Numerical modeling of microwave switchers with subpicosecond time delay

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ABSTRACT

In this article the layout and structure of the microwave switcher based on the managed electron density maximum rearrangement in multi-contacts functionally integrated active region are considered. The basis of the microwave switcher is a normally opened high electron mobility transistor structure (HEMT) with multiple Schottky gates and the corresponding number of switching ohmic contacts. In this research two-dimensional finite-difference physical and topological model of the considered microwave switchers is proposed. The distinctive features of the proposed model are combination of two different sets of variables and explicit first-order upwind discretization scheme for the normalized continuity equation. The obtained results of numerical modeling are discussed.

Keywords: microwave switchers, physical and topological model, numerical modeling

1. INTRODUCTION

Currently, microwave integrated circuits find wide application in the high-speed broadband data transmission systems [1]. The microwave switchers can be considered as the main functional elements of microwave integrated circuits. These switchers are widely used to create the filters, reconfigurable antennas, digitally controlled attenuators and other devices [1]. In some systems it is required that the switching time of microwave signals was comparable with the period of these signals [2].

To solve this problem in the works [3], [4], [5] structures of the microwave switchers based on vertically integrated multiple-contact quantum fields were proposed. The active region of the microwave switcher has multiple switching ohmic contacts and a corresponding number of control gates. Under the influence of the control electric field of the gates a spatial rearrangement of the maximum of charge carrier density in the active region is performed. This spatial rearrangement of the maximum of charge carrier density provide a change of the ratio of conductivities between the ohmic contacts to perform switching.

If changing of the control voltages of the gates is carried out so that the total number of charge carriers in the active region of the switcher remained practically unchanged in the process of spatial rearrangement, the switching time of the switcher is determined by the inertness of the transverse spatial rearrangement of the maximum of charge carrier density in the active region. In this case the switching time of the switcher may be significantly less than the duration of longitudinal transport of charge carriers between the switched contacts. In accordance with the results of numerical modeling, the switching time of the considered switchers can reach 0.1–0.2 ps [3], [4], [5].

The main disadvantages of switchers based on vertically integrated active regions are high leakage currents and the complexity of the technological implementation of the ohmic contacts for vertically integrated quantum wells [3], [4], [5]. The first of these drawbacks significantly limits the application of switchers and the second one leads to the necessity of significant financial investment in the modernization of technological routes of integrated circuits production and consequently to the increasing of the microwave integrated circuits cost.

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2. MICROWAVE SWITCHER WITH MULTIPLE-CONTACTS FUNCTIONALLY INTEGRATED ACTIVE REGION

To reduce leakage currents and improve the manufacturability of the microwave switchers in [6] the construction of the microwave switcher with longitudinal (in the plane of the substrate) spatial rearrangement of the maximum of electron density was proposed. Figure 1 shows the layout and structure of this microwave switcher. The basis of the microwave switcher is normally opened high electron mobility transistor heterostructure (HEMT-heterostructure) with four control Schottky barrier gates (G1 – G4) and with the corresponding number of switching ohmic contacts (C1 – C4). When applying blocking voltages for a particular pair of control gates the longitudinal spatial rearrangement of the maximum of two-dimensional electron gas (2DEG) density, which leads to switching of the corresponding ohmic contacts [6].

