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Non-stationary Drift of Electrons in Submicron High Electron Mobility Transistor with two Heterojunctions

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Introduction

The development of modern high electron mobility transistor (HEMT) is not only caused by an application of multivalley semiconductor materials (GaAs, InP, GaN) and their alloys, but also by technology progress in creating of the multilayer nanostructures. The transistor processing speed increase may also be related with creation of submicron longitudinal and nanometrical cross –section structure sizes, including small dimension multilayered nanostructures [1]. The gate's characteristic sizes of such heterostructure transistors are 0.1-0.2μm with the sizes of the high-doped layers in an active region of the transistor less than 0.1 μm. There are experimental works about creation of heterostructure transistors with InAs quantum dots in a GaAs channel [2, 3]. Particularly in such structures, work [2], arsenide indium quantum dots were formed nearly to heterojunction in two gallium arsenide layers, in such way that on the transistor's cutting-off there was an injection of conductivity electrons to the channel due to collision ionization of quantum dots. A current in such transistor is related with two-dimensional (2-D) electron gas in the heterojunction potential well and electrons, injected from quantum dots. Unlike traditional high electron mobility transistors, the maximum drift velocity value here is essentially higher, and triode current-voltage characteristics have already been received with the length of gate of 0.4 μm. These transistors also have a small gate width (0.4 μm) and can't be an alternative for low-noise heterotransistors with characteristic gate width of above tens micrometers. They also don't have high repetition of characteristics, first of all, because of the various sizes of quantum dots.

The HEMT with two potential wells modelling is of interest because of the carriers' redistribution between two «channels», despite the increase of effective transistor thickness. Weakening in electrons warming-up, decreasing of their intervalley dispersion probability and high drift velocity values, causes this.

Modelling method

These high field and submicron effects predominating in the submicron structures are: non-stationary carrier drift under the condition of intervalley and optical dispersion of charge carriers predominance, «splash» effect of electron drift velocity, quasi-ballistic carrier transfer, substrate influence, etc.

The high field region and non-stationary processes are related with two-dimensional region of interaction electromagnetic field with carrier transfer and distribution of electron gas characteristics like electron temperature (energy), momentum (velocity), effective mass, etc. Therefore one of the approaches to achieve such characteristics is the solution of system of two-dimensional partial derivative equations, which includes the Poisson`s and continuity equations, as well as relaxation equations [4-6] that was obtained from Boltezman's kinetic equation in approximation of relaxation time.

In work [7] the possibility of nanostructure analysis based on hydrodynamic system of equations for two-valley energy band model without using the equation of impulse and energy saving is shown. The results of experimental investigation of submicron heterotransistor based on AlGaN-GaN with two heterochannels (two potential wells with two-dimensional electron gas) that have more attractive high-speed characteristics are presented in work [1].

In this work the possibility of the non-stationary effects in multilayered heterostructure, based on the system of two-dimensional equations that include relaxation equations is researched and the results of AlGaAs heterotransistor simulation with two-dimensional potential wells (length gate is 0.2 microns) are given.

To analyze the non-stationary drift effects it's necessary to solve momentum and energy conservation equations.

The particles (concentration) conservation equation forms to the basic system of equations:

$$\vec{v}.\mathrm{grad}(n) = v_x \frac{\partial n}{\partial x} + v_y \frac{\partial n}{\partial y} = 0. \quad (1)$$

While using a two-valley model of energy band for gallium arsenide (indexes i and j), distribution of electrons is characterized by relative coefficients of valley populations that are the electron temperature and relaxation period functions [2]:

$$b_i(T_e) = n_i/n = n_i/(n_i + n_j) = 1/(1 + n_j/n_i) = \\ = 1/(1 + \tau_{nji}/\tau_{nij}). \quad (2)$$

Average thermal energy for a two-valley model is determined as:

$$E_T = b_\Gamma E_{T\Gamma} + b_L E_{TL}. \quad (3)$$

A ratio between thermal energy and electron gas temperature is determine as $E_T = 3kT_e/2$. Energy conservation equations, using the electron gas temperature are determined as:

$$v_x \frac{\partial T_e}{\partial x} + v_y \frac{\partial T_e}{\partial y} = \frac{T_e - T_0}{\tau_E} + \frac{2E_D}{3k}(\gamma - 1), \quad (4)$$

where drift energy is determined as:

$$E_D = m^* v^2/2 = \frac{m^*}{2}(v_x^2 + v_y^2). \quad (5)$$

The γ coefficient is determined by means of energy τ_E and momentum τ_p relaxation time as $\gamma = 2\tau_E/\tau_p$ where E_0 - equilibrium energy value.

