A Product Engineering Exercise in 6-Sigma Manufacturability: Redesign of a pHEMT Wide-Band LNA

Marcus King, Porter Hull[*], Mark Tanner[*], John Beall, Scott Walthers, Keith Salzman, and Matthew Parker[*]
TriQuint Semiconductor, P.O. Box 833938, Richardson, TX 75083
[*]Raytheon Systems, P.O. Box 660246, M/S 255 Dallas, TX 75266

ABSTRACT

The ability to design any MMIC to meet given performance specifications requires accurate knowledge of the nominal equivalent circuit parameters (ECPs) used to describe the frequency response of the FET building block, and a knowledge of the long-term statistical variation of the ECPs at the bias point of the particular MMIC. Normal SPC control procedures in semiconductor manufacturing accumulate long-term data on DC and RF parameters. The basic DC measurements of the FET building block are relatively easy to maintain, monitor, and characterize for long-term statistical variation. However, resource limitations prevent similar accumulation of RF data for the many different bias conditions used in various MMICs. Instead, long-term RF data are usually accumulated at a fixed bias using FET building blocks included on each wafer.

This paper will describe the application of an alternative scheme to the redesign of a pHEMT wideband distributed LNA, originally designed using a model generated from a small set of FET building blocks. Performance before and after the redesign will be compared. Also, a straightforward scheme for maintaining a long term database of RF performance at standard conditions will be described.

INTRODUCTION

Many designs require bias conditions for FETs that often differ from the bias conditions upon which SPC monitoring is based. Foundry engineers often respond to this situation by spending some effort to quickly measure a sample of devices to determine appropriate ECPs for the design. The particular LNA design that is the subject of this paper demonstrated less than desirable gain performance when a sample approach was used to generate models. Thus, it illustrated that a snapshot approach is prone to at least a couple of problems that can degrade design robustness: 1) inadequate estimation of the long term variability for the design specific model; and 2) misleading ECPs caused by the selection of nonrepresentative FET building blocks. An alternative is to correlate the performance of the same set of data derived from devices measured at the design specific bias conditions to the set of data for the same group of devices measured at a standard bias condition.

STANDARD ECP TRENDS

The ECP database used at Triquint Semiconductor Texas consists of ECP data sets for several standard bias conditions. These data were derived from s-parameter measurements of a 300 um SCC (standard cell coupon). Standard FET cell s-parameters were measured from 0.5 GHz to 26 GHz. An optimization routine was used to fit the FET ECPs to the measured s-parameter data. The figure below represents an equivalent circuit model including noise sources:

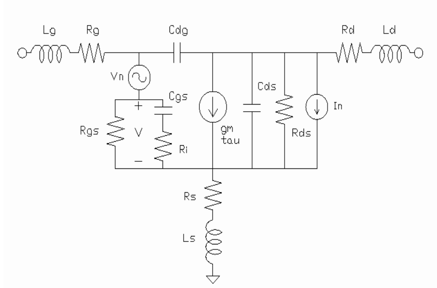

Figure 1: ECP Model Representation

Since the pHEMT structure was originally conceived as a power device, ECPs are routinely extracted at a bias consistent with power amplifier applications. However, TriQuint's pHEMT structure has demonstrated outstanding performance as an LNA building block and has been used to fabricate state of the art LNA MMICs. For distributed LNA applications, Gm and parasitic capacitances are probably the most important ECPs. The following plots show trends of Gm and Cgs at the standard bias condition:

