MICROWAVE LOW-NOISE GaAs HBTs

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ABSTRACT

In this paper we present our approach to improving microwave noise performance of HBTs. A minimum noise figure of 0.83 dB was obtained at 2 GHz by using an emitter guardring structure which improves the DC current gain particularly at low current densities. We also fabricated HBTs with regrown extrinsic base layers and InGaAs graded base layers which drastically reduce base contact resistance and base transit time, respectively. It is shown that this type of HBTs not only improve the noise-figure at X-band or Ku-band but also make the noise impedance matching easier.

INTRODUCTION

The markets for wireless applications have recently been growing and these applications require front-end active devices with high performance and low cost. GaAs heterojunction bipolar transistors (HBTs) are major candidate devices for such applications because their high-power density, high linearity, and low 1/f noise offer advantage for variety of RF components such as power amplifiers and low-phase noise oscillators. Moreover, recently applications of HBTs as low-noise amplifiers (LNAs) have received wide interest due to their superior noise-figure under low DC power operation, higher linearity, and smaller chip size compared to MESFETs[1]. In this paper, we present our design and fabrication approaches to improving the performance of HBTs from 2 GHz to 18 GHz.

NOISE PARAMETER ANALYSIS

The noise characteristics of bipolar transistors can be well described using Hawkins' equation derived based on a macroscopic equivalent circuit [2]. Recently, the applicability of the Hawkins' noise model to microwave HBTs have been demonstrated [3-5]. To obtain a design guideline to optimum HBT structure for LNAs, we examined the relations between the device parameters and noise characteristics using Hawkins' model.

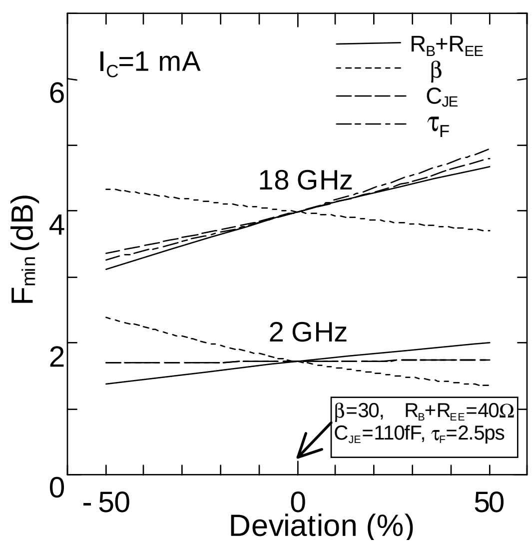

Fig.1. The sensitivity of F_{min} to principal HBT parameters calculated the Hawkins' equation.

In Fig. 1, we show the sensitivity of four parameters, i.e., sum of resistance $R_B + R_{EE}$, current gain β, carrier transit time delay τ_F (= $\tau_B + \tau_C$), and emitter junction capacitance C_{JE}, to the F_{min} calculated for our conventional HBT with an emitter size of 2μm×10μm. It can be seen that all four parameters impact the minimum noise figure F_{min} at 18 GHz, but at 2 GHz only R_B+R_{EE} and β are the key parameters. Indeed, at low frequency limit the F_{min} can be simplified as:

$$F_{min} \cong 1 + \frac{1}{\sqrt{\beta}} \sqrt{\frac{2\,(R_B + R_{EE})\,qI_C}{kT} + 1} \qquad (1)$$

which indicates that HBTs must be operated at low current levels to reduce the shot noise. However, it is well known that when I_C is decreased, the current gain of GaAs-based HBTs tends to decrease mainly due to the high surface recombination velocity of GaAs. Moreover, since device layout with large emitter periphery

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is preferred to reduce R_B, improving β at low current levels is one of the primary goals in designing a low-noise HBT for low frequency applications. Another important features in Fig.1 is that at 18 GHz τ_F and C_{JE} come into play in determining the noise-figure. However, so far the trade-off relation between the base transit time τ_B and the base sheet resistance has set the limit on the maximum frequency of low-noise HBTs.

