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Analysis of nonlinear distortions of DpHEMT structures based on the GaAs/InGaAs compound with double-sided delta-doping

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Computational and experimental studies of the characteristics of a high-power AlGaAs/InGaAs/GaAs DpHEMT were performed. A self-consistent numerical solution of the Schrödinger and Poisson equations was used to calculate the band diagram and the electron concentration in the channel of the transistor under study. The electron mobility in the transistor channel was estimated experimentally at $9300\,\mathrm{cm^2/V\cdot s}$. The obtained transfer current–voltage characteristic of the transistor was used to calculate the parameters of a model differential amplifier (small-signal gain and third-order non-linear distortion factor).

Keywords: AlGaAs/InGaAs/GaAs DpHEMT, nonlinear distortion, spacer layers.

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1. Introduction

High-electron-mobility transistors (HEMTs), which are field transistors with a narrow-gap semiconductor forming a quantum well with two-dimensional electron gas in their channel layer, are now used widely in solid-state microwave electronics [1]. The HEMT channel is normally left undoped to reduce the electron scattering rate. The needed carrier concentration in the channel is achieved through the use of a delta-doping layer located at the transistor gate side. It was demonstrated in [2] that the addition of another delta-doping layer at the substrate side in next-generation GaAs-based HEMTs provides an opportunity to obtain a more linear transfer current–voltage characteristic (CVC) and suppress non-linear distortion [2]. The dependence of nonlinearity of the transfer CVC of a transistor on the electron distribution in the transistor channel was analyzed in [3]. The error of calculated data on non-linear distortion was attributable to the use of a standard analytical dependence for mobility, since in HEMT structures with double delta-doping, the mobility actually varies within a wide range at room temperature: $\mu_n = 3000{-}7500\,\mathrm{cm^2/(V\cdot s)}$ [4]. The scientific novelty of the study consists in the calculation of a transfer CVC with the use of a combination of numerical (self-consistent solution of the Schrödinger and Poisson equations for the determination of the electron concentration in the channel) and analytical (estimate of the electron mobility in the channel based on the measured resistance and electron concentration in the channel) models and the experimental voltage–capacitance characteristics factored in. The calculation method detailed in [5] was used to determine non-linear distortion.

2. Object under study

The parameters of a multisection pseudomorphic HEMT (pHEMT) based on GaAs/$\mathrm{In_{0.53}Ga_{0.47}As}$ with two δ-layers with a sheet impurity concentration of $2.4\cdot10^{12}$ and $0.7\cdot10^{12}\,\mathrm{cm^{-2}}$ were calculated. The composition of layers is presented in the table.

3. Procedure of calculation of parameters of the studied structure

Numerical calculations were performed by solving the steady-state one-dimensional one-electron Schrödinger equation (in the effective mass approximation) consistent with the Poisson equation [6]. The applied numerical solution procedure provides an opportunity to determine the potential profiles, size quantization levels, and the electron concentration in a quantum well with both uniform and nonuniform coordinate grids. The transistor gate voltage, the doping impurity concentration, and a number of other process parameters may be varied smoothly in these calculations. Sets of band diagrams and carrier concentration profiles in the channel for various gate voltages of a transistor at saturation are presented in Figs. 1 and 2, respectively. The obtained dependence of the electron concentration on gate voltage was approximated with quadratic function $n_{2\mathrm{Dcalc}}(U_{GS}) = a\cdot U_{GS}^2 + b\cdot U_{GS} + c$ (see the inset in Fig. 2), which was used to determine threshold transistor cutoff voltage $U_{TH} = -b/(2a) \approx 0.74\,\mathrm{V}$.

4. Calculation results and discussion

The carrier mobility for calculation of the transfer CVC and further analysis of non-linear distortion was measured

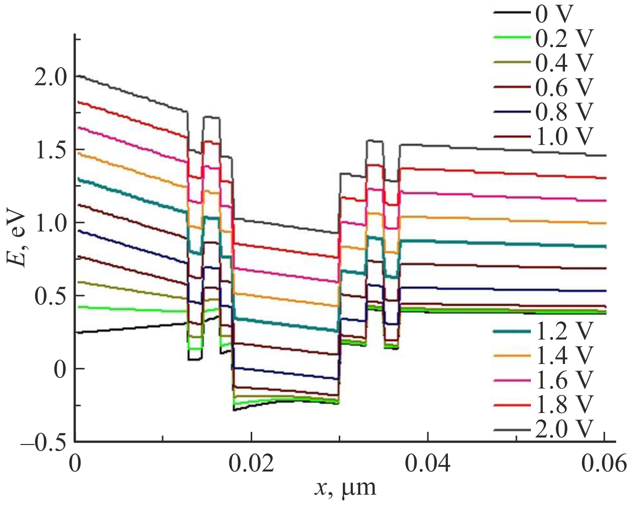

Figure 1. Results of numerical calculations of the band diagram of the studied DpHEMT structure. (A color version of the figure is provided in the online version of the paper).

