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THE INFLUENCE OF NON-IDEAL BASE CURRENT ON 1/F NOISE BEHAVIOUR OF BIPOLAR TRANSISTORS

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Abstract

The improved performance of a new description of the low-frequency noise behaviour of bipolar transistors, taking into account the magnitude of the non-ideal base current component, is demonstrated. This new model allows geometrical scaling of noise parameters. Also the effect of current gain degradation due to aging on transistor noise behaviour can be described with the new model.

Introduction

One of the important aspects of compact bipolar modelling is the description of transistor noise behaviour not only for the white noise found at intermediate frequencies, but also for the noise in the low frequency ranges. This is especially the case for modern BiCMOS processes, where bipolar transistors are often applied for their low noise levels compared to MOS. At low frequencies the 1/f noise contributions become dominant in the transistor noise spectrum and may even cause a degraded high frequency performance of integrated circuits.

A commonly used low frequency noise model [1] associates the major part of the noise with the base current and describes the noise behaviour in forward mode as

$$S_{Ib} = 2q(I_{b1} + I_{b2}) + K_f \frac{(I_{b1} + I_{b2})^{A_f}}{f}, \quad (1)$$

with K_f,A_f as parameters and I_{b1}, I_{b2} as the ideal and non-ideal base current components respectively. This base current noise is amplified by the transistor and becomes very significant in the collector current. The non-ideal base current component can be described by

$$I_{b2} = IBF \exp\left(\frac{qV_{b2e1}}{mkT}\right), \quad (2)$$

with *IBF* and *m* as parameters, and V_{b2e1} the internal base-emitter voltage.

The description of the noise behaviour as in equation 1 implies that the different 1/f-noise contributions in the base current are taken to be fully correlated. Our experiments have shown, however, that it is not possible to describe the noise behaviour for a large number of transistors – having identical parameter sets except for the parameter *IBF* – with this model: for each transistor a different set of noise parameters is necessary. This is illustrated in figures 1 and 2. In figure 1 the difference in h_{FE} is shown for the same device before (drawn line) and after (dotted line) stressing. The degradation of h_{FE} is caused by an increase of the non-ideal base current. The noise measurements shown in figure 2 were made at bias conditions where $I_{b1} \gg I_{b2}$ (moderate to high currents). This large difference in noise behaviour cannot be described using only one set of noise parameters for both cases (drawn line in figure 2) because according to equation 1 the influence of I_{b2} is here negligible compared to that of I_{b1}.

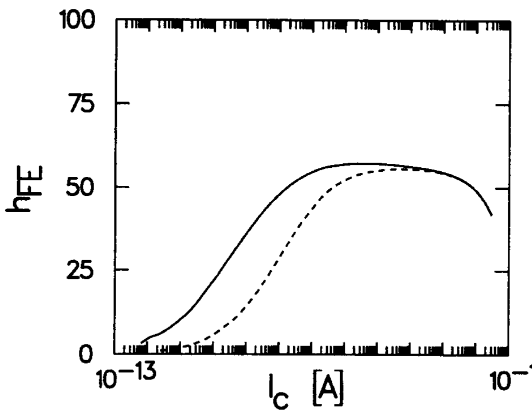

Figure 1: *$H_{fe}(I_c)$ curves for typical transistor before (—) and after (--) stress. Emitter area A_{em} = 2.5 × 24μm^2.*

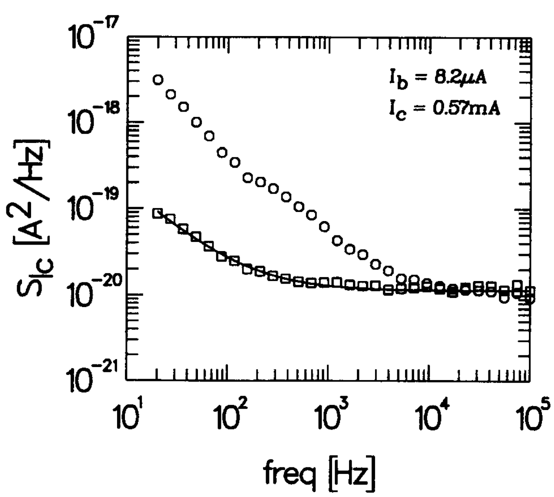

Figure 2: *Spectral noise current density measured at the collector for transistor of figure 1. (Experimental data: □ before stress, ○ after stress, — eq. 1 using identical noise parameters for both cases.)*

