Relation Between Low-Frequency Noise and Long-Term Reliability of Single AlGaAs/GaAs Power HBT's

Saeed Mohammadi, Dimitris Pavlidis, *Fellow, IEEE*, and Burhan Bayraktaroglu

***Abstract*—Self-aligned AlGaAs/GaAs single heterojunction bipolar transistors (HBT's) were fabricated using an advanced processing technology for microwave and millimeter-wave power applications. These devices were processed simultaneously, on different epilayers with similar layer structure design supplied from different vendors. They showed similar dc characteristics (current gain, $\beta = 30$) and their microwave performance was also identical ($f_T = 60$ GHz, $f_{\max} = 100$ GHz). The HBT's showed different noise and reliability characteristics depending on their epilayer origin. HBT's from the high-reliability wafer showed MTTF of 10^9 h at junction temperature of 120 °C. They also presented very small $1/f$ noise with corner frequencies in the range of a few hundred Hz. Devices were subjected to bias and temperature stress for testing their noise and reliability characteristics. Stressed and unstressed devices showed generation-recombination noise with activation energies between 120–210 meV. Stress was found to increase the generation-recombination noise intensity but not its activation energy. These HBT's did not show any surface-related noise indicating that processing did not significantly influence noise characteristics. It was found that the base noise spectral density at low frequency can be correlated to the device long term reliability.**

I. Introduction

FLICKER noise ($1/f$ noise) is a type of excess noise that has been observed in almost every electron device and can be a detrimental factor in the performance of high-frequency nonlinear circuits such as mixers and oscillators. It can also be a very sensitive measure of the quality and reliability of the device since its time dependence reveals presence of imperfections and traps associated with the quality and reliability. Another type of excess noise, known as generation-recombination noise, is due to centers existing in the device structure and can be also attributed to device quality and reliability. Excess noise ($1/f$ or g-r noise) is easily differentiated from the white noise since it has a frequency-dependent spectrum.

In compound semiconductor devices, a major part of the flicker noise is related to the surface and periphery of the device. Therefore, HBT's, due to their vertical structure and thus less exposed surface, have advantage over HEMT's and MESFET's in terms of flicker noise. Generation-recombination noise, on the other hand, is present in all III–V devices including HBT's. For AlGaAs/GaAs materials, DX centers are thought to be the dominant source for this kind of noise [1], [2]. The excess noise can also originate from the parasitic resistance of device terminals. However, the contribution of resistance excess noise is minimal in devices used for power applications such as those studied in this case, since they are optimized for very low access resistance.

Many researchers have verified correlation between excess noise and different properties of semiconductors. Photoluminescence studies of AlGaAs materials and AlGaAs/GaAs heterojunctions show agreement with excess noise results [3]–[5]. Other works demonstrated that noise can be used to study the properties of traps within semiconductors [6], [7]. The use of noise as a criterion for selecting low and high quality devices has been suggested for PN diodes, GaAs MESFET's, Zener diodes, and varactors [8], [9]. Yiqi *et al.* has shown correlation between $1/f$ noise and reliability of silicon BJT's [10].

Device quality and its reliability characteristics are measured using lifetime tests. These tests, also used to estimate the reliability of HBT's, are usually performed on small number of samples using accelerated failure processes induced by applying high temperature and bias stress. Since small sample numbers are used, the results are statistical in nature and thus not accurate. Another disadvantage of such tests is that due to high stress applied to the device, the failure mode experienced in the accelerated life test may be different from the failure mode experienced during the normal operation [11]. Also, these tests can be very costly and time-consuming and unlike noise tests, they are destructive.

As previously reported by the authors, a correlation exists between low-frequency noise and long-term reliability of single heterojunction AlGaAs/GaAs power HBT's [12], [13]. These HBT's demonstrated high reliability characteristics by means of a stable, well-controlled fabrication technology [14]. This paper presents differences between spectral noise densities of stressed and unstressed HBT's with different degrees of reliability and provides further details and more analysis of the results presented in previous reports. It also shows the importance of noise bias-dependence for determining the noise origin. Low-frequency noise measurements were used as a better alternative to lifetime tests for determining the reliability of AlGaAs/GaAs HBT's. An investigation has been undertaken for this purpose to correlate the epitaxial layer properties to long-term reliability.

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The compared devices were of the same type and were fabricated on wafers obtained from different vendors. Tests performed include tracking of the current gain change as the devices are stressed and measurement of baseband noise before and after degradation. Noise measurements were also used to identify the source and the nature of mechanisms that lead to degradation under bias stress.

Henderson and Tutt studied eight AlGaAs/GaAs HBT's and found no correlation between low-frequency base noise and long-term reliability [15]. Their conclusion is different from the results of this paper, possibly because of the fact that the noise and degradation mechanism in the investigated devices do not correspond to the same origin. For example, in devices where the low-frequency noise originates from the surface while the degradation mechanism is associated with the bulk of the material, no correlation will exist between reliability and noise. In the HBT's studied here, the degradation mechanism occurs in the base-emitter heterojunction, therefore, the reliability characteristics are determined by the quality of the interface as well as the heavily-doped GaAs base material. Since the base noise in these HBT's also originates from the base-emitter region, a correlation between the noise and reliability is observed.

The outline of the paper is as follows: Section II provides information about the HBT technology used and its reliability characteristics. Noise measurements of devices with different geometry are reported in Section III. Section IV presents noise characteristics for different bias of devices before and after stress. Low-temperature noise measurement and identification of generation-recombination centers of HBT's studied in this work are then presented in Section V. Finally, a thorough discussion is presented in Section VI to explain the trends observed in this work.

