The Role of Measurement Uncertainty in Achieving First-Pass Design Success

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Abstract— **We investigate the role of measurement uncertainty in achieving first-pass design success at microwave frequencies. We develop a model for state-of-the-art 250 nm heterojunction bipolar transistors, and demonstrate the propagation of correlated measurement uncertainties through the model-extraction and verification process. We then investigate the accuracy of the extracted model parameters and the role of measurement uncertainty in gauging the ability of the model to predict the behavior of the transistor in large-signal operating states.**

***Index Terms*—measurement uncertainty, microwave measurement, model verification, transistor model.**

I. INTRODUCTION

COMPACT models are designed to capture the essential physics governing a transistor's behavior and to be used well outside the space of measurements used in the model-parameter extraction process. Nevertheless, practical limitations always restrict the data sets used in even the most comprehensive transistor-model extraction procedures, and models are often used well outside of the operating conditions under which they were developed. Here, we investigate the role of uncertainty in microwave measurements used to extract model parameters that are later used to predict transistor behavior outside of the measurement space.

A number of authors have studied two-tier approaches [1-5] and parasitic extraction techniques [5-8] to improve transistor characterization. Lin and Zhang studied error propagation in large-signal network analysis in [9]. Lenk and Rudolph performed a very interesting sensitivity analysis of a heterojunction bipolar transistor (HBT) extraction process in [10]. 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 high-electron-mobility-transistor (HEMT) models at microwave frequencies in [11]. Williams *et al*. argue that on-wafer thru-reflect-line calibrations improve the accuracy of HBT and complementary-metal-oxide (CMOS) transistor measurements in [12;13].

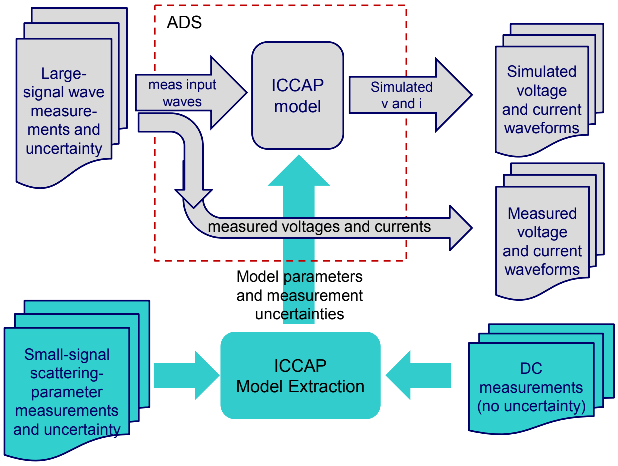

Fig. 1. Our extraction and verification approach. Measurement uncertainties were accounted for in both the model-extraction and verification procedures. From [16].

Avolio *et al.* examined the impact of measurement uncertainty on transistor capacitances and the temporal current and voltage waveforms and impedances at the transistor current-generator plane in [14], and used the measurements to develop a measurement-based transistor model.

In [15;16], we demonstrated the propagation of measurement uncertainty through the model-extraction process, and compared the measured behavior of the transistor under large-signal operating conditions to its simulated performance.

II. MODEL EXTRACTION

Figure 1 shows the model-verification procedure we used in our prior work [16]. The transistors we studied were

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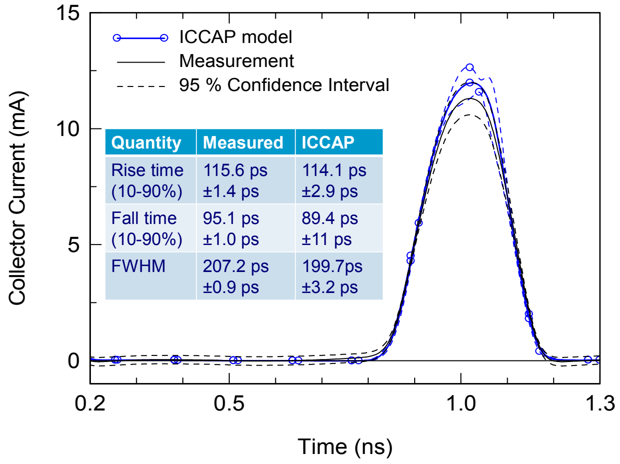

Quantity	Measured	ICCAP
Rise time (10-90%)	115.6 ps ±1.4 ps	114.1 ps ±2.9 ps
Fall time (10-90%)	95.1 ps ±1.0 ps	89.4 ps ±11 ps
FWHM	207.2 ps ±0.9 ps	199.7ps ±3.2 ps

Fig. 2. 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. After [16].

fabricated at Teledyne Scientific with a state-of-the-art 250 nm HBT process. We extracted a model based on version 2.0 of the Keysight[1] HBT model using the Keysight Integrated-Circuit Characterization and Analysis Program (ICCAP) software. implemented in their Advanced Design System (ADS) software (see [17]). In [16], we were able to 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 to evaluate the impact of measurement errors on the verification procedure.

