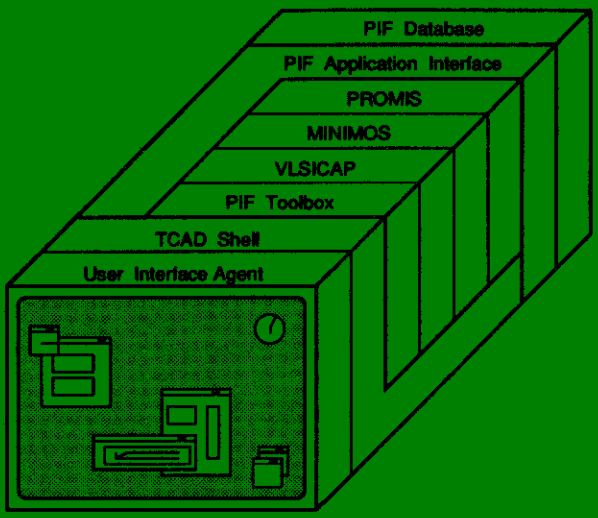
TU

TECHNICAL UNIVERSITY OF VIENNA



Annual Review
June 1991

INSTITUTE FOR MICROELECTRONICS

ANNUAL REVIEW

JUNE 1991

INSTITUT FÜR MIKROELEKTRONIK
Technische Universität Wien
Gußhausstraße 27 – 29
A – 1040 Wien
AUSTRIA

Tel: *43/1/58801/3850
Fax: *43/1/5059224

Staff

Robert Bauer	Dipl.Ing. (2. Apr. 91 –)
Peter Dickinger	Dipl.Ing., Dr.techn. (– 16. Aug. 90)
Franz Fasching	Dipl.Ing.
Claus Fischer	Dipl.Ing.
Peter Grubmair	Dipl.Ing. (2. May 91 –)
Predrag Habaš	Dipl.Ing., mr. techn.
Stefan Halama	Dipl.Ing.
Otto Heinreichsberger	Dipl.Ing.
Hans Kosina	Dipl.Ing.
Erasmus Langer	Dipl.Ing., Dr.techn.
Philipp Lindorfer	Dipl.Ing., Dr.techn.
Peter Nebenführ	Ing. (– 30. Apr. 91)
Hubert Pimingstorfer	Dipl.Ing.
Siegfried Selberherr	O.Prof., Dipl.Ing., Dr.techn.
Martin Stiftinger	Dipl.Ing.
Hannes Stippel	Dipl.Ing. (1. Jul. 90 –)
Peter Verhás	Dipl.Ing.
Karl Wimmer	Dipl.Ing.
Sylvia Zentner	

Preface

Siegfried Selberherr

This brochure is the third research review of our institute. Provision has been made this year by the Austrian Ministry of Science and Research for two additional full time scientists in order to support under-graduate education. Thus the staff supported by the Ministry consists now of seven full time employees: the head of institute, four scientists, a secretary and a technician. Eleven (!) additional scientists are presently funded through scientific projects with industrial institutions. This might be close to the upper bound of "additional" scientists which we can integrate into our institute. Nevertheless, we have received many more queries regarding positions from both students and industry.

There is one new partner in our collaborative research activities, namely "Motorola" in Austin, USA. All our partners from the last review year have continued to support the institute.

The projects of the institute are still focused on microelectronics modeling issues. We put most emphasis on analysis and simulation of the fabrication steps and the electrical behaviour of miniaturized semiconductor devices for integrated circuits. However, since Technology Computer Aided Design (TCAD) has become one of the most challenging microelectronics topics, we have initiated in addition the highly collaborative effort VISTA, the Viennese Integrated System for Tcad Applications. This has been motivated in particular by the significant changes in computing environment and not only by the

demands of the semiconductor industry. As one can deduce from the individual contributions, we assume that integrated Technology CAD will play a major role for the development of next generations of devices for Ultra Large Scale Integrated (ULSI) circuits. We sincerely hope to keep pace with the requirements of industry.

Regarding academic and scientific output we are quite satisfied. We are particularly pleased with the number of papers which have appeared in reviewed journals this year. We all enter the fourth year of our institute with high expectations!

Siegfried Selberherr was born in Klosterneuburg, Austria, in 1955. He received the degree of 'Diplomingenieur' in electrical engineering from the Technical University of Vienna in 1978. Since that time he has joined the 'Institut für Allgemeine Elektrotechnik und Elektronik' – previously called the 'Institut für Physikalische Elektronik' – at the Technical University of Vienna. He received his doctoral degree in 1981. Dr. Selberherr has held the 'venia docendi' on 'Computer-Aided Design' since 1984. He has been the head of the 'Institut für Mikroelektronik' since 1988. His current topics are modeling and simulation of problems for microelectronics engineering. Dr. Selberherr is editor of 'The Transactions of the Society for Computer Simulation', of 'Electrosoft', of 'Mikroelektronik' and of the Springer-Verlag book series 'Computational Microelectronics'

Sylvia Zentner was born in Tulln, Austria, in 1965. She joined the institute in October 1988. Since that time she has been in charge of all the organizational and administrative work of the institute.

Three-Dimensional Interconnect Simulation

Robert Bauer

With the advances in technology the integrated circuit chip size, complexity and the device packing density is continuously increasing. The development of new lithographic and etching techniques have resulted in reduction of the device sizes and multilevel interconnects used in today's integrated circuits.

The theory of scaling states that smaller dimensions of a MOS transistor should enhance its speed. Indeed, for the device itself and for small circuits the speed increases proportionally with the scaling factor. However, for larger circuits, the time delays associated with the interconnections play a significant role in the performance of the device. Considerably increased packing densities cause the length of interconnections to increase. For very large chips with extremely small geometries, the time delay associated with the interconnections becomes an appreciable portion of the whole time delay, and hence the circuit performance cannot be determined by the device performance alone.

The time delay of the interconnect lines shows a strong dependence on the resistance and capacitance of the interconnections. The usage of, e.g., aluminium in place of polysilicon improves the conductivity by a factor 100. The RC time constant can be significantly lowered by the usage of metals or silicides instead of polysilicon as interconnect materials. The capacitance of an interconnection is determined by the dielectric medium which is mostly SiO_2.

The excellent properties of silicon and its easy oxidation limit the choice to this material. Besides the usage of new materials, an improvement of the layout by optimization to lower the resistance and capacitance can be done.

