Low-Frequency Noise Characterization of Self-Aligned AlGaAs/GaAs Heterojunction Bipolar Transistors with a Noise Corner Frequency Below 3 kHz

Jin-Ho Shin, *Member, IEEE*, Jiyoung Kim, Yujin Chung, *Student Member, IEEE*, Joonwoo Lee, *Member, IEEE*, Youngsuk Suh, *Member, IEEE*, Kyu Hwan Ahn, and Bumman Kim, *Senior Member, IEEE*

***Abstract*— To find dominant $1/f$ noise sources, generalized noise analyses have been performed for self-aligned AlGaAs/GaAs heterojunction bipolar transistors (HBT's). For shorted base–emitter condition, the resistance fluctuation $1/f$ noise is dominant, while for open base–emitter condition, the base–emitter current $1/f$ noise is dominant. The collector–emitter $1/f$ current noise, though generally considered an important noise source, is negligible. The resistance $1/f$ noise stems mainly from the emitter resistance fluctuation. Our noise-reduction works are focused on the reduction of the base–emitter current $1/f$ noise. We have investigated the base–emitter-current noise properties as a function of emitter–base structure and surface passivation condition. It is found that the surface-recombination $1/f$ noise can be significantly reduced by the heterojunction launcher of the abrupt junction with 30% aluminum mole fraction emitter. The depleted AlGaAs ledge surface passivation further suppresses the surface-recombination currents. Consequently, we have achieved a very low $1/f$ noise corner frequency of 2.8 kHz at the collector current density of 10 kA/cm^2. The dominant noise source of the HBT is not a surface-recombination current, but a bulk current noise. This is the lowest $1/f$ noise corner frequency among the III–V compound semiconductor transistors, and is comparable to those of low-noise Si bipolar junction transistors (BJT's).**

***Index Terms*— Heterojunction bipolar transistor, $1/f$ noise, oscillator, phase noise.**

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J.-H. Shin was with the Pohang University of Science and Technology (POSTECH), Hyoja-Dong Pohang, Kyung-pook 790-784, Korea. He is now with the LG Corporate Institute of Technology (LG CIT), Seocho-Gu, Seoul 137-724, Korea.

J. Kim was with the Pohang University of Science and Technology (POSTECH), Pohang, Kyung-pook 790-784, Korea. He is now with Samsung Advanced Institute of Technology, Suwon 440-600, Korea

Y. Chung and B. Kim are with the Department of Electronic and Electrical Engineering and Microwave Application Research Center, Pohang University of Science and Technology (POSTECH), Pohang, Kyung-pook 790-784, Korea.

J. Lee was with the Pohang University of Science and Technology (POSTECH), Pohang, Kyung-pook 790-784, Korea. He is now with Mobile Telecomminications Terminal Division, Hyundai Electronics, Icheon 467-701, Korea.

Y. Suh was with the Pohang University of Science and Technology (POSTECH), Pohang, Kyung-pook 790-784, Korea. He is now with Yeungnam University, Kyong-San 712-749, Korea.

K. H. Ahn was with the Pohang University of Science and Technology (POSTECH), Pohang, Kyung-pook 790-784, Korea. He is now with the Korea Advanced Institute of Science and Technology (KAIST), Taijun 305-701, Korea.

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I. Introduction

DUE TO THEIR excellent microwave performance and potential for low $1/f$ noise characteristics, AlGaAs/GaAs heterojunction bipolar transistors (HBT's) have been emerging as main devices for low phase-noise oscillator applications in microwave and millimeter frequency bands [1]–[3]. For these applications, the low $1/f$ noise of an HBT is very important since in oscillator circuit the $1/f$ noise can be upconverted to the near-carrier spectra via device nonlinearities, degrading the phase noise [4], [5]. AlGaAs/GaAs HBT's have relatively low $1/f$ noise levels due to vertical operation, compared to FET devices such as GaAs MESFET's and high electron-mobility transistors (HEMT's), which are operating near the surface or heterojunction interface (which may have high trap density) [6]. However, AlGaAs/GaAs HBT's still exhibit inferior $1/f$ noise performances compared to Si bipolar junction transistors (BJT's) and other newly emerging material-based HBT's. The $1/f$ noise corner frequencies of Si or Si/SiGe BJT's [7]–[9], GaInP/GaAs HBT's [10], [11], and AlInAs/InGaAs HBT's [12] are below 100 kHz, while those of AlGaAs/GaAs HBT's [13]–[19] are above 100 kHz. For most Si BJT's, the $1/f$ noise is known to be limited by the diffusion $1/f$ noise [20]. However, for the AlGaAs/GaAs HBT's, the $1/f$ noise is very sensitive to the processing techniques and materials, and is not in the diffusion $1/f$ noise limit. This means that better understanding of the $1/f$ noise properties of an AlGaAs/GaAs HBT will lead to the significant reduction of $1/f$ noise. Moreover, this understanding will create better low-frequency noise equivalent-circuit model, and will prompt the more systematic design of low-phase noise HBT oscillators.

For AlGaAs/GaAs HBT's, various low-frequency noise-generating mechanisms have been suggested to understand the physical origins of $1/f$ noise, but the understandings are not well established. Most works concluded that the dominant $1/f$ noise would stem from the fluctuations of the extrinsic GaAs base surface-recombination velocity due to its high surface states [14]–[16]. Using the depleted AlGaAs surface-passivating ledge structure over the extrinsic base surface region Hayama *et al.* [14] showed that the surface-recombination $1/f$ noise could be reduced considerably. Costa *et al.* corroborated the results of Hayama *et al.* further by investigating the $1/f$ noise properties as a function of surface passivation condition, device geometry, bias, and temperature [15]. Although these experimental results and the implications have been generally believed, it is also noteworthy that there have been large deviations of more than 10 dB in the magnitude of $1/f$ noise among the surface-passivated HBT's [14]–[17], strongly indicating that the major part of $1/f$ noise is closely related to the detailed HBT structure. Furthermore, the bias dependencies of the noise power spectral density (S) for HBT's reported did not provide a unanimous relationship of $S \propto I^2$, which was predicted from the surface-recombination $1/f$ noise theory [15], [21], making it very difficult to know the dominant noise source. These noise works used only the base–emitter current noise source $(S_{I_{\rm be}})$ as a measure of low-frequency noise magnitude, without evaluating the effect of other proposed noise sources.

Meanwhile, some earlier works dealt with the location of physical noise sources. Since the noise upconversion mechanism in an HBT oscillator may depend on the exact location of the noise sources, these works are very important in modeling the low-frequency noise equivalent circuit of an HBT. Most of the works in this area assumed only the intrinsic noise sources such as base–emitter $(S_{I_{\rm be}})$, collector–emitter $(S_{I_{\rm ce}})$, and base–collector current fluctuations $(S_{I_{\rm bc}})$, and they interpreted the intrinsic noise sources based on the base (S_{I_b}) and collector current noise spectra (S_{I_c}), which were measured with the collector and base short circuited, respectively. Zhang *et al.* examined the S_{I_b} and S_{I_c} as a function of emitter feedback resistance [22]. For an AlGaAs/GaAs double HBT, they found that S_{I_c} was dominantly larger than S_{I_b} and that $S_{I_c} \propto I_C^{2.0}$. For small-size self-aligned AlGaAs/GaAs HBT's, Rama *et al.* also measured a nearly same bias dependency of $S_{I_c} \propto I_E^{2.0}$, and attributed the noise origin to the minority carrier trapping at the emitter–base (E-B) heterojunction interface [23]. More recently, Tutt *et al.* [18] found a bias dependency of $S_{I_c} \propto I_C^{2.5}$ for self-aligned AlGaAs/GaAs HBT's with a multifinger emitter, and they also found that S_{I_c} was much larger than S_{I_b}, similar to the results given by Zhang *et al.* [22]. The bias dependencies of $S_{I_c} \propto I_c^m$ with $m \geq 2.0$ cannot be explained by the existing models. Either diffusion $1/f$ noise [20] or minority carrier trapping $1/f$ noise [24] would cause $1/f$ noise in S_{I_c}, but the theories would provide the bias dependency with $S_{I_c} \propto S_{I_{\rm ce}} \propto I_c^{1.0}$. Moreover, the dominance of S_{I_c} in an HBT is quite a different phenomenon from the case of a Si BJT, where S_{I_c} is comparable to S_{I_b} [25]. The results of previous works suggest that a more general approach, including a new noise source, is needed to understand the noise behavior.