II. HBT Technology and Long Term Reliability

Reliability of heterojunction bipolar transistors has been studied extensively and shown a steady improvement over the last decade [14], [16], [17]. The short-term instability due to thermal runaway is addressed by thermal and electrical management and poses no difficulty in today's HBT power application design [18]. HBT long-term instability, due to various failure mechanisms is still under investigation [16], [19]. Most of the failure mechanisms are attributed to the crystalline quality, dopant diffusion, excessive leakage current at higher temperatures, and contact as well as passivation layer failure [19]. State of the art HBT's have reached median time to failure (MTTF) in the order of 10^9 h at junction temperature of 120 °C. The improvement in reliability characteristics has been achieved by various techniques. These techniques include but are not limited to:

1) growth at lower temperature to suppress positively charged interstitial dopants and avoid redistribution of charge under stress conditions [20];
2) improved passivation techniques in addition to use of ledge to suppress nonideal base currents [17];
3) use of nonalloyed contacts and also InGaAs emitter cap to improve ohmic contact stability [21];
4) In co-doping of the base [22];
5) employment of C-doped GaInP emitter in conjunction with C-doped GaAs base to suppress performance sensitivity to dopant redistribution [23].

All devices used in this investigation were fabricated on wafers grown by metal organic chemical vapor deposition (MOCVD) technique. Wafers were obtained from three different commercial vendors. The same epitaxial layer design was maintained for all the wafers although some variations in layer properties or interfaces between layers may have existed due to the particular features of individual epitaxial growth techniques. The base layer was doped with carbon at 4×10^{19} cm^{-3} concentration. Its thickness was kept constant at 100 nm. The measured sheet resistivity was in the 220–240 Ω/sq. range. A thin layer of InGaAs was used for nonalloyed emitter contacts. The collector layer thickness was 1000 nm with a uniform doping level of 2×10^{16} cm^{-3}. A self-aligned emitter-base fabrication process was used to consistently fabricate base contact 0.4 μm away from emitter mesa edge. The extrinsic base surface was passivated with a silicon nitride layer. No intentional ledge structures were employed although such approaches have shown to have an influence on baseband noise characteristics of HBT's [14]. Nonalloyed Ti/Pt/Au contacts were used for emitter and base layers, whereas alloyed AuGeNi contacts were used for the collector.

Thermal shunt structures were used between emitter fingers to avoid thermal instability [16]. Several emitter finger designs were used to obtain cells with varying emitter periphery/area ratios. To ensure that the wafer processing did not introduce variations, wafers from all vendors were processed simultaneously in the same lot. All devices were mounted in special packages for stress and electrical tests. The dc analysis of eight finger 2.5×20 μm^2 HBT's from all wafers revealed a current gain (β) of 30 and very similar Gummel, β versus I_C and I_C–V_{CE} characteristics. The microwave analysis of HBT's revealed f_T and $f_{\max}$ values of 60 and 100 GHz, respectively.

High-current high-temperature dc stress rather than RF stress tests were used to evaluate the long-term reliability characteristics of these HBT's. Although no RF stress tests were carried out, it was assumed that the HBT gain degradation mechanisms for both dc and RF stress tests are equally and significantly impacted by the quality of the base-emitter heterojunction region. Therefore, the correlation between low-frequency noise characteristics and reliability of the HBT's assessed from the dc stress tests would hold between the low-frequency noise and the reliability characteristics of the HBT's determined from RF stress tests.

The HBT's were subjected to stress at 125 °C under 25 kA/cm^2 collector current density to identify the reliability behavior of devices. These stress conditions were found to be sufficient to distinguish among the groups of devices. Although devices from the same wafers and wafers from the same epilayer vendor showed similar degradation rates, there were substantial differences when devices from wafers obtained from different vendors were compared. Devices that showed rapid degradation were termed "low-reliability" devices whereas devices that showed essentially no degradation for several thousands of hours at this stress condition were termed "high-reliability" devices. Devices from wafers of the third vendor showed degradation but at a slower rate than the "low-reliability" devices. These devices were called the "medium-reliability" devices. Fig. 1 compares the current gain variation as a function of time at 125 °C junction temperature on the same device type fabricated with low and high-reliability wafers. Each device was biased at 3 V, and 25 kA/cm^2 emitter current density. Under these conditions, the low-reliability devices show degradation within a few hours, while the high-reliability device performance remains unchanged for thousands of hours. The performance of devices fabricated on medium-reliability wafers was about an order of magnitude better than the low-reliability devices. Therefore, the degree of device reliability appeared to depend on the choice of material used for fabrication.

Accelerated lifetime tests were carried out to determine the projected lifetimes. Because the failure rates were rapid with devices fabricated on low and medium-reliability wafers, only the high-reliability devices were subjected to these tests. Using 30% degradation in current gain as the failure criteria on devices stressed at elevated temperatures, a MTTF of 10^9 hr was extrapolated at a junction temperature of 120 °C. The activation energy was 1.5 eV. These results are shown in Fig. 2.

No studies were performed to evaluate the correlation that may exist between RF stress induced degradation and low-frequency noise. However, based on the strong resemblance of device degradation characteristics found both under dc and RF stress conditions [24], it is expected that such a correlation should exist provided that the induced degradation and low-frequency noise originate from the same region of the device.

The effect of device design on reliability is shown in Fig. 3 for devices fabricated on medium reliability wafers. While the emitter area was kept at 160 $\mu\mathrm{m}^2$ in these devices, changing the emitter finger width and length varied the periphery. Although the degradation rates are different from one another, Fig. 3 shows that there is no particular lifetime dependence on the periphery/area ratio indicating that the long-term degradation is not primarily due to surface recombination currents.

III. Low-Frequency Noise of HBT's with Different Geometry

AlGaAs/GaAs materials due to their high surface-recombination velocity present extensive recombination around the periphery. Since the recombination process is a very noisy process, one expects to observe a significant low-frequency noise stemming from the periphery of the AlGaAs/GaAs HBT's. Fig. 4 shows the base and collector short-circuit current noise spectral density measured for four different HBT's with different geometry. These HBT's had periphery/area ratios of 0.9 $\mu\mathrm{m}^{-1}$ to 1.2 $\mu\mathrm{m}^{-1}$ as indicated in the figure. The measurements were carried out at similar bias conditions for each device, namely $I_B = 0.5$ mA, $V_{CE} = 3$ V for base noise and $I_C = 10$ mA, $V_{CE} = 3$ V for collector noise. These measurements show no dependence on periphery/area ratio and therefore indicate that the low-frequency noise in these HBT's is not a surface-related noise. This also indicates insignificant recombination current at the base-emitter and collector-base peripheries. The results are in agreement with the results of reliability tests, which showed no particular dependence on device geometry.