Multilevel wiring increases the problem of crosstalk between adjacent conductors. A serious calculation of a complex three dimensional wiring structure can only be done with a three dimensional simulator.

Our capacitance simulator VLSICAP is capable of calculating this linear interconnect capacitances in two dimensions; it also handles nonlinear capacitances (i.e. reverse biased junctions).

A present task is to find an optimum grid generation method for three dimensions. The key element of a capacitance simulator is the grid generator which must be able to perform grid refinement and boundary point insertion automatically. In order to keep the number of grid points modest, a mesh with tetrahedral elements is preferred to a tensor product grid.

Robert Bauer was born in Vienna, Austria, in 1963. From 1983 to 1984 he was working in the support of medical analysis devices. During the time of studying he held various summer positions in the medical branch. He received the degree of 'Diplomingenieur' from the Technical University Vienna in electrical engineering in 1990. After seven months of industrial development of Brain Mapping Systems – a medical brain diagnostic device, in spring 1991 he joined the 'Institut für Mikroelektronik', where he is currently working toward his doctoral degree in the field of three-dimensional interconnect simulation of multilevel wired VLSI circuits.

VLSI Interconnect Simulation and Databases for Technology CAD

Franz Fasching

VLSICAP is our program to simulate linear (dielectrics) and nonlinear (reverse biased semiconductor junctions) interconnect capacitances for arbitrary two-dimensional geometries. Recent extensions include improved automatic initial grid generation, automatic computation of capacitance coefficients (both for the linear and nonlinear case) and capacitance characteristics (nonlinear case).

The continuous miniaturization of semiconductor circuits and devices calls for accurate and comprehensive simulation of their electrical behaviour. Device and process engineers have to perform increasingly complex development tasks such as optimization and sensitivity analysis, where simply coupling simulation tools is not enough — a Technology CAD (TCAD) Environment is needed, the basis of which is made up by a simulation data interchange format not only capable of storing TCAD relevant information, but also suited for building simulation databases.

The VISTA project at our institute uses PIF (Profile Interchange Format) as data exchange format. Homogeneously integrated into the TCAD shell through its LISP-like syntax, this data representation serves as a general-purpose format, carrying geometry, grid and attribute information as well as process flow representations or even whole task level programs. In order to build efficient databases, a PIF binary file structure has been devel-

oped. It implements LISP data types for complex expressions and also accounts for storage of huge data amounts through the implementation of (even compressed) arrays of those types. This takes care of integration possibilities for existing FORTRAN applications even on this low level. A PIF Application Interface (PAI) is used by the TCAD tools to access PIF binary files. Its layered structure is designed for system independence (system layer), access speed (caching layer), networking (network layer) and data compression (file layer). Generic LISP expressions can be stored using the basic layer, while the interface layer deals already with PIF objects. The application layer then is especially designed for use with existing FORTRAN applications, facilitating their integration into the VISTA environment.

The VISTA project integrates VLSICAP, enabling it to cooperate with other TCAD tools. Furthermore, its modularized design provides the ability to use different grid generators, or to use VLSICAP's grid generator with other simulators.

Franz Fasching was born in Steyr, Austria, in 1965. He received the degree of 'Diplomingenieur' from the Technical University Vienna in electrical engineering in 1989. In February 1990 he joined the 'Institut für Mikroelektronik', where he is currently working towards his doctoral degree. His work is focused on interchange formats for Technology CAD environments and improvement and extension of the capacitance simulator VLSICAP.

Technology CAD, MINIMOS and PIF

Claus Fischer

The encapsulation of a simulation program like MINIMOS is a welcome opportunity to perform some structural modifications. The general goal is to open MINIMOS and to allow communication with a wide TCAD landscape.

Consequently, the data structures of a modern simulation tool will have to obey some communication standards. TCAD-MINIMOS will use the PIF standard to represent the input and output information, which gives new impulses especially to the description of the geometric data.

For the conversion of the conventional input deck into a PIF file, an input file translator has been developed. The PIF binary file created by this translator then contains all the information necessary for the analysis of the FET transistor.

A FORTRAN/C interface to the PIF application layer has been implemented to allow access to the PBF (PIF binary file). The restructuring of MINIMOS into a TCAD tool requires a clear functional structure of the program. Different aspects of device simulation (physical models, discretizers, solvers) are put into different tools which communicate via PIF. Thereby, replacement of some parts will easily be possible.

Another redesign of MINIMOS had to be done which concerns the program flow. The sequential control of the simulation program must be accessible from the TCAD shell. To influence the sequence in which the tools are invoked, this sequence may no longer be "hard coded". Instead, a

"stack machine" concept has been developed which guarantees both flexibility in composition of the program flow and flexibility in the programming language.

The program flow must often be adapted to the problem, since the variety of new devices and physical effects calls for a flexible composition of well-tailored program solutions. Moreover, many researchers need a quick and flexible way of embedding their physical models into a rigorous and stable simulation environment. The comparison of different models is just one point of interest which can be seen in this context.

Flexibility with regard to the programming language, on the other hand, is of some importance, because many of the simulation tools are working in a heterogenous environment where the layers of the TCAD system use the language which is best suited for their purposes. Nevertheless, the communication between these layers is enabled in an easy way.

Claus Fischer was born in Vienna, Austria, in 1967. He received the degree of 'Diplomingenieur' from the Technical University Vienna in 1989 in electrical engineering. In January 1990 he joined the 'Institut für Mikroelektronik'. His work deals with the new structure of MINIMOS, in particular with the integration of MINIMOS into the Viennese TCAD environment and the PIF data format specification. At present, he is working towards his doctoral degree.

MODFET Simulation

Peter Grubmair

Modulation Doped Field Effect Transistors (MODFET's) based on Si/Si-Ge heterostructures will soon claim significant industrial importance. Their advantages are their remarkable high frequency behavior, good noise performance and short switching times on one hand and further development of Silicon molecular beam epitaxy as a low temperature process on the other hand. This enables an on-chip-combination with conventional Silicon devices. Therefore it is necessary to have recourse to an accurate simulation tool for process optimization. So the capabilities of the well-approved MINIMOS program will be extended to deal with such devices.

The new version will be able to take into account variable band gaps, controlled by the Germanium contents and different elastic strains which depend on the thickness of the layers. Because of the strict localization of DX-traps, delta doping will be a possible doping profile input to the simulator for carrier concentration modulation.

