Forecasting Methods for MMIC RF Yield

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Abstract

Accurate MMIC RF yield forecasting is a critical tool for proactively defusing yield problems and planning the efficient use of manufacturing resources. TRW has investigated several methods for forecasting the RF yield of HEMT MMICs. We have considered and investigated: Monte Carlo statistical models, correlated statistical models, boundary device models, transforming maps, database models, and Semi-Physical device models. We compare the advantages and disadvantages of these methods, and illustrate examples of yield prediction with the two best solutions that we have found. Of the two, the semi-physical device modeling approach has provided the most elegant and versatile solution, but is more complicated to implement

INTRODUCTION

The capability to accurately forecast product yield is an invaluable asset in manufacturing. Yield forecasting allows better planning for the allocation of manufacturing resources, proactive identification of yield problems, and ultimately reduced manufacturing cost. In GaAs MMIC manufacturing, the drive to field new products under reduced design cost and time-to-market cycles have naturally increased the risk of incurring RF yield problems. These risks become even more apparent when RF performance specifications are pushed to the limits of the process, which is likely to happen in an ever more competitive environment.

Addressing the cause of poor MMIC RF yield can be an insidious problem in that it may not be specific. Instead, RF yield problems may occur as the result of unrealized shortcomings, which are distributed across the entire manufacturing process. The principle mechanisms that cause general yield loss in MMIC manufacturing are shown in the flowchart in Figure 1. Four out of the seven possible mechanisms relate strongly to RF yield loss. Factors such as unrealistic performance specifications, poor design-for-manufacturing, and process variability may individually or cumulatively reduce RF yield, hence raising long-term manufacturing cost.

RF yield forecasting is able to feed forward and feedback information to help identify and mitigate RF yield detractors. Forecasting information enables design and manufacturing sides to set realistic performance goals and design MMICs that are robust against process variation, thus reducing risks.

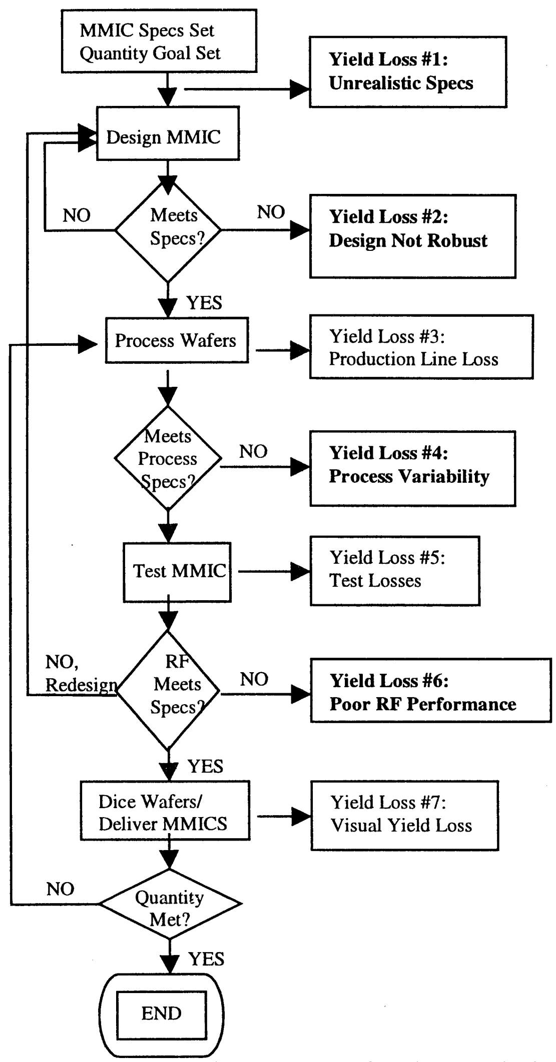

Fig. 1 MMIC yield loss mechanisms in manufacturing. Mechanisms that accumulate to RF yield loss are in bold.

