# Diagnostics of GaAs HEMT based on noise measurements

M. M. JEVTIC[*], J. HADZI-VUKOVIC[a]

*Institute of Physics, Pregrevica 118, 11080 Belgrade, Yugoslavia*
[a]*Infineon Technologies , Siemensstraße 2, Villach Austria*

In this paper we have proposed a procedure for HEMT's diagnostic based on measurements of phase noise of test oscillator. From phase noise measurement in high frequency range we have estimated parameters of low frequency noise using a methodology based on the theory of noise up conversion, and then we have been used these parameters in diagnostic of transistors and to propose a criteria for selection of them. Suggested procedure is suitable for those who are interfered in applying HEMT's in high frequency circuits, because it enables to use noise spectroscopy in HEMT's diagnostic without direct measurements of low frequency noise. Experimental results that illustrate applying of procedure are given.

## 1. Introduction

Design and manufacture of electronic oscillators for high frequency range is usually followed by measurements of phase noise, because the low phase noise is one of the basic demands for use the oscillators in telecommunication and other electronic systems. The significant phase noise source is low frequency (LF) noise of oscillators active components. The conversion of this noise in phase noise was studied in several papers. Still, there is not given a complete theoretical explanation of the conversion mechanism [1 - 4]. HEMT has LF noise, which is lower than one of MOS transistor, and there is growing interest for use of HEMT in high frequency (HF) circuits. Accordingly, there is the interest for researches the methods for diagnostic and selection of these transistors in HF oscillator applications. We have suggested recently [5] an idea to define a method for analysis of HEMT's LF noise that is based on measurements of a test oscillator phase noise, suitable in HF circuit applications. Using this method, in this paper we present a procedure for diagnostic and selection of HEMT's based on LF noise parameters having in view the fact that LF noise can be an efficient tool for quality estimation and reliability prediction of electronic devices [6]. In Section 2, the procedure is shortly presented and we analyzed the influences of some HEMT's LF noise parameters on test oscillators phase noise and in Section 3 the experimental results and discussion are given. The possible quality indicators are analyzed.

## 2. Determination of LF noise parameters and quality estimation of HEMT based on measurements of phase noise of test oscillator

### 2.1 LF noise parameters of HEMT

The method of determination HEMT's LF noise is based on measurements of phase noise of simple test oscillator with HEMT in which up-conversion of HEMT's LF noise to phase noise is the most significant source of phase noise. This demand is opposite to usual one for design of a good oscillator when the lowest possible phase noise is needed, and thus as small as possible contribution from active components LF noise up-conversion is desirable. On the contrary, basic demands for test oscillator used in this method are simple for realization, big phase noise which is mainly influenced by LF noise of active component, in our case by HEMT's LF noise.

For experimental purposes we designed test oscillator whose equivalent electrical circuit is shown on Figure 1. We chose configuration with grounded drain [7], and coefficient of reflection higher than 1 is obtained by linear simulation. For transistor configuration, used in our experiment, we have simulated coefficient of reflection for different impedances in source circuit (serial connection of inductivity and resistance) with aim to realize this impedance as a micro strip line. We got the maximum of reflection on 14GHz for micro strip line 4.77mm long and 2,5mm width. After adding bias elements, the oscillator is optimized for frequency and output power. The nonlinear analysis (Microwave SPICE) based on equivalent electrical circuit shown on Figure 1 is done. In the analysis we have used nonlinear transistor model and linear package model, and the data from manufacturer sheet. The simulated frequency of oscillation has a value of 13.5GHz. The oscillator is realized on substrate of dimensions of $15 \times 20 mm^2$, thickness of 0.25mm and relative dielectric constant $\varepsilon_r = 2.17$ (alumina). Resistors are realized as micro strip lines.
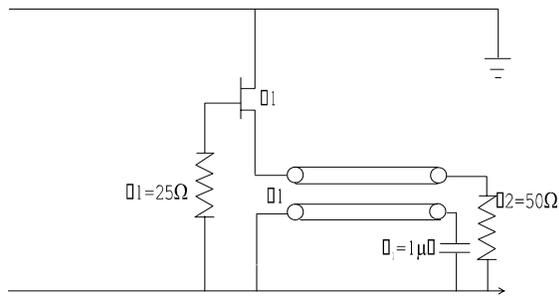
Fig. 1. Electrical circuit of test oscillator with HEMT (H1) and
micro strip line (T1)