The primary goal of this paper is to find an optimum AlGaAs/GaAs HBT structure for reduced $1/f$ noise. To reduce $1/f$ noise, it is essential to know the dominant noise source. To identify the dominant noise sources, we developed a quantitative noise-source extraction procedure based on the generalized noise model, which includes the base–emitter current fluctuation, collector–emitter current fluctuation, and resistance fluctuation sources. Recently, based on the mobility fluctuation theory, Kleinpenning *et al.* suggested that a significant $1/f$ noise can be generated by the parasitic emitter and base series resistances [19]. The existence of the resistance fluctuation $1/f$ noise source (S_{V_r}) had been further verified by us using a very large AlGaAs/GaAs HBT [26]. Since S_{V_r} is proportional to the square of the bias current, the use of S_{V_r} is expected to make it possible to explain the conventionally anomalous bias dependency of $S_{I_c} \propto I_c^m$ with $m \geq 2.0$. The dominant noise sources are identified. They are base–emitter current $1/f$ noise and resistance fluctuation $1/f$ noise. Collector–emitter current $1/f$ noise is negligible. In this paper, noise-reduction works are focused on the base–emitter current $1/f$ noise. As mentioned above, the base–emitter current $1/f$ noise, including a surface-recombination $1/f$ noise source, has been expected to be closely related to the detailed carrier transport through the HBT vertical structure. Recently, the use of an electrically abrupt E-B junction HBT was suggested for the reduced $1/f$ noise [27]. The unpassivated HBT demonstrated a very low $1/f$ noise corner frequency of about 8 kHz, comparable to those of low-noise Si BJT's. The considerable reduction of $1/f$ noise is mainly due to the launching effect of the compositionally abrupt E-B heterojunction discontinuity. Since the extrinsic GaAs base surface region is laterally connected to the E-B interface region, the electrons accelerated by the abrupt E-B junction can cross over the very thin E-B interface region without recombination, and the portion of electrons laterally diffusing to the base surface is significantly decreased. Nevertheless, the dominant noise source for the HBT was still the residual surface recombination [27]. This suggests that the noise can be further reduced by applying the depleted AlGaAs ledge passivation technique [14]–[16]. To find the optimized HBT structure for the reduced base–emitter current $1/f$ noise, the surface-recombination characteristics of HBT's have been investigated as a function of the grading of the E-B junction, Al composition in the emitter, and surface passivation condition.

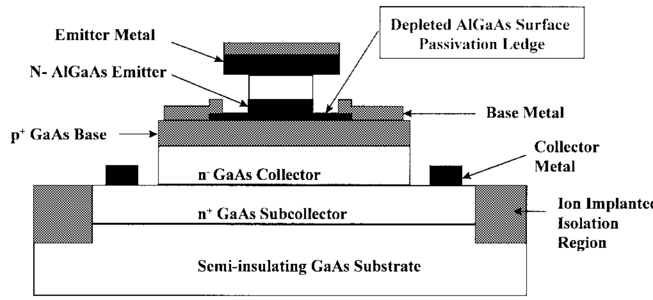


Fig. 1. Schematic cross section of the fabricated self-aligned AlGaAs/GaAs HBT with the depleted AlGaAs surface passivation ledge.

II. Device Structure

A. Fabrication of AlGaAs/GaAs HBT with Self-Aligned Ledge

Mesa-type HBT's were fabricated by a conventional self-aligned base metal (SABM) process [28]. To suppress the extrinsic base surface-recombination current and its related $1/f$ noise, a simple self-aligned ledge fabrication process has been developed and incorporated into the SABM process. Fig. 1 represents the schematic cross section of the fabricated HBT with the depleted AlGaAs surface passivation ledge.

TABLE I
HBT'S USED FOR THIS WORK

Device	E-B Junction Structure	Al Mole Fraction (%)	Base Thickness (Å)	Collector Current Ideality Factor		
				Min.	Typ.	Max.
HBT A	Abrupt	30	1000	1.120	1.180	1.223
HBT B	Graded	30	1400	1.000	1.002	1.010
HBT C	Abrupt	20	1000	1.034	1.067	1.083

(HBT A', B' and C' are the passivated counterparts of HBT A, B and C, respectively.)

TABLE II
MOCVD-LAYER STRUCTURE FOR HBT A AND A'

	Layer	Thickness (Å)	Doping (cm^{-3})	Dopant	Al(In) composition
Cap	n^{+}-InGaAs	400	1×10^{19}	Si	0.5
	n^{+}-InGaAs	400	1×10^{19}	Si	0→0.5
	n^{+}-GaAs	500	5×10^{18}	Si	0
	n-GaAs	700	5×10^{17}	Si	0
Emitter	n-AlGaAs	300	2×10^{17}	Si	0.3→0
	n-AlGaAs	700	2×10^{17}	Si	0.3
Base	p^{+}-GaAs	1000	2×10^{19}	C	0
Collector	n^{-}-GaAs	4000	2×10^{16}	Si	0
Subcollector	n^{+}-GaAs	6000	5×10^{18}	Si	0
Semi-insulating GaAs substrate					

B. Devices Used

Table I shows the device structures studied. To investigate the E-B junction effects on the surface-recombination current and its related $1/f$ noise, we used the unpassivated $Al_xGa_{1-x}As/GaAs$ HBT's with three different E-B structures:

1) HBT A (abrupt/$x = 0.3$);
2) HBT B (graded/$x = 0.3$);
3) HBT C (abrupt/$x = 0.2$).

HBT A', B', and C' are the surface-passivated counterparts of HBT A, B, and C, respectively. Table II describes the MOCVD-grown layer structure for HBT A and A'. To reduce the E-B space charge region (SCR) recombination, the undoped spacer layer between emitter and base layers was not used [29]. HBT B is identical to HBT A, except it has a 1400-Å-thick base. HBT C is identical to HBT A, except it has a 20% Al mole fraction emitter. The typical collector current ideality factors were 1.180, 1.002, and 1.067 for HBT A, B, and C, respectively. The nearly unity ideality factor of HBT B means that it has a graded E-B junction [30]. However, the ideality factors more than unity for HBT A and C mean that they have electrically abrupt E-B junctions and that the heterojunction launchers are effective for HBT A and C. Since the value of the conduction band discontinuity (ΔE_C) for HBT A with 30% Al mole fraction emitter is much larger than that for HBT C, HBT A is expected to have the strongest launching effect and, therefore, the smallest surface-recombination current amongst the unpassivated HBT structures.

