"The boundary element method for modeling the DMOS transistor at high drain voltages"

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Abstract.

Modeling semiconductor devices is usually performed with a finite difference or a finite element method. In some special cases the boundary element method can be used. This method offers the advantage that only the boundary of the given geometry has to be divided into elements. This means a reduction of the dimension of the problem, performed by transforming the original equations and boundary conditions into an equivalent integral equation along the boundary.

The method has been applied to calculate the maximum drain voltage across a DMOS transistor in the "off" state. By varying several parameters such as doping concentration, geometry,... it was possible to design an optimal structure, corresponding to a maximum drain voltage without exceeding a critical field strength.

1. Introduction.

Fig. 1 shows a schematic structure of a DMOS transistor (more specifically the ROMOST type). This device has been designed as a fast switching device. In the "on" state the

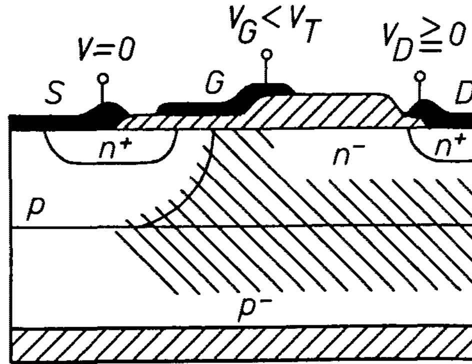

Fig.1: Cross sectional view of a DMOS transistor. The striped areas are depletion regions.

n^- layer together with the n^+ drain contact behaves as a large drain region so that the "on" characteristics are determined by the small p-layer. Both the p and the n^+ source region have been realised by subsequent diffusions through the same mask. For further details one is referred to the literature [1][2][3].

In this paper we shall limit ourselves to the "off" state of the transistor especially at high drain voltages (up to 400 Volt). In the "off" state, the pn^- and the p^-n^- junctions are reverse biased generating depletion layers in the lower doped n^- and p^- regions (fig. 1). It turns out that for the high drain voltages the n^- region is completely in depletion.

High voltages across a semiconductor cause high electric fields. In order to prevent ionisation the electric field should be lower than a critical value E_{crit} in any point. It is well known from the one-dimensional abrupt depletion

theory that the electric field strength shows a linear behaviour. For a depletion thickness d_D, $E_{crit}\, d_D/2$ turns out to be the maximum allowable voltage. If one could realise a homogeneous electric field, then $E_{crit}.d_D$ will be the maximum voltage which is two times higher.
The study of this paper will be to investigate how the electric field can be made more homogeneous in a two dimensional configuration as shown on fig. 1.

2. Mathematical model.

For the mathematical analysis, the structure of fig. 1 is somewhat simplified to the geometry shown on fig. 2. The

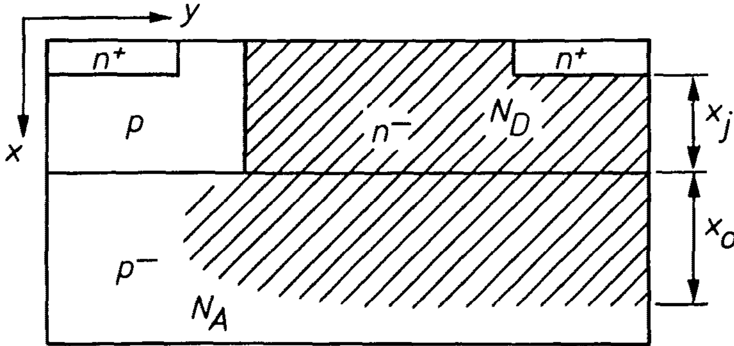

Fig.2: Simplified structure of a DMOS transistor.

depletion regions are shown by striped areas. At the high drain voltages the n^- region is completely depleted. The depletion depth x_o in the p^- region is calculated according to a one dimensional approximation along the x-axis :

$$x_o = \sqrt{\frac{2\varepsilon_o\varepsilon_s}{qN_A} N_D + \frac{x_j^2\ (N_A+N_D)}{N_A}} \tag{1}$$

The geometry of fig. 2 is now simplified furtheron to the structure shown on fig. 3. The equations for the potential are :

$$\nabla^2\phi = -\frac{qN_D}{\varepsilon_o\varepsilon_S} \quad \text{in the } n^- \text{ layer}$$

$$+\frac{qN_A}{\varepsilon_o\varepsilon_S} \quad \text{in the } p^- \text{ layer} \qquad (2)$$

The boundary conditions for ϕ are also indicated on fig. 3.

