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INVESTIGATION OF DC, MICROWAVE CHARACTERISTICS AND NOISE IN SiGe AND A_3B_5 HETEROJUNCTION BIPOLAR TRANSISTORS

Summary of Doctoral Dissertation
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AUKŠTADAŽNIŲ SiGe IR A_3B_5 ĮVAIRIALYČIŲ DVIPOLIŲ TRANZISTORIŲ STATINIŲ, MIKROBANGIŲ CHARAKTERISTIKŲ IR TRIUKŠMO TYRIMAS

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The work topic

Nowadays the global high-speed RF and optical communication market has grown rapidly, setting and stimulating an evolution of epitaxial technology of heterojunction bipolar transistors (HBT). Modern Si/SiGe, AlGaAs/GaAs and InGaP/GaAs HBTs exhibit high-speed and high- frequency operation, high gain, low noise and low signal distortion.

Advanced AIIIBV and SiGe HBTs can be fabricated with a different base doping profile, which can be altered or adjusted for required HBT operation needs. Modern lithographic process and epitaxial technology allows the decrease of the base thickness resulting to the decrease of minority carrier transit time and nearly eliminating recombination current in the base. This yields an increase of emitter efficiency and device high-speed performance. The base conductance increase is desired to achieve device high frequency operation and low noise performance. Therefore a heavy base doping ($\sim 10^{19}$ cm^3) is required to enable an increase of base conductance. To keep out-diffusion of dopants in the base for SiGe HBTs a Carbon (C) is being used. To speed up HBTs performance a Germanium gradient profile in the base is employed. This onsets built-in electric field accelerates minority carriers. The peak unity gain cutoff frequency (f_T) for state of the art SiGe HBT is beyond 400 GHz [1, 2] and for InP HBT it reaches 600 GHz [3], both at room temperature.

Current fluctuations aren't only unwanted phenomena in semiconductor devices. From another hand fluctuations can yield information about carrier kinetic and serve as a method to investigate transport properties in semiconductor devices or semiconductor material. Requirement to increase operation frequency of HBT results to a smaller size of emitter and thinner base. Shrinking of device dimension onsets an internal electric field of the biased transistor, this can be efficiently high at the base/collector junction of the HBT. Therefore an additional noise sources, related to impact ionization in this area have to be considered. Usually circuit designers are trying to avoid this area of bias; nevertheless the device can be driven close to the limiting biases (automotive applications) and can fall to this operation mode incidentally. In certain applications transistors need to be operated at voltage beyond collector - emitter breakdown voltage (BV_{CE0}). As a result of impact ionization in such bias conditions a minimum noise figure (NF_{min}) of the device increases and have to be accounted by in compact model [P2].Therefore the design and optimization of high frequency semiconductor device circuits requires accurate compact models as well as noise models, which could capture all relevant effects.

As it was shown by many authors one of the most important noise source contributor at high frequency is the shot noise cross - correlation power term [P4-P6]. There are several analytical models to account cross – correlation noise power, nevertheless they were never implemented in the compact model approach. The reason for this is that most of the analytical expressions for the correlation are using time delay parameter, so called noise delay. Compact model operates with charges and currents and any time related parameter would create a convergence problem, especially for time domain circuit simulation. Therefore an elegant solution for correlation implementation to compact model is a bottleneck task.

It is well known that SiGe HBTs, opposite to Si BJTs can operate at cryogenic temperatures. An improved gain, high frequency and noise performance for such ambient temperatures is observed [P1]. Most of the research work on SiGe HBTs at cryogenic environment was performed on conventionally doped emitter SiGe HBTs. In this work we have shown that light emitter concentration (LEC) SiGe HBTs are very good candidates for the cryogenic operation. LEC transistors have a heavily doped base which is necessary for high speed low noise applications. It was shown that LEC SiGe HBTs can operate at 4 K. The partial carrier freeze-out is observed, resulting to the reduced base current due to the transport mechanism change. This yields a very high dc current gain and increased f_T. There is a very little market for the cryogenic applications indeed, most of applications are related to the space (NASA) projects, but they are very much dollar efficient.

From another hand it was shown that SiGe HBTs can operate at very high ambient temperatures (300 K-500 K). Due to the mobility models limitations for existing device simulators and compact models, simulations were performed for the most practical temperature regions. It was shown that physics based compact model HICUM l2 v2.23 can capture SiGe HBT I/V and RF performance at ambient temperature region of most practical operation (-25^{o}C to +160^{o}C).

Tasks of the work

The main task of this work is an investigation of dc, microwave and noise characteristics in the relevance frequency range of 1 -30 GHz of Si/SiGe and InGaP/GaAs HBTs. Noise simulations and modeling have been performed to investigate the shot noise source cross - correlation, impact ionization noise modeling and temperature dependences of dc, rf and noise parameters.

Practical value

HBT modeling in device level was performed with transport equation based on hydrodynamic (HD) and drift – diffusion (DD) models [4]. Compact modeling (CM) was performed with HICUM/L2 v2.23 [5] one of the standard Compact Modeling Council confirmed industry bipolar transistor models. Radio frequency (RF) circuit sensibility, high - speed and low noise performance are dependent on their compound semiconductor device properties. Noise performance is especially critical parameter for the low noise amplifiers. The more accurate models of transistors are for the more accurate design of circuit performance is obtained. Intelligent optimization design circle decreases expenses and increases product competitive ability.

Research methods

Current/voltage (I/V) characteristics of the devices under test (DUT) were measured with Agilent E5270 semiconductor parameter analyzer using ICCAP routine and probe station from Süss Microtech PM 8. S-parameters were measured with Vector Network Analyzer (VNA) in the frequency band of 45 MHz to 50 GHz. Noise parameters were measured with Maury ATS mechanical tuner system, Agilent PNA E8364B and Spectral Analyzer Agilent PSA E4448A with noise measurement personality and RF probe station PM 8 from Süss Microtec (now Cascade inc.). RF and high noise measurements require very accurate and repeatable PNA and Noise system calibration with very reliable output. Careful de-embedding of the pad parasitic network influence on noise parameters was performed using 2-step method, based on correlation matrix method [6, 7], implemented in Matlab routine. Measured results were compared to built-in compact model HICUM in Agilent ADS 2008 and to Verilog – A based HICUM, programmed with [8]. Hydrodynamic and drift – diffusion HBTs modeling were performed using GALENE device simulator [4].

Scientific novelty

The shot noise sources cross - correlation in HBTs was investigated. Compact model HICUM simulations were performed to seek the importance of the shot noise source cross - correlation on advanced SiGe and AIIIBV based HBTs high frequency noise characteristics. SiGe HBTs DC, RF and noise characteristics were investigated at biases of impact ionization region. Chynoweth relation based impact ionization noise in CM was found a sufficient way to characterize noise performance of SiGe based HBTs biased at II region. Temperature dependence of dc, rf and noise performance of SiGe HBTs dc, rf was investigated. It was shown that SiGe HBTs, especially LEC can operate in extreme temperature environment (4 K to 500 K). It was shown that CM can capture dc, rf and noise behavior in the practical (- 25°C – 200°C) temperature range.

Defended prepositions

1. Heterojunction bipolar transistor shot noise source cross - correlation can be described using noise correlation transit time, which current value is smaller than transistor forward transit time. An analytical noise model of bipolar transistor with cross – correlated base and collector noise sources and influence of external parasitic elements was derived and verified against SiGe and AIIIBV based HBTs. Good agreement with measured data was found in the practical frequency range.

2. Impact ionization current of SiGe heterojunction bipolar transistor determine a rapid increase of minimal noise figure at biases beyond avalanche breakdown voltages in weak avalanche regime. However noise analysis show that a minor carrier shot noise amplification and self heating have only a weak contribution to the noise performance of SiGe based HBTs. It was shown that Chynoweth‘s law of ionization rate is quite enough to characterize an influence of impact ionization to dc, rf and noise parameters and currents simulation of SiGe transistors.

