A DOE Approach to Product Qualification For Linear Handset Power Amplifiers

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Abstract

Variation in starting wafer material impacts yield and performance of linear power amplifiers for handset applications. This work presents a design of experiment approach for evaluating circuit sensitivities based on epi material variations that can be used for product qualification. This approach provides a systematic understanding of how the epi material influences the final product performance and allows expected parametric spread to be predicted accurately with a minimal number of wafers. As a result, product performance distributions can be quickly and accurately determined in the development phase of a product.

INTRODUCTION

During the development of GaAs HBT products, it is important to understand and characterize the effect of variation of the epi starting material on circuit performance. The circuit performance parameters (Gain, Power-Added Efficiency (PAE), and Linearity) largely depend on the device characteristics (DC gain, RF gain, turn-on, etc). Ultimately, these device characteristics depend on the fundamental properties of the starting epi material, such as doping and thickness of the various layers. Unfortunately, many of the device characteristics depend on several material parameters (e.g. doping and thickness) that cannot be uniquely measured using typical DC PCM measurements. Two excellent examples of this are the DC gain, β, and the base sheet resistance, R_{bsh}. These two parameters depend on doping and thickness (both depend on the product of the doping and thickness).

In order to fully investigate the impact that epi material variation has on the circuit, we have developed a design of experiment (DOE) approach that minimizes the number of wafers required to fully explore the expected material variation window. In this approach, we purposely vary the material specifications over a wide window and measure the effect on the circuit. This methodology allows product variations to be well characterized and accurately communicated to the customer in the early phases of production.

We begin with a discussion of parameter selection. This leads our DOE matrix and after considering additional practical constraints. We then present experimental data showing the application of this approach. This application highlights the wealth of information gained by using this methodology. Finally, we summarize our findings.

PARAMETER SELECTION AND DESIGN OF EXPERIMENT

Many different parameters can affect the performance of an HBT and circuit fabricated using them. One practical constraint we needed to impose was that any epi material DOE used for product qualification fit within a single process lot (i.e. is less than 20 wafers). This basically allows for three independent epi parameters to be used with two full sets of the experiment. Our electrical PCM (Parametric Control Monitor) set already includes orthogonal determination of many important parameters (R_e, C_{bc}, C_{be}, etc.) so we focused on parameters that (1) had a potentially large impact on the circuit performance and (2) could not be uniquely determined from DC PCM data.

For bipolar transistors, it is well know that the properties of the base play a large roll in determining the major device characteristics [1]. Because carbon doped III-V HBTs are grown by well-controlled epitaxy, we can accurately specify the base thickness and doping. The base thickness (BT) and base doping (BD) have a substantial impact on the DC current gain β, turn-on voltage, (V_{be}), the base resistance (R_{bsh}), and RF gain (f_T or f_{MAX}). The base thickness and doping occur as a product in both β and R_{bsh}. This makes it impossible to understand (using non-destructive methods) whether an observed change in DC gain or base sheet resistance is due to a thickness change or a doping change. Therefore, base doping and thickness were selected as two parameters for our DOE. Another important circuit parameter is the base-collector capacitance, C_{bc}. Since PAs are operated with large voltage swings on the base-collector junction, the collector thickness (CT) determines the C_{bc} for a significant portion of the operating range. An interaction between the DC gain and the breakdown voltage, BV_{ceo} was also expected (and breakdown also depends on the collector thickness). Therefore, CT was selected as the third parameter. Using RS1 software, we developed the experimental matrix shown in Table 1. We varied the

Run Number	BT	BD	CT
1	Nom	Nom	Nom
2	Nom+11%	Nom+12.5%	Nom+12.5%
3	Nom+11%	Nom+12.5%	Nom-12.5%
4	Nom+11%	Nom-12.5%	Nom+12.5%
5	Nom+11%	Nom-12.5%	Nom-12.5%
6	Nom-11%	Nom+12.5%	Nom+12.5%
7	Nom-11%	Nom+12.5%	Nom-12.5%
8	Nom-11%	Nom-12.5%	Nom+12.5%
9	Nom-11%	Nom-12.5%	Nom-12.5%

Table 1. DOE Material Matrix.

parameters well outside the expected range to insure that we captured the normal variations within the DOE range. Fig. 1 shows the measured dependence of several key parameters (β, R_{bsh}, and BV_{ceo}) on the base thickness and doping with a nominal collector thickness. Analyzing this data, we found several interesting results. First, the β and R_{bsh} are linearly related to one another (slope=1.06), as shown in Fig. 2. This was unexpected since the formulas for DC Gain of HBTs limited by bulk recombination have a different doping dependence for the β and R_{bsh} [3]. We expected β to follow:

