Analysis of High Frequency Noise of AlGaAs/GaAs HBT

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SUMMARY Hawkins noise model is modified for HBT application. The non-ideal ideality factor of HBT is included in both dynamic resistance and noise figure equations. Emitter resistance is also included. The extraction method of noise resistance $R_e$ is derived based on the method, a simple analytic equation of $R_e$ is derived and experimentally verified. The effects of noise sources on minimum noise figure are analyzed. The dominant noise sources are the shot noise of emitter and collector currents. Generally, when the minimum noise figure is measured at various current levels, there exists an current level at which the slope of minimum noise figure curve is zero. The zero slope current level coincides with the current level at which the noise contribution of the emitter and collector shot noises including the cancellation by correlation of two sources is minimum. Parasitic resistance degrades output noise through the shot noise amplification with a minor effect of the thermal noise of itself.

key words: Hawkins model, minimum noise figure, noise resistance, ideality factor, correlation

1. Introduction

Due to the low 1/f noise, high maximum oscillation frequency $f_{\text{max}}$ and good linearity, AlGaAs/GaAs Heterojunction Bipolar Transistor (HBT) is emerging as a very useful device for a low phase noise oscillator and power amplifier at microwave and millimeter wave bands. As a device for low noise amplifiers, HBT has a poor minimum noise figure $F_{\text{min}}$ than FET. Therefore, it could be assumed that HBT is not useful as a low noise device. But the noise figure of HBT is around 1 dB at mobile cellular/PCS band, which is quite usable. They have a lower optimum impedance, closer to 50 $\Omega$ and smaller noise resistance. Moreover, the current level for minimum $F_{\text{min}}$ is about 1 mA, which is much lower than FET. Due to these favorable characteristics, HBT is a very promising low noise device at a low operation frequency range (which is less than about 5 GHz).

Hawkins model [1] is a simple noise model for Si-BJT. This model includes the analytic expressions for noise figure and optimum source impedance. The high frequency noise model [2]–[4] of HBT is a little different from that of Si-BJT. But the difference mainly stems from the higher operation frequencies of HBT than those of Si-BJT. Within a low frequency range at which HBT is applicable to low noise device, however, it is possible to describe the noise characteristics of HBT using the noise models of Si-BJT with minor modifications. This paper proposes a modified Hawkins model for HBT noise analysis. A method for the extraction of noise resistance $R_e$ from Hawkins model is also developed. Using the new extraction method and modified analytic equation of noise figure, the $R_e$ is calculated and compared with measured results. We have also analyzed the effect of noise sources on $F_{\text{min}}$ using the modified Hawkins noise model with correlated emitter and collector shot noise sources.

2. Modified Noise Model for HBT

2.1 Modified Hawkins Model

A simple noise equivalent circuit of Si-BJT is shown in Fig. 1(a) where $i_e$ emitter current shot noise source, $i_c$ collector current shot noise source, $e_{tb}$ thermal noise source due to base resistance($R_b$), $e_{m}$ thermal noise source due to emitter resistance($R_e$), $C_{TE}$ junction capacitance, $r_e(=kT/qE)$ dynamic resistance, $\alpha$ common base current gain. $\alpha$ is a single pole function of the form

$$\alpha = \frac{\alpha_0}{1 + jf/f_b^\prime}$$

(1)

where $\alpha_0$ common base current gain at D.C., $f_b^\prime$ cut-off frequency of base transit time($\tau_b$) plus base-collector depletion layer transit time($\tau_c$). The form of single pole function of Eq. (1) is valid within a low operation frequency range ($\omega \tau_c < 0.5$). Actually, in Si-BJT, $f_b^\prime$ was the cut-off frequency $f_b$ of only base transit time because base transit time of Si-BJT was normally much larger than base-collector depletion layer transit time. It is somewhat inconvenient to use the equivalent circuit of Fig. 1(a) in which emitter and collector shot noise sources are strongly correlated. To avoid the complexity of the noise model, in Fig. 1(b), the correlated shot noise sources $i_e$ and $i_c$ are transformed to the uncorrelated noise sources $e_e$ and $i_{cp}$ given by [5].

$$\overline{e_e^2} = 2kT \tau_e$$

(2)

$$\overline{i_{cp}^2} = \frac{2kT(\alpha_0 - |\alpha|^2)}{r_e}$$

(3)
\[ r_e = kT/qIE \]  

Hawkins model uses the equivalent circuit of Fig. 1(b) without emitter resistance.

