Low $1/f$ Noise Characteristics of AlGaAs/GaAs Heterojunction Bipolar Transistor with Electrically Abrupt Emitter–Base Junction

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***Abstract*— It is shown that the use of an electrically abrupt emitter–base junction considerably reduces the $1/f$ noise of self-aligned AlGaAs/GaAs heterojunction bipolar transistor (HBT). Although this device does not have depleted AlGaAs ledge passivation layer, the low-frequency noise spectra show a very low $1/f$ noise corner frequency of less than 10 kHz, which is much lower than previously reported value of about 100 kHz from conventional passivated or unpassivated AlGaAs/GaAs HBT's. Except for a residual generation–recombination (g–r) noise component, the noise power is comparable to that of Si BJT. It is also found that the low-frequency noise power of the AlGaAs/GaAs HBT is proportional to the extrinsic GaAs base surface recombination current square. Unlike the other HBT's reported, the noise sources associated with interface state and emitter–base (E–B) space charge region recombination are not significant for our device.**

I. INTRODUCTION

THE LOW $1/f$ noise characteristics of AlGaAs/GaAs HBT's are very important for low-phase noise oscillator applications [1], [2]. The dominant $1/f$ noise source of AlGaAs/GaAs Heterojunction Bipolar Transistor (HBT) is the recombination at the extrinsic GaAs base surface [3]. Using a thin depleted AlGaAs surface passivation ledge over the entrinsic GaAs base region, N. Hayama *et al.* showed that $1/f$ noise of AlGaAs/GaAs HBT's can be reduced considerably [4]. However, there have been large deviations more than 10 dB in $1/f$ noise data among the surface-passivated HBT's [3]–[5]. This fact indicates that $1/f$ noise is significantly influenced by the transport of carriers across the vertical HBT structure. To find optimized HBT structure, we demonstrated that a large emitter size AlGaAs/GaAs HBT (120×120 μm^2) with an abrupt emitter–base (E–B) junction has a very low $1/f$ noise corner frequency of about 100 Hz [6]. This very low $1/f$ noise characteristic comes from the reduced recombination of abrupt E–B junction as well as the reduced surface recombination due to small emitter periphery/area ratio of the HBT. Compared to other large emitter size AlGaAs/GaAs [7] and GaInP/GaAs [8] HBT's, the HBT demonstrated at least 20 dB lower bulk $1/f$ noise level. Since both the bulk [9] and surface $1/f$ noise increase with the decrease of emitter area, both noise sources become increasingly important for small size HBT's. Since the abrupt AlGaAs/GaAs E–B heterojunction has the launching effect [3] and the large potential barrier to the base surface [10], the structure is expected to reduce the surface current and its $1/f$ noise. In this letter, we have demonstrated experimentally the effectiveness of using an electrically abrupt E–B junction for reducing the $1/f$ noise of small size HBT's.

II. DEVICE STRUCTURES

To compare the effect of abrupt and graded E–B junction structures on the $1/f$ noise, we used two kinds of MOCVD-grown HBT's: HBT A (abrupt E–B junction) and HBT B (graded). The epitaxial structure of HBT A has a 700-Å thick 30% Al mole fraction emitter layer and 1000-Å thick carbon-doped base layer. The emitter, base, and collector dopant concentrations are 2×10^{17}, 2×10^{19}, and 2×10^{16} cm^{-3}, respectively. HBT B is identical to HBT A except 1400-Å thick base. The typical collector current ideality factors were 1.12 and 1.01 for HBT A and B, respectively. The collector current ideality factor of 1.12 for HBT A means that the electron transport mechanism of HBT A is affected by the heterojunction discontinuity of E–B junction [11]. But, the almost unity ideality factor for HBT B means that it has a graded E–B junction and the electron transport is limited by diffusion, not by an E–B heterojunction discontinuity [11]. The grading of E–B junction for HBT B was further ascertained by the almost identical $I_c - V_{BE}$ (in forward active mode at $V_{BC} = 0$ V) and $I_E - V_{BC}$ characteristics (in reverse active mode at $V_{BE} = 0$ V) [11]. Several different size HBT's were fabricated by conventional MESA-type self-aligned base metal HBT process without surface passivation [12]. To estimate the magnitudes of extrinsic base surface recombination currents of the above two HBT structures, we depict H_{FE}^{-1} versus P_E (emitter periphery)/A_E (emitter area) characteristics in Fig. 1. The emitter-edge base current density $(J_{B,\,\mathrm{edge}} = I_{B,\,\mathrm{edge}}/P_E)$ can be extracted from the slope of the fitted line in Fig. 1 [13], where the area $(I_{B,\,\mathrm{area}})$ and edge currents $(I_{B,\,\mathrm{edge}})$ are related to dc current gain H_{FE} by

$$H_{FE}^{-1} = I_{B,\,\mathrm{area}}/I_c + (J_{B,\,\mathrm{edge}}/J_C) \times (P_E/A_E). \quad (1)$$