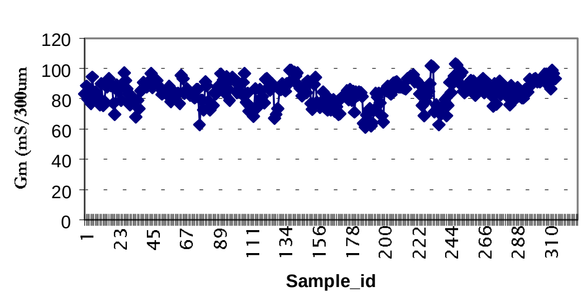

Figure 2: RF Gm Trend for PWRPHEMT Devices Measured at Standard Bias Conditions

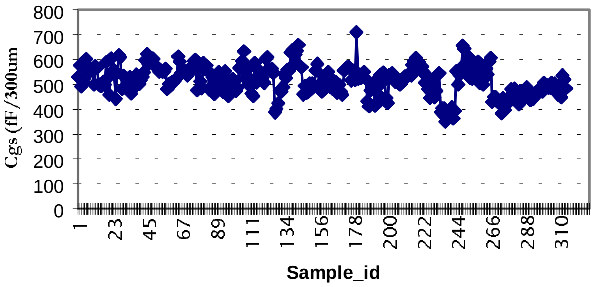

Figure 3: Cgs Trend for PWRPHEMT Devices

NOISE PERFORMANCE CONSIDERATIONS

The redesign methodology emphasized the most accurate determination of the ECPs, especially Gm, since gain performance was the primary problem affecting the robustness of the original LNA. Using the correct ECP set would allow correctly designing for higher gain while simultaneously driving the noise figure in the right direction. Experience has shown that there is not much that can be done to independently tweak a distributed amplifier design to improve noise while implementing tweaks to improve gain response. In summary, virtually all efforts to improve the LNA design focused on tweaks to increase gain. There was no deliberate effort to significantly improve noise figure. Once the gain tweaks were completed noise parameters were then used to predict noise performance and define a noise performance spec.

Since a long term estimation of noise performance was not as imperative as long term ECP extraction for this design, the noise prediction models used were based only on device cells built on the wafers which housed the original design. The sample size was not outstanding, but it was believed large enough to make the engineers involved in the effort sufficiently comfortable about the accuracy of noise predictions. The table below summarizes the noise parameter statistics:

Table 1: Noise Parameter Statistics for 75 um cell at LNA bias

PARAMETER	MEAN	STDEV
Vn	0.387	0.038
In	201.713	81.257
Recorr	-0.995	0.607
Imcorr	-0.553	0.856

STATISTICAL MODELING APPROACH

The first step in characterizing the long-term behavior of ECPs at the customer's bias condition was to collect measurements from a sample of SCC devices biased at the both the TriQuint standard condition and the design specific bias condition. Regression fits between important pairs of parameters were derived and used to transform the historical trends to predict corresponding performance trends at the MMIC specific bias condition. Gm and Cgs were considered to be the most important parameters. Despite the fact that the SCC and the actual amp device cells differ in size by a factor of 4X with the SCC measuring 300 um and the amplifier cell measuring 75um, Gm and Cgs scale directly as functions of total gate periphery. Therefore, the results obtained for the 300 um cells after applying the regression fits were easily converted into corresponding values for the 75 um cell. The following plots illustrate the regression fits between Gm@3.8V/20mA (design bias condition) and Gm@8.0V/22.5mA (facility standard bias condition) and the regression fit between Cgs@3.8V/20mA and Cgs@8.0V/22.5mA, respectively:

