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Equivalent Circuit Models for InP/InGaAs HPT

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Abstract — Equivalent circuit models for InP/InGaAs HPT are developed. Particularly, the effects of optical illumination on device parameters are considered. Using the models, the optical modulation responses are evaluated and compared with measurement results. The anomalous behavior that photonic bandwidth of HPT decreases as optical power increases can be explained by the increased base-emitter and base-collector capacitances.

Index Terms — Equivalent model, HPT, modulation response, bandwidth reduction, optical power dependency.

I. INTRODUCTION

InP/InGaAs Heterojunction Photo-Transistors (HPTs) are very useful devices for radio-on-fiber applications because they provide not only high optical responsivity but also several attractive functions such as optoelectronic mixing and optical injection-locked oscillation [1-2]. In addition, HPTs can be monolithically integrated with HBT without modification of epitaxial layers, which allows simple optoelectronic integrated circuit (OEIC) process [2].

For the design of HPT-based OEIC, equivalent circuit models that include optical illumination effects are required. The object of this paper is to establish equivalent circuit models for HPT and to describe the effect of optical illumination on the model parameters.

The device used in our investigation is InP/InGaAs single-heterojunction N-p-n HPT with base doping of \(4 \times 10^{19}\) cm\(^{-3}\) and emitter size of 2x10 \(\mu m^2\). The epitaxial layer structure for the device is shown in Fig. 1.

II. HPT DEVICE CHARACTERIZATION

DC characterization was performed with semiconductor parameter analyzer (HP4145B) with different base currents under dark and illuminated conditions. When top illumination is applied to the optical window located on the top of base layer, the HPT exhibits responsivity of 0.22A/W.

Scattering parameters of HPT under dark and illuminated conditions were measured with a vector network analyzer (HP8722D) from 50MHz to 40GHz. Optical modulation responses were measured with the network analyzer and a directly modulated DFB LD from 50MHz to 13.5GHz frequency range after careful calibration of experimental setup.

![Fig. 1. Schematic diagram of InP/InGaAs HPT used in this work.](image-url)
comparable to the directly measured optical responsivity of 0.22A/W.

![Diagram of InP/InGaAs HPT DC model](image)

**Fig. 2.** Developed DC model of InP/InGaAs HPT

The DC model also includes several extrinsic resistances such as \(R_B\), \(R_C\), and \(R_E\). It is well-known that nonlinear base resistance, \(R_B\), has \(I_B\) dependence, which can be modeled with complex equations [6]. In this work, we used a simpler exponential equation given as

\[
R_B = R_{BM} + R_{BB} \times e^{-I_B/A}
\]

where \(R_{BM}\) is the minimum value, and \(R_{BB} + R_{BM}\) is the maximum value of base resistance. \(A\) is the reduction coefficient of base resistance over base current increase. The numerical values for these parameters were obtained by fitting the equation to the value of \(R_B\) determined from small-signal modeling.

![Gummel plot for measured data (point) and simulation results from the DC model (solid line)](image)

**Fig. 3.** Gummel plot for measured data (point) and simulation results from the DC model (solid line).

With the nonlinear relationship between extrinsic resistances and terminal currents, our DC model shows good agreement with measured data for wide ranges of base currents and optical illumination powers as shown in fig. 4.

![IC-VCE characteristics with different \(I_B\) for dark and 0dBm illumination conditions](image)

**Fig. 4.** \(I_C-V_{CE}\) characteristics with different \(I_B\) for dark and 0dBm illumination conditions.

### III. AC SMALL-SIGNAL MODELING

Fig. 5 shows the schematic for the AC small-signal model for InP/InGaAs HPT, which is based on the conventional hybrid-\(\pi\) model. The small-signal model parameters were extracted from measured S-parameters by numerical fitting through the optimization process. These were done for \(I_B\) bias points from 0uA to 150µA with 50µA step, in different illuminated optical power conditions. The parasitic components of HPT on-wafer pad structure were eliminated with the de-embedding technique based on open and short test structures [7]. During numerical fitting process, we found that initial values for model parameters are very important to obtain reasonable model parameters. Therefore, we estimated the initial values in the following manner. The developed DC model indicates the approximate values of \(R_{BE}\) and \(g_m\). It is found that the low frequency value of measured \(S_{11}\) and \(S_{22}\), indicating reflection coefficients of base and collector.
terminals, are strongly related to $R_{BE} + R_{BB}$ and $R_O$ as expressed by

$$R_{bc} + R_{bb} = 50 \times \frac{1 + |S_{11}|}{1 - |S_{11}|}$$  \(\text{(4)}\)

and 

$$R_o = 50 \times \frac{1 + |S_{22}|}{1 - |S_{22}|}.$$  \(\text{(5)}\)

From these estimations, we obtained the approximate values of $R_{BE}$, $R_{BB}$, $R_O$ and $g_m$. These values were employed as the initial values of parameter optimization process.

