BJT Modeling with VBIC, Basics and V1.3 Updates

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ABSTRACT

This paper reviews the VBIC BJT model, and details updates in the version 1.3 release. VBICv1.3 includes explicit interaction with simulator global parameters `gmin` and `pnjmaxi`, explicit limiting of local temperature rise and exponential arguments to aid convergence, and an excess phase formulation that obviates the need for inductor currents and is implementable with only voltage controlled current and charge sources. Enhancements to VBIC include modeling of quasi-neutral base recombination, depletion modulation of R_C for vertical PNPs, an arbitrary collector doping profile model for C_{bc} for accurate large-signal distortion modeling, improved electrothermal modeling, and a collector pinning modeling for PNPs.

Keywords: VBIC, BJT modeling, SPICE.

1 VBIC BJT MODEL

The VBIC BJT model was introduced in 1995 [1-4], and has become widely used since then, for III-V HBTS [5] and high voltage devices, as well as for silicon [6] and SiGe [7] devices.

VBIC is based on the SPICE Gummel-Poon (SGP) model, with a modified version of the Kull-Nagel quasi-saturation model [8]. As such, it has proven very easy to migrate modeling and design experience with SGP to VBIC, and a translation program `sgp2vbic` is available [3,4] to translate SGP model parameters to VBIC.

Basic improvements in VBIC over SGP include:

- Separation of I_c and I_b, not empirically linked via B_F
- Early effect modeling based on depletion charge
- Improved depletion and diffusion charge models
- Full parasitic PNP modeling
- Constant overlap capacitances
- Weak base-collector avalanche model
- Base-emitter breakdown modeling
- Self-heating modeling
- Improved temperature modeling (including, physically, no negative built-in potentials at high temperatures)

Besides the different Early effect model, these differences with respect to SGP are by default turned off, so it is relatively simple to add effects as needed, when migrating from SGP to VBIC.

VBIC is the only public domain model that has never been defined in low-level code, it has always been defined in a high-level language (initially a specific syntax for VBIC, now in the standard behavioral modeling language Verilog-A) and low level simulator code has been automatically generated from the high level description. Consequently, the model did not include explicit handling of things like junction limiting or linearization of exponentials, as these are simulator specific and were intended to be added during implementation.

However, there are some common numerical and convergence aids used across most simulators, and these have been explicitly added to VBICv1.3. Details are provided here.

Also, there have been requests for specific additions to and improvements in various facets of VBIC modeling, and these have also been addressed. Details are provided here.

2 ROBUSTNESS IMPROVEMENTS

As noted above, simulator specific convergence tricks were not included in the VBIC Verilog-A code. These have now been added, in a manner that for implementation as a built-in model links to global simulator parameters, yet for simulation using Verilog-A directly allows the parameters to be passed as model parameters.

Global variables `gmin` and `pnjmaxi` (the current level at which exponentials are linearized) have been explicitly added. This both overcomes ambiguities in the linearization scheme used by the `[$]limexp` function, and allows run time modification of both of these parameters to help with convergence. Previously, it was expected that these, or limiting via the `pnjlim` function, would be added.

Explicit numerical protection was also added to the weak avalanche function `avalm`.

Absolute limits on the minimum and maximum device temperature, which help convergence for self-heating simulations, have been added. These are alterable as model parameters, as they are not commonly defined as global simulator variables. Limiting of the temperature rise between Newton iterations still must be implemented specifically for each simulator.

Some simulators support a `shrink` capability, which allows a specific optical shrink factor to be applied. This has been implemented, however as VBIC does not include explicit geometric scaling, the shrink factor is applied as part of the area (or magnitude factor `m`) scaling. This directly scales all currents and charges.

Also, improved clamping of internal model calculations to prevent numerical problems has been implemented, primarily in the normalized based charge calculation.

3 MODEL UPDATES FOR VERSION 1.3

Updates are at present being made to VBIC for V1.3. Many of these are directed at improved modeling of higher voltage devices.

