# Low-Frequency Noise Characteristics of p-n-p InAlAs/InGaAs HBTs

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***Abstract*—The low-frequency noise characteristics of p-n-p InAlAs/InGaAs heterojunction bipolar transistors (HBTs) were investigated. Devices with various geometries were measured under different bias conditions. The base noise current spectral density ($3.11 \times 10^{-16}$ A$^2$/Hz) was found to be higher than the collector noise current spectral density ($1.48 \times 10^{-16}$ A$^2$/Hz) at 10 Hz under low bias condition ($I_C = 1$ mA, $V_{EC} = 1$ V), while the base noise current spectral density ($2.04 \times 10^{-15}$ A$^2$/Hz) is lower than the collector noise current spectral density ($7.87 \times 10^{-15}$ A$^2$/Hz) under high bias condition ($I_C = 10$ mA, $V_{EC} = 2$ V). The low-frequency noise sources were identified using the emitter-feedback technique. The results suggest that the low-frequency noise is a surface-related process. In addition, the dominant noise sources varied with bias levels.**

***Index Terms*—Heterojunction bipolar transistors (HBTs), noise.**

## I. Introduction

THE low-frequency noise characteristics of semiconductor devices can be used as a sensitive measure to investigate the quality of materials and reliability of devices [1]. In addition, low-frequency noise can limit the performance of nonlinear circuits such as mixers and oscillators. In compound semiconductor devices, a significant part of the low-frequency noise is related to the surface and periphery properties of devices. InP-based heterojunction bipolar transistors (HBTs), have an advantage over FETs, for applications where low-frequency noise characteristics are important, due to their vertical structure and therefore less exposed surface area. Moreover, they are the preferred solution over GaAs-based HBTs due to their small surface recombination velocity[2]. The low-frequency noise characteristics of n-p-n InP-based HBTs have been reported [3]–[5]. However, no reports are available on the low-frequency noise characteristics of p-n-p InP-based HBTs.The p-n-p InP-based HBTs are relatively new and can be employed to build complementary microwave circuits [6] or used as active loads [7]. In this letter, the low-frequency noise characteristics of p-n-p InAlAs/InGaAs HBTs were studied. In addition to the interest in these devices from the application point of view, a study of their noise properties is also attractive due to the fact that their carrier transport is different than in n-p-n HBTs. Devices with various geometries were characterized under different bias conditions. The noise origin of the devices was identified using the emitter feedback resistor technique [8]. The results provide information about the low-frequency noise mechanism in p-n-p InAlAs/InGaAs HBTs and suggest ways to improve the material quality and processing technology.

Manuscript received July 1, 2002; revised September 20, 2002. This work was supported by ARO (MURI Contract DAAHO4-96-1-0001) and NTT Photonics Laboratories. The review of this letter was arranged by Editor D. Ritter.

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Digital Object Identifier 10.1109/LED.2002.805756

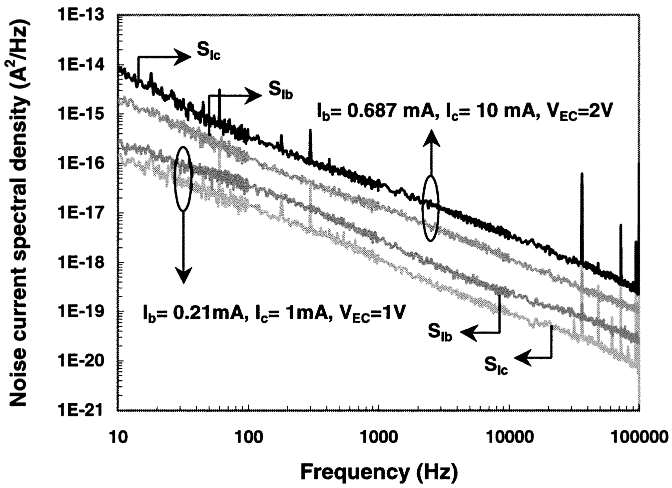
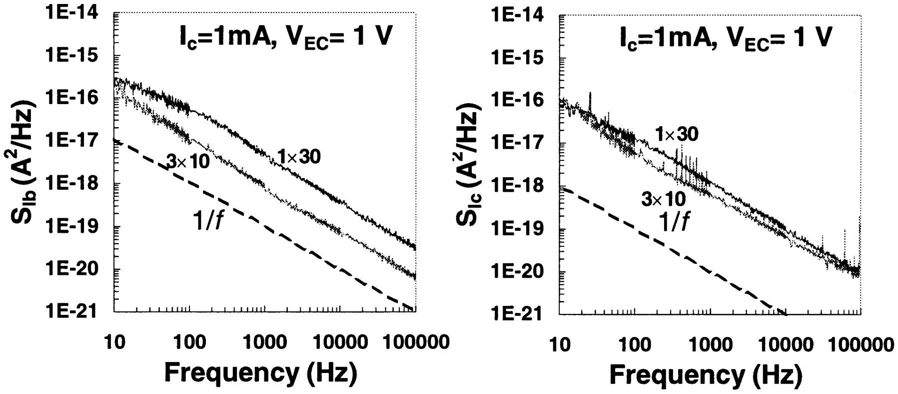



