THREE DIMENSIONAL PROCESS AND DEVICE MODELING

ABSTRACT: This contribution is intended to review the international state of the art in three-dimensional process and device modeling. As one particular example results for ion implantation into a three-dimensional trench are presented. Redistribution of dopants, interstitials and vacancies with fully coupled models are discussed. The recent refinements to carrier transport models in semiconductor devices are presented. As a particular example for three-dimensional device simulation the influence of the shape of the field-oxide in width direction is discussed. Some remarks on the computational requirements are given.

INTRODUCTION

In the development of miniaturized devices for integrated circuits and particularly their technology, the demand for models being capable to predict the various processing steps of device fabrication on the one hand and the electrical behavior of devices on the other hand is growing dramatically due to the tight coupling of electrical device effects with the doping profile.

As a lack of space it is not possible here to give an extensive overview about all international activities on three-dimensional process and device modeling. Therefore, the paper has been restricted to the description of some interesting and recently performed investigations.

1. PROCESS MODELING

Device fabrication processes can be principally categorized into two groups. Lithographical processes which serve patterning purposes and doping processes which determine for a given structure the electrical properties of the intended semiconductor device. The first group consists of deposition and etching with spatial selectivity in order to enable
structuring. It may be viewed as a fixed process which provides flexibility in layout. The second group is composed of ion implantation, diffusion, thermal oxidation and epitaxy.

This chapter deals with a simulation of ion implantation into a three-dimensional trench [25] and with a new model of phosphorus diffusion in silicon [12] including the redistribution of dopants, interstitials, and vacancies.

1.1. ION IMPLANTATION INTO A 3-D TRENCH

Ion implantation doubtless is a central point in the fabrication of semiconductor devices. Therefore, as one particular example for three-dimensional process modeling, results for ion implantation into a three-dimensional trench are presented in this chapter. In order to demonstrate the necessity of three-dimensional process simulation tools additionally the two-dimensional solution is shown as comparison.

The calculations have been performed with a two- and three-dimensional program package for the simulation of ion implantation based on the “Monte Carlo”-method, including some additional features to increase computational efficiency [25]. The first step in the development of that software tool was a two-dimensional model of ion implantation which accounted for position dependent lateral moments [26]. With this model the analytical description of ion implantation profiles has been essentially improved by specifying a modification of the Gaussian distribution function. The benefit of the use of distribution functions evidently lies in the low computer resources required. The enormous drawback is the restriction of the applicability to simple geometries only. To investigate ion implantation in connection with arbitrary geometries a rigorous simulation method has to be applied.

Fig. 1 and fig. 2 show the geometry of the investigated trench for the two- and three-dimensional case, respectively. The three-dimensional trench has a square cross-section. The substrate material is silicon in which boron ions are implanted with an energy of 25 keV. The angle of incidence of the ion ray amounts 7° with respect to the perpendicular of the wafer surface.

Fig. 3 and fig. 4 show the concentration of dopants in a quasi three-dimensional representation as a result of the two- and three-dimensional simulation, respectively. The result of the three-dimensional simulation (fig. 4) is displayed for the symmetry plane between front wall and back wall (see fig. 2). The surface of the wafer is located on the left side of the top of the drawings. The vertical axis denotes the logarithm of the boron concentration divided by the implantation dose. The left axis lies parallel to the shady side of the trench and represents the depth whereas the right axis is parallel to the bottom of the trench and represents the width. Regarding fig. 3 one can see the considerable concentration on the shady side which is just about a factor five smaller than the concentration on the sunny side. A comparison between fig. 3 and fig. 4 shows on the
one hand that the concentrations on the sunny sides are rather the same, but on the other hand the concentrations on the shady side differ about a factor two. Such an inaccuracy of the two-dimensional simulation certainly is not acceptable as small variations of a doping profile persistently influence the electrical behavior of a semiconductor device.

1.2. PHOSPHORUS DIFFUSION IN SILICON

Under extrinsic concentrations the diffusion of phosphorus in silicon shows a considerable deviation from the Gaussian, the complementary error-function distributions or concentration distributions of other dopants. The phosphorus profile has a "kink and tail" diffusion behavior. The diffusion coefficient in the intrinsic region under thermal annealing conditions depends on the surface concentration of phosphorus. This diffusion is faster than the diffusion in the lower concentration part of the extrinsic region. In the high concentration part of the extrinsic region the diffusion is proportional to the square of the electron concentration. From coupled diffusion with other dopants and stacking fault growth it is known that phosphorus produces a supersaturation of interstitials in the "tail" region depending on the surface concentration of the profile [32].

