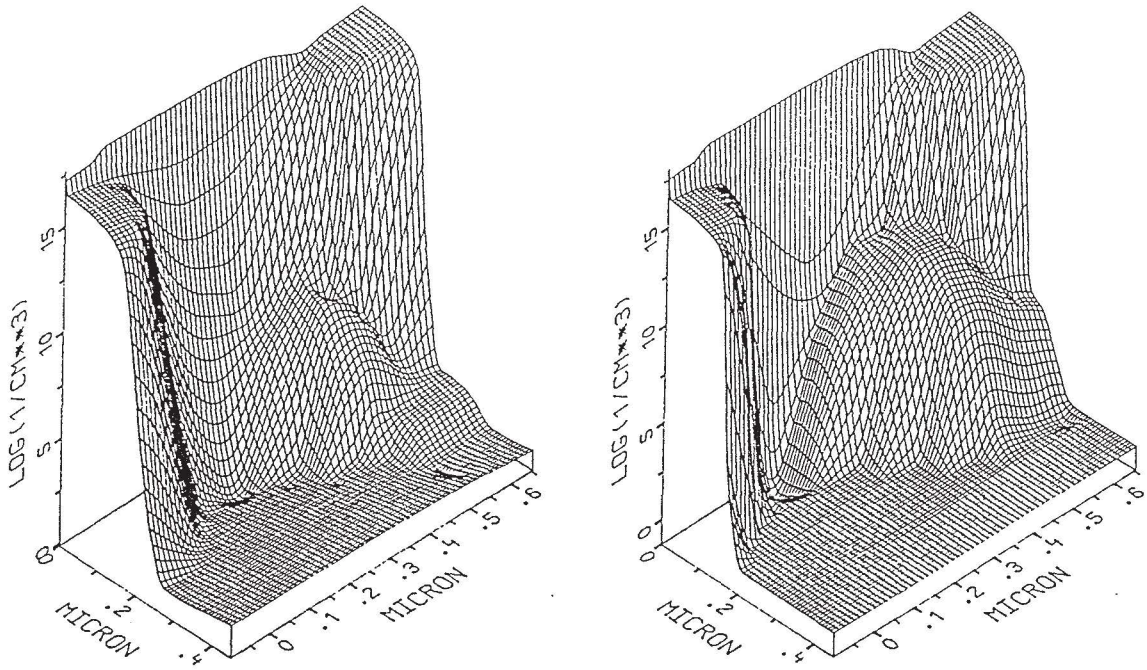


Fig.3: Output Characteristics

Fig.3 show the simulated output characteristics for three different gate biases (UG=1V, UG=3V, UG=5V, UB=0V). If we take current output for the same gate drive as measure of device quality, the low temperature operation resulted in approximately 60% improvement compared to room temperature operation. This improvement decreases with shrinking channel length as observed in [47]. The gain in threshold voltage is remarkable 300mV.

In the following a few results about the distribution of the various physical quantities in the interior of the device will be presented. An operating point of UG=3V, UD=3V and UB=0V has been chosen. Fig.3 shows the electron concentration at room temperature and liquid nitrogen temperature. One can nicely observe the inversion layer which is much steeper for the low temperature simulation. Furthermore, one can see that there are considerably more electrons generated by impact ionization close to the drain. The impact ionization rate is shown in Fig.4. The peak concentration which occurs in both cases at the surface is roughly two orders of magnitude higher for low temperature operation. The substrate cur-