3. Investigation of SiGe heterojunction bipolar transistors exhibited limitations of CM and device level simulations capabilities at low temperatures. Investigated DC characteristics and scattering parameters at wide temperature range (4 – 423 K) revealed that low emitter concentration SiGe heterojunction bipolar transistors performed efficiently better compared to conventionally doped emitter HBTS at cryogenic temperatures (rapid growth of dc current gain and cut – off frequency at 4K, in contrast the growth of those parameters for the conventionally doped emitter transistors stops down to 50 K). It shows that impurities don’t freeze out completely in low emitter concentration SiGe transistors at cryogenic ambient temperatures.

The scope of the work

The doctoral thesis consists of introduction (as first chapter), six main chapters, conclusions and references.

1. Introduction

The motivation of the main investigation problems, topicality and aim of the work, the solved problems, novelty of the results, the practical value and the statements of the thesis are presented in the introduction.

2. Bipolar transistors

This chapter is devoted to the review theory of bipolar transistors. Main focus is addressed to the bipolar transistor technology evolution, main differences of HBTs to bipolar junction transistors (BJTs) technology. The relevant basic theory is presented in this chapter.

3. Noise in semiconductor devices

In this chapter the fluctuation theory in electronic systems and devices is discussed. The main bipolar transistors noise sources and noise parameters are described. Main aspects of linear two port noise description using correlation matrix are discussed.

4. Modeling and simulation of bipolar transistors

This chapter deals with transistor modeling aspects. Main focus on the physical modeling and compact model level simulation of semiconductor devices is addressed. Noise and the dc, RF performance approximation using the hydrodynamic and drift – diffusion models is presented in brief. A compact model HICUM l2 v2.23 was selected to describe and analyze HBT operation.

5. Cross-correlation of base and collector current noise sources in heterojunction bipolar transistors

This chapter carry an investigation of InGaP and SiGe HBT base and collector shot noise source cross – correlation. At first various analytical noise models of HBTs are discussed, verified and compared. The HBTs are investigated using analytical noise model based on the hybrid π – type equivalent circuit (Fig. 2). According to obtained analytical modeling results, the correlated noise model was systematically implemented to compact model. The correlation term concept was realized in Verilog-A code for HICUM. On wafer measurements were performed with InGaP HBTs and two type SiGe HBTs: conventional emitter doping (CED) (Fig. 1a) and low emitter doping (LEC) (Fig. 1b)

Emitter current and collector currents have a full shot noise, which is correlated since the same electrons participate in the current flow [9, 10]. In compact models only currents and charges are available, resulting to the fact that frequency effects only to the first order will be captured [11]. Therefore at higher frequencies an approximation with the first in order of frequency term can be used. Such approach of the base and collector terminal cross- correlation power spectral density term yields the following:

$$S_{cb}(\omega)=2qI_C\left[1-\frac{\alpha_s}{\alpha_{s0}}\frac{G_{e0}\left(1-\dfrac{j\omega\tau_F}{3}\right)}{G_{e0}}\right]\cong 2qI_C\left(1-\frac{j\omega\tau_F}{3}\right),\qquad(1)$$

where q is a elementary charge, G_{e0} the low frequency value of base – collector conductance, τ_F is a delay time, α_s is the ratio of alternating emitter current to collector current and is α_{s0} it's low frequency value. This equation was derived using Shockley diffusion theory for *pn* junction and thus can be applied for the diffusion transistor.

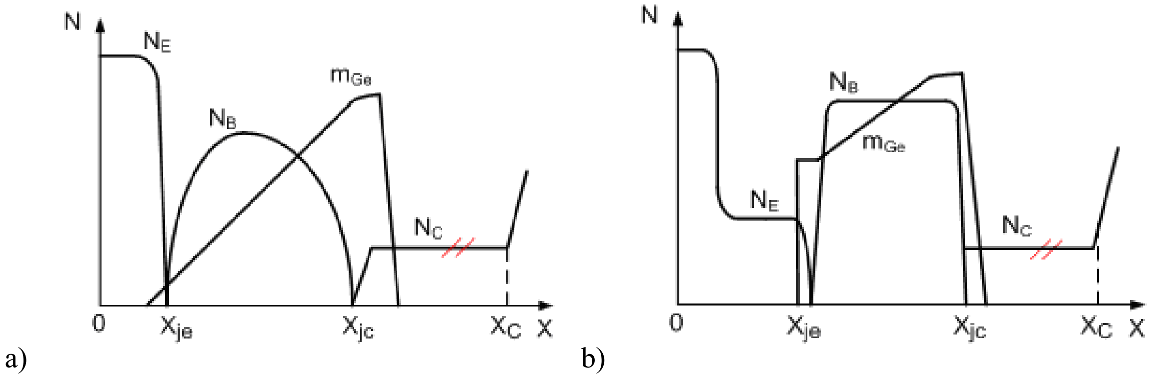


Fig.1. Sketch of net doping and Ge profiles for (a) CED transistors and (b) LEC transistors. x_{je} and x_{jc} denote the emitter and base junction depth; m_{Ge} indicates the Ge contents. [35].

Nowadays minority carrier transport for example in SiGe HBTs base due to Ge profile grading is more drift than diffusion. Therefore the delay time is no more defined as $\tau_F \approx \tau_B = w_b^2 / 2D$, where D is the minority carriers diffusion coefficient and stands for the diffusion transistor. Delay time τ_F can be shorter due graded base related effects. The delay time should account the complete delay of minority carriers from emitter to collector especially for modern high speed HBTs. The analytical noise model based on π-equivalent circuit (Fig.2) is derived to account cross – correlation of noise source power. At a given bias point compact model (HICUM) can be reduced to π−type equivalent circuit (EC) model. This is enables the proper comparison of analytical model with CM, using equivalent circuit parameters, obtained either from compact model solution or from measured s-parameters and from collector and base currents. Bipolar transistor high frequency performance is described using equivalent circuit with internal transistors

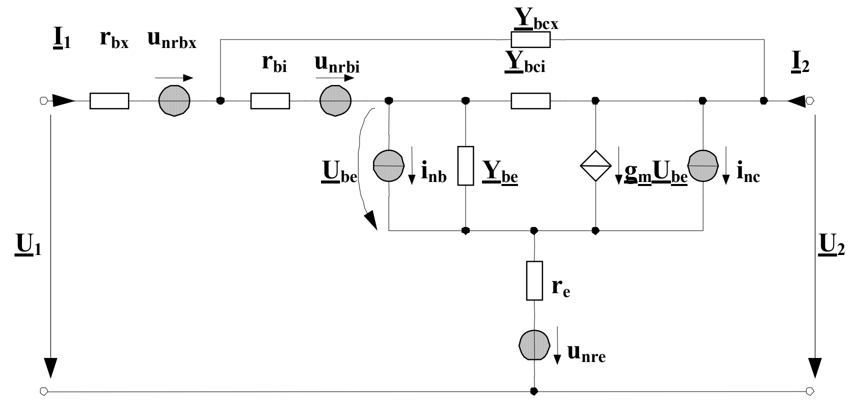


Fig.2. Hybrid π-type equivalent circuit is used in analytical noise model [P5].

parameters (internal base resistance r_{bi}, base – emitter capacitance C_{be}, internal base – collector capacitance C_{bci}, transfer conductance UUg_{m}). For the modern bipolar transistor technology due to shrinking transistor dimensions, influence of external equivalent circuit model parameters (external base resistance r_{bx}, external base – collector capacitance C_{bcx}, emitter resistance r_{e}) on rf and noise performance are becoming of importance. Therefore for the accurate s- and noise parameter modeling external model parameters must be taken into consideration.