The oscillation frequency of the oscillator has the value of 13.769 GHz. Power supply is with the voltage of –3V and current of 18 mA. Linearity of oscillator is defined by linearity of exchange of phase as a consequence of small current perturbation. This is checked by injection of current impulses of ± 100 µA and ± 50 µA, which correspond to charge impulses of ± 0.7 fC and 0.35 fC, and by simulation of phase change of output signal. The results are shown in Fig. 2. It can be seen that the test oscillator has a linear phase response on small charge injections.
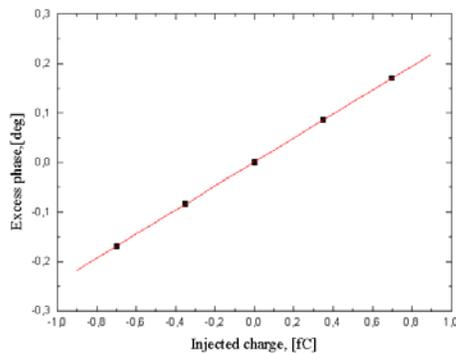


Fig. 2. The dependence of excess phase of test oscillator
as a function of injected charge

By an analysis of electrical circuit of oscillator, which includes all parameters of HEMT's nonlinear model (H1 in Fig.1) and the equivalent resistance $R_E$ of the transmission line, we have obtained that the source electrode node is the node in which the noise source influences the oscillators phase noise. If the current noise spectra in the particular node is $S_{in}(\Delta f)$, then in accordance with general theory of up-conversion of LF noise in phase noise [2] we can write the conversion relation in the form [5]:

$$S_\Phi(\Delta f) = \frac{k_H}{(\Delta f)^2} S_{in\,0} + \frac{k_L}{(\Delta f)^2} S_{inf}(\Delta f), \qquad (1)$$

where $S_\Phi(\Delta f)$ – is the phase noise spectrum, $\Delta f$ – the offset frequency which is equal to frequency in the case of LF noise spectra, $S_{in0}$ and $S_{inf}(\Delta f)$ – the spectra of white and colored noise in given node, respectively, $k_H$ и $k_L$ – the conversion factors which are characteristic of test oscillator for particular node. In our case they have values: $k_L = 6.82 \times 10^{26}(rad)^2/C^2$ and $k_H = 3.8 \times 10^2(rad)^2/C^2$.

The current noise spectrum in particular node can be expressed as

$$S_{in}(\Delta f) = S_{in\,0} + S_{inf}(\Delta f) =$$
$$A_{0n} + B_{0n}\left(\frac{\Delta f_0}{\Delta f}\right)^\gamma + \sum_i \frac{C_{in}\tau_i}{1 + (\Delta\omega)^2\tau_i^2}, \qquad (2)$$

where the first term on right hand side, $A_{0n}$, is the white noise spectrum, the second term – the 1/f noise spectrum and the sum presents the noise components with Lorentzian spectrum. For our test oscillator we obtain that the noise spectrum in the given node, $S_{in}(\Delta f)$, is connected with HEMT's current noise spectrum, $S_i(\Delta f)$, by the following expression:

$$S_i(\Delta f) = k_S S_{in}(\Delta f). \qquad (3)$$

The value of the coeficient $k_S$ depends from equivalent resistance $R_E$ and nonlinear HEMT's elements. By use of data for HEMT nonlinear elements given by manufacturer, we have obtained for $k_S$ the value of $2.06\times10^3$. If we use the general expression for HEMT's current noise spectrum in the case of independent noise sources:

$$S_i(\Delta f) = A_0 + B_0\left(\frac{\Delta f_0}{\Delta f}\right)^\gamma + \sum_i \frac{C_i\tau_i}{1 + (\Delta\omega)^2\tau_i^2}, \qquad (4)$$

