

Low-frequency noise in modern bipolar transistors: impact of intrinsic transistor and parasitic series resistances

Citation for published version (APA):

Kleinpenning, T. G. M. (1994). Low-frequency noise in modern bipolar transistors: impact of intrinsic transistor and parasitic series resistances. *IEEE Transactions on Electron Devices*, 41, 1981-1991.
<https://doi.org/10.1109/16.333815>

DOI:

[10.1109/16.333815](https://doi.org/10.1109/16.333815)

Document status and date:

Published: 01/01/1994

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Low-Frequency Noise in Modern Bipolar Transistors: Impact of Intrinsic Transistor and Parasitic Series Resistances

Theo G. M. Kleinpenning

Invited Paper

Abstract—In modern submicrometer transistors, the influence of the internal base and emitter series resistances, on both the I-V characteristics and the LF noise at higher bias currents, becomes important. In this paper expressions are presented for the LF noise in transistors, where the influence of the series resistances has been taken into account. The expressions have been compared with recent experimental results from the literature obtained from modern submicrometer (heterojunction) bipolar transistors. At low forward currents the LF noise in such transistors is determined by spontaneous fluctuations in the base and collector currents. In most transistors at higher forward currents, the parasitic series resistances and their noise become important.

I. INTRODUCTION

IT is well known that low-frequency (LF) noise in bipolar transistors and FET's can limit the bandwidth and stability of circuit operation at high speed [1].

Bipolar transistors featuring very low noise are of considerable interest for high-frequency applications. Low LF noise transistors will not only improve the performance but also significantly reduce the size of microwave and millimeter-wave radio communication equipment, since such devices eliminate the need for a dielectric resonator to stabilize frequency oscillations [2]. Low-frequency noise also causes phase noise in oscillators and therefore has to be as low as possible. In general, we can state that LF noise restricts the sensitivity of a system and sets a limit in small signal processing. Consequently, it is necessary to have an understanding of the LF noise sources in transistors in order to improve techniques for device modeling and design.

Up to the present a number of papers have been published on low-frequency noise, especially $1/f$ noise, in bipolar transistors. In the most recent papers, the $1/f$ noise in bipolar transistors has mainly been discussed in terms of fluctuations in the mobility or diffusivity of free charge carriers. A survey of the interpretation of $1/f$ noise in bipolar transistors until 1986 has been given by Van der Ziel [3]. A review of the literature over the period 1985–1989 has been given by Kleinpenning at the 10th International Conference on Noise in Physical Systems in 1989 [4]. Until 1990 the low-

frequency noise sources in bipolar transistors were generally accepted as being located between emitter and collector and between emitter and base. In principle, there is also a noise source between base and collector. In practical cases the base-collector junction is reverse-biased, so that the base-collector current is slight and its noise can be neglected.

Recent developments in transistor technology have led to a significant lateral down scaling of bipolar devices. In such down-scaled transistors, deviations from the expected current dependence of the low-frequency noise in the collector current and in the base current are observed. Kleinpenning [4] suggested that these deviations may be ascribed to resistance fluctuations in the internal parasitic series resistances. It is well known that in submicrometer bipolar transistors the influence of the internal base and emitter series resistances on the $I_C - V_{EB}$ and $I_B - V_{EB}$ characteristics at higher currents becomes important [5]. Recently, papers on low-frequency noise in bipolar transistors have been published taking the influence of the internal series resistances into account [6], [7].

The purpose of this paper is to present a survey of the state-of-the-art of low-frequency noise in modern transistors, like polysilicon emitter bipolar transistors and heterojunction bipolar transistors.

The organization of the paper is as follows.

In Section II, we describe the measuring methods of LF noise in transistors.

In Section III general formulas for the LF noise in transistors are presented, taking the contributions from the parasitic series resistances into account.

In Section IV we discuss the noise sources in transistors, and in Section V we compare experimental data from literature with the general noise formulas.

In Section VI the conclusions are presented.

II. CIRCUITS FOR NOISE MEASUREMENTS

Usually the low-frequency noise of a bipolar transistor is measured with the transistor in circuits as shown in Fig. 1. The internal series resistances are given by r_e , r_b , and r_c , respectively. In Fig. 1(a) three external wire-wound or metal-film resistors R_C , R_B and R_E are inserted. Such resistors only have Nyquist noise ($4kTR$). Here, we consider a p-n-p transistor with the emitter-base junction to be forward-biased and the base-collector junction to be reverse biased.

Manuscript received October 29, 1993; revised June 29, 1994. The review of this paper was arranged by Editor-in-Chief R. P. Jindal.

The author is with the Department of Electrical Engineering, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands.
IEEE Log Number 9405576.

0018-9383/94\$04.00 © 1994 IEEE

DC biasing is performed with the help of batteries. The spectral noise densities of the voltage fluctuations across the resistors R_C , R_B , and R_E can be measured with the help of a low-noise voltage amplifier and a Fast Fourier Transform digital spectrum analyzer. In the common-emitter configuration ($R_E = 0$) the voltage noise across the resistor R_C is often measured as a function of both R_B and the current I_E . In the common-collector configuration ($R_C = 0$), the voltage noise across the resistor R_E is often measured as a function of both the current I_E and the value of the external resistance R_B .

In the circuit of Fig. 1(b) the spectral noise densities of the current fluctuations ΔI_C , ΔI_B , and ΔI_E can be measured with the help of a low-noise current amplifier and an FFT spectrum analyzer. Both the currents and its noise are measured by inserting the measuring apparatus in the external lead. In the next section we shall present general noise formulas for both the voltage spectral noise densities across the external resistors and the current spectral noise densities in I_C , I_B , and I_E .

III. GENERAL FORMULAS

We consider a p-n-p transistor with the emitter-base junction to be forward biased ($V_{eb} \gg kT/q$) and the base-collector junction to be reverse-biased ($V_{bc} \gg kT/q$). For the fluctuations in the base, collector, and emitter currents we have

$$\Delta I_B = \Delta I_b + \Delta V_{eb}/r_\pi \quad (1)$$

$$\Delta I_C = \Delta I_c + g_{mc}\Delta V_{eb} \quad (2)$$

$$\Delta I_E = \Delta I_B + \Delta I_C. \quad (3)$$

Here $g_{mc} = dI_c/dV_{eb}$ is the collector transconductance, $r_\pi = dV_{eb}/dI_B$ the input resistance, ΔI_b and ΔI_c the spontaneous fluctuations in the base and collector currents at constant V_{eb} , with V_{eb} the voltage drop across the emitter-base junction, excluding the voltage drops across the series resistances r_e and r_b . The fluctuations in V_{eb} are given by

$$\begin{aligned} \Delta V_{eb} = & -(R_B + r_b)\Delta I_B - I_B\Delta r_b - (R_E + r_e)\Delta I_E \\ & - I_E\Delta r_e + \Delta V_{eb}^N \end{aligned} \quad (4)$$

with ΔV_{eb}^N the fluctuations in V_{eb} due to the Nyquist noise in R_B , r_b , R_E and r_e . The spontaneous fluctuations in the base and emitter series resistances are given by Δr_b and Δr_e . In (1)–(3) we have assumed I_B and I_C to be independent of V_{bc} , so the Early effect has been neglected.

Combining (1)–(4), the fluctuations in the currents ΔI_E , ΔI_C , and ΔI_B can be expressed in terms of the spontaneous noise sources ΔI_b , ΔI_c , Δr_b , Δr_e , and ΔV_{eb}^N . For the fluctuations across the external resistors in Fig. 1(a), we have

$$\begin{aligned} \Delta V_E &= \Delta V_E^N + R_E\Delta I_E \\ \Delta V_C &= \Delta V_C^N + R_C\Delta I_C \\ \Delta V_B &= \Delta V_B^N + R_B\Delta I_B. \end{aligned} \quad (5)$$

Here, ΔV_E^N , ΔV_C^N , and ΔV_B^N are the open-circuit Nyquist voltage fluctuations in the external resistance of R_E , R_C , and R_B , respectively.

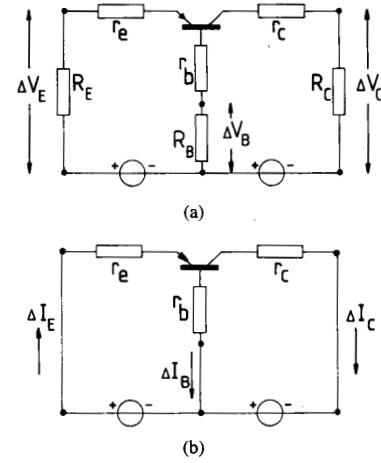


Fig. 1. (a) General circuit for LF voltage noise measurements. (b) General circuit for LF current noise measurements. (See [7]).