The model developed to describe the anomalous phosphorus diffusion in silicon [12] is based on the motion of impurity-point defect pairs. Though the following derivation is laid out for one spatial dimension the model evidently is applicable to two- and three-dimensional simulations. The impurity (A) can react with point defects (D) (interstitials and vacancies):

\[ AD \rightleftharpoons A + D \] (1)

The point defects and impurity-point defect pairs have different charge states and react with electrons or holes.

\[ D^{i-1} \rightleftharpoons D^i + e^- , \quad D^{i+1} \rightleftharpoons D^i + h^+ \] (2)

\[ AD^{i-1} \rightleftharpoons AD^i + e^- , \quad AD^{i+1} \rightleftharpoons AD^i + h^+ \] (3)

For all these combinations a diffusion equation describes the motion through the bulk including the electrical potential \( \psi \) which is normalized to the thermal potential. The substitutional dopants are assumed not to diffuse at all. Therefore the following expressions are obtained for the particle current densities:

\[ J_{AD}^i = -D_{AD}^i \left( \frac{\partial c_{AD}^i}{\partial x} - (i - d(A))c_{AD}^i \frac{\partial \psi}{\partial x} \right) \] (4)
The number of these equations can be reduced under the assumption that the reaction with the electrons and holes happens very fast and the charge states are in thermal equilibrium. The different concentrations \( c^{i}_{AD} \) are summarized to a total concentration \( c_{AD} \). Similarly a total point defect concentration \( c_{D} \) is defined.

\[
c^{i}_{AD} = k^{i}_{AD} c^{0}_{AD} \left( \frac{n}{n_{i}} \right)^{i}, \quad c^{i}_{D} = k^{i}_{D} c^{0}_{D} \left( \frac{n}{n_{i}} \right)^{i}
\]

\[
c_{AD} = \sum_{i} c^{i}_{AD}, \quad c_{D} = \sum_{i} c^{i}_{D}
\]

The new current equations yield a mean diffusion coefficient and a mean electrical charge \( \overline{Q} \) depending on the electron concentration.

\[
J_{AD} = -D_{AD} \left( \frac{\partial c_{AD}}{\partial x} + \overline{Q}_{AD} c_{AD} \frac{\partial \psi}{\partial x} \right), \quad J_{D} = -D_{D} \left( \frac{\partial c_{D}}{\partial x} + \overline{Q}_{D} c_{D} \frac{\partial \psi}{\partial x} \right)
\]

\[
\overline{D}_{AD} = \frac{\Sigma_{i} D^{i}_{AD} k^{i}_{AD} \left( \frac{n}{n_{i}} \right)^{i}}{\Sigma_{i} k^{i}_{AD} \left( \frac{n}{n_{i}} \right)^{i}}, \quad \overline{D}_{D} = \frac{\Sigma_{i} D^{i}_{D} k^{i}_{D} \left( \frac{n}{n_{i}} \right)^{i}}{\Sigma_{i} k^{i}_{D} \left( \frac{n}{n_{i}} \right)^{i}}
\]

\[
\overline{Q}_{AD} = \frac{\Sigma_{i} (d(A) - i) k^{i}_{AD} \left( \frac{n}{n_{i}} \right)^{i}}{\Sigma_{i} k^{i}_{AD} \left( \frac{n}{n_{i}} \right)^{i}}, \quad \overline{Q}_{D} = \frac{\Sigma_{i} - i k^{i}_{D} \left( \frac{n}{n_{i}} \right)^{i}}{\Sigma_{i} k^{i}_{D} \left( \frac{n}{n_{i}} \right)^{i}}
\]

The formation of \( AD \)-pairs and the decay into their components is expressed by a generation term \( G_{AD} \) which accounts for the tendency towards thermal equilibrium. The “Frenkelpair” mechanism is described by \( G_{F} \) (\( I + V \Rightarrow 0 \)).

