Physical Models for Silicon VLSI

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1. INTRODUCTION

Device Modeling based on the self-consistent solution of fundamental semiconductor equations dates back to the famous work of Gummel in 1964 [31]. Since then numerical device modeling has been applied to nearly all important devices. For some citations regarding the history of modeling the interested reader is refered to [55].

2. BASIC TRANSPORT EQUATIONS

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 [35], [49]. 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], [17], [26], [56]. Anyway, recent investigations on ultra short MOSFET's [50] do not give evidence that it is necessary to waive these well established basic equations for silicon devices down to feature sizes in the order of $0,1$ microns [58].

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

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

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

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

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

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.

3. SPACE CHARGE

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).

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

This approach holds well for room temperature. At low ambient temperature, for instance, at liquid nitrogen temperature, some enhancements have to be made to this model. 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 [63]. These ionization energies are recommended to be modeled

doping dependent in [18], however it seems not to be important for MOSFET's regarding my experience. 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).

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

A convenient fit to (16) is given by (19).

$$G_{1/2}(x) = \frac{\ln(x)}{1 - x^2} + \frac{\left(\frac{3 \cdot \sqrt{\pi} \cdot x}{4}\right)^{2/3}}{1 + \frac{1}{\left(0,24 + 1,08 \cdot \left(\frac{3 \cdot \sqrt{\pi} \cdot x}{4}\right)^{2/3}\right)^2}} \tag{19}$$

The first term in (19) has to be replaced by a truncated series expansion if the argument x is in the vicinity of 1.

$$\frac{\ln(x)}{1 - x^2} = \frac{x - 2}{2} + O((x-1)^2) \tag{20}$$

A review about approximations to Fermi functions and their inverse functions can be found in [12], [19], [55].

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 (19).

$$n_i = \sqrt{N_c \cdot N_v} \cdot \exp\left(-\frac{E_g}{2 \cdot k \cdot T}\right) \tag{19}$$

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]. Note that most publications which present equation (20) contain a typographical error. The linear temperature coefficient for E_g below 170K is $1,059 \cdot 10^{-5}$eV and not as usually found $1,059 \cdot 10^{-6}$eV [39].

$$E_g = \begin{cases} 1,17\text{eV} + 1,059 \cdot 10^{-5}\text{eV} \cdot \left(\frac{T}{\text{K}}\right) - 6,05 \cdot 10^{-7}\text{eV} \cdot \left(\frac{T}{\text{K}}\right)^2 & T \leq 170\text{K} \\ 1,1785\text{eV} - 9,025 \cdot 10^{-5}\text{eV} \cdot \left(\frac{T}{\text{K}}\right) - 3,05 \cdot 10^{-7}\text{eV} \cdot \left(\frac{T}{\text{K}}\right)^2 & T > 170\text{K} \end{cases} \tag{20}$$

The prefactor in (19) can be fitted to experiments by (21).

$$\sqrt{N_c \cdot N_v} = \exp\left(45,13 + 0,75 \cdot \ln\left(\frac{m_n^*}{m_o} \cdot \frac{m_p^*}{m_o} \cdot \left(\frac{T}{300\text{K}}\right)^2\right)\right) \text{cm}^{-3} \tag{21}$$

With (13) and (21) 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. [36], [53]. Just modeling a temperature dependence of the ionization energies will not account adequately for the underlying physics in this case. It appears to be appropriate 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. Anyway, it should be noted that freeze-out is of major importance only for depletion mode devices and devices with a partially compensated channel doping [30].

In view of this dilemma with heavy doping one may for many applications well use asymptotic approximations for the Fermi function (10) and its inverse (16) (see [55]). This is not in contradiction to the partial ionization model given with (6)-(21).

4. CARRIER MOBILITIES

The next set of physical parameters to be considered carefully for silicon device 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.

$$\mu_n^L = 1430\frac{\text{cm}^2}{\text{Vs}} \cdot \left(\frac{T}{300\text{K}}\right)^{-2}, \qquad \mu_p^L = 460\frac{\text{cm}^2}{\text{Vs}} \cdot \left(\frac{T}{300\text{K}}\right)^{-2,18} \tag{22}$$

The expressions (22) fit well experimental data of [2], [15] and [46].

