A Nonfundamental Theory of Low-Frequency Noise in Semiconductor Devices

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***Abstract*—A general low-frequency noise theory based on the fluctuation in the number of carriers is presented. In this theory, the low-frequency noise is attributed to the traps within the bandgap of a semiconductor, which are the sources of the generation-recombination noise. The cumulative effect of the generation-recombination noise from each trap center generates a $1/f$ type noise. It is shown that in fact, $1/f$ noise may have any frequency dependence between $1/f^0$–$1/f^2$. If not masked by thermal noise, the low-frequency noise generated from these traps becomes $1/f^2$ at very high frequencies. Also, if the lifetime of the carriers in the semiconductor under nonequilibrium condition is finite, at very low frequencies, the noise spectral density reaches a plateau. While this theory can be applied to any semiconductor device, only heterojunction bipolar transistors (HBTs) were considered in details. Based on this theory, a model for low-frequency noise in the base of HBTs is derived. Frequency and current dependence of low-frequency noise are modeled. Results of the base noise measurements in AlGaAs/GaAs HBTs were found to agree with the noise theory presented here. This significant theory, for the first time, proves the possibility of the number fluctuation model as a general $1/f$ noise cause without a need for specific and nonrealistic carrier lifetime probability functions.**

***Index Terms*—Flicker noise, generation-recombination noise, heterojunction bipolar transistor, low-frequency noise, $1/f$ noise.**

I. Introduction

FLICKER noise, also known as $1/f$ noise (due to its close to $1/f$ dependent spectra), observed in almost every electron device, has been the center of attention for the last few decades [1]. It can be a detrimental factor in the performance of high-frequency nonlinear circuits such as mixers and oscillators. It can be also a measure of the quality and reliability of the device [2]–[4]. The origin of flicker noise is still a controversial dispute; some researchers believe that the fluctuation in the mobility of carriers causes $1/f$ noise while others consider the presence of imperfections in the device structure as the predominant source of this type of noise.

The fluctuation in a semiconductor resistance was empirically modeled by Hooge according to

$$\frac{S_I(f)}{I^2} = \frac{S_R(f)}{R^2} = \frac{\alpha_H}{fN} \tag{1}$$

where

- $S_I(f)$ fluctuation in the current I;
- $S_R(f)$ fluctuation in resistance R;
- f frequency;
- N number of the carriers in the semiconductor;
- α_H Hooge parameter.

Since resistance is inversely proportional to the product μN, where μ is the carrier mobility, there can be two sources of fluctuations, mobility and number of carriers. It is shown that if the mobility fluctuation dominates, the Hooge equation [(1)] always holds [1]. If the fluctuation in the number of carriers dominates, the Hooge equation only holds for specific lifetime distributions. These lifetime distributions are often nonrealistic and cannot be applied to general cases.

Generation–recombination (G–R) noise is another type of excess noise often observed in compound semiconductor devices. It has been suggested that this type of noise is due to generation–recombination centers existing in the device structure. These centers occupy certain energy levels that can be evaluated using temperature-dependent noise characterizations. G–R noise has a flat spectrum at low frequencies below a characteristic frequency, which is the reciprocal of the maximum timescale over which the variation in the fluctuation may occur. At frequencies above the characteristic frequency, G–R noise decreases with frequency with a -20 dB/decade slope. Excess noise ($1/f$ or G–R noise) is easily identified from white noise since it has a frequency dependent spectrum.

Unlike silicon bipolar junction transistors, HBTs often present significant excess noise (flicker noise or G–R noise) at low frequencies [5]. Although the authors have reported AlGaAs/GaAs HBTs which show no surface related excess low-frequency noise [6], with the current HBT technology, the excess noise in most HBTs, despite their vertical structure, is influenced by the device external surface and periphery [7]–[9]. Moreover, the current noise spectral density $(S_I(f))$ is not usually proportional to I_B^1 or I_C^1. A noise bias dependence of I_B^1 or I_C^1 is generally an indication of mobility fluctuation related noise, since in the model responsible for this mechanism, $S_I(f)/I$, turns out to be independent of bias current [10]. The low-frequency noise in HBTs appears to be associated with the fluctuation in the number of the carriers rather than the mobility of the carriers [7].

In this paper, a novel nonfundamental low-frequency noise theory based on the fluctuation in the number of carriers in the device active region is presented. The theory presented in this work is nonfundamental because it relates the low-frequency noise to the existence of traps and imperfections in the crystal rather than basic crystal properties. It shares a similar approach

Manuscript received October 6, 1999; revised April 7, 2000. This work was supported in part by ARO-MURI (Contract DAAH04-96-1-0001) and by the University of Michigan Rackham Predoctoral Fellowship. The review of this paper was arranged by Editor A. S. Brown.

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Publisher Item Identifier S 0018-9383(00)09643-X.

to the model suggested by Blasquez and Sauvage for PNP bipolar transistors [11]. However, in their model, Blasquez and Sauvage assumed that a single G–R trap is responsible for the $1/f$ noise in the base of PNP BJTs, while the theory presented here assumes that a whole band of traps with distribution in energy and position is responsible for the low-frequency noise. The noise integral presented in this paper for the low-frequency fluctuation of carriers in the base of bipolar devices can be easily extended to any semiconductor device. Experimental verification using the measured base noise of AlGaAs/GaAs HBTs is presented to further support this theory.

Section II describes the previous $1/f$ noise models based on the fluctuation in the number of carriers. Section III presents a simplified picture of carrier trapping and detrapping processes which are responsible for different low-frequency noise mechanisms. Section IV contains the mathematical formulations of the low-frequency noise according to the theory presented in this work, while comparison of this theory to the experimental results is provided in Section V.