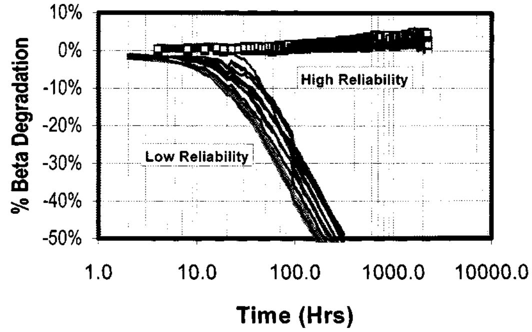

Fig. 1. Variation of dc current gain with time for same HBT's with same geometry on low and high-reliability substrate. The test condition was $J_C = 25$ kA/cm^2 and $T_j = 125$ °C.

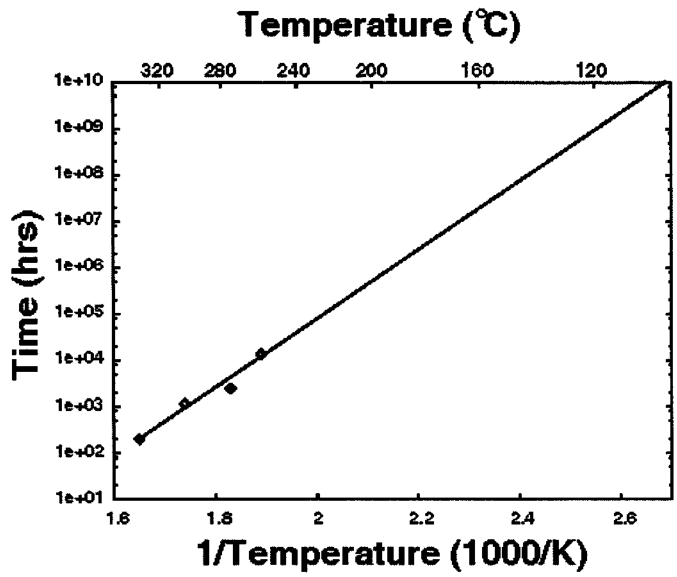

Fig. 2. Estimation of lifetime and activation energy for high-reliability HBT's. The criterion for failure was 30% degradation in the dc current gain. The device was an eight emitter finger 2.5×20 $\mu\mathrm{m}^2$ HBT.

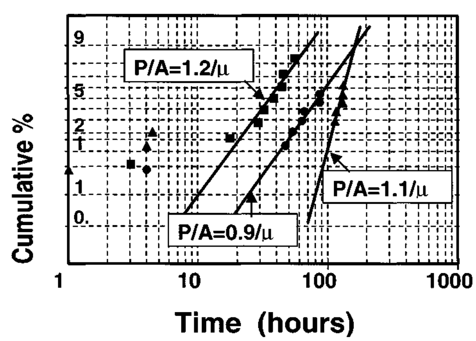

Fig. 3. Results of reliability tests for HBT's with the same emitter area and different periphery/area ratio. The devices were tested at $J_C = 25$ kA/cm^2 and $T_j = 125$ °C on medium-reliability wafer.

IV. Low-Frequency Noise of HBT's at Different Bias Currents

Low-frequency noise characterizations were performed using an HP3561A dynamic signal analyzer and a computer

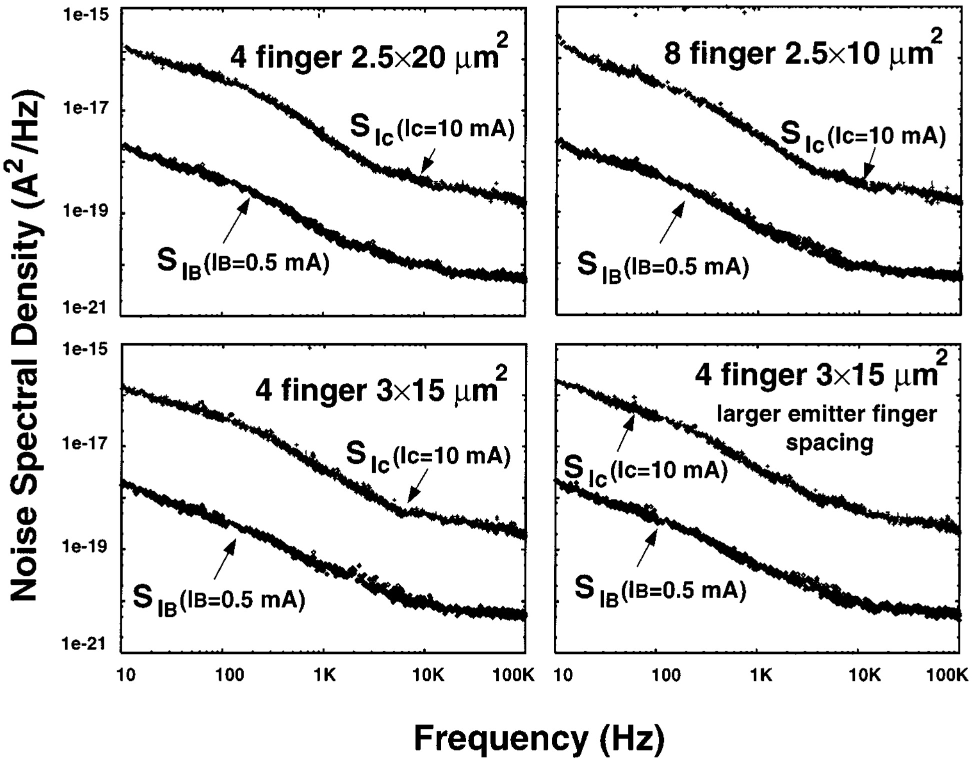

Fig. 4. The base and collector noise spectral density for four different HBT geometry. The periphery/area ratios are indicated in the figure The tests were performed at $I_B = 0.5$ mA, $V_{CE} = 3$ V for base noise and $I_C = 10$ mA, $V_{CE} = 3$ V for collector noise. The results permit investigation of periphery/area influence on noise.

