2^{nd} Generation Device Modeling for MMIC Design & Manufacturability

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Abstract

We have developed a revolutionary "Second-Generation" (2G) device modeling strategy for the efficient implementation of complete, CAD-ready MMIC design kits. 2G models transcend conventional "black-box" device-modeling approaches by including the Physics-based and distributed nature of real devices through the use of a Semi-Physical/Semi-Distributed modeling method. We have successfully deployed 2G model-based design kits for TRW's sub-micron GaAs and InP HEMT MMIC product lines. These design kits have enabled accurate microwave/millimeter-wave IC design up to 200 GHz while providing full support of advanced design-for-manufacturability capabilities for MMIC RF yield prediction.

INTRODUCTION

Semiconductor device modeling is a critical service that all foundries need to provide. This is particularly true for those in the business of making microwave, millimeter-wave, and high-speed analog/digital IC's. For these products, the qualities of the design models can directly determine first pass success – or failure. Rarely do designers have the time or resources to develop their own sets of adequate models, so most depend upon those furnished by the foundry. So, beyond the qualities of a foundry's manufacturing, customer satisfaction and successful product deployment can be won or lost on the virtual "drawing board."

Unfortunately, it is also rare that a foundry has the resources to develop design kits that are satisfactory to all customers. It has been our experience that MMIC design customers tend to demand extremely complete design kits. In addition to passive MMIC component models such as spiral inductor, capacitor, resistor, and backside via, device model demands include small-signal, noise, and large-signal models covering all available device sizes and bias conditions - active and passive, temperature-dependent models, and statistical models supporting design-for-manufacturability (DFM) simulations [1].

Is there a way to make everybody happy without spending millions on modeling?

We have developed a revolutionary device modeling approach that satisfies needs for a foundry to stay lean, while also providing complete and accurate model kits for customers. We view this development as a natural evolutionary step in the field of semiconductor device modeling, and have thus proclaimed it as the "2G" model.

EVOLUTION OF DEVICE MODELING

We envision three major generations in the evolutionary roadmap of high frequency and high-speed device modeling.

The first-generation (1G), which is the currently accepted practice, involves modeling devices in a "black-box" fashion. This is typified by the use of lumped element equivalent circuit models and empirical, data-fitting analytical models, which are programmed directly into IC CAD. The second-generation (2G) begins to incorporate an understanding of what's inside the black box by employing Physics-based device models. However, these physical models are not integrated directly with the CAD environment and must be deployed in an indirect manner. Future third-generation (3G) models represent the ultimate level of understanding by utilizing advanced numerical physical device simulation, which will then be seamlessly integrated with IC CAD.

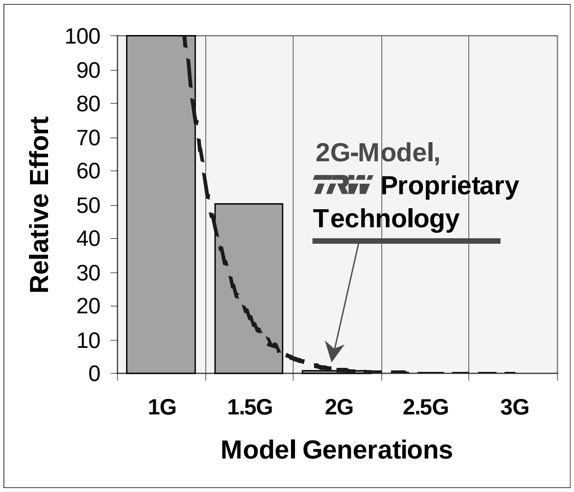

Fig. 1 Relative consumption of resources for generating complete design kits for 1G, 2G, and 3G based modeling methods.

By incorporating a knowledge-based understanding of the device technology, our 2G models have reduced consumption of resources by a factor of 100 compared to 1G-based methods. A relative comparison of total effort/expense for completing a full design kit is shown in Figure 1 for 1, 2, and 3G approaches. We predict that the pinnacle of physical model evolution, 3G models, will be

100 times even more efficient than our current 2G model. Essentially, the incorporation of Physics-based knowledge in device modeling substantially reduces the effort that is required to develop accurate and complete design kits.

