MICROWAVE NOISE AND SMALL-SIGNAL PARAMETERS SCALING OF InP/InGaAs DHBT WITH HIGH DC CURRENT GAIN

Y. Z. Xiong, G. I. Ng, H. Wang, C. L. Law, K. Radhakrishnan and Jeffrey S. Fu

Microelectronics Center, School of Electrical and Electronics Engineering, Nanyang Technological University, Singapore 639798, Corresponding author, Tel: (65) 7904234, Fax: (65) 7933318, e-mail: eyzxiong@ntu.edu.sg

ABSTRACT

Scaling of microwave noise and small-signal parameters of InP-based Double Heterojunction Bipolar Transistors (DHBTs) with high DC current gain is presented. Three different sizes of InP/InGaAs DHBT are investigated in this work. Because of the low surface and intrinsic recombination of the InP-based DHBT with high current gain, the extrinsic parasitic effect of the device can be neglected. Thus, the microwave parameters of large size InP DHBT can be obtained by scaling the parameters of the smaller emitter size device. Good agreement was obtained between the measured and the calculated results. This scaling technique is very useful for the design of high frequency circuits using InP-based HBTs.

1. INTRODUCTION

InP/InGaAs Heterojuction Bipolar Transistors (HBTs) have exhibited excellent microwave and noise performance and are very attractive for many applications such as high-speed digital circuits, oscillators and low noise amplifiers [1], [2], [3]. The high performances are due to the excellent electron transport properties of InGaAs and the low surface recombination velocity [4]. In GaAs HBT, many researchers have used emitter-ledge to reduce the surface recombination current, thereby increasing the current gain to improve the HBT performances [5]. By using an ultra-thin AlGaAs emitter layer for the extrinsic base surface passivation, the current gain of GaAs HBTs with small size emitter can be maintained to that of large-size emitter devices [6]. As a result, the impact of the device geometric structure and the emitter size on the device performance is significantly reduced. Although the noise scalability of SiGe bipolar transistor was reported in [7], the relationship of noise parameters with emitter-size is not given accurately, and the operating frequency is only 1.6 GHz. Since InP Double Heterojunction Bipolar Transistors (DHBTs) possess inherent low surface recombination velocity, the emitter-size does not have a big effect on the current gain. As a result, an InP-DHBT of larger size emitter can be viewed as consisting of many smaller emitter sub-cells of identical size connected in parallel [8], [9]. Once the microwave parameters of the sub-cells are known, the parameters of the large-size DHBT can be obtained using the technique developed in this study. The impact of the external base-collector capacitor on the scalability of InP/InGaAs DHBTs is also addressed in this work. The good agreement obtained between the measured and the fitted results validate the technique, which is helpful for the design of high frequency circuits using InP-based HBTs.

2. SCALING THEORY

Fig.1 shows the top view of a large-size emitter DHBT. The large-size emitter DHBT can be viewed as consisting of two identical sub-cells with smaller emitter strip width connected in parallel. Assuming that one of the two sub-cells has Y-parameters $[Y_1]$ and noise parameters $[NF_{NIM}{}^1]$, $[R_N{}^1]$ and $[Y_{OPT}{}^1]$, and the other sub-cell has Y-parameters $[Y_2]$ and noise parameters $[NF_{NIM}{}^2]$, $[R_N{}^2]$ and $[Y_{OPT}{}^2]$, and that the two sub-cells are identical, then the noise parameters of the large-size emitter DHBT can be expressed as:

$$[Y]=[Y_1]+[Y_2] \qquad (1)$$

$$NF_{MIN}=NF^1_{MIN}=NF^2_{MIN} \quad (2) \qquad R_N=\frac{R^1_N}{2}=\frac{R^2_N}{2} \qquad (3)$$

$$G_{OPT}=2G^1_{OPT}=2G^2_{OPT} \quad (4) \qquad B_{OPT}=2B^1_{OPT}=2B^2_{OPT} \quad (5)$$

where the NF_{MIN} is the minimum noise figure of the large-size emitter DHBT, and $NF_{MIN}{}^1$ and $NF_{MIN}{}^2$ are the minimum noise figures of the sub-cells. R_N, $R_N{}^1$ and $R_N{}^2$ are the noise resistances, G_{OPT}, $G_{OPT}{}^1$, and $G_{OPT}{}^2$ and

B_{OPT}, $B_{OPT}{}^{1}$, and $B_{OPT}{}^{2}$ are the real and imaginary parts of the optimum input admittances for the large-size emitter and sub-cells, respectively.