and compare it with the expression (2) and (3), we can conclude that the parameters of HEMT's current noise spectrum are $A_0 = k_S A_{0n}$, $B_0 = k_S B_{0n}$ and $C_i = k_S C_{in}$. In this way, the parameters of HEMT noise are defined by the parameters of test oscillator and by the parameters of noise in particular node. Thus, the procedure for estimating LF noise parameters based on measurements of phase noise of test oscillator may be defined by following steps:

a) The first step is measurement of test oscillator's phase noise spectrum, $S_\Phi(\Delta f)$. Because the measured phase noise is usually characterized in terms of the single sideband noise spectral density, $\Lambda$, given in units of decibels below the carrier per hertz, dBc/Hz, thus,

$$S_\Phi(\Delta f) = 10^{\Lambda/10} \qquad (5)$$

b) The second step is the estimation of current noise spectrum in particular node, $S_{in}(\Delta f)$, by fitting the experimental and theoretical curve according to expressions (1) and (2). The presence of phase noise

caused by LF noise up-conversion is indicated by log-log curve of phase noise spectrum.

c) In the third step we use the relations (2), (3) and (4) to estimate the parameters of HEMT's LF current noise: $A_0$, $B_0$ ($\Delta f_0 = 10^3$Hz), $\gamma$, $C_i$ and $f_i = 1/(2\pi\tau_i)$. The diagnostic and selection of HEMT's is based on these parameters.

### 2.2 Quality estimation of HEMT

In view of quality estimation of HEMT, the following information obtained from the particular parameters of LF noise are of interest: noise level, value of $\gamma$ parameter (equal or different from unity), the existance of noise sources with Lorentzian spectrum (number of such sources, values of characteristic frequencies). Informitivity of such parameters related to the defects may be explained in following way. White noise, expressed with parameter $A_0$ is mostly connected with thermal noise which is always presented and together with 1/f noise with $\gamma = 1$, belongs to fundamental noises. They are presented in the case of ideal structure (without structural defects) also. In the presence of defects the noise level increases and the parameter $\gamma$ can be different from unity. The defects can also contribute to the appearance of noise sources with Lorentzian spectrum. In that way the defects contribute to appearance of nonfundamental noise sources which give information about the magnitude of structure nonideality. Thermal noise could be quality indicator of the structures with small resistance, because the bad contacts with increased resistance could contribute to thermal noise raise. We assume that it is not the case with HEMT's. There from point of view HEMT's diagnostic and selection, we are interested in 1/f noise spectrum parameters ($B_0$, $\gamma$) and Lorentzian spectrum ($C_i$, $\tau_i$). Accordingly we have analyzed how these parameters influence test oscillator's phase noise.
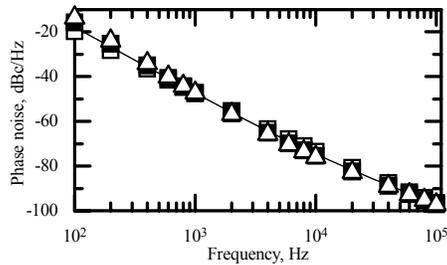


Fig.3. Test oscillator's phase noise as a result of conversion of white and 1/f noise with parameter : $\Delta$– 1.4; ■ – 1.2; — - 1 and □ – 0.8.

First we analyzed the influence of $\gamma$ parameter. If $\gamma = 1$ and there are no the sources with Lorentzian spectra, in the range of 1/f noise conversion dominancy, phase noise spectrum according to expression (1) and (2) has the dependence as $S_\Phi(\Delta f) \sim (\Delta f)^{-3}$. In the range of white noise

conversion dominancy, phase noise spectrum has the dependence as $(\Delta f)^{-2}$. The influence of $\gamma$ parameter on change of these dependances is illustrated by numerical results shown on Fig. 3.

