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Microwave noise sources in AlGaAs/GaAs HBTs

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Abstract — **Scattering and noise parameters of AlGaAs/GaAs HBTs from Conexant with 30 and 35% of Al mole content were measured and modeled. De-embedding of the pad parasitics was accurately performed by using a "two step" method and small-signal modeling. Small-signal hybrid Π type model parameters were extracted from "cold" and "hot" HBT measurements. Thermal, hot electron and correlated base and collector current shot noises were included in the noise model, which accounted well for the measured noise parameters. From the resolution of noise sources it was found that minimum in noise figure at 5 GHz stems from the correlation of base and collector shot noise. Al content in the alloy does not influence the high frequency noise properties of the AlGaAs/GaAs HBTs.**

I. INTRODUCTION

Heterojunction bipolar transistors are promising devices for the power, analog and high speed applications. The advantage of HBTs is high gain per amplification stage and very good linearity. Modern technology allows to reduce emitter area so reducing power consumption and keeping high current densities and high speed of operation. Since the devices are used in analog applications the important issue is noise as well. Usually to achieve a better noise performance, high base doping ($\sim 10^{19} cm^{-3}$) is used. Nevertheless the noise properties of bipolar devices still remain to be improved and at the moment are not able to compete with those of HEMTs, where NFmin at 26 GHz is close to 1 dB. In this aspect microwave noise investigation in $A_{III}B_V$ HBTs is important and challenged a set of works [1]-[13]. Small signal and noise modeling opens the way to resolve noise sources in the HBTs [3], [8] and to find the solutions to fabricate high speed and low noise devices.

In this work we have measured S and noise parameters with a following modeling by using hybrid Π model. We have investigated the contribution of different noise sources on to the NFmin and the influence of the Al content in the AlGaAs/GaAs to the NFmin.

II. DEVICES, RESULTS, MODELING

We have measured AlGaAs/GaAs HBTs with 30% and 35% of Al mole fraction in emitter alloy with an area of $Ae=56 \mu m^2$. The devices were designed and fabricated at Conexant. The layout data of the HBTs is presented in the Table 1.

TABLE I
DEVICE LAYER STRUCTURE

	type	Material	Mole fract.	Concent. (cm^{-3})	Thick. (nm)
7	n	$In_yGa_{1-y}As$	y=0 -0.6	$1*10^{19}$	100
6	n	GaAs		$8*10^{18}$	120
5	n	$Al_xGa_{1-x}As$	x=0.30 -0	$4*10^{17}$	20
4	n	$Al_xGa_{1-x}As$	x=0.3/0.35	$4*10^{17}$	72.5
3	p	GaAs		$4*10^{19}$	90
2	n	GaAs		$7*10^{15}$	70
1	n	GaAs		$5*10^{18}$	1000

The photo of the single finger HBT see in the Fig.1.

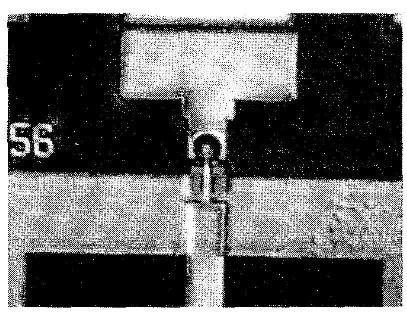

Fig.1. The photo of the single finger AlGaAs/GaAs HBT.

The measurements of S and noise parameters were performed at Chalmers university with HP8510 and ATN NP5 noise parameter system. The de-embedding was performed by "two step" method. Parallel and series parasitics were extracted by using measured S-parameters of the "open" and "short" dummy structures. The parameters of the small-signal model, see Fig.2, were

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extracted and used further in noise modeling when the complete model (with pads) was required. Simulated Y-parameters were fitted to measured by means of optimization, see Fig.3, 4.

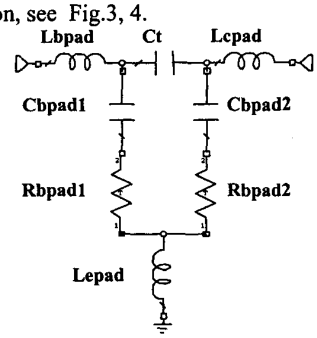

Fig.2. Small-signal model of the "open "dummy" structure.