Another important issue in designing low-noise HBTs is impedance matching. While typical LNA ICs utilize spiral inductors for noise matching, these passive elements waste the chip area and also degrade the noise performance due to series resistance of non-ideal inductors. At low frequencies, using Hawkins' equation the optimum source impedance Z_{opt} ($=R_{opt}+jX_{opt}$) and the equivalent noise resistance R_n can be simplified as:

$$R_{opt} \cong \sqrt{\beta r_e\,[2(R_B + R_{EE}) + r_e]} \qquad (2)$$

$$X_{opt} \cong \omega\beta C_{JE} r_e^{\,2} \qquad (3)$$

$$R_n \cong R_B + R_{EE} + \frac{r_e}{2} \qquad (4)$$

where r_e is emitter dynamic resistance. First, it can be seen from eq. (4) that the most effective way of improving R_n is to reduce R_B, which is usually accomplished by multi-fingered device layout. However, increasing the emitter size with fixed current decreases the RF power gain as well as the DC current gain, thus it is important to reduce the base resistance without increasing the emitter size. Maintaining the device size small is also beneficial from matching circuitry point of view, because minimizing C_{JE} decreases X_{opt}.

DEVICE DESCRIPTION

To confirm the above analysis, we fabricated three types of HBTs with different device structures (Fig.2) in which the parameters R_B, β, and τ_B can be controlled in an independent manner. Table• summarizes the features of these HBTs. First, to improve β at low current levels we fabricated HBTs with emitter guardring (or AlGaAs passivation ledge) [6] (type-A1) which reduces the surface recombination current at the emitter mesa edge. This type of HBTs were compared with HBTs without emitter guardrings (type-A2). Second, we fabricated HBTs with regrown extrinsic base layers and InGaAs graded base layers (type-B) [7]. The regrown GaAs extrinsic base layers with extremely high doping density reduce the base contact resistance, resulting in about one-fifth of the base resistance for non-regrowth type HBTs (type-A1 or A2). Note that this type of HBT makes it possible to minimize R_B without increasing the emitter periphery length which only degrades RF and DC gain under fixed current conditions. The InGaAs graded base layer (40nm) leads to short base transit time of 0.15 ps, which is compared to 1.5 ps for type-A HBTs.

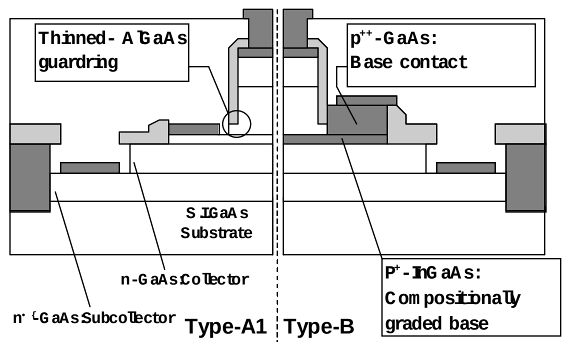

Fig.2. Cross-sectional view of type-A1 and type-B HBTs.

	A1	A2	B
Base Contact (R_B: Emitter size)	Conventional (6 Ω: 2μm×20μm×3)	•	Regrowth (7 Ω: 2μm×10μm)
Base Layer Structure (τ_B)	GaAs uniform $4E19cm^{-3}$ / 80nm (1.5 ps)	•	InGaAs graded $6E19cm^{-3}$ / 40nm (0.15 ps)
Emitter Guardring (β@5 kA/cm^2)	Yes (107)	No (44)	Yes (50)

Table• Summary of HBT structures used in this work.

NOISE PERFORMANCE

In Fig. 3 we plot F_{min} versus β at 2 GHz for type-A1 and A2 HBTs. Also shown in the figure is the fitted curve using Hawkins' equation. It can be seen that although the HBTs are operated at low current density (J_C=0.8 kA/cm^2), type-A1 HBTs have β of greater than 50 and thus show low F_{min} values of less than 1 dB. On the other

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hand, type-A2 HBTs suffer from degradation in β resulting in F_{min} far above 1 dB.