Noise model equations were derived using the small-signal EC model (Fig.2). This EC model noise description consists on three thermal noise sources (emitter u_{nre}, internal base u_{nrbi} and external base u_{nrbx}) and two shot noise sources (base i_{nb} and collector i_{nc}) and transistors noise-free small signal circuits elements (r_{bi}, r_{bx}, r_{e} resistances, g_{m}, and base – emitter Y_{be}, internal base –collector Y_{bci}, external base collector Y_{bcx} admittances). For the analytical model verification purpose we need to know few variables such as Y (J_{C}) - parameters and EC model parameters: r_{bx}, r_{bi} (J_{C}), r_{e}, $C_{\mathrm{bcx}}(J_{\mathrm{C}})$, $C_{\mathrm{bci}}(J_{\mathrm{C}})$, $r_{\mathrm{be}}(J_{\mathrm{C}})$, I_{B} and I_{C}. For bias dependent noise parameter calculation it is convenient to use compact model which can yield a set of bias dependent small-signal model parameters.

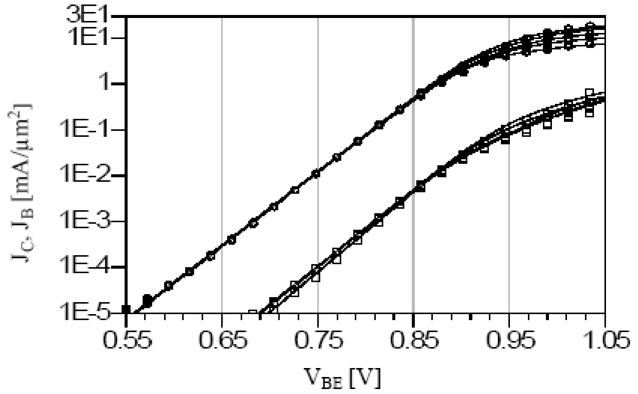
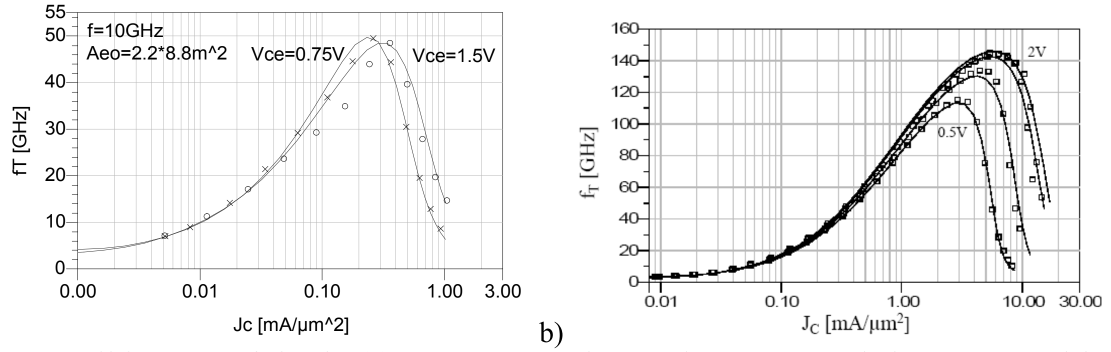


Fig.3: Forward Gummel plot for the CED SiGe HBT with emitter area A_{E0}=0.2x10.16 μm^2, V_{CE} [V]=0.5, 0.8, 1.5, 2.



a) b)

Fig.4. Cut-off frequency f_{T} for the (a) InGaP HBT and CED SiGe HBT. Symbols are extracted from measured s-parameters, lines are HICUM.

From another point of view comparison of analytical noise parameters and those, obtained from compact model equations to measured data enables accurate verification, since both compact and analytical models are using the same required variables. This method can reveal an impact of correlation between base and collector current shot noise, since compact model noise equations does not contain cross-correlation term. For the noise investigations, a DC and small-model model verification of both the compact and the lumped small-signal model is a prerequisite. DC characteristics were verified first (Fig.3). The transit frequency was determined from s-parameters using the single frequency method. Measured data are in good agreement with HICUM as it is seen in Fig. 4.

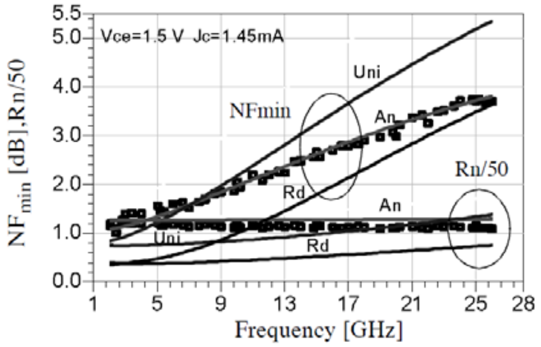


Fig.5. NF_{min} and R_n/50 vs. frequency for InGaP HBT. Symbols are measured. Indication “An” is analytical model, “Uni” is [10] and “Rd”is [8]. [P5]

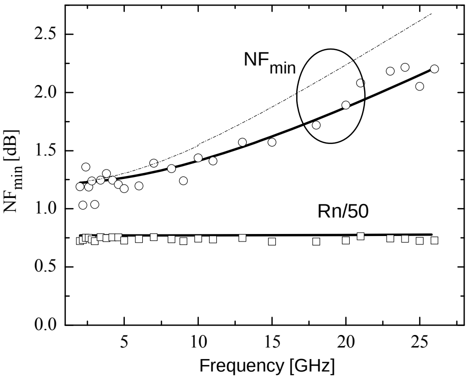


Fig.6. NF_{min} of CED SiGe HBT, V_{CE} = 1.5 V, J_C = 1.19mA/µm^2. Symbols are measured data, solid lines are correlated noise model and dashed-dotted line is noise model without correlation

Verification with the most known T- and π - EC based analytical noise models [12-14], have been performed, using the same circuit element values, all obtained from the detailed compact model analysis within the circuit simulator (the bias dependent circuit model parameters were obtained) (Fig.5). The impact of the correlation to noise parameters, using T-EC [12-14] in reference to measured noise parameters, was found not sufficient.

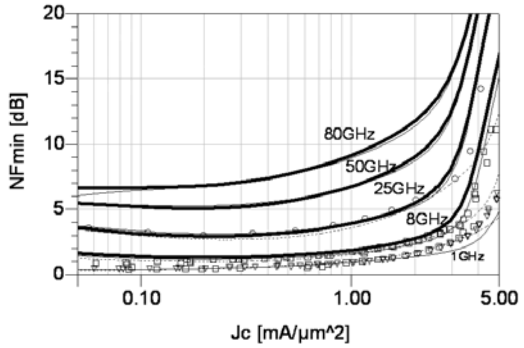


Fig.7: NF_{min} versus J_C for SiGe LEC HBT. Symbols are measured data, thick lines – HICUM, thin lines – analytical model, dashed lines - hydrodynamic model.

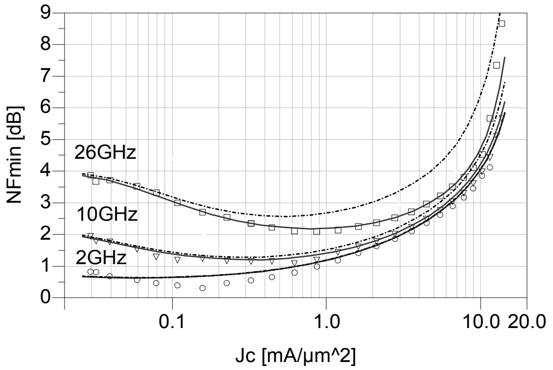


Fig. 8. NF_{min} of CED SiGe HBT, V_{CE}= 1.5 V. Symbols are measured data, solid lines are correlated noise model and dashed-dotted lines are noise model without correlation. [P4]

In order to verify analytical model in a general way, LEC SiGe HBT was selected. Comparison was performed with HICUM, TCAD Hydro Dynamic (HD) model [4] simulated and experimental data. Since noise measurements were done up to 26GHz, at higher frequencies model validity was verified against HICUM and HD. In the Fig. 7 NF_{min} at 1, 8, 25, and 50 and 80 GHz are presented. Device level HD simulations were performed with Galene III [4] simulator using SIMS concentration and Ge content profile. HD model was calibrated against DC and AC response and yielded perfect agreement. Note that HD simulation was performed on 2D device; therefore some mismatch at high currents is observed. For the LEC devices base and collector shot noise correlation was found negligible. Therefore other analytical models, which were used above also yielded fair agreement.

