A Comparison of Numerical and Analytical Short Channel MOST-Models

Bernd Meinerzhagen and Heinz K. Dirks

Institut für Theoretische Elektrotechnik der Rheinisch - Westfälischen Technischen Hochschule Aachen, Kopernikusstr.16,
D-5100 Aachen, West-Germany

SUMMARY

For two n-channel MOST's with effective channel lengths of 3.3µm and 1µm, respectively, two analytic charge sharing models are compared with the exact numerical simulator GALENE and a recently developed highly efficient two-dimensional numerical MOST-model. If device characteristics are increasingly influenced by charge sharing or even punch through the examples demonstrate the breakdown of the analytical models whereas the efficient numerical model preserves its pedictive capability.

1. INTRODUCTION

With decreasing device dimensions the influence of short channel effects on electrical characteristics of MOST's increases. Among these parasitic effects charge sharing and punch-through are important examples. In classical analytical MOST-models these effects are not included. Hence, various attempts have been made to incorporate the charge sharing. One approach often used is to describe the bulk charge shared by the gate by a trapezoid. This method is best justified below or near threshold resulting in improved threshold voltage models /1,2/ and more accurate models for the subthreshold /3/ current. Nevertheless these improved models can fail if the device operates near punch-through.

A well established approach to avoid this problem is the "exact" two-dimensional numerical device simulation requiring the solution of Poisson's equation and at least one continuity equation. Unfortunately the relatively high computational effort prevents the extensive use of this highly accurate predictive tool. Therefore, a simplified two-dimensional numerical MOST-model has recently been developed.

Using two n-channel MOST's with different channel lengths the accuracies of two analytical charge sharing models and the new numerical model are examined by comparing their results with "exact" two-dimensional simulations.

2. DESCRIPTION OF THE MODELS

a) Model 1:

Model 1 is the device simulation program GALENE /4/ which is used here to solve numerically Poisson's equation and the electron continuity equation in two dimensions. All relevant physical mechanisms like doping dependent mobility, mobility degradation in the channel region, and velocity saturation etc. are taken into account. For both examples described later a nonequidistant grid of 30 horizontal and 50 vertical grid lines has been used. All linear systems occuring during the solution procedure have been solved by direct elimination.

b) Model 2:

Model 2 is the new efficient numerical MOST-model which comprises similar to de la Moneda /5/ the two-dimensional Poisson equation and a simplified one-dimensional electron (or hole) continuity equation

$$\Delta\Psi(x,y) = -\frac{\rho(x,y)}{\varepsilon} \qquad (1)$$

$$\frac{d}{dy}\left(\int_0^{depth} \mu_n n(x,y)\frac{d}{dy}\phi_n(y)dx\right) = \int_0^{depth}(G-R)dx \qquad (2)$$

where the mobility dependence on doping and fields is modeled as in GALENE. In contrast to de la Moneda's original approach both equations are discretized using the box integration method. The Newton Raphson method is used for solving the resulting nonlinear system of finite difference equations, thus overcoming the well known convergence problems of the decoupled method (Gummel's nonlinear relaxation method). Again the linearized system is solved by direct elimination. Moreover, the efficiency of this model is increased by an improved space discretization scheme allowing coarser grids in regions where electron density varies rapidly. For the examples discussed later a nonequidistant grid of 15 lateral and 24 vertical grid lines has been used.

c) Model 3:

Model 3 is the analytical charge sharing model for subthreshold current as first proposed by Taylor /3/. In this model the region of the bulk charge shared by the gate is approximated by a trapezoid. The space charge layer widths defining this trapezoid are approximated using the formula for a one-sided planar abrupt junction. This model is a generalization of Yau's threshold voltage model /1/ which is implemented in the SPICE level 2 MOST-model.

d) Model 4:

Model 4 is a generalization of Dang's threshold voltage model /2/ and describes the drain current in the subthreshold region. This generalization is similar to Taylor's generalization of Yau's model. Again a trapezoid is used to describe the region of the bulk charge shared by the gate, but now the lateral space charge layer widths are approximated by the formula for a one-sided cylindrical abrupt junction. Dang's model is implemented in the SPICE level 3 MOST-model.

3. EXAMPLES AND DISCUSSION

Two n-channel MOST's with effective channel lengths of 3.3µm and 1µm have been chosen as examples. In order to show only the influence of channel length reduction all other parameters are identical for both transistors, i.e. oxide thickness d_{OX}=22nm, substrate doping $N_A=1.5\cdot10^{15}cm^{-3}$, and junction depth x_j=0.36µm.

For the 3.3µm MOST the subthreshold characteristics of the four models are compared in figures 1 and 2 for V_D=0.5V and V_D=5V, respectively. It can be seen that in both cases the difference between model 1 and 2 is negligible (see also table 1) whereas the deviation of the analytical models is significant especially for model 3 and higher drain voltage. The following ratio measures the influence of drain voltage on subthreshold current:

$$m(V_G) = \frac{I_D(V_D = 5V\ ,V_G)}{I_D(V_D=0,5V,V_G)} \qquad (3)$$

For the numerical models and model 4 this ratio is independent on the gate voltage m=1.5 and m=2.1, respectively, whereas it varies with gate voltage between m=6 and m=8.4 for model 3. This result clearly indicates that both analytical models overestimate the influence of drain voltage. The reason for this discrepancy of the analytical models is their poor approximation of the charge shared by the gate as can be seen from comparing in figures 3 and 4 the trapezoids predicted by the analytical models with the corresponding regions resulting from model 1.

