In-situ noise system measurement for SiGe HBT characterization at 150 GHz

S. Bouvot[1], J.C. Azevedo Gonçalves[1], T. Quémerais[2], D. Gloria[1]
[1]STMicroelectronics, 38920 Crolles, France
[2]STMicroelectronics, 38000 Grenoble, France
simon.bouvot@st.com

G. Ducournau, S. Lépilliet, F. Danneville
Univ. Lille, CNRS UMR 8520 – IEMN
59650 Villeneuve d'Ascq

Abstract**—This paper presents an extraction of the four noise parameters of a BiCMOS SiGe heterojunction bipolar transistor (HBT) at 150 GHz using an in-situ characterization system. Due to the non-availability of commercial G-band impedance tuner, an integrated active impedance tuner designed in the BiCMOS 55 nm technology was used to characterize a HBT from the same technology. Furthermore, the active part of the tuner increases the measurement accuracy by the validation of the minimum detectable signal (MDS) condition. Lane's algorithm was employed to extract transistor noise performances from 146 to 156 GHz.**

Keywords—in-situ, impedance tuner, HBT, SiGe

I. INTRODUCTION

Advanced silicon technologies today have cutoff frequencies above 300 GHz [1]. Such performances make it possible to design millimeter-wave (mmW) circuits. For applications to be robust with reliable component models, the noise characterization of HBTs is of utmost importance. The main objective of its characterization is the extraction of the noise parameters [2]: it includes the minimum noise factor F_{min} corresponding to the optimal source admittance Y_{opt} and the noise equivalent resistance R_n (1). This extraction is possible knowing at least four values of the characterized device under test (DUT) noise factor (F_{DUT}) versus its corresponding input admittance ($Y_s=G_s+j.B_s$). An impedance tuner used at the input of the DUT allows to bring a set of input impedances and enables the use of multi-impedance method to extract noise parameters (see Fig. 1).

$$F_{DUT}(Y_s) = F_{min} + \frac{R_n}{G_s}.\left|Y_s - Y_{opt}\right|^2 \qquad (1)$$

Today, commercial off-wafer impedance tuners are limited to 110 GHz. Furthermore, the probes used to connect these tuners to the silicon DUT reveal important losses. That significantly limits the magnitude of the maximum reflection coefficient Γ_S provided by the tuner to the DUT. Therefore, due to the required optimal source admittance Y_{opt} needed to reach minimum noise factor, that are far from 50 Ω, the optimum matching of HBTs remains sensitive with an external tuner.

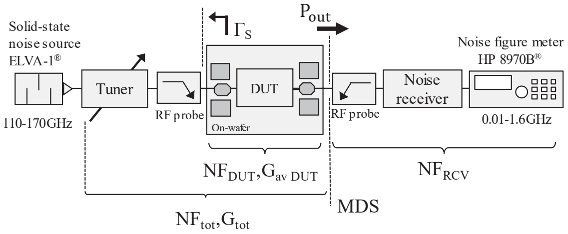


Fig. 1. Block diagram of a typical bench used for noise characterization of a DUT integrated on-wafer

This constraint motivated the development of in-situ impedance tuners integrated close to the DUT. In W-band (75-110 GHz) [3] and D-band (110-170 GHz) [4][5], tuners are designed in STMicroelectronics BiCMOS technologies. Recently, an active impedance tuner [6] was developed to increase measurement accuracy. The latter, used in this study, will be directly connected at the input of a DUT in order to extract its noise parameters while validating the receiver sensitivity condition.

The sensitivity condition is of utmost importance to ensure a correct measurement and extraction of noise parameters, which corresponds to the minimum detectable signal (MDS) imposed by the noise receiver. Thus, the MDS must be guaranteed over the entire studied frequency band. As a matter of fact, for the measurement to be valid, the receiver noise figure (NF_{RCV}) must be less than the sum of the noise figure (NF_{tot}) and the power gain (G_{tot}) of the characterized structure (see Fig. 1), with a 3-dB margin (2). We can note that, on the one hand, the noise factor of the off-wafer noise receiver must be low to ensure a good sensitivity to the measurement. On the other hand, the power gain of all elements between the noise source and the MDS plan condition (G_{tot}) must be important to compensate its noise figure (NF_{tot}) which must remain low. Since the noise power levels to be detected are low, particular care must be taken in calibrating the noise receiver. The latter exhibits a noise figure of 9 dB at 150 GHz, including RF output probe.

