SIMULATION OF SEMICONDUCTOR DEVICES AND PROCESSES Vol. 5
Edited by S. Selberherr, H. Stippel, E. Strasser – September 1993

3D Simulation of MOS Transistors with Inversion Condition in Two Directions

G. Punz

PSE, Siemens AG Österreich
Gudrunstraße 11, A-1101 Wien, AUSTRIA

Abstract

The 3D device simulator MINIMOS has been extended for simulation of complex oxide structures, allowing inversion condition in two dimensions. The results for a test structure with a threefold bent gate oxide show enhanced channel formation in regions where the inversion condition is fulfilled in two directions.

1. Introduction

Full 3D simulation is a necessity in order to describe the effects of e.g. narrow channel width or field implants for realistic MOSFET structures. Compared to the heavy numerical and computational effort of general–purpose simulators [1], [2] specialized codes for MOSFET's are more efficient. In MINIMOS [3] the simulation is performed in steps, seeking first a full solution for a 2D cut plane which serves as an initial guess for the 3D problem, and introducing a quasi–2D mode (during which only Poisson's equation is solved fully threedimensionally, whereas the solution of the carrier continuity equations are estimated assuming vanishing currents in the third dimension) to benefit further from the computationally cheaper 2D solution. However, this restricts the allowed 3D geometries to be smoothly generable from the 2D geometry and allows only modest variation of the solution with respect to the third coordinate.

In this paper simulations of 3D MOS structures with complex geometry features with respect to the width direction are presented. MINIMOS has been extended to allow flexible oxide body specification by polygons (see sketch of a quarter transistor in fig. 1). A heuristic scheme for the setup of an appropriate 3D initial solution from the 2D solution is introduced. The applicability of our method is demonstrated for an extreme test example.

2. Method

The first step is to adapt the grid generation algorithm – also for 2D – for a redefinition of the simulation area where carrier continuity equations are solved by shifting the corresponding milestone up to the overall maximum of the lower oxide contour. (Like for 2D nonplanarities, MINIMOS masks all points assigned to boxes fully in oxide for the continuity equations).

Next the 3D initial distributions have to be specified. In plain MINIMOS the initial potential (ψ) and carrier distributions (n, p) are taken from the 2D simulation plane and continued with constant values along the width direction. This is sufficient for oxide bodies with a monotonous variation from the thin gate oxide to the field oxide. With our complex structures, however, this is not well defined for semiconductor regions higher than the oxide contour in the 2D simulation plane (region A in fig. 2). The possibility to solely extend the distributions from the well defined region B upwards suffices in the case of only moderate parameters h as compared to the inversion layer depth d, but leaves too many carriers in subregion C of B and is not convergent for $d \sim h$. Therefore a heuristic transformation is applied to extend the distributions in z–direction according to the upper and lower oxide contours $f^u(x,z), f^l(x,z)$ (z_c is a cutoff for the channel width estimated from the oxide thickness, for meaning of other symbols see figures 1 and 2):

$$\psi(x,y,z) = \psi(x,y_{ref},z_0)$$

$$n(x,y,z) = n\ (x,y_{ref},z_0)\cdot\Theta(z_c - z) \qquad p(x,y,z) = p\ (x,y_{ref},z_0)\cdot\Theta(z_c - z) \tag{1}$$

$$y_{ref} = \begin{cases} \Big(y - f^l(x,z)\Big)\cdot\dfrac{y_{max} - f^l(x,z_0)}{y_{max} - f^l(x,z)} + f^l(x,z_0) & \text{for } y > f^l(x,z) \\ \Big(y - f^u(x,z)\Big)\cdot\dfrac{f^l(x,z_0) - f^u(x,z_0)}{f^l(x,z) - f^u(x,z)} + f^u(x,z_0) & \text{for } f^u(x,z) < y < f^l(x,z) \\ \Big(y - y_{min}\Big)\cdot\dfrac{f^l(x,z_0) - y_{min}}{f^l(x,z) - y_{min}} + y_{min} & \text{for } y < f^u(x,z) \end{cases} \tag{2}$$

For the carrier concentrations only the first line of eq. (2) is relevant.