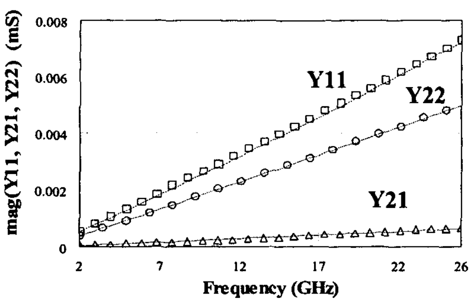

Fig.3. A magnitude of the Y-parameters of the "open" pattern. Lines represent modeled, squares, circles and triangles are measured Y11, Y22, and Y21 respectively.

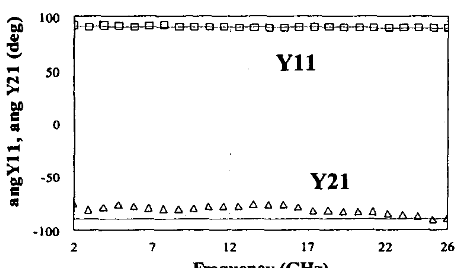

Fig.4. A phase of the Y-parameters of the "open" pattern. Lines are simulated, triangles and squares are measured respectively Y21, Y11.

Very good fit enabled an extraction of parasitic base, Lbpad=47pH, collector Lcpad=5pH and emitter Lepad=6pH inductivities and pad capacitances Cbpad1=37fF and Ccpad2=26fF and Ct=3.8fF. The extraction of the emitter, base and collector parasitic intermetallization capacitances (Cbep=17fF, Cbcp=23F and Ccep=5,2fF) was performed by using a set of measured "cold" (Vc=0, Ic=0, Vb=0, Ib=0) HBT data. S-parameters of "cold" device were de-embedded from pad parasitics and then modeled. Note, that those capacitances are not included to pads as usually taken [9], [10], [13]. Since the pad parasitics contain resistive elements, there is no way for neglecting Cbep, Cbcp and Ccep just including them into pad parasitics. Further the HBT emitter/base junction was "opened" by applying Vc=0,Vb=1.4V (Ib=10mA). The parasitic base and emitter inductivity together with base Rb1 and emitter Re resistances were determined from modeled de-embedded S-parameters, see Fig.5. This approach allowed finding the magnitudes of bias independent Re. Since the total resistance was distributed to bias independent Rb1 and dependent Rb2, only Rb1 and Re were further fed into modeling approach.

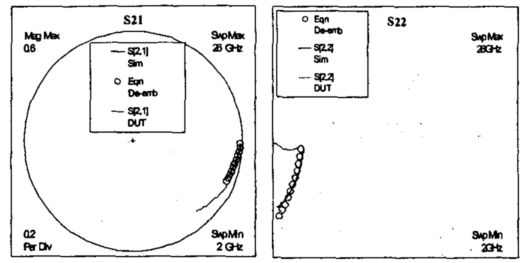

Fig.5. S-parameters of the DUT (line) and de-embedded "open HBT" (Vc=0,Vb=1.4V (Ib=10mA)) measured (open circles) and simulated (lines).

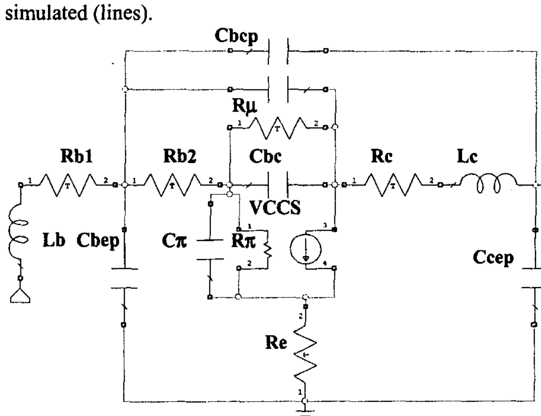

Fig.6. Small-signal model of the pads free HBT.