\[
\frac{\partial c_{AD}}{\partial t} + \frac{\partial J_{AD}}{\partial x} = -G_{AD}, \quad \frac{\partial c_{A}}{\partial t} = \sum_{D} G_{AD}, \quad \frac{\partial c_{D}}{\partial t} + \frac{\partial J_{D}}{\partial x} = \sum_{A} G_{AD} + G_{F}
\]

\[
G_{AD} = k_{\text{decay}} c_{AD} \sum_{i} k^{i}_{D} \left( \frac{n}{n_{i}} \right)^{i} - k_{\text{generation}} c_{AD} \sum_{i} k^{i}_{AD} \left( \frac{n}{n_{i}} \right)^{i}
\]

In this form the model needs three equations for each species plus two for the point defects. The boundary conditions for point defects are set to their thermal equilibrium.
values dependent on the electron concentration. \( c_{D}^{eq} \) is the thermal equilibrium value under intrinsic conditions for vacancies and interstitials.

\[
e_{D} = c_{D}^{eq} \sum_{i} k_{D}^{i} \left( \frac{n}{n_{i}} \right)^{i} \sum_{i} k_{D}^{i}
\]

(13)

For the impurities and impurity-pairs the boundary conditions are either \( J_{AD} = 0 \) and \( J_{D} = 0 \) or a constant concentration under consideration of the thermal equilibrium condition for the reaction between impurities and point defects.

\[
e_{AD} = F_{AD} c_{AD}, \quad F_{AD} = \frac{k_{\text{generation}} c_{AD} \sum_{i} k_{AD}^{i} \left( \frac{n}{n_{i}} \right)^{i}}{k_{\text{decay}} c_{AD} \sum_{i} k_{D}^{i} \left( \frac{n}{n_{i}} \right)^{i}}
\]

(14)

Fig. 5 shows a comparison between calculation and measurement of a profile generated by a coupled phosphorus-boron diffusion experiment. The doping profile has been measured by SIMS (dashed lines). The calculation has been performed by implementing the diffusion model into the program package ZOMBIE [29], which is a one-dimensional general solver for systems of coupled parabolic, elliptic, and ordinary differential equations with non-constant coefficients. The good agreement between calculation and measurement can be explained by the fact that the diffusion model takes into account both the vacancies and interstitials.

2. DEVICE MODELING

Since Silicon VLSI Technology has evolved to a standard that hundreds of thousands transistor devices are integrated in a single chip it has become crucial to understand even second order effects of basic device operation. The application of numerical simulation packages for the development of prototype devices is therefore a basic requirement.

Device Modeling based on the self-consistent solution of the well known fundamental semiconductor equations [37] dates back to the famous work of Gummel in 1964 [20]. Since then numerical device modeling has been applied to nearly all important devices. Today there are ongoing arguments in the scientific community whether the semiconductor equations are adequate to describe transport in submicron devices. Particularly the current relations (15) and (16) which are the most complex equations out of the set of the basic semiconductor equations undergo strong criticism in view of, for instance, ballistic transport [23], [34]. 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 for, e.g., [8], [11], [19], [38]. Anyway, recent investigations on ultra short MOSFET's [35] 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 [39].

\[ \mathbf{J}_n = q \cdot \mu_n \cdot n \cdot \left( \mathbf{E} + \frac{1}{n} \cdot \text{grad} \left( \frac{k \cdot T_p}{q} \right) \right) \] \hspace{1cm} (15)

\[ \mathbf{J}_p = q \cdot \mu_p \cdot p \cdot \left( \mathbf{E} - \frac{1}{p} \cdot \text{grad} \left( \frac{k \cdot T_n}{q} \right) \right) \] \hspace{1cm} (16)

In this chapter recent refinements to models of physical parameters concerning the current relations, namely the carrier mobilities and carrier temperatures are discussed. Furthermore, the influence of the shape of the field-oxide in width direction is presented as a particular example for three-dimensional device simulation.

2.1. MODELING CARRIER MOBILITIES

The models for the carrier mobilities \( \mu_n \) and \( \mu_p \) 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.

\[ \mu_n^L = 1430 \frac{\text{cm}^2}{\text{Vs}} \cdot \left( \frac{T}{300\text{K}} \right)^{-2}, \quad \mu_p^L = 460 \frac{\text{cm}^2}{\text{Vs}} \cdot \left( \frac{T}{300\text{K}} \right)^{-2.18} \] \hspace{1cm} (17)

The expressions (17) fit well experimental data of [2], [14] and [31].