TRW's current 2G models accomplish this efficiency by the combined use of Semi-Physical and Semi-Distributed device modeling. These novel approaches provide a reliable method for accurate interpolation between measurement-verified models, and a realistic means to accurately extrapolate those models as a function of layout size, thermal environment, material/process variation, or bias. As a result, the number of measurements required to fully characterize all available devices can be strategically reduced. 1G models are essentially "dumb" because they are black boxes. They are developed directly from measurements. Consequently, 1G models can not explicitly reuse the knowledge and experience that is gained in the process of modeling several devices.

Because 2G+ models operate upon a centralized, core physical device model, the knowledge gained from modeling devices of one technology can easily by applied towards similar device technologies. For example, we were able to recast the Semi-Physical device model [2] for our 0.15-um GaAs Power HEMT technology to serve as one for our 0.1-um GaAs Low-Noise HEMT [3] with the appropriate modifications to physical and material parameters, and minimal adjustment to empirical parameters. Compared to our original effort to construct the 0.15-um Semi-Physical model, we were able to perform 50% fewer measurements to retune and verify our 0.15-um to 0.1-um Semi-Physical model tweak – but lost nothing in terms of millimeter-wave accuracy or design kit completeness for the new models. Recycling and iterative refinement of the 2G+ Physics-based models leads to successive improvements of roughly 50% for the efficiency of new design kit constructions.

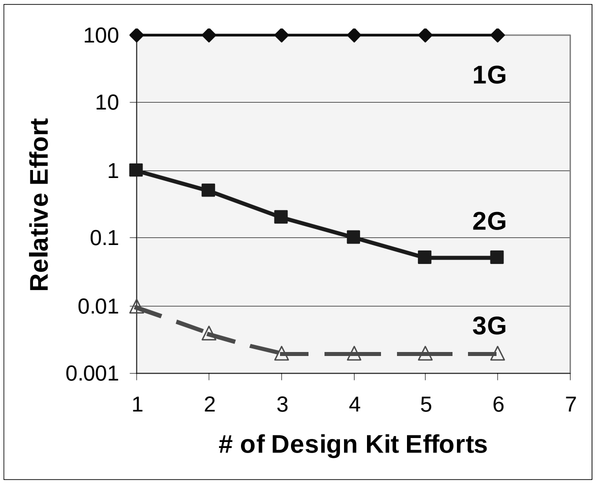

Fig. 2 Concurrent improvements in efficiency upon reapplication of 1G, 2G, and 3G based modeling methods.

On the other hand, Figure 2 depict how remains high and constant for 1G-based approaches. Design kit construction efficiency does not improve in this case because entirely new sets of samples must be measured every time a new 1G-design kit is constructed. For 2G+ kits, reduced sets of strategic measurements can be taken to simply verify the predictions of the Physics-based generator models.

Although the 1G modeling process is simple and unequivocal, in the long run they consume lots of resources and their accuracy depends directly upon the quality of measurements. For example, we have estimated that to adequately support TRW's 0.15-um GaAs HEMT foundry service with a basic set of room temperature nonlinear and noise models, and linear models across military temperature range, for all available device types, we needed to generate 46000 distinct 1G models!! Even worse, we would have had to specify stipulated ranges of use that were commensurate to the original measurement conditions. If we trusted our S-parameter measurements up to only 50 GHz, customers doing V-band MMIC design would be out of luck. Imagine how much more expensive it would be to develop a separate set of trustworthy V-band specific models!

2G DEVICE MODEL

We have developed 2G models for many of TRW's advanced GaAs and InP HEMT technologies. The models have enabled us to deploy complete and accurate design kits for seven of TRW's advanced HEMT MMIC production and pilot-production lines: 4-mil 0.15-um GaAs Power, 0.1-um Power, and 0.1-um Low-Noise; 2-mil 0.15-um GaAs Power; 3-mil 0.1-um InP Low-Noise, and 0.15-um Power; and 2-mil 0.07-um InP Low-Noise. We have been able to accomplish this with far less manpower and test cost than otherwise would have been possible.