II. Previous Nonfundamental Low-Frequency Noise Models

The fluctuation in the number of charge carriers in a semiconductor was first introduced by Burgess [12]. By analogy to a single trap level with a time constant τ responsible for Lorenzian G–R noise, discrete multiple-trap levels can cause G–R spectra according to the following equation:

$$S_N(f) = 4\sum_i \overline{\Delta N_i^2}\frac{\tau_i}{1+\omega^2\tau_i^2} \tag{2}$$

where

- $S_N(f)$ noise due to the fluctuation in the number of carriers;
- ΔN_i variance of the fluctuation in the number of carriers for each individual trap level;
- τ_i time constant associated to each trap level;
- ω angular frequency.

The G–R spectra from discrete multiple-trap levels lead to a $1/f$ rather than Lorenzian spectrum by a proper distribution of the time constants. McWhorter proposed such a distribution of time constants in the following form [13]:

$$g(\tau)\,d\tau = \frac{d\tau/\tau}{\ln(\tau_2/\tau_1)} \quad \text{for } \tau_1 < \tau < \tau_2 \qquad = 0 \quad \text{otherwise} \tag{3}$$

where $g(\tau)\,d\tau$ is the time constant distribution and τ_1 and τ_2 are the two limits of the time constant of G–R centers. The above distribution gives a $1/f$ noise as the discrete multiple trap levels merge to form a continuous trap distribution. The resulting $1/f$ noise spectral density $S_N(f)$ can then be found by considering the fluctuation of carriers expressed in (2) in conjunction with the distribution function of time constant expressed in (3) and integrating over all trap levels through the associated continuum of trap constants. $S_N(f)$ is then found to be

$$S_N(f) = 4\overline{\Delta N^2}\int_0^\infty \frac{\tau g(\tau)\,d\tau}{1+\omega^2\tau^2}. \tag{4}$$

By substituting the McWhorter distribution of time constants into (4) and integrating, one obtains therefore the $1/f$ low-frequency noise spectrum $S_N(f)$ [1] as follows:

$$\begin{aligned} S_N(f) &= \frac{\overline{\Delta N^2}}{f\ln(\tau_2/\tau_1)} && \text{for } 1/\tau_2 < \omega < 1/\tau_1 \\ &= \frac{2\overline{\Delta N^2}}{\pi f\ln(\tau_2/\tau_1)}\tan^{-1}(\omega\tau_2) && \text{for } \omega\tau_1 \ll 1 \\ &= \frac{\overline{\Delta N^2}}{\pi f\ln(\tau_2/\tau_1)} \cdot \left[1-\frac{2}{\pi}\tan^{-1}(\omega\tau_1)\right] && \text{for } \omega\tau_2 \gg 1 \end{aligned} \tag{5}$$

The above derivation is valid only when there is no interaction between trap levels at different energy. If the levels are interacting with each other, instead of $1/f$ noise spectrum, a Lorentzian spectrum is found [14]. McWhorter's time constant distribution was successfully applied to MOSFETs by Christensson *et al.* using a tunneling model for the carriers into the traps inside the oxide [15].

Blasquez and Sauvage took a different approach for PNP BJTs [11]. They assumed that a single rather than multiple (McWhorter) G–R center is responsible for the $1/f$ noise spectra observed in PNP BJTs. No time constant distribution as in McWhorter's theory is therefore considered. Lifetime distribution based on the Shockley–Read–Hall generation and recombination of minority carriers with a single G–R center of density N_T and energy level E_T was calculated with respect to the position. The minority carrier lifetime (τ) of the Shockley–Read–Hall type process is given by

$$\frac{1}{\tau} = C_P[p(x)+p_1] \tag{6}$$

where

- C_P capture cross-section of the traps;
- $p(x)$ distribution of minority carriers inside the base;
- p_1 given by the following equation:

$$p_1 = n_i\exp\left(\frac{E_i-E_T}{kT}\right) \tag{7}$$

where n_i is the intrinsic carrier concentration and E_i is the intrinsic energy level (midgap). By taking into account the concentration of the minority carriers inside the base region $(0 < x < W_B)$:

$$p(x) = p(0)\left[1-\frac{x}{W_B}\right] \tag{8}$$

where $p(0)$ is the minority carrier concentration at the edge of the emitter-base junction and W_B is the base thickness. The authors found the noise spectrum by integrating the G–R noise components at each position (x) using the following integral:

$$S_P(f) = A_E\int_0^{W_B} 4N_T f_T(1-f_T)\frac{\tau}{1+\omega^2\tau^2} \tag{9}$$

where

- A_E emitter area;
- N_T density of the single G–R center;
- $f_T(1-f_T)$ G–R trap level occupation function.

By substituting (6)–(8) into (9), the integral leads to a $1/f$ noise spectrum.

$$S_p(f) = \frac{A_E W_B N_T p_1}{p(0)} \cdot \frac{1}{f}. \tag{10}$$

Unlike Blasquez and Sauvage's model, the low-frequency noise theory presented here assumes that a band of traps with a distribution over energy and distance rather than a single trap is responsible for the low-frequency noise. Therefore a distribution in the lifetime of the carriers $g(\tau)$ along the lines of McWhorter's theory is used to solve the noise integral [(4)]. However, unlike McWhorter's lifetime model, $g(\tau)$ in the presented theory is not a specific function of τ and can assume any form. It is assumed that the carrier lifetime τ is related to the number of carriers $n(x)$ through a general recombination mechanism [not necessarily SRH recombination process of (6)], thus τ is a function of distance x and the integral in (4) can be written as follows:

$$\int_0^\infty \frac{\tau g(\tau)\, d\tau}{1+\omega^2\tau^2} = \int_0^{W_B} \frac{\tau(x) g(x)\, dx}{1+\omega^2\tau^2(x)}. \tag{11}$$

Moreover, unlike McWhorter's theory, the density of the traps responsible for low-frequency noise can vary with respect to energy and distance. In the following section, various trap distributions, which lead to different low-frequency noise mechanisms in semiconductor devices, are discussed.