Using (1)–(5), taking the spontaneous noise sources to be uncorrelated, and going over to the spectra, the voltage noise spectral densities across the external resistors can be written as [6], [8]

$$\begin{aligned} (Z/R_E)^2 S_{V_E} = & [r_\pi - \beta(r_b + R_B)]^2 S_{I_b} \\ & + [r_\pi + r_b + R_B]^2 S_{I_c} \\ & + (\beta + 1)^2 S_{V_r} \\ & + 4kT[(\beta + 1)^2(R_B + R_E) \\ & - 2(\beta + 1)Z + Z^2/R_E] \end{aligned} \quad (6)$$

$$\begin{aligned} (Z/R_C)^2 S_{V_C} = & \beta^2[r_b + R_B + r_e + R_E]^2 S_{I_b} \\ & + [r_\pi + r_b + R_B + r_e + R_E]^2 S_{I_c} \\ & + \beta^2 S_{V_r} + 4kT[\beta^2(R_B + R_E) + Z^2/R_C] \end{aligned} \quad (7)$$

$$\begin{aligned} (Z/R_B)^2 S_{V_B} = & [r_\pi + \beta(r_e + R_E)]^2 S_{I_b} + [r_e + R_E]^2 S_{I_c} \\ & + S_{V_r} + 4kT[R_B + R_E - 2Z + Z^2/R_B] \end{aligned} \quad (8)$$

with

$$S_{V_r} = I_B^2 S_{r_b} + I_E^2 S_{r_e} + 4kT(r_b + r_e) \quad (9)$$

and

$$Z = r_\pi + r_b + R_B + (\beta + 1)(r_e + R_E). \quad (10)$$

Here, S_{I_b} , S_{I_c} , S_{r_b} , and S_{r_e} are the spectral noise densities of the spontaneous fluctuations ΔI_b , ΔI_c , Δr_b , and Δr_e respectively. Considering (6)–(10), the importance of the internal series resistances can be seen. The influence of these resistances is twofold. They can produce LF noise and, they can influence the magnitude of the noise originating from the sources S_{I_b} and S_{I_c} by means of feedback.

For the circuit in Fig. 1(b) the fluctuations ΔI_E , ΔI_B , and ΔI_C can be expressed in terms of the spontaneous noise sources. With the help of (1)–(4), taking $R_B = R_C = R_E = 0$, and going over to the spectra, Kleinpenning found [8]

$$Z_0^2 \cdot S_{I_E} = (r_\pi - \beta r_b)^2 S_{I_b} + (r_\pi + r_b)^2 S_{I_c} + (\beta + 1)^2 S_{V_r} \quad (11)$$

$$Z_0^2 \cdot S_{I_C} = \beta^2(r_e + r_b)^2 S_{I_b} + (r_\pi + r_b + r_e)^2 S_{I_c} + \beta^2 S_{V_r}, \quad (12)$$

$$Z_0^2 \cdot S_{I_B} = (r_\pi + \beta r_e)^2 S_{I_b} + r_e^2 S_{I_c} + S_{V_r}, \quad (13)$$

with

$$Z_0 = r_\pi + r_b + (\beta + 1)r_e. \quad (14)$$

Note that for $r_b = r_e = 0$, we obtain $S_{I_C} = S_{I_c}$, $S_{I_B} = S_{I_b}$, and $S_{I_E} = S_{I_c} + S_{I_b}$.

Several remarks should be made with respect to the derivation of the noise formulas given by (6)–(8) and (11)–(13).

First, the Early effect has been neglected. Taking into account this effect one has to rewrite (2) as

$$\Delta I_C = \Delta I_c + g_{mc} \Delta V_{eb} + h_{22} \Delta V_{bc} \quad (15)$$

with

$$\begin{aligned} \Delta V_{bc} = & -(R_C + r_c) \Delta I_C - I_C \Delta r_c \\ & - (R_B + r_b) \Delta I_B - I_B \Delta r_b + \Delta V_{bc}^N. \end{aligned} \quad (16)$$

Here, ΔV_{bc}^N is the fluctuation in V_{bc} due to the Nyquist noise in R_C , r_c , R_B and r_b . In modern transistors the output conductance h_{22} is very low, so that the term $h_{22} \Delta V_{bc}$ can be neglected.

Second, we neglect current crowding, leakage currents, and injection of electrons from the collector into the base.

Third, the base series resistance r_b consists of a part r_{b1} for the region outside the emitter and a part r_{b2} for the base region under the emitter. Consequently, we have a distributed base current. Hence, the base series resistance r_b and its fluctuations Δr_b have to be considered as effective quantities (see also Section IV-C). Current crowding in the base can be neglected on condition that $I_B r_{b2} < kT/q$.

Fourth, with respect to the voltage-noise spectral densities S_{V_E} , S_{V_C} , and S_{V_B} , we find that till 1990 only expressions can be found where $S_{r_b} = S_{r_e} = 0$ in the literature. These expressions can be derived from (6)–(10) making the appropriate approximations. In the common-emitter configuration the voltage noise S_{V_C} is mostly measured. With $S_{r_b} = S_{r_e} = 0$ and $r_e = R_E = 0$, (7) leads to the well known relation

$$\begin{aligned} S_{V_C}/R_C^2 = & S_{I_c} + \left[\frac{\beta(r_b + R_B)}{r_\pi + r_b + R_B} \right]^2 \left[S_{I_b} + \frac{4kT}{r_b + R_B} \right] \\ & + \frac{4kT}{R_C}. \end{aligned} \quad (17)$$

Fifth, with the help of the general formulas (6)–(10), one can determine the LF noise sources in bipolar transistors, as well as the magnitude of the series resistances r_b and r_e . For that the transistor has to be set in a circuit with variable external base, emitter, and collector resistances. By measuring the LF noise at the emitter, base, and collector contact at different values of the external resistances and at different currents, the LF noise sources can be located. Some examples are presented in [8] and in Section V.

In the next section we shall present expressions for the spontaneous LF noise sources.

IV. LOW-FREQUENCY NOISE SOURCES

A. Base Current Noise

The current-noise spectral density of the spontaneous fluctuations in the base current S_{I_b} can consist of several contributions. There always is shot noise and $1/f$ noise and, occasionally, there is generation-recombination (GR) noise and burst noise, or so-called random telegraph signal (RTS) noise. The shot noise contribution is given by the well known relation

$$S_{I_b} = 2qI_B. \quad (18)$$

Currently, the $1/f$ noise in bipolar devices is often discussed in terms of mobility fluctuations [3], [4]. According to the mobility fluctuation model, we have three expressions for the $1/f$ noise in the base current. If the base current and its noise is determined by carriers recombining in the space-charge region between emitter and base we have [9], [10]

$$S_{I_b} = 2\alpha q I_B / 3f\tau_j \quad (19)$$

and

$$I_B = (qWAn_i/\tau_j) \exp(qV_{eb}/2kT) \quad (20)$$

where τ_j is the carrier lifetime in the space-charge region, f the frequency, α the Hooge parameter, W the effective width of the junction, n_i the intrinsic concentration, and A the emitter area. If the base current and its noise are determined by carriers injected from the base into the emitter, we have two expressions both for S_{I_b} and for I_B . If the width of the emitter W_E is thicker than the minority carrier diffusion length, $L_n = (D_n\tau_n)^{1/2}$, then we have [9, 11]

$$S_{I_b} = \alpha q I_B / 4f\tau_n \quad (21)$$

and

$$I_B = (qAD_n^{1/2}n_i^2/N_E\tau_n^{1/2}) \exp(qV_{eb}/kT) \quad (22)$$

where τ_n is the minority carrier lifetime in the emitter, D_n its diffusivity, and N_E the dope concentration in the emitter. For $W_E < L_n$ we obtain [4], [12]

$$S_{I_b} = \frac{\alpha q I_B D_n}{fW_E^2(1 + D_n/s_n W_E)^2} \cdot \ln[1 + s_n W_E/D_n] \quad (23)$$

and

$$I_B = [qAD_n n_i^2 / N_E W_E (1 + D_n/s_n W_E)] \exp(qV_{eb}/kT) \quad (24)$$

with s_n the recombination velocity of minority carriers at the emitter contact.

Sometimes GR noise or RTS noise in the base current is observed in bipolar transistors. The experimental results are discussed with the help of fitting formulas like $S_{I_b} = AI_B^k / (1 + (2\pi f\tau)^2)$ with A and k parameters [14]. Burst noise and GR noise in bipolar transistors are often associated with traps or g - r centers near the emitter-base space-charge region.