Fig. 4 compares the frequency dependence of F_{min} for type-A1 and type-B HBTs with an emitter size of 2μm×20μm×3 and 2μm×10μm×2, respectively. It can be seen that even though the type-B HBT has lower β its advantage over the type-A1 HBT increases as the frequency goes up. Noting that both HBTs have similar values of R_B+R_{EE}, this can be attributed to smaller C_{JE} and τ_B for type-B HBT. Thus the real essence of using epitaxial regrowth technique for low-noise HBTs is that it allows a small emitter-size HBT design to reduce C_{JE} while maintaining low R_B. In Table• , we summarize the noise parameters measured for type-A1 and type-B HBTs at optimum bias conditions. These noise performance are the best yet reported for bipolar devices in microwave region [1, 3-5, 8-10].

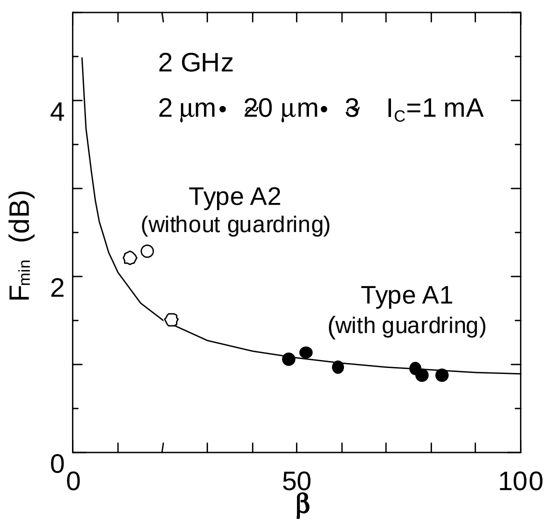

Fig.3. A dependence of F_{min} on β at 2 GHz. The solid line denotes fitted curve using Hawkins' equation.

Fig.5 plots the noise source impedance Γ_{opt} for the three types of HBTs at 2 GHz. First, comparing HBTs of type-A1 and type-A2, the Γ_{opt} of type-A2 HBT is closer to real 50 Ω impedance due to the lower β (see eq. (2) and (3)). Since β must be kept high for low noise

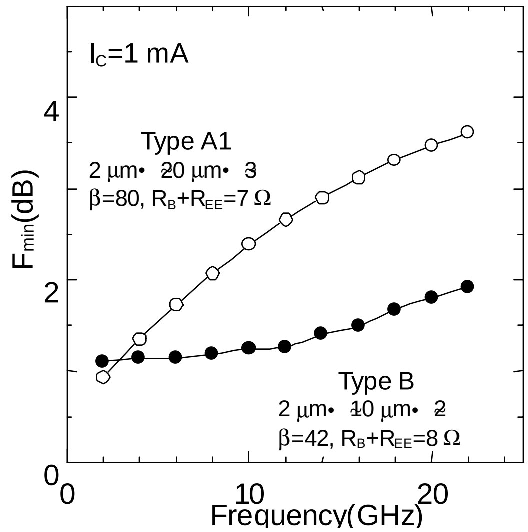

Fig.4. Frequency dependence of F_{min} for type-A1 and type-B HBTs.

Structure A1 (Emitter size: 2 µm×20 µm×3)

Frequency(GHz)	F_{min}(dB)	G_a(dB)	I_C(mA)
2	0.83	16.9	6

Structure B (Emitter size: 2 µm×10 µm)

Frequency(GHz)	F_{min}(dB)	G_a(dB)	I_C(mA)
2	0.9	16.7	0.2
12	1.2	10.3	1.5
18	1.7	8.7	2.5

Table• Summary of microwave noise performance at optimum bias conditions.

figure, the LNA design usually employs series inductive matching [1]. In this respect, the noise source impedance matching is relatively easier for type-B HBT because the reactive component X_{opt} (of Z_{opt}) can be minimized by small-emitter-size design. Thus type-B HBTs have potential for low-frequency applications as well because they may eliminate the need to use spiral inductors, thereby reducing the chip cost.