controlled system with special bias networks to minimize the influence of external components on noise measurement [1]. A total of 38 low and high-reliability HBT's were measured for their low-frequency base and collector short-circuit noise for different bias currents. The measurements on these devices were carried out before and after stress test upon which 30% degradation in dc current gain was resulted. The stress tests for low-reliability HBT's were performed at current density $J_C = 25$ kA/cm^2 and junction temperature T_j =125 °C.

Much higher stress conditions were required to show similar degree of degradation with high-reliability devices. These HBT's were stressed at current density $J_C = 50$ kA/cm^2 and junction temperature T_j =320 °C to show such degradation.

Fig. 5 shows the collector noise spectral density of typical low and high-reliability HBT's measured before the stress is applied. The bias condition was $V_{CE} = 3$ V and $I_C = 0.5$ and 10 mA. For this measurement, the base was grounded to avoid any base noise current being forwarded to the collector. As shown in the figure, the low-reliability HBT has slightly higher noise at lower-frequencies (below 1 kHz) comparing to high-reliability HBT. The collector noise has also a significant bias-dependent behavior, namely noise increases as collector current increases. The roll-off of $1/f$ noise is also bias dependent and varies, in average, from $1/f^{1.01}$ to $1/f^{1.34}$ for low-reliability HBT's and from $1/f^{0.70}$ to $1/f^{0.62}$ for high-reliability HBT's as the collector current increases from 0.5 to 10 mA, respectively. These trends suggest that the $1/f$ noise component of collector noise spectral density can be indicative of the device quality. Although, in average, the collector $1/f$ noise of low-reliability HBT's is stronger than that of high-reliability HBT's, individual devices showed that the collector noise spectral densities of low and high-reliability HBT's may be comparable. The collector noise density measured at 10 Hz at bias condition $I_C = 10$ mA, $V_{CE} = 3$ V varied from 2×10^{-18} to 6×10^{-16} A^2/Hz for high-reliability HBT's and from 8×10^{-17} to 3×10^{-15} A^2/Hz for low-reliability HBT's. Thus, the collector noise is not an accurate measure for the reliability of these HBT's.

Fig. 6 shows the base noise spectral density of typical low and high-reliability HBT's measured before the stress is applied. The bias condition was $V_{CE} = 3$ V and $I_B = 50$ and 250 μA. For this measurement, the collector was grounded to eliminate any collector noise current being fed back to the base. As the figure shows, low-reliability HBT's show much higher base low-frequency noise. The noise becomes comparable only at higher frequencies where $1/f$ noise is not a dominant noise source and thermal and shot noise become significant. The average base noise density at 10 Hz for low-reliability HBT's was 4×10^{-17} A^2/Hz which was almost two orders of magnitude higher than that of high-reliability HBT's (which was 5×10^{-19} A^2/Hz). The base noise density at 10 Hz for low-reliability HBT's ranged from 7×10^{-18} to 1×10^{-16} A^2/Hz while it varied from 3×10^{-20} to 9×10^{-19} A^2/Hz for high-reliability HBT's. Therefore, statistically, the base noise of individual low-reliability HBT's at 10 Hz was also found to be higher than the base noise of high-reliability HBT's at 10 Hz by about one order of magnitude. The average base noise roll-off was found to be $1/f^{1.33}$ for low-reliability HBT's and $1/f^{0.97}$ for high-relia-

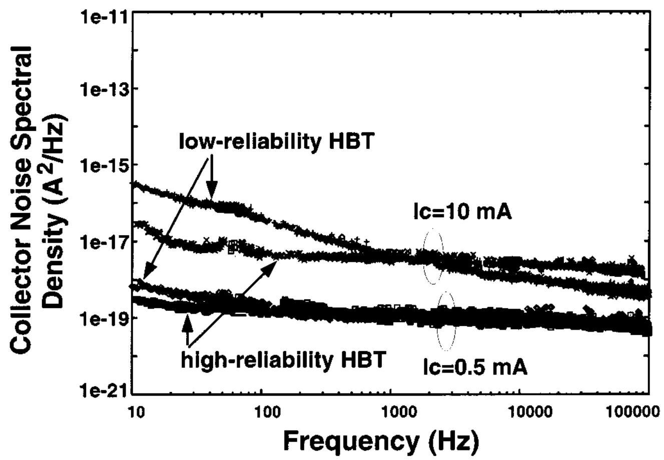

Fig. 5. Collector noise spectral density of low and high-reliability HBT's. The bias condition was $V_{CE} = 3$ V and $I_C = 0.5$ and 10 mA.

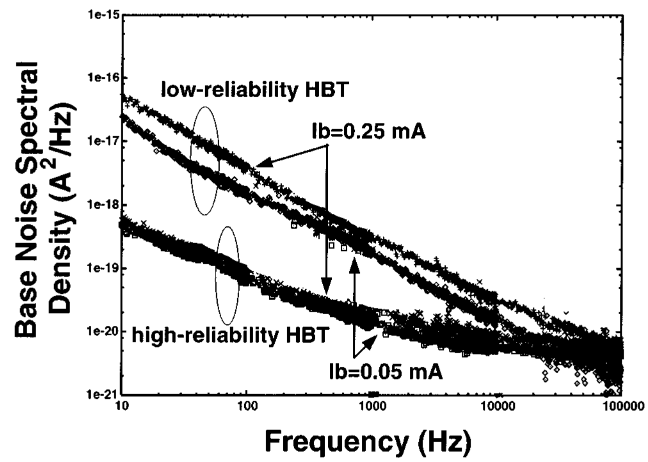

Fig. 6. Base noise spectral density of low and high-reliability HBT's. The bias condition was $V_{CE} = 3$ V and $I_B = 50$ and 250 μA.