In this simulation we used the constant parameters: for white noise: $A_0 = 10^{-25}$A$^2$/Hz, for 1/f noise: $B_0 = 5 \cdot 10^{-23}$A$^2$/Hz and $\Delta f_O = 10^3$Hz, and we assumed that there are no noise sources with Lorentzian spectrum. According to results from Fig. 3, in the part of the curve which is result of 1/f noise conversion in to the phase noise, the phase noise decrease with the exponent $2+\gamma$, while in the part which is influenced by white noise conversion, decrease with exponent 2. In the case of these results, the boundary between this dependence is $\Delta f_{0p} = 8,95 \cdot 10^3$Hz. It is important to notice that 1/f noise conversion is possible to be seen with measurements of test oscillator's phase noise if the measurements include offset frequency lower than corner frequency $\Delta f_{0p}$. This boundary frequency depends on corner frequency between HEMT's 1/f and white noise, $\Delta f_{0f}$, and of test oscillator's characteristics. Because limitations in measurement resolution, with increase in test oscillator's central frequency, the condition $\Delta f < \Delta f_{0p}$ is more difficult to fulfill. This means that during the design of test oscillator, special care should come to an agreement between central frequency of the oscillator, resolution of measurement and the need to cover the frequency range of 1/f noise up-conversion.
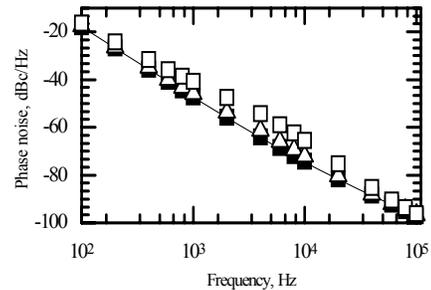


Fig. 4. Test oscillators phase noise in the presence noise of sources with Lorentzian spectrum with parameters $\tau_i = 1.99 \times 10^{-4}$s and $C_i(A^2)$: — - 0; ■ - $10^{-19}$; $\Delta$ – $10^{-18}$; □ - $10^{-1}$
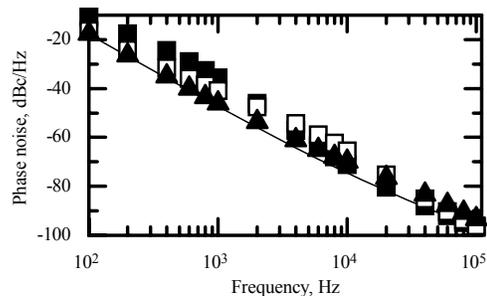


Fig.5 Test oscillators phase noise in the presence noise sources with Lorentzian spectrum with parameters $C_i = 10^{-17}A^2$ and $\tau_i(s)$: ■ – $1.99 \times 10^{-4}$; □ – $1.99 \times 10^{-5}$ and ▲ - $1,99 \cdot 10^{-6}$, straight line – without the presence of noise source with Lorentzian spectrum

