RESEARCH IN COMPUTER SIMULATION
OF INTEGRATED CIRCUITS

FINAL REPORT

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INTEGRATED CIRCUIT SIMULATION

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The research work supported by the U.S. Army Research Office under Grant DAAG28-76-G-0161 has been concerned with investigations and development activities in the circuit simulation of integrated and discrete component electronic circuits. The research activities under this research grant commenced on February 23, 1976 and were concluded on June 30, 1980. As brought out below the results of the research activities have been reported in six publications, in the support of seven research students, and in the development and issuing of four computer programs for integrated circuit simulat-

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SPICE 2 PROGRAM

The SPICE 2 program was originally released as an engineering program in July 1975 and the original SPICE 1 program was first released in May 1972. At the beginning of 1976, i.e., the beginning of the ARO research grant, work had just been initiated which would lead to the 2D version of SPICE 2.

In the three previous versions of SPICE 2, principal attention had been given to algorithmic and circuit solution aspects of SPICE, particularly to improve the speed of simulation and to reduce problems of no convergence.

For the 2D version of SPICE 2, under ARO sponsorship, attention was especially directed into the topics of MOSFET device modeling and program transportability. For the 2D version the major MOS model was rewritten to include process-level model parameters, weak inversion and some short-channel effects on threshold voltage. This MOS model, labelled MOS-2, constituted a conventional collection of first-order effects to provide a reasonable modeling of MOSFET electronic behavior.

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A new MOS model, MOS-3, based on the ElMansy-Boothroyd (E-B) model was also incorporated into the 2D version of SPICE to provide us with working experience with the different equation formulation in this model. By Version 2D.6, sufficient problems had been uncovered and corrected to indicate that we had achieved a reasonable solution to the modeling problem for all but short-channel, narrow-channel devices.

In SPICE 2E, a slight change in the user input format was made to incorporate a MOS level parameter.* Level 2 which pertains to MOS-2 is the usual model to be used, i.e., the work horse; level 1 (based on the Shichman-Hodges formulation) is the most elementary and is commonly used for initial studies. Level 3 is reserved for a specialty model such as the E-B model mentioned above. The default value for the level parameter is 1 and relates to the simplest model.

In the 2D and 2E versions of the program a series of changes were also made concerning default parameters of device parameters. Values have been successively chosen which conform more closely to present-day practice. In addition, as thermal problems have become more important with MOS devices, it has been necessary to introduce a different or a new temperature dependence for the various MOSFET parameters. Of course as new circuit types have been simulated or existing types with new operational requirements, numerous undiscovered problems have been noted and solved. The sequence of initial issue dates of various versions of SPICE 2 are listed in "Programs Issued under ARO Grant Sponsorship."

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*In the designation of the version, for example SPICE 2E.3, the initial parameter 2 refers to the generation of the program. The second parameter, E, pertains to the version. If this parameter is changed, it means there has been change in the users manual. The last (numeric) parameter pertains to changes or corrections which have been made in the program and which do not affect the user.

In the 2F version of the program, the levels of the 2E series were retained; however, new MOS-2 and MOS-3 models for MOSFET devices were included. The new MOS-2 model is a new collection of electronic effects which gives a more accurate modeling of devices with very small geometries and very shallow geometries. In addition, an improved charge formulation, originally introduced by Ward and Dutton at Stanford University, has been included. Charge conservation is now present in the modeling as the program iterates to a solution. Finally, two new parameters have been introduced. VMAX, the maximum drift velocity of carriers, is used in the calculation of the drain-to-source saturation and NEFF, the total channel charge coefficient is needed for a more accurate calculation of the MOSFET output conduction in saturation.

The new MOS-3 model in SPICE 2F is based upon a semi-empirical approach to include simple threshold-voltage sensitivity to the length and width of the device due to the two-dimensional nature of the potential distribution. In addition, the effect of the drain voltage on the theshold voltage due to drain-induced barrier loading is included. The relaxed transition between the linear and saturation regions and the lowered saturation voltage current due to velocity saturation of hot electrons is incorporated. Finally, the charge-conservation capacitance model of the MOS-2 model is also implemented in MOS-3. The MOS-3 model is aimed toward rapid efficient CAD use. Typically, simulation times with MOS-3 are 1/3 less than the simulation times with MOS-2.

Another major feature of the 2F series of SPICE is an extensive set of internal changes to make the installation of this program on non-Cyber computers a much easier task. The new SPICE 2 program will run with a minimum of changes on all major computers. Our present

program development technique involves using an internal but a very effective editor on a Hewlett-Packard 1000 series computer. During the editing, several flags can be set to institute portions of the code that make the program run on CDC, IBM, or DEC/VAX machines.

There are probably over 1000 copies of SPICE 2 now in use. Up to this point we have issued from Berkeley several hundred copies of the program, principally for the CDC 6000 series machines (Cyber systems), although now we are issuing, as noted above, versions suitable for the CDC, IBM or DEC machines. Through the 2E version of SPICE, the Texas Instruments Company issued an IBM version and probably issued a larger number of copies than the CDC versions we distributed. Other groups using other major machines, such as those of Univac, Honeywell, Xerox and DEC, have converted SPICE to their machines and have also issued copies to interested users. Since SPICE 1 and SPICE 2 have been issued in the public domain, each group who obtains a copy is at liberty to reissue copies of their program. Thus, it is virtually impossible to know exactly the number of SPICE programs which are now in use not only in this country but internationally.

