Device Zoo: A Smart Tool for Device Performance Optimization

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Abstract

GaAs/AlGaAs pseudomorphic high electron mobility transistors (PHEMTs) and InAlAs/InGaAs metamorphic HEMTs (MHEMTs) have been used as modeling devices for investigation of the power of the statistical Design of Experiment (DoE) approach. The Device Zoo presented here is based on the DoE approach and is shown to be an effective tool for adjusting the layout and epi-structure parameters of HEMTs for any system or application requirements. This approach may also shorten time-to-market by selecting the optimal device.

Empirical models for the small signal parameters and threshold frequency have been developed and verified and will be presented as an application example of the Device Zoo. Since the small signal performance parameters are sensitive to the HEMT lateral geometry, the models have been used for process variation control and definition of the layout parameters. The Device Zoo approach emerges as a useful tool for correlating structural and performance parameters and for design optimization.

INTRODUCTION

Optimization of HEMT performance for different frequency bands and applications involves tradeoffs of the device parameters. Device performance is dictated by the interplay between lateral layout and vertical epi-structure parameters. The interplay leads to complicated dependence of the DC and RF device parameters on device geometry, which may be analyzed only through a robust statistical approach.

In the present work, we demonstrate the strength of the Device Zoo approach, where the device matrix has been based on orthogonal two-level factorial DoE. In the framework of this approach, we have succeeded to extract reliable empirical models of the key device parameters, demonstrating clear and unambiguous impact of the device geometry on its performance.

We have found that application of this approach is highly effective at different stages of technology development. At the feasibility stage, the Device Zoo is used as a “technology debugger”, revealing various “side-effects” through “non-physical” behavior of the empirical model. At the device optimization stage, the Device Zoo makes it possible to successfully achieve “one – pass” design, where the optimal device parameters may be reached through a single fab run. At the technology evaluation stage, in addition to the traditional manufacturing monitors, among which the Device Zoo is the most sensitive, the latter can monitor the coefficients of the empirical model rather than the absolute values of the device parameters. At the design and simulation stage, empirical models can provide additional optimization parameters.

EXPERIMENT

The lateral geometrical parameters and their interactions have a complex influence on the small signal performance of the transistor. Therefore, the Design of Experiment (DoE) approach [1],[2] has been used to develop an empirical model for small signal transistor performance. The DoE method makes it possible to design a device matrix with different lateral geometrical parameters in such a way that correlations between the geometrical parameters and measured electrical performance can be statistically established.

The device matrix has been designed by a two-level factorial DoE and consisted of 16 different devices. Various combinations of lateral layout parameters are shown in Figure 1. The key lateral layout parameters of a transistor are shown in Figure 2. The matrix is referred to as a Device Zoo. The variables for the Device Zoo were based on a combination of the key lateral layout parameters of the baseline 0.15 μm PHEMT and MHEMT. The Device Zoo was designed such that the modeled electrical characteristics of the matrix would take into account all the main and second order effects. The general form of the equation describing the effect of the layout parameters on the performance parameters is given by:

$$\Phi = A_0 + \sum_n A_n \cdot P_n + \sum_{n,m} A_{nm} P_n P_m \qquad (1.1)$$

where Φ is the modeled performance parameter, $P_{n,m}$ are the layout parameters and $A_{n,m}$ are the correlation coefficients.

For modeling purposes, the Device Zoo was defined on a mask set and fabricated on 4" diameter wafers. The layout parameters and dimension ranges are presented in Table I. All measurements were performed "On-wafer", using a HP 4155C semiconductor analyzer and an 8510C network analyzer. The statistical data analysis was carried out using SAS software (JMP 5.0).