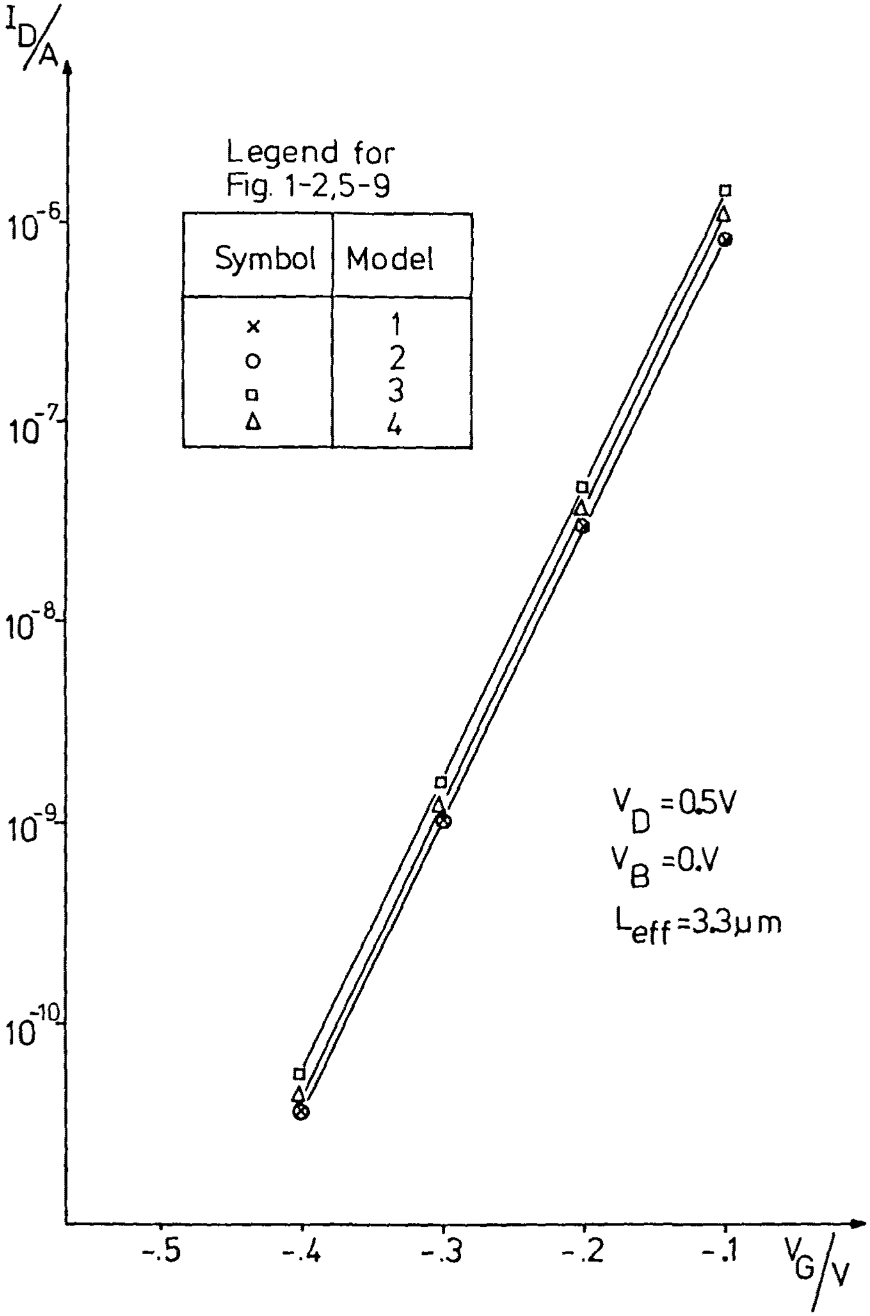

Figure 1: Subthreshold characteristic for example 1

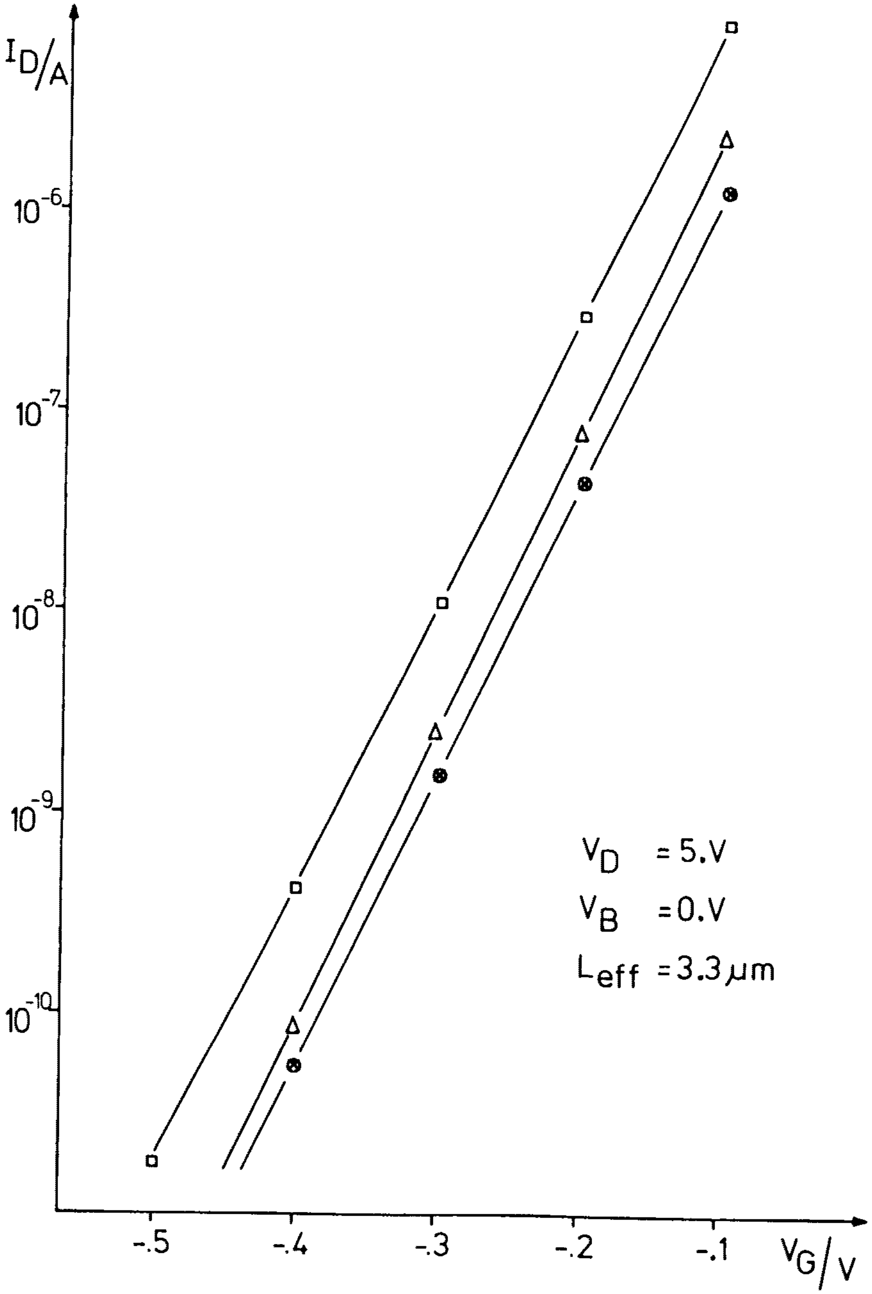

Figure 2: Subthreshold characteristic for example 1

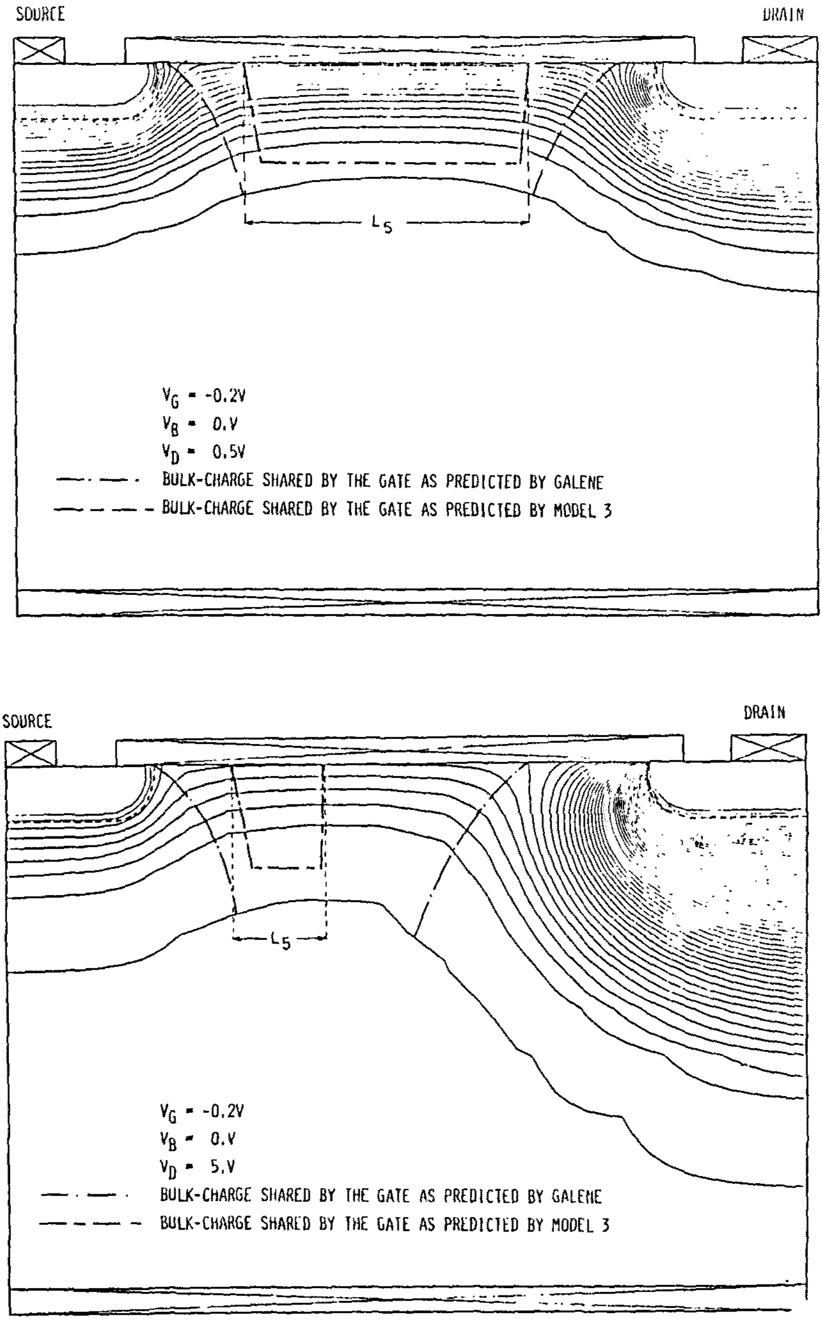

Figure 3: Plots of equipotentiallines for example 1

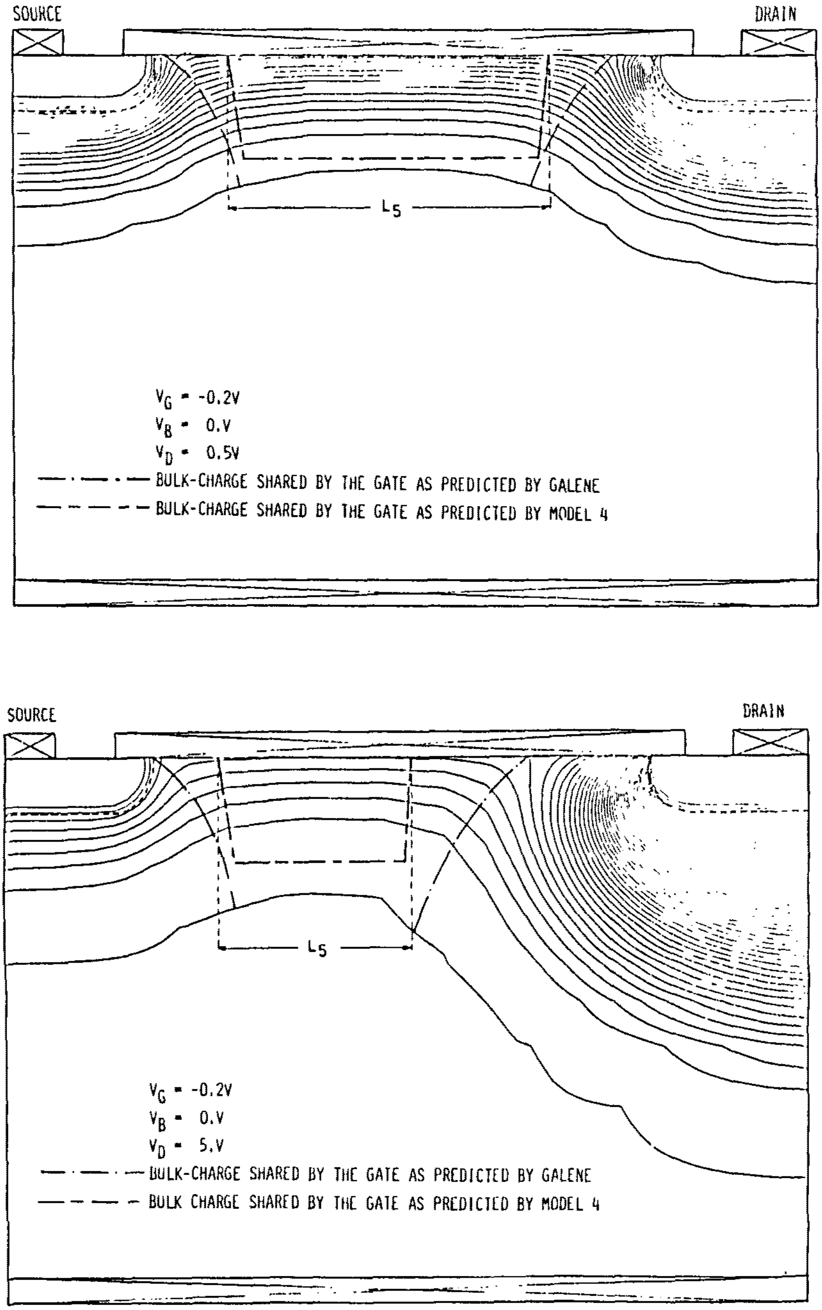

Figure 4: Plots of equipotentiallines for example 1

Table 1

Performance of model 2 in comparison to model 1

characteristic	$L_{eff}=3.3\mu m$			$L_{eff}=1\mu m$		
	E_{max}	E_{mean}	Gain	E_{max}	E_{mean}	Gain
$V_D=.5V, -.5V\leq V_G\leq -.1V$	4.9	2.4	31	8	4.4	33
$V_D=5.V, -.5V\leq V_G\leq -.1V$	3.5	1.6	31	28	24	32
$V_G=0.V,\ .5V\leq V_D\leq\ 5.V$	4.1	3.3	28	12.1	6.8	34
$V_G=2.V,\ .5V\leq V_D\leq\ 5.V$	5.6	3.8	31	5.2	4.7	36
$V_G=4.V,\ .5V\leq V_D\leq\ 5.V$	7.6	7	31	10.6	7.6	38