III. Simplified Picture of Traps Responsible for Low-Frequency Noise

The low-frequency noise theory presented here reflects the fact that the fluctuation in the number of carriers in the bulk or at the surface of a semiconductor is a result of trapping and detrapping of the carriers by trap centers. Ideally, there is no allowed energy level between the valence band and the conduction band. However, in this theory, the trap centers with finite density of states may assume any energy between the valence band and the conduction band and their density may vary with the location. The discussions below describe the traditionally accepted picture of trap mechanisms responsible for G–R, burst and surface $1/f$ noise and highlight the new principles employed in the nonfundamental theory to explain such noise.

Fig. 1 shows a simple case for the distribution of the trap centers. The trap density in this figure is not a function of distance (x), but does show energy dependence. Moreover, except for a very sharp peak at a certain energy level, the density of the traps with respect to energy is constant between the valence band and the conduction band. The sharp peak of the trap density distribution occurs only at a certain energy level (G–R trap level in Fig. 1) and causes generation–recombination (G–R) noise. In particular, the G–R noise is due to the trapping and de-trapping of the carriers by the sharp peak where the Fermi-level is within a few kT of the trap level. In places where the trap level is far from the Fermi-level, the sharp trap centers are always filled or empty and therefore do not significantly contribute to the G–R noise. The constant density of traps between the valence band and the conduction band has much smaller density compared to the peak and therefore may not be detectable with techniques such as DLTS or low-temperature noise measurements. However, the small density of traps can cause a cumulative G–R noise effect since for each energy value, some of the traps are within a few kT apart from the Fermi-level in the entire length of the semiconductor. As we shall see in the next section, the traps with constant density within a few kT of the Fermi level may be the source of flicker noise (see Fig. 1) if the cumulative G–R noise leads to a $1/f$ type spectrum.

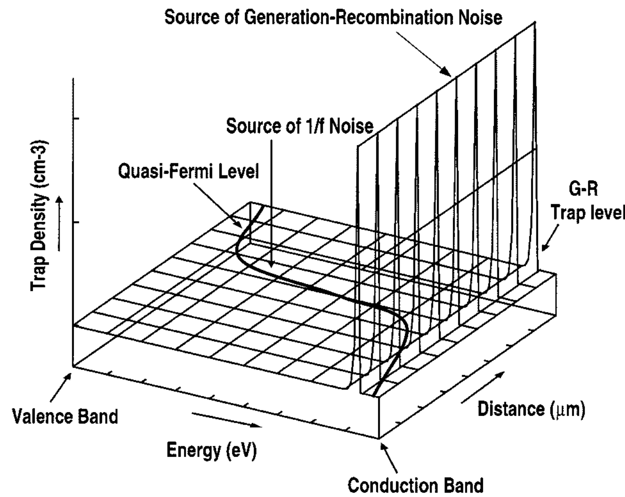

Fig. 1. Trap distribution inside the bandgap of a semiconductor. A constant trap density with respect to energy and distance is responsible for nonfundamental $1/f$ noise. Source of G–R noise is a high-density trap distribution at a certain energy level called the trap level. The valence and conduction bands are depicted straight and the Fermi-level is bent for simplicity in depicting the trapping mechanism.

It should be noted that at equilibrium, the Fermi-level is flat and the conduction and valence bands bend according to the potential distribution across the semiconductor. However, in Fig. 1, for the sake of simplicity in depicting the noise mechanism, the valence and conduction bands are presented straight and the Fermi level is bent. Under nonequilibrium condition, the Fermi level is substituted by the quasi-Fermi level.

Burst noise (random telegraph noise) is a special kind of generation–recombination noise due to a single trap in the active region of a device. Burst noise is often observed in submicron devices or in devices with very poor crystalline quality. In such devices, a trap level with certain energy and at specific location in the active region of the device (a single localized trap) traps and detraps the carriers and causes an on-off time-dependent signal similar to telegraph signal [16]. This is unlike Blasquez's theory where a single but not necessarily localized trap is considered. In the frequency domain, the burst noise, like the G–R noise, presents a Lorenzian spectrum (flat response at frequencies below a characteristic frequency and a -20 dB/decade slope at frequencies above the characteristic frequency). Fig. 2 shows the possible mechanism of the burst noise as explained by the nonfundamental noise theory. The "single trap" is substituted by a hump in the density of traps within the bandgap of the semiconductor, accounting for simultaneous energy and position dependence of these distributions. Trapping and detrapping of the carriers with energies close to

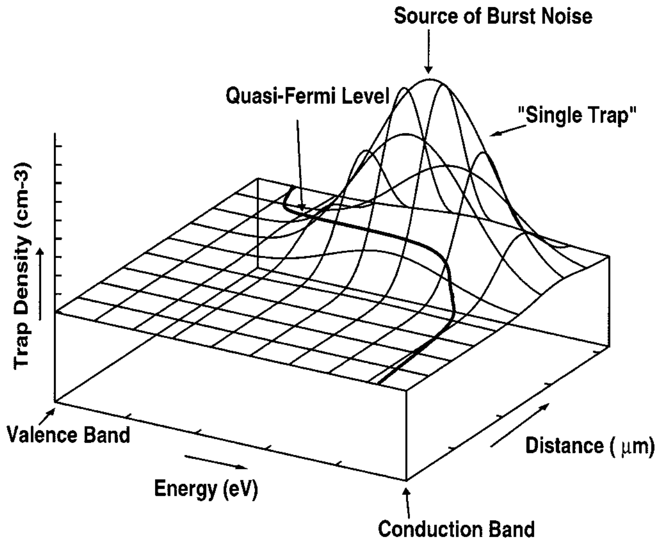

Fig. 2. Distribution of traps inside a semiconductor that cause burst noise. The valence and conduction bands are depicted straight and the Fermi level is bent for simplicity in depicting the trapping mechanism.