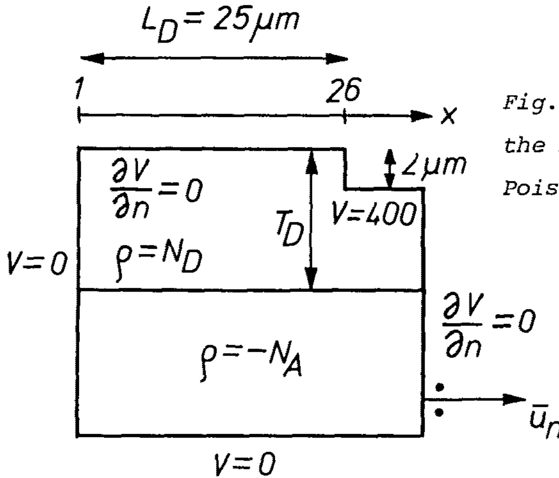

Fig.3: Geometry used for the numerical solution of Poisson's equation.

A program CALC based on a boundary integral equation technique has been developped to solve the equation (2) for arbitrary polygonal geometries.

3. The boundary element method.

The boundary element method is a well known technique using the conversion of a partial differential equation with the associated boundary conditions into an equivalent integral equation defined along the boundary of the original problem. This reduction of the dimension offers a lot of advantages. The boundary element method has also been used in several semiconductor problems such as Hall effect devices [4][5][6], two dimensional modeling of pn junctions and solar cells [7][8][9] . Time dependent problems in semiconductor devices have also been analysed [10].

In the abrupt depletion approximation, the equation (2)

can be written more generally as :

$$\nabla^2\phi = \frac{-\rho(x,y)}{\varepsilon_o\varepsilon_S} \tag{3}$$

where ρ is the charge density. Using the Green's function :

$$G(\bar{r}|\bar{r}') = \frac{1}{2\pi}\ln|\bar{r}-\bar{r}'| \tag{4}$$

which is a solution of :

$$\nabla^2 G(\bar{r}|\bar{r}') = \delta(\bar{r}-\bar{r}') \tag{5}$$

We obtain after applying Green's theorem (fig. 4) :

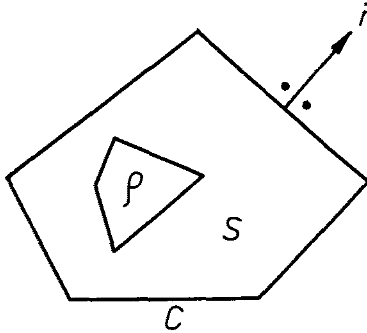

Fig.4: Polygonal structure used in CALC.

$$\oint_C [\phi(\bar{r})\frac{\partial G(\bar{r}|\bar{r}')}{\partial n} - G(\bar{r}|\bar{r}')\frac{\partial\phi(\bar{r})}{\partial n}]dC =$$

$$= \phi(\bar{r}') + \frac{1}{\varepsilon_o\varepsilon_S}\iint_S \rho(\bar{r})G(\bar{r}|\bar{r}')dS \tag{6}$$

The surface integral can be calculated because the charge density ρ is a known function. The potential $\phi(\bar{r}')$ can then be evaluated in an arbitrary point $\bar{r}'$ by performing an integration along the boundary. This requires however the knowledge of both ϕ and $\partial\phi/\partial n$ along the entire boundary, which is not the case here because only ϕ or $\partial\phi/\partial n$ are given boundary conditions (fig. 3). By putting the point $\bar{r}'$ on the boundary, the relation (6) is transformed into an integral equation. If ϕ is known on the boundary, $\partial\phi/\partial n$ acts as the unknown function and vice versa on the remaining part of the boundary.

For the numerical solution of the boundary integral equation, the boundary is divided into N elements, explaining the name boundary element method. In each element ΔC_j, the unknown function is replaced by an unknown constant ϕ_j or $(\partial\phi/\partial n)_j$ and the integral equation is reduced to a linear algebraic set which can be easily solved numerically.

The program CALC represents the unknown function by a piecewise constant approximation in each interval. All matrix coefficients can be calculated analytically. Also the surface integral appearing on the right hand member of (6) can be calculated analytically if the charge density is piecewise constant in polygonal structures. The program CALC constructs and solves the integral equation for arbitrary polygonal geometries up to 10 regions each having a different charge density. The program evaluates the potentials and field strengths along the boundary and internally.