This scheme does not claim to be based on sound physical arguments, but is extremely practical for two reasons: (i) it is well defined for the whole MOS transistor and is applicable for quite general oxide contours (ii) looking at yz–cuts within the channel region, the resulting initial potential and carrier distributions match the oxide boundaries well and are sufficiently close to to their final solutions, which is crucial for reaching convergence. (For the regions near source and drain more sophisticated initial potential distributions might be found.)

Considering the 3D solution hierarchy for MINIMOS we notice that a quasi–2D mode is feasible for h small compared to d, but fails – for the same, abovementioned reasons – in the general case of highly nonplanar oxide bodies. In this case Poisson's and continuity equations for both carrier types are solved fully 3D from the very start.

For most flexible applications we combine gate oxide nonplanarities within the 2D simulation plane with complex oxide geometries within the cut normal to it in the middle of the channel. A user interface allowing oxide specification by two (upper, lower) polygons $\left(x_i, f_x^{u,l}(x_i)\right)$ and $\left(z_i, f_z^{u,l}(z_i)\right)$ is already implemented in our version of MINIMOS. Two algorithms have to be specified: (i) for 3D doping profile generation from 2D cuts and (ii) for matching and extending oxide contours from 2D cuts to full 3D oxide surfaces. For the second task e.g. we use

$$f^l(x,z) = f_x^l(x) + \Big(f_z^l(z_{max}) - f_x^l(x)\Big)\cdot\frac{f_z^l(z) - f_z^l(z_0)}{f_z^l(z_{max}) - f_z^l(z_0)} \tag{3}$$

for the lower contour, assuming the oxide boundary to be lowest at z_{max} (and an analogous formula for the the upper contour). Ideally – using reliable full 3D process simulation – the effort of constructing oxide contours from 2D cuts should be obsolete.

3. Results

To demonstrate the capability of the method a rather drastic geometry is chosen as a test example (1 μm transistor at $U_G = 1V, U_D = 3V$ with a threefold bent gate oxide along the width direction combined with a nonplanarity in length direction, a yz–cut in the middle of the channel is seen in fig. 3). Figs. 4 and 5 show the solutions for potential and minority carrier concentrations in the region where the horizontal and vertical inversion interact (a cut plane intersecting on the source side of the gate is shown). The resulting enhancement of the channel is clearly seen. Table 1 lists the drain current I_D as a function of the "horizontal" gate oxide thickness t_h.

$t_h[nm]$	80	100	120	140	160
$I_D[mA]$	1.79	1.59	1.43	1.31	1.15

Table 1

CPU time is about one hour on an HP 900-750 for a 59· 66· 60 grid.

4. Conclusion

An enhancement of the 3D device simulator MINIMOS for the efficient simulation of MOS transistors with complex oxide structures has been implemented, allowing routine analysis and assessment of their usefulness in VLSI design. Effects stemming from inversion conditions in two directions may now be investigated in detail.

References

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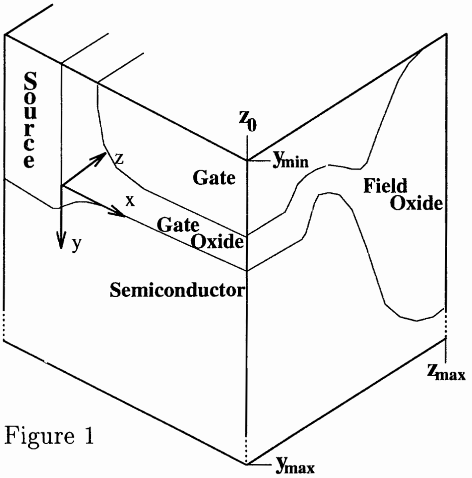