GR noise in the base current can be attributed to fluctuations in the recombination (trapping) rate R_t of the excess carriers either in the space-charge region between emitter and base, or in the emitter, or at the emitter contact. These fluctuations

ΔR_t are related to fluctuations in the occupancy of the traps ΔN_t . Since the rate R_t is proportional to the number of excess carriers N and the number of empty trap states $Z_t - N_t$, we have $R_t \sim N(Z_t - N_t)$ and $\Delta R_t/R_t = -\Delta N_t/(Z_t - N_t)$. For the spectral noise densities we obtain

$$S_{R_t}/R_t^2 = S_{N_t}/(Z_t - N_t)^2 \quad (25)$$

and

$$S_{N_t} = 4\tau_t \langle \Delta N_t^2 \rangle / [1 + (2\pi f \tau_t)^2] \quad (26)$$

with $\langle \Delta N_t^2 \rangle$ the variance of the fluctuations in N_t , and τ_t the relaxation time of carriers in the trap. The quantities τ_j , τ_n and s_n in (20), (22), and (24) are related to the trapping rate as $\tau_j \sim 1/R_t$, $\tau_n \sim 1/R_t$, and $s_n \sim R_t$. If the base current is given by (20), (22), and (24) we have successively

$$\begin{aligned} S_{I_b}/I_B^2 &= S_{R_t}/R_t^2, \\ S_{I_b}/I_B^2 &= (1/4)S_{R_t}/R_t^2 \end{aligned} \quad (27)$$

and

$$S_{I_b}/I_B^2 = (1 + s_n W_E/D_n)^{-2} S_{R_t}/R_t^2. \quad (28)$$

Sometimes the $1/f$ noise in I_B is interpreted as a sum of GR spectra with a particular distribution of relaxation times. In that case the noise has a I_B^2 dependence. Since $1/f$ noise is observed over a broad frequency range, the τ_t -distribution has to meet very specific requirements.

B. Collector Current Noise

Usually, the noise in the collector current is the sum of shot noise and $1/f$ noise. The shot noise is given by

$$S_{I_c} = 2qI_C \quad (29)$$

and the $1/f$ noise, according to the mobility fluctuation model, by a similar expression as (23)

$$S_{I_c} = \frac{\alpha q I_C D_p}{f W_B^2 (1 + D_p/v_p W_B)^2} \cdot \ln [1 + v_p W_B/D_p]. \quad (30)$$

The collector current is given by

$$I_C = [qAD_p n_i^2 / N_B W_B (1 + D_p/v_p W_B)] \exp(qV_{eb}/kT). \quad (31)$$

Here D_p is the diffusivity of minority carriers in the base, W_B the base width, v_p the velocity of minority carriers in the base at $x = W_B$, and N_B the dope concentration in the base.

It should be noted that the derivation of the expressions for both S_{I_b} in (23) and S_{I_c} in (30) can be found in [12]. This derivation is more accurate than in [3]. For $D_p \ll v_p W_B$ and $D_n \ll s_n W_E$ the expressions given in [3] and in [12] become the same.

C. Series Resistance Noise

The internal base resistance r_b consists of contact resistance r_{bc} , resistance between contact and emitter r_{b1} and resistance for the base region under the emitter r_{b2} , thus $r_b = r_{bc} + r_{b1} + r_{b2}$. The resistance r_b always has Nyquist noise ($4kTr_b$) and can have $1/f$ noise, GR noise, and possibly, RTS noise. For a circular emitter with radius R , Kleinpenning [20] found the $1/f$ resistance noise in r_{b2} to be

$$S_{r_{b2}} = 4\alpha r_{b2}^2 / 3fN \quad (32)$$

with $r_{b2} = \rho/8\pi W_B$ and $N = \pi R^2 W_B n$ being the total number of majority carriers in the base region below the emitter. Here, ρ is resistivity of the base and n the majority carrier density. For a rectangular emitter the factor $4/3$ in (32) has to be replaced by $18/5$ [4]. According to the Hooge relation [13] we can put

$$S_{r_b} = \alpha r_b^2 / f N_b^* \quad (33)$$

with N_b^* the effective number of charge carriers in the total base region.

The internal emitter series resistance r_e consists also of contact resistance and bulk resistance. Here we have

$$S_{r_e} = \alpha r_e^2 / f N_e^* \quad (34)$$

with N_e^* the effective number of charge carriers.

For any GR noise contribution we can similarly write

$$S_{r_b}/r_b^2 = S_{N_b^*}/N_b^{*2} = \frac{4\langle \Delta N_b^{*2} \rangle \tau / N_b^{*2}}{1 + (2\pi f \tau)^2} \quad (35)$$

with $\langle \Delta N_b^{*2} \rangle$ the variance and τ the relaxation time. A similar expression holds for GR noise in r_e .

V. EXPERIMENTAL DATA

In this section we shall discuss a number of experimental results obtained during the last decade. First, we start with some results obtained from conventional bipolar junction transistors (BJT's) with deviations in the expected current dependence of the $1/f$ noise at higher emitter currents. These deviations are the first indication that series resistances influence the LF noise. Subsequently, we shall discuss recent experimental results from polysilicon-emitter BJT's and from heterojunction bipolar transistors (HBT's).

A. Conventional BJT's

Pawlikiewicz *et al.* [15] studied the $1/f$ noise in p⁺-n-p silicon BJT's. At higher collector currents (~ 2 mA), they found the $1/f$ noise in the collector current to be less than proportional to I_C . If the $1/f$ noise is due to mobility fluctuations, the noise density should be proportional to I_C (see (30)). This deviation may be ascribed to the influence of the emitter series resistance. According to (12) and (14) we have

$$S_{I_C} = \left[\frac{r_\pi}{r_\pi + (\beta + 1)r_e} \right]^2 S_{I_c} \quad (36)$$

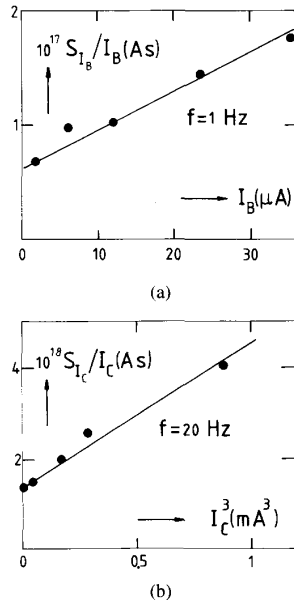


Fig. 2. (a) S_{I_B}/I_B versus I_B . Data are from Table 2 in [15]. (b) S_{I_C}/I_C versus I_C^3 . Data are from Fig. 4 in [16].

provided that $r_\pi \gg r_b + r_e$, and that the contributions from both S_{I_b} and S_{V_r} can be neglected. At $I_C = 2$ mA they found S_{I_C} a factor 4 too low. On the other hand, it holds $(\beta + 1) \approx 170$ and $r_\pi \approx 2$ k Ω . Consequently, an emitter series resistance of $r_e \approx 12$ Ω can explain the observed deviation. For low values of I_B the $1/f$ noise in S_{I_B} was found to be proportional to I_B , which is in agreement with the mobility fluctuation model (23). At higher values of I_B they found $S_{I_B} = AI_B + BI_B^k$ with $k \approx 2$. This is illustrated in Fig. 2(a), where S_{I_B}/I_B is plotted versus I_B .

According to (13) this deviation can be ascribed to a noise contribution from the series resistances. Here we have

$$S_{I_B} \approx S_{I_b} + \frac{S_{V_r}}{(r_\pi + \beta r_e)^2} \approx S_{I_b} + S_{V_r} / \beta^2 r_e^2 \quad (37)$$

with $S_{I_b} \sim I_B$ and $S_{V_r} \sim I_B^2$. Using (23) and (30) the Hooge parameter α was found to be of the order of 10^{-8} , both for the $1/f$ noise in the base current and in the collector current [15]. It is not possible to obtain α -values from series resistance $1/f$ noise, since in [15] data are missing to calculate S_{r_e} and S_{r_b} .

It cannot be excluded that the existence of some recombination related $1/f$ noise is responsible for the contribution BI_B^2 . In view of the specific requirements for the distribution of relaxation times such a contribution is not very likely. A clearer indication for the existence of series resistance $1/f$ noise will be given in Section V-B.

Zhu *et al.* [16] investigated the $1/f$ noise in n-p-n microwave transistors. The collector current noise was measured with a short-circuited base ($R_B = 0$) and with $R_E = 0$. According to (7) and (12), and the approximation $Z = Z_o \approx r_\pi$, the $1/f$ noise in the collector current is given by

$$S_{I_C} = g_{mc}^2 (r_b + r_e)^2 S_{I_b} + S_{I_c} + g_{mc}^2 S_{V_r}. \quad (38)$$

Zhu *et al.* established that the first term in (38) is considerably smaller than S_{I_c} , the third term has not been taken into account. Consequently, one can expect

$$S_{I_C} \approx S_{I_c} + g_{mc}^2 S_{V_r} = AI_C + BI_C^4. \quad (39)$$

Interpreting the contribution AI_C in terms of mobility fluctuations, Zhu *et al.* found a Hooge parameter of the order of magnitude of 10^{-8} . It is not possible to determine α values from S_{V_r} for lack of data in [16].

