A Designed Experiment
for the Optimization of PHEMT Layout and Profile

by
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ABSTRACT
Results are reported of a designed experiment focused on channel layout and profile parameters for a GaAs/AlGaAs/InGaAs Kx-Band PHEMT with a double heterostructure active layer, a double recess, and 0.25 μm T-Gate. On a single mask, a two-level full factorial $L_4(2^3)$ array of discrete PHEMT layouts was incorporated with the following input variables: wide (channel) recess size, gap between wide recess and source ohmic contact, and gap between gate and source edge of wide recess. On the mask set, complete $L_4(2^3)$ arrays were included for differing sizes of the channel defined by the source/drain ohmic space to test the impact of this variable. To evaluate importance of active layer, PHEMTs were fabricated on wafers with their planar doping adjusted to provide three levels of 2DEG, 2.1E12 cm$^{-2}$, 2.7E12 cm$^{-2}$, and 3.0E12 cm$^{-2}$.

Introduction
Optimization of PHEMT performance for differing frequency bands and applications involves tradeoffs among the various device parameters. An increase in breakdown voltage, for example, is generally accompanied by a reduction in $F_t$, making it difficult to simultaneously obtain both high frequency and high voltage operation. Several factors in layout and design control device parameters. The study described here was an attempt at sorting out which parameters are most important in defining PHEMT performance and how they should be adjusted to achieve desired requirements. This data is especially useful for designing multi-function devices where separate PHEMTs fabricated in the same MMIC are required to perform with the optimal tradeoff for power and gain applications.

The methodology adopted for this study was that of two-level factorial designs described in reference [1] with modifications. This enabled the maximum acquisition of data from the minimum number of experimental runs. It is an empirical technique, providing a path to performance optimization requiring little theoretical insight.

Description of Experiment
PHEMT Process. The variables for the designed experiments were perturbations of the parameters of a baseline Kx-band power PHEMT process well-defined in the Northrop Grumman Lab during several years of fabrication. The key elements are illustrated in Figure 1. Salient points of this process include: (i) double heterostructure GaAs/AlGaAs/InGaAs MBE-grown starting wafers which incorporate Si-planar doping to produce a two-dimensional electron gas (2DEG) in the InGaAs channel, (ii) conventional alloyed AuGeNiAu alloyed ohmic contacts and device isolation by oxygen damage implant, (iii) an initial “wide” recess to increase breakdown, (iv) a recessed 0.25 μm T-gate, and (v) 4 mil final thickness with dry etched via holes for ground contacts.

![Figure 1. PHEMT cross-section showing key parameters evaluated in this study.](image-url)
The PHEMT design chosen was that of a standard, wafer-level probeable test pattern shown in Figure 2. It is a 500μm total periphery discrete with gates arranged as 10x50μm fingers on a 21μm pitch and has been used as a final process monitor for several years. Its characteristics for the baseline process are well understood. The standard test is an rf-probe for extraction of the circuit model elements shown in Figure 3 as well as dc- and rf-parameters. For the work described here, experimental layouts were designed by incorporating modifications of the parameters in Figure 1 into this basic layout.

The size of the gap between the source and drain ohmics, L_{sd}, was also considered significant and was chosen as a fourth dimension in variable space. Moving the ohmics closer to the wide recess would reduce the source and drain resistive parasitics, thereby improving gain. To test this, several splits on the value of L_{sd} were chosen and for each of these an L_{sd}(2) array of experimental layouts varying L_{wr}, L_{nwr} and L_{wr,g} was designed. For each value of L_{sd} a different high value of L_{wr} in the two-level factorial was chosen.

The general effects of changing the channel layout parameters in Figure 1 are well known. The objective of this study was to quantify their impact so that optimum choices can be made between competing requirements for use in MMIC designs.

A dedicated mask set incorporating these variations in layout plus some other designs was prepared. The values of L_{sd} and two-levels chosen for each parameter are given in Table I. These dimensions are in microns and are CAD dimensions. Actual dimensions on a processed wafer will be slightly different. The labelling convention for each cell was in the order given in Table I. Thus, for L_{sd}=2.5μm, the cell with L_{wr}=1.25μm, L_{nwr}=center, and L_{wr,g}=0.075 is (+1+1-1).