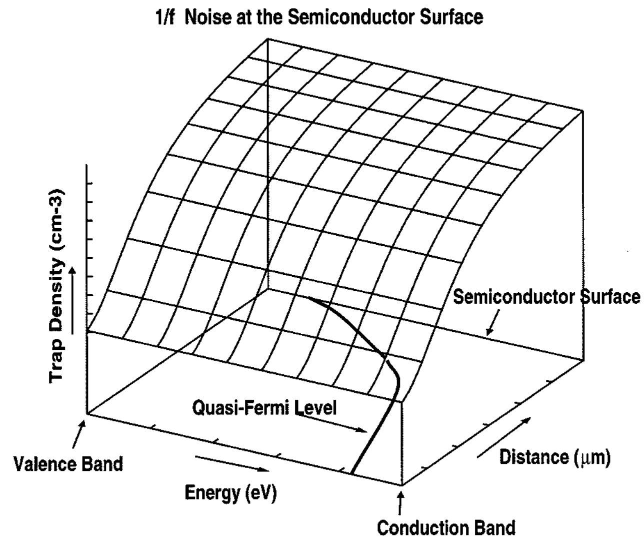

Fig. 3. Distribution of traps at the surface of a semiconductor that causes surface $1/f$ noise. The valence and conduction bands are depicted straight and the Fermi level is bent for simplicity in depicting the trapping mechanism.

the pick of the hump cause a G–R like noise, which is referred to burst noise.

Various experimental observations have suggested that the surface of the semiconductor can cause $1/f$ type noise [7], [8], [17], [18]. The surface $1/f$ noise is attributed to the existence of traps at the semiconductor surface and deep-level traps inside the oxide and oxide-semiconductor interface [17], [19], [20]–[22]. McWhorter lifetime distribution using a model based on the tunneling of the carriers from semiconductor surface to the traps within the oxide and oxide semiconductor interface was used to explain the surface $1/f$ noise [1], [22]. On the contrary, in the theory presented here, there is no need to account for a tunneling mechanism to explain surface $1/f$ noise. Instead, it is assumed that the density of traps increases as the semiconductor surface is approached. Due to an increased number of trapped carriers close to the surface, the conduction and valence band bend. Therefore, the Fermi level crosses a high density of trap energies at the vicinity of the surface with different energy level. This is shown in Fig. 3, where the valence and conduction bands are depicted straight and the Fermi level is bent for simplicity in depicting the trapping mechanism. Traps within a few kT of the Fermi level close to the semiconductor surface are responsible for the surface $1/f$ noise.

IV. Mathematical Formulation of the Low-Frequency Noise

In this section, the low-frequency noise due to a continuous band of traps inside the base region of an NPN heterojunction bipolar transistor (HBT) is analyzed. To simplify the formulation, it is assumed that only the traps within the base region of HBT rather than surface and base-emitter heterojunction are responsible for low-frequency noise. This is justified by experimental studies of HBTs [6], which show that the bulk emitter-base space charge region or heavily doped base region is a prime contribution to low-frequency base noise. The low-frequency noise due to base-emitter interface traps as well as semiconductor surface traps may be added to the theory presented here by employing a more involved mathematical treatment that requires numerical methods for solving the noise integral. Moreover, the analysis presented here is not limited to bipolar transistors and can be easily extended to any semiconductor device.

The traps inside the base of the HBT have finite density of states and produce G–R noise, which according to the nonfundamental theory presented here cumulatively becomes $1/f$ noise when integrated over the energy, E and distance, x.

$$S_N(f) = \iint_{Base} S_N(f, x, E)\, dx\, dE \tag{12}$$

where $S_N(f)$ is the low-frequency noise spectrum and $S_N(f, x, E)$ is the noise spectrum at position x and energy E inside the base region. $S_N(f, x, E)$ is given by the noise integral as mentioned before and repeated below by (13). Its derivation is based on McWhorter theory that assumes a distribution of time constant $g(\tau)$ and a fluctuation of carriers ΔN.

$$S_N(f, x, E) = 4\overline{\Delta N^2} \int_0^\infty \frac{\tau g(\tau)\, d\tau}{1 + \omega^2\tau^2} \tag{13}$$

where the energy dependence of $S_N(f, x, E)$ according to McWhorter's theory is reflected by $\overline{\Delta N^2}$, which is the variance of the fluctuation in the number of carriers. Unlike McWhorter's theory $\overline{\Delta N^2}$ is not constant but a function of energy and distance and is given by

$$\overline{\Delta N^2} = N_T(E, x)\, dE\, dx f_{Fermi}(x)[1 - f_{Fermi}(x)] \tag{14}$$

where $N_T(E, x)$ is the distribution of the traps with respect to energy (E) and position (x) inside the base, and $f_{Fermi}(x)[1 - f_{Fermi}(x)]$ is the Fermi occupation function. The distance dependence of $S_N(f, x, E)$ is reflected by $\overline{\Delta N^2}$ as well as the lifetime function $\tau = \tau(x)$.

The base of the high-performance HBTs is often heavily doped to allow small base access resistance and thus improved maximum oscillation frequency. The recombination process inside the bulk heavily doped base is often dominated by Auger recombination. However, in many semiconductor devices, Shockely–Reed–Hall recombination is dominant. In order to solve the noise integral, a general lifetime model, which contains both Auger and SRH recombination is adopted.

$$\frac{1}{\tau(x)} = [an(x)^2 + bn(x) + c] \tag{15}$$

where

- τ minority carrier (electron) lifetime;
- a, b, and c constants related to the properties of the semiconductor material;
- $n(x)$ distribution of the minority carriers inside the semiconductor (base region of HBT in this case).