The experimental results of Zhu *et al.* are replotted in Fig. 2(b) as S_{I_C}/I_C versus I_C^3 . An excellent linear relationship was found, which is a strong indication that the $1/f$ noise in series resistances becomes important at higher currents.

B. Polysilicon-Emitter BJT's

Polysilicon emitter bipolar transistors have higher current gain than conventional transistors. Such high gain transistors are good candidates for analog applications. For these applications the LF noise performance of the transistor is very important. Here we shall discuss some experimental data of LF noise presented in the literature.

Kleinpenning and Holden [6], [17] investigated the low-frequency noise in self-aligned, polysilicon-emitter, n-p-n silicon BJT's, with emitter areas A of 0.5×1.5 , 0.5×4.5 , 0.5×9.5 , and 1.25×4.5 μm^2 , respectively. For all transistors the collector current at room temperature can be described by $I_C = I_{C0} \exp(qV_{be}/kT)$ with $I_{C0}/A \approx 7 \times 10^{-11}$ A/cm 2 . For most devices at collector currents in the range of 0.1 μ A–1 mA, the base current followed the relation $I_B = I_{B0} \exp(qV_{be}/kT)$ with $I_{B0}/A \approx 6 \times 10^{-13}$ A/cm 2 . Noise measurements were presented only for devices with ideal base current (i.e., ideality factor $n = 1$), putting the transistor both in the common-collector (CC) configuration with $R_E \gg R_B + r_b + r_e + r_\pi$ and in the common-emitter (CE) configuration. Generally, the spectra consisted of two components. At low frequencies, a $1/f$ component and at higher frequencies a white component. Most of the spectra measured had corner frequencies f_c in the range of 10 Hz–10 kHz, where at $f = f_c$ the $1/f$ noise density equals the white-noise density. Typical plots of the voltage-noise spectral density S_{V_E} of the white noise at high frequencies and the $1/f$ noise at $f = 1$ Hz versus emitter current are shown in Fig. 3. The data are obtained with the transistor in the CC-configuration with $R_B = 0$ and thus $Z \approx (\beta + 1)R_E$. For both the white noise and the $1/f$ noise, a changeover of the current dependence was found at $I_E \approx 30$ μ A. Such a changeover is predicted by (6). At low currents (6) can be approximated by

$$S_{V_E} = [r_\pi / (\beta + 1)]^2 [S_{I_b} + S_{I_c}] \sim I_E^{-1} \quad (40)$$

and at high currents by

$$S_{V_E} = S_{V_r} \sim I_E^2. \quad (41)$$

At low currents the experimentally observed white noise agrees with $[r_\pi / (\beta + 1)]^2 2qI_E$ and at high currents with $4kT(r_e + r_b)$.

At low currents ($I_E < 10$ μ A) the $1/f$ noise can be strongly reduced by adjusting $R_B = r_\pi / \beta - r_b$, and according to (6)

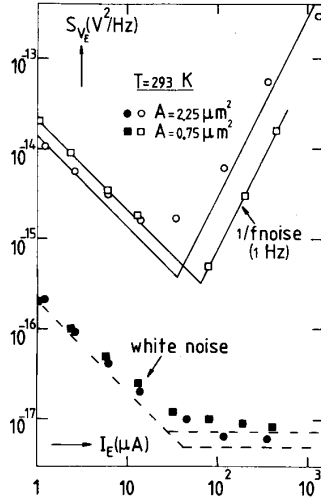


Fig. 3. White noise and $1/f$ noise versus I_E of two polysilicon-emitter transistors in the common-collector configuration [6]. The current-dependency lines are described by (40) and (41). The calculated values of $4kT(r_e + r_b)$ are given by dashed lines, the upper line belongs to $A = 0.75 \mu\text{m}^2$ and the lower line the other one. (See [6]).

it can be concluded that the $1/f$ noise in S_{I_b} is dominant. Consequently, for the $1/f$ noise (6) and (40) reduce to

$$S_{V_E}^{1/f} = [r_\pi / (\beta + 1)]^2 S_{I_b}^{1/f}. \quad (42)$$

Since $S_{V_E}^{1/f} \sim I_E^{-1}$ and $r_\pi \sim I_B^{-1}$, the current noise $S_{I_b}^{1/f}$ is proportional to I_B , which is predicted by the mobility fluctuation model (23).

Kleinpenning and Holden [6], [17] investigated about 15 transistors and they found ($f = 1 \text{ Hz}$ and $I_B = 10^{-8} \text{ A}$) the current noise $S_{I_b}^{1/f}$ to be in the range of $3 \times 10^{-24} - 3 \times 10^{-23} \text{ A}^2/\text{Hz}$. So the quantity $f S_{I_b}^{1/f} / I_B$ is in the range of $3 \times 10^{-16} - 3 \times 10^{-15} \text{ A}$. Using (23), α values are found to be in the range of $2 \times 10^{-6} - 2 \times 10^{-5}$. At high currents ($I_E > 100 \mu\text{A}$) it was found $S_{V_E}^{1/f} \sim I_E^2$, which can be ascribed to resistance fluctuations in either r_e or in r_b . Using (33) and (34) α values in the range of $10^{-6} - 10^{-3}$ were reported.

Kleinpenning and Holden have also measured S_{V_C} in the CE-configuration with $R_E = 0$ and $R_B \gg r_\pi + r_b + (\beta + 1)r_e$, thus $Z \approx R_B$, and at emitter currents in the range of $1 \mu\text{A} - 1 \text{ mA}$. In this case (7) reduces to

$$S_{V_C} / R_C^2 = \beta^2 S_{I_b} + S_{I_c} + 4kT / R_C \approx \beta^2 S_{I_b}. \quad (43)$$

The white noise observed agrees with $\beta^2 \cdot 2qI_B$ and the $1/f$ noise with $\beta^2 \cdot S_{I_b}^{1/f}$, taking the result from the CC-configuration measurements for $S_{I_b}^{1/f}$. In other words, both the magnitude and the current dependence of S_{I_b} , obtained in the CC-configuration at $I_E \leq 10 \mu\text{A}$, correspond with the results obtained in the CE-configuration in the current range of $1 \mu\text{A} < I_E < 1 \text{ mA}$.

In some transistors Kleinpenning and Holden [17] observed RTS noise or burst noise. In the CC-configuration the RTS noise can be removed by adjusting $R_B = r_\pi / \beta - r_b$ (see Fig. 4(a)). Consequently, the RTS noise stems from fluctuations

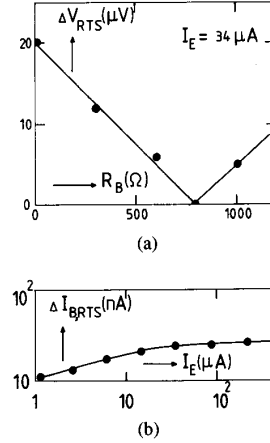


Fig. 4. (a) RTS voltage step across R_E versus external base resistance R_B in an n - p - n polysilicon emitter BJT [17]. (b) RTS base current step $\Delta I_{B,RTS}$ versus emitter current I_E of the same BJT as in Fig. 4(a) [17].

in the base current. The magnitude of the RTS step in the base current $\Delta I_{B,RTS}$ was found to be almost independent of I_E (see Fig. 4(b)). With respect to the RTS current step of about 20 nA, it is striking to notice the following. The base current is equal to $I_B = qP_{exc} / \tau$, with P_{exc} the excess number of holes in the emitter and $\tau = W_E^2 / 2D_p$ the transit diffusion time in the emitter. A step $\Delta P_{exc} = 1$ leads to a step $\Delta I_B = q / \tau \approx 10 \text{ nA}$. So, low-frequency fluctuations in the number of excess carriers by trapping in the emitter could be the origin of RTS noise.

Pong-Fei Lu [18] studied the LF noise in self-aligned n - p - n bipolar transistors with a polysilicon emitter. The transistors were biased in the CE-configuration. Generally, at low frequencies he observed $1/f$ noise and sometimes burst (RTS) noise and at higher frequencies the usual shot noise. The magnitude of the RTS noise was found to be unchanged when the base current was varied, in line with to the results of Kleinpenning and Holden (see Fig. 4). From the RTS noise spectra in [18] the RTS step $\Delta I_{B,RTS}$ can be estimated using the relation

$$S_{I_B}(f) = \frac{4\Delta I_{B,RTS}^2 \tau_p^2 / \tau_s}{1 + (2\pi f \tau_p)^2} = \frac{S_{I_B}(0)}{1 + (2\pi f \tau_p)^2} \quad (44)$$

with $\tau_p^{-1} = \tau_l^{-1} + \tau_h^{-1}$ and $\tau_s = \tau_l + \tau_h$, where τ_h and τ_l is the average time in the high and low noise state, respectively. From (44) it follows:

$$\Delta I_{B,RTS} = [\tau_s S_{I_B}(0) / 4\tau_p^2]^{1/2} \geq [S_{I_B}(0) / \tau_p]^{1/2}. \quad (45)$$

Here we have used the inequality $\tau_s / \tau_p \geq 4$. Using (45) the current steps for the spectra in Figs. 4 and 5 in [18] are found to be at least 15 nA, 7 nA, and 1 nA, respectively. These steps are of the same magnitude as the RTS steps in [17].