It is necessary to develop parameter equations for a modified drift diffusion model by quantum transport considerations in the two-dimensional carrier gas. Eventually Monte-Carlo simulation for dealing with bulk transport near drain, hot carriers and velocity overshoot needs to be involved as it has been carried out at our institute recently for conventional MOSFET's. Tunneling across the barrier and thermionic emission will also be taken into account when modeling the inversion layer. Evaluation of carrier mobility will be done with regard to interface

states at band discontinuities and anisotropy due to mechanical tensions.

In the final version of the simulator the special features of the gate contact will be taken into account. The user would then be able to choose between Schottky and MOS-Gate.

Since last year a program is available which computes the wave envelope functions and energy eigenvalues of the Schrödinger equation for the quantum well at the heterojunction with a self-consistent potential and under the effective mass approach. It will be used for estimating transversal quantum size effects in thermodynamic equilibrium. In particular the deviation of the carrier concentration from the classical model at the heterojunction will be characterized.

Currently the enormous amount of literature available for MODFET's and the related problem of heterojunctions is studied in order to start from a solid basis.

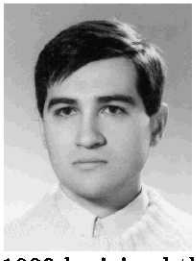
Peter Grubmair was born in Scheibbs, Austria, in 1961. During his study of Control Engineering and Industrial Electronics at the Technical University of Vienna he held various vacation jobs at local firms. He also worked as student assistant at the 'Institut für Nachrichtentechnik und Hochfrequenztechnik', where he was concerned with Multi Carrier Data Transmission. After having received the degree of 'Diplomingenieur' in March 1991 he joined the 'Institut für Mikroelektronik' in May 1991, where he works towards his doctoral degree. His interests now lie in the fields of MODFET's and Semiconductor Physics in general.

Analysis of Physical Effects in Very Small MOS-Devices

Predrag Habaš

Our activity in modeling physical effects in small, thin oxide, MOSFET's covers several projects: Firstly, physics and modeling of the gate-depletion effect, secondly, hot carrier injection and carrier tunneling into oxide, and rigorous numerical simulation of the charge pumping technique, and thirdly, physics and simulation of several extended leakage effects in small devices (band-to-band and trap-assisted tunneling).
In the gate-depletion project we have implemented into MINIMOS, in addition to a full two-dimensional approach, an efficient one-dimensional technique for simulation of this effect. We studied the impact of the gate-depletion effect on the performance of MOSFET's with further reduced oxide thickness. Comparing the simulations with our experimental data the implemented physical models have been examined, and several physical effects important in the modeling of a heavy doped polysilicon-gate are extracted. To perform these comparisons an efficient technique for the calculation of the quasi-static gate capacitance has been implemented into MINIMOS and examined by comparing with the analytical results for several ideal cases. In addition a new physics based grid generation close to the oxide/bulk interface has been developed and implemented, which enables an accurate drain current calculation also for devices with very thin oxide. In the hot carrier degradation project special attention has been paid to the development and the implementation of a rigorous self-consistent transient simulation of the charge pumping experiment. The imple-

mented model accounts for the traps-dynamic (repopulation due to emission and capture of carriers) assuming a consistent coupling with the Poisson's and carrier continuity equations. Our approach is based on the transient simulation and a very accurate terminal current calculation. We think such an approach will become a valuable technique in investigation and application of the charge pumping experiment, especially for the interpretation of the charge pumping data in very small MOS-devices where twodimensional effects become important. In addition it can be applied to analyze SOI devices as well. Our goal was to formulate a consistent model for the interface states, their dynamics, and the corresponding surface generation-recombination rates. It could be applied to study surface-traps related leakages and similar phenomena interesting in the design of very small low power MOS devices. We are investigating the frequency- and wave form-effect, the lateral profiling of the interface states distribution, the estimation of an eventual influence of the geometrical component in current, and further improvements of the physical model.



Predrag Habaš was born in Vrbas, Yugoslavia in 1962. He received the Dipl.Ing. degree from the Faculty of Technical Sciences Novi Sad in electrical engineering in 1985 and the Mr degree from the Faculty of Electrical Engineering Beograd in physical electronics in 1989. From 1985 he worked at the Institute for Power and Electronics University of Novi Sad as Research Assistant and Instructor, where he became a full Assistant in 1989. In April 1989 he joined the 'Institut für Mikroelektronik', where he currently works towards his doctoral degree. He held a Visiting Research Position at the Advanced Semiconductor Development Department at Digital Equipment Corporation, Hudson, MA in 1990. His research area includes physical electronics in general, and physics of small MIS-devices and analytical and numerical modeling of MOSFET's in particular.

Towards an Open Process Simulation System

Stefan Halama

The rapid development of new semiconductor devices and structures imposes several demands on the tools which are used to design new devices and new fabrication processes.

An integrated system which will be used to simulate a complex fabrication process must be able to provide for the integration of existing tools and should significantly facilitate the implementation of new simulators which are developed according to the evolution of fabrication technology. Additionally, the system itself should provide enough flexibility to accommodate to all changes in the process flow and to the changing demands on the type of desired output. These issues were tackled as part of the VISTA project:

In order to communicate correctly and efficiently via the underlying PIF data layers, the simulation tools need, additionally to the pure syntax definition, a semantical standardization of the PIF language. This standard for the description of physical problems and their solutions was established during the PIF language definition phase.

A so-called PIF toolbox (see titlepage) takes care of tasks which are common to many tools or which arise from coupling simulators, thus freeing simulation tools from these tedious tasks. The functionality of the toolbox includes, e.g., PIF geometry decomposition and consistency checking, grid interpolation, or manipulation of distributed attributes.

Another important part of the VISTA system is a set of visualization modules which can be combined in a flexible way to produce arbitrary visualization output of simulation data.

All tools (like simulators, visualization modules, toolbox functions, etc.) are accessed through a unified user interface which is based on an integration of the X11 Athena widgets and additional special widgets into the LISP interpreter. As a next step a visual programming interface for control of the flow of simulation and postprocessing will be developed.

A new process simulation module which uses specially tailored triangular grid generation and discretization methods has been verified by comparison with the existing PROMIS transformation method using a nonplanar trench structure. The new method uses automatic grid generation based on a Delauney triangulation. The comparison between the two diffusion simulation modules showed satisfying results. The triangular discretization is expected to be used for large problems with complex geometrical structures which can not be mapped onto rectangular regions.