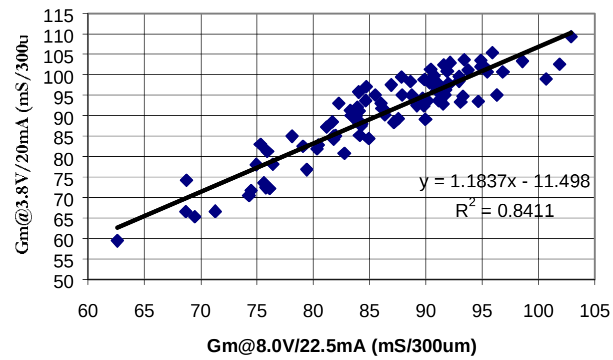

Figure 4: Gm@3.8V/20mA Vs Gm@8.0V/22.5mA

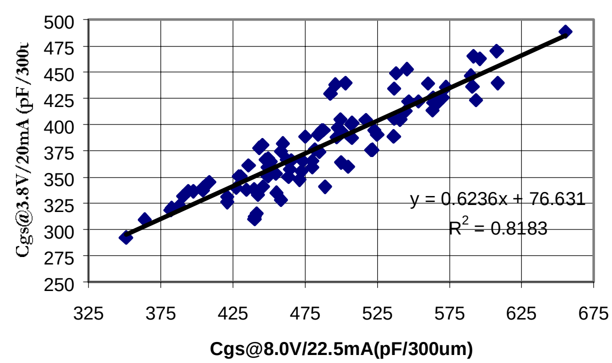

Figure 5: Cgs@3.8V/20mA Vs Cgs@8.0V/22.5mA

Similar fits were derived for other ECPs, but all of those will not be presented here. The following table summarizes the results of the Gm and Cgs regression fits:

Table 2: Summary of Important Regression Fits

PARAMETER	LINEAR FIT	CORRELATION COEFFICIENT
Gm	1.1837*x-11.498	0.9171
Cgs	0.6236*x+76.631	0.9046

RESULTS OF ECP TREND TRANSFORMATIONS

The data used to plot the trends of ECPs at the standard bias condition were transformed via the regression fits described earlier. The resulting trends were studied and used to derive statistics for later use during circuit simulation. The following trend charts demonstrate the predicted trends of Gm and Cgs for LNA devices biased at the design specific condition:

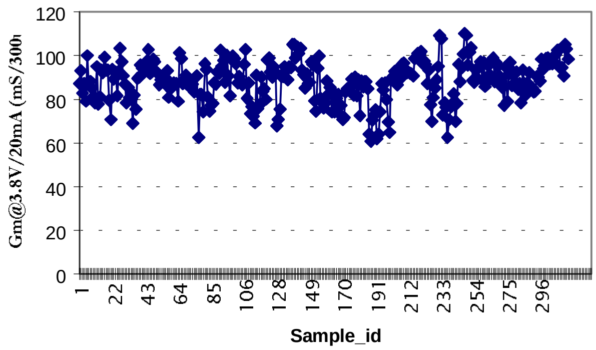

Figure 6: Simulated Long Term Gm Trend Based on Linear Transformation

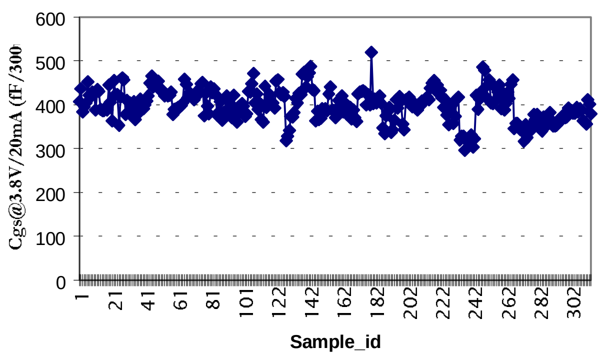

Figure 7: Simulated Long Term Cgs Trend

The following table summarizes the projected long-term statistics for the design specific LNA model:

Table 3: ECP Statistics for 75 um cell

PARAMETER	MEAN	STDEV
Gm (mS)	22.33	1.94
Cgs (fF)	100.43	8.39
Cgd (fF)	12.69	0.73
Ri (Ohm)	14.14	1.69
Rds (Ohm)	1380.43	221.36
Cds (fF)	24.86	4.12
Tau (ps)	3.10	0.39
Rs (Ohm)	3.02	0.69
Rd (Ohm)	4.44	0.12

CIRCUIT SIMULATION AND MODEL VERIFICATION

Once the ECPs were derived they were programmed into LIBRA circuit files to verify the accuracy of our approach to determine long-term variability. Comparisons were made between measured and modeled RF performance traces of the original design including input return loss, output return loss, and gain. The following plot demonstrates the agreement between measured and modeled S21 responses:

