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# A Comprehensive Analysis of the Kink Phenomenon in Scattering Parameters $S_{22}$ and $S_{12}$ of GaInP/GaAs HBTs

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## 1. Introduction

A theory based on dual-feedback circuit methodology was used to explain the kink phenomenon in scattering parameters $S_{22}$ and $S_{12}$ of GaInP/GaAs HBTs for the first time. Our results show that the output impedance of GaInP/GaAs HBTs can be represented by a simple series RC circuit at low frequencies and a simple parallel RC circuit at high frequencies in a very accurate way without any corrections. This is because the collector-emitter resistance $r_o$ in GaInP/GaAs HBT is usually very large, quite different from that in MOSFET or GaAs FET which usually exhibits far smaller drain-source resistance $R_{ds}$. In addition, the created small-signal model can not only fit the behavior of $S_{22}$ very well, but also fit all S-parameters accurately in a wide frequency range.

## 2. Expressions of Scattering Parameters $S_{22}$ and $S_{12}$

If the expression for the output impedance $Z_{out}$ of a two-port circuit has been found, then $S_{22}$ is given by

$$S_{22} = \frac{Z_{out} - Z_O}{Z_{out} + Z_O}. \qquad (1)$$

Fig. 1 shows the simplified small-signal π-model and the extracted values of each parameter of our GaInP/GaAs HBTs. If the circuit in Fig. 1 is viewed as a dual feedback circuit [1], [2], at low frequencies, the intrinsic output impedance can be simplified to a series RC circuit as follows:

$$Z_{out,\,i} \approx \left(\frac{Z_{O1}'}{1+g_m' Z_{O1}'} + \frac{g_m'}{(Y_{O1}'+g_m')^2} \times \frac{C_\pi'}{C_\mu'}\right) + \frac{1}{j\omega(1+g_m' Z_{O1}')C_\mu'} \approx r + \frac{1}{j\omega C_s} \qquad (2)$$

On the other hand, at high frequencies, the intrinsic output admittance can be simplified to a parallel RC circuit as follows:

$$Y_{out,\,i} = \frac{1}{Z_{out}} \approx \left[Y_{O1}'\left(\frac{C_\mu'}{C_\pi'+C_\mu'}\right)^2 + g_m' \frac{C_\mu'}{C_\pi'+C_\mu'}\right] + j\omega\left(\frac{C_\pi' C_\mu'}{C_\pi'+C_\mu'}\right) \approx g + sC_P. \qquad (3)$$

where $C_\pi' = C_\pi/(1+g_m R_e)$, $g_m' = g_m/(1+g_m R_e)$, $C_\mu' = C_\mu$, $Z_{O1} = Z_O + R_b$, and $Y_{O1}' = 1/Z_{O1}' = 1/Z_{O1} + 1/r_\pi$. It is this inherent ambivalent characteristic of the output impedance that results in the kink phenomenon in scattering parameter $S_{22}$ of GaInP/GaAs HBTs.

The physical meaning of $S_{12}$ is twice the reverse voltage gain $V_{O1}/V_2$. Therefore, it can be expressed as follows:

$$S_{12} = 2\frac{Z_{out,\,i} \| r_0'}{Z_{out,\,i} \| r_0' + R_c + Z_O} \cdot \frac{sC_\mu'}{sC_\mu' + sC_\pi' + Y_{O1}'} \cdot \left(1 - R_b Y_{O1}'\right) \qquad (4)$$

## 2. Results and Discussions

Key physical and electrical parameters of the GaInP/ GaAs HBTs are listed in Table I. Fig. 2(a) shows that the measured S-parameters of our GaInP/GaAs HBTs range from 0.1 MHz to 20 GHz. Note that the kink phenomenon of $S_{22}$ and $S_{12}$ appear at about 7.5 GHz and 4.5 GHz, respectively. The S-parameters generated from our created simplified small-signal π-model were also shown in Fig. 2. Note that the model data are almost identical with the experimental data and the kink points also appear at about 7.5 GHz and 4.5 GHz, respectively, for $S_{22}$ and $S_{12}$.