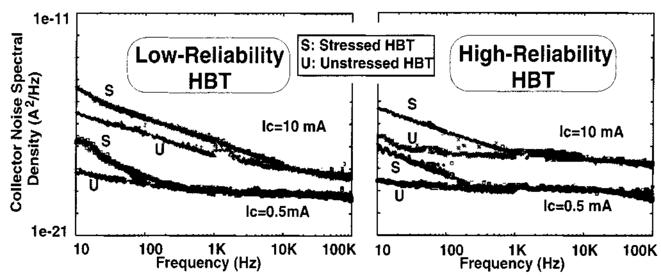

Fig. 7. Effect of stress on collector noise spectral density of low and high-reliability HBT's. The bias condition was $V_{CE} = 3$ V and $I_C = 0.5$ and 10 mA.

bility HBT's for base currents between 50–250 μA. Therefore, the $1/f$ noise in low-reliability HBT's has deeper slope and thus is stronger at lower-frequencies comparing to that of high-reliability HBT's. These results suggest a significant selection criterion, namely the correlation of the base noise of AlGaAs/GaAs single HBT's to their long-term reliability characteristics.

The low-frequency noise characterization of high-reliability HBT's shows that these HBT's present extremely small low-frequency base noise. The results are comparable to the lowest reported values for AlGaAs/GaAs HBT's which was base noise density of 8×10^{-20} A^2/Hz at 10 Hz for a 2 emitter finger 3×20 μm^2 HBT with abrupt emitter-base junction [25].

Fig. 7 shows the effect of stress on the collector noise spectral density of typical low and high-reliability HBT's. Stress results in an increase of $1/f$ noise component of low-frequency noise for both low and high-reliability HBT's. It, however, does not affect the noise at higher frequencies where noise is dominated by thermal noise, shot noise and other mechanisms that do not affect the $1/f$ noise. The distribution of the traps responsible for $1/f$ noise can change the slope of $1/f$ noise in the same way that the traps responsible for generation-recombination noise can change the slope of $1/f$ noise around the characteristic frequency. Therefore, not only the density of the traps responsible for $1/f$ noise increases as stress is applied, but also the distribution of these traps may change upon stress application. As a result, the roll-off slope of the $1/f$ component of collector noise changes with stress.

Fig. 8 depicts the effect of stress on the base noise spectral density of typical low and high-reliability HBT's. Unlike the collector noise, stress application affects the low-frequency base noise for both low and high-reliability HBT's over the entire measured frequency spectrum. For low-reliability HBT's, the effect of the stress on the base noise is only observed at higher base currents ($I_B = 250$ μA) where noise increases by more than an order of magnitude over the spectrum. For high-reliability HBT's, stress increases the base noise at both low and high base currents ($I_B = 50$ and 250 μA). The increase is more significant at higher currents (more than an order of magnitude increase). The slope of $1/f$ noise can be an indication of the trap distribution inside the active region of the HBT. The base noise of these HBT's, having similar $1/f$ slope before and after stress, seems to stem from traps with similar distribution but much higher density upon stress application. Further details on this dependence are provided in the discussions of Section VI.

In average, stressed low-reliability HBT's showed a collector noise roll-off of $1/f^{1.41}$ to $1/f^{1.38}$ at $I_C = 0.5$ and 10 mA, respectively. Stressed high-reliability HBT's had a collector noise roll-off of $1/f^{1.23}$ to $1/f^{1.10}$ at $I_C = 0.5$ and 10 mA, respectively. The increased deviation of $1/f$ slope from the ideal value of one in case of low reliability HBT's is possibly affected by the presence of additional g-r noise. Although the origin of this noise is not clear, our study suggests that the E–B junction may be the source of it. Comparing the collector noise roll-off of stressed and unstressed HBT's, one finds that only $1/f$ noise component of the collector noise increases as stress is applied. Therefore the density and distribution of the traps responsible for collector $1/f$ noise varies such that the $1/f$ noise component becomes stronger as the stress is applied. For both low and high-reliability HBT's, the base noise roll-off slope was only slightly decreased as a result of stress application despite the increase in the noise level. This is due to the fact that, unlike collector noise, the base noise is due to the traps which their density increases while their distribution remains unchanged as the stress is applied. Therefore, the base noise has higher frequency noise components that increase by the stress application such that the entire base noise spectrum rises as stress is applied.

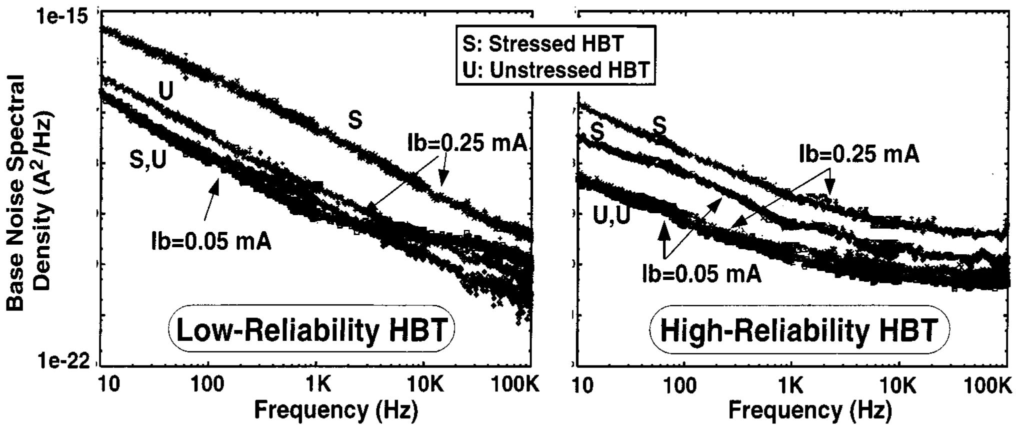

Fig. 8. Effect of stress on base noise spectral density of low and high-reliability HBT's. The bias condition was $V_{CE} = 3$ V and $I_B = 50$ and 250 μA.