High frequency noise was measured for CED SiGe HBTs in the 2-26 GHz frequency band. For the model verification the noise sources cross - correlation cutout of Verilog-A code was introduced into existing Verilog-A HICUM L.2 v.2.3 model. Good agreement of simulated against measured dc and high-frequency data was obtained, (Fig. 8). Beyond f~10 GHz, simulation results without the effect of correlation deviate from the measured data significantly, whereas those including the effect of correlation are found to be in a perfect agreement up to 26 GHz (Fig. 6, 8).

Minimum noise factor of heterojunction bipolar transistors is reduced due base and collector currents shot noise cross – correlation at practical currents and frequency range (f < f_T). At higher frequencies this reduction becomes more obvious. Base and collector currents cross – correlation at high frequencies is depended on base transit time and transistor transconductance variation. Therefore only dynamic component of base current is correlated with collector current. Cross - correlation of base and collector currents can be reduced due to stored charges and reduced shot noise of collector current. Therefore cross – correlation effect is strongly influenced on the subject of transistor technology yet. Base and collector currents cross – correlation of LEC SiGe HBTs is negligible and have not influence to noise characteristics, differently than CED SiGe HBTs and InGaP HBTs (Fig. 9). Noise model was used to estimate noise correlation delay as function of transistor transconductance variation. Noise correlation delay is found a smaller compared to the total transit time (Fig.10.).

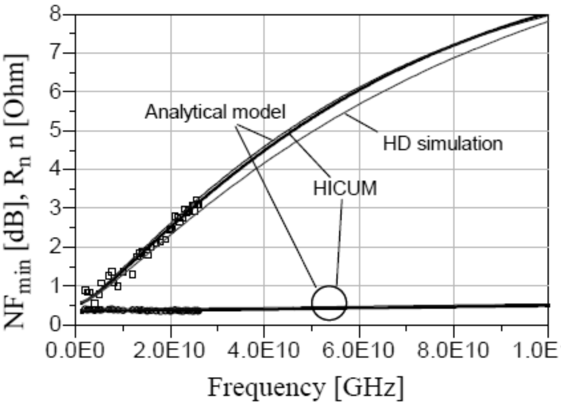
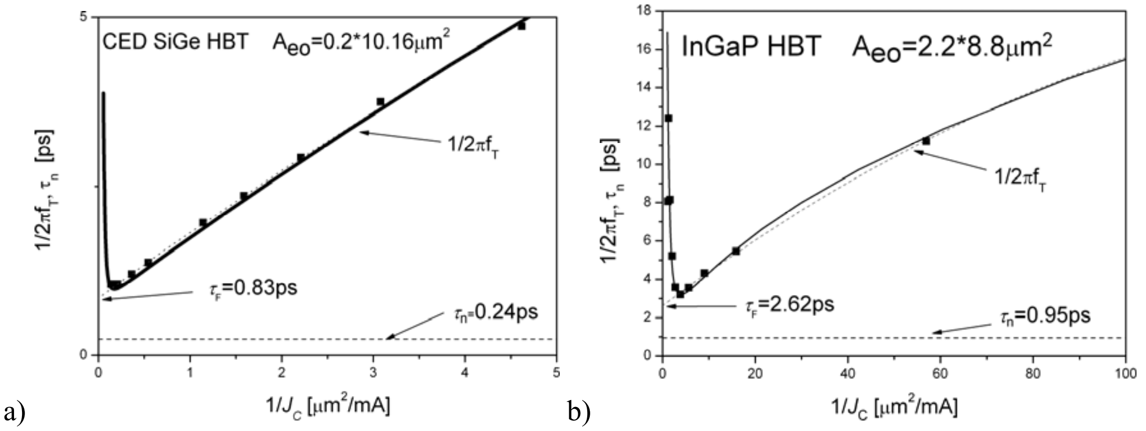


Fig.9. NF_{min} and normalized to 50 noise resistance versus frequency for SiGe LEC HBT, V_{CE}=1.5 V.



a) b)

Fig.10. Total transit time and noise correlation delay vs. collector current density.

It is well known that minimal noise figure (NF_{min}) of HBT is reduced due to cross-correlation of base and collector current shot noises. The cross-correlation is described via base delay time approach. This might be not applicable to thin-base AIIIBV HBTs mainly because of the quasi-ballistic nature of electron transport. In particular, the stored charge in the B/C region of AIIIBV HBTs reduces the collector shot noise resulting to a lower shot noise cross-correlation power. The electrons emitted into the base through the E/B heterojunction acquire additional kinetic energy due to the conduction band offset. They move across the base with a high almost constant velocity if the base is neutral. This ensures high speed performance.

However, the electrons can acquire higher energies in the B/C junction and reach energies sufficient for their transfer from Γ valley to L or X valleys where the effective mass is higher. The inter-valley transfer is responsible, in part, for the electron jam arising from lower drift velocity in L or X valleys. The space charge of the jammed electrons introduces additional signal delay.

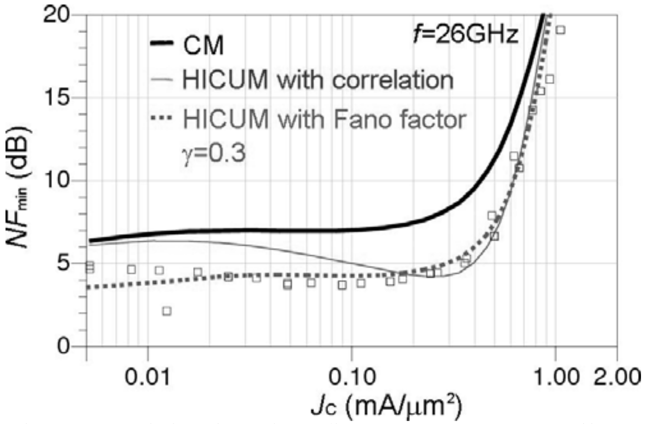


Fig. 11 Minimal noise figure NF_{min} vs. collector current density J_C for InGaP HBTs with w_B = 90 nm, symbols: measured data, lines: HICUM.[P6]

We assume that Coulomb shot noise blockade by the accumulated charge in the collector region is a significant factor for reduction of collector current shot noise [15]. The dotted curve in Fig. 11 illustrates the effect of Fano factor (γ) that enters the expression for the spectral density of collector current noise power:

$$S_{Ic}(\omega) = 2qI_C\gamma\,, \tag{2}$$

where q is an elementary charge, I_C is the collector current. A very good agreement of HICUM with introduced Fano factor ($\gamma = 0.3$) and the noise delay time $\tau_n = 1/3\ \tau_B$ against experimental data was obtained (Fig. 11).

6. Impact ionization influence to SiGe HBTs performances

This chapter investigation of impact ionization in SiGe HBT is represented. The investigated HBT was modeled by generalized hydrodynamic device simulation with a local temperature approach for avalanche generation, drift-diffusion simulation with a local field model, and the compact model HICUM L.2 [16] (Fig.12). Local temperature model parameters were calibrated by matching the avalanche multiplication factor (M) to results obtained from full-band Monte Carlo (MC) simulations. Experimental and device simulation data were verified against results obtained using weak avalanche current approach, implemented in compact bipolar transistor model, in this particular case HICUM [P4]. Higher operating frequencies in HBTs can be achieved, among other measures, by increasing the collector doping, which in turn increases the operating collector current density. However, high collector doping results in higher electric fields at the collector-base junction, leading to a reduction in collector-emitter breakdown voltage (BV_{CEO}). In certain applications transistors need to be operated at voltages beyond BV_{CEO}. This, however, leads to degradation of the transistor noise performance due to impact-ionization noise, which was view to be important for SiGe HBTs in [17, 18]. Experimental results indicate a strong increase of the transistor noise figure for a collector-emitter voltage (V_{CE}) larger than approximately (BV_{CEO}) [17]. This additional noise is induced by the random nature of the impact ionization (II) events and their influence on collector current.

