UDK 621.3:(53+54+621+66), ISSN 0352-9045 Informacije MIDEM 20(1990)4, Ljubljana

TWO-DIMENSIONAL MODELING OF REVERSE BIASED PN STRUCTURES

Dejan Križaj, Slavko Amon

KEY WORDS: semiconductor devices, 2D modeling, pn structure termination, numerical modeling, computer aided modeling, computer program

ABSTRACT: The paper presents a program for two-dimensional modeling of reverse biased pn structures. The analysis is simplified with zero-current approximation that allows solving the Poisson equation only. Breakdown voltage is calculated with the ionization integral. The program includes the possibility of guard-ring and field-plate junction termination modeling.

MODELIRANJE ZAPORNIH LASNOSTI PN STRUKTUR

KLJUČNE BESEDE: polprevodniški elementi, 2D modeliranje, zaključitve pn spojev, numerično modeliranje, računalniško modeliranje, računalniški program

VSEBINA: V delu je opisan program za dvodimenzionalno modeliranje zapornih lastnosti pn struktur. Analiza je zato poenostavljena z uvedbo aproksimacije ničelnega toka, kar omogoča reševanje samo Poissonove enačbe, prebojne napetosti pa so določene z rešitvijo integrala ionizacije. Program omogoča poleg simulacij pn struktur tudi modeliranje zaključitvenih tehnik pn spoja z zaščitnim obročem (guard-ring) ali s kontaktom preko oksida (field-plate).

Glossary of symbols:

ψ	electric potential
Δ	Laplace operator
q	elementary charge
ε	permittivity
n	free electron concentration
p	free hole concentration
C	net doping concentration
n_i	intrinsic carrier concentration
φ_n, φ_p	electron and hole quasifermi potential
u_t	thermal voltage
h,k	lateral and vertical distance between two mesh points

1. INTRODUCTION

The limitations of analytical semiconductor device modeling have led to numerical modeling with the use of computers. The growing speed and affordability of computers has made computer aided device modeling accessible to a wide spectrum of users.

The system of three semiconductor equations (Poisson's and two continuity eq.) that needs to be solved can be very large. For example, on a mesh of 100x100 points, 3x10000 mutually dependent nonlinear equations need to be solved. In the matrix notation **A.x=b** the matrix **A** has 30000 rows and columns. Solving such a system of equations is time consuming and numerically exacting and therefore still an interesting problem not only for reserachers in microelectronics area but also for mathematicians, physics and computer experts. Sometimes we are interested in physical and electrical properties of precisely determined structures and we do not need a general sophisticated program that would be capable of arbitrary semiconductor device modeling. In this case some admissible simplifications can be made such as neglecting minority carriers in MOS structure analysis or solving only Poisson equation for reverse biased structure modeling. The last method is most suitable for planar junction breakdown modeling because otherwise (taking into account all three semiconductor equations) the system of three equations is strongly coupled. Therefore more complicated solution algorithms are needed.

The program developed in the Laboratory for Semiconductor Devices at the Faculty of Electrical and Computer Engineering in Ljubljana allows various types of two dimensional (2D) reverse biased planar structure modeling. If we solve only the Poisson equation, the breakdown properties should be determined through the ionization integral calculation.

2. NUMERICAL MODELING OF REVERSE BIASED JUNCTIONS

Assuming there is no current flow through the reverse biased structure (zero current approximation) the system of three semiconductor equations can be reduced to only one - Poisson equation

$$\Delta\psi = \frac{q}{\varepsilon} \cdot (n - p - C) \qquad (1)$$

Besides it is possible to neglect electron and hole concentrations in the depletion layer, but in this case, depletion layer edges should be determined iteratively[2]. The following approach, used also in our program, is to consider quasifermi potentials constant through the entire structure and to express free carrier concentrations as a function of varying potential and constant quasifermi potential

$$n = n_i \cdot e^{\frac{\psi - \varphi_n}{u_t}} \tag{2}$$

$$p = n_i \cdot e^{\frac{\varphi_p - \psi}{u_t}} \tag{3}$$

There are many ways to solve the discretized system of equations involved. The most common are Newton's method or some kind of relaxation method (SOR). In our approach, equation (1) is locally linearized and the resulting system is solved with the Gauss-Seidel relaxation (or over relaxation) method. Since we perform relaxation on a linearized system of equations the method can be named Gauss-Seidel-Newton relaxation. The potential value in point $_{i,j}$ in the next iteration step $_{k+1}$ is (in program code these equations are scaled)