V. Temperature-Dependent Low-Frequency Noise Measurement

Generation-recombination noise is a type of low-frequency noise with flat response at frequencies below the characteristic frequency and a -20 dB/decade slope at frequencies above the characteristic frequency. The characteristic frequency is the reciprocal of the average of the trapping and detrapping time of the carriers responsible for noise. The trapping (detrapping) time follows an Arrhenius characteristic using

$$\tau = \frac{\tau_o}{T^2} \exp\left(-\frac{E_A}{KT}\right)$$

where

- E_A activation energy of traps;
- T absolute temperature; and
- τ trapping (detrapping) time.

By varying temperature and measuring the characteristic frequency, one can find the activation energy from Arrhenius plots provided that trapping and detrapping times are not of the same order of magnitude. Generation-recombination noise may be partially masked by $1/f$ noise at low frequencies. Therefore, it can be best identified by plotting "noise spectral density $\times$ frequency" as a function of frequency to cancel the $1/f$ slope. In such a plot, the characteristic frequency of generation-recombination noise appears at the frequency where noise reaches a maximum.

AlGaAs/GaAs HBT's have shown considerable generation-recombination noise stemming from traps within the bandgap of these materials. AlGaAs DX centers are believed to be one of the origins of this type of noise in HBT's, although this type of noise is observed even when DX centers are not present [26]. For AlGaAs/GaAs HBT's, activation energy of traps responsible for generation-recombination noise ranging from 160 to 600 meV have been reported [27], [28].

In order to find the activation energies of generation-recombination noise present in our HBT's, we performed low-temperature base and collector noise characterization on low and high-reliability HBT's. These tests were performed before and after stress application to allow a study of the effect of stress on generation recombination noise. Fig. 9 shows such a measurement performed for the collector noise of stressed and unstressed low-reliability HBT's as a function of temperature. The characteristic frequency shifts toward higher frequency as temperature is increased from 200 to 280 K.

Base and collector noise trapping time were plotted in Arrhenius plots to find activation energies of base-emitter and collector-emitter trap centers, respectively (Fig. 10). The activation energies of the low-reliability HBT collector and base noise were found to be 125 and 149 meV, respectively. Stress resulted in an insignificant change of the activation energy for collector and base noise to 120 and 140 meV, respectively. High-reliability HBT's did not show measurable generation-recombination base noise before or after stress application. The collector generation-recombination noise had activation energy of 207 and 202 meV before and after stress application, respectively. Therefore, stress did not change the activation energy of the collector noise in high-reliability HBT's either.

VI. Discussions

While the electrical performance of multifinger HBT's under high-current condition is superior to large single-finger HBT's with the same emitter area, multifinger devices are more susceptible to long-term failure due to uneven distribution of current density among emitter fingers. This is shown in Fig. 3 where the devices with different periphery/area ratio as a result of different number of fingers or emitter finger geometry, yet with same emitter area show different degradation characteristics; $P/A = 1.2/\mu$, $1.1/\mu$, and $0.9/\mu$ corresponds to 8 finger 2.5×10 μm^2, 4 finger 2.5×20 μm^2, and 4 finger 3×15 μm^2 devices, respectively. On the other hand, noise measurements of HBT's with the same emitter finger area and different periphery/area ratio shown in Fig. 4 have not shown any significant difference. Since noise measurement is done at close to the equilibrium, the effect of high-current distribution is not observed. Devices did not show significant surface recombination currents resulting in similar noise performance. This is an indication of the well-controlled processing technology used to fabricate these HBT's. Further measurements using feedback resistor on emitter on stressed devices have indicated that stress added a surface recombination component to the noise. Therefore stress increases

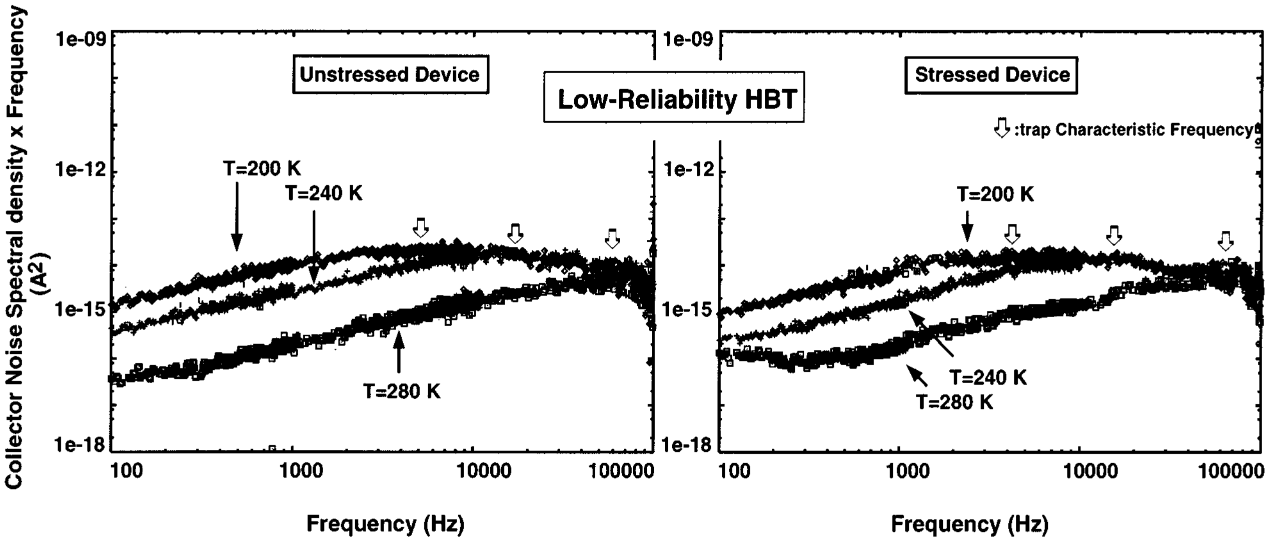

Fig. 9. Temperature dependent collector noise spectral density of unstressed low-reliability HBT. The bias condition was $V_{CE} = 3$ V and $I_C = 0.5$ mA.