Experiments

To investigate the influence of the non-ideal base current on transistor noise behaviour, measurements have been done on a number of transistors fabricated in a LOCOS isolated high-frequency process featuring an emitter junction depth $x_{je} = 0.35\mu m$, a collector junction depth $x_{jc} = 0.63\mu m$ and walled emitters at two edges. The transistors have a cut-off frequency $f_T \approx 7GHz$. The device structure is shown in figure 3. Four device geometries with emitter dimensions $(A) 2.5 \times 8.0\mu m^2$, $(B) 2.5 \times 24.0\mu m^2$, $(C) 12.0 \times 24.0\mu m^2$ and $(D) 12.0 \times 90.0\mu m^2$ on mask were considered.

In order to vary the non-ideal base current component the emitter-base junction was stressed using a reverse bias. After each stress case a full set of measurements, including noise measurements were done, and the transistors were fully characterized. From characterization only changes in *IBF* were found. Noise measurements were performed under base current drive conditions, using a large external series resistance at the base side of the transistor. Noise was measured directly at the collector over an external series resistance and recorded as a spectral density of noise current.

The resulting non-ideal base current after stress appeared to be proportional to the emitter length. This indicates that damage was done at the silicon sidewall of the emitter. This is clearly illustrated in figure 4, where IBF/L_{em} as a function of V_{stress} is shown for the four different geometries. Only a small influence of the emitter area and the emitter oxide edge is observed.

Noise measurements – as shown in figure 5 – clearly indicate a correlation between the parameter *IBF* and noise level. For small *IBF* the spectral noise density saturates: here the noise level is determined by the ideal base current component part of the transistor, which is flowing through the bottom of the emitter. For high *IBF*, the spectral density varies with IBF^2, as can be observed from figure 5. Such a quadratic dependence was also reported in [2,3].

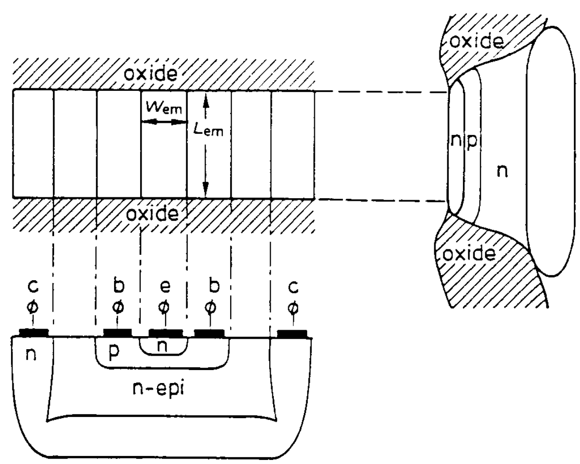

Figure 3: *Schematic floorplan and cross section of the transistors used in the stressing experiments, showing LOCOS isolation and walled emitters.*

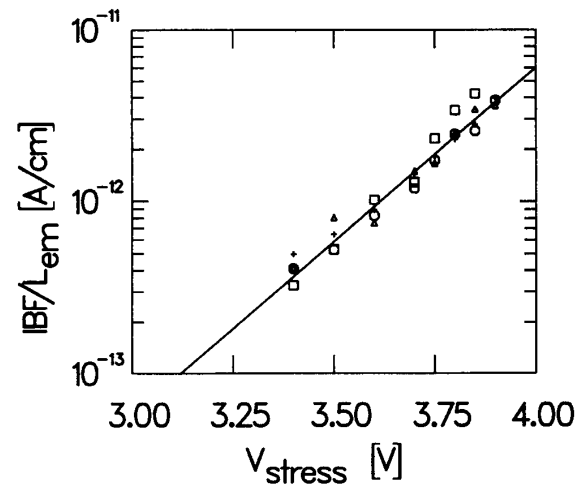

Figure 4: *IBF/L_{em} after stressing as a function of stress voltage for four device geometries. (□ : type A, ○ : type B, △ : type C, + : type D.)*