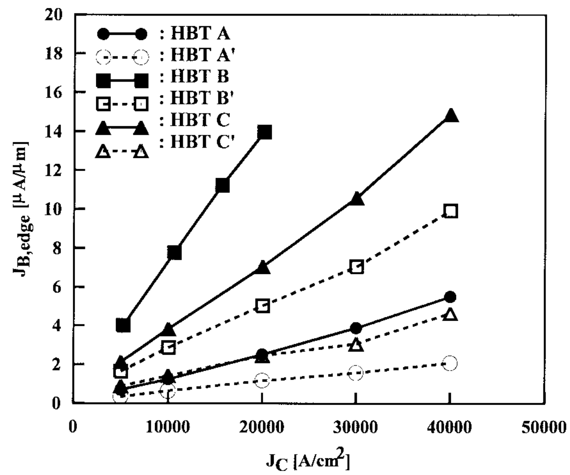


Fig. 2. Emitter–edge base current density $(J_{B,\text{edge}})$ versus collector current density (J_C) characteristics for HBT's.

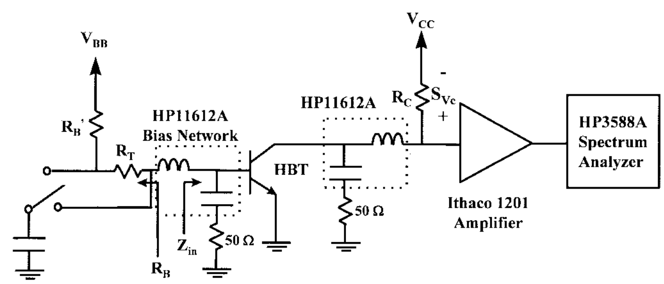


Fig. 3. Test setup for low-frequency noise measurement of HBT's.

C. Surface-Recombination Characteristics

To estimate the magnitude of surface-recombination base currents for the various HBT structures, we used the H_{FE}^{-1} versus P_E (emitter periphery)/A_E (emitter area) characteristics. The area $(I_{B,\text{area}})$ and edge $(I_{B,\text{edge}})$ currents are related to dc current gain H_{FE} $(= I_C/I_B)$ by [31]

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

The emitter–edge base current density $(J_{B,\text{edge}} = I_{B,\text{edge}}/P_E)$ can be extracted from the slope of the line.

Fig. 2 shows the emitter–edge base current density $(J_{B,\text{edge}})$ versus collector current density (J_C) characteristics for the various HBT's. HBT A and HBT A' have the lowest edge current densities, confirming our expectation. It is noteworthy that the $J_{B,\text{edge}}$ value of 1.24 μA/μm for the unpassivated HBT (HBT A) is, within our knowledge, the lowest value among the unpassivated AlGaAs/GaAs HBT's. At $J_C = 10$ kA/cm^2, the $J_{B,\text{edge}}$ reduction factors by surface passivation are 2.22, 2.71, and 2.73 for HBT A and A', HBT B and B', and HBT C and C' pairs, respectively.

III. LOW-FREQUENCY NOISE CHARACTERISTICS

A. Low-Frequency Noise-Measurement System

A noise-measurement system is shown in Fig. 3. HBT's are arranged in the common emitter configuration. The collector voltage noise (S_{V_c} in V^2/Hz) is amplified by the low-noise amplifier (ITHACO 1201 preamplifier), and its output spectrum

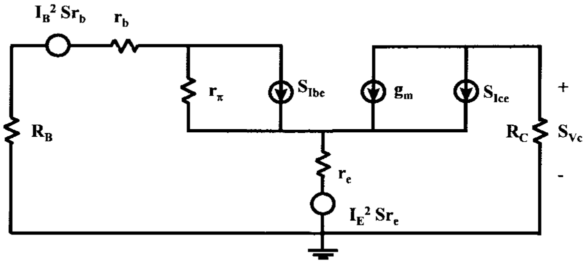


Fig. 4. Low-frequency noise equivalent-circuit model for the HBT.

is measured from 10 Hz to 100 kHz by using an HP3588A spectrum analyzer. Noise measurements are carried out by the computer-controlled HP3588A spectrum analyzer and consist of several noise measurements at the separate subbands into which the overall measurement bandwidth is divided. The system provides an added option of changing the effective low-frequency base termination resistance R_B via switching the large-valued capacitance of 2.2 mF to the proper node. To avoid the parasitic oscillation of the biased HBT, 50-Ω-terminated bias networks (HP11612A) are used. The noise levels at the input of spectrum analyzer can be kept at least 15 dB higher than the noise floor of the spectrum analyzer by adjusting the voltage gain of the low-noise amplifier. The level of collector voltage noise (S_{V_c}) can be kept at least 40 dB higher than the noise floor of the low-noise amplifier by increasing the collector bias resistance R_C. Biases are applied to the base and collector terminals through batteries to reduce noise added by the power supplies. Wire-wound resistors are used to avoid $1/f$ noise from biasing circuit elements. Except for the spectrum analyzer, all the system components are shielded by the aluminum box.

B. Low-Frequency-Noise Equivalent-Circuit Model

Fig. 4 is the low-frequency-noise equivalent-circuit model of the HBT used in this work. To start, we initially assumed the above generalized noise equivalent-circuit model, including all noise sources ($S_{I_{\rm bc}}$, $S_{I_{\rm cc}}$, and S_{V_r}). The second assumption is that the separate noise sources are uncorrelated and stem from physically independent mechanisms within the device. $S_{I_{\rm bc}}$ represents the base–emitter current noise such as surface-recombination $1/f$ noise generated at the extrinsic base GaAs surface [15], generation–recombination (g-r) noise generated at the AlGaAs emitter SCR [15], and E-B hetero-interface recombination $1/f$ noise [32]. $S_{I_{\rm cc}}$ represents the collector–emitter current noise stemming from the fluctuation of base diffusivity [20] (diffusion $1/f$ noise) or from the number fluctuation due to the minority carrier trapping at the base bulk or at the E-B heterojunction interface [24]. As suggested by Kleinpennig [19], S_{V_r} represents the voltage fluctuation $1/f$ noise generated by emitter and base series resistances, and the expression is given by

$$S_{V_r} = I_B^2 S_{r_b} + I_E^2 S_{r_e} \tag{2}$$

where I_B and I_E are base and emitter currents, respectively. The expressions for S_{r_b} and S_{r_e} are given as follows:

$$S_{r_b} = \alpha_b r_b^2/(fN_b^*)$$

and

$$S_{r_e} = \alpha_e r_e^2/(fN_e^*) \tag{3}$$

where α_b (α_e) is the Hooge parameter for the base (emitter) layer, f is the frequency, and N_b^* (N_e^*) is the effective total number of majority carriers in the base(emitter) resistance. The base resistance (r_b) and the emitter resistance (r_e) are extracted from the measured S-parameters [33]. $r_\pi = (n_b kT)/(qI_B)$ and $g_m = \beta/r_\pi = (qI_C)/(n_c kT)$ are a base input resistance and transconductance of the intrinsic transistor, respectively, where n_b (n_c) is a base (collector) current ideality factor and β is a differential current gain.