Stefan Halama was born in Vienna, Austria, in 1964. He studied electrical engineering at the Technical University of Vienna, where he received the degree of 'Diplomingenieur' in 1989. During his study he was with several austrian companies where he worked on software development projects in the CAD and computer graphics field. He joined the 'Institut für Mikroelektronik' in September 1989, where he currently works towards his doctoral degree. His research interests are focused on process simulation using triangular grids, grid generation and simulator tool integration.

Three-Dimensional Device Simulation on Supercomputers

Otto Heinreichsberger

The solution of the semiconductor device equations in three dimensions in reasonable time requires enormous processor and memory resources that can only be provided by high performance computers. The usage of supercomputers such as the CRAY Y-MP or the Fujitsu VP200 is therefore standard in present industrial research and development sites. The hardware of such computing machinery is very complex and expensive due to cycle times of a few nanoseconds. An alternative to such systems are massively parallel computers that achieve high performance by thousands of processors that work in parallel. Such a novel computer architecture is efficient, if operations of the same kind are to be performed on large sets of data. This is typically the case for the solution of partial differential equations on tensor-product grids. An implementation of the three-dimensional device simulator MINIMOS on a massively parallel system, the Connection Machine, was carried out to study the potential benefits of such a data parallel computer.

The implementation has been carried out by porting the computationally most expensive code, the linear system solution, onto the Connection Machine, whereas the matrix assembly is performed on the host computer. The emphasis of this work was placed on parallel iterative methods for solving the very large sparse linear systems of equations that arise at each step of the nonlinear solution procedure. The basic result of this investigation is that the Connection Machine is usable for device simulation and is especially well-suited for very large problems

though some serious problems still remain to be solved. The conjugate gradient (CG) method and the biconjugate gradient stabilized (BiCGSTAB) method were used for the solution of the symmetric (Poisson) and the nonsymmetric (Continuity) linear equations. Multicolor incomplete Cholesky (IC) and LU (ILU) factorization preconditioners were compared with polynomial preconditioners. Common to all applied massively parallelizable preconditioners is a significant loss of convergence speed compared to incomplete factorization type preconditioners of the naturally ordered unknowns, the standard techniques used on vector-computers. In the performed device simulations this loss was mostly in the range of three, in some cases larger than ten. Optimization of many basic linear algebra subprograms such as multiwire nearest neighbour communication for stencil operations, overlapping of communication and computation leads to an execution speed of the linear solvers approaching one gigaflop. Assuming a mean convergence deterioration factor of four corresponding to the IC and LU preconditioned solvers, this corresponds to 250 megaflops of the vectorized IC-CG and ILU-BiCGSTAB solvers.

Otto Heinreichsberger was born in Amstetten, Austria, in 1963. He received the degree of 'Diplomingenieur' from the Technical University Vienna in 1987 in electronic engineering. After one year at the 'Institut für Geodäsie', where he worked with automatic ranging and survey measurements, he joined the 'Institut für Mikroelektronik' in October 1988. In 1990 he held a Visiting Research position at the 'Center for Computational Mathematics and Mechanics' at the 'Royal Technical Institute' in Stockholm. He is currently working towards his doctoral degree. His work is focused on mathematical models and algorithms in multi-dimensional process and device simulation.

Monte Carlo–Poisson Coupling

Hans Kosina

The carrier transport problem in a semiconductor device has to be solved self-consistently with the electrostatic potential. Therefore a new coupling scheme between Poisson equation and Monte Carlo (MC) transport has been developed. The algorithm is based on the following set of equations which is assumed to be valid both near equilibrium and in the hot carrier regime. Neglecting pair generation and recombination, the electrons equations are:

$$\Delta\psi = \frac{q}{\epsilon} \cdot (n - C) \tag{1}$$

$$\nabla J_n = 0 \tag{2}$$

$$J_n = q \cdot n \cdot \mu \cdot (-\nabla\psi + \nabla U_T + \frac{U_T}{n} \cdot \nabla n) \; . \tag{3}$$

Poisson equation (1) and continuity equation (2) are valid in the entire device regardless of the electrons energy distribution. The equation for the first moment of the Boltzmann Transport equation can be cast in the form of the generalized current relation (3). It states the momentum balance for electrons and includes nonlocal effects such as velocity overshoot and the occurrence of an energy gradient field ∇U_T.

In device areas where the electric field is low or the situation is homogeneous, the energy gradient field vanishes in (3) leading to the conventional drift diffusion (DD) current relation. Furthermore the mobility μ and the electron thermal voltage U_T can be related analytically to local quantities such as doping concentration, electric field or the driving force.

Just in the critical device region which is far from thermal equilibrium the MC method has to be invoked to calculate the parameters (μ, U_T) since they are to a high degree nonlocal. Thus, if significant portions of the device allow accurate modeling by the more efficient DD-method, this hybrid approach using both the MC- and the DD-method saves computation time compared to a full MC-approach. The final solution is obtained by an iterative procedure where the mobility- and carrier temperature profiles are updated. The convergence rate of this MC-Poisson coupling scheme is very good.

A method for assigning Monte-Carlo calculated quantities to nonuniform grids has been developed which advances the widely used nearest grid point (NGP) scheme and the cloud in cell (CIC) scheme. Assignment is done once after the MC-simulation by convolution with an assignment function. Higher order assignment functions can be used without an increase of computational effort. Choosing an odd assignment function one obtains the derivative of a quantity in a consistent manner. The assignment of both the quantity and its derivative to a nonuniform grid is fully independent of the grid spacing.

Hans Kosina was born in Haidershofen, Austria, in 1961. After having received his degree of 'Diplomingenieur' from the Technical University of Vienna in 1987 in electrical engineering, he was with the 'Institut für flexible Automation' for one year. Since September 1988 he has been an assistant at the 'Institut für Mikroelektronik' where he is working towards the doctoral degree. His current scientific interests include solid state device technology and -behavior in general, and problems related to MOS transistors in the sub-micron regime in particular.