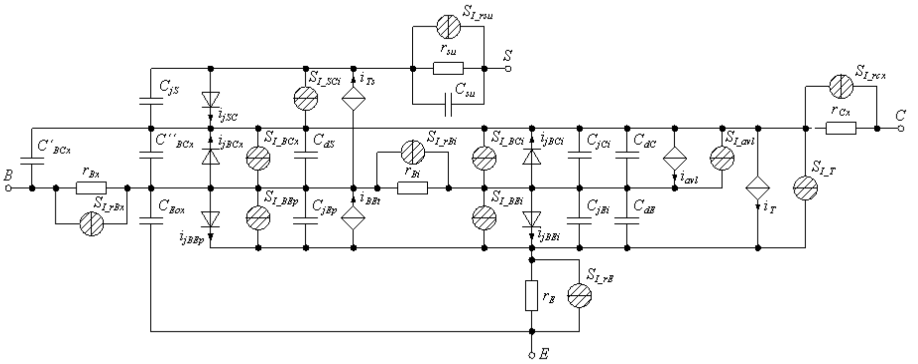


Fig.12. HICUM equivalent circuit with noise sources

The most accurate semi-classical method for carrier transport based noise modeling is the solution of the Boltzmann transport equation, generally using Monte Carlo (MC) techniques. This method includes details of carrier scattering due to its stochastic nature and inherent noise information. However, generation–recombination processes with large time constants introduce long tails in the autocorrelation functions, making accurate MC simulation of noise computationally very expensive. Therefore, hydrodynamic (HD) and even drift-diffusion (DD) models are attractive and often employed for noise simulation.

Fundamentally, II is a “threshold” effect, since prior to generating electron–hole pairs, carriers must gather sufficient energy through an electric field. DD models and classical theory using the *local* field for calculating II [18] ignore the distance necessary for accumulating this energy (“dead” zone). This leads to an overestimation of the multiplication factor *M* and the associated noise in advanced transistors where the “dead” zone length can be a significant portion of the high-field collector–base space charge region [19, P4]. Furthermore, particularly in HBTs, carriers related to the main (transfer) current already have accumulated significant energy when entering the high-field region which, in turn, shortens the length required for II. This process can be described by a history-dependent theory, which yields very good agreement with MC simulated ionization coefficients as well as with measured II noise in short Si and GaAs photodiodes [18].

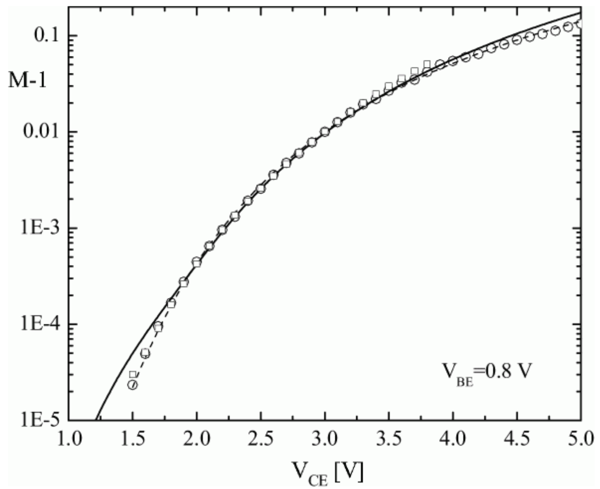


Fig.13: Avalanche multiplication factor dependence on the applied collector-emitter voltage. Comparison between HD model (dashed lines), HICUM (solid lines), and full-band Monte Carlo (MC) simulation (symbols).[P2]

Device simulations were performed with Galene III [20], using its HD and DD formulation. Doping profiles were generated with the help of SIMS measurements and adjusted according to electrical data (i.e. by inverse modeling). Standard physical models were used with all required noise and transport parameters obtained through full-band MC simulation under homogeneous bulk conditions [21]. The II process is included in Galene III using the modified Chynoweth law, in which dependence of the II coefficient α on the field E is given by:

$$\alpha = A\exp\left(-\frac{B}{E}\right). \tag{3}$$

The semi-empirical constants A and B are well established for bulk silicon. However, under nonlocal transport conditions the parameters A and B have to be adjusted [22]. Full-band MC device simulations were used to calibrate the II model parameters for the investigated HBT. A simplified model of the actual transistor (without external parasitic elements and self-heating) was used to analyze a pure impact ionization induced noise. The purpose was to resolve from the impact on noise of self heating effect. Finally the comparisons to CM and measured data were performed with a complete 2D model (including self heating and parasitic network). In case of the DD model E is the local electric field, while for HD simulations the local temperature model is used:

$$E_{ef} = \sqrt{\frac{3}{2}\frac{U_{T_c} - U_{T_l}}{\mu(T_c)\tau_{\omega}(T_c)}}; \tag{4}$$

$$U_{T_c} = \frac{k_B T_c}{q};\ U_{T_l} = \frac{k_B T_l}{q}, \tag{5}$$

Here, T_C as the carrier (electron) temperature obtained from HD simulation and T_L as the lattice temperature; k_B is the Boltzmann constant, q is the electron charge, $\mu(T_C)$ is the carrier temperature dependent electron mobility, and τ_w is the carrier energy relaxation time. Self-heating was included in device simulation self-consistently, based on a lumped thermal resistance R_{th} (as in compact models). The dissipated power and resulting change in lattice temperature is calculated from the power balance equation:

$$\Delta T_l = R_{th}(V_{CE}I_C + V_{BE}I_B), \tag{6}$$

Where I_B and I_C are the base and collector currents, respectively, and V_{BE} is the base-emitter voltage. The ambient temperature T_0 is used as a starting value for the first iteration to calculate the terminal currents using the HD or DD model. The updated temperature from (eq. (6)) is then used for the next iteration, and calculations are continued until the required accuracy was achieved.

Based on the HD simulation results for standard DC and AC characteristics, the II related model parameters can be calibrated. For this, HD simulations of the HBT are performed first without II. The resulting solution is used as input for non-self-consistent MC simulations. The resulting (electron) avalanche multiplication factor is then used for adjusting the constants A and B in (eq. (3) used for HD simulation. As it is seen in Fig.13, excellent agreement is obtained between HD and MC results for *M* over a wide collector-emitter voltage range. A similar calibration procedure was performed for DD simulation. Since in HICUM the avalanche multiplication factor is not directly available it was determined from internal variables, namely the avalanche current I_{avl} and the transfer current I_{T}, and the equation:

$$M - 1 = \frac{I_{avl}}{I_T}. \tag{7}$$

According to Fig.13 HICUM agrees very well with HD and MC result between 1.8 V and 4.0 V, but starts to overestimate *M* outside of this range. The standard noise parameters as a function of V_{CE} at the selected frequencies 1 GHz and 8 GHz are view (Fig.14). According to Fig.14, the NF_{min} is fairly constant between 0.2 and 2.5 V, but increases rapidly beyond 2.5 V and below 0.2V. In these regions, the curves for different frequencies tend to merge. NF_{min} increase at low V_{CE} is due to gain drop, (Fig.14). More detailed investigations revealed that although self-heating considerably increases the collector terminal current, its impact on NF_{min} remains limited though; for instance, without self heating NF_{min} (4.5 V) drops to 2.75 dB from 3.5 dB). The voltage and frequency dependence of NF_{min} is described very well by both HD simulation and HICUM.