$$\psi_{i,j}^{k+1} = \psi_{i,j}^{k} - \frac{F_{i,j}(\psi^k)}{F'_{i,j}(\psi^k)} \tag{4}$$

where (5)

$$F_{i,j}(\psi^k) = \Delta\psi_{i,j}^{k} - \frac{q}{\varepsilon} \cdot \left\{ n_i \cdot e^{\frac{\psi_{i,j}^{k} - \varphi_n}{u_t}} - n_i \cdot e^{\frac{\varphi_p - \psi_{i,j}^{k}}{u_t}} - c_{i,j} \right\}$$

and (6)

$$F'_{i,j}(\psi^k) = -\left\{ \frac{2}{h^2} + \frac{2}{k^2} \right\} - \frac{q}{\varepsilon} \cdot \frac{n_i}{u_t} \cdot \left\{ e^{\frac{\psi_{i,j}^{k} - \varphi_n}{u_t}} + e^{\frac{\varphi_p - \psi_{i,j}^{k}}{u_t}} \right\}$$

$\Delta\psi_{i,j}^{k}$ is approximated on a rectangle grid (fig.1) by the 5-point finite difference equation

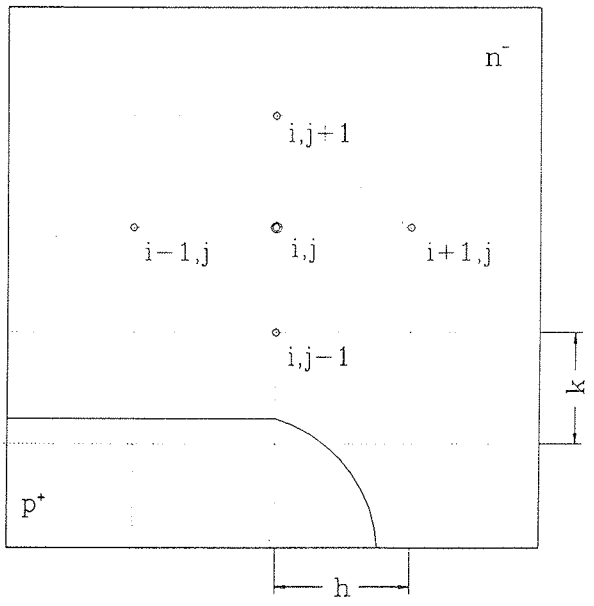

Fig. 1: Numbering of points on a rectangular grid

$$\Delta\psi_{i,j}^{k} = \frac{1}{h^2}\left\{\psi_{i+1,j} + \psi_{i-1,j}\right\} - \left\{\frac{2}{h^2} + \frac{2}{k^2}\right\} \cdot \psi_{i,j} + \frac{1}{k^2} \cdot \left\{\psi_{i,j+1} + \psi_{i,j-1}\right\} \tag{7}$$

To reduce further the solution time i.e. time needed to solve the system of equations to predetermined accuracy, the multigrid method[4] is applied.

The program written in Pascal is basically developed for PC AT computers but with minor changes it can be transferred to VAX computers (not the graphics). For easier handling, menu items are used (fig.2) and an additional iteration menu (fig.3) allows control over intermediate results (specially important in the development stage). Representation of the results can be graphical (3D graphs or equipotential,field,.., lines) or numerical (tables). The program computes potential values in mesh points. Besides, electrical field, electron and hole concentrations, charge density and ionization integral can be evaluated. The doping profile can be abrupt, linear or defined with a gaussian or erfc function with optional radius of curvature (lateral diffusion).

