3D Parallel Finite Element Simulation of In-Cell Breakdown in Lateral-Channel IGBTs

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In this paper we describe the use of 3D parallel finite element solution of the Poisson equation to calculate the in-cell breakdown voltage in lateral channel IGBTs. The solver is based on topologically rectangular grids, and uses a domain decomposition approach to partition the problem on an array of mesh connected processors. A parallel BiCGSTAB solver has been developed to solve the Possion equation. Hole and electron ionisation integrals are calculated to determine the breakdown voltage. The effects of varying the doping concentration in the n^- base region and stopper surface concentration are investigated.

Keywords: 3D simulation, parallel, finite element, breakdown, IGBT

INTRODUCTION

Insulated Gate Bipolar Transistors (IGBTs) [1] are among the leading devices in the power semiconductor market, combining a low on-state voltage typical of bipolar devices, with MOS gated switching. Modern IGBTs have a cellular structure such as that shown in Figure 1. The optimisation of the cell design is an ongoing issue. The current density, for example, can be increased by reducing the cellto-cell separation. Unfortunately in lateral channel IGBTs the minimum cell-to-cell separation is restricted by cell-to-cell pinch-off which limits the current density. Although vertical-channel non pinch-off devices have been demonstrated [2] the lateral channel IGBTs with stopper implantation are still the preferred technological choice. The stopper, however, should not compromise the overall device breakdown. The calculation of the in-cell breakdown in the stopper design process requires an accurate 3D solution of the Poisson equation [3] with fine resolution around the metallurgical p-n junction.

In this paper we describe the calculation of the in-cell IGBT breakdown using a parallel finite element 3D solution of the Poisson equation on an array of processors. The 3D discretisation is based on a topologically rectangular finite element (FE) grid which facilitates the partitioning of the domain over arrays of processors. Results for the

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FIGURE 1 Schematic view of the top of an octagonal cell IGBT.

dependence of the breakdown voltage on the device geometry and the doping profile are presented.

PARALLEL IMPLEMENTATION

The Poisson solver used to study the in-cell IGBT breakdown is part of a general purpose device simulator in development [4]. This simulator is designed for parallel MIMD architectures based on a 2D array of mesh connected processors. The current version runs on an 8 node PowerPC Parsytec X-plorer under Parix. This provides the necessary computing power for computationally intensive 3D simulation.

The parallel implementation is based on the spatial domain decomposition approach, whereby the solution domain is partitioned across the 2D array of processors. Each processor stores information and updates the solution only for the nodes which belong to its subdomain. The partitioning is greatly simplified by the use of a topologically rectangular grid which is described later. Both a parallel 4-colour block Newton SOR solver, and a parallel BiCGSTAB solver have been developed and used for the solving the Poisson equation. While the SOR solver is efficient and works well at low applied voltage, convergence problems at the high voltages require for breakdown calculations were encountered. The BiCGSTAB solver in combination with Newton iterations, and appropriate damping, works well in the high voltage range.

Due to the large problem size, there is not sufficient memory to run the program on an individual processor of the Parsytec system and to have a proper speed-up assessment. However the speed-up obtained by running on the 8×90 MHz PPC601 Parsytec system, compared to a single 170 MHz UltraSparc Workstation is approximately 2.25.

GRID GENERATION

In order to obtain the required accuracy in the solution of the Poisson equation it is essential to have a finite element grid which conforms to the shape of the metallurgical p-n junctions and to the cell topology. The use of unstructured finite element grids can present serious problems when the parallel implementation is based on domain decomposition, and can lead to very low efficiency of the parallel code. To avoid these difficulties we have developed a topologically rectangular FE grid [5].

The structured topologically rectangular grid retains the number of grid nodes in any particular index direction. This makes the partitioning of the grid over an array of mesh connected processors a straight forward procedure. The partitioning is done by dividing the number of grid nodes in each index direction by the number of processors available in the processor array in the same direction [6]. For such partitioning only nearestneighbour communications are required in the design of iterative solvers, because adjacent nodes in adjacent partition subdomains appear on neighbouring processors.