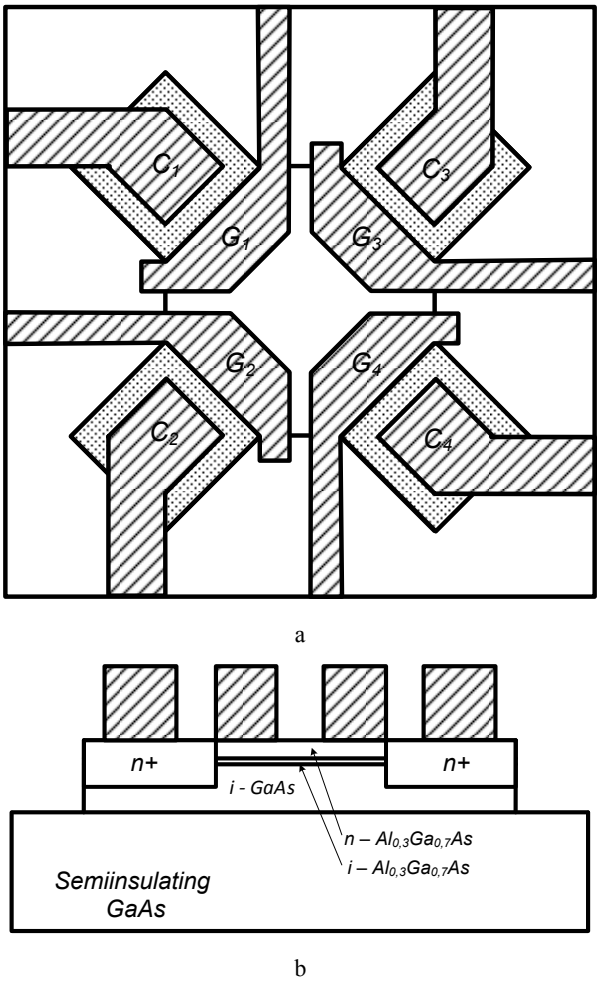

Figure 1. Layout (a) and structure (b) of the four-contact integrated microwave switcher with managed rearrangement of the maximum of electron density

The layout of functionally integrated active region of the microwave switcher and the layout of Schottky barrier gates provide the desired small leakage currents, as well as, most importantly, the full technological compatibility with the routes the manufacture of microwave integrated circuits based on the normally opened HEMT-heterostructures.

For evaluation of the effectiveness and switching time of the planar microwave switchers which are presented in [6], primarily necessary to perform a numerical modeling of electrons transport processes in microwave switcher to test an assumption about decreasing of the switching time of the microwave switcher while maintaining the unvarying total number of electrons during the processes of their longitudinal spatial rearrangement in the functionally integrated active region under the influence of the control electric field of the Schottky barrier gates considering the fact that design rules of the main part of Russian microwave integrated circuits determining the longitudinal dimensions of integrated elements active regions currently make up 0.5 μm or more. The results of this modeling and analysis are the purpose of this work.

3. MODEL OF MICROWAVE SWITCHER

The switcher model was developed taking into account the following aspects:

- for switching delay evaluation of the investigated microwave switchers needed a model of nonstationary processes of electron transport in semiconductor heterostructures;
- the study of the dynamics of the managed rearrangement of the maximum of charge carrier density in the active region of the switcher is possible only on the basis of the analysis of electron density spatial distributions at different moments during the transient process. This aspect requires the numerical solution of the corresponding system of partial differential equations. Ordinary differential equations will not satisfy this requirement;
- in the studied heterostructure longitudinal rearrangement of the maximum of electron density is initiated by the transverse electric field of the control gates. Therefore, the number of spatial dimensions in the model should not be less than two;
- the defining role of longitudinal transport of electrons in the investigated switchers leads to the fact that to obtain adequate comparative assessment of their switching delay in different management regimes accounting of the dimensional energy quantization in the transversal direction is a minor factor, in contrast to the effects that determine the electron mobility (dependence of mobility on temperature, concentration of dopants and electric field intensity, the effect of drift velocity saturation, the overshoot effect, the effect of inter-valley transitions).

Taking into account the above aspects, a diffusion-drift model [7] for the study of heterostructure which is presented in Figure 1,b was considered:

$$\varepsilon_0 \nabla\left(\varepsilon \cdot \nabla \varphi\right) = q\left(n - N_{EF}\right); \tag{1}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \overrightarrow{j_n} + G - R; \tag{2}$$

$$\overrightarrow{j_n} = q\mu_n\left\{-n \cdot \nabla\left(\varphi + V_n\right) + \varphi_T \nabla n\right\}, \tag{3}$$

where n is the electron density; φ is the electric potential; N_{EF} is the effective concentration of impurities; V_n is the heterostructure potential in the conduction band; ε is the semiconductor permittivity; ε_0 is the vacuum permittivity; q is the elementary charge; j_n is the electron current density; μ_n is the electron mobility; φ_T is the temperature potential; t is the time; G is the generation rate of the charge carriers; R is the recombination rate of the charge carriers.