The next effect to be considered is ionized impurity scattering. The best established procedure for this task is to take the functional form (23) of the fit provided by Caughey and Thomas

[16] and use temperature dependent coefficients.

$$\mu_{n,p}^{LI} = \mu_{n,p}^{min} + \frac{\mu_{n,p}^{L} - \mu_{n,p}^{min}}{1 + \left(\frac{CI}{C_{n,p}^{ref}}\right)^{\alpha_{n,p}}} \tag{23}$$

$$\mu_n^{min} = \begin{cases} 80\frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-0,45} & T \geq 200\mathrm{K} \\ 80\frac{\mathrm{cm}^2}{\mathrm{Vs}} \left(\frac{200\mathrm{K}}{300\mathrm{K}}\right)^{-0,45} \cdot \left(\frac{T}{200\mathrm{K}}\right)^{-0,15} & T < 200\mathrm{K} \end{cases} \tag{24}$$

$$\mu_p^{min} = \begin{cases} 45\frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-0,45} & T \geq 200\mathrm{K} \\ 45\frac{\mathrm{cm}^2}{\mathrm{Vs}} \left(\frac{200\mathrm{K}}{300\mathrm{K}}\right)^{-0,45} \cdot \left(\frac{T}{200\mathrm{K}}\right)^{-0,15} & T < 200\mathrm{K} \end{cases} \tag{25}$$

$$C_n^{ref} = 1,12 \cdot 10^{17}\mathrm{cm}^{-3} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{3,2}, \qquad C_p^{ref} = 2,23 \cdot 10^{17}\mathrm{cm}^{-3} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{3,2} \tag{26}$$

$$\alpha_{n,p} = 0,72 \cdot \left(\frac{T}{300\mathrm{K}}\right)^{0,065} \tag{27}$$

The fits (24)-(27) are from [34]. Similar data have been provided in [6] and [23].

In view of partial ionization, i.e., for low temperature simulation, one should consider neutral impurity scattering [55]. However, considering 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.

I prefer to model surface scattering with an expression suggested by Seavey [52].

$$\mu_{n,p}^{LIS} = \frac{\mu_{n,p}^{ref} + (\mu_{n,p}^{LI} - \mu_{n,p}^{ref}) \cdot (1 - F(y))}{1 + F(y) \cdot \left(\frac{S_{n,p}}{S_{n,p}^{ref}}\right)^{\alpha_{n,p}}} \tag{28}$$

$$\mu_n^{ref} = 638\frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-1,19}, \qquad \mu_p^{ref} = 160\frac{\mathrm{cm}^2}{\mathrm{Vs}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{-1,09} \tag{29}$$

with:

$$F(y) = \frac{2 \cdot \exp\left(-\left(\frac{y}{y^{ref}}\right)^2\right)}{1 + \exp\left(-2 \cdot \left(\frac{y}{y^{ref}}\right)^2\right)} \tag{30}$$

$$S_n = \max\,(0,\ \frac{\partial \psi}{\partial y}), \qquad S_p = \max\,(0, -\frac{\partial \psi}{\partial y}) \tag{31}$$

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], [37], [38], [47]. A u-shaped mobility behavior for surface scattering at low ambient temperature as found in [8], [10] seems not to be worthwhile to synthesize 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 (32). These are again fits to experimental data with, however, a theoretical background considering their functional form [2], [41], [42].

$$\mu_n^{LISE} = \frac{2 \cdot \mu_n^{LIS}}{1 + \sqrt{1 + \left(\frac{2 \cdot \mu_n^{LIS} \cdot E_n}{v_n^{sat}}\right)^2}}, \qquad \mu_p^{LISE} = \frac{\mu_p^{LIS}}{1 + \frac{\mu_p^{LIS} \cdot E_p}{v_p^{sat}}} \tag{32}$$

E_n and E_p are the effective driving forces given by (33). Their derivation can be found in [32].

$$E_n = |\mathrm{grad}\ \psi - \frac{1}{n} \cdot \mathrm{grad}\ (Ut_n \cdot n)|, \qquad E_p = |\mathrm{grad}\ \psi + \frac{1}{p} \cdot \mathrm{grad}\ (Ut_p \cdot p)| \tag{33}$$