S-parameter simulation results from developed AC small-signal model biased at $I_B = 100\mu A$ and $V_{CE} = 1.0$ V are compared with measured S-parameters in Fig. 6. From extracted small-signal model parameters with several base currents and optical powers, the dependence of small-signal parameters on input optical power were observed. $R_{BE}$, $R_O$ and $R_{BB}$ are inversely proportional to optical powers, and $C_{be}$ and $C_{bc\text{, int}}$ increase exponentially with optical power. These results are summarized in Table 1.

<table>
<thead>
<tr>
<th>Optical Power (dBm)</th>
<th>$R_{BB}$ (Ω)</th>
<th>$R_{BE}$ (Ω)</th>
<th>$R_O$ (KΩ)</th>
<th>$C_{BC\text{, ext}}$ (fF)</th>
<th>$C_{BC\text{, int}}$ (fF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark</td>
<td>350</td>
<td>475</td>
<td>7.5 K</td>
<td>212</td>
<td>5.3</td>
</tr>
<tr>
<td>-12dBm</td>
<td>315</td>
<td>434</td>
<td>5.3 K</td>
<td>261</td>
<td>6.15</td>
</tr>
<tr>
<td>-8dBm</td>
<td>290</td>
<td>388</td>
<td>4.4 K</td>
<td>303</td>
<td>6.8</td>
</tr>
<tr>
<td>-5dBm</td>
<td>262</td>
<td>320</td>
<td>2.2 K</td>
<td>375</td>
<td>6.8</td>
</tr>
<tr>
<td>-2dBm</td>
<td>225</td>
<td>103</td>
<td>1.6 K</td>
<td>953</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Table 1. Optical power dependencies of AC small-signal model parameters biased at $I_B = 100\mu A$ and $V_{CE} = 1.0$ V

IV. OPTICAL MODULATION RESPONSE

For the high-speed photo-detection applications, the photonic bandwidth is one of the important parameters. However, our experimental results show that the photonic bandwidth of HPT strongly depends on incident optical powers [8]. The photonic bandwidth is inversely proportional to optical power as shown in Table 2. To analyze this phenomenon, we simulated the optical modulation response with the developed small-signal model.

<table>
<thead>
<tr>
<th>Optical Power (dBm)</th>
<th>BW-3dB (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark</td>
<td>1.6</td>
</tr>
<tr>
<td>-12dBm</td>
<td>1.32</td>
</tr>
<tr>
<td>-8dBm</td>
<td>1.09</td>
</tr>
<tr>
<td>-5dBm</td>
<td>0.95</td>
</tr>
<tr>
<td>-2dBm</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 2. Optical power dependence of photonic 3dB bandwidth

As shown in Fig. 5, the incident optical signal was modeled by an AC current source between base-collector junction. The detected powers were observed at the collector node. The simulations for optical modulation response were executed for several small-signal models for different optical powers with the fixed bias of $I_B = 100\mu A$ and $V_{CE} = 1.0$ V. The comparison between simulated and measured optical modulation responses at optical power of -12, -8 and -5dBm are shown in Fig. 7. Simulation results are well-matched to experimental results at frequencies below 2GHz. However, at higher frequencies, there is some discrepancy.

From modulation response simulation, we found that $C_{BE}$, $C_{BC\text{, int}}$, $C_{BC\text{, ext}}$ and $R_{BE}$ are the dominant parameters for determining optical modulation response, particularly for
optical 3dB bandwidth. Among these parameters $C_{BC_{-ext}}$ does not show the optical power dependence, and $R_{BE}$ is inversely proportional to optical power. On the other hand, $C_{BE}$ and $C_{BC_{-int}}$ exponentially increase in proportion to optical power as shown in fig. 8. Therefore, the bandwidth reduction effect in high incident optical power can be explained by the increased $C_{BE}$ and $C_{BC_{-int}}$.

Fig. 7. Comparison of measured and simulated optical modulation responses biased at $I_B = 100\mu A$ and $V_{ce} = 1.0\ V$

Fig. 8. $C_{be}$ and $C_{bc_{-int}}$ versus illuminated optical power

V. CONCLUSION

In this paper, equivalent circuit models of InGaAs/InP HPT were developed for DC and AC. The device parameters of developed model can describe the effects of optical illumination. Using the AC small-signal model, the optical modulation responses for HPTs were evaluated and compared with measurement results. In addition, we analyzed the anomalous behavior that photonic bandwidth of HPTs decreases as optical power increases with changes in AC small-signal model parameter values. Based on our model, the photonic bandwidth reduction of HPT in illumination condition can be explained by increased base-emitter and base-collector capacitances.

REFERENCES