Finally, having the de-embedded S–parameters of the HBT and using extracted Cbep, Cbcp, Ccep, Re, Rb1 and having gm from the DC measurements S-parameters were fitted to de-embedded ones of the HBT at different bias points by exploiting the small signal model, see Fig.6. For the presentation we have chosen not the best (in terms of noise and gain), but interesting point (minimum in NFmin (f)). Modeled and measured S-parameters are presented in the Fig.7. Very good fit enabled extraction of small-signal and further, noise model parameters.

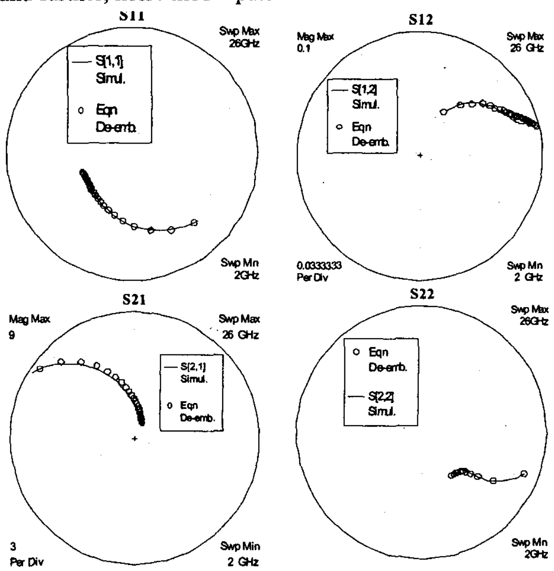

Fig.7. S-parameters of the pads-free measured (lines) and simulated (open circles) HBT. Vc=0.75V, Vb=1.4V (Ic=6.32mA, Ib=94μA).

Since we think that the extracted small signal model parameters are quite physical and accurate thus capable to account for RF performance, (see Fig.8 of the HBT) we have added two correlated shot noise sources (base and

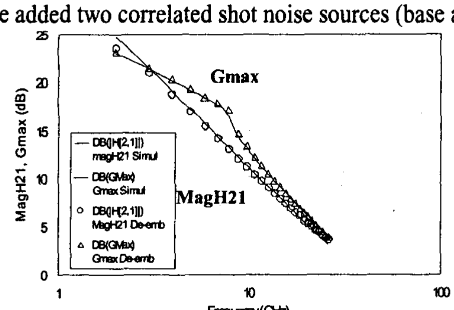

Fig.8. Magnitude of H21 and Maximum available gain Gmax of the pads-free measured (lines) and simulated (open circles) HBT Vc=0.75V, Vb=1.4V (Ic=6.32mA, Ib=94μA).

collector current) and thermal noise model of all resistive elements plus collector temperature in the intrinsic part of collector resistance [3], [6]. For this bias point, as can be seen from extrapolation of 20dB/dec. slope, Ft=40GHz. Simulated noise parameters fits well with the measured data, see Fig. 9,10. NFmin exhibits a minimum at around 5GHz. Shot noise alone is not capable to account for it. The correlation between base and collector shot noises was found to be responsible for the observed minimum: $<Ib^*Ic>=(C_R+jC_I)(Ib^2Ic^2)^{1/2}$, where $C_R=0.004$, $C_I=0.58$ Similar minimum was observed in [8] and explained by bias dependent influence of burst noise. In that work only NFmin was modeled, while Rn and especially Gopt were neglected. All three noise parameters are very sensitive to correlation changes. We have obtained good agreement of simulated and measured Rn and Optimum source reflection coefficient Gopt as well, (see Fig.9, 10). Even a tiny "hook" in the Gopt at low frequencies was accounted for, see Fig.10. The minimum in NFmin versus frequency was also observed in [13], but no explanation followed.

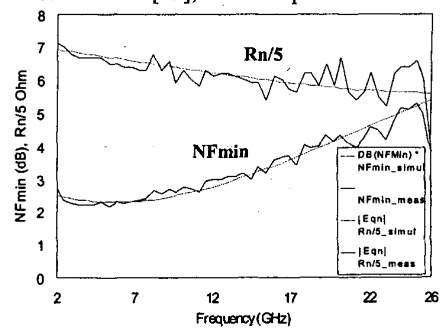

Fig.9. Measured (scattered lines) and simulated (smooth) NFmin, Rn/5 of the HBT Vc=0.75V, Vb=1.4V (Ic=6.32mA, Ib=94μA).