TABLE 1.
FIVE KEY LAYOUT PARAMETER RANGES FOR THE 16-DEVICE ”DEVICE ZOO” MATRIX

Lg [μm]	Lds [μm]	Lsg [μm]	Lsr [μm]	Wr [μm]
0.1 ÷ 0.15	2 ÷ 2.5	0.6 ÷ 0.8	0.4 ÷ 0.6	0.6 ÷ 0.8

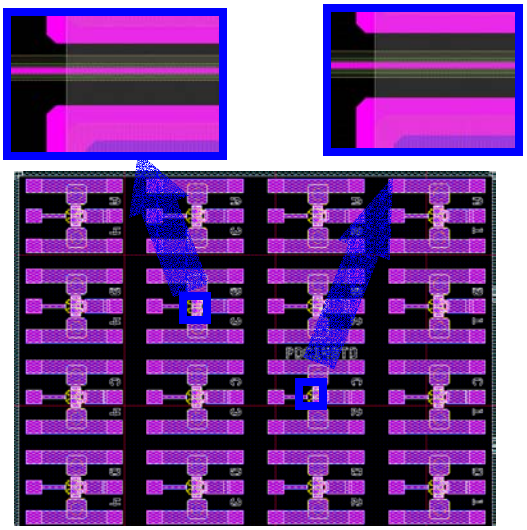


Figure 1. Matrix contains 16 different devices with various combinations of key lateral layout parameters

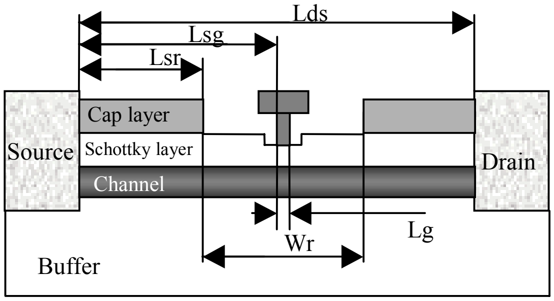


Figure. 2. Schematic diagram of the double-recessed HEMT used. Source-drain distance (Lds), source-gate distance (Lsg), source-recess distance (Lsr), recess width (Wr) and gate length (Lg) are indicated. Their ranges of numerical values are given in Table I.

RESULTS AND DISCUSSIONS

The summary of the DoE analysis is presented in this section. The small signal gain (S21), input and output return loss (S11, S22), maximum available gain (MAG), current gain (H21) are the common figures of merit for high frequency transistor performance. These figures of merit are taken as the performance parameters used in the empirical model, which relates transistor performance and its lateral geometrical parameters. For illustration purposes, we have focused on S11, both angular and amplitude values, since they are indicative parameters for transistor characterization.

Figure 3 shows the correlation of S11 with geometrical parameters on the frequency of interest (40 GHz). The figure shows that the amplitude of S11 is mostly affected by the Lsg. This is in agreement with the accepted physical model of HEMT [3,4], since Lsg relates to the input capacitance, Cgs. We also note that the S11 amplitude is inversely proportional to Lsg and its phase is directly proportional to Lds, Lsg, and Lsr.

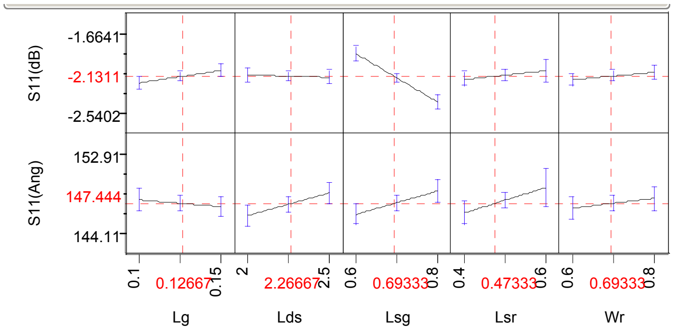


Figure 3. Correlation of S11 with lateral geometry parameters

Fig. 3 shows how geometrical variation may be translated into device performance. For example, if Lsg is increased from 0.6 µm to 0.8 µm, S11 improves by 0.52 dB. This result highlights the sensitivity of the device performance to Lsg. Fig. 3 provides only visual information but quantitative empirical model is obtained by considering the sensitivity coefficients summarized in Table 2.