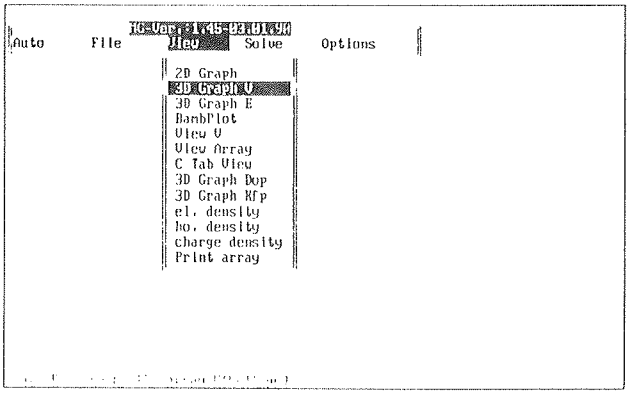

Fig. 2: Main menu items

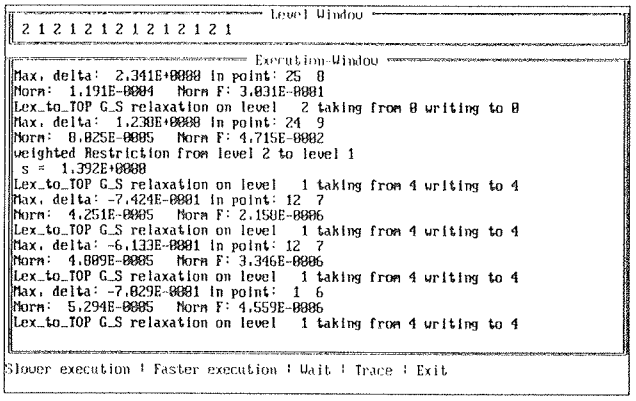

Fig. 3: Iteration menu

3. MODELING EXAMPLES

As an modeling example p^+n structure with substrate concentration $5.10^{14}cm^{-3}$, gaussian doping profile with surface concentration $2.10^{18}cm^{-3}$, junction depth 8μm and lateral diffusion 70% of the vertical one, is analyzed (fig.4). For reverse bias 208V (breakdown voltage ob-

tained with ionization parameters from[5]) the potential and field distributions are shown in fig. 5 and 6 respectively. Breakdown is a consequence of the high electric field at the junction curvature (field crowding effect). Spreading the depletion layer laterally would reduce the junction curvature effect and thus raise the breakdown voltage. This can be achieved with various junction termination techniques among which guard-ring and field-plate are the most common ones.

The next example is a guard-ring structure (fig.7) where the ring potential is floating (not fixed) and depends on the applied reverse voltage. Reverse current flow into the ring needs to come out (of the ring) at one point and there the ring should be slightly forward biased[3]. According to this, the quasifermi potential of the ring should be iteratively changed until the upper conditions are met.

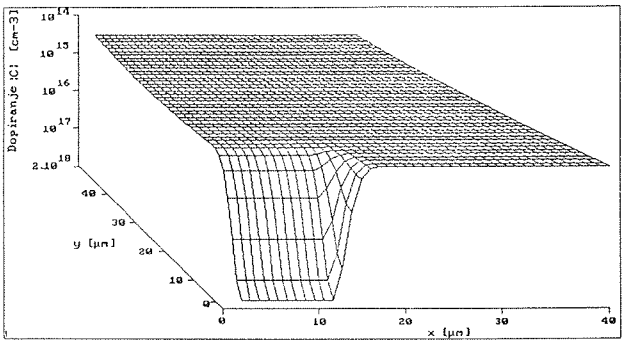

Fig. 4: Doping profile of a simulated p^+n structure

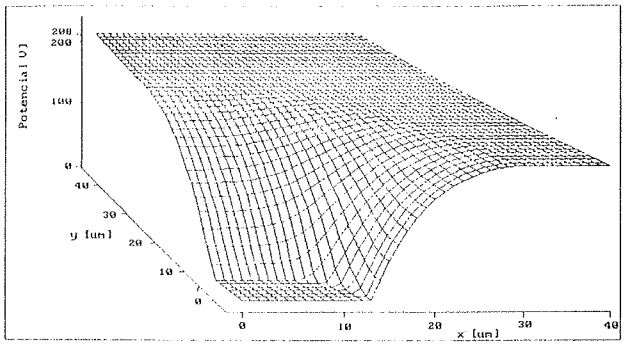

Fig. 5: Potential distribution of a simulated p^+n structure

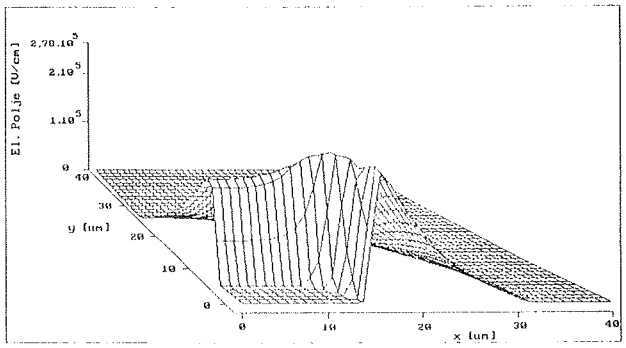

Fig. 6: Field distribution of a simulated p^+n structure

For the guard-ring structure with a 10µm distance between ring and contact junction the calculated potential and field distribution are shown in fig. 8 and 9 respectively.

