Verification of a Foundry-Developed Transistor Model Including Measurement Uncertainty

Dylan Williams,[1] Wei Zhao, [1] Richard A. Chamberlin, [1] Jerome Cheron, [1] and Miguel Urteaga[2]

[1]National Institute of Standards and Technology

[2]Teledyne Scientific

Abstract — We verify a foundry model for state-of-the-art 250 nm heterojunction bipolar transistors with large-signal measurements. We demonstrate the propagation of correlated measurement uncertainties through the verification process, and use them to quantify the differences we observe in the measurements and models.

Index Terms — Model, transistor, measurement.

I. Introduction

We propagate the uncertainty in large-signal measurements through a transistor-model verification process, and use those uncertainties to better quantify the differences in our measurements and simulations. This gives us far greater insight into the model and how well it performs under large-signal operating conditions.

Practical limitations always restrict the data sets used in even the most comprehensive transistor-model extraction procedures. Compact models such as the foundry model studied here are designed to capture the essential physics governing the transistor's behavior and to be used well outside the space of measurements used in the extraction process. Nevertheless, we neeed to verify the model in regions of operation not used in the extraction process.

Measurement uncertainties are not usually considered in the verification process. This leaves open the possibility that observed differences between the actual and predicted behavior of the transistor in the verification process are due to measurement error, and not to process variations or the inability of the model to predict the transistor behavior in regions of operation not used in the extraction process.

A number of authors have studied two-tier approaches [1-5] and parasitic extraction techniques [5-8] to improve transistor characterization. Lenk and Rudolph performed a very interesting sensitivity analysis of an heterojunction bipolar transistor (HBT) extraction process in [9]. They used it as a tool for evaluating the sensitivity of the extraction process to measurement error and identifying poorly conditioned models. Miranda *et al*. studied the impact of on-wafer calibration kits on the extraction of HEMT models at microwave frequencies in [10]. Williams *et al*. argue that on-wafer thru-reflect-line calibrations improve the accuracy of HBT and CMOS transistor measurements in [11;12].

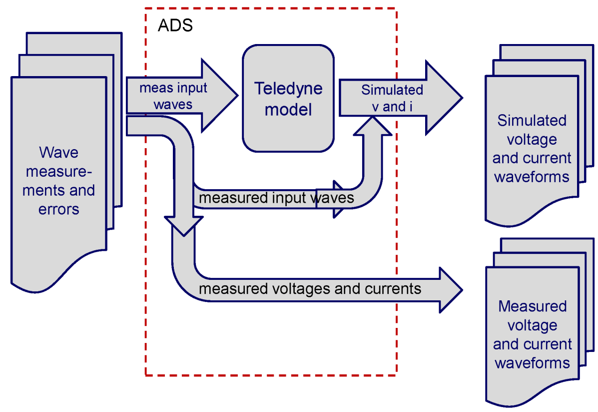

Fig. 1. The verification approach. We programmed ADS to read in the measured wave parameters, simulate the response of the Teledyne HBT model to the input waves, and convert the input and output waves to voltage and current waveforms.

Here, we propagate measurement uncertainties through the process of verifying the large-signal performance of a compact Keysight[1] HBT model [13] derived from DC and small-signal measurements. We use the uncertainty information to better quantify the results of the comparisons between measurements and models.

II. Model Verification

The transistors we studied were fabricated at Teledyne Scientific with a state-of-the-art 250 nm HBT process. Teledyne Scientific provided a model for the transistors based on version 2.0 of the Keysight HBT model (see [13]) implemented in their Advanced Design System (ADS) software, and included that model in their design kit. The

[1] We identify commercial products only to accurately describe the experiments and analysis we performed. The National Institute of Standards and Technology does not endorse commercial products. Other products may work as well or better.

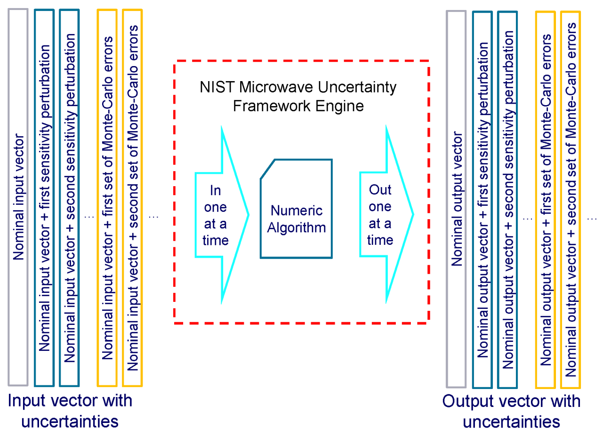

Fig. 2. Approach used for uncertainty propagation by the NIST Microwave Uncertainty Framework.