Using the same analogy, the noise parameters and Y-parameters of the large-size emitter DHBT consisting of n identical sub-cells can be expressed as follows:

$$[Y] = n[Y^{sub}] \quad (6)$$

$$NF_{MIN} = NF_{MIN}^{sub} \quad (7) \qquad R_N = \frac{R_N^{sub}}{n} \quad (8)$$

$$G_{OPT} = nG_{OPT}^{sub} \quad (9) \qquad B_{OPT} = nB_{OPT}^{sub} \quad (10)$$

where [Y] and [Y^{sub}] are the Y-parameters of the large-size emitter DHBT and the sub-cells, respectively; NF_{MIN} and $NF_{MIN}{}^{sub}$ are the minimum noise figures, R_N and $R_N{}^{sub}$ are the noise resistances, G_{OPT}, $G_{OPT}{}^{sub}$ and B_{OPT}, $B_{OPT}{}^{sub}$ are the real and imaginary parts of the optimum input admittances of the large-size emitter DHBT and the sub-cells, respectively.

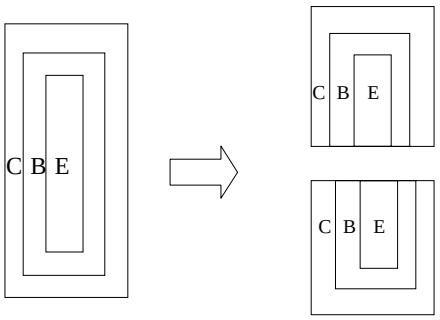

Fig. 1 The top view of a large-size emitter DHBT viewed as two sub-small size emitter DHBTs.

3. EXPERIMENTS AND VERIFICATION

In order to verify the microwave parameter scalability, lattice-matched InP/InGaAs DHBTs were used. Details of the layer structures and the fabrication process have been reported in [10]. The three InP/InGaAs common-emitter DHBTs with emitter area of 5x20μm^2, 5x10μm^2 and 5x5μm^2, respectively, were investigated in this work. Fig. 2 shows a typical Gummel plot for 5x5 μm^2 of InP-DHBT. These devices exhibited an average extrinsic peak current gain of 180 and are almost constant over the entire operating range. The ideality factors of the collector and the base currents for the emitter area of 5x5μm^2 are ~1.1 and ~1.2, respectively.

Microwave parameters were measured on-wafer over the frequency range of 2 to 20 GHz using an ATN-NP5

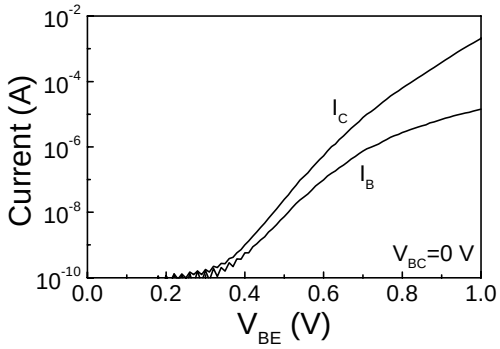

Fig.2 A typical Gummel plot for 5x5μm^2 of InP DHBT.

microwave noise measurement system and Cascade microwave probes. In order to verify the device scalability, the noise parameters and S-parameters for 5x20μm^2, 5x10μm^2 and 5x5μm^2 devices at the same collector current density and collector-emitter voltage were also measured. Fig. 3 shows the fitted and measured S-parameters for the 5x20 μm^2 device. Fitted Y-parameters for 5x20 μm^2 can be calculated using Equation (6) from the measured Y-parameters of 5x10 μm^2 device. Good agreements were obtained between the fitted and the measured S-parameter. However, the errors increased if the S-parameters of the 5x5μm^2 device were used to fit the S-parameters of the 5x20μm^2 device. To explain the observed errors, different ratios between the internal base-collector and external base-collector capacitors due to the different DHBT geometry and layout for the three devices were extracted. The ratios between the emitter-base area and the base-collector area of the 5x20 μm^2, 5x10μm^2 and 5x5μm^2 devices are 100/321, 50/181 and 25/111, respectively. The extracted internal/external base-collector capacitors of 5x20 μm^2, 5x10μm^2 and 5x5 μm^2 devices at the same collector current density J_C = 40A/mm^2 and collector-emitter voltage V_{CE} = 1.5V are 46.2ff/132ff, 24.3ff/78.5ff and 13.2ff/55.5ff, respectively. From the above results, it is shown that the internal base-collector capacitors are almost scalable, but the external base-collector capacitors are not scalable as a result of the non-scalable base-collector area.