The next effect to be considered is ionized impurity scattering. The best established procedure for this task is to take the functional form (18) of the fit provided by Caughey and Thomas [15] and use temperature dependent coefficients.

\[ \mu_{n,p}^{LI} = \mu_{n,p}^{\text{min}} + \frac{\mu_{n,p}^L - \mu_{n,p}^{\text{min}}}{1 + \left( \frac{C_I}{C_{n,p}^{\text{ref}}} \right)^{\alpha_{n,p}}} \] \hspace{1cm} (18)

\[ \mu_n^{\text{min}} = \begin{cases} 80 \frac{\text{cm}^2}{\text{Vs}} \cdot \left( \frac{T}{300\text{K}} \right)^{-0.45} & T \geq 200\text{K} \\ 80 \frac{\text{cm}^2}{\text{Vs}} \left( \frac{200\text{K}}{300\text{K}} \right)^{-0.45} \cdot \left( \frac{T}{200\text{K}} \right)^{-0.15} & T < 200\text{K} \end{cases} \] \hspace{1cm} (19)

\[ \mu_p^{\text{min}} = \begin{cases} 45 \frac{\text{cm}^2}{\text{Vs}} \cdot \left( \frac{T}{300\text{K}} \right)^{-0.45} & T \geq 200\text{K} \\ 45 \frac{\text{cm}^2}{\text{Vs}} \left( \frac{200\text{K}}{300\text{K}} \right)^{-0.45} \cdot \left( \frac{T}{200\text{K}} \right)^{-0.15} & T < 200\text{K} \end{cases} \] \hspace{1cm} (20)
\[ C_n^{\text{ref}} = 1.12 \cdot 10^{17} \text{cm}^{-3} \cdot \left( \frac{T}{300 \text{K}} \right)^{3.2}, \quad C_p^{\text{ref}} = 2.23 \cdot 10^{17} \text{cm}^{-3} \cdot \left( \frac{T}{300 \text{K}} \right)^{3.2} \] (21)

\[ \alpha_{n,p} = 0.72 \cdot \left( \frac{T}{300 \text{K}} \right)^{0.065} \] (22)

The fits (19)-(22) are from [22]. Similar data have been provided in [5] and [17].

In view of partial ionization one should consider neutral impurity scattering [37]. 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 [36].

\[ \frac{\mu_{n,p}^{\text{ref}}}{\mu_{n,p}} = \frac{\mu_{n,p}^{\text{ref}} + (\mu_{n,p}^{\text{II}} - \mu_{n,p}^{\text{ref}}) \cdot (1 - F(y))}{1 + F(y) \cdot \left( \frac{S_{n,p}}{S_{n,p}^{\text{ref}}} \right)^{\alpha_{n,p}}} \] (23)

\[ \mu_n^{\text{ref}} = 638 \frac{\text{cm}^2}{\text{Vs}} \cdot \left( \frac{T}{300 \text{K}} \right)^{-1.19}, \quad \mu_p^{\text{ref}} = 160 \frac{\text{cm}^2}{\text{Vs}} \cdot \left( \frac{T}{300 \text{K}} \right)^{-1.09} \] (24)

with:

\[ F(y) = \frac{2 \cdot \exp \left( -\left( \frac{y}{y_{\text{ref}}} \right)^2 \right)}{1 + \exp \left( -2 \cdot \left( \frac{y}{y_{\text{ref}}} \right)^2 \right)} \] (25)

\[ S_n = \max \left( 0, \frac{\partial \psi}{\partial y} \right), \quad S_p = \max \left( 0, -\frac{\partial \psi}{\partial y} \right) \] (26)

\( S_n^{\text{ref}} \) is assumed to be \( 7 \cdot 10^5 \frac{\text{V}}{\text{cm}} \); \( S_p^{\text{ref}} \) is \( 2.7 \cdot 10^5 \frac{\text{V}}{\text{cm}} \) and \( y_{\text{ref}} \) 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., [6], [24], [33]. A u-shaped mobility behavior as found in [7], [9] has not been synthesized because we 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 [18].
Velocity saturation is modeled with formulae (27). These are again fits to experimental data with, however, a theoretical background considering their functional form [2], [27], [28].