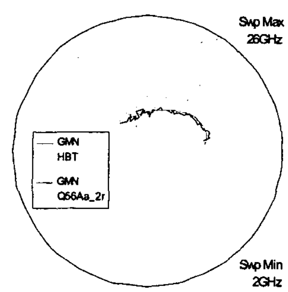

Fig.10. Gopt of the pads-free measured (scattered line) and simulated (smooth line) HBT Vc=0.75V, Vb=1.4V (Ic=6.32mA, Ib=94μA).

We think that this is an *experimental evidence* of the influence of base and collector shot noise correlation. Moreover, we have used in the noise model the collector temperature Tc= 4600 K, which can be treated in the noise model as the noise temperature of the lightly doped collector layer. The physical meaning behind lies in the electron heating in the lightly doped collector at very high electric fields [3], [11]. Electrons enter base being accelerated due to the spike in the emitter/base junction, gain energy and then enter the collector region with high energy ($\varepsilon > \varepsilon_{\Gamma L}$). Due to the high electric field in the collector, the drift velocity of the electrons reaches its maximum value and then drops due to the Γ-L, Γ-X transfer with the following emission of the LO phonons. An effective mass and mobility changes so resulting the fluctuations of the drain current. Decomposition of the

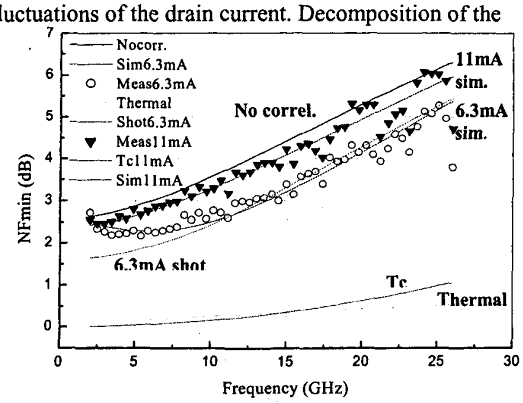

Fig.11. NFmin and resolved noise sources of the HBT, biased with Vc=0.75V, Vb=1.4V (Ic=6.32mA, Ib=94μA), open circle and Vc=3.0V, Vb=1.4V (Ic=11mA, Ib=163μA), solid triangles.

NFmin to the different noise terms shows that shot noise is the dominant noise source in the HBT, see Fig.11. If the correlation is excluded, the NFmin is increased and the minimum disappears. Noise model yield good agreement

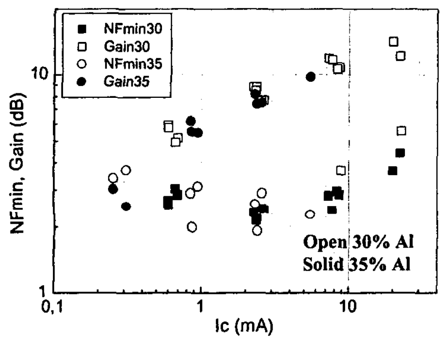

Fig.12. NFmin and associated gain of the 30%, 35% Al HBTs.

with the measured noise parameters at different bias and for the set of different devices. It is evident that at higher Vc and Ic the correlation diminishes. The contribution of Tc to NFmin increases (at 26 GHz is 1dB). Nevertheless it remains small due to the low collector resistance Rc=3Ω. Drain current shot noise was found less than its theoretical value. This supports the model of G.Niu [14], where collector current shot noise is considered as a result of the base shot noise only. It was found that Al content in the alloy does not significantly influence the high frequency noise properties of the AlGaAs/GaAs HBTs, see Fig.12, where NFmin versus drain current for the set of devices is presented.

III. Conclusion

The minimum of NFmin in AlGaAs/GaAs HBTs versus frequency is due to the cross correlation term, which reduces the total NFmin. The dominant noise source in the HBTs is the shot noise. The contribution of the hot electron noise in the lightly doped collector region becomes significant to NFmin at higher bias and frequencies.

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