(1) $$\beta = v\tau / w_b = v \cdot 2.8\text{x}10^{38} / w_b N_b^2$$

where v is the average carrier velocity in the base, τ is the minority carrier lifetime, w_b and N_b the base thickness and doping, respectively. The fact that R_b/β is a constant implies the β varies as $1/N_b$, rather than $1/N_b^2$. This is actually beneficial, since it allows a simpler implementation of statistical process models since knowing R_b or β implies the other. Secondly, we found that the BV_{ceo} is only weakly coupled to β. The typical values found in the literature for the relationship between BV_{cbo} and BV_{ceo} follow [4]:

(2) $$BV_{CEO} = BV_{CBO} / \beta^{1/n}$$

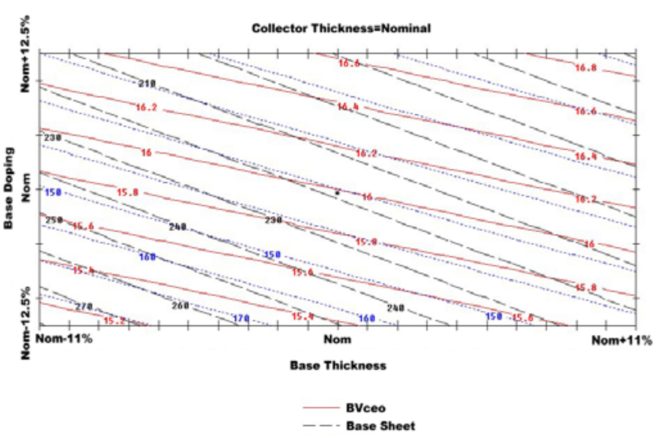

Fig. 1 Plot of several important PCM parameters over the DOE space.

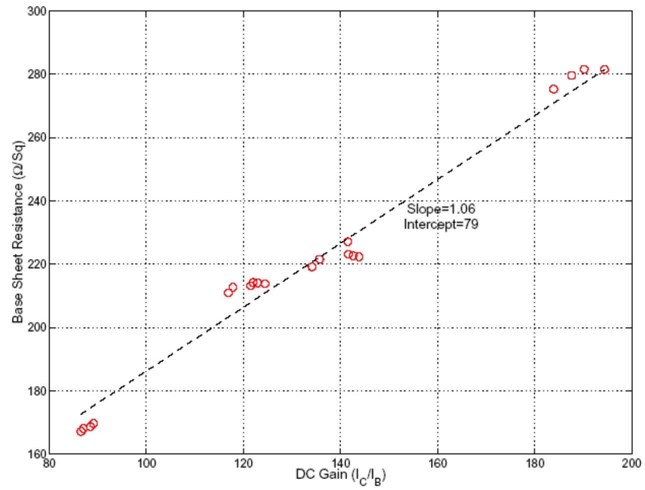

Fig. 2 Relationship between DC current gain, β, and base sheet resistance

Where BV_{ceo} is the open-base breakdown, BV_{cbo} is the open emitter breakdown, and β is the DC gain. However, many modern bipolar transistors (including Si/SiGe) tend to deviate from the n=2 found discussed in most textbooks. For the HBTs measured in this experiment, a value of 9.6 was determined by fitting to the data. A comparison of BV_{ceo} vs. BV_{cbo} to equation (1) with n=9.6 is shown in Fig. 3. One reason for the possible discrepancy is that β for the HBT is typically measured at high currents (near peak β), while the breakdown is measured at low currents. Parasitic resistance effects also cause deviation from this theory, as discussed by Yeats [5]. For variations in the collector thickness, we find that the breakdown and the reverse bias C_{bc} are well correlated to the thickness, as expected. This correlation of PCM behavior is a very important link in relating the circuit results back to the PCM data. Having evaluated the dependence of the PCM parameters on the epi material variations, we next proceed to product level testing.