TABLE 2
CORRELATION COEFFICIENTS FOR S11

	Intercept	Lg [µm]	Lds [µm]	Lsg [µm]	Lsr [µm]	Wr [µm]
Coefficients	A_0	A_1	A_2	A_3	A_4	A_5
S11 amplitude(dB)	-1.03	2.7	-0.06	-2.64	0.49	0.4
S11 phase (deg)	119	-14.5	5	12.8	13.9	5.4

Multiplying the target value for each geometrical parameter by the appropriate sensitivity coefficient from Table 2, and adding the contributions along with the intercept value, the model parameters for S11are calculated.

$$\text{Amplitude (dB)} = -1.03+2.7\cdot Lg-0.06\cdot Lds-2.64\cdot Lsg+0.49\cdot Lsr+0.4\cdot Wr$$

$$\text{Phase (deg)} = 119-14.5\cdot Lg+5\cdot Lds+12.8\cdot Lsg+13.9\cdot Lsr+5.4\cdot Wr$$

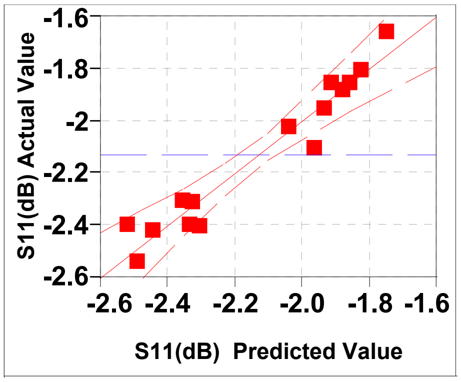


Figure 4. Correlation between measured S11 and predicted values

In Fig. 4 the measured values of S11 are plotted as a function of the predicted values. The model including only the main effects, predicts the measured values with accuracy of 94 %. Therefore, for the sake of simplicity, second order effects are excluded without any loss of information.

Using the same method we have obtained correlation coefficients for S21, S22, MAG and H21. All the coefficients are summarized in Table 3.

TABLE 3
CORRELATION COEFFICIENTS

Parameters	Intercept	Lg [μm]	Lds [μm]	Lsg [μm]	Lsr [μm]	Wr [μm]
Coefficients	A_0	A_1	A_2	A_3	A_4	A_5
S11(dB)	-1.03	2.7	-0.06	-2.64	0.49	0.4
S11(Ang)	119	-14.5	5	12.8	13.9	5.4
S21(dB)	9.19	-16.69	0.1	-3.44	1.81	1.13
S21(Ang)	6.6	-72.1	0.2	16	-2	-3.9
S22(dB)	-5.94	-0.71	0.17	-7.17	5.07	3.24
S22(Ang)	-108.1	-76.8	-1.9	-41.2	47.8	23.9
MAG	18.68	-13.65	-0.16	-9	1.63	1.57
H21	9.85	-10.59	0.19	0.63	-1.89	-0.85

Empirical models to the rest of small signal parameters are represented below:

$$S21(dB) = 9.19 – 16.69 \cdot Lg + 0.1 \cdot Lds – 3.44 \cdot Lsg + 1.81 \cdot Lsr + 1.13 \cdot Wr$$

$$S21(deg) = 6.6 – 72.1 \cdot Lg + 0.2 \cdot Lds + 16 \cdot Lsg - 2 \cdot Lsr – 3.9 \cdot Wr$$

$$S22(dB) = -5.94 – 0.71 \cdot Lg + 0.17 \cdot Lds – 7.17 \cdot Lsg + 5.07 \cdot Lsr + 3.24 \cdot Wr$$

$$S22(deg) = -108.1 – 76.8 \cdot Lg – 1.9 \cdot Lds – 41.2 \cdot Lsg + 47.8 \cdot Lsr + 23.9 \cdot Wr$$

$$MAG = 18.68 – 13.65 \cdot Lg - 0.16 \cdot Lds – 9 \cdot Lsg + 1.63 \cdot Lsr + 1.57 \cdot Wr$$

$$H21 = 9.85 – 10.59 \cdot Lg + 0.19 \cdot Lds + 0.63 \cdot Lsg – 1.89 \cdot Lsr – 0.85 \cdot Wr$$

This set of equations can predict any of the specified small signal parameters and therefore optimize device performance for a given application. This equation set can be integrated into the HEMT model that is used in the circuit simulation software.