Figure 1

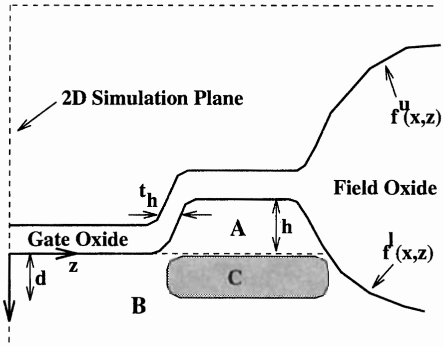

Figure 2

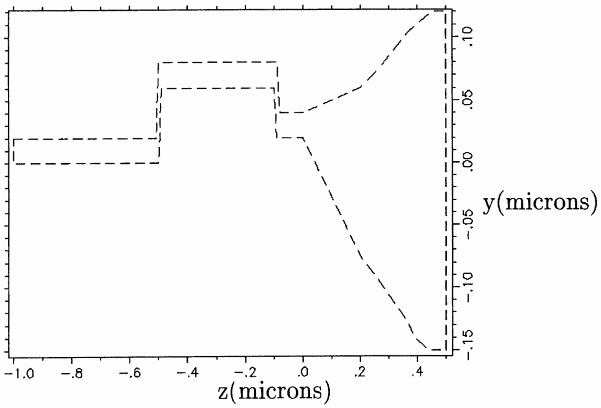

Figure 3

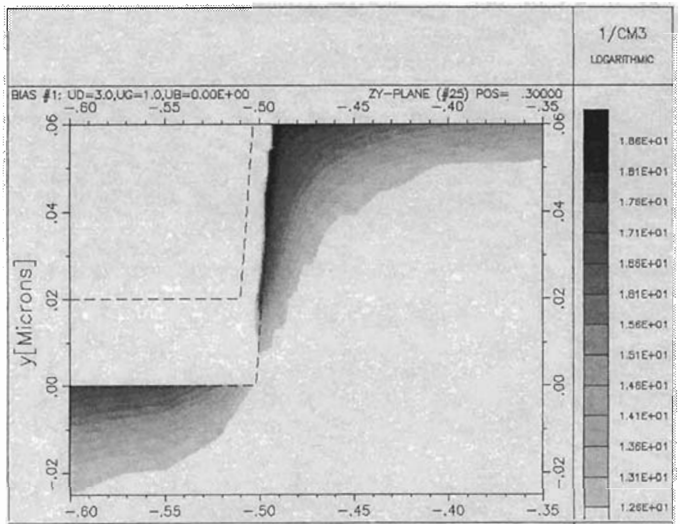

Figure 4

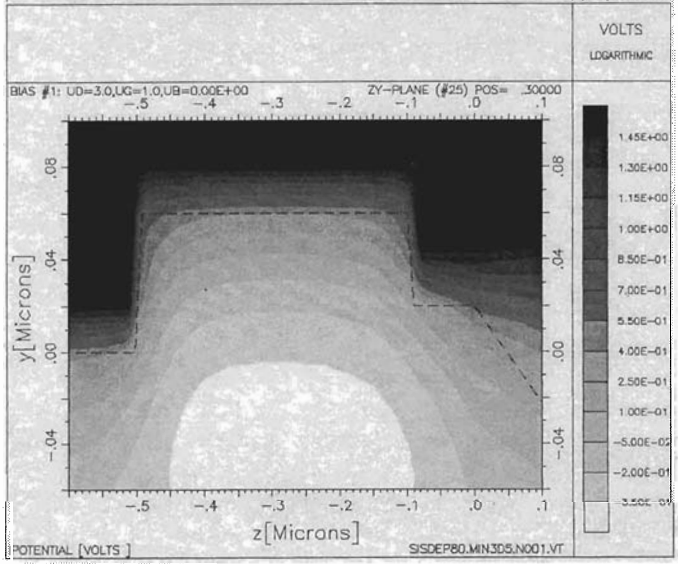

Figure 5