INTEGRATED MODELING OF THE AlGaAs/GaAs HETEROJUNCTION BIPOLAR TRANSISTOR

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A highly accurate and versatile modeling approach is presented for the AlGaAs/GaAs Heterojunction Bipolar Transistor (HBT). This novel method is completely integrated into SPICE-based simulation software, and includes unprecedented consideration of the self-heating based negative transconductance and beta degradation effects, as well as the base-emitter surface recombination current. The new model requires no changes in SPICE device equations and is implemented in a user friendly sub-circuit format, compatible with all commercially available circuit simulation software. The accuracy of the model is based in its rigorous derivation from fundamental HBT device physics. Results are presented that validate both the accuracy and the versatility of the new model.

Thermal effects are very important in HBT devices. Poor thermal conductivity combined with high DC current levels in GaAs devices result in rapid self-heating. SPICE software includes no consideration of self-heating, since it is a minor effect in the traditional Silicon BJT. Modeling of self-heating based effects for the HBT in SPICE are complicated by the facts that mole fraction Aluminum, doping profiles, and base-emitter heterojunction band offsets all play key roles in the thermal behavior of the HBT, and that there is no function to compute power dissipation as a parameter in SPICE. Furthermore, major changes in existing SPICE BJT device equations are not practical due to convergence and source code limitations. Such efforts have been tried with very little success. Finally, the base-emitter surface recombination current plays a very significant role in the HBT operation.

A thorough study of HBT device physics results in the following equation for beta degradation:

$$\beta = \frac{N_e\ v\,(n)b}{P_b\ v\,(p)e}\exp\left[\frac{\Delta E_v + \Delta E_b}{kT}\right] \tag{1}$$

where N and P represent doping levels, v represents velocity, ΔE represents band offsets, and the sub-scripts e and b represent the base and emitter regions, respectively. This equation completely simulates the observed negatively sloping DC I-V characteristics of the HBT device, as verified by an independent software test. Equation (1) demonstrates the desired dependence on doping levels, material system properties, and band offsets. The negative transconductance effect, which causes a degradation in the slope of the Gummel curve for the HBT, is modeled by a temperature dependent thermal resistance, defined by:

$$R_2(T) = R_{20} + \frac{dR_2(T)}{dT}\left(T - T_{amb}\right) \tag{2}$$

and an additional base-emitter diode, D_2, to model the added power consumed in $R_2(T)$. Finally, a representative equation for the complex base-emitter surface recombination current is:

$$I_{sp} = I_1 \exp\left[-q\frac{V_{be}}{mkT}\right], \qquad I_1 = qP_e v_0 L_s n_i \tag{3}$$

which strongly resembles the current equation for a diode.

The successful implementation of these device equations into a SPICE sub-circuit relies on finding representative models for each effect, and the development of a functional thermal sub-circuit to compute self-heating. A novel, ladder type thermal sub-circuit is created using dependent current and voltage sources in SPICE to model HBT current and voltages. The output of this sub-circuit is a voltage that models the rising temperature of the HBT, and serves as an input for the device equations above. The beta degradation effect is modeled by negative feedback dependent current and voltage sources from base to emitter, given in SPICE code for immediate integration as:

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gfeedback    base emitter    vol='1/(exp((DEV + DEB)/(VT*(V(THERM)/TAMB))))'     (4)
efeedback    bext bb         vol='abs(((V(bext)*V(THERM))/V(GABY)))/TAMB)'       (5)
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The negative transconductance is modeled by a thermal resistance and an external base-emitter diode. Finally, the base-emitter surface recombination current is modeled by an external emitter resistance, and an external base-emitter diode with resistance. The complete HBT sub-circuit is seen in Figure 1 below.

This brand new sub-circuit is an extremely significant accomplishment. Its features include true modeling of self-heating, and important HBT effects based on device physics, including consideration of the very important emitter spike and band offsets in the emitter-base heterojunction. All device parameters are left as user defined values. This sub-circuit is easily integrated into SPICE software, and works around the existing BJT model for complete DC and AC simulation. This model is useful in VLSI HBT design, as well as device modeling and single transistor applications. Results are presented to demonstrate accuracy.