Basic conservation equations for carrier momentum projections in approximation of relaxation time look like:

$$v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial x} = \frac{e\varepsilon_x}{m^*} - \frac{v_x}{\tau_p}; \quad (6)$$

$$v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial x} = \frac{e\varepsilon_y}{m^*} - \frac{v_y}{\tau_p}. \quad (7)$$

Therefore, basic system of relaxation equations for non-local two-dimensional model for electrons includes the particles conservation equation (1), the energy conservation equation in electron temperature terms (2) and momentum conservation equations (3) and (4).

The system of equations become closed under the condition that the Poisson`s equation in the two-dimensional approximation (5), equation for the current density (6), and corresponding relaxation time approximations are included in it:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = q\Delta n/\varepsilon\varepsilon_0, \quad (8)$$

$$\vec{j} = -qn\vec{v}. \quad (9)$$

Submicron multilayered structure modelling with complex topology is related with nonlinear function in the second member of Poisson`s equation, specifying distribution of charge density, and with application of numerical methods with specified discretization pitch and inhomogeneous boundary conditions.

On receiving of solution for potentials (Poisson`s equation) and concentration (continuity equation) with prescribed accuracy, equations of the system above equations are solved conjointly. The solution algorithm of system of Poisson end continuity equations, taking into account approximations and electric field intensity equation $\varepsilon = -\mathrm{grad}(\varphi)$, is a several nested loops. Each of these equations is a high dimensionality system of finite-element equations. Dispersed matrixes of these systems have diagonal dominance and a belt structure. To solve the systems sweep method in combination with Newton's iterative multi step method is used. After calculating of the electric field intensity distribution in a structure with given values of concentration and dopant profiles (Poisson's two dimensional equation), system of relaxation equations, including a momentum, energy and concentration conservation equations and also equation for current in common was solved.

Simulation results

The test structure of simulated HEMT is presented in Fig.1.

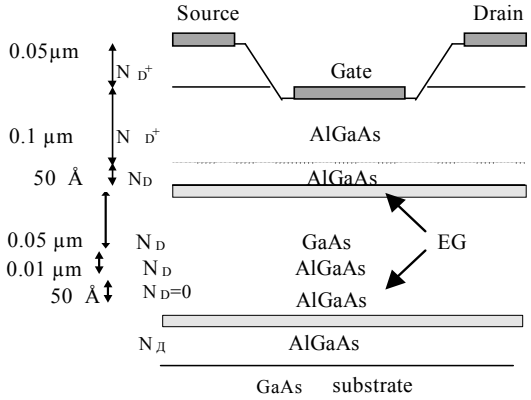

Fig. 1. Submicron HEMT structure with two potential wells

The structure is characterized by the following physical-topological parameters: gate length is 0.2 μm, effective thickness of $Al_xGa_{1-x}As$ (x=0.3) wide-band-gap doping layer under gate is 0.1μm, undoped $Al_xGa_{1-x}As$ layer (spacer) thickness is 50 Å, undoped GaAs layer on semi-insulation substrate with thickness of several tens micrometers, in which surface layer, as a result of zone breaking, a potential well is formed. Parameters of HEMT second channel are similar and shown in Fig.1. As all electronic processes are related with the surface layer and two-dimensional electron gas (EG) in potential wells, modelling region is limited by the effective transistor thickness of 1-2 μm.

In Fig. 2 and 3 two-dimensional potential energy and electron temperature distributions in HEMT channel are shown.

The output transistor current is calculated as a normal current component to the drain contact by the known two-dimensional electron concentration distributions, electrical field intensity and electrons velocity by the results of initial system of equations by achievement of prescribed accuracy of solution in mesh points.