We have implemented two different approaches for the generation of topologically rectangular

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grids in the discretisation of the IGBT cell (Fig. 2). The most straightforward method is to deform a Cartesian grid to fit key contours in the device structure, such as the p-n junctions. This method was used in the generation of the grid in the vertical walls of the IGBT cell. The deformation algorithm has been designed to be as general as possible to allow the use of arbitrarily shaped defining contours described in a parameterised form. This allows the generation of complex grids. A different method was used in the design of the grid for the top plane of the IGBT. This method again uses key contours such as the emitter contact edge and surface p-n junctions. These contours are used to generated additional guiding contours, the spacing of which controls the grid density. The correct number of nodes are placed on each guiding contour to satisfy the criteria for a topologically rectangular grid. This method is more flexible, but has the restriction that the grid must have equal numbers of nodes in each direction.

The full 3D grid is generated by extending the grid for the top surface vertically, and then



FIGURE 2 Topologically rectangular 3D grid showing top and sides of the 3D grids.

deforming this 3D grid by the deformations calculated for the side walls of the cell. Figure 3 shows the full 3D grid for the region down to the $p-n^-$ junction, clearly illustrating the internal curvature of the grid, and the shape of the p-n junction itself.

BREAKDOWN CALCULATION AND RESULTS

The calculation of breakdown voltage is based on the evaluation of the ionisation integrals for holes and electrons. From the solution of the Poisson equation the electric field in each element is calculated, and the point of maximum electric field strength is determined. The integration path for the ionisation integrals passes through this point and is traced along the electric field vector in both directions until either a boundary is encountered, or the electric field strength becomes negligible. The ionisation integrals along this path are then calculated. The hole ionisation integral was found to be more sensitive to changes in applied voltage and was used in the procedure for tracing the breakdown voltage. However we check that both hole and electron integrals become unity at the breakdown voltage.

The point of highest electric field occurs near the corner of the p-n⁻ junction which corresponds to



FIGURE 3 The grid at the metallurgical p-n⁻ junction showing junction curvature.

the corner of the octagonal emitter contact. This is the region where the junction exhibits the highest curvature. The effect of the doping in the n^- base region on the breakdown voltage is shown in Figure 4. The in-cell breakdown is compared to the breakdown voltage for a one-sided planar junction. As expected, the increasing doping concentration of the base region reduces the breakdown voltage significantly. Although the smaller inter-cell distance and the gate potential significantly reduce the curvature of the depletion layer edge, and the strength of the fringing field, the IGBT cell shows a noticeable reduction in breakdown voltage compared to the planar junction.

The introduction of a surface stopper implantation reduces the channel length, prevents the pinch-off of the vertical JFET, and lowers the on-state voltage drop. The stopper concentration, however, affects the in-cell breakdown. Figure 5 shows the effect that increasing the surface concentration of the implantation has on the breakdown voltage of a typical IGBT rated at 600 V. For a surface concentration above 10^{16} cm⁻³ the breakdown voltage falls sharply and the stopper concentration limits the blocking capabilities of the device.



FIGURE 4 Breakdown voltage vs n^- base region doping concentration.



FIGURE 5 Breakdown voltage vs stopper implant surface concentration.

CONCLUSIONS

In this paper we have described 3D parallel finite element simulation of in-cell breakdown voltages in cellular IGBTs. The simulator is based on a topologically rectangular grid which reflects the geometry of the device, and simplifies the partitioning of the solution domain in the domain decomposition based parallel implementation. The results of the breakdown calculations illustrate the importance of realistic 3D simulation in the design of cellular IGBTs.

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John Barker is Professor of Electronics in the Department of Electronics and Electrical Engineering. He has a long standing interest in computational methods, device modelling and transport theory. From 1970–85 he was a member of the Theory group in the Dept. of Physics, University of Warwick, aside from 1978–79 when he worked at IBM T. J. Watson Laboratory, North Texas State University and Colorado State University. From 1987–89 he was academic director of the IBM UK/Glasgow University Kelvin Project on Numerically Intensive Parallel Computing. He is academic director of the Parallel Processing Centre at the University of Glasgow.





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