TRW has investigated several methods for RF yield forecasting. All of them attempt to provide better accuracy by incorporating a more comprehensive representation of the process. The methods we investigated can be classified into two categories: 1) statistical modeling approaches, or those that employ device models and circuit simulation, and 2) empirical approaches, or those that use measured data only.

COMMON STATISTICAL MODELING METHODS

Several statistical device modeling based approaches are commonly used to predict MMIC RF yield. They include Monte Carlo statistical models, correlated statistical models, boundary models, and database models. Monte Carlo statistical models allow device model parameters to vary independently of each other by gaussian statistics, while correlated statistical models represent more realistic statistics in which the variations are constrained with correlation between the model parameters [1]. Long-term model databases are typically created for the purpose of process control monitoring, but can also be used in yield forecasting [2]. Boundary models are a set of models that represent "process corner" performance [3]. Each of these statistical modeling methods has their advantages, along with their own significant disadvantages.

Boundary models are ideal for quickly evaluating the robustness of a new design to the anticipated process variation. In fact, some manufacturers have developed methods that directly evaluate robustness through "process corner" experiments [4]. However, these boundary methods are unable to determine the RF performance distributions, which are fundamental to yield calculation. Thus, they are unsuited for RF yield prediction.

Long-term model databases are a powerful tool for MMIC process control monitoring. Typically, they consist of large samples of small-signal equivalent circuit model extractions for a single, consistent device structure, which is measured under a standard set of bias conditions. Database models unambiguously capture true process variation through uniform sampling. However, their general flaw is that they tend to be limited to applications based closely around the original measurements. For example, accurately extending a database model to represent a device with different bias conditions and layouts is very problematic. Time-consuming, systematic study and labor intensive effort are needed accomplish this properly [2]. In other circumstances, it is impossible or unadvisable to apply database results. Such is the case when trying to predict low noise, or large-signal results from a small-signal model database. In fact, TRW has maintained an extensive long-term small-signal model database for many years. We have thus far rejected its use in RF yield forecasting for many of the reasons given above.

Monte Carlo statistics are simple to implement for RF yield simulations, however its forecasts are highly inaccurate and should be used for "worst-cast" yield analysis only. Correlated statistical models provide a better method, however their results can also be inaccurate. Examples of the inaccurate yield forecasts provided by Monte Carlo and Correlated statistical models are shown in Figure 2, which compares simulated vs. actual noise figure and gain statistics for a 22-26 GHz GaAs PHEMT LNA. It is important to note that the Monte Carlo and correlated statistics that were used