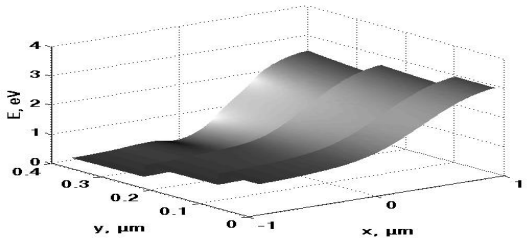

Fig. 2. Potential energy surface in HEMT

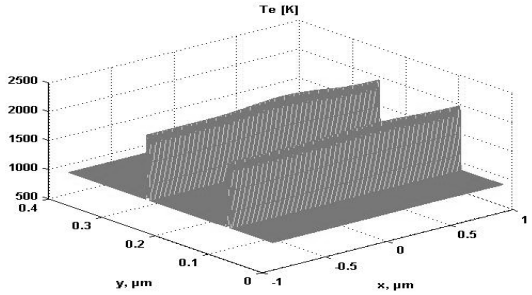

Fig. 3. Electronic temperature distribution

Given characteristics are calculated on source, gate and drain electrodes with such electric bias values: 0V, -0.5 V, 4.0 V, respectively. Band break on the heterojunctions boundaries was assigned as a built-in potential of height about 0.4 V under the solution of Poisson`s equation with the assumption of absence of quantum effects for electrons in a potential well.

According to simulation results electron gas warming-up and electron temperature growth to a greater extent is explained by electron drifting in potential well at the heterojunction boundaries. Electron temperature (Fig.3.) in the first (adjoining the gate) heterojunction is a little higher, than in the second, which points to electrons redistribution by energies. The «splash» effect of drift velocity is noticed for electrons of both heterojunctions. Electron temperature (Fig.3.) and drift velocity simulation results [8] point to lesser extent of carriers' warming-up by electric field and approximately on 30-40% higher values of drift velocity, than in similar HEMT with one potential well [6].

It can be related with the carriers warming-up by the electric field processes delaying, because the carriers drift is basically related with electrons in potential wells and also with carriers «cooling» during their displacement by gate field from one potential well into another and with a carriers energy reduction during their overcoming of the second potential barrier. As the results of several experiments show, during this process the distance between the heterojunctions should be less than the free electrons path. The maximum values of drift velocity are achieved by negative bias at the gate of 0.5-0.6 V.

Analytical model

The two-dimensional numerical model above allows getting approximations and average values of electron velocity and concentration.

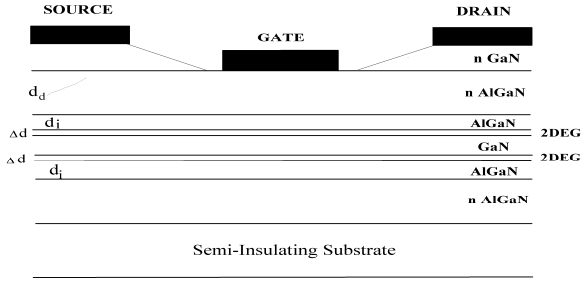

Fig. 4. Structure of submicron high mobility electron transistor (HEMT) for analytical description

These values are used as analytical model parameters of transistor for the current-voltage characteristic, small-signal circuit parameters and microwave characteristics calculation. The structure with following denotations is used for an analytical model.

The gate and drain voltage dependence on electrons concentration in a two-dimensional channel of transistor is used for HEMT static characteristics analysis [9]:

$$n_s = \frac{\varepsilon_0 \varepsilon_{AlGaN}}{q(d_d + \Delta d)}[V_g - V_{t0} - V(x)]; \qquad (10)$$

where d_d – AlGaN layer thickness, as shown on Fig.4; V_{t0} – threshold voltage, $\Delta d = \frac{\varepsilon_0 \varepsilon_{AlGaN} a}{q} \approx$ 80(Å), $a = 0.125 \times 10^{-12}$ (eV/sm^2).

In additional to the average drift velocity and electrons concentration values in the channel, the effective geometrical parameters values – W, d_d, Δd, L_g for analytical calculations are also used. They are received from the numerical model too. An analytical expression for the drain current is

$$I_{ds} = \beta \frac{(V_g - V_{t0})V_{ds} - {V_{ds}}^2/2}{1 + \alpha V_{ds}}; \qquad (11)$$

where $\beta = \varepsilon_0 \varepsilon_{AlGaN} \mu W / (d_d + \Delta d) L_g$, μ is the electron's mobility, L_g - gate length; $\alpha = \frac{v(x)/v_0}{E_0 L_g} + \beta R_s$, R_s is the source resistance.