4. Results.

Fig. 5 shows the influence of the thickness T_D of the epi-layer on the field distribution at the semiconductor oxide interface. From this figure it can be easily seen that T_D = 10 μm corresponds to the optimal configuration because the electric field distribution is the most homogeneous. Similar results are found for the influence of the epilayer doping N_D (fig. 6). Figs. 5 and 6 only show the electric field strengths along the interface. It can be expected that the highest electric field strength will occur there. This has been proved by a 3-D plot of the electric field (fig. 7).

Because the theory outlined in the previous sections contain quite a lot of approximations the same transistor structure has also been analysed with the CADDET program [11]. Fig. 8 shows a good agreement between both programs. Note that the calculation with CADDET consumed more than 1 hour

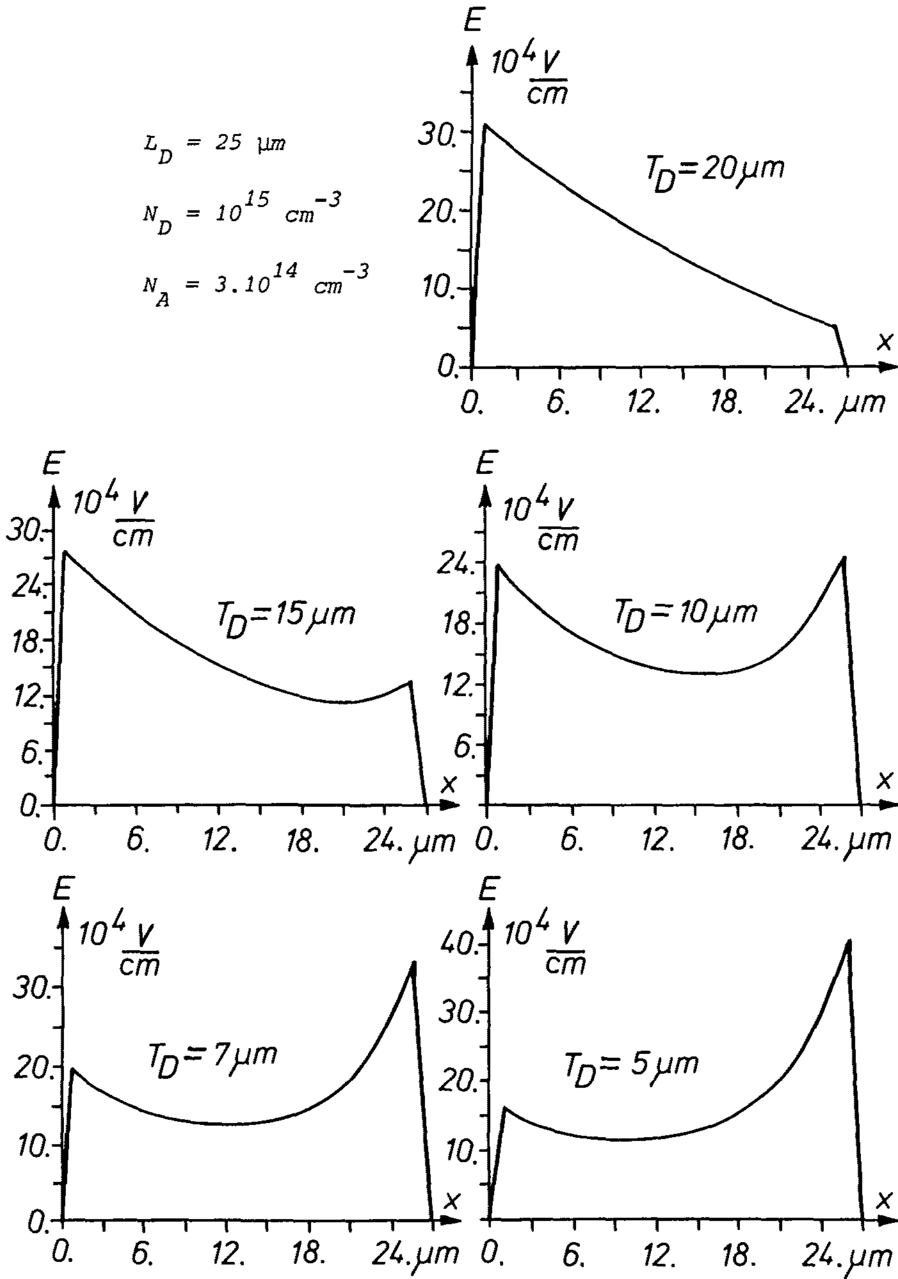

Fig.5: Influence of the epilayer thickness T_D on the electric field distribution.