At the same current density (J_c) of 10^4 A/cm^2, the extracted $J_{B\,\mathrm{edge}}$, for HBT A is 1.27 μA/μm which is much less

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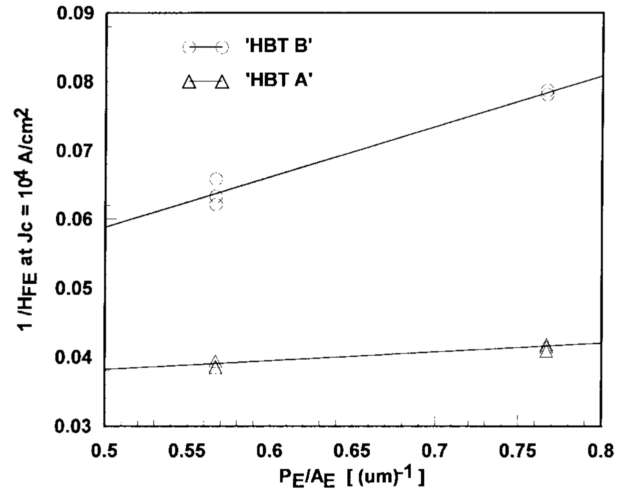

Fig. 1. $1/H_{FE}$ versus P_E/A_E characteristics for HBT's with abrupt E–B junction (HBT A) and with graded E–B junction (HBT B). $J_C = 10^4$ A/cm^2. Emitter sizes used: 4×30 μm^2; two fingers with 3×20 μm^2.

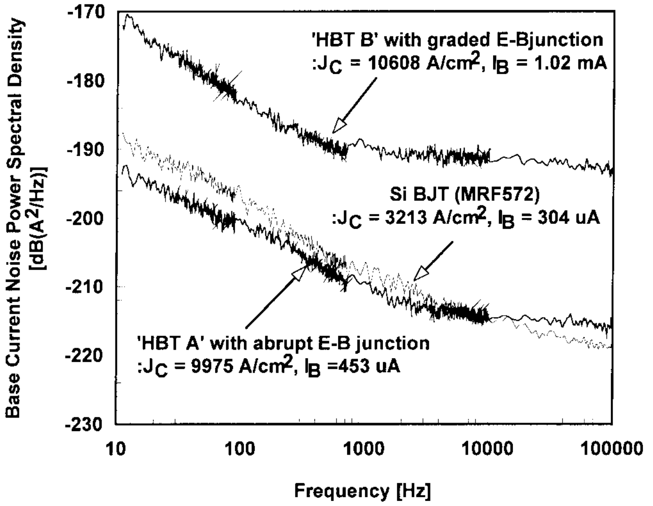

Fig. 2. Low-frequency base current noise spectra for HBT A (abrupt), HBT B (graded), and Si BJT (MRF572). Emitter sizes used: two fingers with 3×20 μm^2 emitter size for HBT A and B; 22 fingers with approximately 1.4×29 μm^2 emitter size for Si BJT.