In order to use Hawkins noise model for HBT, the characteristic difference of HBT from Si-BJT must be considered. First, the non-ideal ideality factor of HBT must be included accurately for both dynamic resistance and noise source equations. Considering ideality factor \( n_e \) of HBT, Eqs. (2)–(4) for Si-BJT are transformed to following forms:

\[ e^2_e = 2n_e kT r_e \]  

\[ i^2_{cp} = 2n_e kT (\alpha_0 - |\alpha|^2) / r_e \]  

\[ r_e = n_e kT/qIE \]

Second, the effect of series emitter resistance \( R_e \) on the noise figure must be included [2]. Because of the small emitter size and small base resistance, the emitter resistance effect on noise figure is not negligible. After some manipulation, analytic expressions for noise figure and optimum source impedance of HBT are extracted as follows.

\[ F_{\text{min}} = \frac{n_e a (R_b + R_e + R_{opt})}{r_e} + \frac{n_e \alpha_0}{|\alpha|^2} + (1 - n_e) \]  

\[ X_{opt} = \frac{\alpha_0 \omega C_{TE} r_e^2}{|\alpha|^2/a} \]  

\[ R_{opt}^2 = (R_b + R_e)^2 - X_{opt}^2 + \frac{\alpha_0 r_e (2(R_b + R_e) + r_e)}{|\alpha|^2/a} + \frac{2r_e(R_b + R_e)(1 - n_e)}{n_e a} \]  

\[ a = \frac{\alpha_0}{|\alpha|^2} - 1 + \frac{\alpha_0}{|\alpha|^2} (\omega C_{TE} r_e)^2 \]

Our modified Hawkins model for HBT, Eqs. (8)–(11), may seem to be the same as Costa model [2] or Chen model [6]. But there are obvious differences between our model and the other models. Chen replaced base transit time cut-off frequency \( f_b \) of original Hawkins model with total transit time cut-off frequency \( f_T \). Except this replacement, Chen’s expressions for noise parameters are the same as original Hawkins model for Si-BJT. But, in the view of equivalent circuit theory, \( f_b' \) must be used in the noise model of recent HBT. Costa model also used \( f_T \) and included emitter resistance. But he included non-ideal ideality factor \( n_e \) in dynamic resistance only. However, non-ideal ideality factor \( n_e \) must be considered in both dynamic resistance and noise source. So, We have propely considered non-ideal ideality factor \( n_e \) and cut-off frequency \( f_b' \) for the noise model of recent HBT which has similar transit times of base layer and base-collector depletion layer.

2.2 Extraction of Noise Resistance from Hawkins Model

The noise resistance \( R_n \) was not considered in the original Hawkins model. To extract \( R_n \) from Hawkins model, R.A. Pucel [7] employed correlation matrix and the procedure is complex. In this paper, we present a simple and direct method for extraction of \( R_n \) from Hawkins model.

A chain representation of a noisy network is shown in Fig. 2(a) where \( e_n \) equivalent noise voltage generator, \( i_n \) equivalent noise current generator, \( e_s \) thermal noise generator due to the real part \( (R_s) \) of input source impedance \( Z_s \). A chain representation of Fig. 2(a) may be converted to the equivalent circuit shown in Fig. 2(b), where \( e_{ni} \) is the equivalent noise voltage generator of the input circuit:

\[ e_{ni} = e_s + e_n + Z_s i_n \]
The current generator \( i_n \), which is partially correlated with \( e_n \), is split into an uncorrelated current \( i_u \) and a fully correlated current \( i_c \).

\[
i_c = Y_e e_n \tag{14}\]

\[
i_n = i_u + Y_e e_n \tag{15}\]

\[
i_n e_n^* = i_u e_n^* + Y_e e_n e_n^* = Y_e e_n^2 \tag{16}\]

where \( Y_e = G_e + jB_e \) is a correlation admittance. From Eqs. (12)–(16), \( e_{ni} \) can be expressed as follows:

\[
e_{ni}^2 = e_n^2 + e_n^2 + |Z_s|^2 + 2Re[Z_i e_n e_n^*] \tag{17}\]

\[
e_{ni}^2|_{Z_i=0} = e_n^2 = 4kTR_n \tag{18}\]

Note that \( e_{ni} \) can be directly derived from the expression for noise figure.