The temperature dependent saturation velocities are given in the following.

$$v_n^{sat} = 1,45 \cdot 10^7 \frac{\mathrm{cm}}{\mathrm{s}} \cdot \sqrt{\tanh\left(\frac{155\mathrm{K}}{T}\right)}, \qquad v_p^{sat} = 9,05 \cdot 10^6 \frac{\mathrm{cm}}{\mathrm{s}} \cdot \sqrt{\tanh\left(\frac{312\mathrm{K}}{T}\right)} \tag{34}$$

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], [44] is presently not taken into account.

5. CARRIER TEMPERATURES

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 energy conservation equations self consistently with the basic transport equations, or by using a model obtained by series expansions of the solution to the energy conservation equations [32]. I believe that the latter is sufficient for silicon devices. For the electronic voltages we have (35) as an approximation. Confirming theoretical investigations can be found in [1].

$$Ut_{n,p} = \frac{k \cdot T_{n,p}}{q} = Ut_o + \frac{2}{3} \cdot \tau^{\epsilon}_{n,p} \cdot \left(v^{sat}_{n,p}\right)^2 \cdot \left(\frac{1}{\mu^{LISE}_{n,p}} - \frac{1}{\mu^{LIS}_{n,p}}\right) \tag{35}$$

The energy relaxation times $\tau^{\epsilon}_{n,p}$ are in the order of $0,5$picoseconds and just weakly temperature dependent [11]. They should however be modeled as functions of the local doping concentration as motivated by the following reasoning. The product of carrier mobility times electronic voltage which symbolizes a diffusion coefficient must be a decreasing function with increasing carrier voltage (see also [11]). Its maximum is attained at thermal equillibrium. Relation (36) must therefore hold.

$$\mu^{LISE}_{n,p} \cdot Ut_{n,p} \leq \mu^{LIS}_{n,p} \cdot Ut_o \tag{36}$$

Note that models for carrier diffusion coefficients are not required in the basic current relations (4), (5).

Substituting (35) into (36) and rearranging terms one obtains relation (37) for the energy relaxation times.

$$\tau^{\epsilon}_{n,p} \leq \frac{3}{2} \cdot Ut_o \cdot \frac{\mu^{LIS}_{n,p}}{\left(v^{sat}_{n,p}\right)^2} \tag{37}$$

In, e.g. MINIMOS 4, the energy relaxation times are modeled on the basis of (37) with a fudge factor γ in the range $[0,1]$ and a default value of $0,8$.

$$\tau^{\epsilon}_{n,p} = \gamma \cdot \frac{3}{2} \cdot Ut_o \cdot \frac{\mu^{LIS}_{n,p}}{\left(v^{sat}_{n,p}\right)^2} \tag{38}$$

For vanishing doping one obtains the maximal energy relaxation times which are at 300K $\tau^{\epsilon}_{n} = 4,44 \cdot 10^{-13}$s, $\tau^{\epsilon}_{p} = 2,24 \cdot 10^{-13}$s and at liquid nitrogen temperature $\tau^{\epsilon}_{n} = 8,82 \cdot 10^{-13}$s, $\tau^{\epsilon}_{p} = 8,68 \cdot 10^{-13}$s.

6. CARRIER GENERATION/RECOMBINATION

Carrier generation/recombination in silicon devices is generally modeled as the simple sum of several partial generation/recombination rates (39).

$$R = R^{SRH} + R^{OPT} + R^{AU} + R^{II} \tag{39}$$

The partial rates are thermal generation/recombination R^{SRH} usually named after the scientists Shockley, Read and Hall. Optical generation/recombination R^{OPT} which is definitely not of relevance for silicon devices, except for very special devices like light-triggered thyristors, Auger generation/recombination R^{AU} and impact ionization R^{II}.