Our 2G model is enabled through the use of two innovative concepts: a Semi-Physical device model serving as an intrinsic model generator, and a Semi-Distributed modeling approach to embed these results within a realistic extrinsic model.

The so-called "Semi-Physical" device model is a Physics-based analytical device model that we use to generate the intrinsic part of CAD-ready linear, noise, and nonlinear device models. Our Semi-Physical model is designed to incorporate empirical parameters within expressions that only coarsely model the actual electron dynamic phenomena inside the device. Although not a purely Physics-based model, empirical fitting parameters ensure that this model meets the demanding accuracy that is required of RF/analog models while maintaining a realistic physical basis.

The distributed nature of device layouts is represented through a "Semi-Distributed" model approach. In this approach, arbitrary device layouts and sizes can be assembled hierarchically with sub components. Instead of a single lumped element or data-fitting model, 2G Semi-Physical/Distributed models are macro-like models. An example of this is depicted in Figure 3, which demonstrates how we construct a small-signal/noise macro model for one of our 4-fingered HEMT device layouts. A single, scalable model can now accurately represent an entire class of device layouts while, by rule of thumb, 1G lumped element models can be scaled only within 25% before their millimeter-wave accuracy becomes questionable. Consequently, our 2G-model approach enables far greater high-frequency/high-speed model accuracy, scalability, reconfigure-ability, and versatility than 1G models.