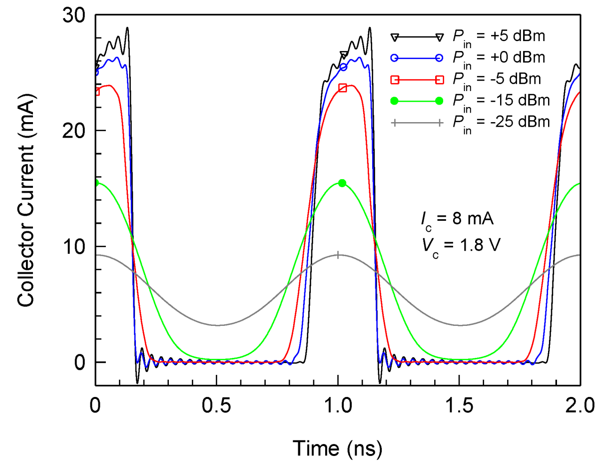

Fig. 3. Representative plots of collector current as a function of 1 GHz drive level.

parameters used in the model were extracted at Teledyne Scientific from DC and small-signal measurements with a proprietary approach.

Here we verify the ability of the Teledyne model to predict the behavior of an HBT with a 6 µm by 250 nm emitter under large-signal excitation, and evaluate the impact of measurement errors on the verification process. By propagating our measurement uncertainties through the verification process, we are able to show when the differences in the transistor behavior predicted by the Teledyne model and the transistor behavior we observed in the verification process were significant and when they were not.

Figure 1 illustrates the approach we took to verify the large-signal performance of the transistor model obtained from Teledyne Scientific. We used a Keysight PNA-X Vector Network Analyzer to excite the transistor in a common-emitter configuration with a 1 GHz sine wave and drive it into a large-signal operating state. We also used the analyzer to measure the incoming and outgoing waves from 1 GHz to 25 GHz at an on-wafer reference plane next to the transistor as a function of the transistor's DC bias state and the drive level of the 1 GHz fundamental. Finally, we used the Keysight ADS software package to emulate our measurement setup, and drive the transistor model with the same incoming waves we measured. We then calculated the voltage and current waveforms at the transistor terminals from our measurements and simulations. Finally, we compared our measured and simulated voltage and current waveforms to each other.

We used the thru-reflect-line calibrations described in [11;14] throughout to ensure the highest accuracy possible and to simplify the uncertainty analysis.

III. Uncertainty Propagation

We used the NIST Microwave Uncertainty Framework [15] to propagate our measurement uncertainties through the model verification process. This allowed us to track and account for correlations in the measured and simulated voltage and current waveforms we compared.

Figure 2 illustrates how the Microwave Uncertainty Framework accomplishes this with a single input and a single output.[2] At each stage of the calculation, each result and its uncertainty is represented by a single vector containing a nominal measurement or simulation result, a series of vectors containing measured or simulated results from a sensitivity analysis, and a series of vectors containing measured or simulated results from a Monte-Carlo simulation. Depending on the stage of the analysis, these vectors contained lists of complex wave parameters measured by the vector network analyzer at the 25 harmonics of the 1 GHz drive frequency, temporal voltage or current waveforms at the transistor terminals, or various metrics determined from these waveforms. This structure maintains correlations between the measurements we performed at different frequencies throughout the analysis.

Over 400 sources of uncertainty were required in the uncertainty analysis to separately capture all of the individual error mechanisms in the measurements.[3] Each of these

[2] The NIST Microwave Uncertainty Framework allows for multiple inputs as well, and includes algorithms for ensuring that elements in the sensitivity analysis are not double counted.

[3] Independent sources of uncertainties cannot in general be combined if all of the correlations are not captured, as it is difficult to predict how correlated uncertainties will add after various transformations are applied to the measurements.