<table>
<thead>
<tr>
<th>L_{sd}</th>
<th>L_{wr}</th>
<th>L_{nwr}</th>
<th>L_{wr,g}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.75</td>
<td>0.5</td>
<td>+1</td>
<td>0.7</td>
</tr>
<tr>
<td>2.0</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>2.5</td>
<td>0.5</td>
<td>1.25</td>
<td>0.5</td>
</tr>
<tr>
<td>3.5</td>
<td>0.5</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>4.5</td>
<td>0.5</td>
<td>2.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

PHEMT Active Layer and 2DEG. It was found from a literature survey of PHEMT devices that a wide range of densities of the two dimensional electron gas (2DEG) in the InGaAs conductive channel were used in the industry. This was chosen as a fifth dimension in variable space. For this experiment, wafers were specified and ordered with the doping in the planar layers modified to produce densities of 2.1e12cm^{-2}, 2.7e12^{-2}, and 3e12cm^{-2}.

Lot Fabrication. Two eight-wafer fabrication runs were completed, one composed entirely of wafers with baseline active layers the other comprising a split among the active layer types. Processing proceeded normally for both lots. The saturation currents measured for the wafers with experimental active layers scaled as the ratio of the 2DEGs. For all wafers the etch rate for the wide recess was proportional to the size of L_{wr}. Thus, a greater than normal variation in L_{ds} was observed across the various L_{sd}(2) arrays. This was accounted for in the data reduction by using only discrete with L_{ds} in a nominal range.
Characterization. Test capacity limitations made it necessary to choose a subset of the total number of discretes for test. Data was obtained for (i) one layout for all wafers, (ii) the complete $L_{sd}(2^2)$ array on wafers with two doping profiles for two selected values of $L_{sd}$, (iv) all values of $L_{sd}$ for one cell on two wafers with one profile, and (v) selected other cells.

Data reduction for the fully saturated arrays proceeded using the techniques outlined in [1]. First, an average value and estimate of its standard deviation, $s$, for a parameter, $P$, is computed for each of the eight cells. These average values plus the overall average are used to derive

$$P(L_{sd}=L_{wtr}=L_{wtr,d}) = P_{avg} + 0.5(AL_{wtr} + BL_{vtr} + CL_{wtr,d} + DL_{sd} + EL_{wtr,d} + FL_{wtr} + GL_{wtr,d} + HL_{wtr})$$

where $P_{avg}$ = average value of $P$ over all, and $A,B,C,D,E,F,G$ = main and interaction effects coefficients computed using Yates' Theorem [1]. The values for $L_{sd}$, $L_{wtr}$, and $L_{wtr,d}$ to be used are +1 or -1 as given in Table I. Using the standard deviations for each cell, a standard error for each effect, $se$, was also computed. An effect was deemed significant if it was $>3se$. An example of this procedure, applying Yates' Theorem and computing $se$ for the data from one wafer for the rf transconductance, $G_m$, for $L_{sd}=2.5\mu m$ we obtained:

\[
\begin{array}{ccccccccc}
\text{Avg} & A & B & C & D & E & F & G \\
169.5 & -46.6 & -1.25 & 9.11 & -1.17 & -8.1 & -2.56 & 4.73 \\
se & =5.3 \\
\end{array}
\]

inspection shows that only parameter $A=3se=15.9$. Thus, we derive

$$G_m=169.5-23.3xL_{wtr} \quad \text{for} \quad L_{wtr}=-1,1$$

Where data was taken that was not a full factorial, a simple statistical test was used to determine the significance of variations. Specifically, for a parameter $P$, the average, $P_{avg}$, and estimated standard deviation, $s_P$, were computed from all the data. If $P_{max}P_{min} > 2s_P$ then the variation was considered significant.

Results

Summary of DOE Analysis. Data taken for the full eight-phantom array on four wafers was reduced and equations of the form of equation (1) derived. The impact of these parameters is summarized by the normalized parameters in Table II. To create this table, for each set of effects coefficients the values were divided by the absolute value of the coefficient with the greatest magnitude. Thus, the most important effect has a magnitude of 1 and a sign that shows whether the parameter is directly or inversely proportional to it. Fractions for the other coefficients show their relative impact and zeroes are entered when the coefficient was less than 3se.