For Auger recombination dominated processes, the constant a is larger than b while for SRH recombination dominated processes, the constant a can be neglected. For any electron devices, the concentration of minority carriers can vary with position (x) inside the semiconductor. For HBTs, the concentration of the minority carriers inside the base region $(0 < x < W_B)$ can be expressed in terms of distance neglecting the recombination in the neutral base region [23]:

$$n(x) = n(0)\left[1 - \frac{x}{W_B}\right]. \tag{16}$$

Additionally, when the Fermi occupation function in (14) is integrated over energy, it can be simplified using the following approximation [20]:

$$\int_E dE \cdot f_{Fermi}(x)[1 - f_{Fermi}(x)] = kTN_T(E_{Fermi}) \tag{17}$$

where $N_T(E_{Fermi})$ is the trap density at Fermi energy level and E_{Fermi} is the quasi-Fermi level for electrons given by

$$E_{Fermi}(x) = E_i + kT \ln\left[\frac{n(x)}{n_i}\right]. \tag{18}$$

In the approximation of (17), the effect of the traps far from the Fermi level is ignored. Depending on their energy with respect to the Fermi level, these traps are very likely to be filled or remain empty for large duration of time. However, they still can participate in trapping and detrapping of the carriers at very slow rates. Therefore, traps with energies farther than a few kT from the Fermi level may indeed contribute to the $1/f$ noise at the very low frequency end of the spectrum (fractions of Hz). Other nonfundamental noise theories need very large values of carrier lifetime to explain the observed $1/f$ noise spectrum in semiconductor devices at very low frequencies. The nonfundamental theory of low-frequency noise presented here does not need such large lifetime values to account for very low frequency $1/f$ noise, due to the consideration of the contribution of the traps far from the Fermi level to the low-frequency noise.

In the following analysis, the effect of the traps far from the Fermi level on low-frequency noise is neglected, thus (17) holds. The very low-frequency limit of $1/f$ noise in this case may not be analyzed accurately. Nevertheless, the low-frequency noise for low to high frequencies can be calculated by substituting (15)–(17) into (13) as in (19), shown at the bottom of the page. Where $g(x) = g(\tau(x))$ is the probability density function of the lifetime of carriers inside the base region and $N_T(x) = N_T(E_{Fermi}(x))$ is the trap density at the quasi-Fermi energy level. The above integral can be solved either analytically or numerically depending on the nature of $g(x)$ and $N_T(x)$. The integral has the general form of

$$S_N(f) = \int_{x=0}^{W_B} \frac{p(x)\tau(x)}{\frac{1}{\tau(x)^2} + 4\pi^2 f^2} \cdot dx \tag{20}$$

where lifetime $\tau(x)$ and $p(x) = 4g(x)kTN_T(x)n(0)/W_B$ $[2an(0) + b - (2an(0)x)/W_B)]$ are functions of position x and not frequency. When $S_N(f)$ is plotted as a function of f, it shows three different regions. At very low frequencies, provided that $c \neq 0$ in (19), i.e., $\tau(x) \neq \infty$ for $x = 0$ in (20), one can ignore the term $4\pi^2 f^2$ and thus the integral [(19)] is simplified to

$$S_N(f) = \int_{x=0}^{W_B} \frac{p(x)\,dx}{\left[an(0)^2\left[1-\frac{x}{W_B}\right]^2 + bn(0)\left[1-\frac{x}{W_B}\right] + c\right]^3}. \tag{21}$$

The noise spectral density at very low frequencies is therefore not a function of frequency and reaches a plateau, i.e. $S_N(f)$ becomes constant at very low frequencies. If the impact of traps far from the Fermi level is also considered, the low-frequency noise may not reach a plateau and continues to increase as the frequency decreases. This is expected neither from McWhorter's theory nor from Blasquez's theory, unless very large lifetime values (few seconds) are assumed.

$$S_N(f) = \int_{x=0}^{W_B} \frac{4g(x)kTN_T(x)\dfrac{\frac{n(0)}{W_B}\left[2an(0) + b - \frac{2an(0)x}{W_B}\right]}{\left[2an(0)^2\left[1-\frac{x}{W_B}\right]^2 + bn(0)\left[1-\frac{x}{W_B}\right] + c\right]}\,dx}{\left[an(0)^2\left[1-\frac{x}{W_B}\right]^2 + bn(0)\left[1-\frac{x}{W_B}\right] + c\right]^2 + 4\pi^2 f^2} \tag{19}$$

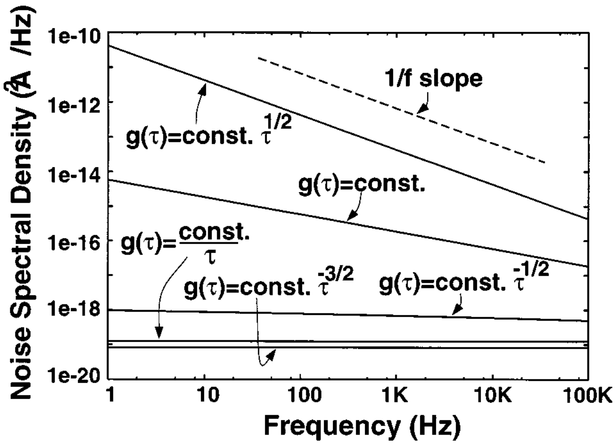

Fig. 4. Calculated noise spectral density as a function of frequency using (19) with uniform trap density and different carrier lifetime probability distribution functions.

At very high frequencies, when $1/\tau(x) \ll 2\pi f$ in (20), the noise spectral density becomes

$$S_N(f) = \frac{\int_{x=0}^{W_B} p(x)\tau(x)\,dx}{4\pi^2 f^2}. \tag{22}$$

Thus, the noise spectral density decreases with a $1/f^2$ dependence.

For frequencies between these two limits, the noise spectral density has an exponent γ for its frequency dependence ($S_N(f) \propto 1/f^{\gamma}$) where γ can vary with frequency but is larger than zero with values usually ranging from 0.5 to 2. This is what one refers to as $1/f$ noise or flicker noise. The exact frequency and bias dependence of $1/f$ noise depends on the lifetime probability distribution function ($g(\tau(x)) = g(x)$) and trap density distribution function ($N_T(E_{Fermi}(x)) = N_T(x)$), as well as the recombination mechanism [constants a, b and c in (15)]; as mentioned earlier, unlike McWhorter's theory, the nonfundamental theory presented here considers a generalized rather than single lifetime distribution function.