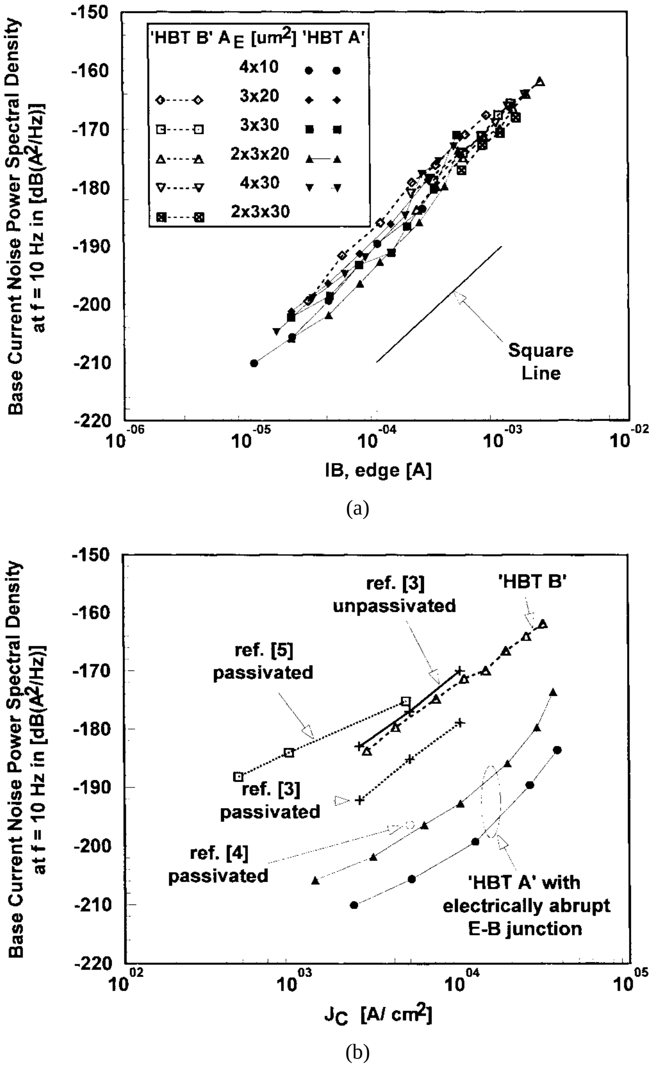

Fig. 3. (a) S_{Ibe} (10 Hz) versus $I_{B,\text{edge}}$ for HBT A (abrupt) and HBT B (graded). (b) S_{Ibe} (10 Hz) versus J_C for various AlGaAs HBT's: HBT A (▲: two fingers with $3 \times 20\,\mu$m^2; •: 4×10 μm^2); HBT B (△: two fingers with 3×20 μm^2); N. Hayama *et al.* [4] (○: graded E–B/passivated/2×10 μm^2); D. Costa *et al.* [3] (graded E–B/4×10 μm^2; + with solid line: unpassivated; + with dotted line: passivated); D. Costa *et al.* [5] (□: nominally abrupt E–B/two fingers with 3.5×30 μm^2/passivated).

than 7.78 μA/μm for HBT B. HBT A has very low surface recombination current and, within our knowledge, this value of $J_{B,\,\text{edge}}$ of HBT A is the lowest value among the unpassivated AlGaAs/GaAs HBT's [13], [14]. Here, the base widths of HBT A and B are different and its effect should be examined. Generally, the thin base can reduce the surface recombination current [15]. According to [3], $J_{B,\,\text{edge}} = J_C\, s\, W_B\, L_d/D_n \propto J_C\, W_B^2$, where s is surface recombination velocity, W_B is base width, L_d ($\propto W_B^{-1}$) is electron lateral diffusion length, and D_n is the electron diffusivity. From the relation, the $J_{B,\,\text{edge}}$ reduction factor is estimated to be about 2, which is much less than the actual measured factor of 6.1. Consequently, the thin base of HBT A does not play a major role in reducing the surface current. Since our HBT has no surface passivating structure, this very low surface recombination characteristics can be attributed to the launcher effect of the E–B heterojunction discontinuity. Since the base surface region is laterally connected to the E–B interface region, the accelerated electrons by the heterojunction launcher of the abrupt E–B junction can transverse the very thin (~50 Å) E–B interface region without recombination, and the portion of electrons diffused to base surface is significantly reduced [3], [10]. In addition, the abrupt E–B junction can reduce the E–B interface and space charge region (SCR) recombination currents [16].