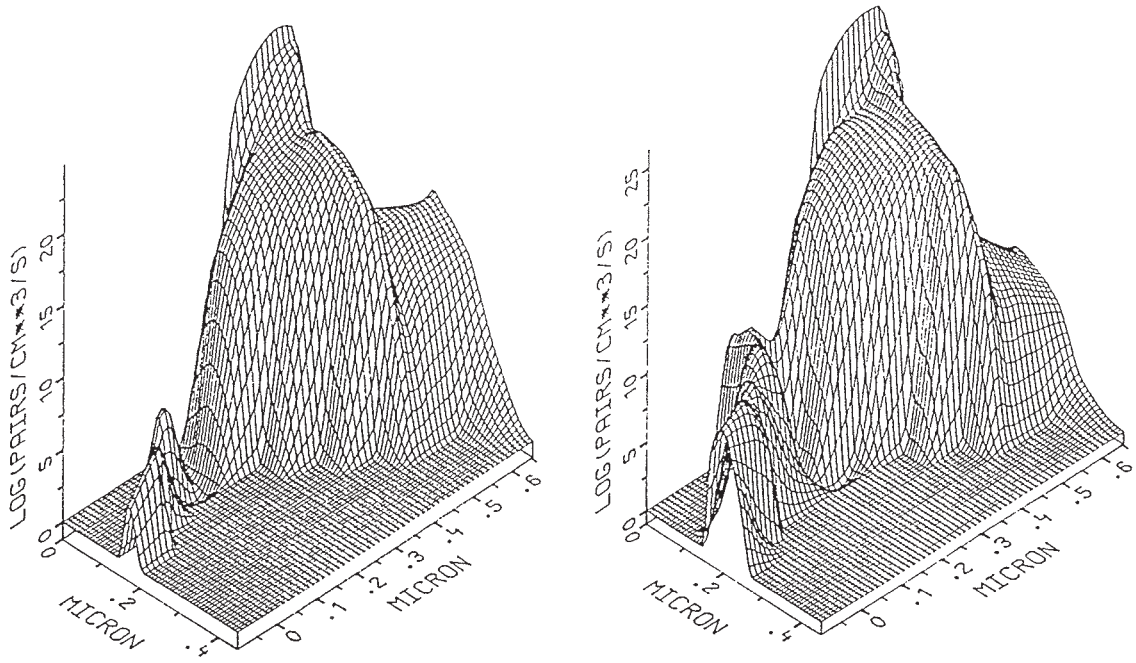
rent to drain current ratio is increased by a factor of 7.3 which is fairly high for n-channel devices [4]. Fig.5 shows the distribution of electron temperature. The maximum temperature increase is 9 % or 27K at room temperature and 2,9 % or 2,25K at 77K. This maximum is in both cases located in the reverse biased drain substrate diode with a smooth transition into the channel. The unexpected phenomenon of smaller carrier heating at liquid nitrogen temperature is a result of a smaller maximum of the driving force.



300K Fig.4 77K

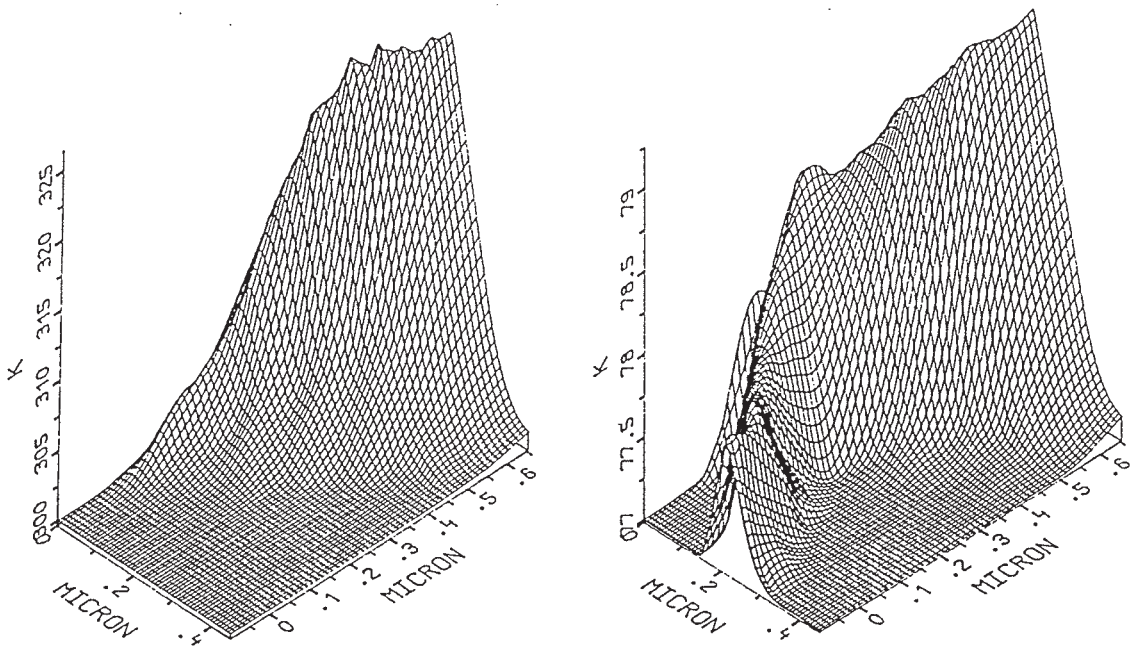
Electron Concentration

The question remains how good these simulation results agree with measurements. The device presented has not been fabricated with 0.5 micron channel length. Satisfactory agreement has been achieved for devices down to 3/4 micron channel length. To be able to judge rigorously the agreement between measurement and simulation at low temperatures one should also look at results obtained with different programs. These can be found, e.g., in [33] for a modified version of CADDET, in [47], [54] for a modified version of FIELDAY and in [58] for a modified version of GEMINI.



300K Fig.5 77K

Impact Ionization Rate



300K Fig.6 77K

Electron Temperature

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