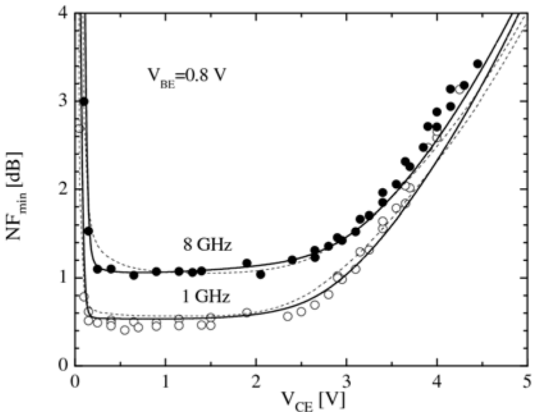


Fig.14: Minimum noise figure NFmin vs. collector-emitter voltage: HD simulation results with self-heating and impact ionization (dashed lines), HICUM (solid lines), and measurements (symbols). Open and filled symbols are experimental data. [P2]

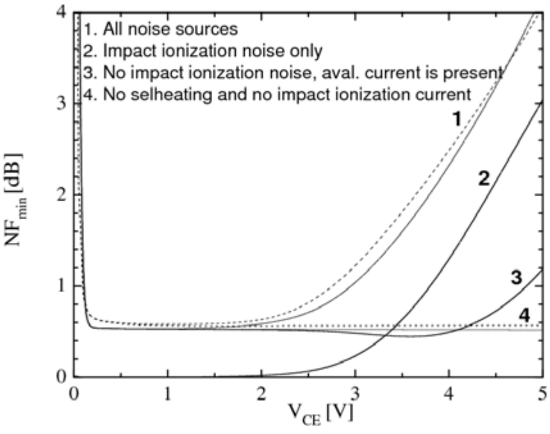


Fig.15. Resolved noise sources for NF_{min} vs. V_{CE} obtained from HICUM simulations (solid lines) at 1 GHz: complete model (curve 1), noise from impact ionization only and no self-heating (curve 2), with avalanche effect and multiplication of shot noise but neglecting II noise (curve 3), and neither II noise nor self-heating (curve 4). In addition, Galene results are inserted for case 1 and 4. [P2]

With the help of calibrated HD and CM, a decomposition of the impact of important effects on noise behavior was performed. The results of this analysis (Fig.15) reveal that the main contribution to the increase in NF_{min} beyond 2.5 V comes from II noise (curve 2). II noise itself is included in HICUM through the additional shot noise source, explaining the excellent agreement observed for the noise parameters. Turning off the II noise source (in HICUM) only and keeping the II effect, the avalanche – multiplication related collector shot noise amplification leads to a visible increase of

$NF_{\min}$ (curve 3) at high V_{CE}, as was explained in [18]. Turning off the II effect completely in the models (curve 4) makes $NF_{\min}$ independent of V_{CE} [P4]. Further decomposition of noise sources exhibit that the main factors influenced of noise increasing are impact ionization and self heating effects.

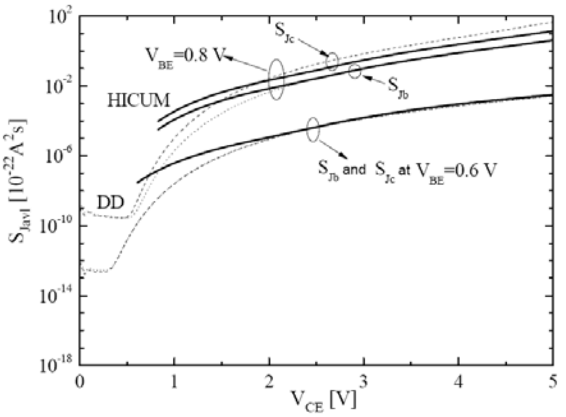


Fig.16. Current fluctuations of the collector terminal current (solid lines) and base terminal current (dashed lines) de to impact ionization for two different voltages VBE: Comparison between DD device simulation (thin lines) and HICUM (thick lines). [P2]

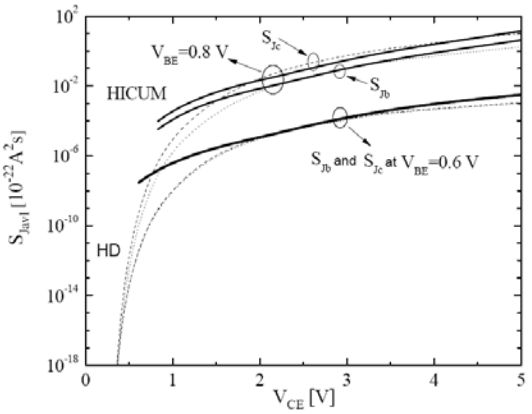


Fig.17. Current fluctuations of the collector terminal current (solid lines) and base terminal current (dashed lines) due to impact ionization for two different voltages *V_{BE}*: definitions are similar to Fig. 17. [P2].

The comparison between DD and HD simulation (Fig.16, 17), respectively, reveals the biggest difference at low V_{CE} which can be explained as follows. The DD model uses the local electric field to calculate the ionization coefficient (eq. (7)), ignoring the fact that carriers need to acquire a certain energy before they are able to ionize. This "threshold" behavior is captured more physically by HD simulation [22]. Therefore, the avalanche current from DD simulation is larger than the one from HD simulation, which uses a smaller non-local field. As a consequence, the II spectral densities are higher for DD than for HD simulation. This is valid for the entire voltage range although much more pronounced at low voltages. Both Fig.16 and Fig.17 also contain HICUM results. At low V_{BE} and V_{CE} values beyond 2V excellent agreement is obtained with device simulation. In the HD case, the slight deviation in curvature towards high V_{CE} is caused by the difference in curvature for the M factor (Fig.13). This difference is not visible for the DD case, since the HICUM avalanche equation is based on the DD equations. Toward slow voltages V_{CE}, the avalanche related spectral densities of HICUM remain higher than those from DD or HD device simulation.

7. Thermal dependence of high frequency SiGe HBTs

SiGe heterojunction bipolar transistor technology nowadays offers high speed transistors, capable to operate in cryogenic environment and featuring f_T and $f_{\max}$ beyond 400 GHz at 40 K [2]. SiGe HBTs, opposite to Si BJT, are suited to use in deep cryogenic temperatures naturally, including 4K [23]. Carefully SiGe HBT profile optimization can yield an improved RF performance at extremely low temperatures [23-25]. It was found that SiGe HBTs can be used for cryogenic applications, such as LNAs for satellite electronics [26], amplifiers for cooled Analog Digital Converters [27] and operational amplifiers working at 4 K [28]. Profile optimization offers to lower emitter concentration and to use trapezoidal Ge profile with a flat base doping.