In transistors without burst noise Pong-Fei Lu observed only $1/f$ noise and shot noise. In device A with I_B in the range of $0.5 - 10 \mu\text{A}$ (i.e., I_E in the range of $50 \mu\text{A} - 1 \text{ mA}$), he found $S_{I_b}^{1/f}$ to be proportional to I_B^2 , instead of I_B as expected for mobility fluctuations. In this current range Kleinpenning and Holden [17] observed a changeover in the

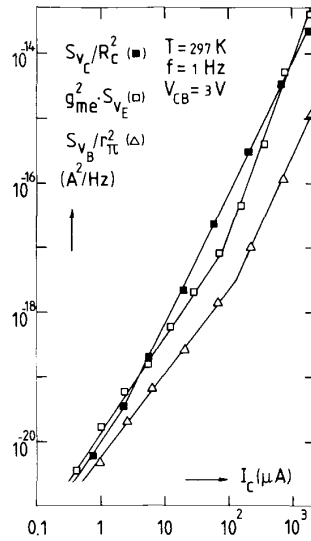


Fig. 5. Typical plots of the $1/f$ noise density versus collector current I_C of a GaAs HBT [7]. The magnitude of the $1/f$ noise is given in terms of S_{V_C} , S_{V_E} , and S_{V_B} (for definitions see (6)–(8)). (See [7]).

current dependence of the noise due to series resistance effects. Note that Pawlikiewicz *et al.* [15] found S_{I_B} to be proportional to I_B at low currents and proportional to I_B^2 at higher currents (see Fig. 2). Such behavior can be ascribed to series resistance effects (see Section V-A). From the spectra presented in [18] the magnitude of the $1/f$ noise in terms of $fS_{I_B}^{1/f}/I_B$ was found to be in the range of $5 \times 10^{-16} - 3 \times 10^{-15}$ A, for I_B values in the range of 1–5 μ A. These values are comparable with the values observed by Kleinpenning and Holden; $3 \times 10^{-16} - 3 \times 10^{-15}$ A. For a conventional diffused transistor with Al metal contact Pong-Fei Lu found $S_{I_B} = 2 \times 10^{-17}$ A at $I_B = 1 \mu$ A, which is comparable with the results presented in Fig. 2(a).

Siabi-Shahrivar *et al.* [21] investigated the $1/f$ noise in polysilicon emitter BJT's. They claim that the introduction of the polysilicon contact significantly increases the $1/f$ noise in transistors. This conclusion is uncertain. Expressing the magnitude of the $1/f$ noise in the base current in terms of $fS_{I_B}^{1/f}/I_B$, conventional transistors have values in the range of $10^{-17} - 10^{-12}$ A [15], [18], [20] and polysilicon emitter transistors in the range of $10^{-17} - 10^{-14}$ A [6], [17], [18], [22]. So the claim that polysilicon emitter transistors have higher $1/f$ noise is questionable.

It has been shown that the $1/f$ noise in polysilicon emitter BJT's is strongly related to the type of surface treatment prior to polysilicon deposition [21]. It is not possible to discuss the results in [21] in more detail on the basis of (6)–(8), (11), and (12), since the authors did not give information about the circuit used for their noise measurements. However, some remarks can be made.

Figs. 2 and 4 in [21] present the input referred noise E_n ($nV/\sqrt{\text{Hz}}$) versus emitter area A_e at fixed emitter current $I_E = 0.2$ mA for four different types of BJT's. After removing the errors in these figures, i.e., the noise data of the BJT's with

area $18 \times 6 \mu\text{m}^2$ are placed at incorrect positions, we find the input noise E_n to be inversely proportional to the root of the emitter area A_e . Such an area dependence can be expected, if the noise is due to $1/f$ noise in the base series resistance. According to (7) and (33) we then have

$$E_n^2 = S_{V_r} = \alpha r_b^2 I_B^2 / f N_b^* \sim 1/A_e. \quad (46)$$

Note that in Fig. 3 the $1/f$ noise above $I_E = 0.1$ mA is also determined by series resistances, most likely by r_b [6].

In order to investigate the effect of emitter junction scaling on the noise performance, Siabi-Shahrivar *et al.* have studied three different BJT's with varying junction depths. They found the referred noise E_n at constant $I_E = 0.2$ mA to be adversely affected by scaling down the vertical dimensions. However, they did not give information about the depth dependence of the base current I_B . Normally, I_B increases with decreasing depth, so according to (46) E_n should increase with decreasing junction depth.

Finally, we discuss the results of Mounib *et al.* [22]. For different technological treatments given to the silicon surface prior to polysilicon deposition, they studied the base and collector $1/f$ current spectral densities as a function of base and collector current, respectively. For the interpretation of their results we have to use (12)–(14). Results are reported of S_{I_B} versus I_B of the same device structure ($A_e = 1000 \times 10 \mu\text{m}^2$) with two different technological treatments: type 1 with an important interfacial oxide and type 2 with no oxide layer. In view of the size of A_e the emitter series resistance r_e can be neglected [5]. Assuming $r_b \ll r_\pi$, formula (13) reduces to

$$S_{I^{1/f}} = S_{I_b^{1/f}} + r_\pi^{-2} S_{V_r^{1/f}} = aI_B + bI_B^4. \quad (47)$$

For $I_B < 1 \mu$ A they found $S_{I_B}^{1/f} \sim I_B$. Just like in [6], [17] they found that for $I_B > 10 \mu$ A the $1/f$ noise increases strongly with increasing I_B . Comparing the experimental data with (47), the conclusion is reasonable that at low base currents the $1/f$ noise is in the base current and at high currents in the base series resistances. For type 1 they found $fS_{I_B}^{1/f}/I_B \approx 10^{-16}$ A, and for type 2 $\approx 3 \times 10^{-17}$ A. These values are lower than the values reported in [6], [17], [18]. Just as is reported in [21] the $1/f$ noise in BJT's with an oxide layer is higher than without an oxide layer. This can be explained as follows. Since the diffusion-recombination length L_p in the emitter is of the order of $0.1 \mu\text{m}$, we have $L_p \leq W_E$ so that (21) prevails rather than (23). If the lifetime of minority carriers in the emitter is influenced by the chemical treatments, then the $1/f$ noise is too. Possibly, this may explain the differences in $1/f$ noise densities.

For the same transistors Mounib *et al.* [22] measured the collector current $1/f$ noise. For $I_C < 10 \mu$ A both types 1, 2 have $S_{I_C} \sim I_C$ and the same noise magnitude. They found $fS_{I_C}^{1/f}/I_C = 10^{-17}$ A, which is of the same magnitude as in Fig. 2(a). Above $I_C = 30 \mu$ A the $1/f$ noise increases strongly with increasing I_C . Now according to (12) we have

$$S_{I_C^{1/f}} = (\beta r_b / r_\pi)^2 S_{I_b^{1/f}} + S_{I_c^{1/f}} + (\beta / r_\pi)^2 S_{V_r^{1/f}}. \quad (48)$$

The conclusion is reasonable that at low currents the noise is determined by $S_{I_C}^{1/f}$ and can be interpreted in terms of

mobility fluctuations of minority carriers in the base (30). Here, it should be noted that according to (30) the magnitude of $S_{I_C}^{1/f}$ has to be independent of the emitter technology, which is in agreement with the experimental findings by Mounib *et al.* At high currents the $1/f$ noise is due to either $S_{I_B}^{1/f}$ or to $S_{V_{rb}}^{1/f}$. Both for the transistors with $A_e = 1000 \times 10 \mu\text{m}^2$ and for small geometry transistors ($A_e = 2 \times 1 \mu\text{m}^2$ or $5 \times 2 \mu\text{m}^2$) there is influence of the chemical treatments only on the $1/f$ noise in the base current. They found that defects created at the Si-SiO₂ interface at the periphery of the emitter-base junction have a fundamental impact on the noise in the base current and a very low influence on the fluctuations in the collector current. This is not surprising, as such defects decrease the minority carrier lifetime and thus increase the noise (see (21)).

C. Heterojunction Bipolar Transistors (HBT's)

HBT's play an important role as sources at microwave and millimeter-wave frequencies. Upconversion of the $1/f$ noise results in phase noise in oscillators. Knowledge of the sources of LF noise provides information on how to design low-noise devices. Here, we shall present an overview of the literature on LF noise in GaAs HBT's during the last five years.

