Large Signal Evaluation of Nonlinear HBT Model

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ABSTRACT — The recently developed LS HBT model was evaluated with extensive Power spectrum, Load pull and Inter-modulation investigations. Some changes of the model were implemented in ADS as SDD. Important future of the model is that the model parameters are organized to use directly measured parameters in rather simple and understandable way. Modeling results were compared with multiple DC, S-parameters and LS data and show good accuracy despite the simplicity of the model. To our knowledge the HBT model is one of the few HBT models which can handle high current & Power HBT devices, with significantly less model parameters and good accuracy.

1. 1. HBT Thermal dependence
The characteristics of all HBT are quite sensitive to the temperature changes[1-22]. A careful thermal layout design, use of good quality via and thick air bridges improves the thermal stability and reduces some problems like current collapse. The thermal modelling problem is becoming difficult when the dissipating power is more than 0.5 w and very few HBT models can handle this at all. This is reflected in the published literature- we rarely see results of modelling HBT devices with currents above 0.5A and powers above 1W in published papers.

Often the device is biased with the fixed base current. The devices with small amount of fingers are thermally stable up till the maximum dissipating power they can handle from reliability (junction temperature) itself and using FG data for extraction will give us a higher accuracy at low dissipated power at the junction BC and lower BC junction temperature. If we want to have a higher accuracy for the practical currents and power we can use the FG data for preliminary extraction and then refine the temperature coefficients to provide a good fit in the FE condition at high dissipated power close to condition we will operate the device.

Leakage temperature dependence.

Because materials are not ideal we will always have some residual small currents, when the device is biased at the pinch – off. Typically the residual current in the pinch-off region for a good quality process is less then10^-10and it is exponentially dependent with the temperature.

Fig. 1 show measured and modeled leakage. This exponential dependence can be modeled as addition or modification of the current source, but it is more stable in the simulations and easier to understand & extract if we model the leakage as a temperature dependent resistor.

Following equations are proposed and implemented in ADS to model the temperature dependence of these:

\[ R_{\text{leak}} = T_{\text{anark}} - R_c R_t \]

\[ R_{\text{leak}} = 1/(0.00001 + \exp(-T_{\text{total}} \cdot DT)) \]

The Rleak is the corresponding leakages, RleakBe,Bc,Ce measured at room temperature and a small number is added to the denominators to improve the numerical stability. The leakages are available from the FG and RG measurements, but even an ohmmeter will give values good enough.

2 Model implementation in ADS

\[ y = (V_{\text{bc}}/V_{\text{JC}} \cdot x - z) = (V_{\text{bc}}/V_{\text{JC}} - 1) \]

\[ C_{\text{bedep}} = (m + y^2)/(-1 - M\text{JC}) \cdot (m + 1 - 2\text{MJC}) \cdot y^2 \]

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\[ C_{\text{bedep}} = C_{\text{bedep}}^\ast \cdot (1 + 1/(\text{C}_{\text{dep}}/(\exp(V_{\text{bc}}/V_{\text{Cm}})))) \]

\[ + C_{\text{dep}} \cdot \exp((19.347/N_{\text{c}}) \cdot \tanh(V_{\text{bc}}/V_{\text{JC}}))) \]

\[ th1 = ((1.00001 + \tan(P1 \cdot *(V_{\text{bc}}/P10))) \]

\[ C_{\text{sh}} = C_{\text{sh}} \ast (A * th1 + C_{\text{shdep}}) \]

\[ + C_{\text{shp}} \cdot C_{\text{sh}} \ast \text{th2} = ((1.00001 + \tan(P2 \cdot *(V_{\text{bc}}/P20))) \]

\[ C_{\text{sh}} = C_{\text{sh}} \ast (A * th2 + C_{\text{shdep}}) \cdot C_{\text{shp}} \]

Several changes were made in the model implementation to reflect the refined temperature dependencies. The equations for the temperature dependent leakage and capacitance equations were refined to provide convenience and easier fit.

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**Fig. 1** Leakage temperature dependence. **Fig. 2** Ice vs. Vce FE

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3DC and S-parameters. In the following figures are shown some results from the IV and S-parameter evaluation for 2 and 8 finger devices whose emitter sizes are 80 um². Measured DC S-parameter biases are simulated and available in the ADS project already delivered. Generally the 2 finger device shows better accuracy as it is expected (it is simpler, the thermal distribution is better), but for both transistor overall accuracy is good for these rather high current devices. The model is able to predict such fine details as the loops in S12 and S22 as in Fig.3 at high voltage.

Fig. 3 Evaluation of the model with Power Spectrum measurements.

Power spectrum (PS) measurement is very important tool for evaluation of large signal models. It is rather easy to assemble the PS measurements set-up - it consists of general set of measurement equipment like input sweeper (synthesizer) and harmonic measurements equipment. It is important to provide a good 50 ohm match for the fundamental and harmonics that is why it is recommended to use decoupling attenuators connected directly at the bias tees close to the device. In the following figures are shown the equivalent circuit of the measurements and simulations Fig.5,6 and results of the PS evaluation.

Generally, if the model provides a good accuracy in modeling IV characteristic this is a good sign, which means that the model should be able to predict the fundamental power quite accurately. The harmonic content is much more difficult to model accurately for various reasons. Harmonics generation is critically dependent on the intrinsic Junction voltage, Leakage and Device Junction Temperature, Ideality factor etc. If for some reasons there is a change in some of these parameters this will lead to very different results in the measured and correspondence with simulated harmonics. The simplest reason for the difference is, if one device is used for model extraction and other was mounted and measured with PS or load pull measurements system. In the Fig 6-8 are shown measured and simulated PS for different bias conditions for the 2 and 8 finger devices. Generally the model describes the PS with accuracy good for practical purposes.

For the smaller device as expected the accuracy is better. To our knowledge it is not existing simple HBT model which can describe the PS with better accuracy. The accuracy is comparable with what can be obtained from FET models, but FET is easier to model. Load-pull measurements will be much more sensitive to the actual temperature, thermal resistance, biasing conditions and device parameter tolerances, because in this case the impedance is very different from 50-ohm at fundamental and harmonics.

Fig. 4 Load Pull Evaluation of the model

In order to improve the accuracy of the PS measurements and evaluate the sensitivity of the generated harmonic content to the impedance the device actually face a new set of measurements was performed. The impedances at the input and output were precisely measured and later used in the simulations. I.e. in the corrected PS simulations set-up, Fig.5,6 measured input and output impedance were used. As expected, the accuracy is much better with corrected impedances with accuracy surpassing the accuracy we have seen published on HBT models. Device is biased in two modes - with voltage source at the input and outputs and with current source at the output and floating base at the input. The bias conditions in the current mode are difficult to reproduce in the simulator, but for the voltage source biasing quite reasonable results are obtained.

Fig 5 Load-pull evaluation measurements and simulations.

6 Inter-modulations measurements and simulations.

Fig. 7, 8 shows measured and modeled IMD3. The accuracy of IMD simulations is better then the typical accuracy you can get from the IMD3 simulations for high current HBT. The reason for this is that the currents in our model are precisely defined and derivatives are exponential anyway. As can be seen from the waveforms, the voltage swing is rather high and reaching nearly 5V. This means that if we want our model to be more accurate in practical biasing conditions, some data should be available for high Vce or LSVNA measurements. The convergence of the HBT model is good, considering that quite often there are convergence problems with IMD simulations with any large signal model. We can greatly improve the accuracy of the predictions if we use on-wafer measurements to verify the IMD3 generated correctly. In this case we exclude the bonding inductances and pads from elements creating problems which sacrifice the accuracy.

REFERENCES