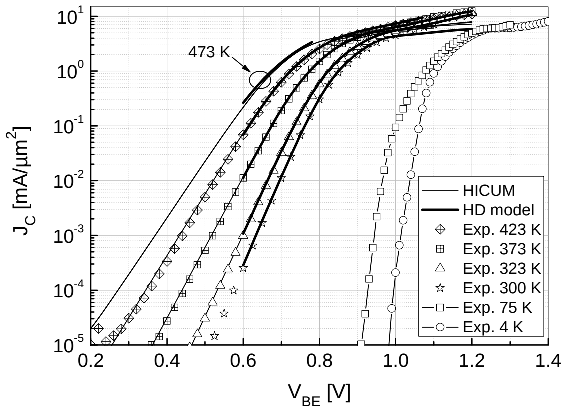


Fig.18 Forward Gummel plot for the LEC SiGe HBT at different T_0. [P1]

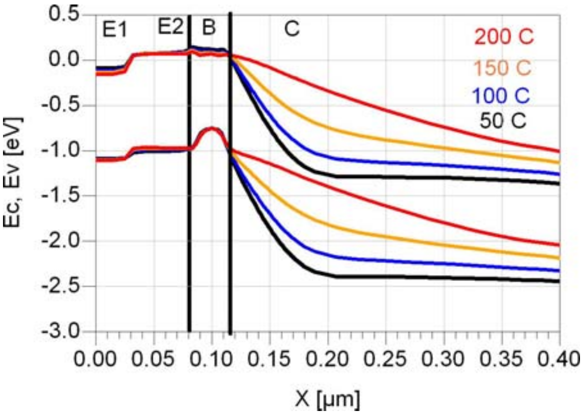


Fig.19. HD simulated LEC SiGe HBT energy band at different ambient temperatures. [P2]

Actually, LEC SiGe HBTs [29] meet all these requirements in a perfect way and are good candidates toward cryogenic operation. It was obtained that SiGe HBTs are also reliable devices for high temperature applications [30], what is not the case for Si BJTs. Along with high speed, a reduced high frequency noise of cooled SiGe HBTs is an advantageous feature for LNA design. It was found that a significant improvement of $NF_{\min}$ was achieved for conventional doping profile SiGe HBT at cryogenic temperatures [25, 31-33]. Circuit design for these applications requires an accurate physics based compact models, like HICUM [16], which could capture all important effects of HBT, operating in extreme temperature environment. In this chapter experimental and modeling results of LEC SiGe HBT at different ambient temperatures are presented.

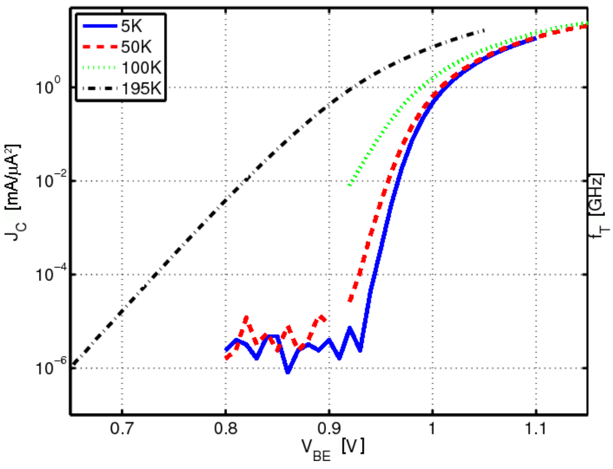


Fig.20. Forward Gummel plot for the CED SiGe HBT at different T_0.

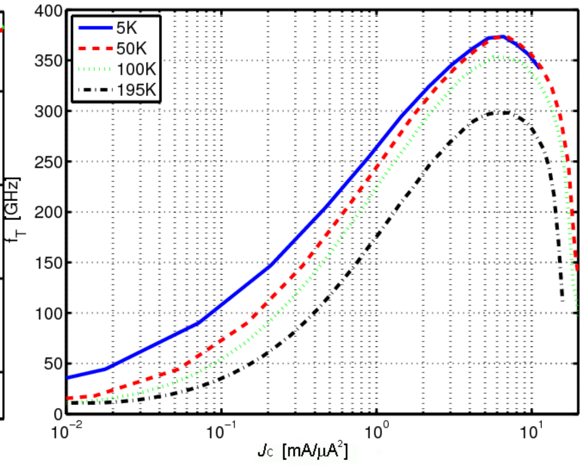


Fig.21. Forward Gummel plot for the CED SiGe HBT at different T_0.

Measured and simulated Gummel characteristic of SiGe HBT at different ambient temperature T_0 is presented in Fig.18. Good agreement of compact model and hydrodynamic simulations with experimental data in the range of T_0 (300 K-423 K) and at T_0 =473 K between HD and CM is obtained. At cryogenic temperatures collector current density (J_C) do not view additional leakage, associated with the field associated tunneling via trap states in the base [25], resulting to non-ideality increase. As expected J_C curve at cryogenic temperatures is view steep and shifted (in V_{BE}) behavior. Toward higher T_0, J_C increases with a following threshold V_{BE} decrease, what can be explained by energetic band (Fig.19) as well as carrier concentration T_0 dependence. Base current density (J_B) exhibit bumps, related to hetero-barrier effect enhancement (at high V_{BE}), tunneling and probably generation-recombination process [34].

The band gap in Si is increased by decreasing ambient temperature. The carriers concentration decreases due impurities freezing. SiGe HBT DC characteristics at low temperatures become sharper and push in higher voltages due energy band gap widening (Fig.18, 20). LEC SiGe HBT f_T maximum value is growing actually by 4 K differently than CED SiGe HBT. CED SiGe HBT cut – off growing stop approximately at 50 K ambient temperature (Fig.19, 21). It shows that LEC SiGe HBT carrier is not absolutely frozen at cryogenic temperatures.

Cut-off frequency behavior is well captured by CM and HD at moderate T_0=300-423 K (Fig.22). The f_T decrease is related to increase of electron delay in emitter and base (Fig.23). At cryogenic temperatures f_T reaches 160 GHz (Fig.22). Peak value of f_T exhibit linear dependence on T_0 [P1], what indicates that generation - recombination term at the surface of E and B separation, which is known to compensate the current gain increase [34], is negligible, favoring LEC HBTs for common emitter operation. NF_{min} analysis revealed that the main noise contributors are related to collector current fluctuations (shot-like noise) and thermal noise in the base. Base current fluctuations related noise becomes an important at high injection only. Simulated diffusion noise distribution demonstrate that electronic noise stems at BE junction but not in base-collector junction area. Hole diffusion noise is more sensitive to T_0, compared to electronic [P1]. Noise factor of SiGe HBT at T_0 = 4K was found relatively high (NF=3 dB). This can be explained by the weak temperature dependency of electronic diffusion noise, which is the dominant at T_0=323, 423 K.

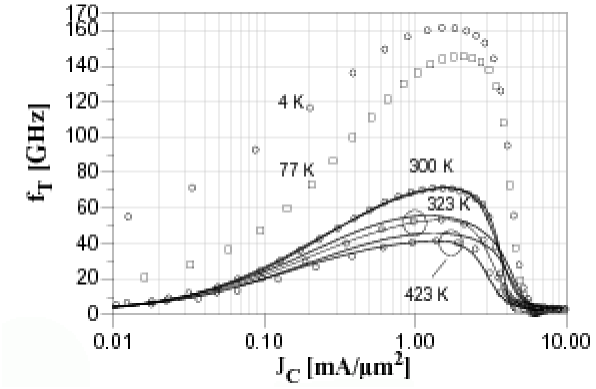


Fig.22. LEC SiGe HBT cut-off frequency vs. collector current density. Symbols are representing measured data, thick line-HD, thin line HICUM. [P1].

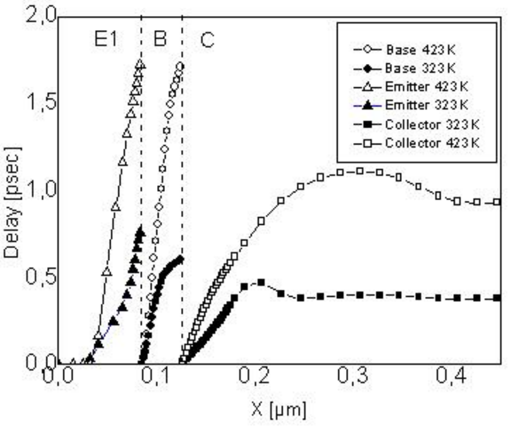


Fig.23. HD simulated LEC SiGe HBT total delay distribution at V_{CE}=1.5 V, V_{BE}=0.8 V. [P1]

Conclusions

- Compact model HICUM simulation of InGaP/GaAs and SiGe HBTs noise was compared with measurements and show a good agreement for the frequency range below ~ 10 GHz. Noise figure deviations beyond 10 GHz and higher current densities are affected by base and collector shot noise cross – correlation power. Derived analytical noise model with shot noise sources cross - correlation showed very good agreement with measurement data.