(40) is the established formula for thermal generation/recombination which, however, should only be appropriate for moderate recombination/generation rates [55].

$$R^{SRH} = \frac{n \cdot p - {n_i}^2}{\tau_p \cdot (n + n_1) + \tau_n \cdot (p + p_1)} \tag{40}$$

The coefficients for the established model of Auger recombination (41) can be made weakly temperature dependent with (42). The fit has been made to the data of [24].

$$R^{AU} = (C_{cn} \cdot n + C_{cp} \cdot p) \cdot (n \cdot p - {n_i}^2) \tag{41}$$

$$C_{cn} = 2,8 \cdot 10^{-31} \frac{\mathrm{cm}^6}{\mathrm{s}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{0,14}, \qquad C_{cp} = 9,9 \cdot 10^{-32} \frac{\mathrm{cm}^6}{\mathrm{s}} \cdot \left(\frac{T}{300\mathrm{K}}\right)^{0,2} \tag{42}$$

A particular comment should be made on the model for the impact ionization rate R^{II}. It still seems, though under heavy dispute of the scientific community, that the old Chynoweth formulation (43) of impact ionization can be used quite satisfactorily for device simulation.

$$R^{II} = -\alpha_n \cdot \frac{|\vec{J}_n|}{q} - \alpha_p \cdot \frac{|\vec{J}_p|}{q} \tag{43}$$

with:

$$\alpha_{n,p} = \alpha_{n,p}^{\infty} \cdot \exp\left(-\frac{\beta_{n,p}}{E}\right) \tag{44}$$

The coefficients of (44) can be modeled temperature dependent by (45) and (46) to fit experimental data [20], [22], [48]. It should be noted that there is some lack of data for liquid nitrogen temperature, cf. [62]. However it seems that this impact ionization model is probably somewhat too pessimistic for a proper quantitative prediction of substrate currents as already stated in [45], [57].

$$\alpha_n^{\infty} = 7 \cdot 10^5 \mathrm{cm}^{-1} \cdot \left(0,57 + 0,43 \cdot \left(\frac{T}{300\mathrm{K}}\right)^2\right)$$
$$\alpha_p^{\infty} = 1,58 \cdot 10^6 \mathrm{cm}^{-1} \cdot \left(0,58 + 0,42 \cdot \left(\frac{T}{300\mathrm{K}}\right)^2\right) \tag{45}$$

$$\beta_n = 1,23 \cdot 10^6 \frac{\mathrm{V}}{\mathrm{cm}} \cdot \left(0,625 + 0,375 \cdot \left(\frac{T}{300\mathrm{K}}\right)\right)$$
$$\beta_p = 2,04 \cdot 10^6 \frac{\mathrm{V}}{\mathrm{cm}} \cdot \left(0,67 + 0,33 \cdot \left(\frac{T}{300\mathrm{K}}\right)\right) \tag{46}$$

7. SOME RESULTS

Results of investigations about submicron n-channel enhancement mode MOSFET's at room and liquid nitrogen ambient temperature are presented. A single drain technology designed with a 3/4 micron coded channel length (0,39 micron metallurgical channel length) has been analyzed where the geometric channel length has been shrunk to 0,51 micron (0,15 micron metallurgical channel length). The gate oxide thickness is 9nm and the work function of the donor doped gate polysilicon is -570mV. A window of the critical drain profile corner is depicted in Fig.1.

The actual analysis has been carried out with MINIMOS 4 which is a further development of the MINIMOS program [32], [51], [54] to include also quantitative capabilities for low temperature simulation.

Figure 2 shows the simulated subthreshold characteristics for two different drain biases (UD=0.1 UD=2V, UB=0V) at room and liquid nitrogen temperature. The subthreshold slope is obviously much steeper at liquid nitrogen temperature with about 25mV/decade compared to 95mV/decade at room temperature. It is interesting that the improvement of the slope is almost as good as 3,9 the ratio of 300K/77K [40]. 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 50mV larger at 77K temperature compared to the room temperature shift. To have a larger influence of drain induced barrier lowering at lower temperature is in contradiction with the sound results of [65]. The observed phenomenon must therefore be of different origin. Detailed 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 [43], [64]. This reasoning is partially confirmed in [28]. The second cause is the formation of a sort of parasitic channel by impact ionization which has also been reported in [51].