$$NF_{tot}\,(dB) + G_{tot}\,(dB) \geq NF_{RCV}\,(dB) + 3 \qquad (2)$$

II. METHODOLOGY

To extract the four noise parameters of the HBT under test, the multi-impedance methodology is employed by the resolution of the Lane's algorithm by knowing at least four tuner presented admittances Y_S and their corresponding noise factors F_{DUT}. The several steps leading to the four noise parameters extraction are proposed in the procedure shown in Fig. 2.

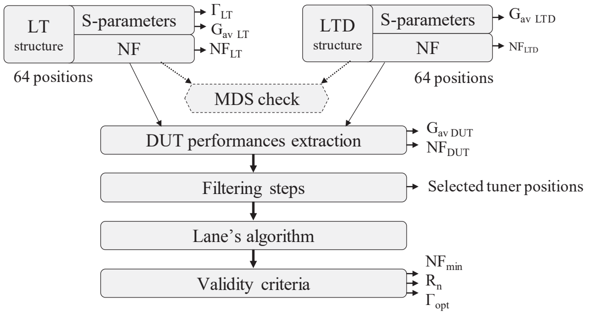


Fig. 2. Procedure established for noise parameters extraction using multi-impedance method

First, the standalone 64 positions active tuner (LT structure, see Fig. 2) is characterized in small signal in order to extract its output reflection coefficient Γ_{LT} after having removed the contribution of the output pad of the test structure. This de-embedding step was performed by first measuring the S-parameters of a pad-OPEN structure comprising only a test pad. Then, this pad is reformed into a matrix chain in order to be able to remove it from the raw measurement. It enables to know exactly the S_{22} parameter of the active tuner which will be presented at the input of the DUT. The available gain of the active tuner $G_{av\ LT}$ is calculated by knowing S-parameters with input reflection coefficient (see Fig. 2). Its corresponding noise contribution NF_{LT} is then extracted with the characterization bench depicted in Fig. 3.

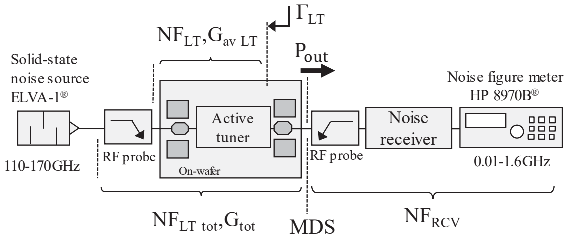


Fig. 3 Block diagram of the bench used for D-band noise characterization of the active tuner (LT)

The LTD structure, composed of the active tuner (LT) directly connected to the DUT, is also characterized for each position of the tuner to extract its available gain $G_{av\ LTD}$ and noise factor NF_{LTD}. The extracted available gains and noise factors of LT and LTD structures enable to check the MDS condition for each structure and to calculate the DUT contribution in available gain $G_{av\ DUT}$ and noise NF_{DUT}.

Then, several filtering steps are applied to the extracted DUT noise factor and corresponding Γ_{LT} in order to select the positions of the tuner enabling to execute accurately the Lane's algorithm. A final check is implemented in order to validate that the extracted noise parameters are physical.

A. D-band Active Impedance Tuner Integration

To perform source-pull characterization, an in-situ active impedance tuner based on previous work [6] was designed to cover area located in the inductive part of the Smith chart, close to the optimal source admittance (Y_{opt}) of the DUT corresponding to its minimum noise factor. This on-wafer integration removes losses induced by the use of high frequency probe to contact the off-wafer impedance tuner to the silicon DUT. The active impedance tuner is composed of a passive tuner preceded by a low noise amplifier (LNA) which main objective is to compensate the losses induced by the passive tuner in order to increase P_{OUT} and ensure the sensitivity condition validation.

