Large Signal Evaluation of Nonlinear HBT Model

I.Angelov[1], A.Inoue[2], S. Watanabe[2]

1Chalmers University of Technology, Microwave Electronics Laboratory, SE 412 96 Göteborg, Sweden

2 High Frequency & Optical Device Works R&D Dept.
Mitsubishi Electric Corporation
4-1 Mizuhara Itami City Hyogo 664-8641 JAPAN

***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 made, like improved temperature, leakage resistance and capacitance models. The corresponding changes 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 with good accuracy.**

I. 1.1 HBT Thermal dependence

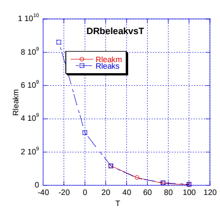
The characteristics of all HBT are quite sensitive to the temperature changes[1-22]. A careful thermal layout design, use of good quality via and thick air bridges improves the thermal stability and reduces some problems like current collapse. The thermal modelling problem is becoming difficult when 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 dissipated power they can handle from reliability (&junction temperature point of view). In this case with fixed Ibe biasing the Ice is gradually decreasing at high dissipating power. The decrease of Ice is very small for low dissipated power Pdc <100mW and it is more severe for high dissipating powers, as can be seen from Fig.1. The slope of Ice vs. Vce will depend on the thermal resistance- with high thermal resistance we can get a significant reduction of Ice. The bipolar transistors are voltage control devices with exponential dependence on the controlling voltage Vbe and when current source is used for Ibe, the base voltage required to sustain the base current is reduced when the dissipated power or temperature is increased, Fig.2.

If the device is biased with a voltage source Vbe, increasing the dissipated power will change the junction temperature and we will observe exponential increase of Ice. The slope of this increase is determined by the thermal coefficient of Vbe and the thermal resistance. When the thermal resistance is high and the device is biased with pulses comparable with the thermal constant Rtherm. Cthermal, the current compliance should be fast enough to keep the device undamaged.

In RF applications when we very quickly swing the device from pinch off to high currents such a mode of biasing with voltage source Vbe can be beneficial to obtain high power and efficiency. This mode can be used in the final stages to boost the efficiency, but the self-biasing should be carefully designed. A problem with the extracted coefficient can be that fact that thermal resistance is a function of the temperature(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.



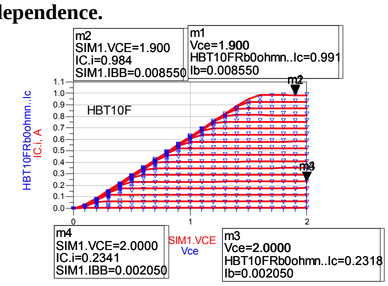


Fig. 1 Leakage temperature dependence. Fig.2 Ice vs. Vce FE

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:

$DT_{JL}=T_{chanK}-T_{refK};$

$R_{leakti}=R_{leaki}*(1/(0.00001+\exp(-T_{cRleaki}*DT_{JL})))$

The Rleaki are 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.

2Model implementation in ADS

$y=((V_{bec}/VJC) -1);z=((V_{bcc}/VJC)-1)$

$C_{bedepl}=((m+y\hat{}2)\hat{}(-1-MJC))*(m+(1-2*MJC)*y\hat{}2)$

$C_{bcdepl}=((m+z\hat{}2)\hat{}(-1-MJC))*(m+(1 -2*MJC)*z\hat{}2)$

$C_{bcdepl1}=C_{bcdepl}*(1+1*(C_{dep1}/(\exp(V_{bec}-V_{cmin}))$

$+C_{dep2}*\exp((19.347/N_{cf1})*\tanh(V_{bec}-VJC))))$

$th1=((1.00001+\tanh(P_{11}*(V_{bec}-P_{10}))))$

$C_{be}=C_{be0T}*(A*th1+C_{bedepl})+C_{bepi};C_{bcdif}=C_{bc0T}*th2$

$th2=((1.00001+\tanh(P_{21}*(V_{bcc}-P_{20}))))$

$C_{bc}=C_{bc0T}*(A*t_{h2}+C_{bcdepl})+C_{bcpi}$

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

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 um^2. 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.