Figure 3 shows the simulated output characteristics for four different gate biases. If we take current output for the same gate drive as measure of device quality, the low temperature operation resulted in approximately 50% improvement compared to room temperature operation. Similar results have been experimentally obtained (cf.[60]). This improvement decreases with shrinking channel length as observed in [50].

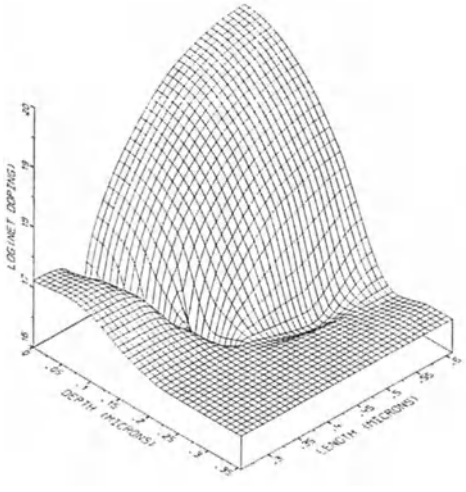


Fig.1: Detail of Doping Profile

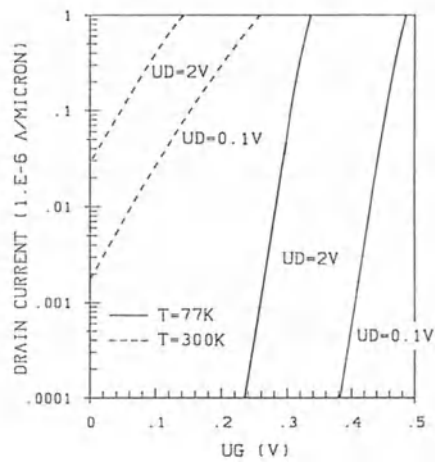
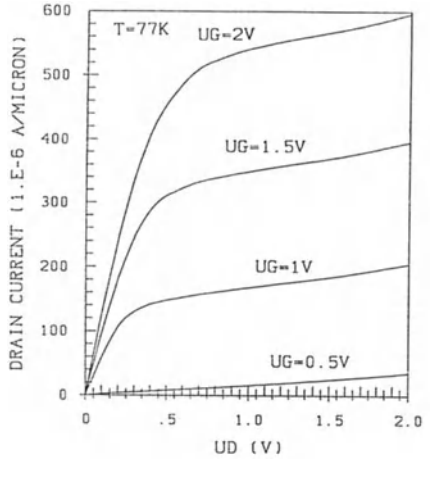
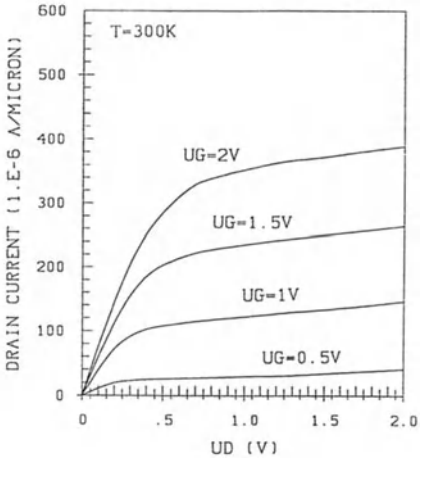


Fig.2: Subthreshold Characteristics





77K Fig.3: Simulated Output Characteristics 300K

In the following a few results about the distribution of the various physical quantities in the interior of the device will be presented. The off-state at UG=0V, UD=2V is despicted with the electron concentration given by Fig.4 at liquid nitrogen temperature and room temperature. It is easily visible that the device is not satisfactorily off at room temperature. The channel is perfectly depleted at 77K.

The on-state is documented with a bias of UG=2V, UD=2V. Fig.5 shows again the electron concentration at liquid nitrogen temperature and room 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 rates are shown in Fig.6. The peak concentration which occurs in both cases at the surface is almost two orders of magnitude higher for low temperature operation. The substrate current to drain current ratio is increased by a factor of 5.2 which is fairly high for n-channel devices [4].