III. LOW-FREQUENCY NOISE CHARACTERISTICS

Since the $1/f$ noise of HBT is generated mainly from the base surface and E–B junction recombination currents, we have measured the base current noise spectra (S_{Ibe}). The measurement method can be found elsewhere [6]. Fig. 2 shows the S_{Ibe} spectra of HBT A, HBT B, and Si BJT (MRF572). Two finger 3×20 μm^2 size emitter HBT's were used for HBT A and B. At $J_C \cong 10^4$ A/cm^2 and $f = 10$ Hz, the S_{Ibe} of HBT A is about 20 dB lower than that of HBT B, proving the effectiveness of the electrically abrupt E–B junction in reducing the $1/f$ noise. HBT A exhibits a corner frequency of about 8 kHz, which is much lower than that of conventional AlGaAs/GaAs HBT's ($>$100 kHz) [3]–[5] and is comparable to that of Si BJT. Since the measurement for Si BJT has been done at $J_c = 3213$ A/cm^2 (typical bias point) lower than $J_c \cong 10^4$ A/cm^2 for HBT's, the magnitude of the spectra for Si BJT will increase by about 7 dB for $J_c = 10^4$ A/cm^2. Based on the relation of S_{Ibe} (10 Hz) $\propto I^2_{B,\,\mathrm{edge}}$ [3] and the magnitudes of $J_{B,\,\mathrm{edge}}$ for HBT A and B, the relative $1/f$ noise reduction in HBT A can be estimated as 16 dB, which is roughly agreeing with the actual reduction of 20 dB within a scatter of noise data. The spectra of both HBT's exhibit $1/f$ and generation–recombination (g–r) noise. While the g–r noise plateau of HBT A is about 3 dB larger than the shot noise floor of $2qI_B$, that of HBT B is at least 20 dB larger than the $2qI_B$. However, Si BJT does not show any g–r noise. Despite the clear existence of g–r noise in HBT A, its level is considerably lower than that of other AlGaAs/GaAs HBT's [4]. From the very low $1/f$ and g–r noise levels of HBT A, we postulate that the noise associated with base surface recombination, bulk or surface E–B SCR recombination, and E–B interface recombination can be significantly reduced by the launcher effect and the recombination suppression effect of abrupt E–B junction. To determine the dominant $1/f$ noise source, it is necessary to examine the bias dependencies of noise spectra. However, the bias dependencies of other AlGaAs/GaAs HBT's previously reported did not give an unanimous relationship, making it very difficult to know which source is dominant [3]–[5]. This anomalous bias dependencies may stem from the fact that the total base current (I_B) consists of various components. To avoid the confusion, we have separated $I_{B,\,\mathrm{edge}}$ from I_B, by using the (1), and characterized the S_{Ibe} spectra as a function of $I_{B,\,\mathrm{edge}}$. Fig. 3(a) shows S_{Ibe} (10 Hz) versus $I_{B,\,\mathrm{edge}}$ for HBT A and B with various emitter sizes. It is found within a noise data scatter of individual device that S_{Ibe} (10 Hz) is proportional to $I^2_{B,\,\mathrm{edge}}$, regardless of A_E, P_E/A_E, and E–B structure. This clearly demonstrates that the $1/f$ noise of HBT A and B stems mainly from the extrinsic base surface recombination fluctuation. For comparison purposes, Fig. 3(b) exhibits S_{Ibe} (10 Hz), versus J_C for HBT A, HBT B, and previously reported AlGaAs/GaAs HBT's. Although our HBT does not have a depleted AlGaAs ledge, the noise level is at least 10 dB lower than that of any other passivated or unpassivated AlGaAs/GaAs HBT's reported. By considering both the ultralow $1/f$ noise level of our HBT and its clear bias dependency of S_{Ibe} (10 Hz) $\propto I^2_{B,\,\mathrm{edge}}$, we know that the recombination-related noise sources other than base surface recombination $1/f$ noise source are not significant for our devices. However, other AlGaAs/GaAs HBT's may suffer from E–B SCR or hetero-interface recombination-related $1/f$ noise sources as well as surface recombination $1/f$ noise source.

IV. CONCLUSION

We have achieved a very low $1/f$ noise corner frequency of less than 10 kHz for a practically featured small size AlGaAs/GaAs HBT by using the electrically abrupt E–B junction. Unlike the other low-noise AlGaAs/GaAs HBT's, our HBT does not incorporate a complicated passivation ledge structure. Nevertheless, the low-frequency noise characteristics of our unpassivated AlGaAs/GaAs HBT surpass those of any passivated or unpassivated AlGaAs/GaAs HBT, and are comparable to that of Si BJT. Considering its high linearity characteristics as well as excellent microwave performances. AlGaAs/GaAs HBT with an electrically abrupt E–B junction is expected to be a main vehicle for low-phase noise oscillator applications.

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