\[
F = \frac{e_{ni}^2}{e_n^2} \tag{19}\]

Using above Eqs. (18) and (19) and the equation for noise figure of our modified Hawkins model, \( R_n \) can be directly extracted as follows:

\[
R_n = R_b + R_c + \frac{n_e r_e}{2} + \left( \frac{\alpha_0}{|\alpha|^2} - 1 \right) \frac{n_e (R_b + R_c + r_e)^2}{2r_e} + \frac{\alpha_0}{|\alpha|^2} \frac{n_e}{2r_e} (w C_T r_e (R_b + R_c))^2 \tag{20}\]

3. Experimental Results

A 3 \times 20 \mu m^2 emitter finger self-aligned AlGaAs/GaAs HBT with abrupt junction was fabricated and evaluated. The epitaxial structure consists of a 800 Å InGaAs contact layer \((n = 1.0 \times 10^{19} \text{ cm}^{-3})\), a 1200 Å GaAs cap layer \((n = 5.0 \times 10^{18} \text{ cm}^{-3})\), a 1000 Å AlGaAs emitter layer \((n = 2.0 \times 10^{17} \text{ cm}^{-3})\), a 1000 Å GaAs base layer \((p = 2.0 \times 10^{19} \text{ cm}^{-3})\), a 4000 Å GaAs collector layer \((n = 2.0 \times 10^{16} \text{ cm}^{-3})\), a 6000 Å GaAs subcollector layer \((n = 5.0 \times 10^{18} \text{ cm}^{-3})\) on a semi-insulating GaAs substrate.

The AuGe/Ni/Au and Pt/Ti/Pt/Au metal system[8] are used for emitter and self-aligned base electrode. The specific contact resistance of base contact was measured to be \(3.0 \times 10^{-6} \Omega \text{ cm}^2\). The device had base and collector current ideality factors of \(n_b=1.37\) and \(n_c=1.23\), respectively. The ideality factor of emitter current \(n_e\) was 1.29. On-wafer s-parameter measurements was performed using HP8510C network analyzer. As shown in Fig. 3, the device has a common emitter current gain of 30 and a total transit time cutoff frequency \(f_T\) of 36 GHz at a collector current of \(I_C=6\) mA. A base resistance of \(R_b=15\) \Omega, a series emitter resistance of \(R_e=2.5\) \Omega were extracted from the s-parameter data.

To calculate noise parameters, it is necessary to accurately extract circuit parameters. The circuit parameters for noise modeling were derived as follows. The common base current gain at D.C. \(\alpha_0\) and ideality factor \(n_e\) were extracted from the Gummel plot. The
which was agreed with the extracted value of the simple Hawkins model in which many parasitic circuit elements are not included. Specially, the optimum noise susceptibility resulting from simple noise model without external base-collector capacitance $C'_{bc}$ does not agree well with the measurement data [11]. As shown in Fig. 5(d), the calculated $R_n$ using Eq. (20) agrees very well with measurement. Therefore, we could verify our extraction method of $R_n$.

4. Effect of Noise Source on $F_{min}$

In Hawkins model, to avoid complexity of calculation of $F_{min}$ due to the correlation between emitter and collector shot noise sources, the correlated shot noise sources $i_e$ and $i_c$ are transformed to the equivalent uncorrelated noise sources $e_e$ and $i_e$. However, to investigate the $F_{min}$ dependence on the noise sources, it is more efficient to use $i_e$ and $i_c$ instead of $e_e$ and $i_e$. The noise figure $F$ for HBT using $i_e$ and $i_c$ was derived using equivalent circuit of Fig. 1(a).

$$F = 1 + \frac{(R_b + R_e)}{R_s} + \frac{n_e}{2R_s r_e} \left[ (R_s + R_b + R_e)^2 + X_s^2 \right]$$

$$+ \frac{\alpha_0}{|\alpha|^2} \frac{n_e}{2R_s r_e} \left[ (R_s + R_b + R_e + r_e (1 - \omega C_{TE} X_s))^2 \right]$$

$$- \frac{n_e}{R_s r_e} \left[ (R_s + R_b + R_e + r_e) (R_s + R_b + R_e) + X_s^2 \right]$$

(21)

where $R_s$ and $X_s$ the input source impedance terms. The 2nd term in Eq. (21) is due to the base thermal noise $e_r$ and emitter thermal noise $e_e$, the 3rd term due to the emitter shot noise, the 4th term due to the collector shot noise, and the 5th term due to the correlation [12] between the emitter and collector shot noise sources. The calculated minimum noise figure using Eq. (21) is identical to the results of Eq. (8) using uncorrelated noise sources $e_e$ and $i_e$. Therefore, we could know that the correlation between emitter and collector noise sources was actually included in Hawkins model.