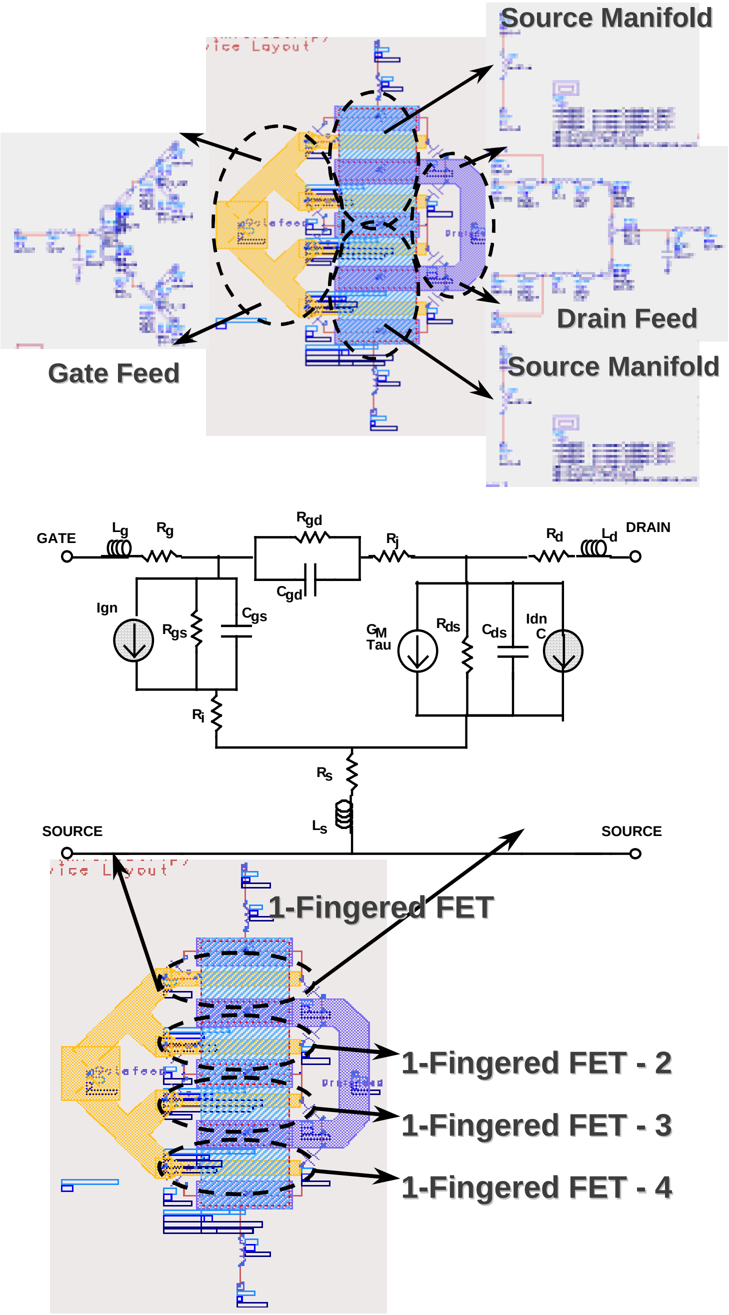

Fig. 3 Semi-Distributed approach for macro-like linear/noise model for TRW 4-fingered HEMT device class.
(Top) Extrinsic embedding model of gate/drain feed and source manifold interconnects with distributed and lumped elements.
(Bottom) Intrinsic model includes on-mesa parasitic. Four parallel 1-fingered FET models: conventional linear model with Pucel noise model [4]

A number of proprietary innovations have enabled our development of the Semi-Physical model. Chief among them has been a method of extracting unique and physically significant linear models from device S-parameter measurements. This capability has proven crucial because it has enabled us to build a physical device model that is not only grounded in theories of device Physics, but also derives from actual measured quantities. By definition, this physical model generates models that compare accurately with real, measured devices.

ACCURACY FOR MMIC DESIGN

We have used 2G models to accurately simulate MMIC RF performance for applications as low as 2 GHz and as high as 200 GHz for linear, low-noise, high-power, medium-power, and high efficiency power amplifiers. The highest frequency example has been a 190 GHz LNA that was developed for radiometric applications [5]. Our 2G model simulates gain very well compared to measured, on-wafer gain, as shown in Figure 4. Simulated MMIC noise-figure also matches with fixture measurements considering transition losses.

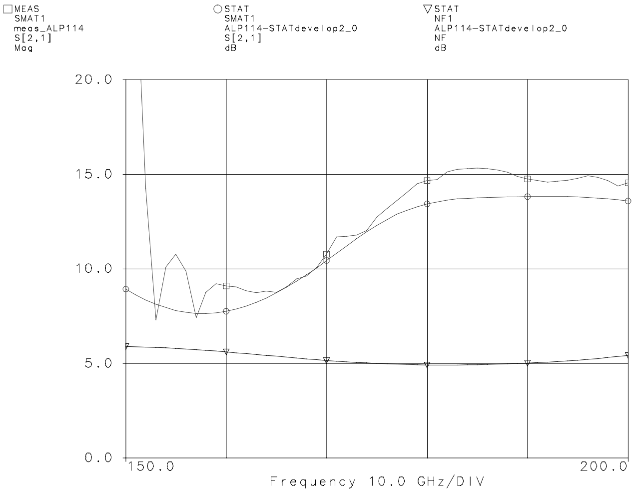

Fig. 4 Accuracy of 2G model approach verified up to 200 GHz. 2G Semi-Physical/Semi-Distributed model for 2-mil 0.07-um InP HEMT. 150-200 GHz Measured on-wafer gain (▬) compared to simulated gain (▬)and noise figure (▬).

2G nonlinear models have been equally successful in the accurate simulation of saturated output power, PAE, and linearity for MMIC power amplifiers. An example of this is shown in Figure 5, which shows the measured and modeled gate/drain current, gain, and PAE under drive for a 29 GHz 1-stage PA. The simulated gain compression and driven drain current match very well with measured data up to P1dB, where the data range ends. The nonlinear model we implemented in this simulation has been described in [6]. We have seen this model simulate accurate compression characteristics well into P5dB. However, it does not model breakdown voltage, which may account for deviation between measured and modeled gate current starting around 10 dBm input drive.