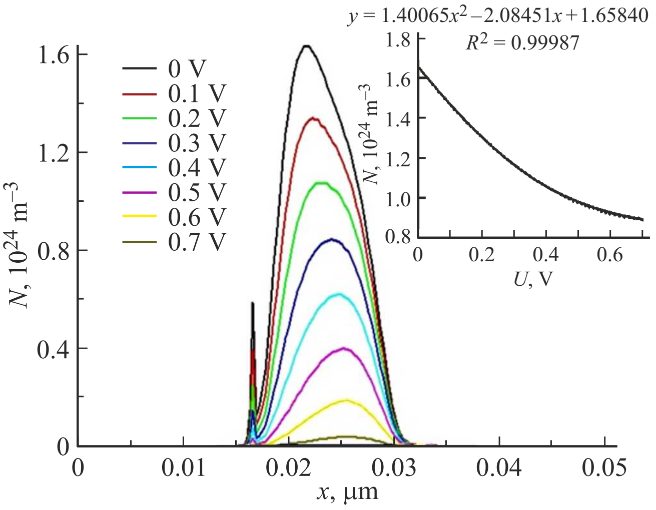

Figure 2. Results of numerical calculations of the electron distribution profile of the studied DpHEMT structure. The dependence of the carrier concentration on the gate voltage of a transistor at saturation is shown in the inset.

experimentally. At the first stage, the voltage–capacitance characteristics were used to determine the carrier concentration in accordance with the procedure outlined in [7]. Note that since the capacitance was measured between the gate and combined drain and source transistor electrodes, concentration $n_{2D\text{meas}}$ reconstructed based on these measurements differs from calculated concentration $n_{2D\text{calc}}$ in the channel of a transistor at saturation and cannot be used to obtain a transfer CVC and calculate non-linear distortion.

At the second stage, the channel resistance was measured with a diode „drain–source“ connection and a zero HEMT gate voltage. The carrier mobility was then estimated as $\mu_n = l/R \cdot S \cdot q \cdot n_{2D\text{meas}}$, where l is the channel length, R is the channel resistance, and S is the cross-section area of the channel. The following value of carrier mobility in two-dimensional electron gas at zero gate bias was obtained as a result: 9300 cm^2/(V · s). It is higher than the mobility value in a bulk material and agrees well with literature data.

Composition of the studied DpHEMT*

	H, nm	N_d, m^{-3}
Layer doped with silicon, $Al_{0.23}Ga_{0.77}As$	13	$5 \cdot 10^{22}$
Spacer layer, GaAs	0.4	
δ-layer GaAs	3	$1.2 \cdot 10^{25}$
Spacer layer, GaAs	0.4	
Spacer layer, $Al_{0.23}Ga_{0.77}As$	2	
Spacer layer, GaAs	15	
Channel layer, $In_{0.53}Ga_{0.47}As$	12	
Spacer layer, GaAs	3	
Spacer layer, $Al_{0.23}Ga_{0.77}As$	2	
Spacer layer, GaAs	0.4	
δ-layer, GaAs	3	$0.7 \cdot 10^{25}$
Spacer layer, GaAs	0.4	
Spacer layer, $A_{l0.23}Ga_{0.77}As$	100	
Buffer heterostructure, GaAs	440	
Substrate	1000	

Note. * channel length $L_g = 0.1\,\mu$m, channel thickness $W = 1000\,\mu$m, H is the layer thickness, and N_d is the doing impurity concentration.

The results of calculation of the steady-state transfer CVC are presented in Fig. 3. The steady-state CVC of the studied pHEMT was measured additionally with an L2-56 semiconductor device analyzer to verify the obtained results. The diagram of the measurement setup and the experimental procedure were detailed in [8]. It should be noted that the error of L2-56 measurements for high-power high-frequency submicron-scale transistors with capacitances of ∼ 10 pF and a flowing current of ∼ 600 mA exceeds 15%. This makes it considerably harder to analyze

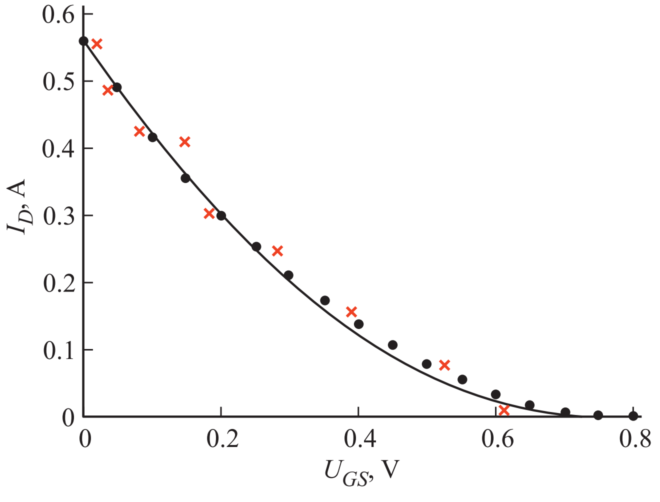

Figure 3. Steady-state transfer CVC measured using an L2-56 semiconductor device analyzer (crosses), calculated transfer CVC (dots), and quadratic approximation (solid curve) $I_d = K\,(U_{GS} - U_{TH})^2$ with parameters $K = 1\ 1/\text{V}^2$, $U_{TH} = 0.75$ V.