Using the terms in noise figure equation (21) with optimum noise matching condition, the contribution of each noise sources to the minimum noise figure at 4 GHz has been calculated and depicted in Fig. 6. As shown in Fig. 6(a), comparing the noise due to the total shot noise sources with that due to the thermal noise sources, we know that the shot noise sources are the dominant term. The noise figure due to the each shot noise sources are much higher than that due to the total shot noise sources. However, the correlation factor of the two shot noises are almost -1 and they are canceling out almost exactly. As a result, noise figure due to the total shot noise sources($i_e$, $i_c$, and correlation) is much smaller than that due to the each shot noise source. The correlation between the shot noise sources is stronger at a higher current level, and the noise due to the correlation increases strongly as current increases. Figure 6(b) shows the noise figure due to the total shot noise sources using the input impedance terms.
noise sources and the thermal noise sources. Due to the reduced correlation at a low current level, there is a current level at which the noise figure coming from the total shot noise sources($i_c$, $i_e$, and correlation) is minimum. This current level ($I_{min}$) agrees with the current at which noise figure due to the total noise sources($i_c$, $i_e$, correlation and thermal noises) is minimum. The terms of noise figure due to the thermal noise sources increases with current.

Figure 7 compares the calculated $F_{min}$ due to the each noise source. The complete noise model model-21 (see Eq. (21)) accurately predicts measured noise figure. The model-22 is the output noise due to the total shot noise sources($i_c$, $i_e$, and correlation) with $R_e + R_b \neq 0$ (the output noise without the thermal noise sources), the model-23 due to the total shot noise sources with $R_e = R_b = 0$. Comparing model-21 with model-22, we know that $F_{min}$ due to the thermal noise sources increases with current. Comparing model-22 with $R_e + R_b \neq 0$ and model-23 with $R_e = R_b = 0$, we found that $F_{min}$ of model-22 is higher than that of model-23. The higher $F_{min}$ of model-22 is due to the shot noise amplification by $R_e + R_b$. Therefore, we conclude that base and emitter resistances degrade output noise through the shot noise amplification with a lesser important effect of the thermal noise itself. This amplification effect of $R_e + R_b$ is seen once more from the result of comparison model-11 with model-12. The model-12(with $R_e = R_b = 0$, $i_c = 0$, $i_e \neq 0$) have approximately constant value of $F_{min}$ versus current. However $F_{min}$ of the model-11(with $R_e + R_b \neq 0$, $i_c = 0$, $i_e \neq 0$) is not only higher than model-12 but also increases with current. It is due to the shot noise amplification effect of $R_e + R_b$ and the increased thermal noise with current. We have seen a quite similar behavior for emitter shot noise sources in our model.

5. Conclusions

We have proposed the modified Hawkins model for HBT. First, non-ideal ideality factor of HBT is considered in both dynamic resistance and noise figure derivation in our model. Second, we have used cut-off
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Fig. 6 Contribution of each noise sources to minimum noise figure. The curves are extracted from the each terms of noise figure equation (21) under the condition of optimum noise matching.

(a) Noise figure due to each noise sources. (b) Noise figure due to total shot noise sources \((\frac{i_c}{C_T}, \frac{i_e}{C_R}, \text{correlation})\) and thermal noise sources.

frequency \(f'_k\) of base transit time combined with base-collector depletion layer transit time. New extraction method of \(R_n\) was also proposed. \(R_n\) is directly derived from noise figure equation in our model and it has been experimentally verified.

We have analyzed the effect of noise sources on \(F_{min}\) of AlGaAs/GaAs HBT using our modified Hawkins model with \(i_c\) and \(i_e\) instead of \(e_c\) and \(i_{cp}\). We found the dominance of shot noise sources and the amplification effect of \(R_c + R_b\). Parasitic resistance degrades output noise through the shot noise amplification with some thermal noise contribution. The correlation coefficient of shot noise sources is approximately -1. The noise contribution of thermal noise source increases with current. The current level for the minimum \(F_{min}\) coincides with the current level at which output noise due to the total shot noise sources is minimum.

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References


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