Technical Programming in FORTRAN

Erasmus Langer

Most of the worldwide existing scientific programs are written in the programming language FORTRAN which has been developed during the early sixties especially for numerical applications. Even at our institute, all basic simulation tools (e.g. MINIMOS, BAMBI, PROMIS, VLSICAP, SABAWA,...) are written in FORTRAN. The reason for this is not only the efficiency of the executable program code most of the FORTRAN compilers can achieve but also the strict standardization of FORTRAN which makes the software easily transferable from one computer and/or operating system to another.
During the last years the programming language C gained importance as a result of the increasing use of the operating system UNIX (with all its variations). Nevertheless, it is doubtful that the importance of FORTRAN as the dominant programming language in the scientific and technical fields using numerical methods will be diminished essentially within the immediate future. The reason for this assumption lies on the one hand in the widespread use of FORTRAN program libraries and on the other hand in the continuous development of the language standard.
FORTRAN has been standardized the first time in 1966 and the second standard followed eleven years later. The most important progress between these two standards was the introduction of variables and constants of character type associated with the corresponding functions for string handling. Furthermore, the standard 77 included new language elements which allow more "structured programming" (which is some kind of buzzword of

the later developed programming languages). The new standard 90 certainly doubles the number of language elements — thus, a program written in the new standard and using all new features (e.g. neither depreciated nor obsolete language elements) hardly has any similarity to a FORTRAN 77 program. Nevertheless, the new standard is fully upward compatible and, therefore, a standard 77 program (without operating system dependent extensions) will — hopefully — be translatable with a standard 90 compiler without any changes.
The aim of this project is the publication of a book in German with the translated title "Technical Programming in FORTRAN" which describes the programming language according to the new ANSI standard 90. As from experience it will last some time until the first compilers according to the new standard will be available. In the book, all new features are emphasized as well as the old ones. Therefore, the book can also be used as manual for the old standard 77. Furthermore, it serves as a basis for the solution of technical–mathematical problems in engineering as the topics "operating system specific applications" and "numerical mathematics" are included.

Erasmus Langer was born in Vienna, Austria in 1951. After having received the degree of "Diplomingenieur" from the Technical University of Vienna in 1980 he was employed at the "Institut für Allgemeine Elektrotechnik und Elektronik" first as a research assistant (until 1984) and then as assistant professor. His research field was first the numerical simulation of semiconductor devices and later the generation and excitation of electro-acoustic waves in anisotropic piezoelectric materials where he also received his doctoral degree in 1986. Currently he works mainly in the field of technical programming in FORTRAN and parameter extraction for the improvement and miniaturization of integrated semiconductor devices.

GaAs–MESFET Analysis with MINIMOS

Philipp Lindorfer

The final step in the development of a GaAs MESFET simulator which can be used as an optimization tool for the fabrication of both low noise and power devices, was the comparison of simulation and experimental data. At this stage the physical models can be checked for their range of validity and physical parameters can be fine tuned. Both ion-implanted MESFET's fabricated using a SIEMENS SAGFET process and recessed gate types based on epitaxially grown substrates have been investigated to verify this enhanced version of MINIMOS. This comparison between experiment and simulation revealed the most critical physical effects which have to be taken into account for successful simulations.

The substrate and the surface of a MESFET have a major influence on its device characteristics. The effect of Fermi level pinning at the GaAs surface is included by accounting for surface charges. The widely used semi-insulating substrate can be modelled by considering deep traps in the material. Both deep donor (e.g. EL2) and deep acceptor (e.g. Chromium) concentrations can be specified.

The use of enhancement mode MESFET's in most GaAs logic families requires an accurate description of the forward biased Schottky contact. The reformulation of the Schottky boundary conditions at the gate contact allows the specification of an 'ideality' factor, which is easy to determine and gives precise quantitative results for the gate current.

The program has been successfully used to investigate the nature and the location of avalanche breakdown in GaAs MESFET's, which could also be verified by electroluminescence measurements at SIEMENS.

An easy-to-use determination of the doping profiles for implanted MESFET's plays a key role in the daily use of simulation for development purposes. A very important point in this respect was the refinement of the built-in process models, which were amended by a simple activation model. This has proven very helpful to specify e.g. LDD profiles in SAGFET's.

Moreover the conventional mobility model was replaced by the use of a reduced two-band formulation to describe electron transport in GaAs. This model should be extended to account for nonlocal effects ('velocity overshoot'), which have been shown to be very important in small devices (gatelength $< 1\mu m$).

Philipp Lindorfer was born in Steyr, Austria, in 1962. He received the degree of 'Diplomingenieur' from the Technical University Vienna in 1987 in electrical engineering. In November 1987 he joined the 'Institut für Mikroelektronik'. His work was focused on the development of models for III-V compound semiconductors in multi-dimensional device simulation, particularly the simulation of GaAs MESFET's. In 1990 he held a Visiting Research position at National Semiconductors, Santa Clara, CA. In June 1991 he received his doctoral degree from the Technical University of Vienna.

A Technology CAD Shell for Process and Device Engineering

Hubert Pimingstorfer

The use of CAD tools for analysis and prediction of IC technology is generally a substitute for physical experimentation to save time, effort and money, and to provide more insight. A recent trend is to integrate simulation tools into a Technology CAD environment to meet demands that range from simple simulator coupling over process and device characterization to technology optimization. The aim of our TCAD shell is to ease and automate this in a way that allows the user to concentrate on performing complex development tasks rather than on supervising single simulator runs.

The TCAD shell represents the task level of the VISTA system. We have chosen LISP as the implementation language as well as the extension language, in which new functionality is added, customizations are specified, and macros or just shortcuts for often used shell command sequences are defined.

Presently the device simulator MINIMOS, the process simulator PROMIS, and the interconnect capacitance simulator VLSICAP have been integrated into this TCAD environment.

For example, shell functions specialized for MOS transistors compute the threshold voltage and drain and/or bulk current by invoking MINIMOS and returning the value as a LISP expression. These functions combined with a one-dimensional optimizer are used to find the

maximum of the bulk current or of the relative transconductance. Combined with looping constructs, the shell functions are tailored to compute I/V characteristics or any other variation of an output quantity versus any allowed input variable while applying constant or adaptive step sizes.

For each simulator run, the user is exempted from modifying an input deck with an editor, starting the simulator on the command line and getting the required values from the output. With few lines of TCAD shell code a new shell function, tailored to the very specific needs of the user, can be written as a combination of any tool callable at the shell level and normal LISP code. The TCAD shell allows arbitrarily complex tasks to be performed, ranging from simply calling a single module interactively over coupling simulators to running whole optimization loops as background processes. It is highly extensible, customizable and operating system independent.

The TCAD shell is applied within our cooperation with Austria Mikrosysteme International GmbH (AMS), gaining valuable feedback and useful suggestions for further development. A significant substrate current reduction of an AMS high voltage technology due to spacer optimization is one of the first highly motivating result.