E_{max}, E_{mean} are the respective errors in %;
Gain = CPU-time(model 1)/CPU-time(model 2)

The simplified numerical model 2 is not only sufficiently accurate for subthreshold currents but also for the output characteristics shown in figure 5 and 6. For the 3.3µm transistor the deviation from model 1 is less than 8% as can be seen from table 1. This tolerable loss of accuracy reduces the required CPU-time by a factor of about 30, though model 1 is significantly accelerated by utilizing the fine grid solutions of model 2 as accurate starting conditions. For this example the 8% error of model 2 is mainly due to the coarse grid and the error reduces to less than 1% if the same grid is used as for model 1. Comparable results are obtained from model 2 for the 1µm transistor (see table 1 and figures 7-9). But here the somewhat larger errors for the subthreshold characteristic with V_D=5V are mainly caused by the underlying simplifications of this model and less by the coarse grid, since the deep punch-through current occuring in this device for higher drain voltages (see figure 10) is not precisely described by the one-dimensional equation (2).

For the 1µm transistor no subthreshold current can be calculated from the analytical models, since both models predict for all bias points a vanishing bulk charge shared by the gate. As can be seen from the exact solutions in figure 10 this is only true for the punch-through case (V_D=5.V) whereas for smaller drain voltages a significant part of the bulk charge is shared by the gate.