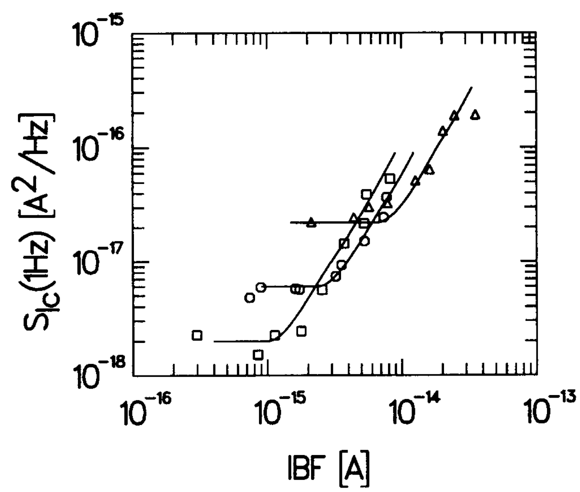

Figure 5: *Spectral density of noise current (extrapolated to 1Hz) from measurements at the collector as a function of non-ideal base current parameter IBF. (□ : type B, ○ : type C, △ : type D.)*

Model

The noise sources have been incorporated in a compact noise model derived from a low frequency approximation – valid for forward biased transistors – of the MEXTRAM model [4]. Other models – such as SPICE Gummel-Poon – can also be used.

For a correct description of noise behaviour, however, a split up of the emitter-base junction in a bottom and a sidewall junction is necessary. In the MEXTRAM model, this split-up follows quite naturally from the model topology, since bottom and sidewall emitter-base junctions are modelled seperately. White noise caused by series resistances and diode shot noise is modelled according to Claessen [5]. An equivalent noise circuit of the transistor in common emitter configuration is shown in figure 6.

The model includes effects such as high current emitter crowding and its effects on noise behaviour of the internal base resistance, separate modelling of bottom and sidewall of the emitter and charge modulation of the internal base resistance. R_{out} is modelled as the differential resistance $\partial V_{ce}/\partial I_c$, and is calculated for each measurement from the full MEXTRAM model description. In order to make the equivalent circuit diagram in figure 6 suitable for noise calculations, the emitter-base bottom- and sidewall diodes and R_{bv} are replaced by their differential resistances ([5]).

Taking into consideration that the physical mechanisms giving rise to I_{b1} an I_{b2} are different, that experiments show that the ideal base current I_{b1} flows through the bottom of the emitter and the non-ideal base current I_{b2} originates from the sidewall, it can be assumed that the noise contributions of the two current components are uncorrelated and have to be taken into account seperately.

We therefore propose a new, improved model describing the noise originating from the emitter-base diode as

$$S_{Ib} = 2q(I_{b1} + I_{b2}) + KF\frac{I_{b1}^{AF}}{f} + KFN\frac{I_{b2}^2}{f}, \qquad (3)$$

with parameters AF, KF and KFN. For noise calculations, the noise contributed by I_{b1} is located at the bottom of the emitter-base diode, while the noise contributed by I_{b2} is located at the sidewall of the emitter.

Model performance

For this new noise model the parameters AF, KF and KFN have been extracted for all four geometries by fitting noise-model calculations to the measured results.

From the noise measurements the parameter AF proved to be $AF = 2$ for all transistors. Noise parameter extraction shows that the parameters KF and KFN are inversely proportional to the effective emitter area A_{em} and effective emitter length L_{em} respectively, as is shown in figures 7 and 8. These geometrical dependencies are in accordance with the results found from DC measurements – where I_{b1} was found to flow through the bottom of the emitter and I_{b2} through the sidewall – and show the physical validity of the model.

The model performance at different bias conditions for a transistor of geometry B is illustrated in figure 9. Comparing with the bias dependency of the old model (equation 1) shown in figure 10, this is not essentially better. The main advantage of the new model (equation 3) becomes apparent when we consider the various stress conditions: with the same parameters we can now describe correctly the noise behaviour of transistors having different non-ideal base current parameters, as is shown in figure 11 (compare with figure 2).