C. Extraction of Low-Frequency Noise Sources

To extract three unknown noise sources ($S_{I_{\rm bc}}$, $S_{I_{\rm cc}}$, and S_{V_r}), we measured three kinds of collector–current noise spectra of the HBT under the same bias condition by varying the E-B termination resistance R_B. These are S_{V_c}/R_C^2 with open E-B condition ($R_B \gg Z_{\rm in}$), S_{I_c} with shorted E-B termination condition ($R_B \approx 0\ \Omega$), and S'_{I_c} with intermediate E-B termination condition ($R_B = R_T$), where $Z_{\rm in} = r_b + r_\pi + (1+\beta)r_e$ is the common-emitter input resistance of the HBT. Following the generalized noise analyses given by Kleinpenning *et al.* [19], we can derive the expressions for the aforementioned collector–current noise power spectral densities as follows:

$$\begin{aligned} S_{V_c}/R_c^2 &= \beta^2 S_{I_{\rm bc}} + S_{I_{\rm cc}} + [\beta/(R_B+Z_{\rm in})]^2 S_{V_r} \\ &\quad + 2qI_B\beta^2 + 2qI_C \end{aligned} \tag{4}$$

$$\begin{aligned} S_{I_c} &= [\beta(r_b+r_e)/Z_{\rm in}]^2 S_{I_{\rm bc}} + [(r_b+r_\pi+r_e)/Z_{\rm in}]^2 S_{I_{\rm cc}} \\ &\quad + (\beta/Z_{\rm in})^2 S_{V_r} + (S_{I_c})_w \end{aligned} \tag{5}$$

and

$$\begin{aligned} S'_{I_c} &= [\beta(R_T+r_b+r_e)/(R_T+Z_{\rm in})]^2 S_{I_{\rm bc}} \\ &\quad + [(R_T+r_b+r_\pi+r_e)/(R_T+Z_{\rm in})]^2 S_{I_{\rm cc}}] \\ &\quad + [\beta/(R_T+Z_{\rm in})]^2 S_{V_r} + (S'_{I_c})_w \end{aligned} \tag{6}$$

where $(S_{I_c})_w$, and $(S'_{I_c})_w$ are white noise components of S_{I_c} and S'_{I_c}, respectively, and are given by

$$\begin{aligned} (S_{I_c})_w &= [\beta(r_b+r_e)/Z_{\rm in}]^2 2qI_B + [(r_b+r_\pi+r_e)/Z_{\rm in}]^2 2qI_C \\ &\quad + (\beta/Z_{\rm in})^2 4kT(r_b+r_e) + 4kT/R_C \end{aligned} \tag{7}$$

and

$$\begin{aligned} (S'_{I_c})_w &= [\beta(R_T+r_b+r_e)/(R_T+Z_{\rm in})]^2 2qI_B \\ &\quad + [(R_T+r_b+r_\pi+r_e)/(R_T+Z_{\rm in})]^2 2qI_C \\ &\quad + [\beta/(R_T+Z_{\rm in})]^2 4kT(R_T+r_b+r_e) + 4kT/R_C. \end{aligned} \tag{8}$$

$S_{I_{\rm bc}}$ can be extracted from S_{V_c}/R_c^2 due to virtually open circuited base ($R_B \gg Z_{\rm in}$) and large β via the simplified relation

$$S_{I_{\rm bc}} = S_{V_c}/(R_c\beta)^2. \tag{9}$$

TABLE III
RESULTS OF NOISE-SOURCE EXTRACTION FOR HBT A' AND HBT B AT 10 Hz

Items	Symbols	Units	HBT A' $A_E = 4 \times 30\ \mu m^2$			HBT B $A_E = 4 \times 30\ \mu m^2$		
Base current	I_B	μA	277	411	686	438	729	1320
Collector current	I_C	mA	6.39	10.1	18.9	6.28	11.2	22.1
Differential current gain	β		26.6	28.4	31.8	15.9	17.0	18.6
Input resistance	Z_{in}	Ω	275	243	225	125	102	90.0
Base termination for S_{Vc}/R_c^2	R_B	kΩ	10.0	6.55	5.75	7.10	6.30	2.30
Base termination for S_{Ic}'	R_T	Ω	60	50	50	20	20	20
Collector bias resistance	R_C	Ω	700	300	330	500	540	240
Measured S_{Vc}/R_c^2	S_{Vc}/R_c^2	dB(A²/Hz)	-166.8	-161.3	-152.3	-154.4	-149.3	-143.5
Measured S_{Ic}	S_{Ic}	dB(A²/Hz)	-157.9	-150.6	-145.5	-168.6	-163.7	-154.4
Measured S_{Ic}'	S_{Ic}'	dB(A²/Hz)	-159.3	-151.7	-146.8	-165.7	-160.4	-153.1
White noise of S_{Vc}/R_c^2	$2qI_B\beta^2 + 2qI_C$	dB(A²/Hz)	-191.9	-189.6	-186.4	-194.3	-191.5	-188.1
White noise of S_{Ic}	$(S_{Ic})_w$	dB(A²/Hz)	-206.2	-204.8	-203.2	-204.3	-202.1	-200.0
White noise of S_{Ic}'	$(S_{Ic}')_w$	dB(A²/Hz)	-199.6	-198.2	-195.9	-200.7	-198.2	-195.6
Extracted S_{Ibe}	$(S_{Ibe})^{ext}$	dB(A²/Hz)	-195.3	-190.4	-182.4	-178.4	-173.9	-168.9
Extracted S_{Ice}	$(S_{Ice})^{ext}$	dB(A²/Hz)	-164.2	-152.4	-148.3	-172.6	N/P	N/P
Extracted S_{Vr}	$(S_{Vr})^{ext}$	dB(V²/Hz)	-137.9	-132.5	-128.6	-151.4	-146.7	-139.8
Extracted S_{Vr} from Eq. (11)	$(S_{Vr})_s^{ext}$	dB(V²/Hz)	-137.6	-132.0	-128.4	-150.7	-148.1	-140.8
S_{Ic} due to $(S_{Ice})^{ext}$	$S_{Ic}\|(S_{Ice})^{ext}$	dB(A²/Hz)	-170.1	-160.3	-159.3	-177.0	N/P	N/P
S_{Ic} due to $(S_{Ibe})^{ext}$	$S_{Ic}\|(S_{Ibe})^{ext}$	dB(A²/Hz)	-194.7	-188.1	-178.5	-176.3	-169.4	-162.5
S_{Ic}' due to $(S_{Ice})^{ext}$	$S_{Ic}'\|(S_{Ice})^{ext}$	dB(A²/Hz)	-168.7	-158.3	-156.0	-176.2	N/P	N/P
S_{Ic}' due to $(S_{Ibe})^{ext}$	$S_{Ic}'\|(S_{Ibe})^{ext}$	dB(A²/Hz)	-180.3	-174.9	-165.4	-168.1	-161.5	-154.7
S_{Vc}/R_C^2 due to $(S_{Vr})^{ext}$	$(S_{Vc}/R_C^2)\|(S_{Vr})^{ext}$	dB(A²/Hz)	-189.7	-180.0	-174.1	-204.5	-198.3	-182.0

(※ N/P means nonphysical value, i. e., negative value of noise power spectral density.)

Since the $S_{I_{\rm bc}}$ term in (5) is negligible, the expression for S_{I_c} can be written as

$$S_{I_c} = [(r_b + r_\pi + r_e)/Z_{\rm in}]^2 S_{I_{\rm ce}} + (\beta/Z_{\rm in})^2 S_{V_r}. \quad (10)$$