- Investigation of base and collector shot noise showed an importance of shot noise cross - correlation at high frequencies. Implemented correlated shot noise model solution in CM (HICUM L.2 v.2.3) via Verilog-A code was verified against CED SiGe and LEC SiGe HBTs. Performed simulations with this topical model exhibit a good agreements with measured data in practical frequency range ($f < f_T$)
- Chynoweth law describe well weak impact ionization in SiGe HBT (without device degradation, at M-1<<1). MC method was used to calculate electron multiplication factor. Simulations of LEC SiGe HBT with HICUM with implemented impact ionization model were in a perfect agreement with measured data in impact ionization bias range.
- LEC SiGe HBTs are capable to operate at 4 – 423 K ambient temperature range. At cryogenic temperatures a rapidly growing dc gain and cutoff frequency was observed. Hydrodynamic and compact model describes SiGe DC and noise characteristics only in the limited 300 – 423 K temperature range. The main noise sources of LEC SiGe HBT at 300 – 423 K temperature range are collector shot noise and base thermal noise.

List of publications

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Santrauka

Pastaruoju metu pasaulinėje rinkoje auganti paklausa dideliam informacijos perdavimo greičiui belaidžiuose ir optiniuose ryšiuose pastūmėjo įvairialyčių dvipolių tranzistorių (ĮDT) epitaksinių technologijų raidą ir tarpusavio konkurenciją. Šiuolaikiniai Si/SiGe, AlGaAs/GaAs bei InGaP/GaAs ĮDT pasižymi dideliu informacijos perdavimo sparta, dideliu signalo stiprinimu, žemu triukšmų lygiu ir mažu signalo iškraipymu. Mažėjant tranzistorių matmenims, neišvengiamai išauga elektriniai vidiniai laukai, elektronų įkaitimas darosi žymus. Tranzistorių veikimui tokiose sąlygose aprašyti reikia vis tikslesnių modelių, o triukšmų tyrimai padeda atmesti neadekvačius modelius ir yra labai aktualūs. Vienas iš svarbių aspektų, lemiančių tranzistoriaus triukšmo modeliavimo tikslumą, yra triukšmo šaltinių koreliacijos įskaitymas. Įprastiniai triukšmo modeliai, kurie naudojami kompaktiniuose modeliuose (tokiose kaip VBIC, HICUM, MEXTRAM), neatsižvelgia į šratinio triukšmo šaltinių abipusę koreliaciją ir greitaveikių tranzistorių triukšmines charakteristikas aprašo su paklaida (minimalus triukšmo rodiklis (NF_{min}) ženkliai viršija matuotas vertes, ypač aukštų dažnių bei didelių srovės tankių srityje). Šiuolaikiniai puslaidininkiniai prietaisai kartais priversti dirbti veikoje ties smūginės jonizacijos riba. Tranzistoriui veikiant stipriuose elektriniuose laukuose, kai ribinė įtampos vertė viršija slenkstinę jonizacijos įtampą (BV_{CE0}), staigų triukšmo padidėjimą lemia tranzistoriaus kaitimo ir smūginės jonizacijos efektai. Kai kuriems taikymams, tokiems kaip NASA kriogeniniai taikymai kosminiams tyrimams, auto radarams, X bangų mažatriukšmiams stiprintuvams, reikia stabiliai veikiančių puslaidininkinių įtaisų. Pasirodo, kad SiGe ĮDT yra geras kandidatas dirbti ypatingai ekstremalioje temperatūrinėje aplinkoje. Žeminant temperatūrą gerėja įvairialyčių dvipolių tranzistorių stiprinimas, aukštadažnės ir triukšminės charakteristikos, tai leidžia šiuos tranzistorius naudoti plačiame temperatūrų ruože.

Pagrindinis disertacinio darbo tikslas yra įvairialyčių dvipolių tranzistorių aukštadažnių charakteristikų ir triukšmo tyrimas dažnių ruože nuo 1 iki 30 GHz. Tyrimams buvo pasirinkti Si/SiGe ir InGaP/GaAs įvairialyčiai dvipoliai tranzistoriai. Tranzistorių triukšmų modeliavimas atliktas atsižvelgiant į tranzistoriaus šratinio triukšmo šaltinių koreliaciją, smūginę jonizaciją, tranzistoriaus parametrų temperatūrines priklausomybes.

Disertacinį darbą sudaro įvadas, šeši pagrindiniai skyriai, išvados, naudotos literatūros sąrašas ir priedai.

Įvade (pirmas skyrius) aptarti temos aktualumas, naudojami tyrimų metodai, praktinė darbo vertė ir atliktų tyrimų naujumas, apibrėžti disertacijos tikslai, pateikti ginamieji teiginiai ir darbo aprobacija.

Antrame skyriuje aptarti dvipolių tranzistorių teorija, jų raida ir pagrindiniai įvairialyčių dvipolių tranzistorių teoriniai ir technologiniai aspektai.

Trečiame skyriuje pateikti elektroninių sistemų ir įtaisų fliuktuacijų teorija, aprašyti pagrindiniai dvipolio tranzistoriaus triukšmo šaltiniai, apžvelgtas tiesinio keturpolio triukšmų aprašymas naudojant koreliacinę matricą.

Ketvirtame skyriuje aptarti modeliai naudojami dvipolių tranzistorių modeliavimui ir trumpai aprašyti šiame darbe naudojami fizikiniai (hidrodinaminis ir dreifo – difuzijos) ir kompaktinis HICUM modeliai.

Penktame skyriuje pateikti InGaP ir SiGe ĮDT bazės ir kolektoriaus šratinio triukšmo šaltinių abipusės koreliacijos tyrimai. Koreliacijos narys apibūdintas taikant triukšmo delsą, gautą iš keturpolio pilnutinio laidžio parametrų. Pateiktas analitinio triukšmo modelio išvedimas hibridinei π-tipo ekvivalentinei grandinei ir šio modelio taikymas tranzistorių aukštadažnių triukšmų tyrimams. Tyrimo rezultatai, naudojant šį modelį, parodė abipusės koreliacijos svarbą tranzistorių triukšmų modeliavime. Remiantis tiesinių sistemų teorija šis triukšmų koreliacijos modelis panaudotas kompaktiniame modelyje.

Šeštame skyriuje pateikti SiGe ĮDT smūginės jonizacijos tyrimai. Tirtų ĮDT charakteristikos, apimančios silpnos smūginės jonizacijos sritį, buvo modeliuojamos kompaktiniu HICUM L.2 modeliu, taipogi hidrodinaminiu modeliu, naudojant aproksimacijai vietinės temperatūros koncepciją ir dreifo difuzijos modeliu aproksimacijai naudojant vietinio lauko koncepciją. Vietinės temperatūros modelio parametrai yra gaunami kalibruojant krūvininkų dauginimosi faktorių Monte Karlo metodu gautais modeliavimo rezultatais. Gautas, modifikuojant Chinoweth'o dėsnį, silpnos smūginės jonizacijos modelis panaudotas HICUM kompaktiniame modelyje.

Septintame skyriuje pateikti SiGe ĮDT temperatūriniai tyrimai. Tranzistorių charakteristikos tirtos temperatūrose nuo 4 iki 473 K. Tyrimo rezultatai patvirtina silpno emiterio legiravimo SiGe tranzistorių panaudojimo galimybę žemose ir aukštose iki 473K temperatūrose. Gautų temperatūrinių priklausomybių palyginimas parodė silpno emiterio legiravimo SiGe ĮDT geresnes, negu įprasto emiterio legiravimo SiGe ĮDT, stiprinimo ir aukštadažnes charakteristikas žemose temperatūrose.

Apie autorių

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