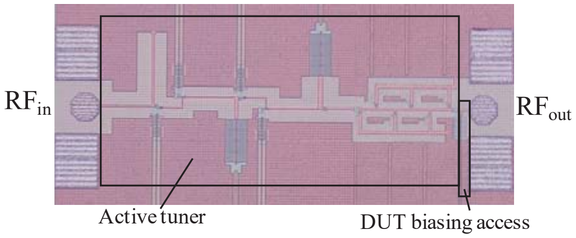


Fig. 4 Microphotograph of the 0.8 mm × 1.2 mm active impedance tuner

B. D-band Active Tuner Characterization

First, an off-wafer LRRM (Line-Reflect-Reflect-Match) calibration is done using the Cascade® ISS calibration kit. Then, S-parameters characterization is performed using a 0.01-24 GHz vectorial network analyzer (VNA) and frequency extender modules enabling to operate in the G-band (140-220 GHz).

The output active tuner reflection coefficient (S_{22}) for the 64 states is proposed in Fig. 5 at 146, 150 and 156 GHz. The obtained output $|\Gamma_{LT}|$ is higher than 0.5 in the 146-156 GHz band. The available gain of the active tuner $G_{av\ LT}$ is then calculated from S-parameters measurements of the latter for the 64 positions, de-embedded of its output pad.

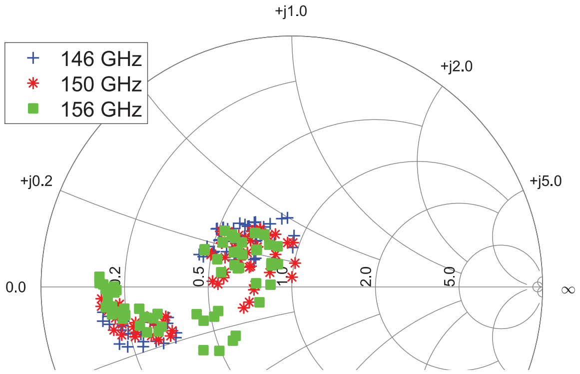


Fig. 5. S_{22} parameter of the 64 positions of the active tuner (LT) de-embedded of the output pad at 146, 150 and 156 GHz

The bench depicted in Fig. 3 is used to extract noise performances of the active tuner. High frequency noise characterization of this structure was performed using Y-factor measurement (3), which corresponds to the ratio of noise powers measured through the NFM when the noise source is at ON state (P_{hot}) and OFF state (P_{cold}). A 12-dB ENR solid-state noise source from ELVA-1® and a noise receiver developed at IEMN laboratory were used, both on D-band frequency range. Noise power measurements were performed at 30 MHz through a HP 8970B® noise figure meter (NFM) located downstream the noise receiver.

$$F_{LT_{tot}}(Y_S) = \frac{ENR - (Y-1)\left(\frac{T_{cold}}{T_0} - 1\right)}{(Y-1)} \qquad (3)$$

With $Y = \frac{P_{hot}}{P_{cold}} \gg 1$

The tuner noise factor $F_{LT\ tot}$ is obtained after calibration procedure done while connecting the noise source to the noise receiver. In (3), the noise temperature T_{cold} corresponds to P_{cold}, while T_0 is the reference temperature (290K).

Noise de-embedding of Cascade Infinity® input and output probes and output GSG pad of the active tuner is then carried out thanks to FRIIS formula. The available gain of the probe is deducted from S-parameters of the probe and the output reflection coefficient of the active tuner.

Sensitivity can be checked by applying (2) to the active tuner structure. The sum of its available gain and the corresponding noise figure shown in Fig. 6 is compared to the noise figure of the receiver including output RF probe (red curve) at each frequency. We observe that several tuner states do not guarantee the minimum detectable signal condition. However, these non-convenient states will be rejected afterward, before executing the Lane's algorithm without any loss of convergence of the extraction procedure.

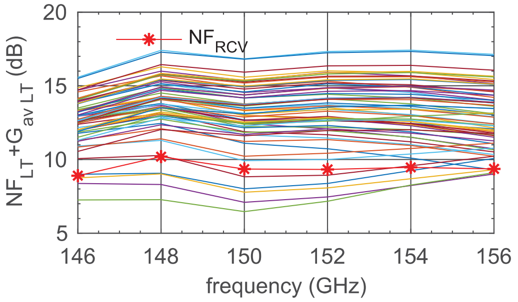


Fig. 6. Comparison of the receiver noise figure (NF_{RCV}) with the sum of the noise figure (NF_{LT}) and the available gain ($G_{av\ LT}$) of the 64 tuner positions

The active tuner being characterized, the following steps are to achieve the same characterizations (noise and S-parameters) on the in-situ test structure (LTD) composed of the active tuner and the DUT in order to extract its performances.