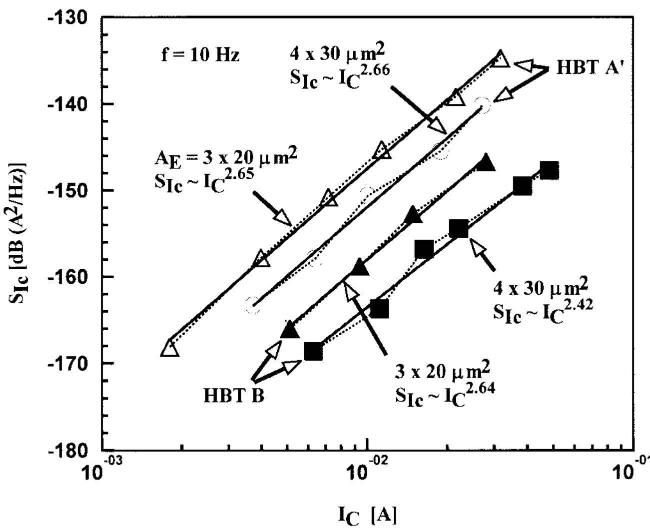
To extract $S_{I_{\rm ce}}$ and S_{V_r}, we have used (6) and (10). A proper value of R_T is chosen so that the $S_{I_{\rm bc}}$ term in S'_{I_c} is not dominantly large, and that the $S_{I_{\rm ce}}$ or S_{V_r} terms in S'_{I_c} are changed more than approximately 1 dB from those in S_{I_c}. This leads to the solution for $S_{I_{\rm ce}}$ and S_{V_r}. Table III summarizes the results of extraction for HBT A' and HBT B at 10 Hz. The contribution of the extracted $(S_{I_{\rm bc}})^{\rm ext}$ to S_{I_c}, i.e., $S_{I_c}|(S_{I_{\rm bc}})^{\rm ext}$ is negligible compared to the S_{I_c} (10 Hz), proving (10). As previously assumed in deriving (10), the effect of S_{V_r} on S_{V_c}/R_C^2, i.e., $(S_{V_c}/R_C^2)|(S_{V_r})^{\rm ext}$, is also negligible compared to S_{V_c}/R_C^2 (10 Hz). By examining the extracted value of $S_{I_{\rm ce}}$, we can find that the noise source is negligible. The contribution of $(S_{I_{\rm ce}})^{\rm ext}$ to S_{I_c}, i.e., $(S_{I_c})|(S_{I_{\rm ce}})^{\rm ext}$, is at least 10 dB lower than the S_{I_c} (10 Hz) values. By neglecting the $S_{I_{\rm ce}}$ term, $(S_{V_r})_s^{\rm ext}$ can be extracted from the simple relation

$$(S_{V_r})_s^{\rm ext} = (Z_{\rm in}/\beta)^2 S_{I_c}. \quad (11)$$

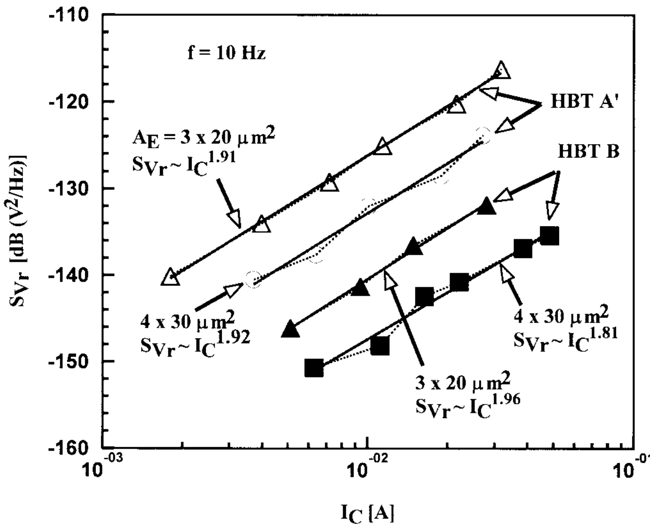
The $(S_{V_r})_s^{\rm ext}$ and $(S_{V_r})^{\rm ext}$ values agree very well within a noise measurement error of about 1 dB, showing that S_{V_r} is the dominant noise source. In a general case of any low-frequency base termination ($R_B = R_T$), the expression for collector current noise of $S_{I_c}|(R_B = R_T)$ can be written by the following equation:

$$S_{I_c}|(R_B = R_T) = [\beta(R_T + r_b + r_e)/(R_T + Z_{\rm in})]^2 S_{I_{\rm bc}} + [\beta/(R_T + Z_{\rm in})]^2 S_{V_r} \quad (12)$$

where $S_{I_{\rm bc}}$ and S_{V_r} are simply given by using (9) and (11), respectively. The effect of base termination on the collector current noise can be calculated by using (12). For both devices, the base–emitter current noise source $(S_{I_{\rm bc}})$ is dominant for the open B-E termination condition, and the resistance $1/f$ noise source (S_{V_r}) is dominant for shorted B-E termination condition. Since the S_{V_r} term is negligible for the open B-E condition, the extraction of $S_{I_{\rm bc}}$ using (9) can be justified with $R_B \gg Z_{\rm in}$. As can be seen from Table III, the values of $S_{I_{\rm bc}}$ for HBT B are much larger than those for HBT A', but the values of S_{V_r} for HBT B are much smaller than those for HBT A'. To prove validity and generality, the results

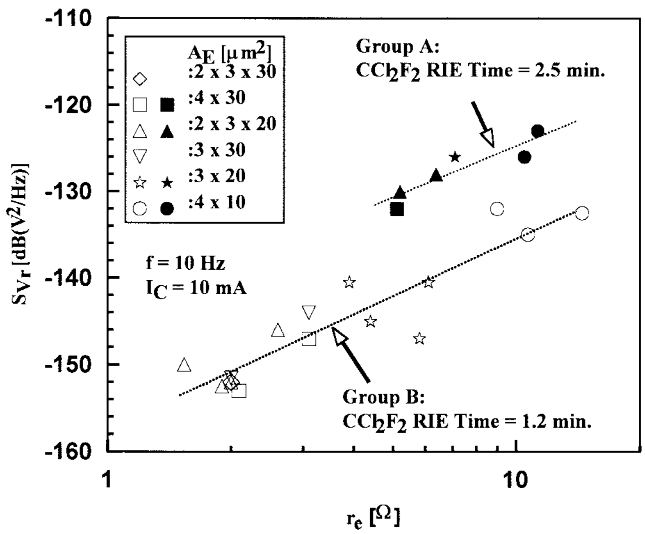


(a)

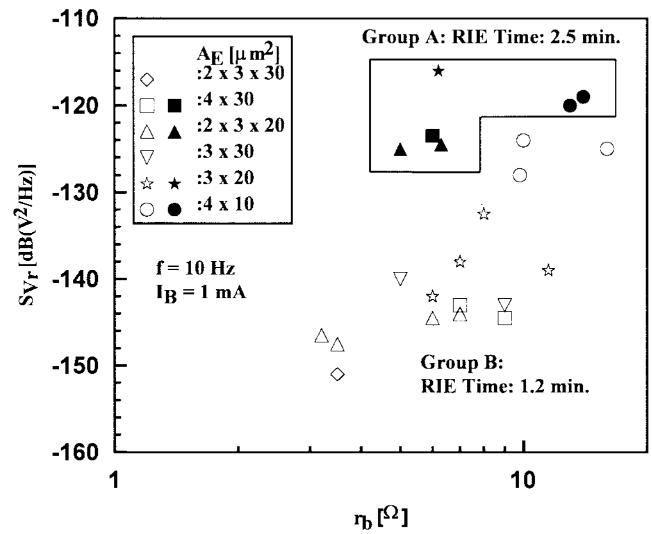


(b)

Fig. 5. (a) S_{I_c} (10 Hz) versus I_C characteristics for HBT A' and HBT B. (b) S_{V_r} (10 Hz) versus I_C characteristics for HBT A' and HBT B. Emitter sizes used: 4 × 30 and 3 × 20 μm^2.