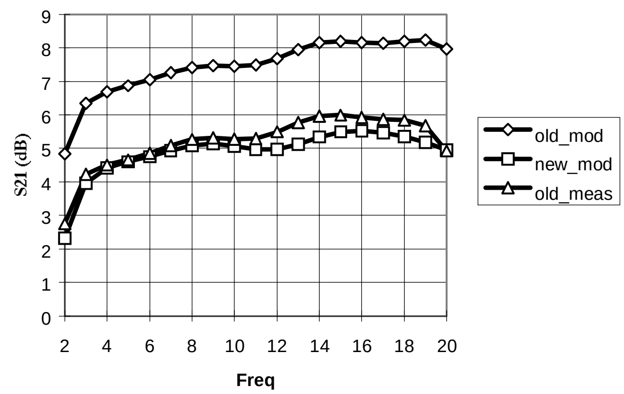

Figure 8: LNA Model Comparison, S21

The plot above shows that the original model which was based on a snapshot in time poorly estimated the actual gain performance of a completed MMIC. The newer model which was derived using the derived long-term statistical data set more accurately predicts the original MMIC's gain response.

NEW DESIGN RESULTS

Given the improved ECP model, design modifications were made to improve the gain response, input and output return loss responses, and noise figure. The following plot demonstrates the gain performance of the new and improved MMIC and shows how the measured results compare to the modeled results:

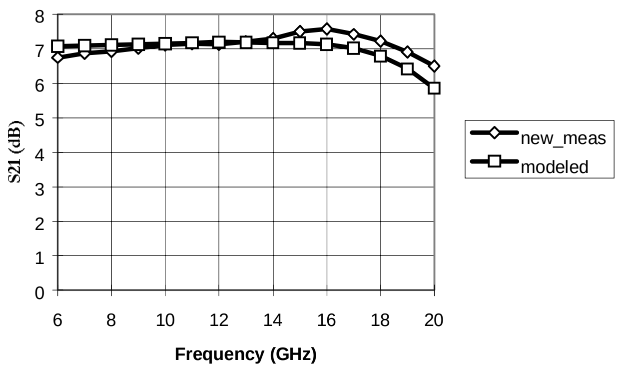

Figure 9: Measured Vs Modeled S21 Response of New Design

The final gain result shown above shows that the redesign approach was effective.

DATABASE FOR LONG-TERM TREND MONITORING

During the past year TriQuint Semiconductor Texas worked to establish a scheme of long term process monitoring that emphasizes the tracking of ECPs for a SFC (Standard FET cell) that is included in the device reticle or dropout of each wafer fabricated. Prior modeling was performed using an SCC (Standard Cell Coupon) which consisted of a number of different FET structures. However, the number of device structures and the number of bias conditions in addition to the manual setup time of individual SCCs resulted in long overall test times and a relatively small data set for design and trend analyses. The SFC strategy involves on wafer probing of only one type of cell that is suited to characterize RF behavior for a number of different device profiles including ion-implanted and epitaxial technologies. A sample of wafers is selected each month for s-parameter measurements and subsequent equivalent circuit parameter extraction using a compact procedure that has been shown to agree very well with the more elaborate techniques used by our FET Modeling Team. These data will be stored in an Oracle database where they will be available for various types of analyses including design centering, trend studies, and process-to-RF performance correlations.

CONCLUSIONS

A redesign approach based on long term ECP trend estimation is important in realizing a robust finished product. The approach used by Triquint's high frequency GaAs facility of first measuring a sample of devices at both standard and customer specific bias conditions and subsequently using the results of regression fits to produce simulated long term trends provided a reliable database to model distributed amp performance.

This approach was quite effective in the case of a distributed amplifier since a distributed amplifier is not reactively matched, per se, and has a gain performance that varies one-to-one with RF Gm. Applying a similar approach to other design types may be somewhat more difficult, but it could also prove just as effective as this particular exercise.

ACKNOWLEDGMENTS

The authors gratefully appreciate the help of the Modeling Team of TriQuint Texas, which includes Marty Jones, Kenneth Wills, Philip Shimon, Gary Christison, and Kim Tiv, in completing the measurements and ECP extractions used during the redesign of the LNA that is the subject of this paper.

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