Fig. 1. Base and collector noise current spectral densities of $5 \times 10$ $\mu$m$^2$ p-n-p InAlAs/InGaAs HBTs under two different bias conditions.

## II. Noise Measurement Results and Discussion

The p-n-p InAlAs/InGaAs HBTs used in this study were fabricated in-house and demonstrated good high-frequency, small-signal, and power characteristics [6]. Devices with $5 \times 10$ $\mu$m$^2$ emitter size presented $f_{\max} = 31$ GHz and $f_T = 11$ GHz, and a maximum power density of 0.49 mW/$\mu$m$^2$ at 10 GHz. The measurements were performed under a common-emitter configuration for both base noise current spectral density $(S_{\rm Ib})$ with short-circuited collector and collector noise current spectral density $(S_{\rm Ic})$ with grounded base terminal.

Fig. 1 shows both $S_{\rm Ib}(f)$ and $S_{\rm Ic}(f)$ of $5 \times 10$ $\mu$m$^2$ devices under two bias conditions. The results followed a $1/f^\alpha$ characteristic, where $\alpha$ is close to one. However, one can see "bulges" superimposed on the $1/f$ curves, which are the so-called "Lorentz components." Such characteristics normally result from the generation–recombination (G–R) noise mechanism due to the trapping–detrapping process of carriers. In addition to the appearance of G–R noise components at different current levels, one can see that $S_{\rm Ib}(f)$ is higher than $S_{\rm Ic}(f)$ under the low bias condition ($I_B = 0.21$ mA, $I_C = 1$ mA, $V_{EC} = 1$ V), while $S_{\rm Ib}(f)$ is lower than $S_{\rm Ic}(f)$ under the high bias condition



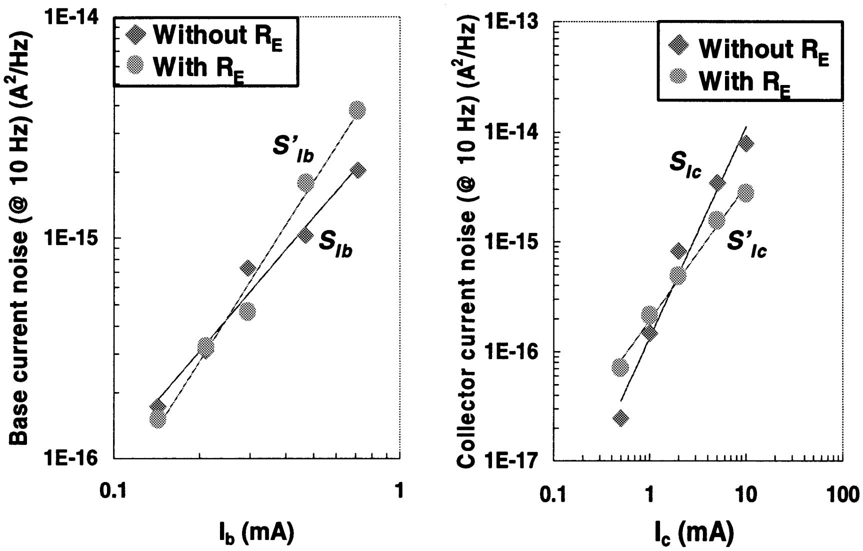

(a) (b)

Fig. 2. Noise current spectral density for same emitter size (30 $\mu$m$^2$) but different P/A ratio p-n-p InAlAs/InGaAs HBTs: (a) base noise current spectral density and (b) collector noise current spectral density.