Further development of the program demonstrated also a possibility to model field-plate (FP) structure (fig.10) without solving the Laplace equation in the oxide. As an example FP structure simulation with substrate concentration $5.10^{14}cm^{-3}$, junction depth 15µm, oxide thickness 2.6µm and the FP edge at 51.75µm was performed. Resulting potential and field distributions are shown in fig. 11 and 12 .

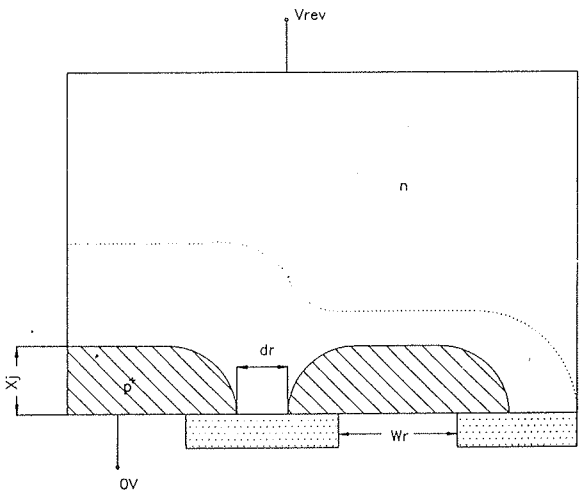

Fig. 7: Guard ring structure

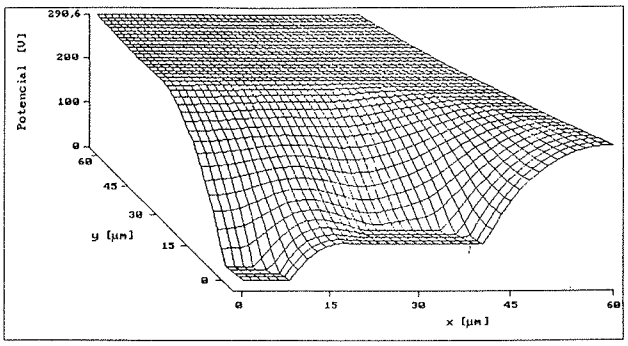

Fig. 8: Potential distribution of a simulated guard ring structure

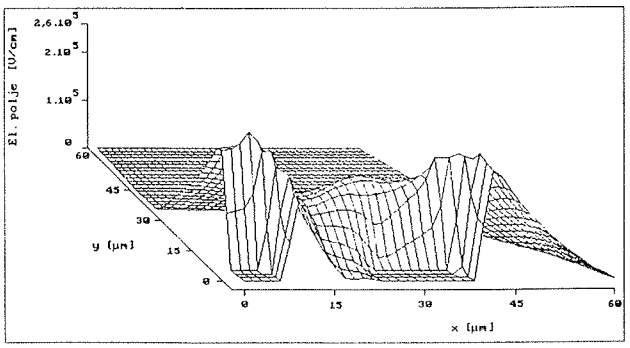

Fig. 9: Field distribution of a simulated guard ring structure

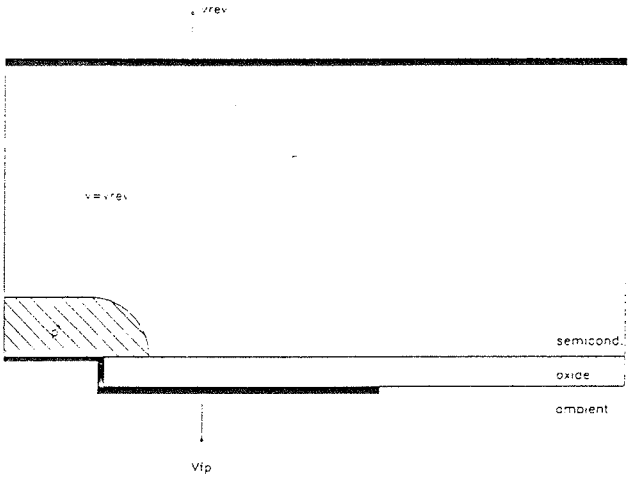

Fig. 10: Field-plate structure

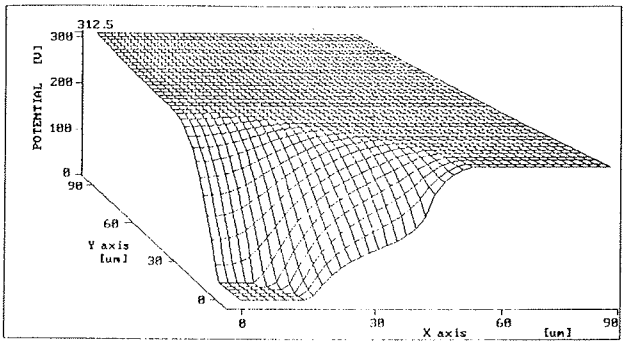

Fig. 11: Potential distribution of a simulated field-plate structure

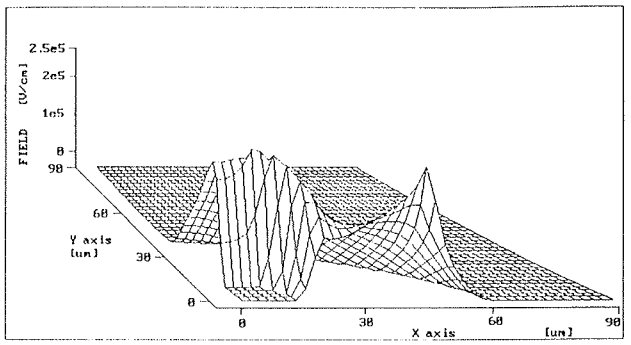

Fig. 12: Field distribution of a simulated field-plate structure

4. CONCLUSIONS

In the paper a possibility of reverse biased semiconductor structure simulation with solving Poisson equation only is demonstrated.. The program written for this purpose is capable of 2D planar structure breakdown modeling and modeling of guard-ring and field-plate junction termination techniques.

Some basic advantages and deficiencies of the resulting program are :

a.) advantages: - reduced number of equations by a factor of three - reduced convergence problems - reduced time consumption due to multigrid method - modeling runs also on a PC AT computer - menu-items for easier handling - 2D, 3D and tabellary result presentation - possibility of intermediate result and iteration control - guard-ring and field-plate termination modeling