3.1 Temperature Dependent Early Voltages

The Early effect model in VBIC is based on depletion charges, and not on an empirical constant output conductance model. The physically based temperature dependence of the depletion charge model provides some temperature dependence in the Early effect modeling, however data shows a different temperature variation than predicted based on the depletion charge model alone.

Data showed the Early voltage to vary nearly linearly with temperature, so linear temperature coefficients were added to both forward and reverse Early voltages,

$$V_{EF}(T) = V_{EF}(T_{NOM})(1 + TC_{VEF}(T - T_{NOM})) \qquad (1)$$

and similarly for V_{ER}.

3.2 Quasi-Neutral Base Recombination

The VBIC base current model was derived based on recombination in the quasi-neutral emitter and in the base-emitter space charge region. For some types of BJTs, especially those with wide base regions, a portion of the base current arises because of recombination in the quasi-neutral base region. For this component of base current, the volume of the base, which determines the amount of quasi-neutral base recombination, is modulated by the Early effect. Therefore there is a V_{cb} dependence of the quasi-neutral base recombination component of the base-emitter part of I_b; the other components have no V_{cb} dependence.

The non-ideal component of the base-emitter part of I_b arises from recombination and generation in the base-emitter space charge region, and is not affected by V_{cb}. In VBIC, the ideal component of the base-emitter part of I_b is split into two, an intrinsic component and an extrinsic component. The latter is associated with the perimeter (or sidewall) portion, and so is not significantly modulated by V_{cb}, compared with the intrinsic portion under the emitter.

The ideal component of the intrinsic I_{be} is

$$W_{BE} I_{BEI}(T)(\exp(V_{bei}/(N_{EI}kT/q)) - 1) \qquad (2)$$

where I_{BEI} is the ideal base-emitter saturation current, N_{EI} the associated emission coefficient, and W_{BE} is the portion of I_{BEI} partitioned to be intrinsic. I_{BEI} includes components associated with recombination in the quasi-neutral emitter and at the emitter contact, which are not affected by V_{cb}, and a component for recombination in the quasi-neutral base region, which is modulated by V_{cb}.

The quasi-neutral base volume is controlled by the Early effect. In VBIC this is modeled by the q_1 component of normalized base charge. The quasi-neutral base recombination is proportional to this. Therefore

$$I_{BEI} = I_{BEI}^{e} + I_{BEI}^{b} q_1 = I_{BEI}^{0}(1 + Q_{NIBEIR}(q_1 - 1)) \qquad (3)$$

where the superscripts e and b denote emitter and base components, $I_{BEI}^{0} = I_{BEI}^{e} + I_{BEI}^{b}$ is the zero-bias value of I_{BEI}, and $Q_{NIBEIR} = I_{BEI}^{b} / I_{BEI}^{0}$ is the ratio of quasi-neutral base component to total I_{BEI}. This is implemented in VBIC as the ideal component of I_{be} being

$$W_{BE} I_{BEI}(T)(1 + Q_{NIBEIR}(q_1 - 1))(\exp(V_{bei}/(N_{EI}kT/q)) - 1) \qquad (4)$$

Fig. 1 shows V_{be} as a function of V_{ce} from forward output data at fixed base current drive. As V_{ce} increases, the quasi-neutral base volume decreases because of the forward Early effect. The base recombination current therefore decreases, and V_{be} must increase to keep I_b constant. Fig. 2 shows the derivative of the data in Fig. 1. At high V_{ce} the non-zero slope is caused by weak avalanche, at low V_{ce} by quasi-neutral base recombination.