Kleinpenning and Holden [7] investigated the $1/f$ noise in n-p-n GaAs/AlGaAs HBT's with an emitter area of $2.5 \times 5 \mu\text{m}^2$. The internal series resistances of the emitter, base, and collector are roughly 40 Ω , 80 Ω , and 30 Ω , respectively. The ideality factor for the collector current I_C was found to be 1.3 and for I_B it was 2.0. The current gain β was found to be proportional to $I_C^{0.4}$, they found $\beta \approx 1$ at $I_C = 1 \mu\text{A}$ and $\beta \approx 20$ at $I_C = 1 \text{mA}$. Noise measurements were carried out in both the CC-configuration with $R_E \gg r_\pi$ and $R_B = R_C = 0$ and the CE-configuration with $R_B \gg r_\pi$, $R_E = 0$ and $R_C = 1 \text{k}\Omega$. In all devices $1/f$ noise was observed, mostly over at least three decades of frequency, generally in the range of 1 Hz–10 kHz. In Fig. 5 typical $1/f$ noise density plots are presented of S_{V_B} , S_{V_C} , and S_{V_E} versus collector current I_C . The $1/f$ noise density S_{V_E} is measured in the CC-configuration, the other two densities in the CE-configuration. For this situation (6)–(8) reduces to

$$g_{me}^2 S_{V_E} = (1 - \beta r_b/r_\pi)^2 S_{I_b} + S_{I_c} + g_{me}^2 S_{V_r} \quad (49)$$

$$S_{V_C}/R_C^2 = \beta^2 S_{I_b} + S_{I_c} + (\beta/R_B)^2 S_{V_r} \quad (50)$$

$$S_{V_B}/r_\pi^2 = (1 + \beta r_e/r_\pi)^2 S_{I_b} + (r_e/r_\pi)^2 S_{I_c} + S_{V_r}/r_\pi^2 \quad (51)$$

Here, $g_{me} = (\beta + 1)/r_\pi$ is the emitter conductance of the intrinsic transistor, thus $g_{me} = dI_E/dV_{be}$. Interpretation of the experimental data of Fig. 5 in terms of the formulas given by (49)–(51) leads to the following results:

- At $I_C = 1 \mu\text{A}$, where $\beta \approx 1$, we obtain $S_{I_C} \approx S_{I_b} \approx 5 \times 10^{-21} \text{A}^2/\text{Hz}$.
- At $I_C = 30 \mu\text{A}$, where $\beta \approx 4$, we obtain $S_{I_C} \approx 1.6 \times 10^{-18} \text{A}^2/\text{Hz}$ and $S_{I_b} \approx 4 \times 10^{-19} \text{A}^2/\text{Hz}$.
- Above $I_C = 100 \mu\text{A}$ there is a change over in the current-dependences of both S_{V_E} and S_{V_B} . The changeover with respect to S_{V_B} can be ascribed to the fact that the term $\beta r_e/r_\pi$ becomes dominant, i.e., larger

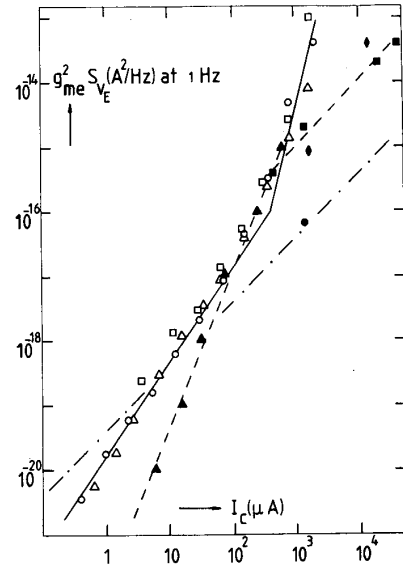


Fig. 6. $1/f$ Noise density in terms of $g_{me}^2 S_{V_E}$ versus collector current I_C of three HBT's: \circ , \triangle , \square [7], and for comparison, S_{I_C} versus I_C as measured by Tutt *et al.* [23] (\blacksquare) and [24] (\blacklozenge), by Jue *et al.* [25] (\blacktriangle), and by Hayama *et al.* [26] (\bullet). The dashed/dotted line is drawn according to (30) with $\alpha = 10^{-4}$. (See [7]).

than one. The change in the slope of S_{V_E} versus I_C can be ascribed to the term $g_{me}^2 S_{V_r}$. In view of the scatter in the experimental data, it is difficult to determine exactly the current dependence of S_{V_r} . Therefore it is impossible to determine which contribution dominates S_{I_b} or S_{r_e} .

In view of these results Kleinpenning and Holden concluded that at lower currents, i.e., $1 \mu\text{A} < I_C < 100 \mu\text{A}$ and $I_B < 25 \mu\text{A}$, the $1/f$ noise density $g_{me}^2 S_{V_E}$ is practically determined by S_{I_C} and the density S_{V_B}/r_π^2 by S_{I_b} . They found $S_{I_C} \sim I_C^{1.4}$ and $S_{I_b} \sim I_B^{1.5}$.

In Fig. 6 the results of $g_{me}^2 S_{V_E}$ versus I_C of three HBT's are plotted together with other data in the literature of S_{I_C} versus I_C . In Fig. 7 S_{V_B}/r_π^2 versus I_B of the same three HBT's as in Fig. 6 are shown, and for comparison other data of S_{I_b} versus I_B . Comparison of the data both in Fig. 6 and in Fig. 7 shows a corresponding magnitude of the $1/f$ noise at lower currents. At higher currents there are differences, which can be ascribed to parasitic series resistances.

Tutt *et al.* [23] also studied the LF noise in GaAs/AlGaAs HBT's. They measured both $S_{I_C}(f)$ and $S_{I_B}(f)$. For frequencies below about 1 kHz, $1/f$ noise was observed. Above 1 kHz they often observed a Lorentz (GR) spectrum. Just like Kleinpenning and Holden, they found the $1/f$ noise in S_{I_C} to be larger than in S_{I_B} . Some of their results are plotted in Figs. 6 and 7. Comparing the $1/f$ noise results of Tutt *et al.* with the results of [7], it can be concluded that the $1/f$ noise densities S_{I_b} and S_{I_C} in [7] and [23] are of the same magnitude. The GR noise is ascribed to traps with an activation energy of 0.16 eV. In view of the experimental data of Tutt *et al.*, we suppose that the GR noise is due to fluctuations in the part of the base resistance below the emitter r_{b2} . The argumentation is

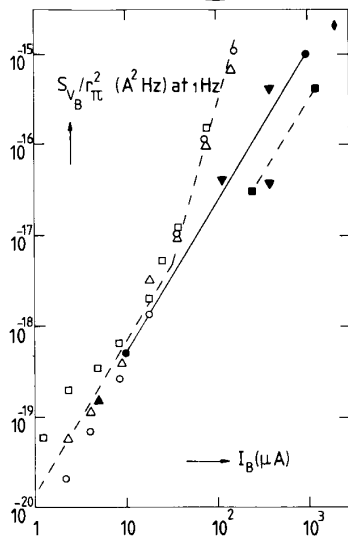


Fig. 7. $1/f$ Noise density in terms of S_{V_B}/r_{TE}^2 versus base current I_B of the same HBT's as in Fig. 6: ○, △, □ [7], and for comparison, S_{I_B} versus I_B as measured by Tutt *et al.* [23] (■) and [24] (◆), by Jue *et al.* [25] (▲), by Costa and Harris [14] (●), and by Plana *et al.* [28] (▼). (See [7]).

as follows. Considering the results in Figs. 2 and 3 in [23] we observe the following at low base currents ($I_B \leq 0.25$ mA).

- 1) $S_{I_C}^{gr}(I_B = 0.25 \text{ mA})/S_{I_C}^{gr}(I_B = 0.125 \text{ mA}) \approx 10$. If the noise is due to fluctuations in r_{b2} , then according to (12) and (14) this ratio can be derived from the relation $S_{I_C} = (\beta/Z_0)^2 I_B^2 S_{r_{b2}}$. If $Z_0 \approx r_\pi$ the ratio is found to be 36, and if $Z_0 \approx (\beta + 1)r_e$ the ratio is 4.5. Here we have used $\beta(0.25 \text{ mA}) \approx 8.3$ and $\beta(0.125 \text{ mA}) \approx 5.5$.
- 2) $S_{I_C}^{gr}(I_B = 0.25 \text{ mA})/S_{I_B}^{gr}(I_B = 0.25 \text{ mA}) \approx 100$. According to (12) and (13) this ratio has to be $\beta^2 \approx 70$.
- 3) At higher base currents (> 1 mA) the GR noise disappears. According to Tutt *et al.* the HBT then operates in the current crowding regime, which implies that the current through r_{b2} becomes reduced and thus the GR noise from r_{b2} does too.

In a more recent paper Tutt *et al.* [24] studied the LF noise in HBT's in more detail. The results obtained are rather similar to the results in [23]. However, they made an important remark in [24]: "An analysis of device noise characteristics based on terminal noise properties may be highly misleading. Knowledge of the internal sources is important for complete understanding of the noise sources." In Figs. 6 and 7 we have plotted some experimental values of the internal $1/f$ noise sources S_{I_C} and S_{I_B} .