Drift velocity may be calculated:

$$v(x) = \frac{v_0 \, E(x)/E_0 + v_s \, [E(x)/E_0]^2}{1 + [E(x)/E_0]^2}; \qquad (12)$$

where v_s is the saturation drift velocity, $v_0 = \mu_1 E_0$, μ_1 is the low field mobility, E_0 is the fitting parameter (~3.0 kV/sm).

The saturation voltage can be found from the expresion:

$$V_{d\,sat} = \frac{\sqrt{1+2\alpha(V_g - V_{t0})} - 1}{\alpha}. \qquad (13)$$

For the drain voltage greater than the saturation voltage, channel current is calculated by (9), but V_{ds} should be replaced by V_{dsat}, and L_g by $L_g - L_s$,

$$L_s = \gamma[\sqrt{1+2(V_{ds} - V_{d\,sat})/\gamma E_{sat}} - 1], \qquad (14)$$

where

$$\gamma = \frac{\varepsilon_0 \varepsilon_{AlGaAs} v_s \Delta d W E_{sat}}{I_{d\,sat}}. \qquad (15)$$

The resulted model allows to analyze both physical processes in a transistor and to calculate its output characteristics.

Conclusions

Models and algorithms of non-stationary drift effects analysis based on the relaxation equations system in two-dimensional approaching for analysis of physical processes in multilayered HEMT with two potential wells has been offered. It is shown, that the average drift velocity values in the structure presented above are higher, than in submicron HEMT with one potential well. Developed models are suitable (at corresponding approximation of relaxation periods) for calculation of submicron heterostructure based on wide spectrum semiconductors connections A_3B_5 with intervalley electrons transfer, including perspective compounds InP, GaN, etc.

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V. I. Timofeyev, M. Amini, E. M. Faleeva. Non-stationary Drift of Electrons in Submicron High Electron Mobility Transistor with two Heterojunctions // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 4(76). – P. 33–36.

Algorithms and numerical procedures for analysis of physical characterizations distributing in a submicron high electron mobility transistor (HEMT) are developed. Based on a two-dimensional physical-topological model processes of non-stationary carriers’ drift in a transistor with two potential wells are considered. It is shown that the average electron gas temperature lower and electron drift velocity is higher in transistors with two potential wells with the submicron gate size (0.2μm), than in traditional transistor structures. Ill. 4, bibl. 9 (in English; summaries in English, Russian and Lithuanian).

В. И. Тимофеев, М. Амини, Е. М. Фалеева. Нестационарный дрейф электронов в субмикронных гетеротранзисторах с двумя гетеропереходами // Электроника и электротехника – Каунас: Технология, 2007. – № 4(76). – С. 33–36.

Разработаны алгоритмы и численные процедуры для анализа распределений физических характеристик в субмикронном гетероструктурном транзисторе (СГСТ). На основе двумерной физико-топологической модели рассмотрены процессы нестационарного дрейфа носителей заряда в транзисторе с двумя потенциальными ямами. Показано, что в транзисторах с двумя потенциальными ямами с субмикронными размерами затвора (0.2 мкм) среднее значение температуры электронного газа ниже, а дрейфовой скорости электронов выше, чем в традиционных структурах. Ил. 4, библ. 9 (на английском языке; рефераты на английском, русском и литовском яз.).

V. I. Timofeyev, M. Amini, E. M. Faleeva. Nestacionarusis elektronų dreifas submikroniniuose heterotranzistoriuose su dviem heterosandūromis // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 4(76). – P. 33–36.

Sukurti algoritmai ir skaitiniai metodai analizuoti fizikinių charakteristikų skirstiniams submikroniniame heterostruktūriniame tranzistoriuje. Remiantis dvimačiu fizikiniu topologijos modeliu, apžvelgti nestacionariojo krūvininkų dreifo tranzistoriuje su dviem potencialų duobėmis procesai. Parodyta, kad tranzistoriuose su dviem potencialų duobėmis vidutinė elektroninių dujų temperatūra esant submikroniniams užtūros matmenims (0,2 μm) yra žemesnė, o elektronų greitis didesnis negu tradicinėse struktūrose. Il. 4, bibl. 9 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).