C. Transistor Noise Figure Extraction

The transistor under test is a 5 µm × 0.2 µm BiCMOS 55 nm high-speed HBT in CBEBC configuration and was biased at a 1.2 V collector-emitter voltage and at current density of J_C=17.8 mA/µm. By knowing LT and LTD performances in noise and available gain, DUT contributions can be extracted. Fig. 7 shows that the sum of the contributions in noise and available gain of the active tuner and DUT leads to a minimum value of 13 dB over the 146-156 GHz frequency range for all tuner states. This validity of the MDS condition allows the noise receiver to be sufficiently sensitive to accurately detect the noise power range at its input.

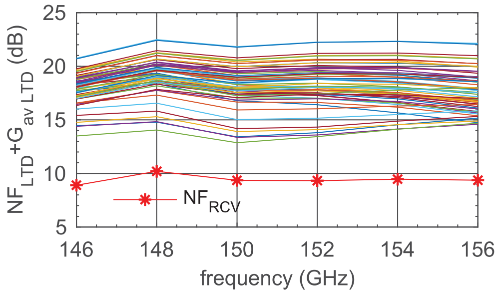


Fig. 7. Comparison of the receiver noise figure (NF_{RCV}) with the sum of the noise figure (NF_{LTD}) and the available gain ($G_{av\ LTD}$) of the test structure for the 64 tuner positions

By knowing noise factor and available gain of both LT and LTD structures, the noise factor F_{DUT} and available gain $G_{av\ DUT}$ of the transistor can be extracted (see Fig. 8 and Fig. 9) with (4) and (5) respectively.

$$F_{DUT} = (F_{LTD} - F_{LT})\ G_{av\ LT} + 1 \tag{4}$$

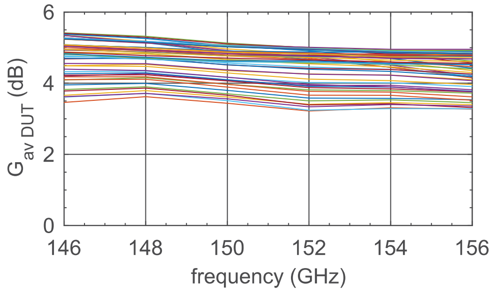


Fig. 8. Extracted available gain of the DUT according to the 64 output impedances of the active tuner

$$G_{av\ DUT} = \frac{G_{av\ LTD}}{G_{av\ LT}} \tag{5}$$

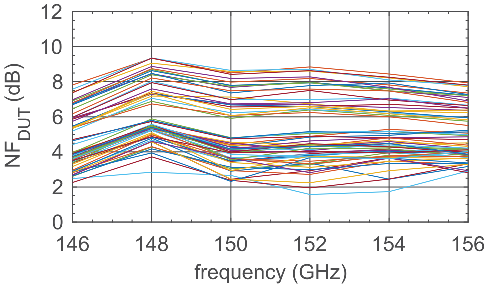


Fig. 9. Extracted noise figure of the DUT according to the 64 output impedances of the active tuner

The multi-impedance method using Lane's algorithm can be executed after a relevant selection of tuner positions to be kept.

D. Filtering Datas from Measurements

Several filtering steps were established in a Matlab® program in order to keep a selection of triplet (F_{DUT}, real part of Y_S and imaginary part of Y_S) sufficiently spaced from each other to be able to accurately execute the Lane's algorithm. The selection of kept tuner states is based on a minimum gap between two noise factors values, then between two values of real parts of Y_S and finally between two values of imaginary parts of Y_S.