Figure 7 shows the distribution of electron temperature at 77K and 300K ambient temperature. The maximum temperature is 213K at 77K and 2220K at room temperature This maximum is in both cases located in the reverse biased drain substrate diode with a smooth transition into the channel. The position of the maximum is deeper in the substrate and closer to the drain area at 77K compared to the room temperature result. The phenomenon of smaller carrier heating at liquid nitrogen temperature is a result of a smoother distribution and a smaller maximum of the driving force. Smaller carrier heating at 77K has been confirmed by many simulations; it is not really expected, particularly in view of larger energy relaxation times at liquid nitrogen temperature.

Similar investigations for a lightly doped drain technology can be found in [57].

The question remains how good these simulation results agree with measurements. The device presented has not been fabricated with 0,51 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 [50], [61] for a modified version of FIELDAY and in [65] for a modified version of GEMINI.

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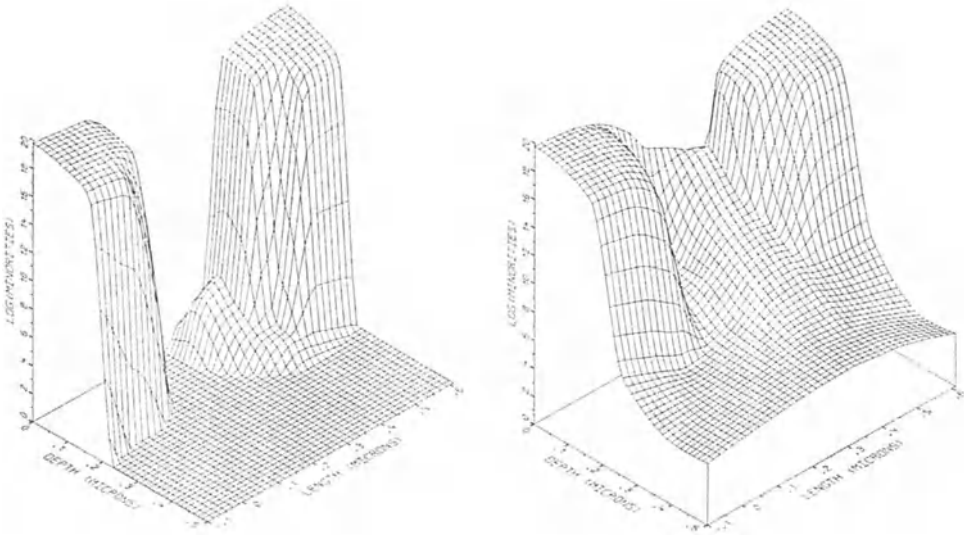
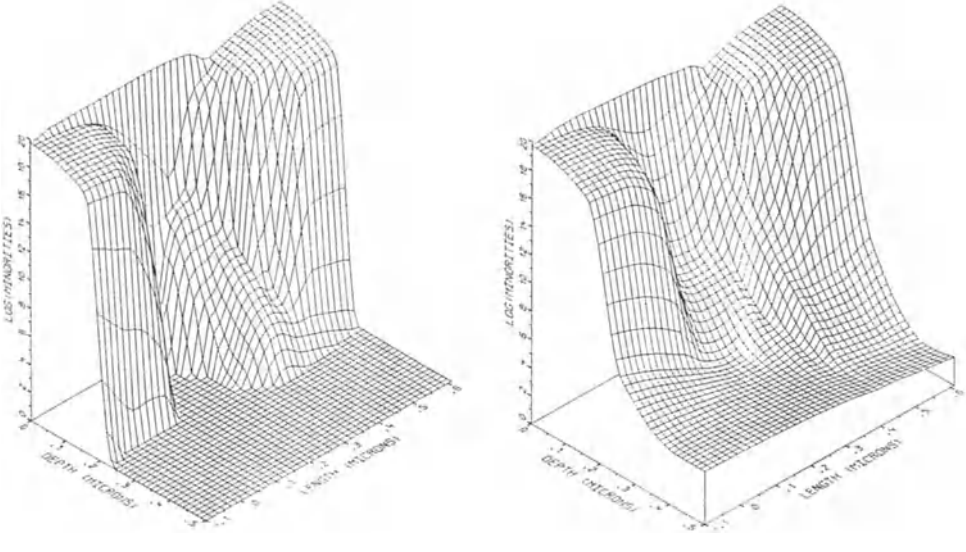
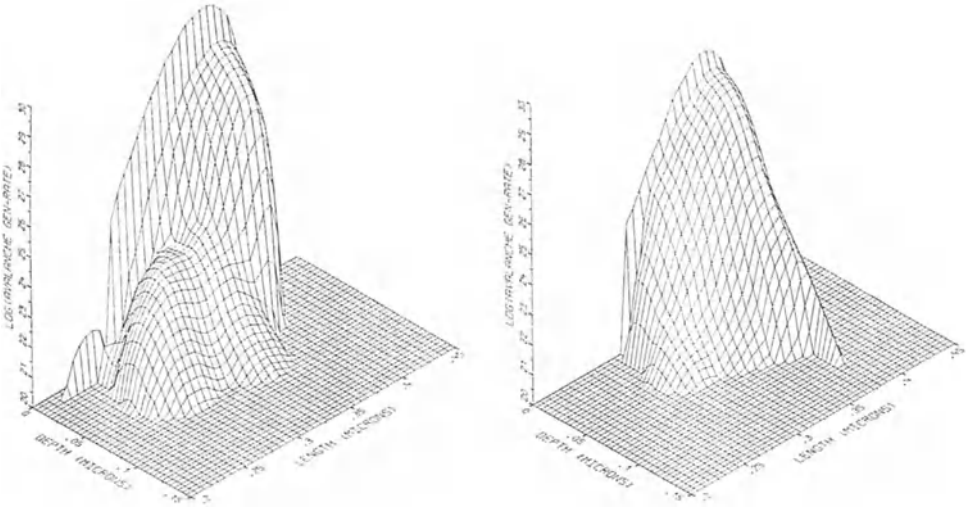