Fig. 4 shows the noise spectrum as a function of frequency when trap density is assumed to be constant ($N_T(E_{Fermi}(x)) = N_T(x) = N_T$) while the lifetime probability density function is changing. In this figure, the recombination mechanism is assumed to be dominated by Auger process, therefore the lifetime is inversely proportional to the square of the carrier concentration. The figure indicates that different lifetime probability density functions can result in different exponent γ of $1/f^{\gamma}$ noise. γ increases as the degree of the dependence of carrier lifetime probability function on lifetime increases, i.e., $g(\tau) = const.\sqrt{\tau}$ results in steeper slope of noise spectrum than $g(\tau) = const.$ or $g(\tau) = const.\tau^{-1/2}$. In Fig. 4, McWhorter's lifetime distribution ($g(\tau) = const./\tau$) leads to almost a constant noise spectral density rather than $1/f$ noise dependence. This does not, however, contradict the conclusions drawn from McWhorter's lifetime model in terms of predicting $1/f$ noise behavior by means of a distribution function of time constants. The dependence of noise on the trap density distribution ($N_T(x)$), as well as, the choice of the recombination model of (15), could change the results of Fig. 4 and may also lead to a $1/f$ noise spectrum for McWhorter's case of $g(\tau) = const./\tau$.

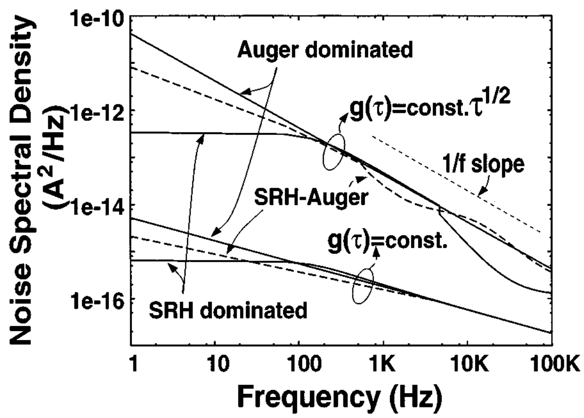

Fig. 5. Calculated noise spectral density as a function of frequency using (19) with uniform trap density and different recombination mechanisms.

Fig. 5 shows the noise spectral density as a function of frequency for different recombination mechanisms. The trap density ($N_T(E_{Fermi}(x)) = N_T(x) = N_T$) is assumed to be constant. The exponent γ in $1/f^{\gamma}$ noise increases as the recombination process changes from Shockley–Reed–Hall to Auger process. The choice of the recombination process in the case of a lifetime distribution $g(\tau) = const.$ leads to a variation of exponent γ at low frequencies. In the case of $g(\tau) = const.\sqrt{\tau}$ lifetime model, the choice of the recombination process impacts the entire frequency spectrum as shown in the figure. Nevertheless, recombination processes dominated by Auger mechanism lead to higher $1/f$ noise (larger γ in $1/f^{\gamma}$ noise) compared to those limited by SRH mechanism. Despite the fact that the trap density is assumed to be constant, a double hump behavior is seen for the case of the curve $g(\tau) = const.\sqrt{\tau}$ with both SRH and Auger recombination mechanisms present. The double hump relates in fact to two G–R centers with characteristic frequencies of 800 Hz and 10 KHz, and indicates how the choice of the recombination mechanisms, may generate G–R noise rather than a cumulative $1/f$ noise.

The noise current dependence can be investigated by plotting the noise spectral density versus collector current. To plot such dependence, the concentration of the carriers at the base-emitter junction is assumed to be proportional to the collector current, i.e., $n(0) \propto I_C$. This assumption is valid if the ideality factor of the base-emitter junction is unity. If the ideality factor is not unity, the collector current would be proportional to $n(0)^{\eta}$, where η is the ideality factor. Fig. 6 shows the noise spectral density at a certain frequency (10 Hz in this case) as a function of the collector current, where the trap density is assumed to be constant and the lifetime probability density function varies. The recombination mechanism in this case is assumed to be dominated by Auger process.

As Fig. 6 shows, the noise current dependence can vary depending on the lifetime probability density function. The noise current dependence also depends on the collector current values and appears to increase as the collector current increases. The highest degree of low-frequency noise dependence on the collector current shown in Fig. 6 is observed for $g(\tau) = const.\tau^{-3/2}$ lifetime distribution. The low-frequency

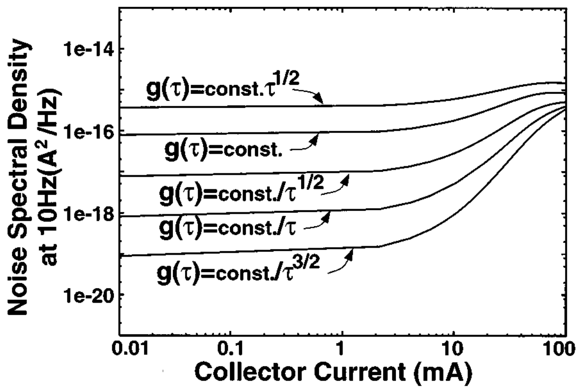

Fig. 6. Calculated noise spectral density at 10 Hz as a function of collector current using (19) with uniform trap density and different carrier lifetime probability distribution functions.

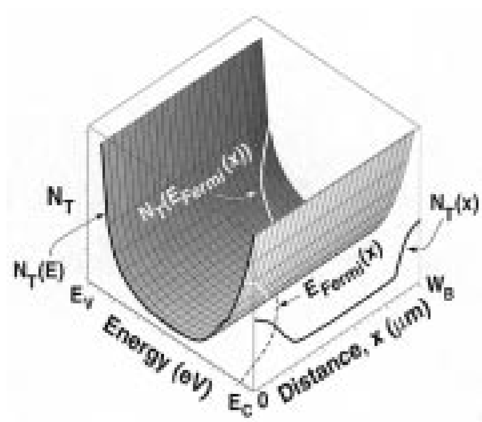

Fig. 7. Hypothetical trap density function as a function of energy and distance. The trap density inside the bandgap increases as the energy becomes close to conduction and valence band levels due to tailing effects.

noise varies as $I_C^{2.7}$ at high collector currents. The noise current dependence also varies with the trap density distribution and the choice of recombination process.