In the typical simulation software HEMT model comprises 3 geometrical parameters: the gate width (Wg) the gate Length (Lg) and the number of gate fingers (n). The Device Zoo modeling approach provides an additional degree of freedom for design optimization and sensitivity analysis at the circuit simulation level. Standard sensitivity analysis includes capacitance, resistance and metal thickness variations of the passive circuits. The sensitivity analysis based on the Device Zoo modeling approach allows taking into account HEMT small signal changes due to process variation.

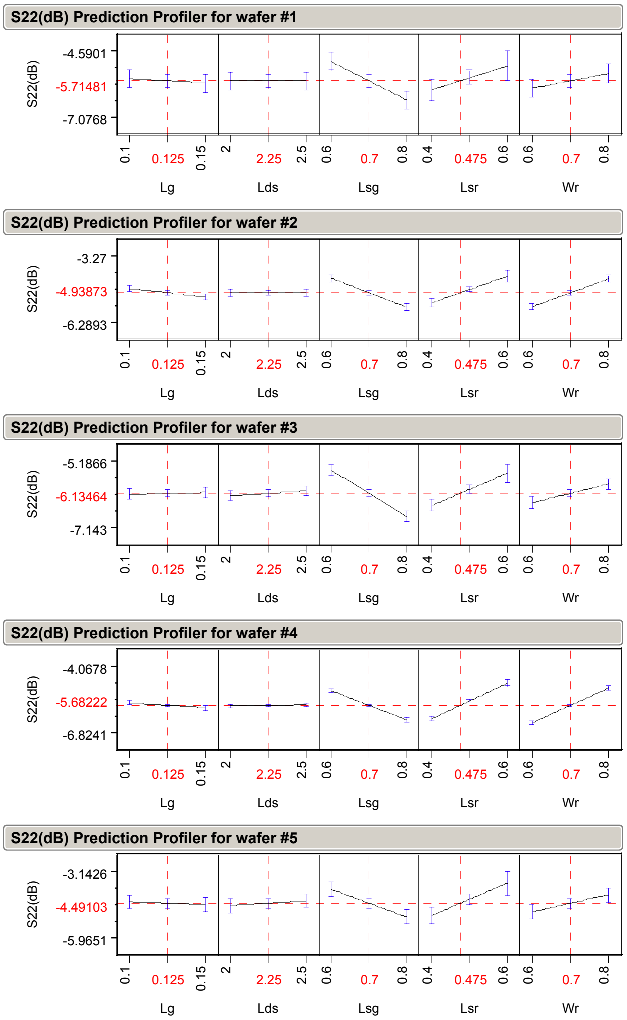
The empirical model presented here can be used as a “technology debugger” also at the production level. It indicates process variations through “non-physical” behavior of the model. A standard debugging tool for process deviation is the Process Control Monitor (PCM), which helps verifying process stability [5].

Small signal transistor parameters are very sensitive to process variation thus they serve as a good PCM. Yet, typical PCM provides only absolute values of the process shift. And there is no information about the source of this shift. However, with the help of Device Zoo approach, the empirical model can translate shifts of the S-parameters into changes of the geometrical parameters of the studied transistor.

In addition to PCM, which is usually applied to a standard matrix, we show that the Device Zoo matrix is a much more informative tool, since it indicates the role of each geometrical factor in determining the performance. The matrix can be reduced to eight devices, because only the first order effects need to be considered. Thus, the higher level of process monitoring can be achieved by tracing the empirical model coefficients.

We have found that S22 is very sensitive to the following physical parameters: Lsg, Lsr and Wr. Thus, S22 can be used as monitoring parameter in the extended PCM.

To illustrate this method, a Device Zoo matrix has been measured on 5 different wafers. Figure 5 presents correlation coefficients for S22 for each wafer.


S22(dB) Prediction Profiler for wafer #1

S22(dB) Prediction Profiler for wafer #2

S22(dB) Prediction Profiler for wafer #3

S22(dB) Prediction Profiler for wafer #4

S22(dB) Prediction Profiler for wafer #5

Figure 5. S22 as a function of Lg, Lsg, Wr, Lsr, Lds for 5 wafers

Fig. 5 shows that all 5 wafers demonstrate very similar slopes. Table 4 summarizes the major correlation coefficients and their variation from wafer to wafer. The small difference in these coefficients represents process variation.