Hubert Pimingstorfer was born in Linz, Austria, in 1964. He received his degree of 'Diplomingenieur' from the Technical University Vienna in 1989 in electrical engineering. In November 1989 he joined the 'Institut für Mikroelektronik', where he is currently working towards his doctoral degree in the field of integrating and applying simulators for the improvement and miniaturization of integrated semiconductor devices.

Simulation and Analytical Modeling of High Voltage DMOS Transistors

Martin Stiftinger

In parallel with the development of a new device for analog circuits an analytical model describing the electrical behavior of the device has to be provided. If the new device cannot be characterized in a sufficiently accurate way by standard models (e.g. the SPICE Level 1–3 models for MOS transistors), the first approach will be a "subcircuit"–description using standard analytical models. Very often knowledge of the important physical processes in the device makes possible a meaningful description of the device by a network consisting of standard devices. The subcircuit–models can be realized easily and quickly in a circuit simulator like SPICE. This implies also flexibility, as various subcircuit–models can straightforwardly be compared. It is also evident that there are limits of subcircuit–models as they do not directly describe the device. Another limitation may be convergence problems in the iterative process of determining the potentials and currents that leads to higher CPU–times. The extraction of the parameters of the various standard devices in the subcircuit–model may also cause problems. On the other hand the development of a new analytical model for the device takes by far more time.

High Voltage DMOS transistors (doubled diffused MOS transistors) are mainly used in automobile electronics and telecommunications systems. In our case the transistor must exhibit a breakdown voltage of $80V$. It is part of an integrated $10V$ logic. The channel length is about

$1\mu m$. The high breakdown voltage is achieved with a lightly doped drift region which reduces the voltage on the channel itself considerably. The drift region has important impact on the device characteristics.

The static behavior of the DMOS transistor can be described in a subcircuit–model by a MOSFET describing the channel, a JFET describing the drift region and a drain resistor. The whole subcircuit–model includes additional elements which account also for the small–signal and parasitic behavior.

To describe the behavior of the device more accurately an analytical model for the DMOS transistor is developed. To additionally be able to make predictions about the device behavior, if the device design is changed, and to have the possibility of worst–case estimations this model is based on the device physics (in contrast to a purely empirical model), i.e. most of its parameters can be interpreted "physically". Only few are fitting parameters. Simulations using our device simulator BAMBI give insight into the important physical processes in the device and form the basis of the development of the analytical model. The proper description of the capacitances is also important for simulating switching applications.

Martin Stiftinger was born in Linz, Austria, in 1964. He received the degree of 'Diplomingenieur' from the Technical University Vienna in 1989 in electrical engineering. In February 1990 he joined the 'Institut für Mikroelektronik', where he first was concerned with the iterative solution of large, sparse, and nonsymmetric linear systems and vectorization of those algorithms. He is working towards the doctoral degree, now focusing his work on device and network simulation of DMOS and high voltage CMOS transistors. His research area includes also parameter extraction and fitting strategies.

Monte Carlo Simulation of Ion-Implantation

Hannes Stippel

The miniaturization of today's semiconductor devices suggests a change from the common two-dimensional layout to three-dimensional structures to increase the number of devices on the same wafer area. Therefore modern process simulators must be capable of modeling these three-dimensional structures.

At present our process simulator PROMIS is designed for planar structures. In preparation for the modeling of three-dimensional structures, changes have become necessary.

The incompatibility of the present geometry specification to three-dimensional structures means that an extension requires a more general geometry description. Also, the amount of data in three dimensions is significantly higher than in two, which increases the probability of mistakes if the input is prepared "by hand". For these reasons PROMIS has been incorporated in a TCAD environment. It now allows a very simple description of the geometry by using a graphical user interface and a graphical editor based on this interface; therewith, additionally, structured errors can easily be detected. To enable the interaction with the TCAD shell, a standard for the data representation is required. The new geometry description is based on the profile interchange format (PIF); and some routines have been designed for the conversion from the PIF to the PROMIS data structure and vice versa.

From the view of the process engineer an automatic grid generation and adaption in the Monte Carlo ion-implantation is desireable. The user has to define a specific grid which takes the interesting parts of the simulation area into account. Besides the inconvenience of defining a grid at all which has no physical meaning in itself – it is needed for the computation –, the process engineer should have some idea of the result of the simulation in order to do so. In two dimensions this might be possible, but in the three dimensional space it becomes painfully harder. Therefore an automatic grid adaption was designed, resembling to that of other parts of PROMIS. The difference being that in the Monte Carlo code a grid line that is once deleted can not be inserted again. Therefore the initial grid is very dense, and careful investigations have to be done whether a grid-line can be deleted or not. In the Monte Carlo part, particles are counted which stop in boxes determined by the grid. Until now, all boxes were stored; in the future only boxes containing particles will be treated and a maximum number of boxes must be defined. On exceeding this maximum, grid lines must be deleted.

Hannes Stippel was born in Vienna, Austria, in 1966. He received the degree of 'Diplomingenieur' in electrical engineering from the Technical University of Vienna in 1990. In July 1990 he joined the 'Institut für Mikroelektronik'. Presently he is working towards his doctoral degree. His work is focused on ion implantation in three dimensional structures.

Automatic Device Characterization

Peter Verhás

The daily simulation work consists of iterating several times through a loop consisting of production of input, executing the simulators and interpretation of the results. A significant amount of research is done nowadays to automatize this.

One approach is to build a device characterization tool that is based on simulations. By running the simulators over a given region of input parameters and automatically adapting to device nonlinearities, the tool will build a table. This table is used later, through interpolation, to derive basic device parameters or in conjunction with a table-driven model in circuit simulators.

The first version of the tool simulates MOS transistors by invoking MINIMOS for several drain and gate bias voltages. The bias points are automatically chosen taking into account the nonlinearities of the transistor characteristics.

One–dimensional characterization was already reported. Based on this work we developed an algorithm for the two–dimensional case. Current investigations face the arbitrary dimensional mapping problem over not only bias but also an arbitrary parameter domain.

To map a function $f(x,y)$ on the domain $x_{min} < x < x_{max}$ and $y_{min} < y < y_{max}$ using the one–dimensional algorithm one can define some g: $[z_{min}, z_{max}] \mapsto I\!R^2$ functions and apply the algorithm for the composite function $h(z) = f(g(z))$. The function $g(z) = (\vec{x} \cdot g(z), \vec{y} \cdot g(z))$

defines a curve on the domain. The simplest way is to chose functions of the form

$$g(z) = (A_x z + B_x, A_y z + B_y)$$

where A_x, B_x, A_y, B_y are constant values and

$$(x_{min} - B_x)A_y = (y_{min} - B_y)A_x$$

holds. In this case the curves defined by $g(z)$ are straight lines including the point (x_{min}, y_{min}). The tools that use the built up table can perform one–dimensional interpolations along the calculated lines.