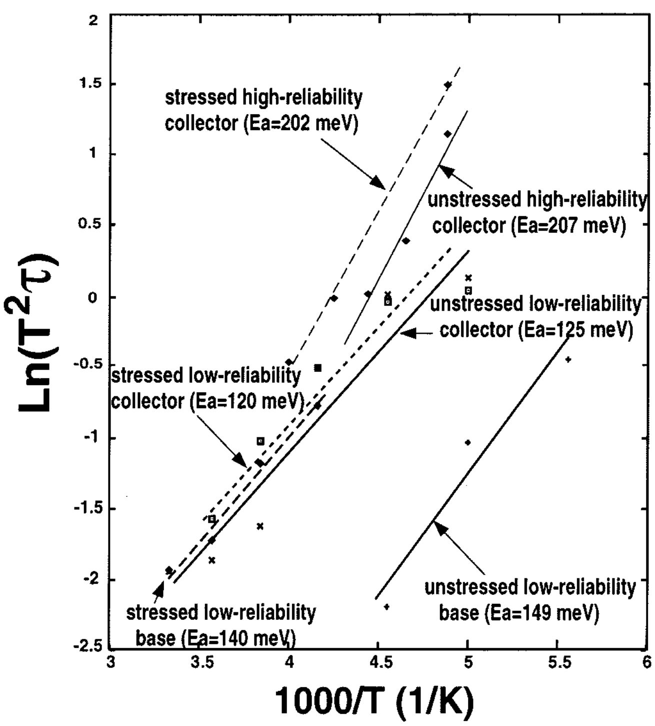

Fig. 10. Arrhenius plots of activation energies of base and collector noise for low and high-reliability HBT's. Results of unstressed and stressed devices are shown.

the leakage currents through nitride passivation as the device is aged. It is important to compare our results with the work by Tanaka *et al.* [29] since their AlGaAs/GaAs HBT showed improved noise performance and also smaller base surface recombination current upon stress application. The difference in the behavior of these two HBT's is that their HBT shows high base surface recombination and upon stress due to surface passivation, the surface recombination currents decreases and thus the base noise increases. While, our HBT's do not show any base surface recombination current, never the less, upon stress application, a component of such current adds up to the total base current, thus the base low-frequency noise increases drastically.

The bias dependence of low-frequency noise can be an indication of the origin of the noise. For HBT's studied in this work, the base low-frequency noise bias dependence was small. Only low-reliability HBT's after being subjected to stress, showed strong base noise bias dependence. Average bias-dependence of stressed low-reliability HBT's over all devices was $I_B^{1.62}$ while it was $I_B^{0.3}$, $I_B^{0.2}$, and $I_B^{0.52}$ for unstressed low-reliability, unstressed high-reliability and stressed high-reliability HBT's, respectively. Based on the model given by Blasquez and Sauvage, $1/f$ noise with an $I_B^{0.5}$ bias-dependence can be attributed to recombination in the bulk of base-emitter space charge region [30]. Therefore, the base low-frequency noise of these HBT's (with the exception of stressed low-reliability HBT's) originates from the bulk recombination in the emitter-base space charge region. After stress application, the bias dependence of the base noise becomes stronger meaning that an additional noise term adds up to the base noise. This component is due to base-collector surface recombination current that increases as the device ages.

The collector low-frequency bias-dependence indicates the origin of the collector noise of the HBT's. Generally a bias-dependence of I_C^1 is an indication of diffusion dominant noise while bias-dependence of I_C^2 indicates that either surface recombination noise or g-r noise in the collector region is responsible for collector noise. The collector noise of low-reliability HBT's has an average bias-dependence of $I_C^{2.09}$ and thus both the g-r noise in the collector and surface recombination noise at collector-base junction can be responsible for the collector noise in these devices. For high-reliability HBT's, the collector noise average bias-dependence is $I_C^{1.63}$, which indicates that merely the g-r noise is responsible for the collector noise. Stress application results in weaker collector noise bias dependence indicating a change in the mechanisms responsible for the collector noise in these devices.

TABLE I
COMPARISON OF DIFFERENT HBT NOISE-RELATED PARAMETERS STUDIED IN THIS WORK

	Unstressed low-reliability	Stressed low-reliability	Unstressed high-reliability	Stressed High-reliability
Base noise density at 10 Hz	low-current: 4×10^{-17} A^2/Hz	-	low-current : 5×10^{-19} A^2/Hz	-
Collector noise density at 10 Hz	low-current : 1×10^{-16} A^2/Hz	-	low-current : 5×10^{-18} A^2/Hz	-
Base noise bias-dependence	$I_B^{0.30}$	$I_B^{1.62}$	$I_B^{0.2}$	$I_B^{0.52}$
Collector noise bias dependence	$I_C^{2.09}$	$I_C^{1.66}$	$I_C^{1.63}$	$I_C^{1.17}$
Base noise roll-off	low-current : $1/f^{1.33}$ high-current : $1/f^{1.33}$	low-current : $1/f^{1.26}$ high-current: $1/f^{0.96}$	low-current : $1/f^{1.01}$ high-current : $1/f^{0.95}$	low-current : $1/f^{0.70}$ high-current : $1/f^{1.00}$
Collector noise roll-off	low-current : $1/f^{1.01}$ high-current : $1/f^{1.34}$	low-current : $1/f^{1.41}$ high-current: $1/f^{1.38}$	low-current : $1/f^{0.7}$ high-current : $1/f^{0.62}$	low-current : $1/f^{1.23}$ high-current : $1/f^{1.10}$
Base G-R noise activation energy	149 meV	140 meV	No G-R center	No G-R center
Collec. G-R noise activation energy	125 meV	120 meV	207 meV	202 meV
MTTF at 120 °C	100 hours	-	10^9 hours	-