In the above examples, it has been assumed that the trap density as a function of distance x is constant. Although its exact variation is not known, a hypothetical variation of trap density with energy and distance was assumed and is shown in Fig. 7. In this figure, the density of traps is small at the middle of the bandgap and increases as the conduction band and valence band energy levels are approached. A similar variation in the dependence of the trap density versus distance x is observed due to the relation of the Fermi level to the E_C and E_V bend following (18) and also shown in the figure.

Shown in the inset of Fig. 8 are three trap distribution functions versus distance x noted as N_{T1}, N_{T2} and N_{T3}. The trap distribution function N_{T1} has a constant distribution with distance x, while N_{T2} and N_{T3} vary with distance according to the following assumed models.

$$N_{t2} = const. \left[1 + 4\left(\frac{x}{W_B} - 0.5\right)^2\right]$$
$$N_{T3} = const. \left[1 - 4\left(\frac{x}{W_B} - 0.5\right)^2\right]. \qquad (23)$$

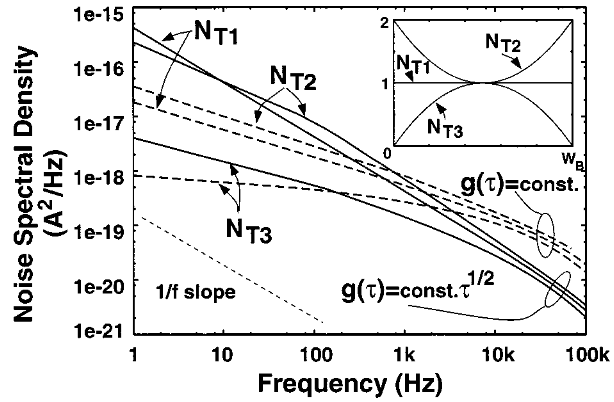

Fig. 8. Calculated noise spectral density as a function of frequency using (19) with three different trap density functions (N_{T1}, N_{T2} and N_{T3} shown in the inset). Auger recombination mechanism was assumed in these calculations. As shown in the figure, two different lifetime probability functions were used in the modeling.

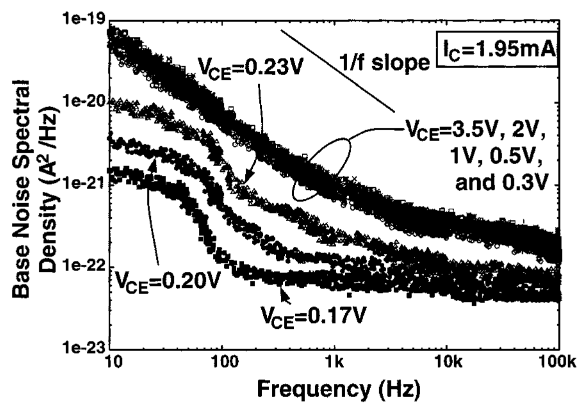

Fig. 9. Measured low-frequency noise of the base terminal of an AlGaAs/GaAs HBT as a function of frequency. The collector current was kept constant at $I_C = 1.95$ mA while the collector–emitter voltage V_{CE} was varied from 0.17 to 3.5 V. Low V_{CE} results in the transformation of $1/f$ noise to G–R noise.

Consideration of the above trap distribution functions shows that N_{T2} corresponds to some degree to the case presented in Fig. 7 where an increase of N_{T2} is observed at the collector-base and base-emitter junctions $(x = 0, W_B)$ and a minimum is shown at the middle of the base region. In contrast to N_{T2}, N_{T3} reaches zero at the collector-base and base-emitter junctions and has a maximum at the middle of the base region. The trap distribution function N_{T2} shows variation with respect to distance x, while the source of this variation could be due to a change in the trap density with energy (Fig. 7) or with distance. In the latter case, for example, the density of states increases as the base-emitter heterojunction is approached. It is possible to have simultaneous variation of trap density with both energy and distance. In such case, the trap density may increase more rapidly compared to the above example as the base-emitter heterojunction is approached.

Fig. 8 shows the results obtained from the noise integral for the low-frequency noise in the base of an HBT with two different lifetime probability functions ($g(\tau) = const.\tau^{1/2}$, $g(\tau) = const.$) and different trap density distributions (N_{T1}, N_{T2} and N_{T3}). Auger recombination is assumed to dominate again in this case. For both lifetime probability functions shown in the figure,