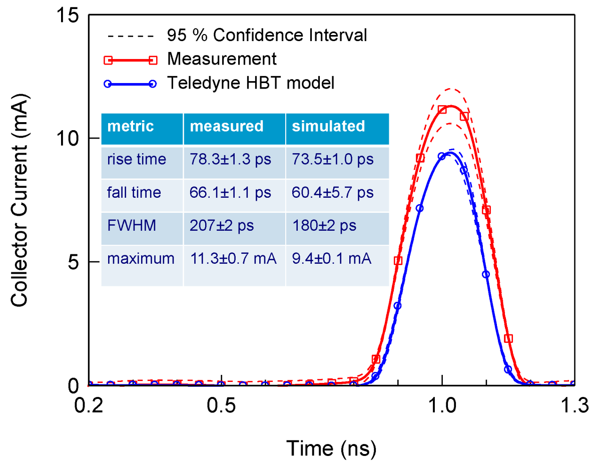

Fig. 4. Transistor collector current, pulse parameters and uncertainties in deep class A/B at a -5 dBm drive level with bias $V_c = 1$ V and $I_c = 2$ mA. Except for an overall scaling factor, the simulates and measured collector-current waveforms are qualitatively quite similar.

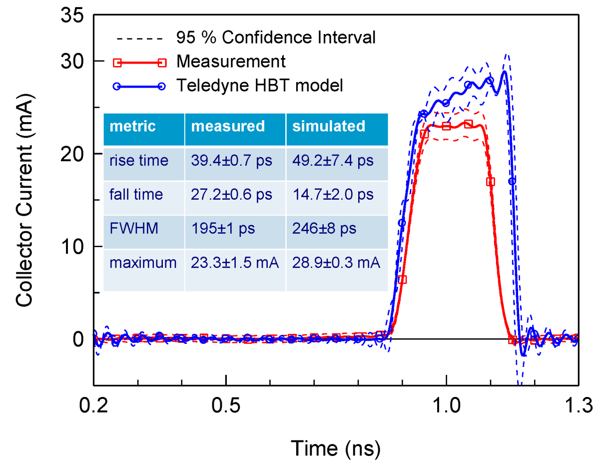

Fig. 5. Transistor collector current, pulse parameters and uncertainties in deep compression at a +5 dBm drive level with bias $V_c = 1.8$ V and $I_c = 8$ mA. The differences in the shapes of the measured and simulated collector-current waveforms are much greater in deep compression.

uncertainty sources was assigned a unique name. These names were used by the Microwave Uncertainty Framework to "turn on" each error mechanism once and only once at each stage of the sensitivity analysis.

The Uncertainty Framework also generates unique seeds for use in the Monte-Carlo analyses. This allows the uncertainties for each error mechanism to be generated separately in different parts of the analysis and still be properly correlated when combined later into a single result.

This attention to correlations is important in this application. The errors in measuring the amplitudes and phases of the incoming waves during the model verification must be propagated through the simulation process before the simulated voltages and currents can be calculated and compared with the measured voltage and current waveforms at the transistor terminals. In addition, the correlations with frequency must be maintained as well if they are to be propagated through the Fourier transform to generate temporal results and to the various metrics we will compare later.

IV. Verification Results

We varied the 1 GHz drive level from -25 dBm to + 5 dBm and performed large-signal measurements at a number of bias states to explore the behavior of the model provided by Teledyne Scientific. Figure 3 plots the collector currents we measured as a function of the drive level.

We found excellent agreement between the measured and predicted base and collector voltage and current waveforms up to a transistor drive level of about -5 dBm. Figure 4 compares the collector current we measured at a drive level of -5 dBm with the predictions from the Teledyne model, and illustrates good agreement in deep class AB. The transistor drive level is high enough that the collector current pulses on and off rapidly as the transistor turns on. Yet the Teledyne model predicted very similar performance within what appears to be a fairly modest scaling factor that might be attributable to differences in process variations.

Nevertheless, the table in the inset reveals some statistically significant differences in the collector-current rise time and full-width-half-max not immediately obvious from the nominal values and uncertainties plotted in the graph. This illustrates how propagating measurement uncertainties can aid in the analysis of the verification results.

Figure 5 compares a measured collector-current waveform in deep compression at a drive level of +5 dBm with the current predicted by the Teledyne model. Here, we see much larger discrepancies.[4] Not only have the differences between the collector-current rise times and the full-width-half-max grown significantly, as we might have expected from the statistics in the inset in Fig. 5, but there is a large reduction in the simulated collector-current fall time that was not evident in Fig. 5.

V. Conclusion

We verified the ability of the HBT models provided with the Teledyne Scientific design kits for their 250 nm HBT process to accurately predict HBT performance under large-signal operating conditions. We also eliminated our measurement

[4] The ringing with an approximately 0.05 ns period in the Teledyne model is due to the 25 harmonics we used in the measurements and simulations. While we were capable of including more harmonics in the harmonic-balance simulations performed by ADS, we found convergence difficult when we increased the number of harmonics beyond 25. We ignored this ringing in our analysis.

uncertainty as a significant contributor to the differences we observed at very high drive levels.

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