We cooperate with AMS (Austria Mikro Systeme International GmbH) simulating and verifying their technology. The electrical device behaviour with the nominal technology parameters and the modified parameters is simulated to help find the optimal set of parameters. For simulation we use the programs PROMIS and MINIMOS. Most recently we analyzed thoroughly the $1.2\mu m$ CMOS technology of AMS.

Peter Verhás was born in Budapest, Hungary, in 1966. He received his degree of 'Diplomingenieur' from the Technical University Budapest in 1989 in electrical engineering. In November 1989 he joined the 'Institut für Mikroelektronik', where he is currently working towards his doctoral degree in the field of integrating and applying simulators for the improvement and miniaturization of integrated semiconductor devices.

Two-Dimensional Process-Simulation in Nonplanar Structures

Karl Wimmer

The treatment of nonplanar structures is an absolute necessity for the simulation of many fabrication steps in modern device technology, in particular for oxidation.

Transformation methods are appropriate for the numerical simulation in nonplanar two-dimensional and three-dimensional domains, and are widely used in computational fluid dynamics. For application in our process simulator PROMIS, the methods must be suitable for moving boundary problems. Additionally, an unknown variety of geometries has to be treated and adaptive transient grid strategies with heavy changes in grid spacing must be supported. The 'mapping function strategy' developed for PROMIS fulfills the above requirements.

The distinctive feature of the mapping function strategy is the separation of the grid generation into two tasks. The first task is the generation of a mapping function $(u, v) \leftrightarrow (x, y)$ from computational (u, v) to physical (x, y) space. The generation is carried out by algebraic, elliptic or variational methods on a grid which resolves all geometric details. This mapping function has to be calculated just once for each geometrical shape. In the second task the grid used for solving the physical equations is generated. The lines of this grid run along constant u or v values. The distance between gridlines is chosen according to the evolving dopant profiles. Two independent criteria guarantee the resolution of steep gradients and the conservation of dose.

The method used for the generation of the mapping function has a major influence on the convergence of the solution of the discretized physical equations. The application of variational methods results in a speed-up as high as a factor three.

For the analytic simulation of ion implantation, a 'numerical range scaling' model has been incorporated in PROMIS. Thus it is now possible to calculate implantation profiles in nonplanar multilayer structures using analytic distribution functions. Additionally the computation of the damage due to implantation can now be performed by analytic models developed inhouse.

Within the scope of the VISTA project a separation of PROMIS into independent parts has been started. These parts will be modules for grid generation, ion implantation by analytical models, Monte-Carlo ion implantation into amorphous targets, diffusion under inert and oxidizing conditions, and a general solver for elliptic PDE's. The different modules communicate exclusively via standard PIF files. This will facilitate further additions of new modules in the future.

Karl Wimmer was born in Ostermiething, Austria, in 1962. He received the degree of 'Diplomingenieur' in electrical engineering from the Technical University of Vienna in 1987. At that time he joined the 'Institut für Mikroelektronik', where he currently works toward his doctoral degree. He held several summer positions in Austria and Switzerland working on industrial automation and adaptive control systems from 1977 to 1986, and a Visiting Research Position at the Advanced Semiconductor Development Department at Digital Equipment Corporation, Hudson, Massachusetts in winter 1990. His research interests include process simulation in nonplanar structures and numerical grid generation.

Papers in Conference Proceedings

[V21] Traar K., Stiftinger M., Heinreichsberger O., Selberherr S.,
Three-Dimensional Simulation of Semiconductor Devices on Supercomputers,
Proceedings ACM Conf. on Supercomputing, (17.-21. June 1991, Köln), pp.154-162.

[V20] Selberherr S., Fischer C., Halama S., Pimingstorfer H., Read H., Stippel H., Verhas P., Wimmer K.,
The Viennese TCAD System,
Proceedings VPAD Workshop, (26.-27. May 1991, Oiso), pp.32-35, (invited).

[V19] Fasching F., Fischer C., Halama S., Pimingstorfer H., Read H., Selberherr S., Stippel H., Verhas P., Wimmer K.,
An Integrated Technology CAD Environment,
Proceedings VLSI Technology, Systems and Applications Symposium, (22.-24. May 1991, Taipeh), pp.147-151.

[V18] Lindorfer Ph.,
An Ideality Factor Formulation of Schottky Boundary Conditions in Numerical Device Simulation,
Proceedings WOCSDICE 91, (14.-17. May 1991, Grönenbach).

[V17] Heinreichsberger O.,
Massively Parallel Solution of the Three-Dimensional Van Roosbroeck Equations,
Abstracts NUMSIM'91 Conf., (5.-8. May 1991, Berlin), p.8.

[V16] Heinreichsberger O., Selberherr S., Stiftinger M.,
3D MOS Device Simulation on a Connection Machine,
Abstracts SIAM Conf. in Parallel Processing for Scientific Computing, (25.-27. March 1991, Houston), p.A2 and Proceedings (in print).

[V15] Halama S., Hobler G., Wimmer K., Selberherr S.,
Eine neue Methode zur Simulation der Diffusion in allgemeinen Strukturen,
Tagungsbericht Seminar GRUNDLAGEN UND TECHNOLOGIE ELEKTRONISCHER BAUELEMENTE, (20.-23. March 1991, Großarl), pp.20-26.

[V14] Wimmer K., Bauer R., Halama S., Hobler G., Selberherr S.,
Simulation nichtplanarer Herstellungsprozesse mit PROMIS,
Tagungsbericht Seminar GRUNDLAGEN UND TECHNOLOGIE ELEKTRONISCHER BAUELEMENTE, (20.-23. March 1991, Großarl), pp.10-19.

[V13] Selberherr S.,
Low-Temperature Operation,
Proceedings EUROPEAN SCHOOL ON DEVICE MODELING, (18.-20. March 1991, Bologna), pp.71-100, (invited).

[V12] Selberherr S., Heinreichsberger O., Stiftinger M., Traar K.,
About the Solution of the Three-Dimensional Semiconductor Device Equations on Vector-Concurrent Computers,
Manuscripts Symposium on Supercomputer Simulation of Semiconductor Devices, (19.-20. November 1990, Minneapolis), pp.1-21, (invited).