The effects of noise sources with Lorentzian spectrum on the test oscillator's phase noise are illustrated by numerical results shown in Figs. 4 and 5. Contribution of Lorentzian spectrum in to the phase noise spectrum depends of $C_i$ and $\tau_i$ parameter values, as well as white and 1/f noise level. In the case of Figures 4 and 5 the parameters of these noises, $A_0$, $B_0$, $\Delta f_0$, have the same values as in Fig. 3, with value $\gamma = 1$. The g-r, RTS and burst noises have the Lorentzian noise spectra. The presence of conversion of these noise sources in phase noise spectrum, as we can see in Figs. 4 and 5, changes a curve slope in that way that part left from characteristic frequency, defined with time parameter $\tau_i$, has smaller slope, and the right part – higher slope. In other words, if the effect of white noise and noise with Lorentzian spectra are dominant, then in the vicinity of boundary frequency the phase noise spectrum dependence changes from $(\Delta f)^{-2}$ to $(\Delta f)^{-(2+n)}$, where n can have a maximum value of 2. In the case of added conversions of 1/f noise and noise with Lorentzian spectrum, the phase noise spectrum dependence changes from $(\Delta f)^{-(3-m)}$ to $(\Delta f)^{-(3+k)}$, where m and k have the values between 0 and 1 in accordance with the relation between 1/f noise level and the level of noise with Lorentzian spectrum. These conclusions suggest that an analysis of phase noise curve slope can give the beginning parameters for fitting experimental and theoretical curves in the procedure of LF parameters estimation. Because conversion factors for white and colored noises are not the same, the boundary frequencies between different frequency ranges in the phase noise spectrum are not the same as boundary frequencies of LF noise spectrum and thus LF noise parameters should be extracted to be used in the purpose of diagnostic and selection of active component. According to the previous results, the presence of nonfundamental noise sources influence by change of level and of frequency dependence of phase noise spectrum related to the expected dependences $(\Delta f)^{-2}$ and $(\Delta f)^{-3}$. In this way the phase noise of test oscillator is sensitive to quality parameters of HEMT and LF noise estimated from phase noise measurement of specially designed HEMT based test oscillator may be a good indicator of HEMT quality. The advantage of this approach in view of HF application is that it uses standard HF measurement, but for diagnostic purposes it use LF noise parameters which are related with physical model of noise sources. Thus, designers of HF electrical oscillators may use the LF noise spectroscopy for analysis of HEMT's without of use of LF noise measure equipment.

## 3. Noise diagnostic of HEMTs - Experimental results and discussion

The experiment is realized with HEMT based test oscillator. The commercial AlGaAs/InGaAs/GaAs HEMTs are used. The oscillator phase noise is measured by HP70000 spectrum analyzer. The results are shown in Fig. 6.
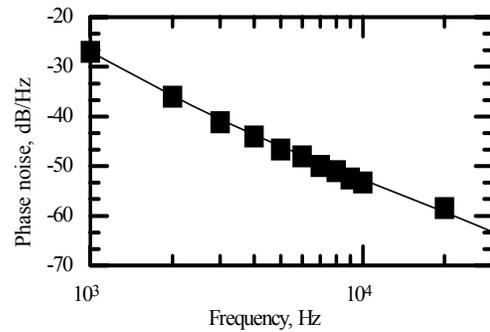


*Fig. 6. HEMT based test oscillators phase noise: ■ – experimental results, ▬ -theoretical curve*

According to the procedure defined in previous section, we have first fitted the theoretical results obtained by use of eqn. (1), (2) and (3) and experimental results. The theoretical results are presented with full line in Fig. 6. The data for noise spectrum in the particular node of test oscillator are used to examine the parameters of HEMT LF noise. We have found that the tested HEMT contains noise with the following sources: white noise – $A_0 = 5.15 \times 10^{-24} A^2/Hz$, 1/f noise – $B_0 = 9 \times 10^{-24} A^2/Hz$, $\Delta f_0 = 10^3 Hz$, $\gamma = 1.32$ and the three components of g-r noise – $C_1 = 1.08 \times 10^{-17} A^2$, $\Delta f_1 = 3.5 \times 10^2 Hz$; $C_2 = 2.88 \times 10^{-18} A^2$, $\Delta f_2 = 2 \times 10^3 Hz$; $C_3 = 8.04 \times 10^{-19} A^2$, $\Delta f = 6 \cdot 10^4 Hz$. Based on these parameters we have calculated the HEMT's current noise spectrum shown in Fig. 7. This figure illustrates that $\gamma \neq 1$ and that there are three noise sources with Lorentzian spectrum. Also, the $1/f^\gamma$ noise level is relatively low. So, the tested transistor contains two sources of nonfundamental noise that are connected with presence of defects.

