(9A-1)

Non-Quasi-Static Modeling/Implementation of BJT Current Crowding for Semi-Numerical Mixed-Mode Device/Circuit Simulation

J. G. Fossum and J. Jin

Department of Electrical Engineering
University of Florida
Gainesville, FL 32611-2030
U.S.A.

VLSI technology CAD (TCAD) requires integrated, physics-based tools for predictive process, device, and (small-scale) circuit simulation. Computational efficiency is desirable, and indeed essential if the TCAD system is to be used in manufacturing CAD involving statistical simulation. Conventional TCAD systems comprise robust, numerical process and device simulators which drive optimization of empirical device model parameters for circuit simulation. This optimization can miss parametric correlations, and hence the integrated system, although CPU-intensive, could yield non-unique (erroneous) predictions.

Numerical mixed-mode device/circuit simulation would obviate this deficiency, but with a high cost of computation time. Alternatively, improvement of the TCAD system can possibly be afforded by incorporation of semi-numerical device models into the circuit simulator which have physical parameters that relate directly to the device structure. The resulting tool is an application-specific, computationally efficient mixed-mode simulator that can easily be integrated with the process simulator by a program that evaluates the model parameters from the doping profile. We are developing such a simulator (MMSPICE), and the program (SUMM) which integrates it with SUPREM-3.

The model development for MMSPICE has emphasized the advanced bipolar transistor (BJT). A physical, one-dimensional model [1], which requires Newton-like iterative solutions within the model routine, has been developed and implemented. High-current effects are physically accounted for in the semi-numerical model, but three-dimensional current crowding is not modeled in the released versions of MMSPICE. We describe in this paper the model extension to include transient (and dc) crowding, which in fact is a significant non-quasi-static (NQS) effect even in contemporary scaled BJTs [2], [3].

The intrinsic base of the advanced (self-aligned) BJT is surrounded by a high-conductivity extrinsic base. Hence the predominant base current flow under a rectangular emitter is along the shorter emitter dimension (W_E); this is assumed in our (two-dimensional) crowding analysis. For transient excitation, the main components of the total base current $I_B(t)$ are typically back-injection current from the base to the emitter (I_{BE}) and majority-carrier charging/discharging current (dQ_{BE}/dt):

$$\begin{aligned} I_B(t) &= I_{BE} + \frac{dQ_{BE}}{dt} \\ &\simeq (J_{EO}+Q'_A)L_E W_E\left[\exp\left(\frac{V_{BE(eff)}}{V_T}\right) - 1\right] \end{aligned} \tag{1}$$

where $V_{BE(eff)}$ is a NQS effective bias on the emitter-base junction defined to account for the current crowding. The transient counterpart Q'_A to J_{EO} can be estimated from the previous time-step solution for dQ_{BE}/dt for use in the current time-step analysis. So our model, when implemented based on the previous time-step solution, accounts for transient crowding non-quasi-statically. For fast switching transients of advanced BJTs, dQ_{BE}/dt is commonly much greater than I_{BE} in (1), which clearly implies the NQS nature of current crowding.

Our novel NQS modeling/implementation of the crowding involves a coupling of the vertical and lateral carrier flows in the base region. For the npn BJT, analysis of the two-dimensional hole flow semi-numerically defines $V_{BE(eff)}$ for each Newton-Raphson iteration at each time step. The effective bias is smaller than the actual bias for switch-on transients, but larger for switch-off transients. The analysis is based on, and subsequently extends the one-dimensional analysis of the ambipolar flow in the MMSPICE model, which characterizes the conductivity modulation in both the metallurgical and widened base regions. The result is a semi-numerical, quasi-two-dimensional NQS BJT model in MMSPICE having a dynamic effective emitter-base bias that depends not only on V_{BE} and V_{BC} but also on the previous time-step solution. No lumped intrinsic base resistor is needed in the physical model.

MMSPICE transient simulations of an advanced-BJT inverter circuit show effects of NQS current crowding on propagation delay. For the switch-on transient, peripheral-emitter crowding causes an added delay, consistent with [2], but one that tends to become insignificant as W_E is scaled to submicron (< 0.5 μm) values as noted in [3]. Predicted switch-on delays versus W_E, with and without the emitter area ($A_E = L_E W_E$) fixed, are plotted in Fig. 1. The effect of the crowding is made apparent by including in the figure delays predicted by one-dimensional simulations. We note that the relative importance of the crowding varies inversely with the extrinsic (plus external) base resistance. Switch-off simulations however show that the added delay due to central-emitter crowding is negligible, at least for $W_E \leq 2$ μm. Indeed they predict that the reduced delay of a scaled (W_E and A_E) device is due predominantly to the reduced charge storage in the BJT. Other simulations show that accounting for only quasi-static crowding (due to I_{BE} in (1)) yields switching characteristics which are virtually identical to those predicted by simulations in which crowding is completely neglected.