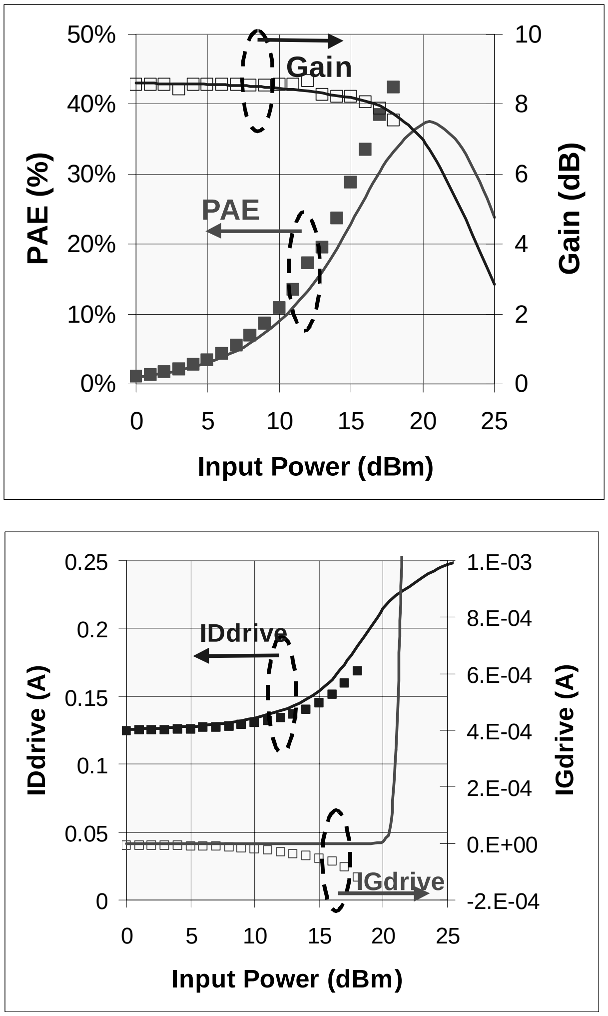

Fig. 5 RF driven measured vs modeled characteristics for a 29 GHz 1-stage MMIC power amplifier.
(Top) RF driven: PAE (☐ measured; ▬ modeled)
Gain (■ measured; ▬ modeled)
(Bottom) RF driven: Drain current (■ measured; ▬ modeled)
Gate current (☐ measured; ▬ modeled)

Our 2G models have also accurately predicted the temperature dependence of DC bias/power dissipation, and RF output power, noise, and gain of fixtured MMICs from temperatures of –50 to 150 °C. This has been useful for some internal TRW applications that have used our MMICs in high-reliability SATCOM and millimeter-wave radio modules sitting at elevated baseplate temperatures.

We have also been able to use these models for accurate passive RF simulation for applications such as RF switches and phase shifters, and accurate high-speed simulation for 40 Gb/s modulator drivers. We have not as of yet verified the accuracy of these models for RF frequency mixing and multiplication, though.

DESIGN FOR MANUFACTURABILITY

Our 2G Semi-Physical generator models have enabled us to seamlessly integrate CAD-ready statistical models with design models to support advanced DFM [1,2]. MMIC RF performance variation is produced by Monte Carlo statistical simulation, now a common feature in most modern IC CAD. The statistical simulation utilizes pre-generated model truth tables to introduce statistical variation into MMIC components such as devices, backside ground vias, and MIM capacitors.

For 2G device models, modulating actual physical parameters in the Semi-Physical model generates the statistical truth tables. In practice, statistical distribution functions for key parameters are well known because physical process/material parameters, such as gate length, Hall mobility, etc., are thoroughly tracked via process control monitors (PCM).