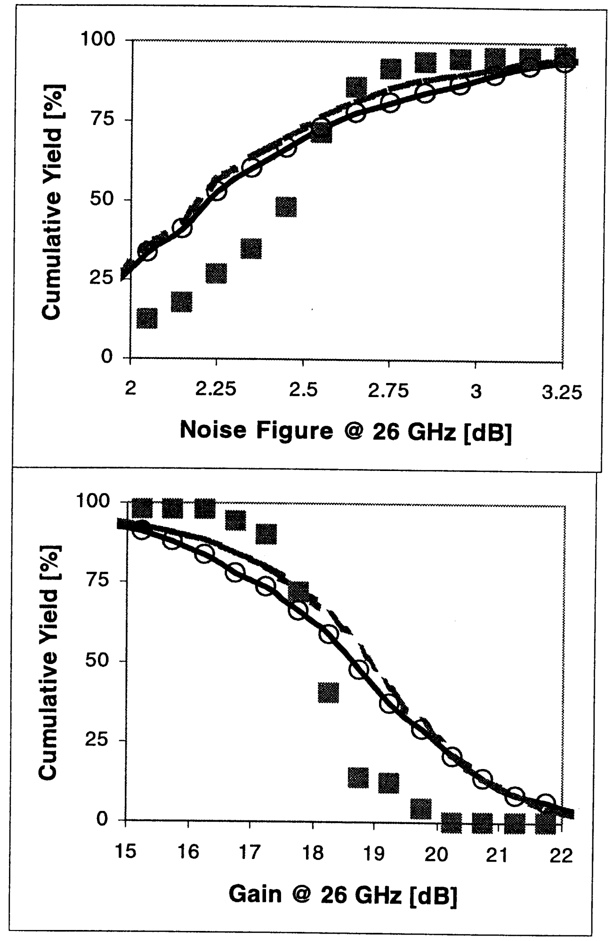

Fig. 2 Simulated vs. measured cumulative yield for NF (top) and gain (bottom) @ 26 GHz using Monte Carlo and Correlated statistical device models. (■) : Measured; (—o—) : Monte Carlo Statistical Model; (— —) : Correlated Statistical Model

in these simulations are exactly those used by TRW's own MMIC designers when employing such analysis.

Another drawback of Correlated statistical models is that substantial model databases are also needed in order to derive the correlation. This requirement subjects the method to similar restrictions that plague long-term model databases.

EMPIRICAL STATISITCAL METHODS

Alternatively, we have pursued empirical forecasting methods in which the long-term RF yield of one circuit is predicted by applying the known process-dependent RF yield characteristics of another. We have called this method "yield mapping." Yield Mapping entails the determination of a linear mapping transformation between a critical RF performance parameter and measured device process-control monitor (PCM) data. The transform can be used to map PCM data into "circuit performance" space. Any distribution of PCM parameters can then be transformed into a distribution of RF performance. A schematic example of such a transformation is shown in Figure 3, which shows a transformation of device PCM to MMIC RF performance. To apply the yield map transform to other circuits, an offset is included to account for differences associated with design. Although this technique is simple to derive and implement, it is obviously questionable.

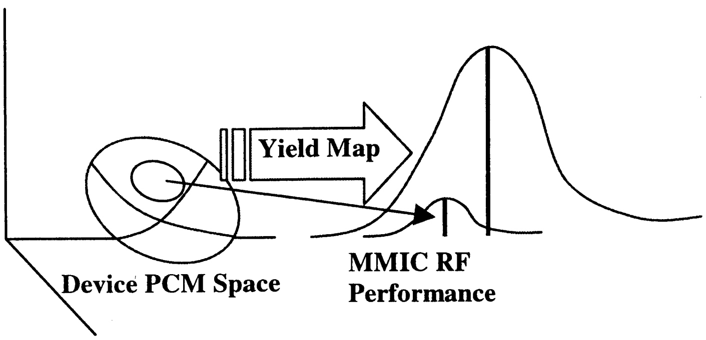

Fig. 3 Schematic representation of the Yield Mapping MMIC RF yield forecasting method.

We have found the method to work surprisingly well for the prediction of noise figure and small-signal gain performance, but not so well for power. A comparison of forecasted and measured noise figure performance for a 35 GHz GaAs PHEMT LNA, shown in Figure 4, demonstrates how this method can produce good results. The Yield map that was used was a simple linear equation containing three PCM statistical variables:

$$NF \equiv \frac{f}{26}\left(0.15\,\overline{f_T}^{-1} - 0.0477\overline{R} - 0.074\overline{I_{max}} + 2.66\right) \quad (1)$$

where NF is in units of decibels, f is the extrapolated frequency of operation, in units of GHz, and $\overline{f_T}^{-1}$, $\overline{R}$, and $\overline{I_{max}}$ are the statistically normalized PCM variables: inverse of cut-off frequency, recess undercut dimension, and maximum drain current, respectively.

Statistical normalization was accomplished by:

$$\overline{X} \equiv \frac{X - X_{ave}}{X_{std}} \quad (2)$$

where $\overline{X}$ is the random variable, X is a sample PCM measurement, X_{ave} is the statistical process average of the parameter, and X_{std} is the standard deviation.