Now considering that the Γ_{opt} of HBT depends on β which is less reproducible compared to other device parameters, it is critically important to reduce the equivalent noise resistance R_n. As indicated by eq. (4), R_n is directly determined by R_B+R_{EE}. To confirm this, we plot the measured R_n versus r_e (by varying the collector current) for three types of HBTs in Fig.6. Here, a 1/2-slope line gives a reasonable fit to the data, which is in good agreement with eq. (4). The smaller extrapolated values of R_n for type-B HBTs clearly indicates the advantage of type-B HBTs

(The extrapolated R_n do not provide the correct R_B+R_{EE} values as obtained from S-parameter analysies, but this is believed to be due to parasitic circuit elements that are not considered in the Hawkins' model).

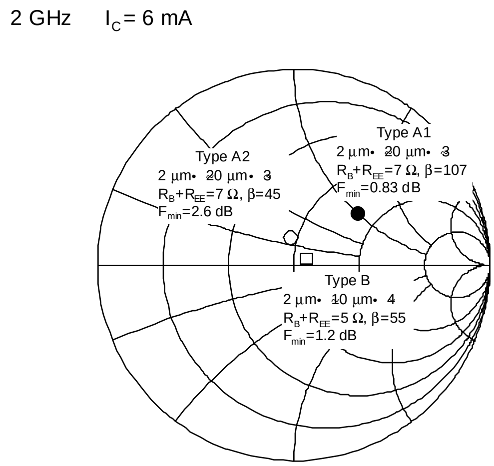

Fig.5. Optimum noise source impedance for the three types of HBTs plotted at 2 GHz.

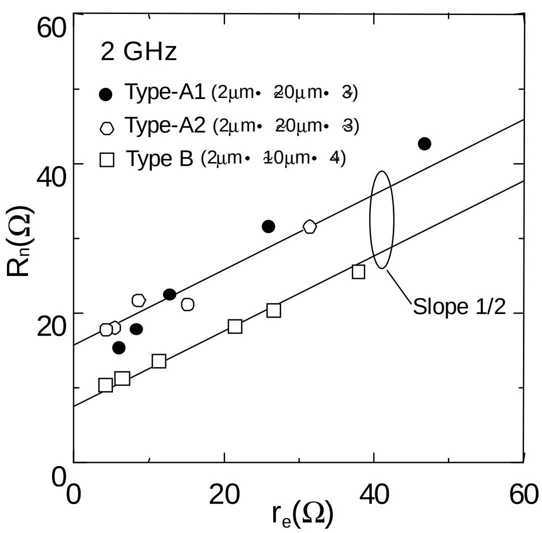

Fig. 6. Equivalent noise resistance for the three types of HBTs as a function of emitter dynamic resistance at 2 GHz.

SUMMARY

Novel HBT structures are presented to improve the microwave noise performance.
Since the DC current gain is one of the critical parameter determining the noise-figure of HBTs, we have developed AlGaAs/GaAs HBTs with emitter guardring to improve particularly the current gain. The result was a minimum noise figure 0.83 dB at 2 GHz. We also fabricated HBTs with regrown extrinsic base layers and InGaAs graded base layer which drastically reduce R_B and τ_B, respectively. It was shown that the improved base contact makes it possible to reduce R_B without increasing the emitter size and thus to minimize C_{JE} which has significant impact on the noise figure at high frequencies. Along with the decrease in the C_{JE} effect of reduced τ_B the noise figure was significantly improved up to 18 GHz. Moreover, it was shown that the regrown-type HBTs may have potential for low-frequency applications as well, because the small emitter design could reduce the inductive part of the optimum noise source impedance, eliminating the need to use spiral inductors for noise matching. The demonstrated low-noise HBT performance makes them even more attractive for low-cost wireless applications at wide range of frequency bands.

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