Module Level DOE Results

To demonstrate this method, several different PA modules were evaluated. The first three parts in Table 2 are 900 MHz Cellular PA Modules. The fourth part is a 1.8 GHz PCS Module. Dies from each wafer were built in distinct assembly runs and the data collected was segregated for each specified epi material variant. The test results allowed process and material dependent PCM parameters to be separated. As anticipated, we found the key RF performance parameters to be strongly dependent on the starting epitaxial material. Table 2 shows the range of key parameters achievable with this DOE for the measured parts. Because of design differences, not all of the parts respond the same way to variations in the parameters we used. As a result, conclusions about how a given parameter affects

Part	Gain	ACPR1	ACPR2	PAE
Cell-1	28.9-30.7	45.6-53.4	57-61.4	NA
Cell-2	26.3-29	49.6-53.3	60.3-63.2	36.4-39.2
Cell-3	24.2-28	42.5-49.6	56.5-58	39.8-42
PCS-4	28.4-31.6	45.3-47.3	53.5-55.6	37.3-39.3

Table. 2 Ranges of RF Parameters from Epi-DOE Material Matrix

circuit performance must be evaluated on a circuit by circuit basis. Note that the parameter ranges we selected are purposely wider than is acceptable for our customer specification so we can interpolate data to the region of interest (i.e. our incoming material specifications). We evaluate the circuit yields and performance for the epi material variations and use this information to set incoming material specifications for given product families. As a result, the circuit yields and performance variations due to epi material variability are quickly established with this approach. From the table, we note that the linearity, APCR1, can be substantially changed due to the material variations. An example of how to tie this back to the PCM results is shown in Figs. 4-6. By plotting a given parameter over the variation space, and comparing it to the PCM data over the same space, we can determine exactly what material parameters (and result PCM space) will give acceptable performance. Fig. 4 shows the RF gain under IS-95 modulation as a function of the base thickness and doping for Cell-3 (data in table is for CDMA-2K). Comparing this figure to Fig. 1, we note that the RF gain for this circuit follows the same general trend as the DC current gain. Fig. 5 shows the linearity characteristics (first and second channel adjacent power ratio's – ACP1 and ACP2, respectively) for this amplifier. Note that in this case, the dependence of these parameters can deviate significantly from just the DC current gain. This shows the importance of separating out the base thickness and doping contributions to the DC gain and RF performance parameters. Finally, Fig. 6 shows the PAE for the circuit. The PAE also is independent of DC gain. The

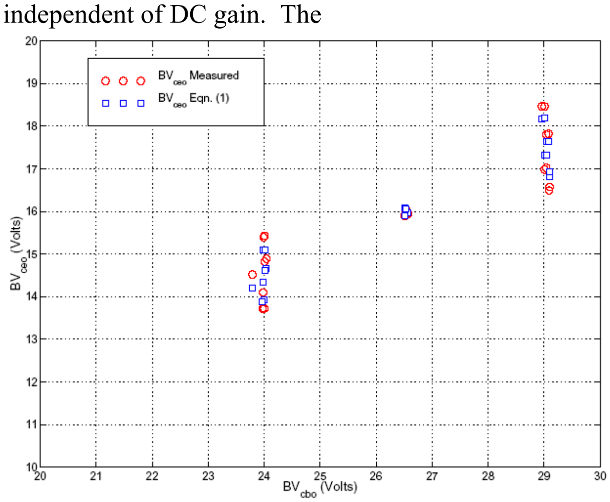

Fig. 3 Open base breakdown voltage, BVceo, versus open emitter breakdown voltage, BVcbo. Circles are measured data, squares are fit to Eqn. 2 using n=9.6

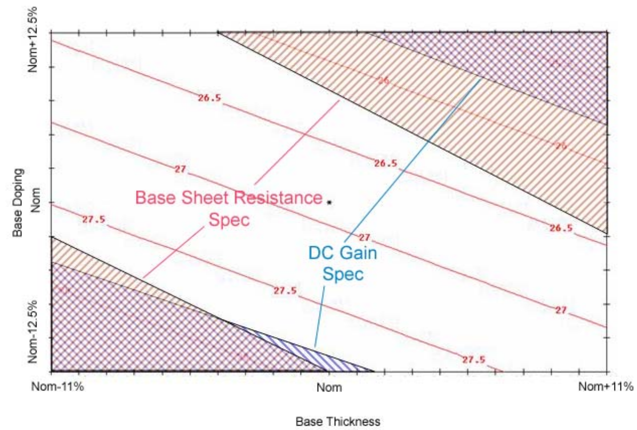

Fig. 4. RF Gain (under IS-95 modulation) for variation in base thickness and doping.

collector thickness did not have a significant affect on this module for this modulation scheme. When the collector thickness does play a role, plots similar to these are generated for each collector thickness and compared to see where parts fall out of spec. This methodology can be applied to any measured parameter from these circuits, including yield. If required, this early feedback on parameter sensitivity allows design fixes to be implemented that result in much improved circuit yield that would otherwise go undetected until full production ramp-up. This type of systematic DOE approach also allows FMEA (Failure Modes and Effects Analysis) analysis for product performance so that if wafer yield varies on future lots, a simple comparison will help identify the root cause. As an example, if a circuit exhibits performance failure at some combination of base doping, base thickness, and collector thickness, but was within PCM pass/fail criteria, we can easily compare it to the parameters in Fig. 1 (or a similar plot) to determine what PCMs should be looked at to identify the cause of the yield loss and tie it back to