One drawback to the Yield mapping method is that it cannot be used to accurately predict RF yield before the designs are produced. Instead, its predictions must be refined, as the design-dependent offset becomes determined through feedback from a pre-production run.

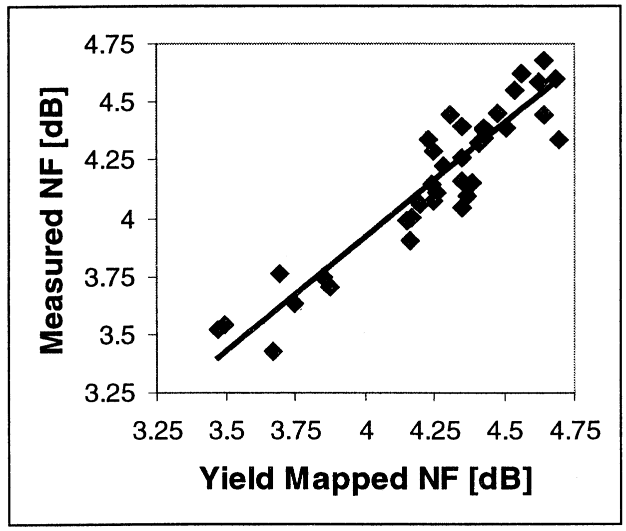

Fig. 4 Forecasted vs. measured NF @ 35 GHz using Yield Mapping method, based on on-wafer PCM data.

SEMI-PHYSICAL STATISITCAL METHODS

The most successful method we have developed is based on a Semi-Physical device model that can be used to simulate the RF yield of circuits. Semi-physical device models simulate RF performance through physically based device models. Our semi-physical model is an analytical model, which is based on empirical expressions that model the physics of HEMT operation – hence we describe the model as "semi-physical." The model incorporates real process parameters, such as gate length, recess etch depth, recess undercut dimensions, passivation nitride thickness, etc. By using empirical expressions, the semi-physical model is able to maintain very good measured-to-modeled accuracy while accounting for the effects of process variations on device performance.

Although the derivation of semi-physical models is much more challenging than conventional models, it is far more versatile and useful. By using the semi-physical model in circuit simulation, we are able to forecast RF performance distributions from a known distribution of physical process parameters, as shown schematically in Figure 5. We have been able to construct tables of small-signal and nonlinear models, which contain simulated, process-dependent device models. Using these tables, commercial microwave circuit CAD tools, like Libra 6.0, are then able to simulate process-dependent RF circuit performance. We have been able to accurately forecast noise, gain, linear and saturated power, and linearity distributions for HEMT MMICs for actual production runs. This is shown in Figure 6, which shows forecasted and measured low-noise RF performance for the same 22-26 GHz GaAs PHEMT LNA used in the comparison of Monte Carlo and Correlated methods. Compared to the inaccurate forecasts provided by former methods, Semi-Physical statistical models and Yield Mapping provide much more accurate RF yield predictions.

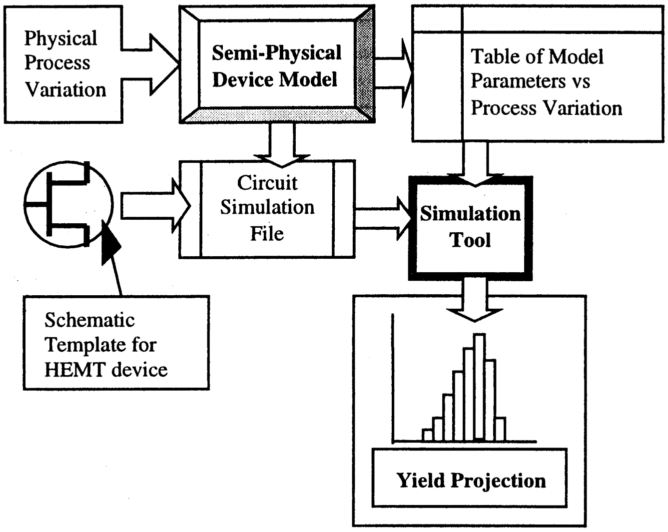

Fig. 5 Schematic representation of Semi-Physical device model used in MMIC RF yield forecasting.