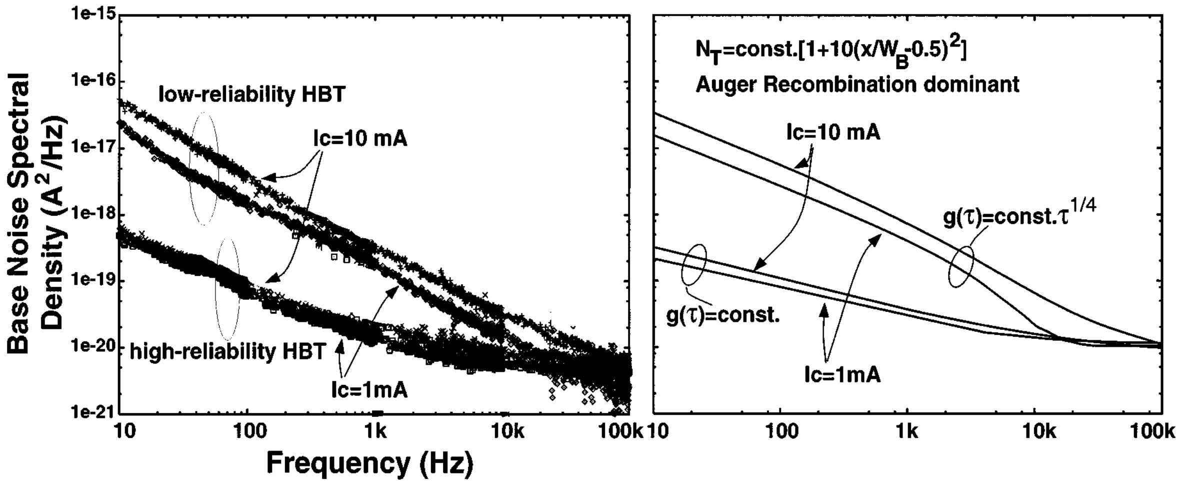

Fig. 10. Measured (left) and modeled (right) base noise spectral densities of two different AlGaAs/GaAs HBTs. The base noise in these devices originates from the recombination in the bulk base-emitter region.

the trap distribution function N_{T2} results in higher exponent γ in $S_N(f) \propto 1/f^{\gamma}$ noise compared to the constant trap density function (N_{T1}), while the trap distribution function N_{T3} leads to smallest γ value. The results demonstrate that the distribution of traps with energy E and distance x inside the base region affects the low-frequency noise characteristics.

Trap distributions similar to that of Fig. 7 with higher trap density close to the conduction and valence band energy levels result in higher exponent γ in $S_N(f) \propto 1/f^{\gamma}$ noise compared to the constant trap density function. Further studies revealed that strong variation in the trap density distribution function N_{T2}, i.e., due to simultaneous variation of trap density with energy and distance with higher trap density at the edge of the base-emitter heterojunction, leads to high values of γ exponent in $S_N(f) \propto 1/f^{\gamma}$.

V. Comparison to Experimental Results

Fig. 9 shows the current noise spectral density in the base region of an AlGaAs/GaAs HBT as a function of frequency for identical collector currents ($I_C = 1.95$ mA) and varying collector–emitter voltages. For collector–emitter voltages (V_{CE}) higher than 0.3 V and up to 3.5 V, the noise spectral density does not vary and shows a $1/f$ behavior with a slope of 1 for frequencies between 10 Hz and 10 kHz. As the collector–emitter voltage decreases further, while the collector current is still constant, the noise starts to change its nature and becomes G–R noise rather than $1/f$ noise. This is due to the fact that the $1/f$ base noise in these devices is due to the cumulative noise from G–R centers in the base region. As the collector–emitter voltage decreases, the distribution of the carriers inside the base region and thus the quasi-Fermi level become more flat within the base region and eventually for very small V_{CE}, the distribution of carriers and quasi-Fermi level become almost constant. Therefore, only a small concentration of traps with energy levels within a few kT of the Fermi level is contributing to the noise. The G–R noise centers with identical energy contribute to the low-frequency noise, but the cumulative effect appears to be a G–R noise rather than $1/f$ noise.

Fig. 10 shows an example of application of the theory in modeling the low-frequency noise characteristics of HBTs. Shown in the figure are the results of base noise characterization in two different AlGaAs/GaAs HBT's (low-reliability and high-reliability HBTs [2]) as well as the calculated values using the low-frequency noise theory presented in this work. These HBTs were tested for the origin of their base low-frequency noise. It was found that the base low-frequency noise in these devices originates from the base-emitter heterojunction bulk space charge region or heavily doped base region rather than the surface [9]. A model along the lines discussed in Section IV for the noise integral [(19)] was used. In this model, the trap density and lifetime distribution functions, as well as, recombination processes were selected in a way that permitted best fit with measurement data. Auger recombination was chosen as the recombination mechanisms in these HBT's since the GaAs base of these devices is highly doped (3×10^{19} cm^{-3}). The selected trap density function had the characteristics of N_{T2} [(23)], presenting therefore an increase of density as the valence band and conduction band energy levels are approached. The results show that the lifetime probability distribution function $g(\tau)$ is different in these devices; $g(\tau) = const.$ and $g(\tau) = const.\tau^{1/4}$ for high and low-reliability HBT's, respectively. This difference in $g(\tau)$ distribution between the two devices is also supported by the fact that the exponent γ in $1/f^{\gamma}$ was measured to be different in the two devices. Good agreement between measured and modeled low-frequency noise for these devices was found and the results presented in this figure show that the theory developed here can be used in order to provide physical insight to the noise mechanisms present in semiconductor devices.

VI. Conclusion

A low-frequency noise theory for solid-state electronic devices was presented, which is based on the fluctuation in the number of carriers in the active region. Examples of noise mechanisms for G–R noise, bulk $1/f$ noise, burst noise, and surface $1/f$ noise were presented. A mathematical formulation for the low-frequency noise in the base of an HBT was derived in the form of a noise integral [(19)]. It was shown that at very low frequencies, the noise reaches a plateau unless the lifetime of carriers becomes infinity within the active region of the devices. Also at very high frequencies, the noise follows a $1/f^2$ roll-off, but in most cases, this region is masked by thermal noise. In the rest of the frequency domain, the low-frequency noise can vary with an exponent γ in $S_N(f) \propto 1/f^\gamma$, and γ can vary with frequency but is larger than zero. The exact value of γ is dictated by the nature of the recombination, the lifetime probability density function and also by the trap density function. It was shown that trap density functions with higher trap densities close to the conduction and valence band lead to higher values of γ. Moreover, it was shown that Auger recombination processes result in higher exponent γ in $S_N(f) \propto 1/f^\gamma$ noise compared to SRH recombination process. Finally, the noise theory was used to successfully model the low-frequency noise characteristics of AlGaAs/GaAs HBT's with different characteristics.

ACKNOWLEDGMENT

The authors would like to acknowledge Dr. B. Bayraktaroglu, Northrop-Grumman, for providing the AlGaAs/GaAs HBT devices and S.-H. Hsu, University of Michigan, for his assistance in HBT noise characterization.

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