Jue *et al.* [25] investigated the LF noise in GaAs/AlGaAs HBT's. Generally, the LF noise under low-bias conditions was found to be $1/f$ in nature. In Fig. 4 of [25] they have plotted S_{I_C} versus I_B , where S_{I_C} is measured in a circuit with $R_B = R_E = R_C = 0$. Using their I - V plots and formula (12), the experimental results of Jue *et al.* lead to the results plotted in Fig. 6. From their results given in Fig. 6 of [25] we obtain S_{I_B} (1 Hz, $I_B = 5 \mu\text{A}$) $\approx 1.5 \times 10^{-19}$ A²/Hz, which is plotted in Fig. 7.

Hayama *et al.* [26] fabricated a low-phase noise Ku -band oscillator using an HBT with a measured collector current $1/f$ noise of about 6×10^{-17} A²/Hz, at $f = 1$ Hz and $I_C = 1.2$ mA. This experimental result is plotted in Fig. 6.

Costa and Harris [14] have investigated the LF noise of n-p-n AlGaAs/GaAs HBT's as a function of bias current, device geometry, and extrinsic-base-surface condition. Their noise measurements were carried out in the CE configuration, where the noise power at the collector was measured. Using a simple low-frequency circuit model for the transistor and the gain of the system, the noise at the output was referred back to the input. According to [27] an equivalent input base noise current $S_{I_{in}}$ was defined. Since Costa and Harris did not present a formula which relates $S_{I_{in}}$ to the LF noise sources in the transistor, it will be done here. According to [27] the input noise voltage $S_{V_{in}}$ for a short-circuited output ($R_C = 0$) is defined by

$$S_{V_{in}} = [(r_b + R_B + r_\pi)/\beta]^2 S_{I_C}. \quad (52)$$

The $S_{I_{in}}$ parameter is obtained from $S_{V_{in}}$ by assuming that R_B has a very large value, specifically $R_B \gg r_\pi$,

$$S_{I_{in}} = S_{V_{in}}/R_B^2 \approx S_{I_C}/\beta^2. \quad (53)$$

According to (7) and (12) for $R_B \gg r_b + r_\pi + (\beta + 1)r_e$ we obtain

$$S_{I_C} = \beta^2 S_{I_b} + S_{I_c} + (\beta/R_B)^2 S_{V_r} \quad (54)$$

and thus

$$S_{I_{in}} = S_{I_b} + \beta^{-2} S_{I_c} + S_{V_r}/R_B^2 \approx S_{I_b}. \quad (55)$$

Consequently, $S_{I_{in}}$ approaches S_{I_b} for $R_B \gg r_b + r_\pi + (\beta + 1)r_e$.

In the discussion of the results of Costa and Harris, it will be assumed that they have used $R_B \gg r_b + r_\pi + (\beta + 1)r_e$, so that it holds that $S_{I_{in}} = S_{I_b}$.

The observed current noise spectra S_{I_b} have three components: $1/f$ noise, burst noise, and white noise. A number of spectra can be found in [14]. These spectra were obtained from HBT's with different emitter areas A_e and from HBT's with and without AlGaAs surface passivation ledge. We have replotted their data in Fig. 8, where $S_{I_b}^{1/f}$ is plotted versus I_B . Here it should be noted that for the spectra given in [14], the corresponding value of I_B was not always given. However, for a number of spectra it was possible to find out the lacking I_B , for example, with the help of the magnitude of the white noise $2qI_B$, or with the help of the values of I_C together with the current gain β . From Fig. 8 we find that $S_{I_b} = CI_B^{1.6}$, with C almost independent of the emitter area, the presence of a passivation ledge, and the Al mole fraction. For comparison the relation $S_{I_b} = C I_B^{1.6}$ is also plotted in Fig. 7. Concerning the observed burst noise, Costa and Harris argued that this noise is associated with traps in the neutral emitter or in the emitter-base space-charge region.

Finally, in Fig. 7 we have plotted some experimental data of $S_{I_b}^{1/f}$ obtained by Plana *et al.* [28] on nonpassivated self-aligned GaInP/GaAs HBT's.

In Section VI we shall discuss the experimental results obtained from BJT's and HBT's.

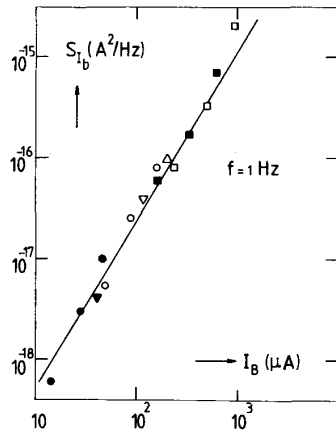


Fig. 8. $1/f$ Noise density S_{I_b} , versus base current I_B of HBT's measured by Costa and Harris [14]. HBT's without ledge and Al mole fraction $x = 0.3$: (o) $A_e = 40 \mu\text{m}^2$; (\square) $A_e = 400 \mu\text{m}^2$; (Δ) $A_e = 144 \mu\text{m}^2$. HBT's with ledge and $x = 0.38$: (\bullet) $A_e = 40 \mu\text{m}^2$; (\blacksquare) $A_e = 400 \mu\text{m}^2$. HBT's with $A_e = 40 \mu\text{m}^2$ and $x = 0.2$: (∇) without ledge; (\blacktriangledown) with ledge.

VI. DISCUSSION AND CONCLUSION

In conventional high-quality silicon bipolar transistors, the emitter series resistance can be neglected, the base series resistance is low, the collector current has an ideality factor $n = 1$, and the base current is due to carriers injected from the base into the emitter, which results in an ideality factor $n = 1$. In such transistors the LF noise is determined by $1/f$ noise in the base current. Normally, one finds that both the base current $1/f$ noise and, if present, the collector current $1/f$ noise are proportional to the base current and collector current, respectively. Such a linear relationship is predicted by the mobility fluctuation model. At high bias currents deviations from the linear relationship between current and its noise are observed. These deviations can be ascribed to the parasitic series resistances.

Recent developments have led to a significant downscaling of bipolar transistors. In such down-scaled transistors the emitter area, the base width, and the emitter width are relative small. Small dimensions lead to relative large values for the base and emitter series resistances. Large series resistances influence the I-V characteristics and the LF noise, especially at higher bias currents. Consequently, it is important to take into account the influence of the series resistances while calculating the LF noise in transistors. The LF noise formulas (6)–(9) and (11)–(13) include the influence of series resistances.

During the last five years a number of papers have been published on LF noise in modern transistors: polysilicon-emitter n-p-n silicon BJT's and n-p-n GaAs/AlGaAs HBT's. Comparison of the experimental noise data with the theoretical expressions (6)–(9) and (11)–(13) led to the following conclusions. In polysilicon-emitter BJT's the white noise is determined by shot noise in the base and collector current, and by Nyquist noise in the emitter and base series resistances. At low bias currents the $1/f$ noise in the base current is dominant. It is found to be proportional to the base current as predicted by the mobility fluctuation model. At higher bias currents

the influence of the series resistances on the noise becomes noticeable. Besides white noise these series resistances have $1/f$ noise. In some BJT's burst (RTS) noise is observed, which can be ascribed to traps in the emitter.

In GaAs/AlGaAs HBT's the white noise is also determined by shot noise in the base and collector currents, and by Nyquist noise in the base and emitter series resistances. Both the base and the collector currents have $1/f$ noise. The $1/f$ noise in the base current can be described by the empirical relation found from the results in Figs. 7 and 8.

$$S_{I_b} = C_B I_B^k / f \text{ [A}^2/\text{Hz]} \\ \text{with } C_B \approx 10^{-10} \text{ [A}^{2-k}\text{]} \text{ and } k \approx 1.6.$$

The value of C_B is almost independent of the emitter area, surface passivation ledge, the technology procedure, and the ideality factor typically in the range of 1.2–2. Here, it should be noted that the current dependence of the base current $1/f$ noise density S_{I_b} deviates from the dependence predicted by both the mobility fluctuation model (19), (21), (23) and the recombination velocity fluctuation model (28). The magnitude of the $1/f$ noise in terms of $f S_{I_b} / I_B$ is in the range of 10^{-14} to 10^{-12} A for $1 \mu\text{A} < I_B < 1 \text{ mA}$, which is some decades higher than in polysilicon emitter BJT's.