The asterisks shown in Fig. 2(b) were the calculated $S_{22}$ data under the conditions that the dual-feedback circuit methodology was adopted to simplify the model shown in Fig. 1 and $1/sC_\pi' >> R_e$ was assumed [1]-[2]. As can be seen, the asterisks fit the experimental data (dash line) of $S_{22}$ well. The calculated frequency corresponding to the kink point is about 6.8 GHz, close to the experimental data 7.5 GHz. To further verify the dual-feedback circuit methodology, we have also applied the method mentioned in [1] to obtain the other three S-parameters, i.e. $S_{11}$, $S_{21}$ and $S_{12}$ (Equation (4)), and compared them with our experimental data. Excellent agreement between theoretical values and experimental data was found (not shown here). What also shown in Fig. 2(b) was the calculated constant resistance (r) circle and constant conductance (g) circle according to Equation (2) and (3). The calculated r and $C_s$ is 70.6 Ω and 0.94 pF respectively for the series RC circuit according to Equation (2). In addition, the calculated 1/g and $C_p$ is 80.0 Ω and 0.057 pF respectively for the parallel RC circuit according to Equation (3) (see Fig. 3). It is clear that the output impedance follows the track of a constant r circle at low frequencies and then a constant g circle at high frequencies precisely without any corrections. This is because the collector-emitter resistance $r_o$ in GaInP/GaAs HBTs is usually very large (in this case, it's about 2.25 MΩ, as shown in Fig. 1), which is very different from that in MOSFETs or GaAs FETs which usually exhibits far smaller drain-source resistance $R_{ds}$, which is between $10^1$ to $10^3$ $\Omega$, generally speaking. Therefore, the $S_{22}$ initiates at a point near the open circuit point of the Smith chart, which makes the low frequency characteristics of $S_{22}$ of HBTs exactly follow a constant r circle without any corrections.

The experimental and calculated magnitude and phase of $S_{12}$ of GaInP/GaAs HBTs were shown in Fig. 4. Note that there is a frequency (4.5 GHz) corresponding to the minimum value of the phase, which in turn corresponds to the kink point of $S_{12}$ in the Smith chart. Kink phenomenon of $S_{12}$ is more commonly seen in HBTs but not in MOSFETs or GaAs FETs mainly because $C_{ce}$ of HBTs is negligibly small ($C_{ds}$ of MOSFETs or GaAs FETs usually much larger than $C_{ce}$). From Equation (4), it is easy to prove there exists a frequency corresponding to a local minimum of phase of $S_{12}$.

## References


[1] S. S. Lu, C. C. Meng, T. W. Chen, and H. C. Chen, *IEEE Trans. on MTT*, vol. 49, no. 2, pp. 333-340, Feb. 2001.

[2] P .R. Gray and R. G. Meyer, *Analysis and Design of Analog Integrated Circuits*, New York: Wiley, 1993, pp. 579-584.


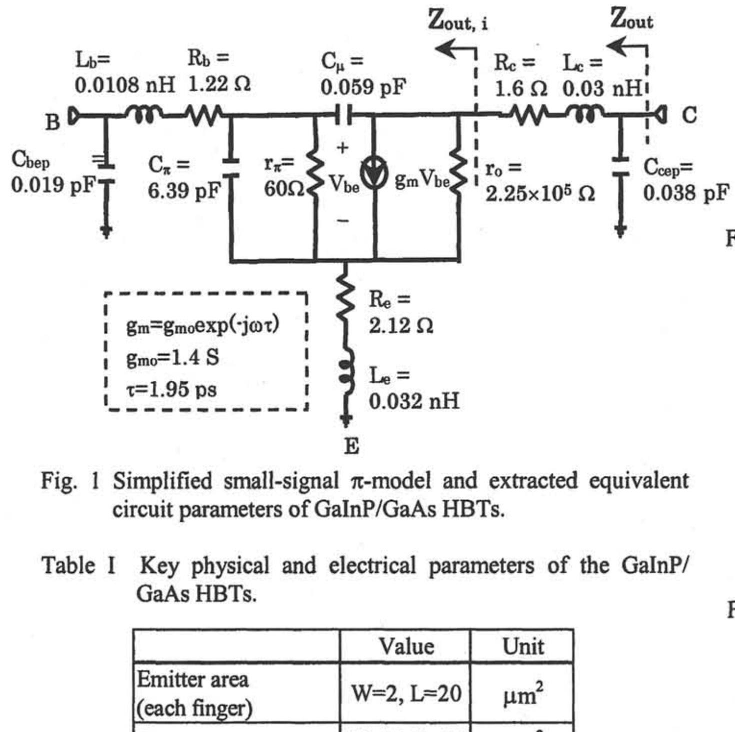


Fig. 1 Simplified small-signal π-model and extracted equivalent circuit parameters of GaInP/GaAs HBTs.