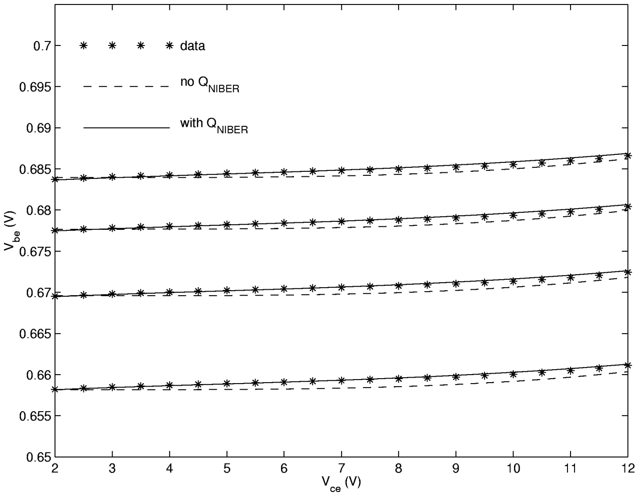

Fig. 1 V_{be} vs. V_{ce} for stepped I_b

3.3 Vertical PNP R_C Modeling

In contrast to vertical NPN devices, which have an n^+ buried collector, vertical PNPs in SmartPower type processes have no p^+ buried collector. This means that the collector resistance under the base is modulated, by depletion pinching, by the collector to substrate voltage. This can be modeled as part of a subcircuit by including a JFET to model R_{CI}. However, this is inconvenient, and the SPICE JFET model is not physically based. A depletion modulated collector resistance model, as an alternative to the Kull-Nagel quasi-saturation model, has been added to VBICv1.3

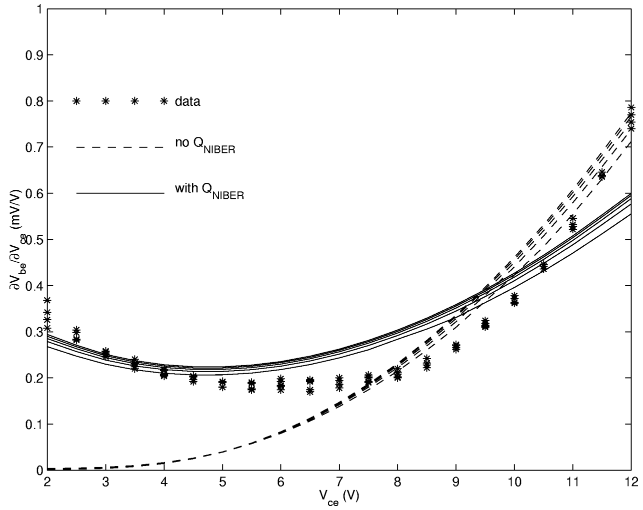

Fig. 2 Derivative of Data in Fig. 1

The formulation follows that of the diffused resistor model of [9], with simplifications to remove the geometry dependence

$$I_{rci} = V_{rci}\,(1 - D_{FC}\sqrt{P_{FC}+V_{rci}})\big/R_{CI} \qquad (5)$$

where D_{FC} is the depletion factor and P_{FC} is twice the built-in potential. Appropriate numerical protection and smoothing to maintain symmetry are used.

4 EXCESS PHASE IMPLEMENTATION

VBIC uses the Weil-McNamee 2nd order frequency domain excess phase model [10]. In the original form this was defined in terms of the finite difference method, and was targeted for transient analysis. Other simulator implementations included only a linear frequency dependent rotation (in complex number space) of g_m, which is only applicable for AC and noise analyses.

A basic requirement for a model is that it should be consistent for all analysis types. In VBIC, the excess phase was implemented with an RLC circuit, which provided the 2nd order frequency dependence and was valid for all analysis types. However, the use of inductors in models is undesirable as it is not a natural element for MNA, and causes an extra system variable (the inductor current) to be added. With the two nodes included in the equivalent network, this caused 3 system variables to be added.

In VBICv1.3 a simpler formulation has been used. Fig. 3 shows the previous excess phase network, where I_{tzf} is the forward transport current with no excess phase and T_D is the excess phase delay parameter. The equations for this network are (KCL at node xf1, recognizing that the currents through the inductor and 1Ω resistor are equal, and both are equal to $V(xf2)$ which is also the phase shifted transport current I_{txf}, and the inductor BCR)

$$I_{tzf} - ddt(T_D V(xf1)) - V(xf2) = 0\,, \qquad (6)$$

$$V(xf1) - V(xf2) - ddt(T_D V(xf2)/3) = 0\,. \qquad (7)$$

Upon reflection, it is apparent that these can be implemented as Fig. 4 shows. This is equivalent to, but much cleaner than, the RLC implementation, and uses only linear capacitors and linear voltage controlled current sources.