From transistor selection point of view a significant information is the qualitative conclusion that defects are present, without taking in to account their nature, because the defects increase the probability of failure of such transistors. Selection can be based on the following criteria:
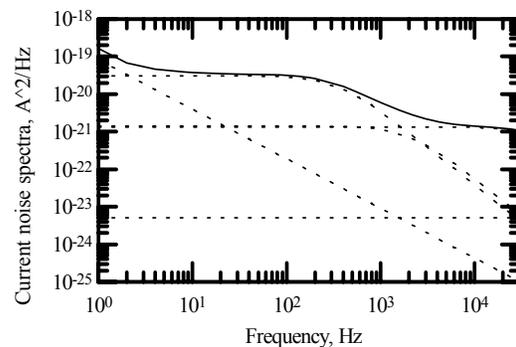


*Fig. 7. LF noise spectrum of HEMT obtained from parameters established from measurements of the phase noise of test oscillator. The dashed lines are LF noise Components.*

a) Without presence of Lorentzian spectra – advantage have transistors with $\gamma = 1$ and the lowest level of 1/f noise (lower $B_0$), b) With presence of Lorentzian spectra and $\gamma = 1$ – advantage have transistors with smaller number of Lorentzian spectra and the lower noise levels (lower $C_i$ and lower $B_0$), c) With presence of Lorentzian spectra and $\gamma \neq 1$ (the less reliable transistors) – advantage have transistors with smaller number of Lorentzian spectra and smaller deviation of $\gamma$ parameters. It has to emphasize that these criteria are connected with the degradation processes in active part of the component, in which on direct or indirect way take part the same defects that are connected with LF noise sources.

From the diagnostic point of view, it is interesting how from LF noise parameters to get the information about origin and defect concentration in transistor. The answer on this question is directly connected with physical model of LF noise sources in HEMT. It was recently observed in the case of structure with spacer (undoped AlGaAs) [8] that $\gamma$ can take values from 0.8 to 1.4 and that 1/f noise on 1Hz, with increasing channel width, pass through a minimum for the channel width of 10nm, and that it decreases with gate voltage increase if the channel width is $d_{ch} > 10$ nm. In [8], it is concluded that such behavior of 1/f noise for higher channel widths is connected with dislocations in the channel, because their concentration increase with width increasing. For smaller channel widths 1/f is connected with electron's wave function penetration in spacer, because the probability of electron capture in spacer increases with increasing wave function penetration in it.

Our results for $1/f^\gamma$ noise show that level of this noise is lower comparing with noise with Lorentzian spectrum and that $\gamma = 1.32$. The high value of $\gamma$ exponent is the sign that significant role in 1/f noise contribution have the slower random processes, and low level can be caused with small defect concentration and/or small number of carriers, which are involved in this processes. Because in our case the structure is without spacer, the presence of defects in AlGaAs with shallow energetic levels (they are far from heterointerface $Al_xGa_{1-x}As/In_yGa_{1-y}As$), on the one side, and existance of subbands in channel region, on the other, could be the reason for such behavior of 1/f noise. Also, missmatch of crystal lattice of channel and neighboring layers could make the strain and creation of dislocations that penetrate deep in to AlGaAs layer. Because lattice constant of InAs (6.06Å) is higher then ones for AlAs (5,67Å) and GaAs (5.46Å) the defects caused by missmatch of lattices on the edges of channel region and neighboring regions may be sensitive on moles part of constitutive materials. Due to the fact that obtained value for $\gamma$ exponent is hard to explain with mobility fluctuations in the channel only, the most probable 1/f noise source is carrier capture by defects in neighboring regions with shallow energetic levels and by this capture induced conductivity channel modulation. But, low level of 1/f noise suggests that there is small concentration of such defects.

The results show also that appearance of noise sources with Lorentzian spectrum are dominant. Sources of this noise can be connected with presence of DX centers in AlGaAs layer [8], [9] or with shot noise modulation on intrinsic junction of source and drain with channel [10]. Our simulation of current voltage characteristics of used HEMT with different values of gate voltage has shown that the serial resistance near channel does not affect the current voltage characteristics in this case. Accordingly it is realistic to suppose that the serial resistance is not the source of noise with Lorentzian spectrum. On the other side, DX centers in AlGaAs are connected with Si-dopants with energetic levels whose position according to $\Gamma$ and L band depends on AlAs mole fraction [9]. Characteristically mole fraction is x = 0,22 at which the DX level is equal with $\Gamma$ zone level. Position of DX level according to L zone is practically not changed. Because there is no spacer, fluctuations of transitions on DX centers could be the cause of noise with Lorentzian spectrum. These transitions taking place including phonon interactions and intervalley transitions. But one effect also should be included, possible presence of subbands in channel.