To analyze the effect of external base-collector capacitor on the scaling of Y-parameters, the relative error values are used [11]. The fitting errors on the Y-parameters caused by non-scalable external base collector capacitor are shown in Table I. It is shown that as the ratios between the emitter-base area and the base-collector area increase, the errors for the fitted Y-parameters increase, especially for Y_{12}. In order to further illustrate the effect of external base-collector on the Y-

parameters, the small-signal equivalent circuit simulation of the 5x20μm^2 device was done using the base-collector capacitor value of four times the 5x5μm^2 device or two times the 5x10μm^2 device instead of using directly the external base-collector capacitor value of the 5x20μm^2 device. HP-ADS was used for the simulation of the equivalent circuit. The agreement between the simulated Y-parameters and the fitted Y-parameters using the Y-parameters of 5x10μm^2 and 5x5μm^2 devices is good when Equation (6) was used. This demonstrates that the fitting errors for Y-parameters in Table I are caused by the external base-collector capacitor. After correcting the external base-collector capacitor value by using four times the capacitor value of 5x5μm^2 device or two times the capacitor value of 5x10μm^2 device, all the fitted errors are found to be less than 1%.

Table I Fitting percentage errors of the Y-parameters and noise parameters between measured and fitted.

	J_C = 40 A/mm^2			J_C = 80 A/mm^2		
	5x10 fit to 5x20	5x5 fit to 5x10	5x5 fit to 5x20	5x10 fit to 5x20	5x5 fit to 5x10	5x5 fit to 5x20
A_{EB}/A_{BC}	5.3	14.0	47.9	5.3	14.0	47.9
Y_{11}	1.7	5.4	15.4	2.0	6.2	17.8
Y_{12}	2.9	20.0	48.5	3.1	21.5	52.1
Y_{21}	2.2	3.1	12.1	1.6	3.2	14.4
Y_{22}	1.2	7.0	16.1	1.2	6.3	14.4
R_N	1.8	6.8	12.7	2.2	5.3	11.7
NF_{MIN}	0.54	7.1	6.3	0.2	7.3	5.5
Total	2.2	13.5	27.7	2.2	12.8	27.7

The measured and the fitted NF_{MIN} of 5x20μm^2, 5x10μm^2 and 5x5μm^2 devices at the same collector current density J_C = 80A/mm^2 and collector-emitter voltage V_{CE} = 1.5V are shown in Fig. 4. Although the base-collector capacitors are different, the agreement between the measured noise figures at the lower frequencies is good for the 5x20μm^2, 5x10μm^2 and 5x5μm^2 devices thus verifying the validity of Equation (7). For 5x10μm^2 and 5x5μm^2 devices, the measured minimum noise figure is slightly lower than the large devices at higher frequencies. This may be due to the fact that the base-collector capacitors act as negative feedbacks thus reducing the minimum noise figure, especially at higher frequencies. Fig.5 shows the measured and the fitted equivalent noise resistance versus frequency. The measured noise resistance of 5x20μm^2 device is almost equivalent to one-fourth of the measured noise resistance of 5x5μm^2 device and half of the 5x10μm^2 device at low frequency range. However, at higher frequencies, the errors increase. If, instead of the external base-collector capacitor of 5x20μm^2, one uses four times of the external base-collector capacitor value of the 5x5μm^2 (4x55.5 ff) device for simulation, the