($I_{\rm B} = 0.687$ mA, $I_{\rm C} = 10$ mA, $V_{\rm EC} = 2$ V). The device showed a low current gain of ~4.8 under low bias level, which indicates significant base–emitter (B–E) recombination. As a result, the base noise current is higher than the collector noise current due to noisy G–R processes taking place in the B–E region. On the other hand, under the high bias condition, the gain of the device increased up to ~14.6, which indicates a relatively higher increase of collector than base current when the device bias varies from low to high, and consequently a higher $S_{\rm Ic}(f)$ than $S_{\rm Ib}(f)$. Given that the noise source is proportional to the bias current, the noise source in the collector–emitter region increases in a more pronounced way than the B–E noise source, and the impact of the latter on $S_{\rm Ic}(f)$ is relatively insignificant. In addition, the extracted $S_{\rm Ic}(f) \propto I_{\rm C}^{1.92}$ dependence (from the $I_{\rm C}$ data of 0.5, 1, 2, 5, and 10 mA) suggests that the noise is generated from the G–R rather than diffusion process in the carrier conduction path and bulk material; G–R is more likely to be the dominant noise mechanism under high bias condition for $S_{\rm Ic}(f)$, since a trend of $S_{\rm I}(f) \propto I^2$ type corresponds to the theoretically predicted noise dependence on bias current for G–R type noise [8].

Fig. 2(a) and (b) compares $S_{\rm Ib}(f)$ and $S_{\rm Ic}(f)$ of devices with the same emitter area (30 $\mu$m$^2$), but different periphery/area (P/A) ratios. The devices with $3 \times 10$ $\mu$m$^2$ and $1 \times 30$ $\mu$m$^2$ emitters have a P/A ratio of 0.87 and 2.07, respectively. Tests were conducted at $I_{\rm C} = 1$ mA, $V_{\rm EC} = 1$ V. Under such a bias condition, the $3 \times 10$ $\mu$m$^2$ device had $I_{\rm B} = 0.126$ mA ($\beta = 7.93$), while the $1 \times 30$ $\mu$m$^2$ device had $I_{\rm B} = 0.338$ mA ($\beta = 2.96$). In Fig. 2(a), one can see that the $1 \times 30$ $\mu$m$^2$ device had a higher base noise and more pronounced "Lorentz" characteristics. The observed results can be attributed to the higher base recombination current and more significant surface recombination process in the B–E area for the higher P/A ratio device. The impact of P/A ratio on low-frequency noise characteristics of InP/InGaAs HBTs has also been reported for n-p-n devices [5]. It was found that the input-referred base noise current spectral density increases with P/A ratio due to increased surface recombination current, which is in agreement with our results for p-n-p HBTs. On the other hand, in Fig. 2(b), the collector noise current spectral density of both devices showed similar values, that were independent of P/A ratio and had both "bulges" present in the $1/f$ characteristics. The similarity in the observed collector noise levels is due to the similar material and technology used for these devices and also the comparable number of carriers flowing through the conducting path to the collector. The observed Lorentz components in $S_{\rm Ic}(f)$ could be contributed from both the noise source existing in the B–E area ($S_{\rm ibe}$) and the noise source existing between the emitter and the collector ($S_{\rm ice}$), since part of $S_{\rm ibe}$ can manifest at the collector terminal even the base terminal is grounded due to the parasitic resistances. Overall, the results indicate that $S_{\rm Ib}(f)$ is surface-related since it is related to the device P/A ratio. In addition, $S_{\rm Ic}(f)$ could also be surface-related since the noise generated in the B–E area can translate to noise in the collector terminal.