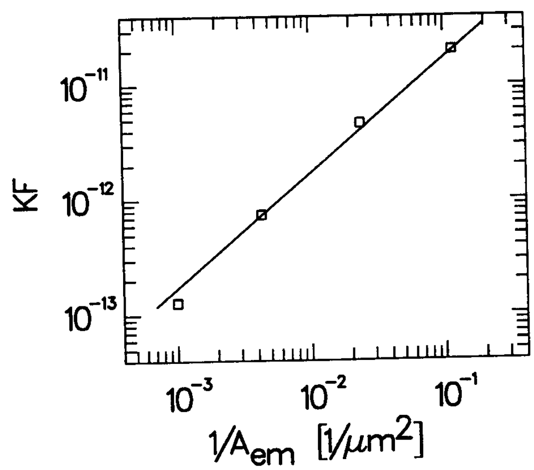

Figure 7: *Experimental ideal base current noise parameter KF as a function of* $1/A_{em}$.

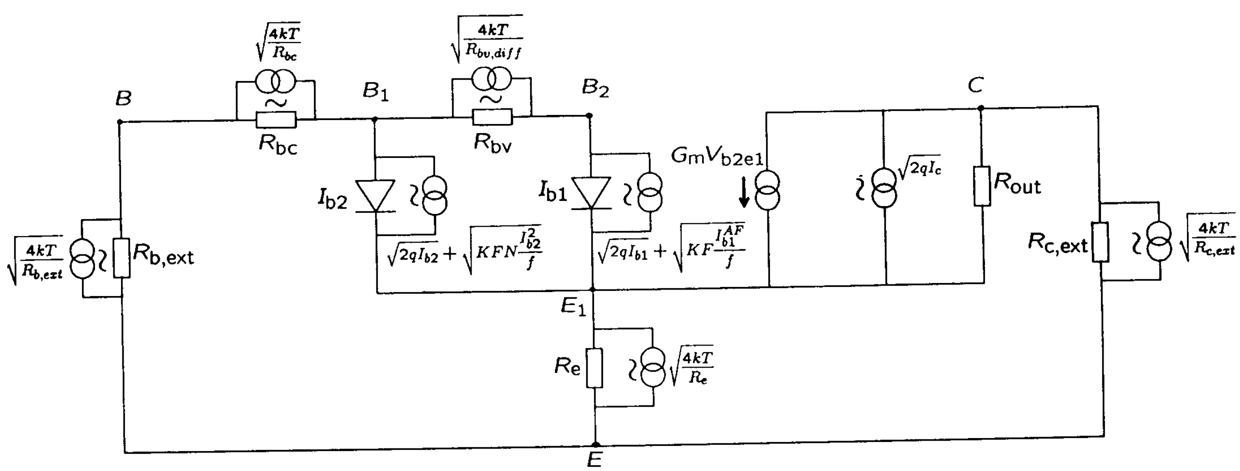

Figure 6: *Full equivalent noise circuit of the transistor in common emitter configuration including external resistances. T, q and k stand for device temperature, elementary electron charge and Boltzmanns constant respectively. External series resistances in the measurement set-up are indicated as* $R_{b,ext}$ *and* $R_{c,ext}$ *respectively. The emitter resistance and the constant and variable part (under the emitter) of the base resistance are shown as* R_e, R_{bc} *and* R_{bv} *respectively. The transconductance and output resistance are given by* G_m *and* R_{out}. *For each resistor and diode – except* R_{out} *– a noise source is present, represented in* $A/\sqrt{Hz}$. *For the emitter base diodes these noise sources introduce both shot noise and 1/f noise.*

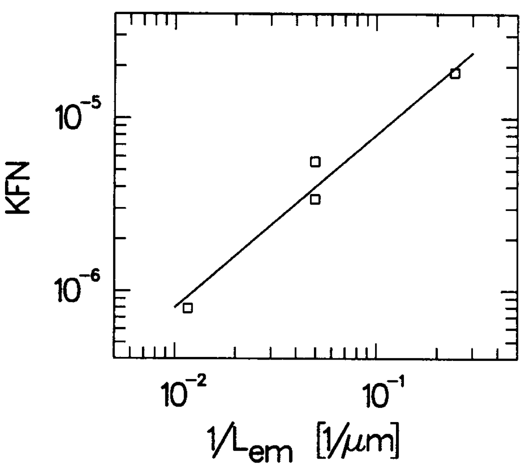

Figure 8: *Experimental non ideal base current noise parameter KFN as a function of $1/L_{em}$.*