A. Calibration

In prior work [18;19], we found that accurate calibrations improve the model extraction process. We used the custom thru-reflect-line (TRL) on-wafer calibration kit described in [20] to calibrate the scattering-parameters and wave parameters measured in this study. We had two reasons for this choice.

First, we have shown in prior work that on-wafer TRL calibration kits allow the measurement reference plane to be moved right next to the transistor under test. In this way, parasitics associated with the contact pads and access line can be removed from the scattering-parameter calibrations and the voltages and currents at the transistor terminals can be measured with greater fidelity than is possible with other methods.

Second, the TRL calibration is based on transmission-line propagation. It rigorously solves for forward and backward-wave amplitudes, and then constructs voltages and current waveforms from those amplitudes in a clearly defined way. As a result, the systematic errors of the TRL calibration are few and are easily characterized with simple, well-understood models. This made it much easier for us to identify and track correlations in measurement uncertainty throughout the analysis.

We also used a conventional first-tier 2.4 mm short-open-load-thru (SOLT) calibration to perform the power and phase calibrations needed to fix the wave amplitudes and phases of the large-signal measurements we made. Both the 2.4 mm SOLT and the on-wafer TRL calibrations were implemented in the NIST Microwave Uncertainty Framework [21], which we used to model measurement errors and propagate them through the calibration and analysis.

B. Uncertainty Propagation Through the ICCAP Model-Extraction Procedure

No measurements are perfect, including the small-signal measurements we used in the ICCAP procedure to extract the HBT model parameters. The errors in these measurements will add error to the HBT model parameters extracted by ICCAP.

We used the NIST Microwave Uncertainty Framework [21] not only to estimate our measurement errors, but also to propagate our measurement uncertainties through the ICCAP model-extraction procedure. That allowed us to estimate the uncertainties of the model parameters determined by ICCAP due to the errors in the measurements used in the model-parameter extraction procedure. Table I lists a few representative parameters and their uncertainties.

The table shows that ICCAP did a good job of extracting model parameters like the transistor's saturation current IS, collector capacitance CJC, and low-current transit time TFC0 despite the errors in the small-signal measurements that we used in the extraction procedure. These parameters are needed to simulate small-signal and high-frequency transistor behavior, as well as transit times when current flow through the transistor is low.

However, Table I also reveals that the ICCAP extraction procedure did not do nearly as good a job of determining the high-current transit time TCMIN from our measured data, and completely failed to determine the Kirk-effect critical current IKRK accurately. These model parameters are used to calculate transit times when current flow through the transistor is very high.

III. MODEL VERIFICATION

The uncertainties listed in Table I indicate that we expect the ICCAP model to accurately predict small-signal performance, but not transistor behavior in large-signal operating states that drive currents in the Kirk-effect region. To test this, we measured the response of our HBTs to a 1 GHz drive signal under large-signal operating conditions at a number of bias states. We varied the drive level of that signal

TABLE I
EXTRACTED ICCAP MODEL PARAMETERS

Parameter	Units	Nominal Value	Standard Uncertainty	Relative Uncertainty
IS	fA	1.39	± 0.09	6 %
CJC	fF	12.1	± 1.1	9 %
TFC0	fs	355	± 55	15 %
TCMIN	fs	74	± 43	58 %
IKRK	mA	46	± 161	350 %

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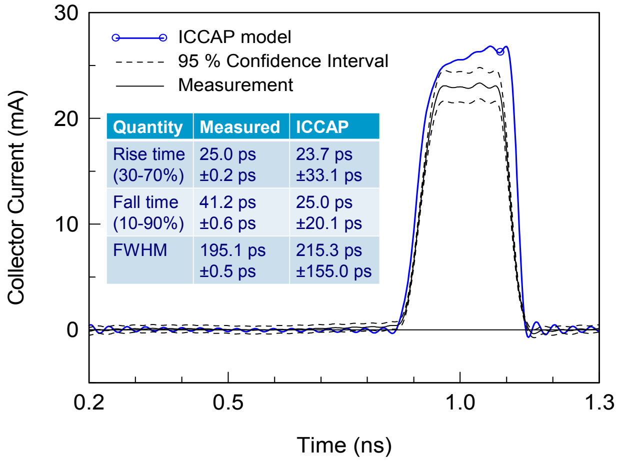
[1] We identify commercial products only to accurately describe the experiments and analysis we performed. The National Institute of Standards and Technology does not endorse commercial products. Other products may work as well or better.