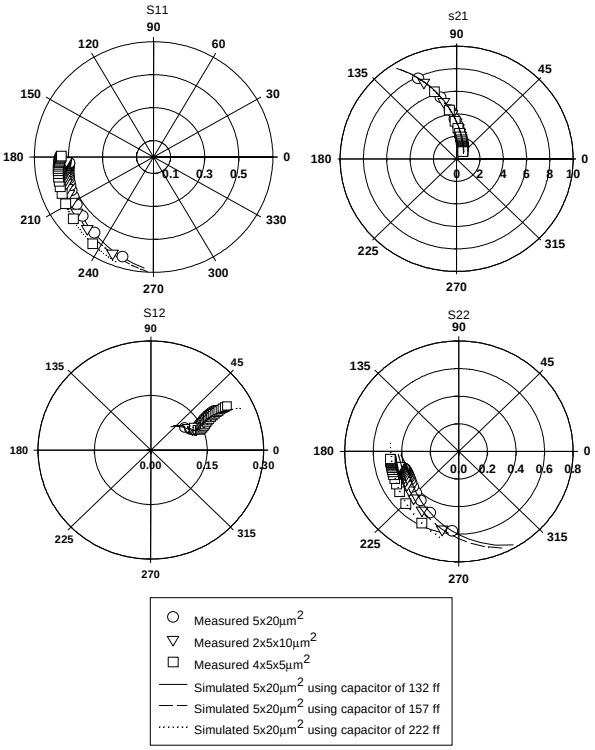

Fig.3 Comparison of measured or fitted and simulated. *S11*, *S21*, *S12* and *S22* from 2-20GHz, V_{CE} = 1.5V and J_C = 40A/mm^2.

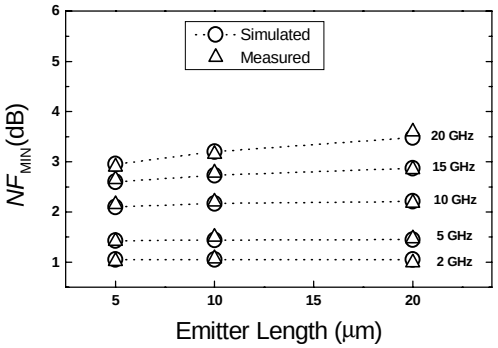

Fig.4 Comparison of the measured and simulated minimum noise figures (NF_{MIN}). Measured minimum noise figures (Δ) for the 5x5μm^2, 5x10μm^2 and 5x20μm^2 at different frequencies. And simulated minimum noise figures (o) for 5x20μm^2 instead of external base-collector capacitor (132 ff) by four times or two times of the 5x5μm^2 (5x55.5 ff) or 5x10μm^2 (2x78.5 ff).

results show that the minimum noise figures agree well with the measured results of the 5x20μm^2 device at low frequency. The simulated noise figures are identical to the measured values of 5x5μm^{2}device. The experimental and simulated results show that the optimum source admittances are also scalable.

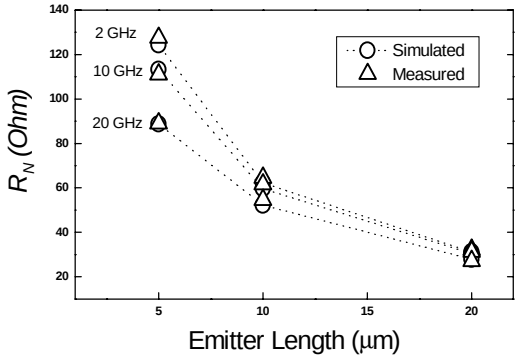

Fig.5 Comparison of the measured and simulated R_N at different frequencies. Measured R_N (Δ) for the 5x5μm^2, 5x10μm^2 and 5x20μm^2. Simulated (o) for 5x20μm^2 instead of external base-collector capacitor (132 ff) by four times or two times of the 5x5μm^2 (4x55.5 ff) or 5x10μm^2 (2x78.5 ff); at emitter length of 5μm, R_N is four times of simulated with 4x55.5 ff; at emitter length of 10μm, the R_N is two times of simulated with 2x78.5 ff.

4. CONCLUSION

The scalability of microwave noise and small-signal parameters of InP double heterojunction bipolar transistor is investigated in this work. Our results show that by taking the external base-collector capacitor into consideration, good scalability can be obtained between large and small devices. A set of equations has been proposed to relate the small-signal parameters and noise parameters of the large and small size devices. Good agreement between the measured and the simulated results was obtained suggesting the validity of our approach. This scalability technique will be useful for the design of high frequency circuits using InP-based HBTs.

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