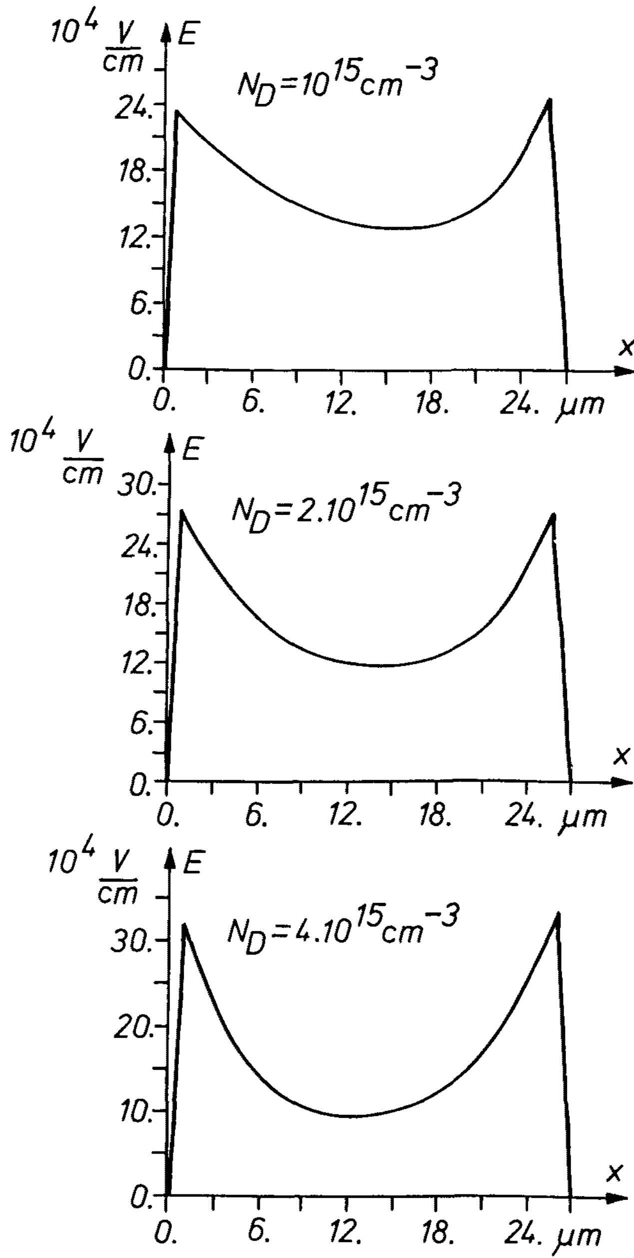

Fig.6: Influence of epilayer doping N_D on the electric field distribution.

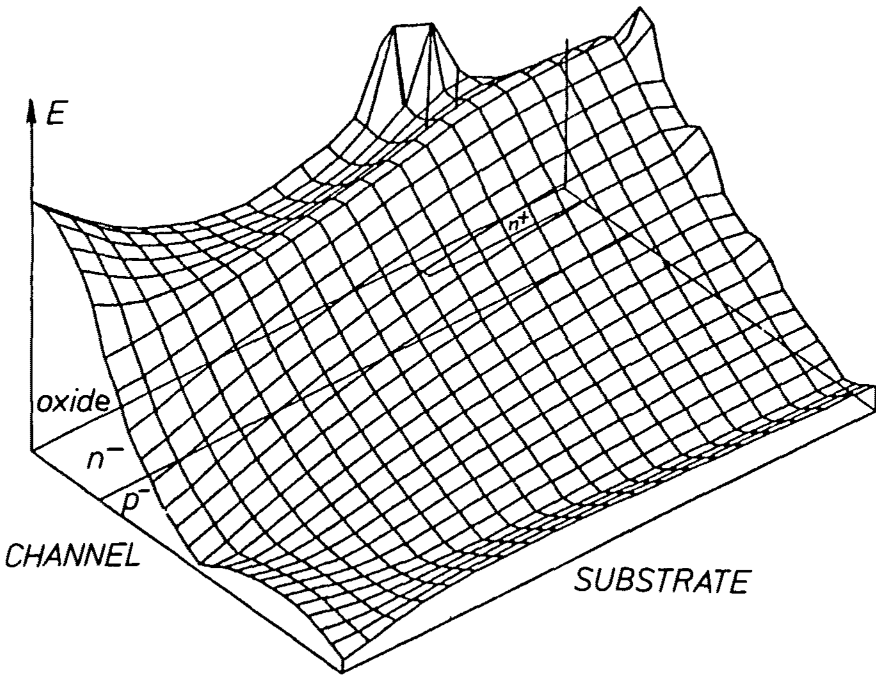

Fig.7: 3-D plot of the electric field strength.