(a)



(b)

Fig. 6. Correlation data (a) between S_{V_r} (10 Hz) and emitter resistance (r_e) at $I_C = 10$ mA and (b) between S_{V_r} (10 Hz) and base resistance (r_b) at $I_B = 1$ mA. The S_{V_r} versus r_e data show strong correlation.

of noise-source extraction have been shown for the above two extreme HBT's. In any case, our noise-source extraction method can be easily applied, and the dominant noise sources in HBT's can be identified. The remaining part of this section is focused on verifying the validity of our newly found noise source (S_{V_r}). Fig. 5(a) shows the S_{I_c} versus I_C characteristics for HBT A' and B. For both devices, the values of S_{I_c} are proportional to I_C^m with m far greater than 2.0. These bias dependencies can be explained not by using the conventional noise theories but by using S_{V_r}, as in our noise analysis, because $S_{V_r} \propto I_C^2$ and Z_{in} decreases with the increase of I_C. As shown in Fig. 5(b), the extracted S_{V_r} data for HBT A' and B are approximately proportional to $I_C^{2.0}$, agreeing with (2). This substantiates the existence of resistance fluctuation $1/f$ noise (S_{V_r}). At the same collector current level, the value of S_{V_r} for HBT A' is at least 10 dB larger than that for HBT B. To determine which factor is the dominant one between S_{r_e} or S_{r_b} terms, Fig. 6(a) and (b) represents S_{V_r} versus r_e (at $I_C = 10$ mA) and S_{V_r} versus r_b (at $I_B = 1$ mA), respectively, which were measured from two groups of HBT's with different CCl_2F_2 reactive ion etching (RIE) times. With the increase of RIE time, the emitter area becomes narrower, thereby increasing the emitter resistance r_e. HBT A', HBT C, and HBT C' belong to group A with an RIE time of 2.5 min, while HBT A, HBT B, and HBT B' belong to group B with an RIE time of 1.2 min. Fig. 6(a) shows the strong correlation between S_{V_r} and r_e, while Fig. 6(b) shows little correlation between S_{V_r} and r_b. Although the effect of S_{r_b} on S_{V_r} cannot be totally neglected, the correlation data suggest that S_{r_e} is more promising candidate for a dominant source for S_{V_r}. In Fig. 6(a), we can also observe that group A devices with longer RIE time have at least 10 dB larger noise levels than group B devices at the same r_e value. Since $S_{V_r} \propto S_{r_e} \propto (\alpha_e/N_e^*)r_e^2$ according to (3), the considerable increase of S_{V_r} for group

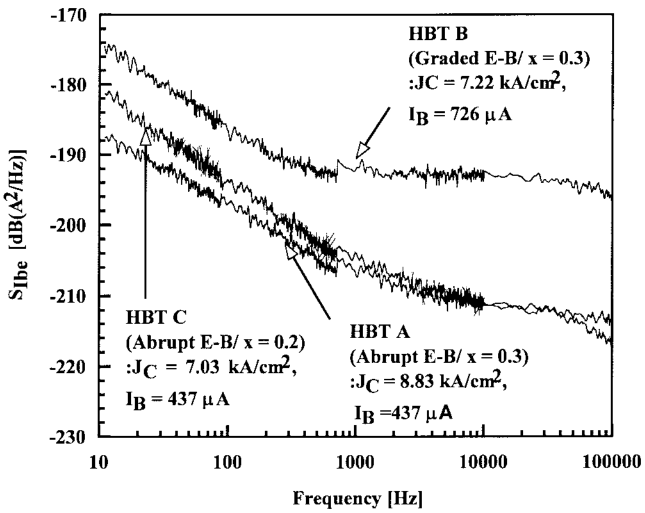
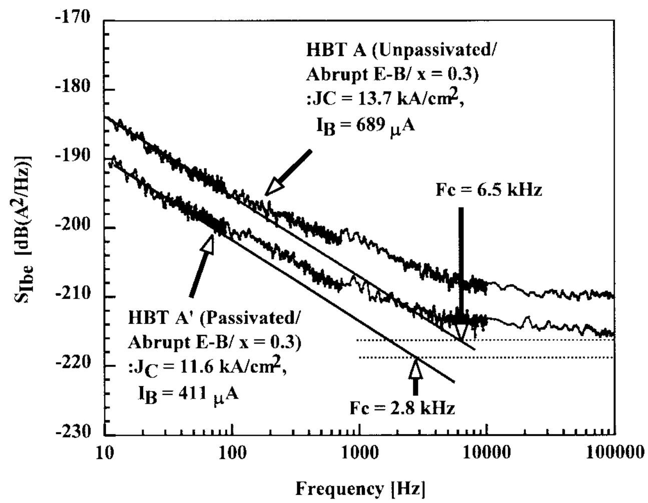


Fig. 7. Low-frequency base–emitter current noise spectra ($S_{I_{\rm bc}}$ versus frequency) for the unpassivated HBT's with different E-B structures: HBT A (abrupt/$x = 0.3$), HBT B (graded/$x = 0.3$), HBT C (abrupt/$x = 0.2$). Emitter size used is $2 \times 3 \times 20$ μm^2.

A devices may be mainly due to the increase in (α_e/N_e^*) factor. At the same r_e value, group A device has much larger nominal emitter dimension than group B device. For example, at the r_e value of about 6 Ω, the nominal emitter dimension of a group A device is $2 \times 3 \times 20$ μm^2, while that for group B device is 3×20 μm^2. According to scanning electron microscrope (SEM) measurements, the undercuts for group A and B devices were about 0.5 and 0.2 μm, respectively. Based on the data, the ratio of $(N_e^*)_{\text{group A}}/(N_e^*)_{\text{group B}}$ $(\approx (A_e^*)_{\text{group A}}/(A_e^*)_{\text{group B}})$ is estimated as 1.5. Nevertheless, $(\alpha_e/N_e^*)_{\text{group A}} \gg (\alpha_e/N_e^*)_{\text{group B}}$. Therefore, the aforementioned increase in the (α_e/N_e^*) factor of group A device means the increase of α_e. That is, the increase in S_{V_r} of group A device stems from the increase of α_e (which may be due to the RIE damage), as well as the increase of r_e (due to the narrower emitter width). To minimize the resistance $1/f$ noise, the emitter RIE process should be studied further.

D. Reduction of Base–Emitter Current $1/f$ Noise Sources

In most of the biasing circuits for the BJT, the high B-E termination condition with $R_B \gg Z_{\text{in}}$ are commonly found because BJT's are current–gain devices with base current driving. Therefore, the base–emitter current noise source $(S_{I_{\rm bc}})$ is a practically more important one. To find the optimum HBT structure for reduced B-E current $1/f$ noise, we have investigated the base–emitter current noise $(S_{I_{\rm bc}})$ characteristics for various HBT's, as described in Section II-B. Fig. 7 shows the $S_{I_{\rm bc}}$ spectra for HBT A, B, and C with different E-B structures. At $J_C \approx 7$ kA/cm^2 and $f = 10$ Hz, we can observe that the magnitude of $S_{I_{\rm bc}}$ for HBT A is the lowest, as can be deduced from the surface current characteristics given by Fig. 2. This indicates that the $1/f$ noise of $S_{I_{\rm bc}}$ can be determined by the magnitudes of surface-recombination currents. In addition, we can also observe that the magnitudes of the g-r noise plateaus for abrupt HBT's (HBT A and C) are much lower than that for the graded HBT (HBT B). While



(a)

HBT's	HBT A	HBT A'	HBT B	HBT B'	HBT C	HBT C'
Fc [kHz]	6.5	2.8	55	7.7	11	5.5

(b)

Fig. 8. (a) Low-frequency base–emitter current noise spectra ($S_{I_{\rm bc}}$ versus frequency) for the abrupt E-B junction $Al_{0.3}Ga_{0.7}As$/GaAs HBT's: HBT A (unpassivated), HBT A' (passivated). Emitter size used is $2 \times 3 \times 20$ μm^2. The $1/f$ noise corner frequencies (F_C) are indicated together with the shot noise floor approximately given by $2qI_B$. (b) Measured $1/f$ noise corner frequencies (F_C) at $J_C \approx 10$ kA/cm^2 for various HBT's.