Characteristic transistor curves are presented versus measured data for the Rockwell HBT device. Figure 2 shows the measured and simulated Gummel Curve for the Rockwell HBT, and the DC I-V curves are seen in Figure 3. Both results show unprecedented accuracy in the simulation of the AlGaAs/GaAs HBT device. Such tests are run for many common HBT structures. Circuit applications are also tested to show that there are no "lag-time" or convergence problems in integrated applications. A 3-input Exclusive OR circuit is successfully tested, as will as a low-noise amplifier and a VCS generator. All show simulated results that correspond exactly to measured values.

A truly integrated modeling approach and sub-circuit are presented for the AlGaAs/GaAs HBT. This approach is very efficient and accurate, and useful for VLSI circuit simulation as well as device modeling. As communications circuitry edges closer to wireless, photonic implementations, this model will be infinitely valuable in integrated HBT circuit design. Over and above what is discussed herein, this model includes complete consideration of optical effects and has been used with accuracy to model the photonic properties of the HBT in purely optical as well as opto-electronic circuit implementations. These results are not discussed here for brevity, but will be presented in detail. This model is a giant step towards complete opto-electronic circuit integration and design.

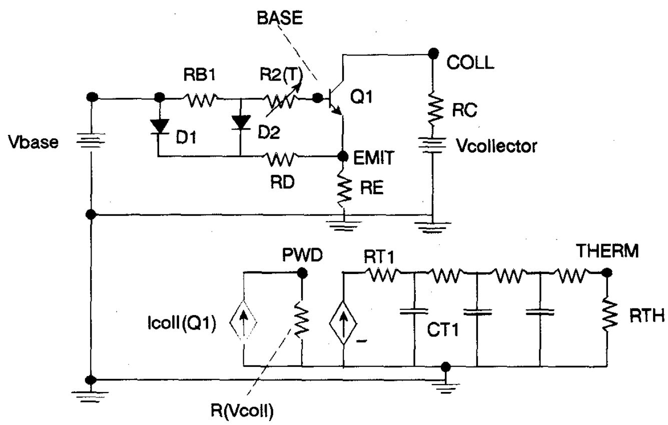

Figure 1 Complete Equivalent Sub-circuit of the HBT Device for Immediate SPICE Integration. The Thermal Sub-circuit is shown here also, and the dependent sources from base to emitter are not shown but given as defined in Eqtns 4 & 5.

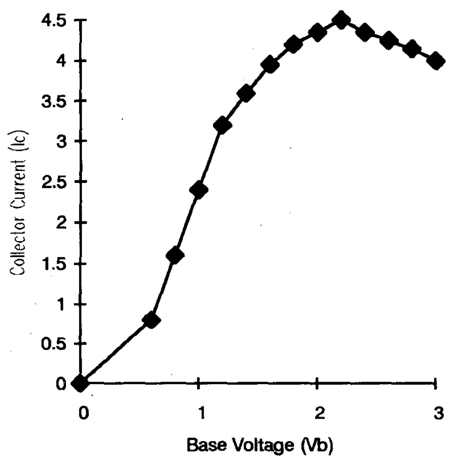

Figure 2 Measured and Simulated Gummel Curve for the Rockwell HBT Device. This Curve shows the negative transconductance effect.

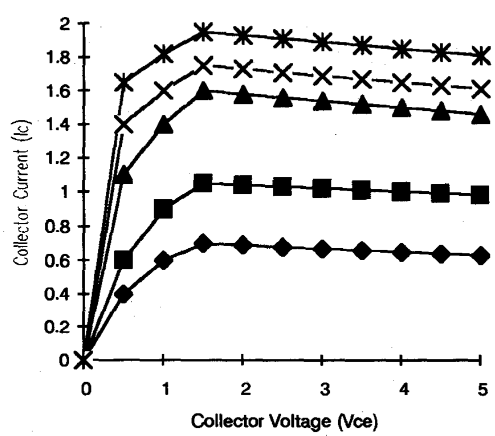

Figure 3 Measured and Simulated DC I-V Curves for the Rockwell HBT. These Curves demonstrate all three modeled effects with great accuracy.