The $1/f$ noise in the collector current observed by Kleinpenning and Holden [7], and by Tutt *et al.* [23], [24] can be described by the empirical relation (see Fig. (6))

$$S_{I_c} = C_C I_C^k / f \text{ [A}^2/\text{Hz]} \\ \text{with } C_C \approx 10^{-12} \text{ [A}^{2-k}\text{]} \text{ and } k \approx 1.3.$$

Here, it also has to be noted that the current dependence of S_{I_c} deviates from the one predicted by mobility fluctuations. The ideality factor of the HBT's in [7] is $n = 1.3$, which implies that the collector current noise is proportional to $\exp(qV_{be}/kT)$. According to (30) such a proportionality is predicted by the mobility fluctuation model for $1/f$ noise in collector currents with ideality factor $n = 1$. For comparison we have drawn the relation between S_{I_c} and I_C in Fig. 6, using (30) with $D = 50 \text{ cm}^2/\text{s}$, $s = 10^6 \text{ cm/s}$, $W_B = 1.3 \mu\text{m}$, and $\alpha = 10^{-4}$. Here, we have to note that α values of the order of 10^{-4} in GaAs are often reported in literature [29]. Now it can be concluded that the experimental values of S_{I_c} are of the same order of magnitude as the values predicted by the mobility fluctuation model.

In what has been stated above it is clear that there is much to be desired with respect to the physical interpretation of the $1/f$ noise both in the base and in the collector current of HBT's. The current dependence of both S_{I_c} and S_{I_b} is not well-understood. The question whether the $1/f$ noise stems from mobility fluctuations or from trapping noise cannot be solved with the help of the current dependences of both S_{I_c} and S_{I_b} .

In some HBT's burst (RTS) noise is observed. This type of noise may be associated with traps in or close to the emitter [14]. At higher bias currents the influence of the series resistance on the LF noise behavior of HBT's becomes noticeable.

REFERENCES

- [1] B. Hughes, N. G. Fernandez, and J. M. Gladstone, "GaAs FET's with a flicker-noise corner below 1 MHz," *IEEE Trans. Electron Devices*, vol. ED-34, pp. 733-741, 1987.
- [2] "New HBT cuts $1/f$ noise significantly," NEC NEWS, NEC Corp., Tokyo, Japan, no. 126, Apr. 1991, p. 3.
- [3] A. van der Ziel, "Unified presentation of $1/f$ noise in electronic devices: Fundamental $1/f$ noise sources," *Proc. IEEE*, vol. 76, pp. 233-258, 1988.
- [4] T. G. M. Kleinpenning, " $1/f$ noise in electron devices," in *Noise in Physical Systems*, A. Ambrozy, Ed. Budapest, Hungary: Akadémiai Kiadó, 1990, pp. 443-454.
- [5] H. C. de Graaff and F. M. Klaassen, *Compact Transistor Modelling for Circuit Design*. Vienna: Springer-Verlag, 1990.
- [6] T. G. M. Kleinpenning, "Location of low-frequency noise sources in submicrometer bipolar transistors," *IEEE Trans. Electron Devices*, vol. 39, pp. 1501-1506, 1992.
- [7] T. G. M. Kleinpenning and A. J. Holden, " $1/f$ noise in n - p - n GaAs/AlGaAs heterojunction bipolar transistors: impact of intrinsic transistor and parasitic series resistances," *IEEE Trans. Electron Devices*, vol. 40, pp. 1148-1153, 1993.
- [8] T. G. M. Kleinpenning, "On the analysis of low-frequency noise in bipolar transistors," in *Noise in Physical Systems and $1/f$ Fluctuations*, P. H. Handel and A. L. Chung, Eds., *AIP Conf. Proc.* 285, New York: American Institute of Physics, 1993, pp. 187-193.
- [9] T. G. M. Kleinpenning, " $1/f$ noise in p - n diodes," *Physica*, vol. 98B, pp. 289-299, 1980.
- [10] T. G. M. Kleinpenning, "On $1/f$ noise in recombination currents in p - n junctions," *Physica*, vol. 132B, pp. 364-366, 1985.
- [11] T. G. M. Kleinpenning, "Charge-control model applied to $1/f$ noise in long p^+ - n diodes," *Physica*, vol. 145B, pp. 190-194, 1987.
- [12] T. G. M. Kleinpenning, " $1/f$ mobility fluctuations in p - i - n and p - v - n diodes," *Physica*, vol. 154B, pp. 27-34, 1988.
- [13] F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, "Experimental studies on $1/f$ noise," *Rep. Progr. Phys.*, vol. 44, pp. 479-532, 1981.
- [14] D. Costa and J. S. Harris, "Low-frequency noise properties of N - p - n AlGaAs/GaAs heterojunction bipolar transistors," *IEEE Trans. Electron Devices*, vol. 39, pp. 2383-2394, 1992.
- [15] A. H. Pawlikiewicz, A. van der Ziel, G. S. Kousik, and C. M. van Vliet, "Fundamental $1/f$ noise in silicon bipolar transistors," *Solid-State Electron.*, vol. 31, pp. 831-834, 1988.
- [16] X. C. Zhu, A. H. Pawlikiewicz, and A. van der Ziel, " $1/f$ noise in n^+ - p - n microwave transistors," *Solid-State Electron.*, vol. 28, pp. 473-477, 1985.
- [17] T. G. M. Kleinpenning and A. J. Holden, "Low-frequency excess noise and RTS noise in submicron bipolar transistors," in *Noise in Physical Systems and $1/f$ fluctuations*, T. Musha, S. Sato and M. Yamamoto, Eds. Kyoto, Japan: Ohmsha, Ltd., 1991, pp. 435-438.
- [18] Pong-Fei Lu, "Low-frequency noise in self-aligned bipolar transistors," *J. App. Phys.*, vol. 62, pp. 1335-1339, 1987.
- [19] T. G. M. Kleinpenning, "On $1/f$ noise and random telegraph noise in very small electron devices," *Physica*, vol. B 164, pp. 331-334, 1990.
- [20] T. G. M. Kleinpenning, "On $1/f$ mobility fluctuations in bipolar transistors," vol. 138B, pp. 244-252, 1986.
- [21] N. Siabi-Shahrivar, H. A. Kemhadjian, W. Redman-White, P. Ashburn, and J. D. Williams, "The Effects of Scaling and Rapid Thermal Annealing on the $1/f$ Noise of Polysilicon Emitter Bipolar Transistors," *Microelectronic Engineering*, vol. 15, pp. 533-536, 1991.
- [22] A. Mounib, F. Balestra, N. Mathieu, J. Brini, G. Ghibaudo, and A. Chovet, "Low-frequency noise sources in polysilicon emitter bipolar transistors: influence of hot-electron-induced degradation," in *Noise in Physical Systems and $1/f$ Fluctuations*, P. H. Handel and A. L. Chung, Eds. *AIP Conf. Proc.* 285, New York: American Institute of Physics, 1993, pp. 288-291.
- [23] M. N. Tutt, D. Pavlidis, and B. Bayraktaroglu, "An assessment of noise sources and characteristics of AlGaAs/GaAs HBT's," *Inst. Phys. Conf. Ser.*, no. 106, IOP Publ. Ltd., 1990, pp. 701-706.
- [24] M. N. Tutt, D. Pavlidis, D. Pehlke, R. Plana, and J. Graffeuil, " $1/f$ noise in AlGaAs/GaAs HBT's using ultrasensitive characterization techniques for identifying noise mechanisms," *Inst. Phys. Conf. Ser.*, no. 120, IOP Publ. Ltd., 1992, pp. 317-322.
- [25] S. C. Jue, D. J. Day, A. Margittai, and M. Svilans, "Transport and noise in GaAs/AlGaAs HBT's-Part II: Noise and gain at low frequencies," *IEEE Trans. Electron Devices*, vol. 36, pp. 1020-1025, 1989.
- [26] N. Hayama, S. R. Le Sage, M. Madhian, and K. Honjo, "A low-noise K u-band AlGaAs/GaAs HBT oscillator," in *IEEE MTT Int. Microwave Symp. Dig.*, vol. II, 1988, pp. 679-682, IEEE Cat. no. 88CH2489-3.
- [27] C. D. Motchenbacher and F. C. Fitchen, *Low-Noise Electronic Design*. New York: Wiley, 1973, p. 66.
- [28] R. Plana, J. Graffeuil, S. L. Delage, H. Blanck, M. A. di Forte-Poisson, C. Brylinski, and E. Chartier, "Low frequency noise in self-aligned GaInP/GaAs HBT," *Electron. Lett.*, vol. 28, pp. 2354-2356, 1992.
- [29] F. N. Hooge and M. Tacano, "Experimental studies of $1/f$ noise in n -GaAs," *Physica*, vol. B190, pp. 145-149, 1993.



Theo G.M. Kleinpenning was born in Doetinchem, The Netherlands, on May 25, 1943. He received the Ph.D. degree in physics from the State University of Utrecht, The Netherlands, in 1972.

In 1972, he joined the Department of Electrical Engineering of the Eindhoven University of Technology, Eindhoven, The Netherlands, where he is currently a Full Professor of Semiconductor Devices. His current research concerns the electrical noise in semiconductors and semiconductor devices. He has published over 60 scientific papers on noise.