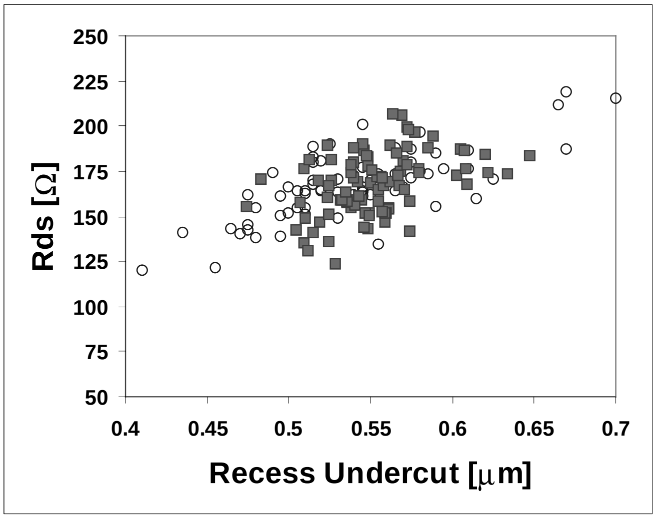

Fig. 6 2G (■) statistical simulation and actual 1G (○) statistical variation of HEMT small-signal output conductance, Rds, vs recess undercut width.

This technique has been very effective at simulating realistic process variation in our devices. We have been able to accurately simulate the variability of HEMT device DC and RF PCM parameters, as well as their interrelation. An example of this is demonstrated in figure 7, which shows how our 2G Semi-Physical generator model has been able to accurately simulate the distribution and correlation of the RF linear model parameter, Rds, with an actual physical parameter, recess etch undercut width. The so-called "measured" values of Rds were taken from 1G models extracted directly from a series of 100 wafer runs.

We have used our 2G-based DFM to accurately simulated performance variation for MMIC LNA noise-figure, gain, and stability up through Q-band, and PA Psat, Gain, and P1dB up through Ka-band. An example of one such statistical simulation is shown in figure 6, which demonstrates the accuracy of our method to produce the correct large-signal gain variation for a K-band HPA driven at 17dBm input power.

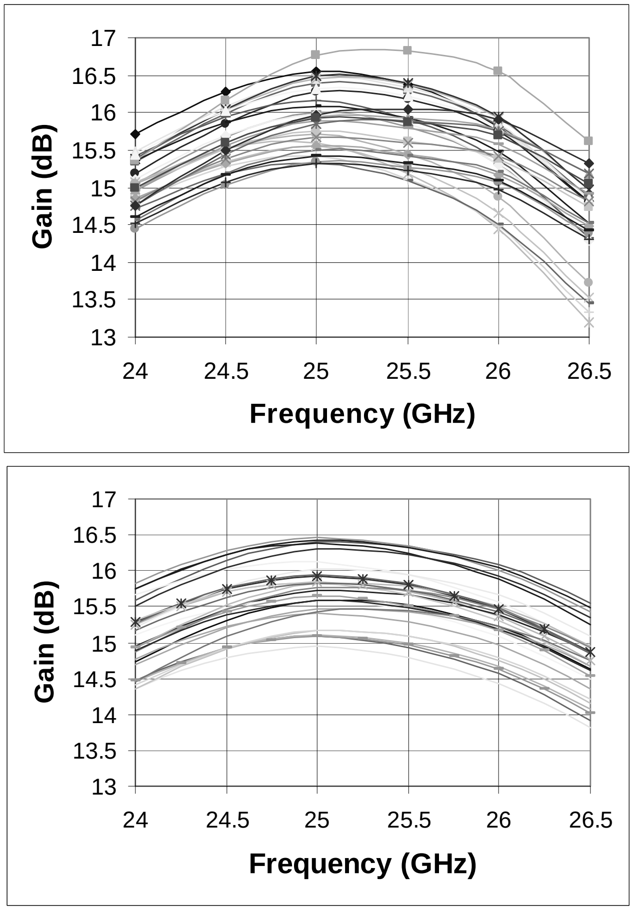

Fig. 7 Statistical variation of RF power gain for a K-band MMIC HPA, 17dBm input drive.
(Top): measured parts from 70 production wafers
(Bottom): DFM statistical simulation, 70 Montecarlo samples.