SPY

A periferal processor program, SPY, has been used on our local CDC 6400 computer as well as our HP 1000 minicomputers, to investigate and optimize performance of several programs. SPY samples the processor program counter (P-counter) while a user program is concurrently executing. Sampling is done in real-time at a high sampling rate. The output data is then processed to produce histograms of the number of time the P-counter was sampled at any address for any instruction address for the program being investigated. The results from the

program provide an accurate picture of where a user program is spending its cpu time.

The SPY program has been used to identify the so-called hot spots in the SPICE 2 program as well as for other programs such as the logic simulation program SALOGS-3 and the timing simulator MOTIS-C. In particular the use of the SPY program with SPICE 2 has aided us in establishing the relative effectiveness of different formulations of the MOS models. For example, we have been able to identify sources of the 2 to 3 times increase in the analysis time demands of the MOS-3 (the E-B) model.

MOTIS-C

MOTIS-C is a MOS timing simulator developed here initially under the sponsorship of the Hewlett-Packard Company. MOTIS-C is based upon similar but proprietary programs developed at Bell Labs and at Texas Instruments. Our version has been further expanded through the research support of this grant, particularly for our local use.

The prototype of MOTIS-C was made available in early 1977. It was further developed under ARO sponsorship to include multiphased clocks and the model tables and table look-up routines were optimized. In addition the program is now capable of simulating NMOS, PMOS and CMOS circuits with both enhancement and depletion mode devices. The model evaluation tables may now be generated from pertinent device parameters and built-in functional model equations. The internal analysis timestep may also now be varied by the program to reduce error. Finally a series of circuit macromodels has been introduced to be able to obtain faster, more inexpensive simulation.

SPUDS

A new simulation program SPUDS has been developed as part of our investigation into the performance limits of circuit simulation on a dedicated microprogrammable microcomputer system. The computer which has been used is a HP 1000, series F. An initial program MICE was developed as part of our investigation of the numerical methods and computational techniques which minimized storage requirements and computer analysis time while yet still providing the necessary accuracy using 32-bit words only, in contrast to the 60 to 64-bit words used on large main-frame computers. The final program in this study, SPUDS, successfully performs circuit analysis with single precision (32-bit) floating-point variables using a combination of numerical pivoting, sparse matrix techniques, a generalization of the indefinite admittance matrix, and a number of specially tailored micro-coded computer instructions which best match the basic computer hardware to the analysis algorithms and data structures of the program. As a result the performance penalties associated with multiword memory references for floating-point variables and with tracing through link-list pointers to manipulate the linear equation coefficient matrix have been essentially eliminated. Both the analysis algorithms and the "effective" computer hardward (through micro-coding) have been modified as part of the development of a fast effective IC simulation program.

The performance results with SPUDS show that 32-bit floating-point computations can be used effectively to obtain analysis results which are almost identical with those from the more common 64-bit arithmetic and that performance speeds of the same order as a DEC, VAX 11/780 can be achieved using the HP 1000, 16-bit minicomputer.

The final report on program SPUDS was in preparation at the conclusion of the grant sponsorship and should be available soon, together with the availability of the program to interested users and developers.

PUBLICATIONS UNDER ARO GRANT SPONSORSHIP

A. R. Newton and D. O. Pederson, "Status of integrated circuit simulation," Proc. Midwest Symp. on Circuits and Systems, Lubbock, Texas, August 1977.

M. Y. Hsueh, A. R. Newton and D. O. Pederson, "New approaches to modeling of electrical simulation of LSI logic circuits," Journies D'Electronique, 1977, EPFL, Switzerland, pp. 403-413, October 1977.

A. R. Newton and D. O. Pederson, "Analysis-time, accuracy, and memory requirement tradeoffs in SPICE 2," Conference Record, Asilomar Conference on Circuits, Systems and Computers, California, November 1977.

E. Cohen, L. Jensen, D. O. Pederson, and A. Vladimirescu, "MICE: A Minicomputer Integrated Circuit Emulator," Conference Record, Asilomar Conference on Circuits, Systems and Computers, California, November 1978.

D. O. Pederson, "Components of an integrated set of IC design aids," Proc. 1979 Int. Symposium on Circuits and Systems.

D. O. Pederson, "Simulation techniques and possibilities for VLSI circuits, NTG-Fachberichte, Band 68, 1979.

An invited series of four lectures was delivered at the 1978 Summer Institute of the ESAT, Catholic University, Leuven, Belgium. The material of these lectures was based in part on the research results of this grant. The proceedings of the Summer Course included the reprints of earlier papers prepared under the support of this grant.

PROGRAMS ISSUED UNDER ARO GRANT SPONSORSHIP

SPICE 2

    Version 2 D.1, 21 June 1976.................2 D.9, 16 November 1977
    "   2 E.0, 18 January 1978.............2 E.3, 20 April 1979
    "   2 F.0, 6 January 1980.............2 F.1, 28 February 1980

MOTIS-C

    Version 1.2, 16 November 1977; 1.3A, 6 April 1978
    "   2.0, 7 May, 1979; 2.1, 15 August 1979

<u>MICE</u>

November 1978

<u>SPUDS</u>

In development

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