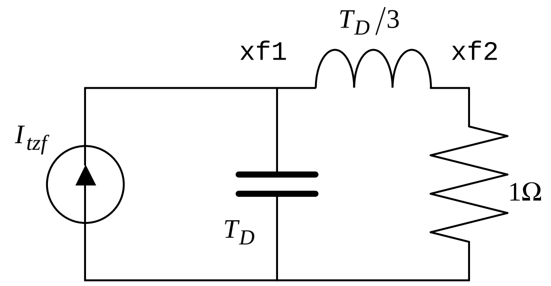

Fig. 3 RLC Network for Excess Phase

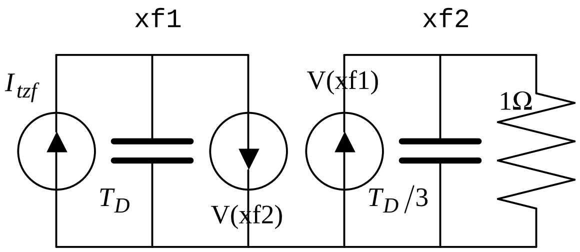

Fig. 4 Simplified Excess Phase Network

5 OTHER UPDATES

Miscellaneous other updates include the following.

Although first order theory implies BJTs should be reciprocal, real devices, especially HBTs, are not. VBIC can model different transport saturation currents in reverse than in forward operation. The saturation current for reverse operation is I_{SRR} times the forward saturation current, and the default value for this parameter is 1. This maintains backward compatibility of parameter sets, yet allows separate modeling of reverse and forward behavior. A separate temperature parameter is also provided, D_{EAR} is the difference in activation energy from E_A used for temperature modeling of the reverse saturation current.

At very high bias the thermal resistance itself has a temperature dependence [5]. A linear $R_{TH}(T)$ model has been added to VBICv1.3.

IBM has reported results using VBIC [7], and delivers VBIC models as part of its design kits. This used a modified form of VBIC, where the node placements were slightly different. The IBM modifications have been included in VBICv1.3 [11]. An additional avalanche element is included between the node `bx` and `cx`, with a separate set of parameters. This has been shown to improve the accuracy of weak avalanche modeling of high breakdown devices [7].

Stepped and spiked collector dopings are being used to optimize the linearity of large signal response [12]. Part of this improvement arises from tailoring the bias dependence of the base-collector depletion capacitance. The standard $1/(1-V/p)^m$ model is not able to comprehend these types of collector profiles. Given that the doping profiles can be rather arbitrary, it is difficult to formulate a physically based capacitance model applicable to all types of profiles. VBICv1.3 therefore has an empirical collector doping model, which modulates the standard $1/(1-V/p)^m$ formulation. Details will provided elsewhere.

Thermal admittance extraction over frequency has shown that the single time constant self-heating model does not capture fine details of the frequency dependence of self-heating [13]. A more complex thermal model has not been added to VBICv1.3. This is because this introduces extra system variables into the model, which increases simulation time. The thermal time constants generally affect behavior at much lower frequencies than signal levels, so getting self-heating correctly at DC for biasing and at signal frequencies is what is important. The single time constant model is accurate for both of these. If accurate modeling is required at frequencies where the self-heating frequency response is not well modeled, this can be done by hooking up an external thermal network to the eternal thermal node of VBIC.

Some vertical PNPs have thin, lightly doped collectors. Besides the depletion pinching effect on R_C noted above, for some structures the base-collector depletion region can push out vertically to the n^+ buried layer that forms the substrate of the device. Unlike the "reach-through" effect in vertical NPNs, where this causes C_{bc} to "pin" at a fixed level, in vertical PNPs is causes the intrinsic vertical component of C_{bc} to drop to near zero. There is still some extrinsic and lateral component, so the total capacitance shows a drop to a finite level, not to zero. This also significantly affects the output characteristics, as the apparent Early voltage appears to increase significantly at the V_{ce} at which reach-through occurs. This effect is being included in VBICv1.3.

Modeling of some other effects not detailed here is also planned.

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