Table I Key physical and electrical parameters of the GaInP/ GaAs HBTs.

| | Value | Unit |
|---|---|---|
| Emitter area (each finger) | W=2, L=20 | $\mu m^2$ |
| Base area | W=13, L=26 | $\mu m^2$ |
| Collector area | W=27, L=28 | $\mu m^2$ |
| No. of emitter fingers | 2 | |
| $BV_{CBO}$ | 25 | V |
| $BV_{CEO}$ | 15 | V |
| $BV_{BEO}$ | 10 | V |
| Maximum $I_C$ | 48 | mA |
| Nominal bias | 12 | mA |
| Peak $f_T$@3.6V | 36 | GHz |
| Peak $f_{MAX}$@3.6V | 135 | GHz |

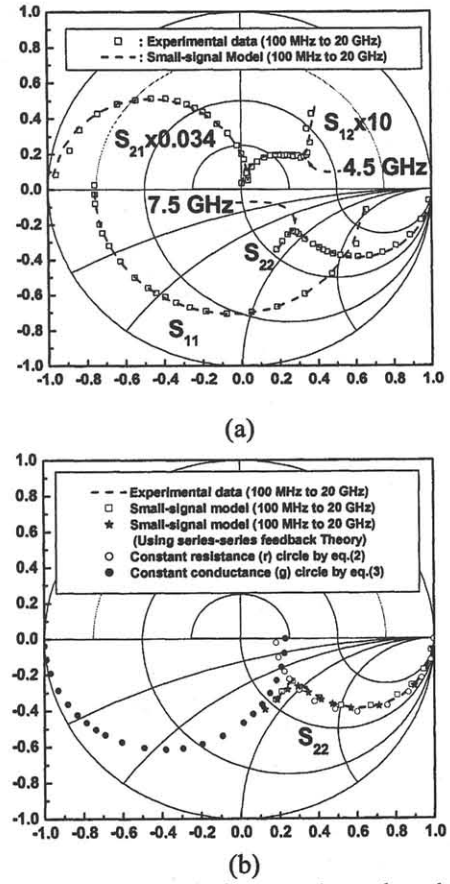


Fig. 2 (a) Comparison of the experimental and calculated S-parameters of GaInP/GaAs HBTs. (b) Comparison of the experimental and various calculated scattering parameters $S_{22}$ of GaInP/GaAs HBTs.

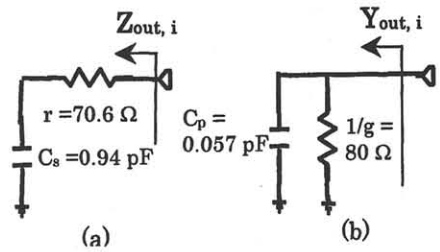


Fig. 3 Equivalent circuit of the intrinsic output impedance/ admittance of GaInP/GaAs HBTs (a) at low frequencies and (b) at high frequencies.

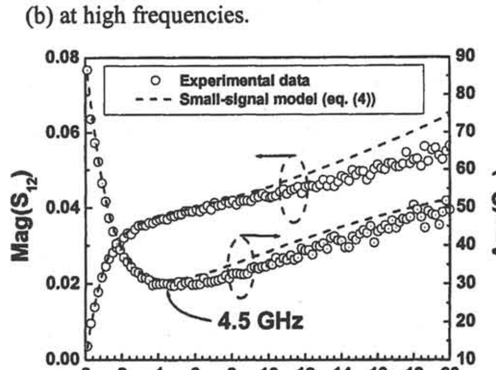


Fig. 4 Comparison of the experimental and calculated magnitude and phase of $S_{12}$ of GaInP/GaAs HBTs.