\[
\mu_n^{LISE} = \frac{2 \cdot \mu_n^{LIS}}{1 + \left( \frac{2 \cdot \mu_n^{LIS} \cdot E_n}{v_n^{sat}} \right)^2}, \quad \mu_p^{LISE} = \frac{\mu_p^{LIS} \cdot E_p}{1 + \left( \frac{\mu_p^{LIS} \cdot E_p}{v_p^{sat}} \right)^2}
\] (27)

\(E_n\) and \(E_p\) are the effective driving forces given by (28). Their derivation can be found in [21].

\[
E_n = |\text{grad} \psi - \frac{1}{n} \cdot \text{grad} (U_n \cdot n)|, \quad E_p = |\text{grad} \psi + \frac{1}{p} \cdot \text{grad} (U_p \cdot p)|
\] (28)

The saturation velocities are given in the following.

\[
v_n^{sat} = 1,45 \cdot 10^7 \text{cm} \cdot \text{s} \cdot \sqrt{\tanh \left( \frac{155\text{K}}{T} \right)}, \quad v_p^{sat} = 9,05 \cdot 10^6 \text{cm} \cdot \text{s} \cdot \sqrt{\tanh \left( \frac{312\text{K}}{T} \right)}
\] (29)

The functional form of these fits is after [2]; the experimental data matched are from [2], [13], [14], [16]. An eventual dependence on the crystallographic orientation which one would deduce from [3], [4], [30], is presently not taken into account.

### 2.2. MODELING CARRIER TEMPERATURES

To describe carrier heating properly one has to account for local carrier temperatures \(T_{n,p}\) in the current relations (15) and (16). 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 [21]. We believe that the latter is sufficient for silicon devices. For the electronic voltages we have (30) as an approximation. Confirming theoretical investigations can be found in [1].

\[
U_{n,p} = \frac{k \cdot T_{n,p}}{q} = U_{to} + \frac{2}{3} \cdot \tau_{n,p}^e \cdot \left( v_{n,p}^{sat} \right)^2 \cdot \left( \frac{1}{\mu_{n,p}^{LISE}} - \frac{1}{\mu_{n,p}^{LIS}} \right)
\] (30)

The energy relaxation times \(\tau_{n,p}^e\) are in the order of 0.5 picoseconds and just weakly temperature dependent [10]. 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 [10]). Its maximum is attained at thermal equilibrium. Relation (31) must therefore hold.
Note that models for carrier diffusion coefficients are not required in the basic current relations (15), (16).

Substituting (30) into (31) and rearranging terms one obtains relation (32) for the energy relaxation times.

\[ \tau_{n,p}^e \leq \frac{3}{2} U_t \cdot \frac{\mu_{n,p}^{LIS}}{(v_{n,p}^{sat})^2} \]  

(32)

In the actual version of MINIMOS [40], the energy relaxation times are modeled on the basis of (32) with a fudge factor \( \gamma \) in the range \([0, 1]\) and a default value of 0.8.

\[ \tau_{n,p}^e = \gamma \cdot \frac{3}{2} U_t \cdot \frac{\mu_{n,p}^{LIS}}{(v_{n,p}^{sat})^2} \]  

(33)

For vanishing doping one obtains the maximum energy relaxation times which are at 300K \( \tau_n^e = 4.44 \cdot 10^{-13} \text{s} \), \( \tau_p^e = 2.24 \cdot 10^{-13} \text{s} \) and at liquid nitrogen temperature \( \tau_n^e = 8.82 \cdot 10^{-13} \text{s} \), \( \tau_p^e = 8.68 \cdot 10^{-13} \text{s} \).

2.3. THREE-DIMENSIONAL MOSFET SIMULATION

This chapter presents three-dimensional effects of MOSFET's due to the nonplanar nature of the field-oxide body. The investigations have been carried out by MINIMOS 5 [40] which is the latest extension of the worldwide used program package now including all three spatial dimensions. Three-dimensional effects like threshold shift for small channel devices, channel narrowing and the enhanced conductivity at the channel edge have been successfully modeled.

