$1/f$ Noise Characteristics of AlGaAs/GaAs Heterojunction Bipolar Transistor with a Noise Corner Frequency Below 1 kHz

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***Abstract*— To reduce the low-frequency noise, HBT's with a large emitter size of 120 × 120 μm^2 are fabricated on abrupt emitter-base junction materials without undoped spacer. The HBT's exhibit an internal noise corner frequency of 100 Hz, which is much lower than about 100 kHz of conventional AlGaAs/GaAs HBT's. From the very low noise HBT's, the existence of resistance fluctuation $1/f$ noise is clearly verified by the simple comparison of collector current noise spectra with different base terminations. It is found that, at a high emitter-base forward bias, the resistance fluctuation $1/f$ noise becomes dominant for shorted base-emitter termination, but the internal $1/f$ noise dominant for open base. Device design rules for low noise small-feature size HBT, including resistance fluctuation, are discussed.**

I. INTRODUCTION

THE low $1/f$ noise of heterojunction bipolar transistor (HBT) is an important feature for low phase noise microwave oscillator applications [1], [2]. The noise corner frequencies of GaInP/GaAs [3]–[5], AlInAs/InGaAs [6], and Si/SiGe [7] HBT's range from 1 kHz to 100 kHz, while those of AlGaAs/GaAs HBT's [8]–[13] are usually above 100 kHz. It is generally believed that the $1/f$ noise of AlGaAs/GaAs HBT stems mainly from the recombination at the extrinsic GaAs base surface due to the high surface recombination velocity [9]. N. Hayama, *et al.* [10] showed that an HBT with a thin depleted AlGaAs ledge over the extrinsic GaAs base region had lower $1/f$ noise compared to a device without the AlGaAs ledge. It is also noteworthy that there have been large deviations of 10–20 dB in $1/f$ noise data among the surface-passivated HBT's [9]–[12]. This suggests that the major part of the $1/f$ noise is closely related to the detailed HBT epitaxial structure. Meanwhile, based on the mobility fluctuation theory, T. G .M. Kleinpenning, *et al.* suggested that, at a high emitter-base (E-B) forward bias, a significant $1/f$ noise can be generated by parasitic emitter and base resistances [13]. Since both the noise power spectral densities of the surface recombination and resistance $1/f$ noises are proportional to bias current square, a direct experimental verification of the existence and amount of resistance $1/f$ noise, other than current dependency, is needed. In this letter, we report a great reduction of internal $1/f$ noise by selecting a proper epitaxial structure, and a direct verification of resistance fluctuation $1/f$ noise for AlGaAs/GaAs HBT.

II. DEVICE STRUCTURE

To reduce the internal $1/f$ noise, we fabricated MESA-type AlGaAs/GaAs HBT on an abrupt E-B junction material without spacer. As indicated by comparative studies on abrupt and graded E-B junctions [14], HBT with an abrupt E-B junction greatly suppresses the space charge region (SCR) recombination. In addition, an abrupt E-B heterojunction launcher injects electrons into the base with kinetic energy, and the accelerated electrons can transverse the interface state region without recombination. It is also well known that the spacer between emitter and base produces a significant SCR recombination [15]. Materials were grown by MOCVD. The epitaxial structure has a 500 Å 30% Al emitter layer and 700 Å carbon-doped base layer. The emitter, base, and collector dopant concentrations are 2×10^{17}, 3×10^{19}, and 2×10^{16} cm^{-3}, respectively. To avoid the $1/f$ noise from extrinsic base surface, we employed a large emitter-size device (120 × 120 μm^2). The spacing between emitter and base metal is 50 μm, which is large enough to enhance base resistance $1/f$ noise. DC current gain (I_C/I_B) is typically 67. Base (n_b) and collector (n_c) current ideality factors are 1.31 and 1.12, respectively. The base current ideality factor is less than typical values of HBT's with graded E-B junction [14] or with spacer [15], indicating a small SCR recombination current of our HBT. The collector current ideality factor of 1.12 implies that the electron transport mechanism is influenced by the thermionic emission through an abrupt E-B heterojunction discontinuity [16]. Emitter resistance (r_e) is 4 Ω, and base resistance (r_b) ranges from 50 to 250 Ω due to the inherent nonuniformity of wet etching in MESA-type HBT process.