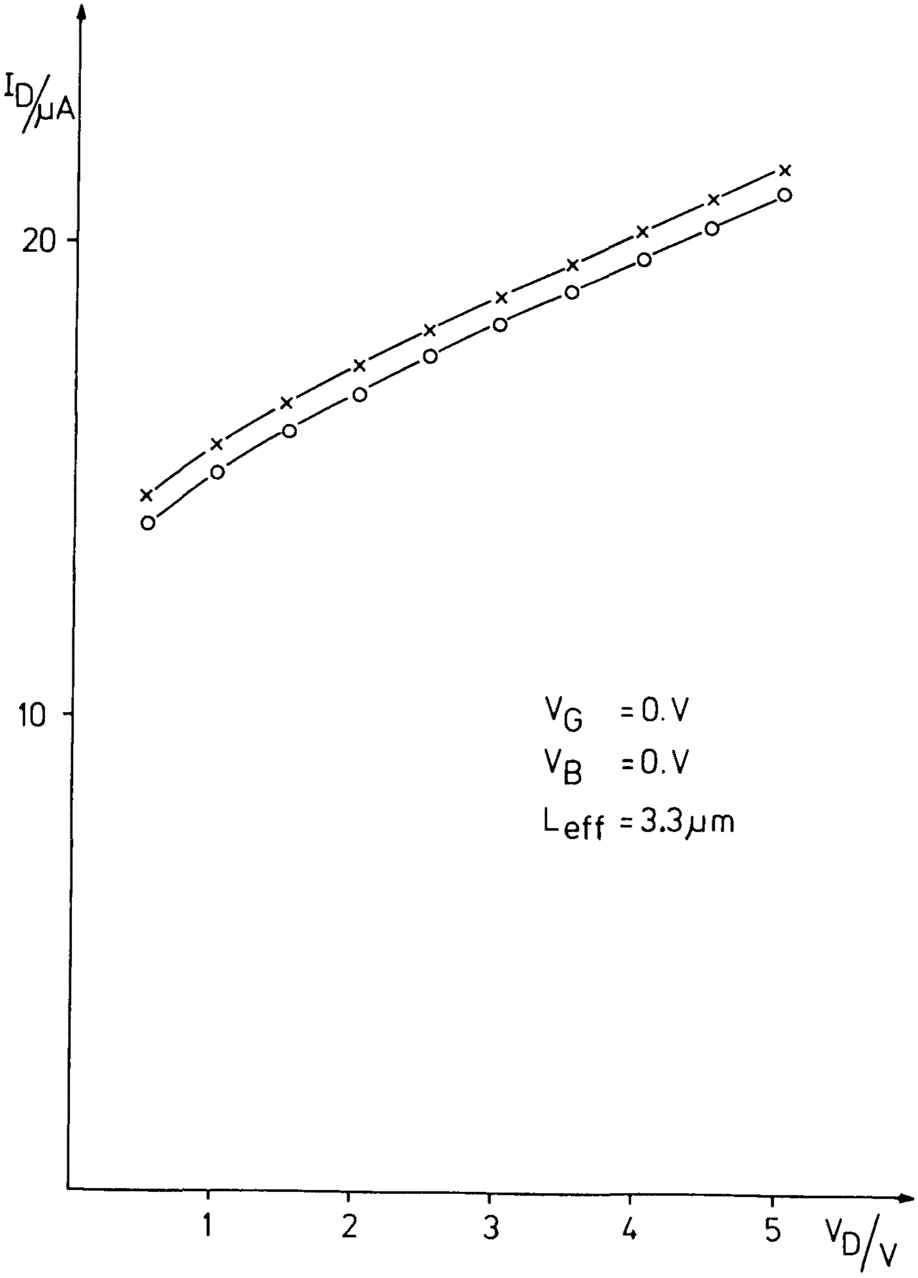

Figure 5: Output characteristic near threshold for example 1

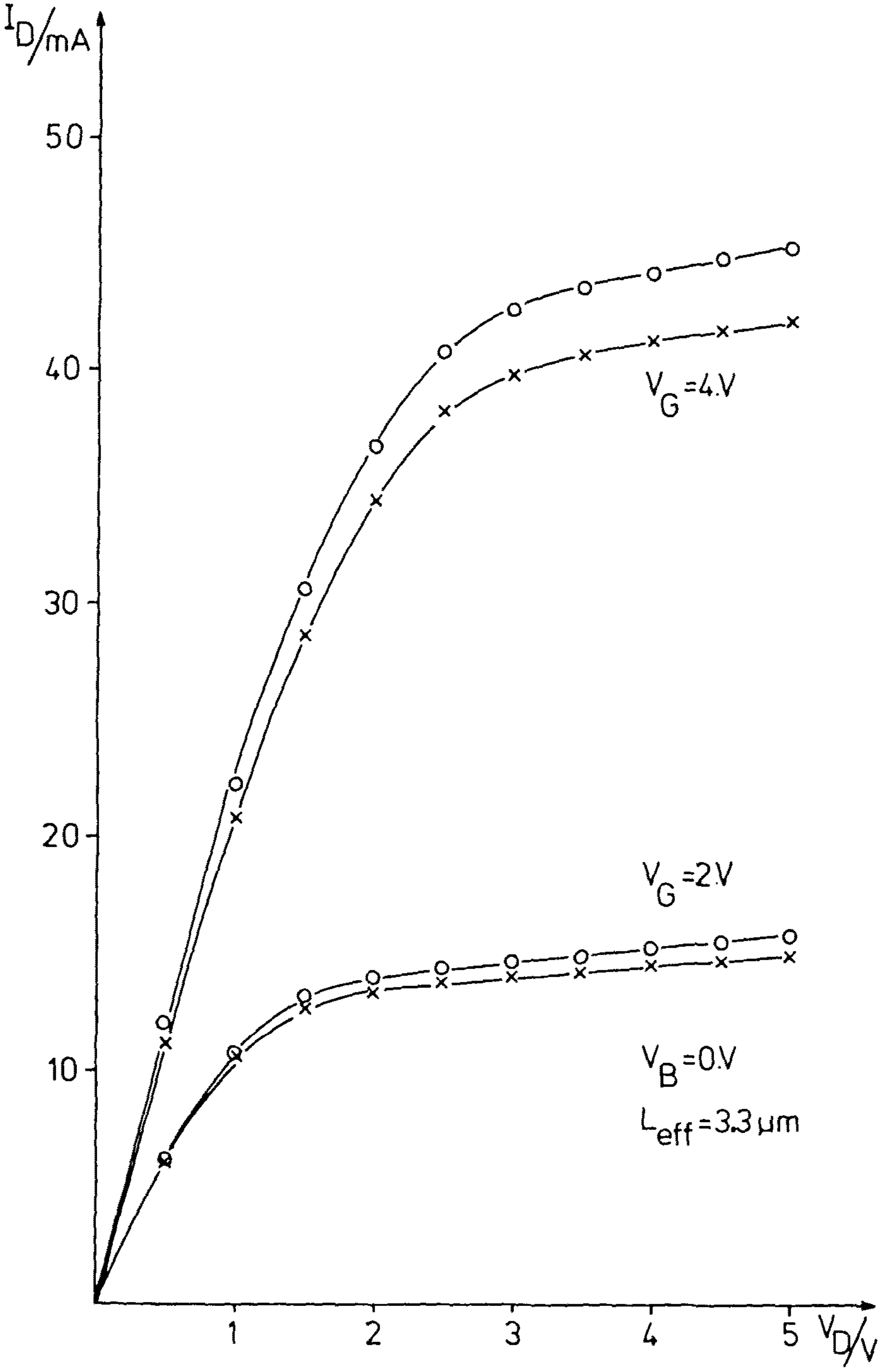

Figure 6: Output characteristics for example 1

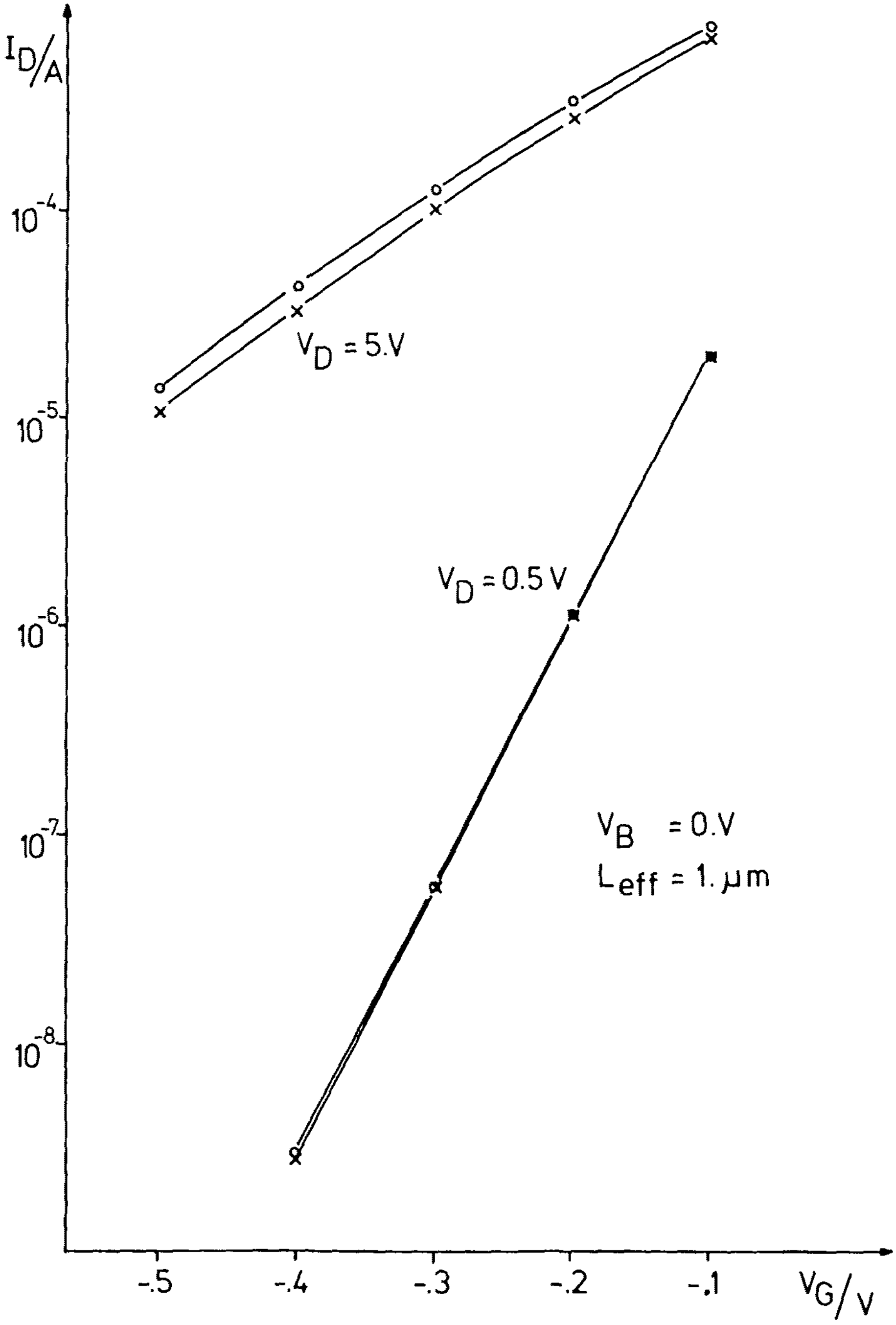

Figure 7: Subthreshold characteristics for example 2

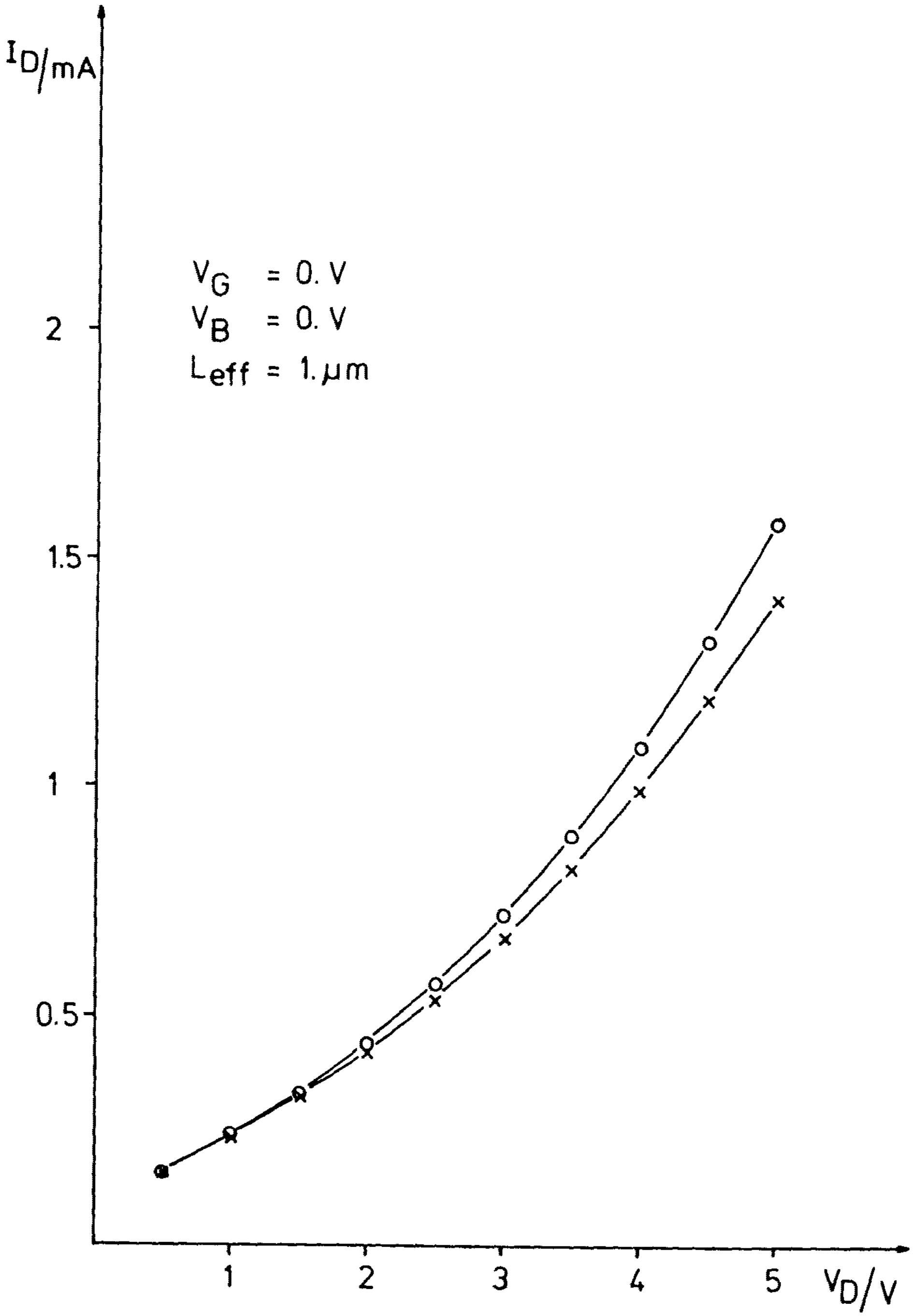

Figure 8: Output characteristic near threshold for example 2

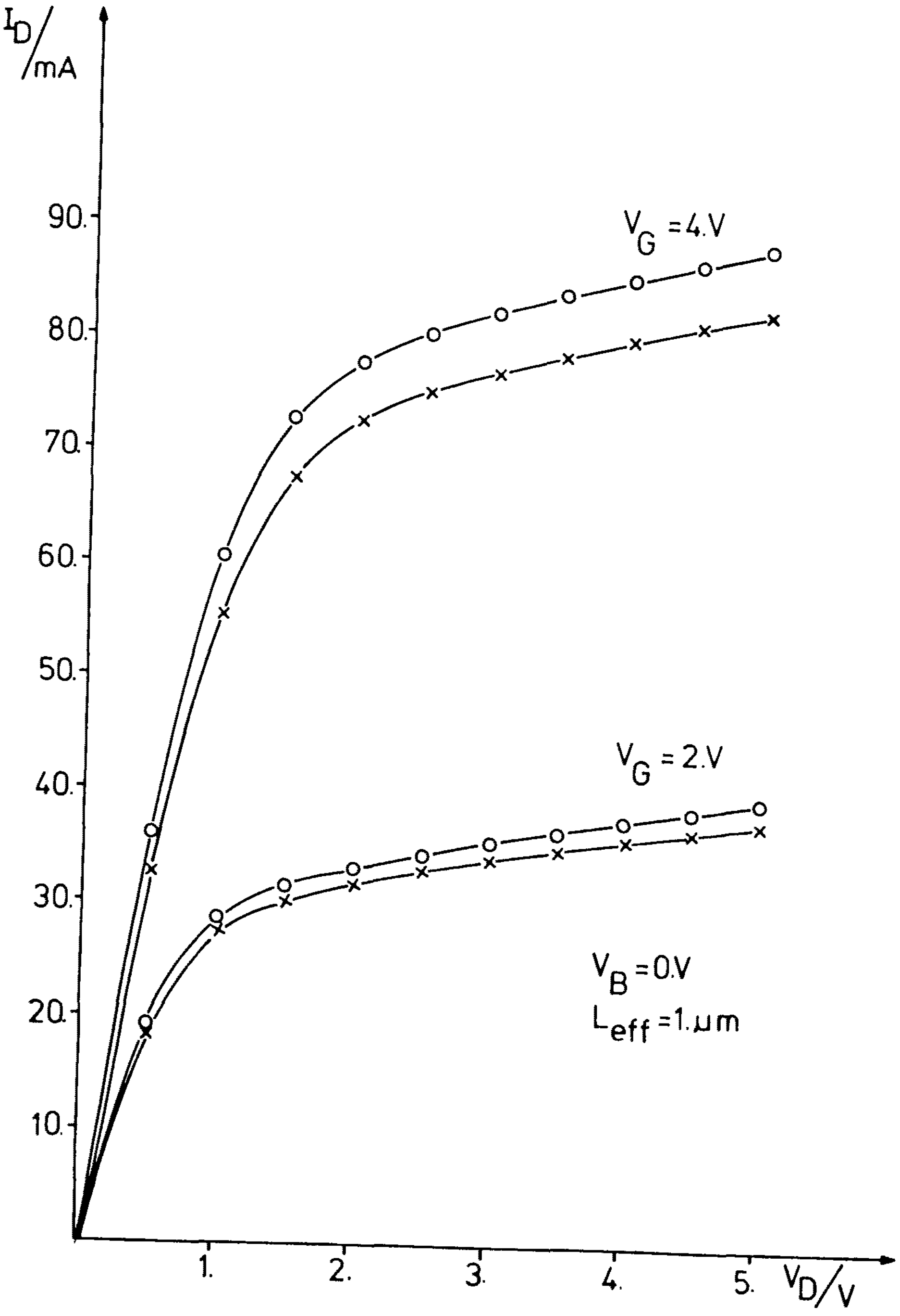

Figure 9: Output characteristics for example 2