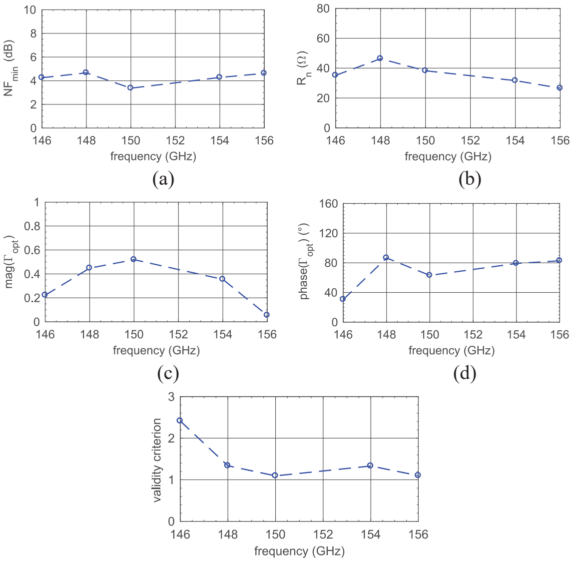
E. Noise Parameters Extraction

The four noise parameters were extracted using multi-impedance method associated to Lane's algorithm [2] after filtering data from measurements. To ensure the physical character of the extracted noise parameters, a check (6) has been performed. Thus, the 4 noise parameters of the DUT extracted are preserved if F_{min} is greater than 1 and when R_n and G_{opt} are positive. In addition, a last filtering is applied thanks to the Lange's criterion defined in (6). The latter must be between 1 and 2 [7].

$$1 \leq \frac{4R_nG_{opt}}{F_{min}-1} \leq 2 \tag{6}$$

III. RESULTS

Extracted noise parameters of the 5 µm × 0.2 µm BiCMOS 55 nm high-speed HBT biased at J_C=17.8 mA/µm² (V_{dd}=1.2V) are shown in Fig. 10 from 146 to 156 GHz. The result of extracting the four noise parameters at 146 GHz is to be discussed since the previously defined validity criterion is not assured.



(a) (b)

(c) (d)

(e)

Fig. 10. 146-156 GHz extraction of the HBT under test 4 noise parameters: (a) Minimum noise figure, (b) Equivalent noise resistance, (c) Magnitude and (d) Phase of the optimal source reflection coefficient and (e) the associated validity criterion.

IV. CONCLUSION

The four noise parameters of a HBT were extracted in the 146-156 GHz frequency range using an active 64 positions impedance tuner designed in the STMicroelectronics BiCMOS 55 nm technology. To ensure the minimum detectable signal condition requirement given by the off-wafer noise receiver, a LNA has been designed and associated with a passive tuner. The Y-factor method was employed for noise characterization of the tuner and dedicated test structure. Then, Lane's algorithm used for noise parameters extraction after a relevant selection of tuner positions.

REFERENCES

[1] P. Chevalier *et al.*, "A 55nm triple gate oxide 9 metal layers SiGe BiCMOS technology featuring 320 GHz fT / 370 GHz fMAX HBT and High-Q Millimetter-Wave Passives," in *IEDM Technical Digest*, 2014, pp. 77-79.

[2] H. Rothe *et al.*, "Theory of Noise Fourpoles," *Proceedings of the IRE*, vol. 44, no. 6, pp. 811-818, Jun. 1956.

[3] T. Quémerais, D. Gloria, S. Jan, N. Derrier, and P. Chevalier, "Millimeter-wave characterization of Si/SiGe HBTs noise parameters featuring fT/fMAX of 310/400 GHz," in *2012 IEEE Radio Frequency Integrated Circuits Symposium*, 2012, pp. 351–354.

[4] K. H. K. Yau, P. Chevalier, A. Chantre, and S. P. Voinigescu, "Characterization of the Noise Parameters of SiGe HBTs in the 70-170-GHz Range," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 8, pp. 1983–2000, Aug. 2011.

[5] M. Deng *et al.*, "Millimeter-Wave In Situ Tuner: An Efficient Solution to Extract the Noise Parameters of SiGe HBTs in the Whole 130-170 GHz Range," *IEEE Microw. Wirel. Compon. Lett.*, vol. 24, no. 9, pp. 649–651, Sep. 2014.

[6] S. Bouvot et al., "A 140 GHz to 160 GHz active impedance tuner for in-situ noise characterization in BiCMOS 55 nm," in 2017 *IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)*, 2017, pp. 153–155.

[7] M. W. Pospieszalski, "Interpreting Transistor Noise," in *IEEE Microwave Magazine*, vol. 11, no. 6, pp. 61-69, Oct. 2010