III. LOW-FREQUENCY NOISE CHARACTERISTICS

Following the generalized small signal noise analysis given in reference [13], we have characterized the low-frequency noise behavior of the HBT. The low-frequency collector noise

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Manuscript received July 27, 1995; revised October 3, 1995. This work was supported in part by the Korea Agency for Defense Development and Korean Science and Engineering Foundation.

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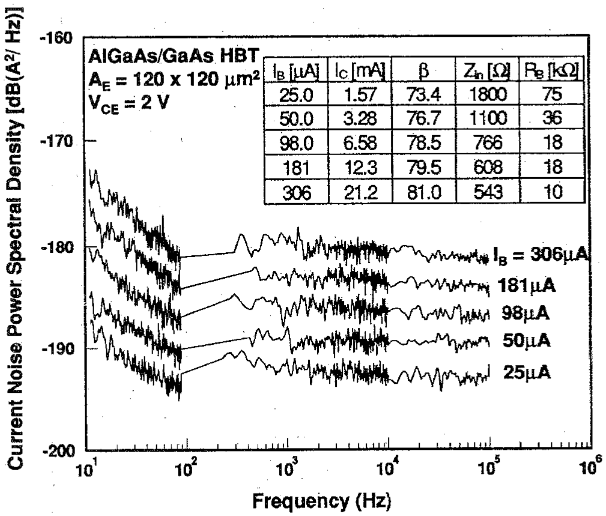
Publisher Item Identifier S 0741-3106(96)01491-7.



I_B [μA]	I_C [mA]	β	Z_{in} [Ω]	R_B [kΩ]
25.0	1.57	73.4	1800	75
50.0	3.28	76.7	1100	36
98.0	6.58	78.5	766	18
181	12.3	79.5	608	18
306	21.2	81.0	543	10

Fig. 1. Low-frequency collector current noise spectra with base open in the common emitter configuration. That is, $S_{Vc}/R_c^2(R_B \gg Z_{in})$ versus frequency S_{Vc}/R_c^2 represents only the internal low-frequency noise without containing resistance $1/f$ noise.

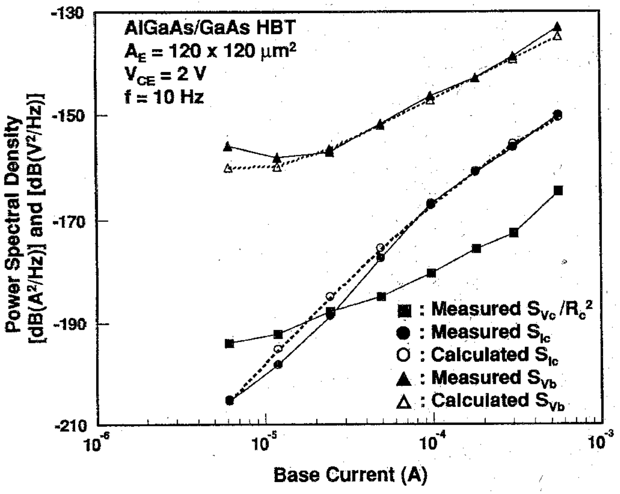


Fig. 2. Base current dependencies of low-frequency noise power spectral densities. $S_{Vc}/R_c^2(R_B \gg Z_{in})$ and $S_{Ic} = S_{Vc}/R_c^2(R_B = 0\,\Omega)$ are in dB (A²/Hz). $S_{Vb}(R_B \gg Z_{in})$ is in dB (V²/Hz).

voltage (S_{Vc}) of HBT was measured from 10 Hz to 100 kHz in the common emitter configuration. Fig. 1 shows the collector current noise spectra (S_{Vc}/R_c^2) when $R_B \gg Z_{in} = r_b + r_\pi + (1+\beta)r_e$. Here, $r_\pi = (n_b kT)/(qI_B)$ and $\beta = (n_b/n_c)(I_C/I_B)$ are a base input resistance and a differential current gain of intrinsic transistor, respectively, where k is Boltzmann's constant, T device temperature, and q electron charge. $R_c(R_B)$ is a collector (base) bias resistance. Here,

$$\begin{aligned} S_{Vc}/R_c^2(R_B \gg Z_{in}) = \beta^2 S_{Ibe} + S_{Ice} \\ + [\beta/(R_B + Z_{in})]^2 S_{Vr} \\ + 2qI_B\beta^2 + 2qI_C \end{aligned} \tag{1}$$