With channel width decrease (less than ~ 20nm) the conditions for continual conductivity of conductive band stop and we have the 2DEG subbands. Surface carrier concentration in the channel is distributed by subbands on logarithmic law [9]:

$$n_s = \sum_j n_{js} = \sum_j \frac{4\pi m^*(kT)^2}{h^2} \ln\left\{1 + \exp\left[(E_F - E_j)/kT\right]\right\} \qquad (6)$$
$$= \sum_j N_{cs}kT \ln\left\{1 + \left[(E_F - E_j)/kT\right]\right\},$$

where $m^*$ - is effective mass of electrons in channel, k – Boltzman's constant, T – ambient temperature (K), h – Plank's constant, $E_F$ – Fermy energy level and $E_j$ - energy level of j-th subband. The consequence of subband existence is that there exist transitions from subbands to DX centers. According to eqn (6), the surface carrier concentration in a subband decreases with increasing ordinal number of subband. There is possibility of transitions of carriers from subband to conductive band of boundary region over barier at interface. Height of the barrier depends on energy difference between conductive band of channel and boundary regions. Also, these transitions depend on the subband level and on the process of inter subband transitions. However, the inter subband transitions occur with frequency much higher than the observed noise frequency range, thus concentrations in subbands, due to these transitions, could be taken as constant. We have used commercial transistors in our experiments, without knowledge of composition x. Thus we can not discuss the quantitative details. For example, if we assume x = 0.22 ($Al_xGa_{1-x}As$) and y = 0.15 ($In_yGa_{1-y}As$), the estimated energy differences on interfaces AlAGaAs/InGaAs and InGaAs/GaAs will be 0,43 and 0.18eV, respectively. In approximation of infinity deep quantum well and channel width of 15nm we estimate the subbands with $E_1 = 0.0269$eV, $E_2 = 0,108$eV and $E_3 = 0.2425$ eV. According to our values of characteristic frequencies: 350 Hz, $2\times10^3$ Hz and $6\times10^4$ Hz

(see Fig. 7), and if we suppose that the frequency of 350 Hz is connected with transition from first subband to conductive band of AlGaAs, then the other transitions from another two subbands will fit to frequencies $8.5 \times 10^3$ Hz and 1.38KHz, which are higher then observed characteristic frequencies. Accordingly, we have concluded that the most probable noise sources with Lorentzian spectrum are the transitions from subband to DX centers. Depending on energy level position of complex DX center, capture time can be attributed with tunneling of electrons from channel to DX trap, and emission time with energy activation processes.

From reliability point of view, it is important to emphasize that the tested HEMT has an increased defect concentration in the boundary region. Due to the fact that the important degradation process in HEMT's is connected with hot electrons [10] and that the hot electron influence on characteristics degradation (trashold voltage degradation) is as higher as the defect concentration in boundary layers increase, the presence of noise sources with Lorentzian spectrum and 1/f noise with $\gamma \neq 1$ is an indicator of lower HEMT's reliability.

## 4. Conclusion

We proposed the method for HEMT's diagnostic based on low frequency noise estimated by measurement of test oscillator's phase noise. Test oscillator with HEMT is designed to have high level of phase noise and that it is mainly contributed by up conversion of HEMT's LF noise. Advance of this method is use of HF measurements to obtain information about LF HEMT's noise, which can be used as tool for quality and reliability predictions. Specially, this method is useful for people who design oscillators for HF range because the method is based on phase noise measurements usually used in electrical oscillator analysis. Experimental results show that the nonfundamental noise sources can be identified by this method. It is shown that they can be connected with defects in boundary regions near the channel. These defects can increase degradation processes connected with hot electrons in channel. The results are discussed from HEMT selection, diagnostic and reliability point of view.

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*Corresponding author: mjevt@phy.bg.ac.yu