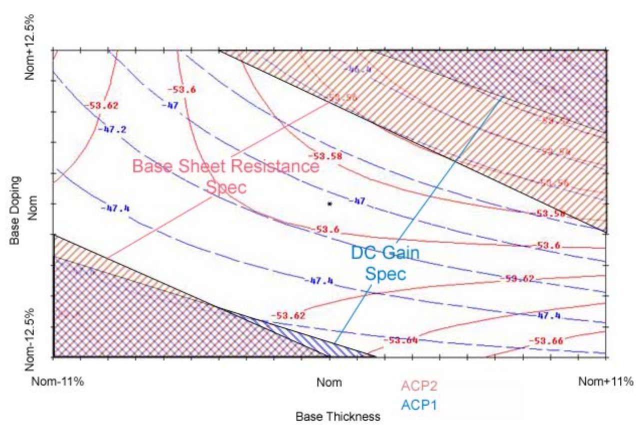

Fig. 5. Linearity variation as a function of base doping and thickness for both first (ACP1) and second (ACP2) channel linearity.

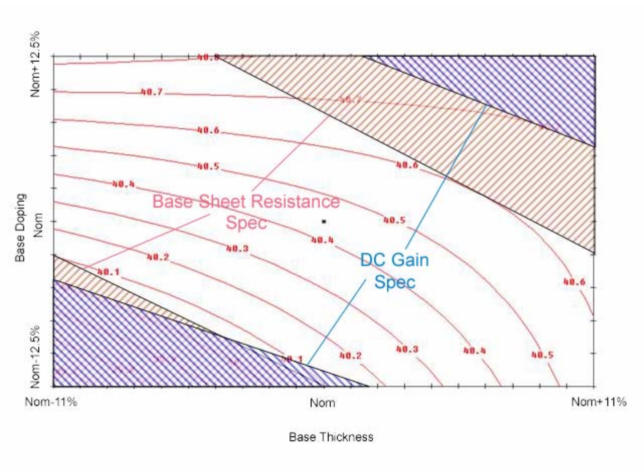

Fig. 6 Power Added Efficiency (PAE) as a function of base thickness and doping

the material characteristics. This information can, in turn, be fed back to material suppliers ensuring that wafer specifications are related to high product yields and not arbitrary values. Combining this performance data with full characterization measurements over temperature, bias, and frequency allows us to confidently set part specifications, and develop data sheets, for our products early in the product development life cycle. The data from these wafers is also extremely useful for guiding future process development and statistical modeling efforts [2]. Such statistical models allow the circuit yield to be optimized in unison by accounting for the expected material variation early in the design cycle. Continuing to run these DOE wafers provides on-going data for validation and refinement of such models and provides greater insight into possible yield pit-falls.

CONCLUSIONS

We have developed and presented a DOE approach to epi material selection for new product qualification. This approach provides us with greater insight into the device characteristics from analyzing the PCM data and comparing to published data. In particular, the relationships between β and R_{bsh}, as well as the effect of β on BV_{ceo} were evaluated and showed behavior contrary to what was expected. This approach allows greater insight into the causes of product variation when the contributing factors are not easily determined from PCM measurements and provides product-based standards for acceptable material specifications. In particular, it allows the effects of base doping and thickness to be independently determined since they cannot be easily separated from normal DC PCM measurements. This approach also provides a critical link between material parameters and PCMs, which then allows the link between PCM and product performance to be made (via the material parameters), as we have demonstrated. It also is very efficient, since the specific structures fit in a single wafer lot and can be “banked” and used for any new product in development, making sure that there is always a good spread of material available to quickly evaluate module sensitivity. This also allows the required sampling of multiple material lots to be achieved within this minimal number of fabrication lots, resulting in time and money savings. Most importantly, this methodology allows us to provide our customers with a data sheet, detailing expected product variations, due to material, in the pre-production phase of the product instead of waiting for high volume production data.

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ACRONYMS

HBT: Hetero-junction Bipolar Transistor
DOE: Design of Experiment
PCM: Process Control Monitor
ACP: Adjacent Channel Power
PAE: Power Added Efficiency
FMEA: Failure Modes and Effects Analysis