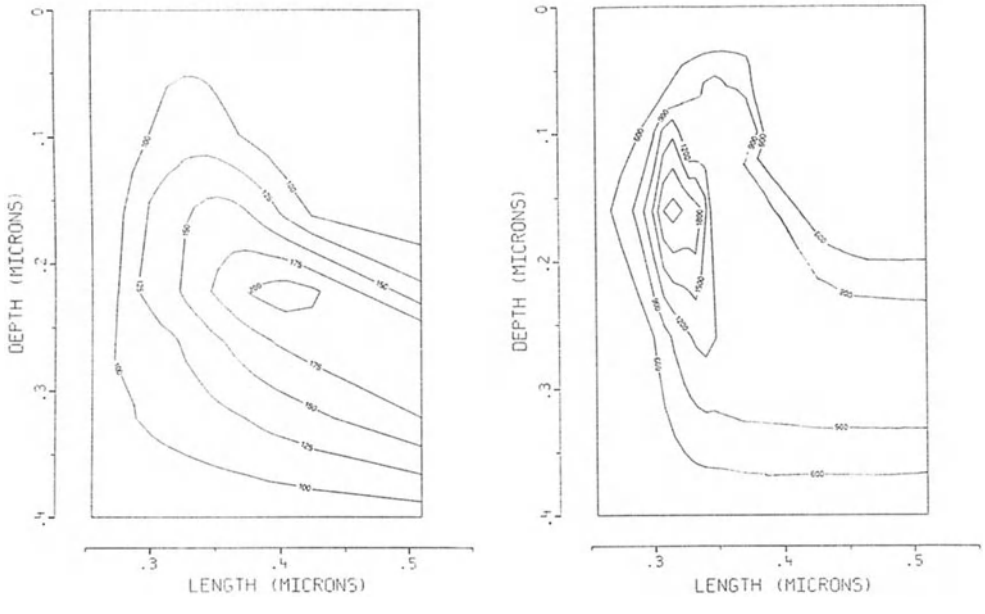
77K Fig.4: Electron Concentration (UG=0V, UD=2V) 300K



77K Fig.5: Electron Concentration (UG=2V, UD=2V) 300K



77K Fig.6: Impact Ionization Rate (UG=2V, UD=2V) 300K



77K Fig.7: Electron Temperature (UG=2V, UD=2V) 300K

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