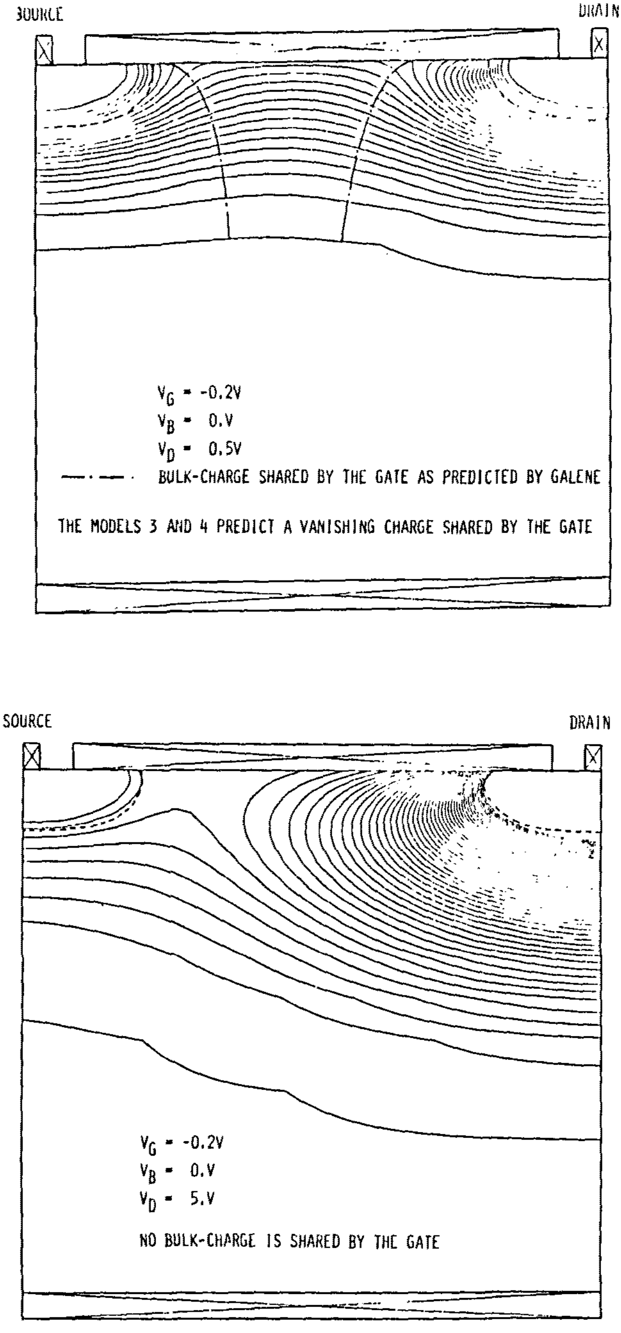

Figure 10: Plots of equipotentiallines for example 2

4. CONCLUSION

The shortcomings of the discussed analytical short channel MOST-models do not exist for the simplified numerical model which preserves its predictive capability even for very short channel devices. Moreover, for the considered examples the new model requires only about 14 sec CPU-time per bias point on a DATA-GENERAL ECLIPSE MV/10000 minicomputer. This high efficiency of the model enables its implementation in a mixed-level device circuit simulator like MEDUSA /6/.

5. REFERENCES

/1/ L.D. Yau, "A simple theory to predict the threshold voltage of short channel IGFET's, Solid State Electronics, Vol. 17, pp. 1059-1063, 1974.

/2/ L.M. Dang, "A simple current model for short channel IGFET and its application to circuit simulation", IEEE J. Solid-State Circuits, Vol. SC-14, pp. 358-367, 1979.

/3/ G.W. Taylor, "Subthreshold conduction in MOSFET's, IEEE Trans. Electron Devices, Vol. ED-25, pp. 337-350, 1978.

/4/ W.L. Engl, H.K. Dirks, B. Meinerzhagen, "Device modeling", Proceedings of the IEEE, Vol. 71, pp. 10-33, 1983.

/5/ F.H. de la Moneda, "Threshold voltage from numerical solution of the two-dimensional MOS transistor", IEEE Trans. Circuit Theory, Vol. CT-20, pp. 666-673, 1973.

/6/ W.L. Engl, R. Laur, H.K. Dirks, "MEDUSA-A simulator for modular circuits", IEEE Trans. Computer-Aided Design, Vol. CAD-1, pp. 85-93, 1982.