where S_{Ibe} and S_{Ice} represent base-emitter and emitter-collector current $1/f$ noise, respectively, and S_{Vr} is a resistance $1/f$ noise given by $I_B^2 Sr_b + I_E^2 Sr_e$. Since $[\beta/(R_B + Z_{in})]^2 S_{Vr}$ is negligible due to large value of R_B, $S_{Vc}/R_c^2(R_B \gg Z_{in})$ represents solely the internal noise, without containing the resistance $1/f$ noise. The spectra exhibit a very low noise corner frequency of 100 Hz, which is comparable to that of Si BJT. The white noise level agrees very well with shot noise level given by $2qI_B\beta^2 + 2qI_C$. Our large size AlGaAs/GaAs HBT has at least 20 dB lower internal noise than the other large [8] and small size AlGaAs/GaAs HBT's [9]–[13]. This data shows that the internal $1/f$ noise sources associated with surface states, E-B interface states and SCR recombination can be greatly reduced by adopting a large size AlGaAs/GaAs HBT with an abrupt E-B junction without spacer. This implies that the major $1/f$ noise source of a small size HBT with such a structure will be a surface recombination noise.

To investigate the resistance $1/f$ noise, we also measured S_{Ic}, i.e., S_{Vc}/R_c^2 with $R_B = 0\ \Omega$, and base noise voltage (S_{Vb}) with $R_B \gg Z_{in}$. Fig. 2 shows the base current dependencies of $S_{Vc}/R_c^2(R_B \gg Z_{in})$, $S_{Ic} = S_{Vc}/R_c^2(R_B = 0\ \Omega)$ and $S_{Vb}(R_B \gg Z_{in})$ at f = 10 Hz. Here,

$$\begin{aligned} S_{Ic} = [\beta(r_b + r_e)/Z_{in}]^2 S_{Ibe} \\ + [(r_b + r_\pi + r_e)/Z_{in}]^2 S_{Ice} \\ + (\beta/Z_{in})^2 S_{Vr} + (S_{Ic})_w \end{aligned} \tag{2}$$

$$\begin{aligned} S_{Vb} = (r_\pi + \beta r_e)^2 S_{Ibe} + r_e^2 S_{Ice} \\ + S_{Vr} + (S_{Vb})_w \end{aligned} \tag{3}$$

where $(S_{Ic})_w$ and $(S_{Vb})_w$ are white noise components of S_{Ic} and S_{Vb}, respectively, and given by

$$\begin{aligned} (S_{Ic})_w = [\beta(r_b + r_e)/Z_{in}]^2 2qI_B \\ + [(r_b + r_\pi + r_e)/Z_{in}]^2 2qI_C \\ + (\beta/Z_{in})^2 4kT(r_b + r_e) + 4kT/R_C \end{aligned} \tag{4}$$

and

$$\begin{aligned} (S_{Vb})_w = (r_\pi + \beta r_e)^2 2qI_B + r_e^2 2qI_C \\ + [Z_{in}/(R_B + Z_{in})]^2 4kTR_B \\ + [R_B/(R_B + Z_{in})]^2 4kT(r_b + r_e). \end{aligned} \tag{5}$$

We can observe that $S_{Ic} > S_{Vc}/R_c^2(R_B \gg Z_{in})$ at a high E-B bias ($I_B > 50\ \mu A$). Since the contribution of S_{Ibe} and S_{Ice} to the collector current noise should be reduced with $R_B = 0\ \Omega$, the observation is a clear evidence of the existence of resistance $1/f$ noise. Our approach of examining resistance $1/f$ noise differs from that of the previously published work [13] in two aspects. First, we used the HBT with very low internal $1/f$ noise which does not mask resistance $1/f$ noise. Second, we directly compared the measured magnitudes of S_{Ic} and $S_{Vc}/R_c^2(R_B \gg Z_{in})$, not relying on the measured bias dependencies. Based on the observation, we assumed $S_{Ic} = (\beta/Z_{in})^2 S_{Vr} + (S_{Ic})_w$ at $I_B > 100\ \mu A$, where S_{Ic} is at least 10 dB larger than $S_{Vc}/R_c^2(R_B \gg Z_{in})$. S_{Vr} can then be expressed as a fitting equation of $S_{Vr} = (7.41 \times 10^{-9}) I_B^{1.65}$, where S_{Vr} is in V²/Hz and I_B is in ampere. In the same way, $S_{Vb} = S_{Vr} + (S_{Vb})_w$. These expressions for S_{Ic} and S_{Vb} agree very well with the measured data as shown in Fig. 2. This experiment using HBT with ultra low internal noise clearly demonstrates the existence of resistance $1/f$