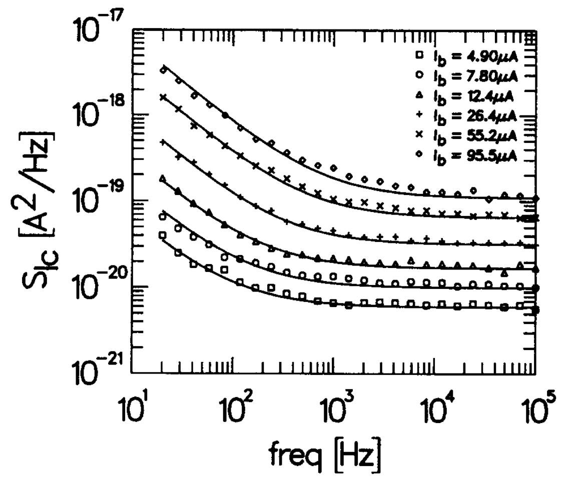

Figure 10: *Spectral noise current density measured at the collector for a transistor of type B for different biases and fixed IBF; calculations done using equation 1. (□, ∘, △, +, ×, ◇: experiments, —: equation 1.)*

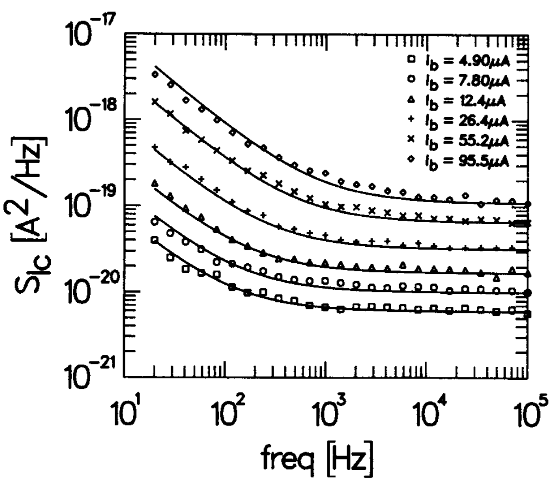

Figure 9: *Spectral noise current density measured at the collector for a transistor of type B for different biases and fixed IBF; calculations done using equation 3. (□, ∘, △, +, ×, ◇: experiments, —: equation 3.)*

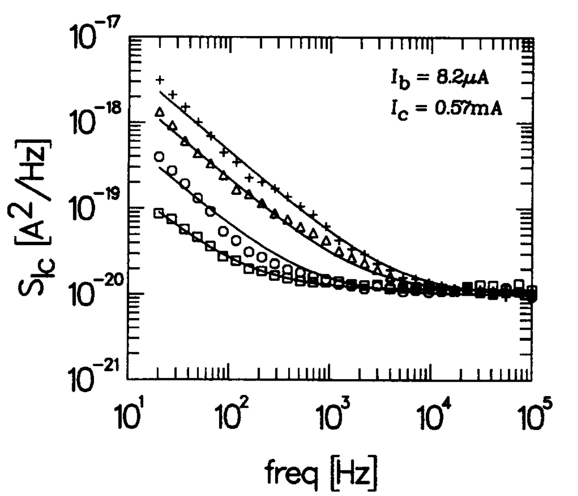

Figure 11: *Spectral noise current density measured for fixed bias conditions at the collector for transistors with different non-ideal base current parameter IBF. (□, ∘, △, +: experiments, —: equation 3.)*

Conclusion

A new, improved model for the low frequency noise behaviour of bipolar transistors, taking into account the magnitude of the non-ideal base current, has been presented.

Noise parameters for this new model have been determined. Measurements show a quadratic dependence of noise level on both ideal- and non-ideal base current, resulting in a constant parameter $AF = 2$. Only two parameters therefore are necessary for a complete description of 1/f noise behaviour.

The new model can describe the effect of transistor aging on the noise behaviour in the cases where h_{FE} degrades due to an increase in non-ideal base current. The new model allows simple geometrical scaling rules for the noise parameters *KF* and *KFN*, illustrating the physical validity of the model.

References

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