A distinct advantage that Semi-Physical modeling has demonstrated over Yield Mapping is the ability to accurately determine design-dependent RF performance before MMICs have been produced. This advantage allows a MMIC fab to estimate cost and plan the allocation of resources starting from the design phase, and represents great savings in time-to-market development/production cycles. For example, three production lots had to be fabricated in order to determine the design-dependent offset that was used in the Yield Map of Figure 6, whereas the Semi-Physical method was able to simulate an accurate forecast directly from the circuit design.

Furthermore, the accurate and physical nature of the Semi-Physical method offers the potential versatility to forecast changes in MMIC reliability and performance with changes in temperature and bias.

CONCLUSIONS

TRW has investigated several methods for forecasting the RF yield of HEMT MMICs. We have found that Yield Mapping, and Semi-Physical device modeling are able to provide RF yield predictions which are accurate enough for good manufacturing cost forecasts. Of the two, the semi-physical device modeling approach has provided the most elegant and versatile solution, but is more complicated to implement.

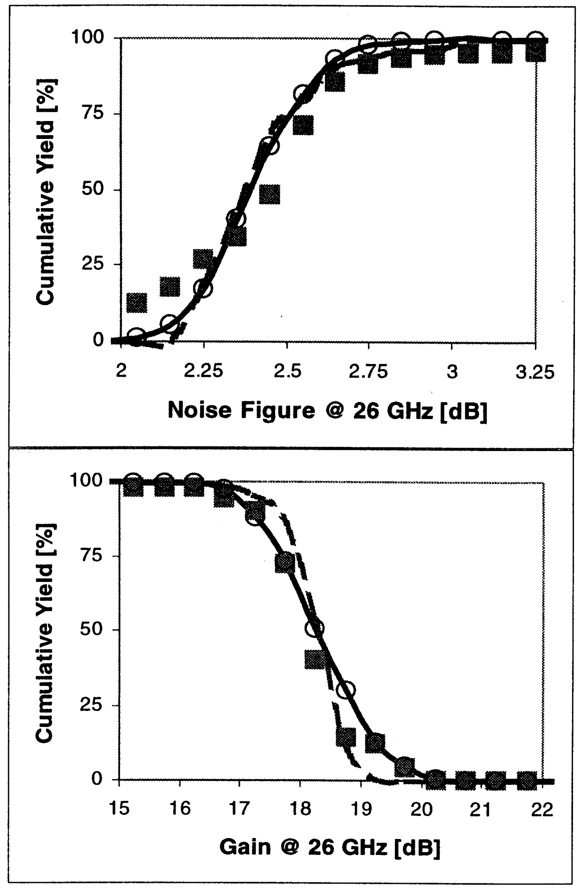

Fig. 6 Forecasted vs measured cumulative yield for NF (top) and gain (bottom) @ 26 GHz using Yield Mapping and Semi-Physical Statistical Modeling methods. (■) : Measured; (—o—) : Yield Mapping Method; (— —) : Semi-Physical Statistical Model

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REFERENCES

[1] M. Thompson., *IC-CAP 5.0 Statistics Package Overview*, customer presentation, March 1999.

[2] M. King, et al., *A Product Engineering Exercise in 6-Sigma Manufacturability: Redesign of a pHEMT Wide-Band LNA*, 1999 GaAs MANTECH Technical Digest, pp. 91-94, April 1999.

[3] HP EEsof, IC-CAP 5.0 Statistical Analysis, (HP Part No. 85190-90050, 1997).

[4] R. Garcia, et al., *A GaAs Fab's Approach to Design for Manufacturability*, 1999 GaAs MANTECH Technical Digest, pp. 99-102, April 1999.