<table>
<thead>
<tr>
<th>$P$</th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
<th>$E$</th>
<th>$F$</th>
<th>$G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{max}$</td>
<td>-1</td>
<td>+0.6</td>
<td>0</td>
<td>+0.4</td>
<td>+0.2</td>
<td>-0.2</td>
<td>0</td>
</tr>
<tr>
<td>$V_{knee}$</td>
<td>+1</td>
<td>+0.4</td>
<td>-0.2</td>
<td>+0.9</td>
<td>-0.1</td>
<td>-0.3</td>
<td>-0.6</td>
</tr>
<tr>
<td>$B_V$</td>
<td>+1</td>
<td>-0.1</td>
<td>-0.3</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$G_m$</td>
<td>-1</td>
<td>0</td>
<td>+0.5</td>
<td>+0.1</td>
<td>-0.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$C_{ap}$</td>
<td>+1</td>
<td>+0.2</td>
<td>-0.5</td>
<td>+0.3</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>$F_i$</td>
<td>-1</td>
<td>0</td>
<td>+0.4</td>
<td>+0.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$R_{ds}$</td>
<td>+1</td>
<td>0</td>
<td>-0.3</td>
<td>0</td>
<td>-0.2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

This result highlights the importance of the wide recess size, $L_{wtr}$ which was the principle controlling factor for all these parameters. Further work on refining the PHEMT layout should focus on finer gradations in this parameter. These results confirmed the working hypotheses for $L_{wtr}$ and $L_{wtr,d}$. As expected, breakdown went up while $F_i$ and $G_m$ went down with $L_{wtr}$. Also, reducing $L_{wtr}$ increased $F_i$ and $G_m$ while reducing $V_{knee}$. The results for $L_{wtr,d}$ went counter to that anticipated. $F_i$ and $G_m$ decreased when $L_{wtr,d}$ was smaller. At present the cause is unclear. In Figure 4 are shown graphs quantifying the relationship between $F_i$ and $L_{wtr}$ and breakdown and $L_{wtr}$. The highest values for $F_i$ (and thus best gain performance) are obtained for the condition where the wide recess is small, offset towards the source ohmic, and the gate is in its center. Highest breakdown (and best high voltage performance) was obtained for larger values of $L_{wtr}$ with the wide recess largest on the drain side, that is, with $L_{wtr}$ and $L_{wtr,d}$ minimized. The choice of $L_{wtr}$ for a particular device design objective would be between these two limits based on the device's spec requirements.

Figure 4. Dependence of $F_i$ and breakdown on $L_{wtr}$ for $L_{sd}=2.5\mu m$. 

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Another implication of this data is that for double recess PHEMT processes control of \( L_{\text{rr}} \) is critical. Small drifts in this dimension cause large shifts in key PHEMT parameters.

Testing for all the choices for \( L_{\text{rr}} \) was done for the \((-1,+1,+1)\) site. Based on the 2\( \sigma \) statistical test described above, only \( V_{\text{knee}} \), \( R_{\text{dd}} \), and \( C_{\text{dg}} \) were dependent on this parameter. Data is in Figure 5. In particular, no dependence of \( G_m \) or breakdown was found. As a consequence, by combining data from the \( L_{\text{rr}}(2^3) \) for \( L_{\text{rr}}=2.5\mu m \) and \( 3.5\mu m \) it was possible to derive the relationships for \( G_m \) and breakdown with \( L_{\text{rr}} \) shown in Figure 6. \( G_m \) continues to decrease but breakdown levels off at about \( L_{\text{rr}} \) about 1.25\( \mu m \).

\[ G_m \text{ and breakdown data as functions of } n_t \text{ are graphed in Figure 7. As can be seen, for decreasing } n_t, \text{ breakdown voltage was consistently higher but at the expense of a much lower } G_m. \text{ In addition, as is noted above, the } I_{\text{dss}} \text{ and } I_{\text{max}} \text{ are lower proportional to the reduction in 2DEG. Low } n_t \text{ devices would be good for low frequency, high voltage applications or possibly for obtaining higher voltage operation with a single recess.} \]

\[ \text{Figure 7. Breakdown voltage is improved but } G_m \text{ reduced for wafers with lower } n_t \text{ as is shown here.} \]

**Conclusions**

1. For double-recess PHEMT processes, the size of the wide recess (\( L_{\text{rr}} \)) is critical to determining performance and is a key parameter for process control.
2. Breakdown voltage can be adjusted upward by adjusting the wide recess. This has a negative impact on gain; however, this can be mitigated to by positioning the wide recess closer to the source ohmic contact.
3. Highest gain occurs for small \( L_{\text{rr}} \), but with low breakdown voltage.
4. Power and high gain PHEMTs or MMICs could be fabricated on the same wafer by structuring the channels appropriately for each.
5. Lower 2DEG doping results in higher breakdown but at the expense of other performance parameters. This could be used for high breakdown, single recess processes or for very high voltage devices.

**References**