[V11] Traar K., Mader W., Heinreichsberger O., Selberherr S., Stiftinger M.,
High Performance Preconditioning on Supercomputers for the 3D Device Simulator MINIMOS,
Proceedings SUPERCOMPUTING 90 Conf., (12.-16. November 1990, New York), pp.224-231.

[V10] Wimmer K., Bauer R., Selberherr S.,
Body-Fitting Coordinate Generation for Two-Dimensional Process-Simulation,
Abstracts AMSE Conf. SIGNALS AND SYSTEMS, (8.-10. October 1990, Chengdu), Vol.2, p.239. and Proceedings Vol.14 (in print).

[V9] Wimmer K., Bauer R., Halama S., Hobler G., Selberherr S.,
Prozeß -Simulation in nichtplanaren Strukturen mit PROMIS,
Proceedings NuTech 90, (20.-21. September 1990, Garmisch-Partenkirchen), p.4.

[V8] Halama S., Wimmer K., Hobler G., Selberherr S.,
Finite-Differenzen Dreiecksnetzgenerierung für die Prozeß - Simulation mit PROMIS,
Proceedings NuTech 90, (20.-21. September 1990, Garmisch-Partenkirchen), p.3.

[V7] Dickinger P., Nanz G., Selberherr S.,
Measurement and Simulation of Degradation Effects in High Voltage DMOS Devices,
Proceedings ESSDERC 90, (10.-13. September 1990, Nottingham), pp.369-372.

[V6] Ashworth J., Lindorfer P.,
Analysis of the Breakdown Phenomena in GaAs MESFET's,
Proceedings ESSDERC 90, (10.-13. September 1990, Nottingham), pp.241-244.

[V5] Habaš P., Selberherr S.,
Numerical Simulation of MOS-Devices with Non-Degenerate Gate,
Proceedings ESSDERC 90, (10.-13. September 1990, Nottingham), pp.161-164.

[V4] Ashworth J., Lindorfer P.,
Analysis of the Breakdown Phenomena in GaAs MESFET's,
Proceedings GaAs and Related Compounds, (September 1990, Jersey).

[V3] Kosina H., Wimmer K., Fischer C., Selberherr S.,
Simulation of ULSI Processes and Devices,
Abstracts Computer Aided Innovation of New Materials 90, (28.-31. August 1990, Tokyo),p.46 and Proceedings (in print) (invited).

[V2] Kosina H., Selberherr S.,
Efficient Coupling of Monte Carlo and Drift Diffusion Method with Applications to MOSFET's,
Proceedings SOLID STATE DEVICES AND MATERIALS Conference, (22.-24. August 1990, Sendai), pp.139-142.

[V1] Selberherr S., Kosina H.,
Simulation of Nanometer MOS-Devices with MINIMOS,
Proceedings 1990 VLSI PROCESS/DEVICE MODELING WORKSHOP, (20.-21. August 1990, Kawasaki), pp.2-5, (invited).

Papers in Journals

[P11] Selberherr S.,
Device Modeling and Physics,
Physica Scripta, Vol.T35, pp.293-298, 1991, (invited).

[P10] Langer E.,
Fundamental Analysis of Surface Acoustic Wave Propagation,
Int.J.Engineering Science, Vol.29, No.3, pp.331-343, 1991.

[P9] Kosina H., Selberherr S.,
Coupling of Monte Carlo and Drift Diffusion Method with Applications to Metal Oxide Semiconductor Field Effect Transistors, Japanese Journal of Applied Physics, Vol.29, No.12, pp.L2283-L2385, 1990.

[P8] Habaš P., Selberherr S.,
On the Effect of Non-Degenerate Doping of Polysilicon Gate in Thin Oxide MOS-Devices — Analytical Modeling,
Solid-State Electronics, Vol.33, No.12, pp.1539-1544, 1990.

[P7] Habaš P., Selberherr S.,
Impact of the Non-Degenerate Gate Effect on the Performance of Submicron MOS-Devices,
Midem, Vol.20, No.4, pp.185-188, 1990.

[P6] Kausel W., Nylander J.O., Nanz G., Selberherr S., Pötzl H.,
BAMBI – A Transient 2D-MESFET Model with General Boundary Conditions Including Schottky and Current Controlled Contacts, Microelectronics Journal, Vol.21, No.5, pp.5-21, 1990.

[P5] Selberherr S., Hänsch W., Seavey M., Slotboom J.,
The Evolution of the MINIMOS Mobility Model,
Solid-State Electronics, Vol.33, No.11, pp.1425-1436, 1990.

[P4] Thurner M., Lindorfer P., Selberherr S.,
Numerical Treatment of Nonrectangular Field-Oxide for 3-D MOSFET Simulation,
IEEE Trans. Computer-Aided Design, Vol.CAD-9, No.11, pp.1189-1197, 1990.

[P3] Thurner M., Selberherr S.,
Three-Dimensional Effects Due to the Field Oxide in MOS Devices Analyzed with MINIMOS 5,
IEEE Trans. Computer-Aided Design, Vol.CAD-9, No.8, pp.856-867, 1990.

[P2] Dickinger P.,
New Models of High Voltage DMOS Devices for Circuit Simulation,
Electrosoft, Vol.1, No.4, pp.298-308, 1990.

[P1] Habaš P.,
A Physics Based Analytical MOSFET Model with Accurate Field Dependent Mobility,
Solid-State Electronics, Vol.33, No.7, pp.923-933, 1990.

Edited Journals

[E1] Langer E.,
Special Issue on *"Semiconductor devices and electronic circuit design"*
ELECTROSOFT, Vol.1, No.4, December 1990.

Doctoral Theses

[T1] Lindorfer P.,
Numerische Simulation von Galliumarsenid MESFETs,
Technische Universität Wien, March 1991.

Master's Theses

[D2] Tuppa W.,
Optimierender Linker für Superpipelining- und Superskalar - rechner,
Technische Universität Wien, February 1991.

[D1] Kocsis T.,
Modeling of Hot-Carrier Effects in MOS-Devices,
Technische Universität Budapest, July 1990.

Sponsors

(in alphabetical order)

Austrian Industries	Wien
Digital Equipment	Hudson, USA
EZM	Villach
Motorola	Austin, USA
National Semiconductor	Santa Clara, USA
Siemens	München, Germany
Sony	Atsugi, Japan