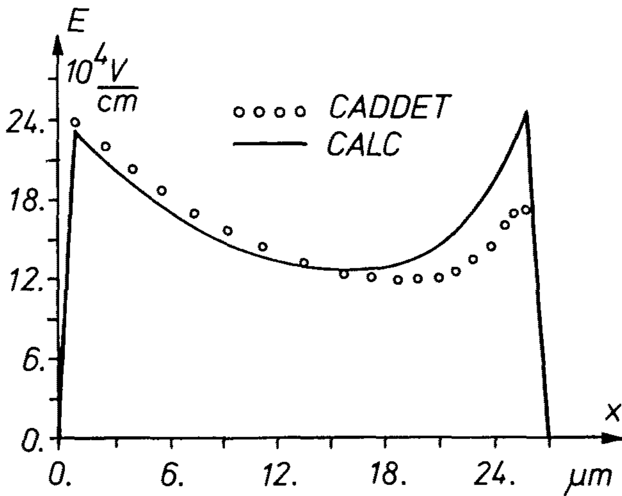

Fig.8: Comparison between CADDET and CALC simulation.

CPU time, whereas CALC was finished in less than 1 minute. The long run time of CADDET was mainly caused by the high drain voltage (400 V). This should not be interpreted as a disapproval of the CADDET program because CADDET solves the fundamental non linear equations of a semiconductor MOS device including the current continuity equation.

In order to make the electric field distribution more rectangular the idea of a buried layer was introduced (fig. 9) and it was found indeed that the electric field behaviour

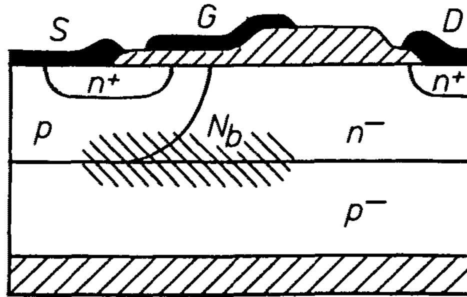

Fig.9: Cross sectional view of DMOS transistor with buried layer.

becomes more rectangular (fig. 10). However, a 3-D plot of

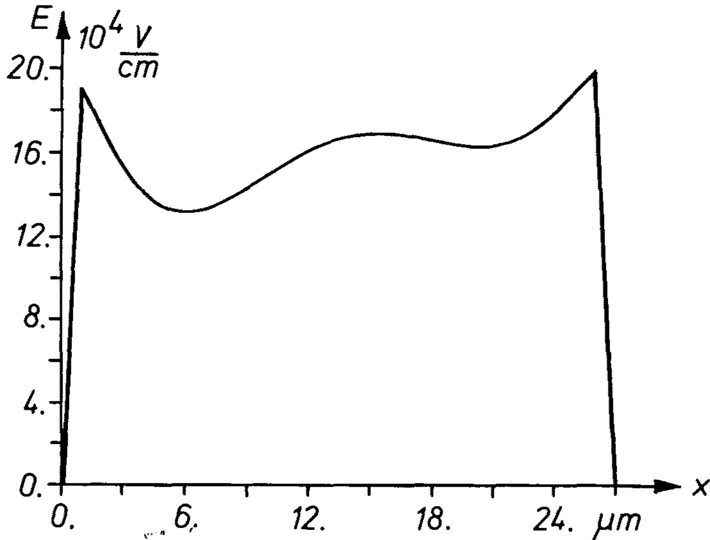

Fig.10: Electric field distribution of a DMOS transistor with buried layer.

the electric field strength showed that the maximum field strength occurs now in the bulk of the semiconductor. Therefore, the idea of buried layer for optimisation of a DMOS device has been dropped.

5. Conclusion.

It has been proved that the boundary element method can be used succesfully for modeling semiconductor components such as the DMOS transistor under high drain voltage. A program CALC has been developped to solve the Poisson's equation using the abrupt depletion layer approximation.

6. Acknowledgements.

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