Figure 8 shows how the actual distributions of mid-band (25 GHz) power gain compares very well against the statistical simulation. We believe the 2G statistical model is accurate for DFM at much higher frequencies and more applications, however, we have applied the 2G DFM for only our highest volume HEMT products, so far.

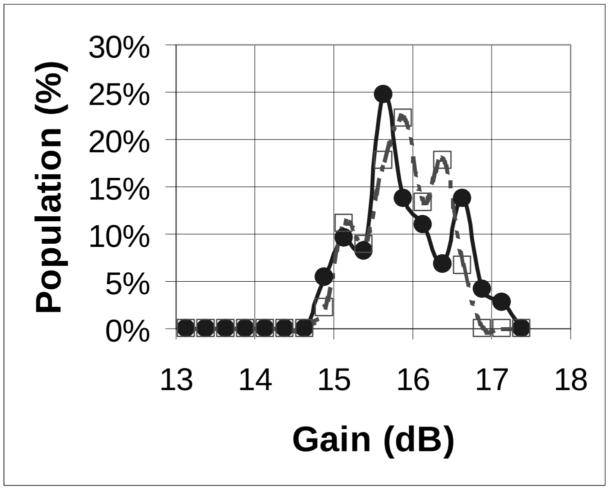

Fig. 8 Measured (●) vs DFM simulated (☐) statistical distribution of power gain for K-band MMIC HPA, 17dBm input drive, 25 GHz.

THE FINAL FRONTIER

It is our belief that the apex of device modeling evolution, the 3G model, is still quite far in the future. We anticipate that true 3G models will employ accurate, real-time, and fully Physics-based device simulators working self-consistently with equally evolved electromagnetic field solvers. These advanced, numerically based 3G simulators will be seamlessly integrated with IC design CAD. Although there has been some work towards this goal, our evaluation of commercially available 3G state-of-the-art has shown their accuracy to be lacking for MMIC design needs.

CONCLUSIONS

TRW has developed a powerful new 2G modeling approach that has been able to incorporate realistic, Physics-based models and distributed modeling methods. These methods enable us to build complete sets of device models that support millimeter-wave accurate, scalable, bias/temperature dependent and statistical simulations for comprehensive MMIC design. At the same time, our new modeling process consumes 100 times less manpower/test cost than conventional 1G methods, and provides a direct path for concurrent improvements upon reapplication.

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REFERENCES

[1] R. Tsai, M. Nishimoto, and R. Lai, Forecasting methods for MMIC RF yield, 2000 GaAs MANTECH Technical Digest, pp. 113-116, 2000.

[2] R. Tsai, Y. C. Chen, M. Nishimoto, L. W. Yang, W. Okamura, and R. Lai, Forecasting method for HEMT MMIC large-signal RF yield, 2000 GaAs IC Symposium Digest , pp. 125-128, 2000.

[3] R. Lai, P. H. Liu, J. Scarpulla, R. Tsai, D. Leung, D. Eng, R. Grundbacher, M. Aust, J. Lee, and M. Hoppe, 0.1-um InGaAs/AlGaAs/GaAs HEMT MMIC production process for high performance commercial Ka-band LNAs, 2000 GaAs IC Symposium Digest, pp. 139-141, 2000.

[4] R. Lai, T. Gaier, M. Nishimoto, S. Weinreb, K. Lee, M. Barsky, R. Raja, M. Sholley, G. Barber, and D. Streit, MMIC low-noise amplifiers and applications above 100 GHz, 2000 GaAs MANTECH Technical Digest, pp. 249-250, 2000.

[5] H. Statz, H. A. Haus, and R. A. Pucel, Noise characteristics of Gallium Arsenide field-effect transistors, IEEE Transactions on Electron Devices, vol. ED-21, pp. 549-562, 1974.

[6] Y. C. Chen, D. L. Ingram, H. C. Yen, R. Lai, and D. C. Streit, A new empirical I-V model for HEMT devices IEEE Microwave Guided Wave Lett, ., vol. 8, no. 10, pp. 342-344, 1998.