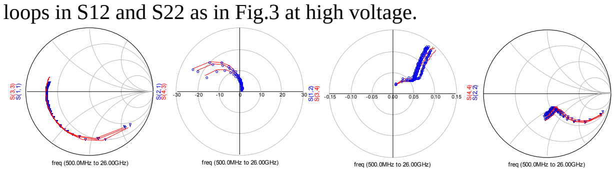


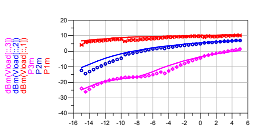
Fig.3 S-parameter Ice vs. Vce Ibe parameter 2finger Vc=3V

4Evaluation 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.



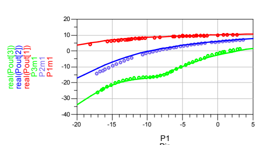


Fig.4 PS e Vce=3V Ibe 50uA Fig.5 PS Vc3v;Ib100um

5Load 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.

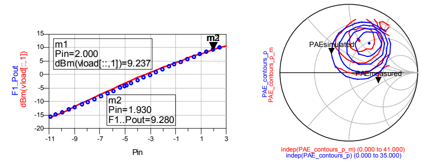
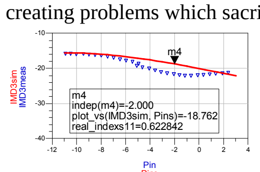


Fig 6 Load-pull evaluation measurements and simulations.

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.



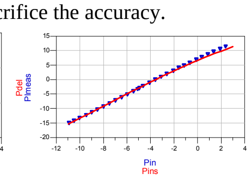


Fig.7. Meas &simulated IMD3 Fig.8. IMD, Meas &simulated Power

The junction temperature Tj is very important for the IMD3 measurements and simulations. Tj is influenced by the thermal resistance of mounting structure and power dissipation. The respective DC current and Tj depend on the load and mounting structure &transistor parameter tolerances. Even simple combination of small tolerances can change the shape of IMD3 dependence and produce error more then 3 dB. A problem which can critically influence the reliability and affect the accuracy of the simulations is the temperature distribution in the chip and difference in the temperature of the fingers. Probably, the lower accuracy in the simulations is not as important as the fact that when hot spots are formed> this is critical for the reliability.

Conclusions.

The HBT model developed jointly between Chalmers and Mitsubishi was evaluated at different temperatures with extensive DC, S-parameter and Large signal measurements. The measurements and simulations were performed on several device sizes. Using these results some model parameters like temperature dependencies, leakages, capacitance model implementation were refined. The model is very compact, with minimum model parameters, but shows very good accuracy despite its simplicity. To our knowledge this is one the very few models that can handle large current & power devices with similar accuracy. The reason for this good accuracy is that the model is mathematically defined in the bias range we practically use the device.

REFERENCES

1. P. C. Grossman at all. "Large Signal Modelling of HBT Including Self—heating and Transit time Effects," MTT, Vol. 40, N.3, March 1992, pp.449-464.

2. Colin et al., "VBIC95, The Vertical Bipolar Inter Company Model," IEEE J. SSC, Vol. 31, N. 10, Oct. 1996, pp.1475-1483

3. R. Anholt, "Electrical and Thermal Characterization of MESFET's HEMTs, and HBTs," Artech House, Boston, 1995.

4. Ke Lu, at all"A new Large Signal AlGaAs/GaAs HBT Model including Self-heating Effects, With Corresponding Parameter Extraction Procedure," IEEE Trans. MTT, Vol.43, N.7, July 1995, pp.1433-1445.

5. Lovell, H Camnitz et al., "An accurate large Signal High Frequency Model for GaAs HBT," GaAs IC Symposium, 1996, pp. 303-306.