`TABLE 4

CORRELATION COEFFICIENTS FOR 5 WAFERS

	#1	#2	#3	#4	#5
Lsg [µm]	-7.1	-6.5	-6.7	-6	-5.8
Lsr [µm]	4.49	5.97	4.71	7.31	6.83
Wr [µm]	3.17	6.17	3.21	7.05	3.59

HEMT is the technology of choice for wide frequency range applications. Therefore it is highly important that the model is compatible across the wide band. In order to verify this statement, we have created an empirical model for different frequencies. This case will be illustrated by a small signal gain model. Figure 6 presents correlations between S21 and geometrical parameters at three arbitrary frequencies: 20 GHz, 30 GHz and 40 GHz.

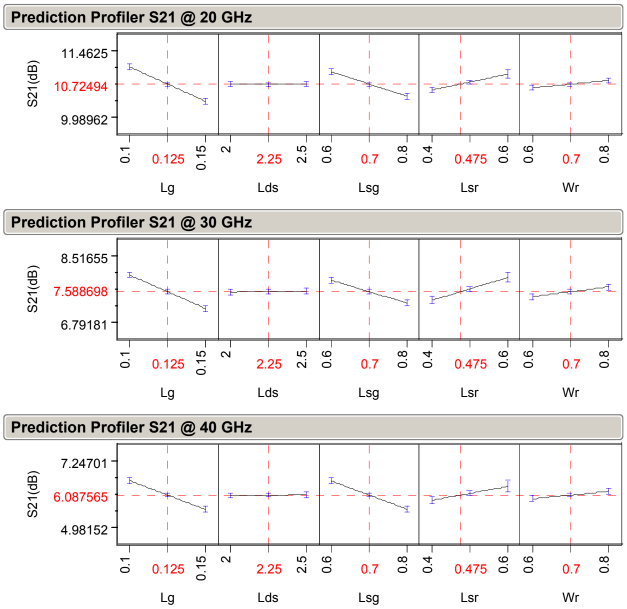


Figure 6. S22 as a function of Lg, Lsg, Wr, Lsr, Lds for 3 frequencies.

TABLE 5

CORRELATION COEFFICIENTS AT 20 GHZ, 30 GHZ AND 40 GHZ.

	Lg [µm]	Lds [µm]	Lsg [µm]	Lsr [µm]	Wr [µm]
20 GHz	-15	-0.015	-2.7	1.7	0.8
30 GHz	-17	0.05	-2.9	2.9	1.2
40 GHz	-19	0.05	-4.7	2.3	1.2

The major coefficients (Lg, Lsg, and Lsr) do not change the trend. Yet, the change in absolute values can be explained in terms of the physical model of HEMTs. Since both Lsg and Lg are related to C_{gs}, the increment of the corresponding coefficient is the result of an impedance change with frequency. Thus, we conclude that the same model is accurate across the 20 ÷ 30 GHz frequency band, while the model for higher frequencies requires coefficient modification. It should be noted that the model modification could be realized on the same Device Zoo. The obtained empirical model can be integrated into the circuit simulation for wide band application.

The Device Zoo approach has been applied to the metamorphic HEMT (MHEMT) technology. Similar small signal empirical models have been obtained, which will be described elsewhere.

Based on this knowledge, models for large signal performance and noise figures will be developed.

CONCLUSIONS

We have presented systematic evaluation of the Device Zoo approach as a powerful tool for HEMT performance optimization through empirical modeling of geometrical process parameters. Thorough analysis shows that the obtained small signal empirical models have a well-defined physical behavior. These models can be integrated into circuit simulation software, enabling high-level optimization for small signal performance. The frequency-dependent analysis shows that the Device Zoo approach can be implemented for empirical model creation for a wide frequency range.

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ACRONYMS

DoE: Design of Experiment
HEMT: High Electron Mobility Transistors
PHEMT: Pseudomorphic High Electron Mobility Transistors
Lg: Gate Length
Lds: Drain-Source Distance
Lsg: Source-Gate Distance
Lsr: Source-Recess Distance
Wr: Width of Recess