the g-r noise plateaus of HBT A and C are about 5 dB larger than the shot noise floor of $2qI_B$, that of HBT B is at least 20 dB larger than the noise floor. This very low g-r noise for the abrupt HBT's may be attributed to the suppression of E-B SCR recombination current of the abrupt E-B junction [34]. To estimate the surface passivation effect on the $1/f$ noise and to evaluate the $1/f$ noise corner frequencies for various HBT structures, the $S_{I_{\rm bc}}$ spectra have been measured. Fig. 8(a) shows the $S_{I_{\rm bc}}$ spectra for HBT A and A'. Fig. 8(b) summarizes the measured corner frequencies for the various HBT's. By passivating HBT's, the noise levels have been reduced by more than 5 dB. The passivated HBT with abrupt E-B junction and 30% Al mole fraction emitter layer (HBT A') has a very low noise corner frequency of 2.8 kHz at the practical bias point of $J_C \approx 10$ kA/cm^2. To our knowledge, this is the lowest noise corner frequency among the III–V compound semiconductor transistors at the practical bias point, and is comparable to that of low-noise microwave Si BJT. Fig. 9 shows the $S_{I_{\rm bc}}$ (10 Hz) versus $I_{B,\text{edge}}$ for HBT's with various emitter sizes. Except for HBT A', the values of $S_{I_{\rm bc}}$ (10 Hz) vary as proportional to only $I_{B,\text{edge}}^2$, independent of the emitter area (A_E), emitter perimeter/emitter area (P_E/A_E), grading of E-B junction, Al mole fraction of the emitter layer, and surface passivation condition. This clearly supports that the dominant $1/f$ noise source for all the HBT's, except that HBT A' is the extrinsic GaAs base surface-recombination velocity fluctuation. All the HBT's we have built have much lower noise corner frequencies than the

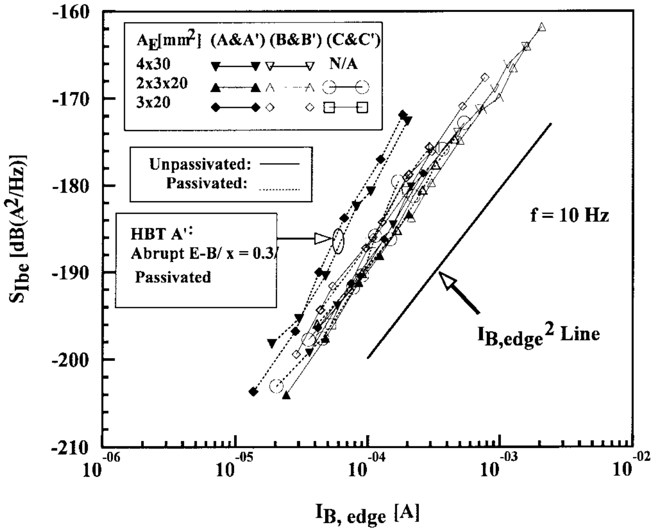


Fig. 9. $S_{I_{\rm bc}}$ (10 Hz) versus $I_{B,{\rm edge}}$ characteristics for HBT's.

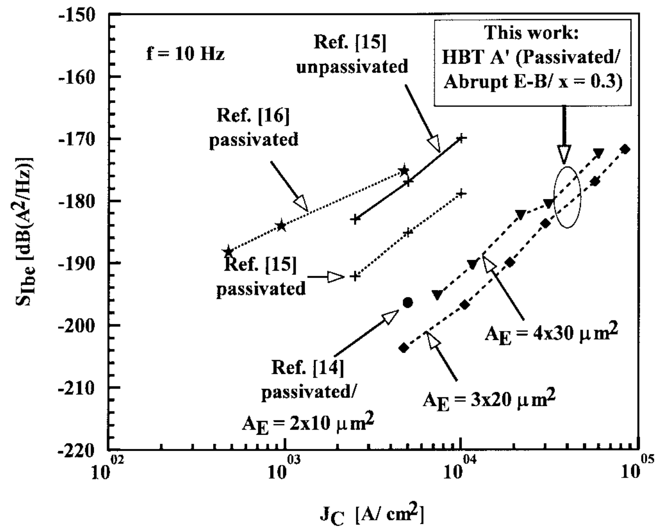


Fig. 11. $S_{I_{\rm bc}}$ (10 Hz) versus J_C characteristics for HBT A' and other AlGaAs/GaAs HBT's.

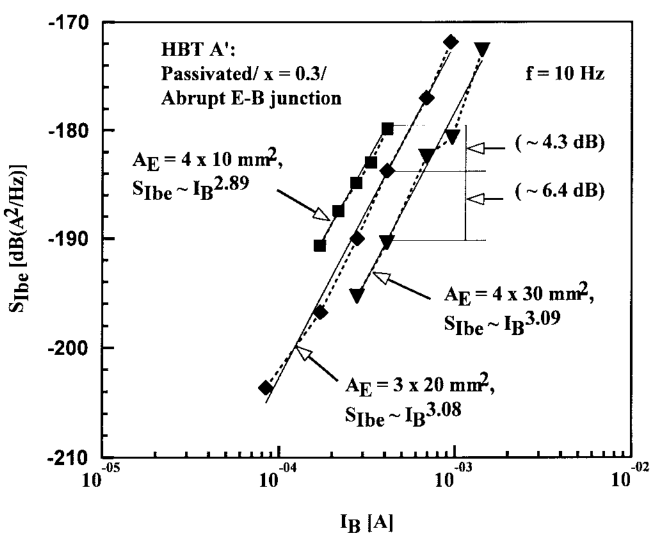


Fig. 10. $S_{I_{\rm bc}}$ (10 Hz) versus I_B characteristics for HBT A' with different emitter sizes: 4 × 10, 3 × 20, 4 × 30 μm^2. $S_{I_{\rm bc}}$ (10 Hz) $\propto I_B^{3.0}$. At the same base current, $S_{I_{\rm bc}}$ (10 Hz) $\propto A_E^{-2.0}$.

previously reported values of about 100 kHz for conventional AlGaAs/GaAs HBT's [14]–[19]. In addition, our HBT's show very clear bias dependency of $S_{I_{\rm bc}}$ (10 Hz) $\propto I^2_{B,{\rm edge}}$, unlike the other HBT's. This indicates that the recombination-related $1/f$ noise sources other than the base surface-recombination $1/f$ noise source are not significant for our HBT's. Therefore, the low corner frequencies for our HBT's can be partly attributed to their low densities of recombination-related bulk noise sources such as the hetero-interface and E-B SCR recombination noise sources. Meanwhile, for the HBT A', $S_{I_{\rm bc}}$ (10 Hz) is not proportional to $I^2_{B,{\rm edge}}$. This means that the noise source for HBT A' is not located at the emitter periphery, but at the bulk area under the emitter. Generally, the spatially uncorrelated bulk $1/f$ noise source ($S_{I_{b,{\rm bulk}}}$), which is uniformly distributed under the emitter, is proportional to $I_B^k A_E^{1-k}$ [9]. To clarify that the $S_{I_{\rm bc}}$ (10 Hz) of HBT A' satisfies the aforementioned bulk noise property, Fig. 10 shows the $S_{I_{\rm bc}}$ (10 Hz) versus I_B characteristics for the HBT A' with different emitter sizes. As shown in the figure, $S_{I_{\rm bc}}$ (10 Hz) $\propto I_B^{3.0}$, and $S_{I_{\rm bc}}$ (10 Hz) $\propto A_E^{-2.0}$ for a fixed I_B, clearly suggesting that the HBT A' is in the fundamental bulk noise limit. However, the base current dependency of $S_{I_{\rm bc}}$ (10 Hz) $\propto I_B^{3.0}$ is still unclear. For comparison purposes, the $S_{I_{\rm bc}}$ (10 Hz) versus J_C characteristics for our optimized AlGaAs/GaAs HBT's (HBT A') and previously reported AlGaAs/GaAs HBT's are shown in Fig. 11. The noise level of our optimized AlGaAs/GaAs HBT is at least 10 dB lower than those of any other AlGaAs/GaAs HBT's reported.