The transient current-crowding analysis coupled to the one-dimensional MMSPICE model provides the basis for a semi-numerical, scalable, NQS BJT model for mixed-mode device/circuit simulation. It increases the CPU time of MMSPICE negligibly because the voltage-derivatives needed in the Newton-Raphson circuit nodal analysis can be adequately approximated by divided differences derived from the model routine with $V_{BE(eff)}$ fixed.

REFERENCES

1. H. Jeong and J. G. Fossum, IEEE Trans. Electron Devices, vol. 36, pp. 124-131, Jan. 1989.
2. D. D. Tang, IEEE Trans. Electron Devices, vol. ED-32, pp. 2224-2226, Nov. 1985.
3. T. Hamasaki, et al., IEEE Trans. Electron Devices, vol. ED-10, pp. 1620-1626, Oct. 1988.

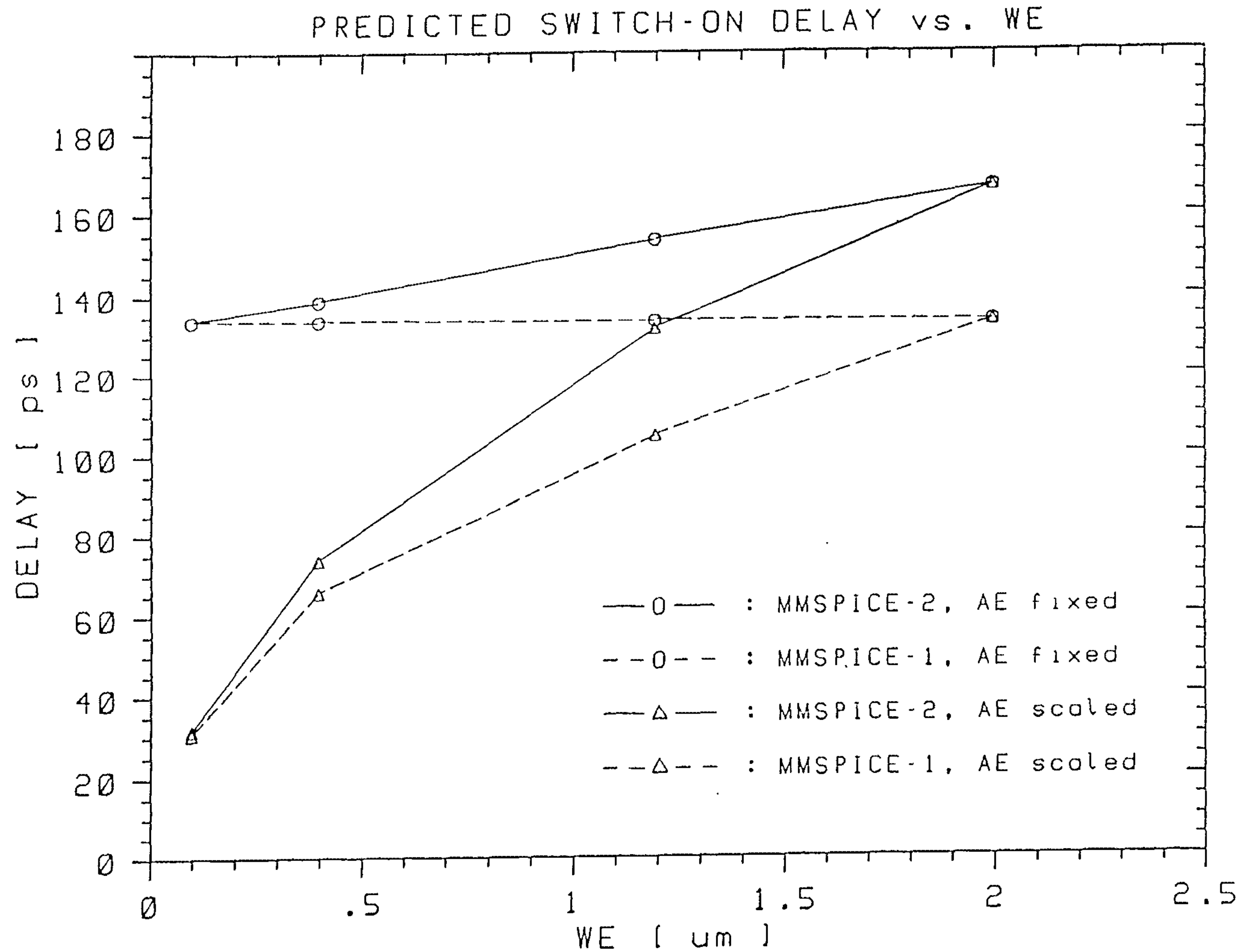

Fig. 1. MMSPICE(-2)-predicted delays versus emitter width for BJT inverter circuit, with and without emitter area fixed. One-dimensional (MMSPICE-1) simulation results are included for comparison. (Geometrical dependences of the extrinsic collector-base junction capacitance were not accounted for in the simulations.)