Fig. 3(a) and (b) shows $S_{\rm Ib}$, $S'_{\rm Ib}$, $S_{\rm Ic}$, and $S'_{\rm Ic}$ of $5 \times 10$ $\mu$m$^2$ devices at 10 Hz, where the parameters with prime indicates that the noise spectral was measured with an additional emitter feedback resistor ($R_{\rm E} = 150$ Ω). The introduction of $R_{\rm E}$ changes the noise current paths and degrades the gain of the device. As a result, the contribution of different low-frequency noise current sources to the base and collector terminal changes as well. The noise sources can be distinguished with the assistance of $R_{\rm E}$, according to the bipolar junction transistor (BJT) noise model proposed by van der Ziel [8] and correspond to three noise current sources located at B–E ($S_{\rm ibe}$), collector–emitter ($S_{\rm ice}$), and base–collector (B–C) ($S_{ibc}$), respectively. $S_{\rm ibe}$ is the noise related to the recombination in the B–E heterojunction and exposed surface/periphery area; $S_{\rm ice}$ is the noise stemming from the transport of carriers in the current conducting path from the emitter to the collector. $S_{ibc}$ can usually be neglected since the number of carriers generated from the reverse-biased B–C junction is insignificant. The impact of $R_{\rm E}$ on the terminal noise can be calculated using equivalent circuit models with emitter degeneration and the results can be described qualitatively as follows. As the feedback resistor is inserted, the contribution of $S_{\rm ibe}$ to $S_{\rm Ib}(f)$ slightly reduces while its contribution to $S_{\rm Ic}(f)$ increases. On the other hand, the contribution of $S_{\rm ice}$ to $S_{\rm Ib}(f)$ increases while its contribution to $S_{\rm Ic}(f)$ decreases significantly




(a) (b)

Fig. 3. Noise current spectral density of the $5 \times 10\ \mu m^2$ p-n-p InAlAs/InGaAs HBTs measured with and without emitter feedback resistor: (a) base noise current as a function of base current and (b) collector noise current as a function of collector current.

when $R_{\rm E}$ is added. In Fig. 3(a), the base noise reduced slightly at low current levels when $R_{\rm E}$ was inserted, while at high current level, the base noise level increased when emitter feedback was added. In the simplified noise model, both $S_{\rm ibe}$ and $S_{\rm ice}$ can contribute to $S_{\rm Ib}(f)$ even when the collector is grounded. However, the portion of $S_{\rm Ib}(f)$ originating from $S_{\rm ibe}$ reduced, while that from $S_{\rm ice}$ increased when $R_{\rm E}$ is inserted. Based on this observation, one can therefore conclude that the dominant noise source of $S_{\rm Ib}(f)$ at low current level is $S_{\rm ibe}$, while the influence of $S_{\rm ice}$ on the base terminal becomes important at high current level. On the other hand, Fig. 3(b) suggests that $S_{\rm ibe}$ impacts significantly to $S_{\rm Ic}(f)$ at low $I_{\rm c}$ while $S_{\rm ice}$ dominates the collector terminal noise current spectral density at high current level. From both $S'_{\rm Ib}(f)$ and $S'_{\rm Ic}(f)$, one can conclude that the noise source stemming from the B–E area is relatively high at low current level. As the current level increases, the noise source originating from the G–R and/or diffusion $1/f$ noise between the emitter and the collector becomes dominant.

## III. Conclusion

In summary, the low-frequency noise characteristics of p-n-p InAlAs/InGaAs HBTs were investigated. The device noise was found to depend on P/A ratio, which indicating that the low-frequency noise mechanisms in p-n-p HBTs are surface-related and could be further suppressed using surface passivation. This treatment may reduce both $S_{\rm Ib}(f)$ and $S_{\rm Ic}(f)$, since part of the noise generated in the B–E area presents at the collector terminal. In addition, emitter feedback experiments indicate that the dominant noise source varies with bias levels. This study provides information on ways to improve the device low-frequency noise performance for low-power, low-noise complementary InP HBT's circuits for wireless and other communication applications.

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