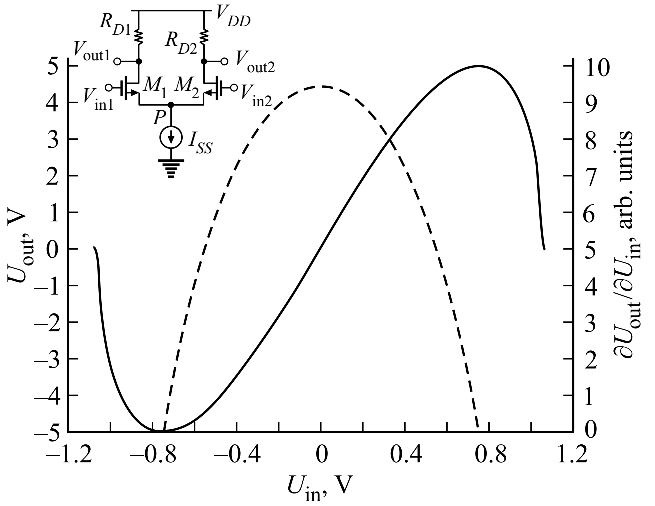

Figure 4. Calculated characteristics of a differential amplifier: solid curve — input/output; dashed curve — gain. The diagram of a differential pair is shown in the inset [5].

non-linear distortion relying directly on experimental data; therefore, third-order non-linear distortion was analyzed based on the results of numerical calculations of the transfer CVC.

The relation between input $u_{\text{in}}(t)$ and output $u_{\text{out}}(t)$ of an inertialess differential amplifier is characterized by a certain odd function $u_{\text{out}}(t) = g(u_{\text{in}}(t))$, which is normally represented in a polynomial expansion form in the analysis of third-order non-linear distortion:

$$u_{\text{out}}(t) \approx \alpha_1 u_{\text{in}}(t) + \alpha_3 u_{\text{in}}^3(t), \tag{1}$$

where α_1 is the small-signal gain and coefficient α_3 characterizes the non-linear properties of an amplifier.

Within the considered approximation, the output signal amplitude at the base frequency becomes equal to the amplitude of output third-order non-linear distortion products at an input signal amplitude of [5]

$$A_{IIP3} = \sqrt{\frac{4}{3}\left|\frac{\alpha_1}{\alpha_3}\right|}. \tag{2}$$

If a quadratic approximation of the transfer characteristic of the form $I_d = K(U_{GS} - U_{TH})^2$ is used, the input–output relation of a differential amplifier is specified by the following expression [5]:

$$V_{\text{out}} = K \cdot V_{\text{in}} \sqrt{\frac{2I_{SS}}{K} - V_{\text{in}}^2} \cdot R_D, \tag{3}$$

where I_{SS} is the net current of a differential pair and R_d are load resistances. It was assumed in calculations that $I_{SS} = 0.5625\,\text{A}$, $R_d = 8.9\,\Omega$. The $u_{\text{out}}(t) = g(u_{\text{in}}(t))$ dependence for a differential amplifier is presented in Fig. 4. Small-signal gain $\alpha_1 = 9.4$, and non-linear distortion coefficient $A_{IIP3} = 1.9\,\text{V}$.

5. Conclusion

A complex computational and experimental study of the characteristics of an AlGaAs/InGaAs/GaAs *p*HEMT and a differential amplifier based on it was performed. A self-consistent numerical solution of the Schrödinger and Poisson equations was used to determine the dependence for the electron concentration in the transistor channel. The maximum electron concentration was $n_{2D\text{calc}}(0) = 1.66 \cdot 10^{18}\,\text{cm}^{-3}$. The measured voltage–capacitance characteristics and channel resistance values were used to determine the electron mobility in the transistor channel at zero gate bias: $\mu_n(0) = 9300\,\text{cm}^2/(\text{V}\cdot\text{s})$. The obtained experimental and theoretical data made it possible to calculate the transfer current–voltage characteristic at saturation (threshold cutoff voltage $U_{TH} = 0.74\,\text{V}$) and estimate the small-signal gain ($\alpha_1 = 9.4$) and the non-linear distortion coefficient ($A_{IIP3} = 1.9\,\text{V}$) of a differential amplifier based on the transistor under study.

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Conflict of interest

The authors declare that they have no conflict of interest.

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