Quantity	Measured	ICCAP
Rise time (30-70%)	25.0 ps ±0.2 ps	23.7 ps ±33.1 ps
Fall time (10-90%)	41.2 ps ±0.6 ps	25.0 ps ±20.1 ps
FWHM	195.1 ps ±0.5 ps	215.3 ps ±155.0 ps

Fig. 3. 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. The uncertainties in the collector current derived from simulations based on the ICCAP model are shown in Fig. 4 for clarity. After [16].

from -25 dBm to + 5 dBm, sweeping through regions of linear operation, deep class A/B operation, and finally, deep compression where we expect the Kirk effect to become important.

A. *Deep Class A/B Operation*

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 2 shows an example at a -5 dBm drive level, which exhibited the worst performance over this range and corresponds to deep Class AB operation. Furthermore, the differences between the ADS simulations and measurements are comparable to the uncertainties we estimated, and we see that the measurement uncertainty predicts well the performance of the model.

B. *Deep Compression*

When the drive level exceeded 0 dBm, the discrepancies between simulations and our verification measurements became quite noticeable, as we might expect from the uncertainties in Table I. Figure 3 compares the measured collector currents and their uncertainties at a drive level of +5 dBm to ADS simulations based on the two models.

We also see that the simulations fall well outside of the uncertainties of the measured collector-current waveform. The uncertainties in the collector-current rise time, fall time, and full-width-half-max (FWHM) simulated with the ICCAP model as listed in the inset table of Fig. 3 are significantly larger than those shown in Fig. 2.

Figure 4 shows the uncertainty in the collector-current waveform calculated from the ICCAP model, and it is also considerably larger than the uncertainties in Fig. 2. These uncertainties in the simulations based on the ICCAP model seem unexpectedly high, at least when compared to the uncertainties in our measurements.

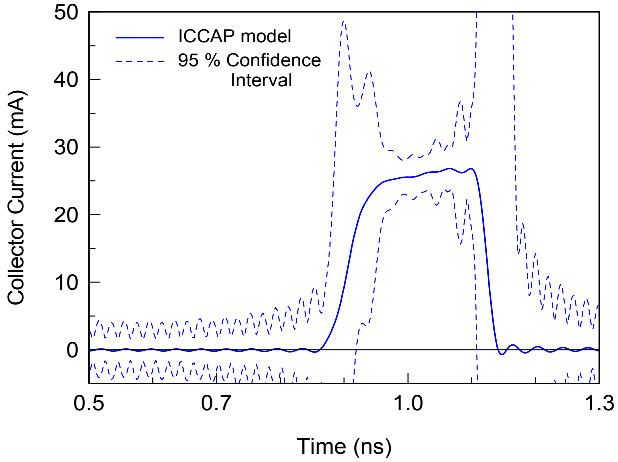


Fig. 4. Uncertainties of the transistor collector-current waveform derived from simulations based on the ICCAP model in deep compression at a +5 dBm drive level with bias $V_c = 1.8$ V and $I_c = 8$ mA. The large uncertainty levels are due in part to instability in the extraction procedure as the model becomes non-physical in the Kirk-effect region. From [16].

C. *Interpretation of Uncertainty in Simulated Results*

The procedure we used in Fig. 1 was designed to propagate our estimates of our small-signal measurement uncertainties through the ICCAP model extraction procedure and our simulations. What we see in Figs. 2-4 is the usefulness of propagating our measurement uncertainty all the way through the simulation process. Here we see that the uncertainty in our simulations due to error in the small-signal measurements used in the model-extraction process is low where we expect the model to perform accurately, but becomes very large when the transistors are driven into operating states that cause the model to fail. This indicates a possible role for measurement uncertainty in predicting first-pass design success that goes well beyond simply increasing confidence in the measurements themselves.

IV. CONCLUSION

We propagated measurement uncertainty through the ICCAP extraction procedure, and assigned uncertainties to the model parameters extracted by ICCAP. This, in turn, led to the identification of the parameters that were determined accurately in the extraction procedure, and which parameters were not.

In this particular case, we found that ICCAP determined most of the parameters of the model quite accurately. However, an examination of the uncertainties in the model parameters we extracted with ICCAP showed that we were not able to accurately determine some parameters in the model needed to characterize the transit time and Kirk effect in deep compression, where the fits used to model the transit time appeared to not be physical.

Later, during the verification stage of the work, we showed that propagating our measurement uncertainty through the simulations allowed us to identify which simulations were accurate and which were not. This points to a possible role for measurement uncertainty in predicting first-pass design success.

A full uncertainty analysis will require adding process variations to the model. This should not be difficult to do in the framework we have adopted for propagating uncertainty. However, additional work will also be required to better quantify errors due to non-physical fits employed in the models, perhaps relying on cross-validation approaches. Even so, we expect to be able to propagate measurement uncertainties all the way through the circuit-design process, and predict the accuracy of circuit simulations based on models extracted from measurement.

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