IV. CONCLUSION

The low-frequency noise characteristics of self-aligned AlGaAs/GaAs HBT's have been studied. The purpose of this paper is twofold: the identification of dominant noise sources in an HBT and the reduction of the noise sources.

To identify the dominant noise sources in an HBT, a quantitative noise-source extraction procedure has been developed. We have used the generalized low-frequency noise model, which includes base–emitter current fluctuation ($S_{I_{\rm bc}}$), collector–emitter current fluctuation ($S_{I_{\rm cc}}$), and resistance fluctuation source (S_{V_r}). We have found that the base–emitter current noise source ($S_{I_{\rm bc}}$) is dominant for the open base–emitter termination condition, and that the resistance fluctuation $1/f$ noise source (S_{V_r}) is dominant for the shorted base–emitter termination condition. However, the collector–emitter current noise source ($S_{I_{\rm cc}}$) is negligible, though it is believed to be an important noise source in other conventional noise works. The extracted S_{V_r} is proportional to the collector current squared, which is consistent with the resistance fluctuation $1/f$ noise theory. By using the S_{V_r} noise source, the noise model can explain the conventionally anomalous bias dependency of AlGaAs/GaAs HBT's that the collector current noise with shorted base–emitter (i.e., S_{I_c}) is proportional to I_C^m with $m > 2.0$. The simple, but exact, noise equivalent-circuit model is expected to be very useful for the design of low phase-noise HBT oscillators.

The resistance $1/f$ noise stems mainly from the emitter-series resistance fluctuation, and the noise is found to be increased by increasing the emitter RIE time. This increase can be attributed to the increase of the emitter Hooge parameter, which can occur during the emitter RIE process. Therefore, to reduce the resistance $1/f$ noise, the RIE process should be optimized further.

To reduce the base–emitter current $1/f$ noise ($S_{I_{be}}$) in an HBT, we have investigated the noise properties as a function of the grading of the E-B junction, the aluminum mole fraction of AlGaAs emitter layer, and the surface passivation condition. It is found that the surface-recombination $1/f$ noise can be significantly reduced by the heterojunction launcher of the abrupt E-B junction. With the increase of the aluminum mole fraction, the launching effect can be enhanced. HBT's with a compositionally graded E-B junction suffer from significant surface-recombination current and large base–emitter current $1/f$ noise. By using both the launching effect and the conventional depleted AlGaAs ledge surface passivation effect, we can greatly suppress the surface-recombination currents of HBT's. Consequently, we have achieved a very low $1/f$ noise corner frequency of 2.8 kHz at the collector current density of 10 kA/cm^2, as compared to the corner frequency greater than 100 kHz for conventional AlGaAs/GaAs HBT's. This is the lowest $1/f$ noise corner frequency among the III–V compound semiconductor transistors and as low as low-noise Si BJT's.

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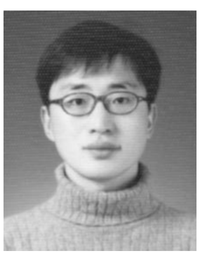
Jin-Ho Shin (M'97) received the B.S. degree in electronic engineering from Seoul National University, Seoul, Korea, in 1985, the M.S. degree in electrical and electronic engineering from the Korea Advanced Institute of Science and Technology (KAIST), Seoul, Korea, in 1987, and the Ph.D. degree in electronic and electrical engineering from the Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1997.

In 1987, he joined the LG Corporate Institute of Technology (LG CIT), Seoul, Korea, where he worked on GaAs monolithic microwave integrated circuits (MMIC's). From 1989 to 1992, he was involved in the development of GaAs high-power MESFET's for cellular phones. From 1993 to 1997, his research was in the area of design, fabrication, and device characterization of AlGaAs/GaAs HBT's, with special emphasis on HBT low-frequency noise equivalent-circuit modeling and noise reduction, aimed at the implementation of low-phase noise HBT oscillator. His current research interests include HBT device improvement (including HBT reliability aspects) and its high-power circuit applications.



Jiyoung Kim received the B.S. degree in physics from Hanyang University, Seoul, Korea, in 1995, and the M.S. degree in electronic and electrical engineering from the Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1997.

In 1997, he joined the Samsung Advanced Institute of Technology, Suwon, Korea. His current research interests include the process development of millimeter-wave devices and their applications.

Yujin Chung (S'97) was born in Taegu, Korea, on May 28, 1971. She received the B.S. degrees in chemistry and electronic and electrical engineering, and the M.S. degree in electronic and electrical engineering from the Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1996 and 1998, respectively, and is currently working toward the Ph.D. degree at POSTECH.

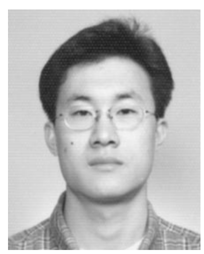
Her current research interests are in the area of HBT noise modeling and its application to nonlinear microwave and millimeter-wave integrated circuits, including oscillators and mixers.

Joonwoo Lee (S'93–A'95–M'96) was born in Kangwon-Do, Korea, in 1963. He received the B.S. degree in electronic engineering from Seoul National University, Seoul, Korea, in 1990, and the M.S. and Ph.D. degrees in electronic and electrical engineering from the Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1992 and 1996, respectively.

From 1996 to 1997, he was with the Photonic Devices Laboratories, Hyundai Electronics, where he was involved in the development of distributed feedback (DFB) laser diodes, HBT's, and photoreceivers. In 1998, he joined the Mobile Telecomminications Terminal Division, Hyundai Electronics, **City, Country,** where he is currently developing radio-frequency integrated circuits (RFIC's) for personal communication system (PCS) handsets. His main research interests are InP- and GaAs-based devices and their integration into MMIC's and optoelectronic integrated circuits.

Youngsuk Suh (S'93–M'96) was born in An-Dong, Korea, in 1963. He received the B.S. degree from Yeungnam University, Kyong-San, Korea, in 1986, and the B.S. and Ph.D. degrees from the Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1991 and 1995, respectively, all in electronic and electrical engineering.

Since 1995, he has been on the faculty of the School of Electrical and Electronics Engineering, Yeungnam University, Kyong-San, Korea. His research interests are in the areas of microwave device modeling, parameter extraction, and microwave circuits.



Kyu Hwan Ahn was born in Icheon, Korea, on August 15, 1974. He received the B.S. degree in electronic and electrical engineering from the Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1997, and is currently working toward the M.S. degree in electrical and electronic engineering at the the Korea Advanced Institute of Science and Technology (KAIST), Taijun, Korea.

His current research interests are in the area of electromagnetics.

Bumman Kim (S'77–M'78–SM'97) received the Ph.D. degree in electrical engineering from Carnegie-Mellon University, Pittsburgh, PA, in 1979.

From 1978 to 1981, he was engaged in fiber-optic component research at GTE Laboratories Inc. In 1981, he joined the Central Research Laboratories, Texas Instruments Incorporated, where he was involved in development of GaAs power FET's and MMIC's. He has developed a large-signal model of a power FET, dual-gate FET's for gain control, and high-power distributed amplifiers, and various millimeter-wave MMIC's. In 1989, he joined the Pohang University of Science and Technology (POSTECH), Pohang, Korea, where he is currently a Professor in the Electronic and Electrical Engineering Department, and Director of the Microwave Application Research Center, where he works on device and circuit technology for MMIC's. He has published over 100 technical papers in this area.

Dr. Kim is a member of the Korean Academy of Science and Technology.