The geometry of the investigated 3-D MOSFET is given in fig. 6: an n-channel with an 1\( \mu \)m x 1\( \mu \)m channel and gate oxide of 15nm. The oxide body of the analyzed structure can be seen in fig. 7 (note that the oxide is between the upper and the lower plane). In order to demonstrate the effects at the channel edge we select two different bias points. The first is near threshold with \( U_S = U_B = 0.0 \text{V}, U_D = 1.0 \text{V}, U_G = 0.5 \text{V} \) (the threshold voltage for this device is \( U_{th} \approx 0.75 \text{V} \)). The potential distribution in channel length and width direction at the semiconductor/gate-oxide interface is shown in fig. 8. (This plane penetrates into the field oxide near the contact boundary of source and drain.) The corresponding minority carrier distribution is given in fig. 9. A remarkable depletion region at the drain side causes the channel charge to be smaller (under certain bias conditions) than predicted by 2-D simulations. The second bias point is far above
threshold $U_S = U_B = 0.0\, \text{V}$, $U_D = 1.0\, \text{V}$, $U_G = 3.0\, \text{V}$. The corresponding potential distribution can be seen in fig. 10. The location of the plane which the distribution is drawn for, is the same as at the previous bias condition. The high increase of the potential distribution out of the channel is due to the gate contact overlapping the field oxide. Also interesting is the minority carrier distribution (fig. 11) which shows the enhanced conductivity at the semiconductor field-oxide interface. Note that only one half of the channel width is shown in fig. 8 - fig. 11; $-0.5\, \mu\text{m}$ denotes the middle of the channel width and $0.0\, \mu\text{m}$ the boundary of source and drain contacts. The consequence on the device characteristics of these effects depends on the gradient of the “bird’s beak” and the channel width. A high gradient in the field oxide shape results in high parasitic current at the channel edge; this effect is less significant for low gradients. Narrow channel devices with high gradient have much higher currents than predicted by 2-D calculations while the agreement with 2-D simulations is good for wide channel devices in any case. Using a low gradient in bird’s beak yields a very smooth potential distribution compared to a nearly rectangular shape.

**CONCLUSION**

The shrinking dimensions of the elements of integrated circuits require suitable process and device models in physics and mathematics for accurate simulation. Although two-dimensional software tools are adequate for many questions the advanced VLSI technology leads to serious problems which can be investigated rigorously by fully three-dimensional simulations only.

One important drawback of three-dimensional process and device modeling is the enormous amount of required computer resources. The calculations presented in this paper have been carried out on a host computer with 64 MB core memory and one million floating point operations per second. In order to obtain the results of the ion implantation into the trench (chapter 1.1.) about $10^8$ particles had to be investigated. The two-dimensional simulation used 0.8 CPU-hours while the three-dimensional one required about 5 CPU-hours. A straightforward Monte Carlo simulation, i.e. without the special acceleration methods implemented in the program package, would have used about 800 CPU-hours. The situation for three-dimensional device modeling is rather similar: the three-dimensional simulation of a MOSFET at difficult bias conditions may require up to 100 CPU-hours. Such a time is only acceptable, if just one program run is needed to solve a special problem. However, the calculation of a characteristics, for instance, would not be completed within a reasonable time. Of course nowadays there exist computers which are much faster than the one mentioned above but unfortunately not each investigator has permanent access to such a super computer. Therefore, three-dimensional process and device modeling actually do not replace the two-dimensional activities, but are absolute necessities as significant completion.
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REFERENCES


Figure Captions

Fig.1: Two-dimensional trench

Fig.2: Three-dimensional trench with square cross-section

Fig.3: Concentration of dopants in the 2-D trench

Fig.4: Concentration of dopants in the symmetry plane of the 3-D trench

Fig.5: Doping profile of a coupled diffusion experiment

Fig.6: Three-dimensional MOSFET structure

Fig.7: Oxide body of the MOSFET structure

Fig.8: Detailed view of the surface potential at bias $U_G = 0.5V$

Fig.9: Detailed view of the minority carrier density at bias $U_G = 0.5V$

Fig.10: Detailed view of the surface potential at bias $U_G = 3.0V$

Fig.11: Detailed view of the minority carrier density at bias $U_G = 3.0V$