b.) deficiencies: - simplified physical model - maximum 49x49 mesh points (for PC AT, only) - limitation to reverse biased structures - lack of current analysis due to zero current approximation - rectangular structure simulation only

Some more details on the program can be found elsewhere[6,7,8].

References:

/1/ S.Selberher,A.Schttz,H.W.Potzl: MINIMOS- A two dimensional MOS transistor Analyser; IEEE Trans.E.D.,Vol.27, p.1540,august 1980.

/2/ S.Colac,E.H.Stupp: Reverse Avalanche Breakdown in Gated Diodes; Sol.St.Elecrtron.,Vol.23,pp.467-472, 1980.

/3/ S.Yasuda,T.Yonezawa: High-voltage planar junction with a field-limiting ring, Sol.St.Electr.,Vol.25,pp.423-427,1982.

/4/ W.Hackbusch: Multigrid method and applications, Springer- Verlag, 1985.

/5/ R. Van Overstraeten,H.De Mann: Measurement of the ionization rates in diffused silicon p-n junctions, Sol.St.Electron.,Vol.13, pp.583-609, 1970.

/6/ D.Križaj, D.Reichmann,S.Amon: Multigrid Method for reverse biased semiconductor simulation in two dimensions; MIEL 90, Ljubljana, 1990.

/7/ D.Križaj, S.Amon: 2D Modeliranje preboja v planarnem pn spoju; ETAN 90, Zagreb, 1990.

/8/ D.Križaj,S.Amon,U.Aljančič: Modeliranje prebojnih lastnosti planarnih struktur; v pripravi

Dejan Križaj, dipl.ing.
prof.dr. Slavko Amon, dipl.ing.
Fakulteta za elektrotehniko in računalništvo
Tržaška 25, 61000 Ljubljana

Prispelo: 23.10.90 *Sprejeto: 12.11.90*