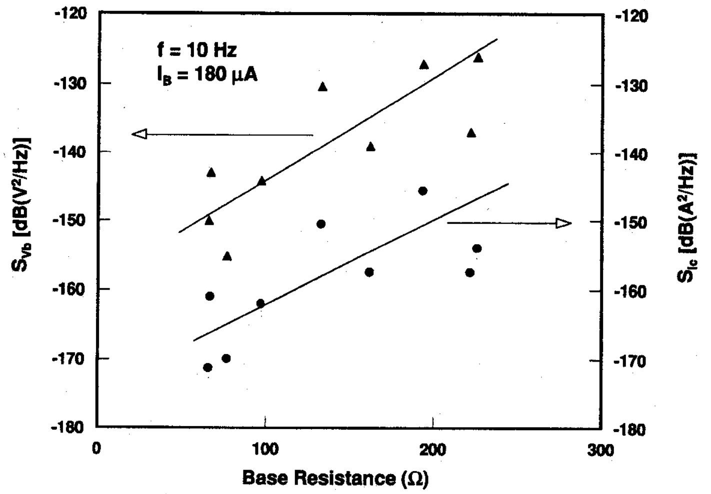


Fig. 3. Base resistance dependencies of base voltage noise with base open (S_{Vb}) and collector current noise with base-emitter short (S_{Ic}).

noise. Fig. 3 shows both S_{Vb} vs. r_b and S_{Ic} vs. r_b which were measured from many HBT's on the same wafer. The data show the strong correlation between them, also proving the above statements. As the base resistance (r_b) varies from 50 to 250 Ω, the corresponding deviation of S_{Vb} is about 20 dB, indicating that $S_{Vr} \propto r_b^3$. In view of the large emitter size and large r_b, S_{Vr} is mainly due to the base resistance fluctuation. Then, $S_{Vr} \propto Sr_b$ and $Sr_b = (\alpha_b r_b^2)/(fN_b)$, where α_b is the Hooge coefficient of base layer, f is a frequency and N_b is the effective total number of carriers (holes) within the extrinsic base layer. Since the variation of r_b mainly comes from that of base thickness (W_b), $r_b \propto W_b^{-1} \propto N_b^{-1}$ and $S_{Vr} \propto r_b^3$, agreeing with the above indication. Since $r_b \propto L_{eb}/(W_b W P_b)$ and $N_b \propto W_b W L_{eb} P_b$, we have $Sr_b \propto r_b^2/N_b \propto L_{eb}/(W_b W P_b)^3$, where L_{eb} is emitter to base metal spacing, P_b is base doping, and W is emitter width. Therefore, to reduce S_{Ic}, base thickness (W_b), base doping (P_b), and emitter width (W) should be kept large and E-B spacing (L_{eb}) small. This device design rule is different from the conventional rule which is concerned with the reduction of surface recombination noise. According to [9], it is desirable to have small W_b for small lateral diffusion, small W for a small periphery/area ratio for the fixed emitter area, and L_{eb} of about 1 μm for surface passivation. Since both resistance and surface recombination $1/f$ noises should be reduced simultaneously, some trade-off in the above two design rules is needed to have an optimized HBT with a very low $1/f$ noise.

IV. CONCLUSION

In conclusion, the internal $1/f$ noise of AlGaAs/GaAs HBT can be greatly reduced by using a proper E-B junction structure. Our large size AlGaAs/GaAs HBT with an abrupt E-B junction and no spacer has a very low internal noise corner frequency of 100 Hz. It is expected that, by adopting our optimized E-B junction structure and minimizing the surface recombination, we can achieve a practical small-feature size AlGaAs/GaAs HBT with very low internal $1/f$ noise, comparable to Si BJT. A direct verification of the existence of resistance fluctuation $1/f$ noise was performed through a simple comparison of the noise magnitudes for different base-termination conditions. Our low-frequency noise analyses of the device also show that, at a high E-B bias, resistance $1/f$ noise becomes dominant for shorted E-B termination, but internal $1/f$ noise dominant for open base termination. To improve the $1/f$ noise characteristics of practical small-feature HBT, device design rules including the resistance fluctuation are also suggested.

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