The $1/f$ noise roll-off of the HBT's was briefly discussed in Section IV. In average, the base $1/f$ noise roll-off at low bias current decreases slightly as the device is stressed. For low-reliability HBT's the slope decreases from $1/f^{1.33}$ to $1/f^{1.26}$. For high-reliability HBT's, the slope decreases more strongly from $1/f^{1.01}$ to $1/f^{0.70}$. This decrease in slope can be attributed to increase of generation-recombination noise with respect to $1/f$ component resulting in a decrease of $1/f$ noise slope. The slope of the collector $1/f$ noise increases significantly as the device is stressed. Since the collector noise at high-frequencies does not change, we conclude that stress results in redistribution of traps which make up the $1/f$ noise. The density of such traps also increases resulting in stronger $1/f$ noise upon stress application.

Moreover, the $1/f$ noise slope of low and high-reliability HBT's is also different. Therefore we can indicate the device quality based on the $1/f$ noise component of both base and collector noise. However, the results show that the base noise has a more distinct difference in low and high-reliability HBT's. While collector noise of a low-reliability HBT is in average, higher than that of high-reliability HBT's, this is not an absolute criterion for all the measured HBT's. Such exception was not observed for base noise within the number of devices we measured. In these devices, the base noise of low-reliability HBT's at 10 Hz was at least one order of magnitude higher than that of high-reliability HBT's, for every individual device. This behavior suggests that the base noise can be used as a very sensitive tool to determine the reliability of this type of HBT's.

The results of temperature dependence noise characterization revealed that the generation-recombination noise in these HBT's originates from traps with activation energies of 120–200 meV. Costa and Harris have suggested that such low activation energies can be in fact related to hole capture and emission time constant [27]. Independent of the origin of these traps, the results suggest that stress does not generate centers with additional or other energy levels, but only increases the trap density responsible for this type of noise. The increase of the trap density in the base of low-reliability HBT's was found to be very significant. No generation-recombination center was detected for base-emitter region of high-reliability HBT's.

Recombination enhanced defect reaction (REDR) has been suggested as possible mechanism for degradation in HBT's [31]. This type of mechanism has usually low activation energy of less than 1 eV compared with the activation energy of 1.5 eV found in the devices reported here. Thus the mechanism responsible for their degradation is expected to be different than REDR. Although, the nature of the HBT degradation mechanism was not identified, it was found that it originates from the bulk of the base-emitter heterojunction (SCR) and its vicinity, especially the heavily doped base region. Irrespective of the degradation mechanism, the results presented here show that the low-frequency base noise is correlated to the reliability characteristics. Therefore, low-frequency noise characterization can be used to detect the degree of degradation, provided that the origin of the noise is the same as the origin of the mechanism determining the reliability characteristics.

A summary of the average noise density at 10 Hz, noise bias-dependence factor, $1/f$ noise roll-off slope, generation-recombination noise activation energy and median time to failure of HBT's studied in this work and discussed in this paper is presented in Table I. This table can be used as reference for better understanding of the trends in this and previous sections.

VII. CONCLUSIONS

The low-frequency noise and reliability of power AlGaAs/GaAs single HBT's were analyzed. The base noise density and the reliability characteristics of these HBT's were found to be in good correlation. Although, the collector noise was statistically correlated to reliability characteristics, the base noise proved to be a very sensitive measure of reliability characteristics. Based on the bias-dependence of base and collector low-frequency noise, we concluded that the base noise of unstressed HBT's originates from the base-emitter bulk recombination, while the collector noise is dominated by generation-recombination noise. Base noise of stressed HBT's originated from surface-recombination current introduced upon stress application. These HBT's did not present any surface-related noise before stress application, but showed generation-recombination noise with activation energies ranging from 120 to 207 meV. Stress was shown to increase the density of the traps responsible for generation-recombination noise, but did not affect the origin of these traps since their activation energies did not change significantly upon stress application.

High-reliability HBT's fabricated in this work showed extremely high median time to failure (MTTF = 10^9 h at junction temperature of 120 °C) while their noise was comparable to the lowest published data achieved for AlGaAs/GaAs HBT's.

The low-frequency base noise and long-term reliability in the AlGaAs/GaAs HBT's studied here are correlated to each other due to the fact that both the noise and degradation mechanisms in these devices originate from the same region (base-emitter junction). For single heterojunction HBT's such as those studied in this paper, provided that the base noise originates from the bulk of the base-emitter SCR or heavily-doped base region, the base low-frequency noise is correlated to the long-term reliability characteristics. For double heterojunction transistors (not discussed here), reliability characteristics may be partly associated to the base-collector junction. In this case, additional noise components may be correlated to HBT long-term reliability. Based on the above, it appears feasible to employ the reported noise characterization techniques by HBT manufacturers in order to screen wafers for good reliability. To introduce such a technique for screening, it is first necessary to study the manufactured HBT's and prove that the low-frequency noise and reliability originate from the same source. Once this is proved, a range of "acceptable" (reliable) noise values at selected frequencies should be specified. Reliability screening could then be performed, by evaluating the noise of individual wafers at the selected frequencies. The described technique is a very cost-effective mean of screening HBT power amplifiers and avoids the use of traditional accelerated life tests for wafer screening.

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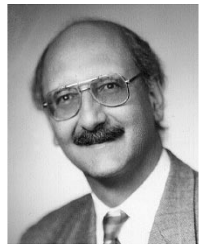

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