After substituting expression (3) into equation (2) and normalization, equations (1)–(3) were expressed using the basis of variables $\{\Phi_n, \varphi\}$, where Φ_n is the exponent of the normalized Fermi quasi-level for electrons in the considered heterostructure, which is expressed as following:

$$\Phi_n = n \cdot e^{-\varphi - V_n}. \tag{4}$$

This basis of variables firstly was proposed by Slotboom in the paper [8].

Numerical solution of the system of equations (1)–(3) was performed using finite-difference method on nonuniform two-dimensional spatial grid and nonuniform time grid. Distinctive features of the developed finite-difference formulation of

the system of equations are combination of two different bases of the variables in the continuity equation and the combination of explicit scheme and the first-order upwind scheme:

$$\begin{aligned}
&\left(\Delta y_j + \Delta y_{j-1}\right)\left(\left(\varepsilon_{i+1,j} + \varepsilon_{i,j}\right)\frac{\varphi_{i+1,j} - \varphi_{i,j}}{\Delta x_i} - \left(\varepsilon_{i,j} + \varepsilon_{i-1,j}\right)\frac{\varphi_{i,j} - \varphi_{i-1,j}}{\Delta x_{i-1}} \right) + \\
&+ \left(\Delta x_i + \Delta x_{i-1}\right)\left(\left(\varepsilon_{i,j+1} + \varepsilon_{i,j}\right)\frac{\varphi_{i,j+1} - \varphi_{i,j}}{\Delta y_j} - \left(\varepsilon_{i,j} + \varepsilon_{i,j-1}\right)\frac{\varphi_{i,j} - \varphi_{i,j-1}}{\Delta y_{j-1}} \right) = \\
&= \left(\Phi_{ni,j} e^{\varphi_{i,j} + V_{ni,j}} - N_{EFi,j}\right)\left(\Delta x_i + \Delta x_{i-1}\right)\left(\Delta y_j + \Delta y_{j-1}\right);
\end{aligned} \tag{5}$$

$$\begin{aligned}
&n^*_{i,j} = n_{i,j} + \Delta t_m \left\{ \frac{2}{\Delta x_i + \Delta x_{i-1}} \left[\left(\mu_{ni+1,j} e^{\varphi_{i+1,j} + V_{ni+1,j}} \theta\left(-\Phi_{ni+1,j} + \Phi_{ni,j}\right) + \right.\right.\right. \\
&+ \left.\left.\left. \mu_{ni,j} e^{\varphi_{i,j} + V_{ni,j}} \theta\left(\Phi_{ni+1,j} - \Phi_{ni,j}\right)\right) \frac{\Phi_{ni+1,j} - \Phi_{ni,j}}{\Delta x_i} - \right. \\
&- \left(\mu_{ni,j} e^{\varphi_{i,j} + V_{ni,j}} \theta\left(-\Phi_{ni,j} + \Phi_{ni-1,j}\right) + \right. \\
&+ \left.\left. \mu_{ni-1,j} e^{\varphi_{i-1,j} + V_{ni-1,j}} \theta\left(\Phi_{ni,j} - \Phi_{ni-1,j}\right)\right) \frac{\Phi_{ni,j} - \Phi_{ni-1,j}}{\Delta x_{i-1}} \right] + \\
&+ \frac{2}{\Delta y_j + \Delta y_{j-1}} \left[\left(\mu_{ni,j+1} e^{\varphi_{i,j+1} + V_{ni,j+1}} \theta\left(-\Phi_{ni,j+1} + \Phi_{ni,j}\right) + \right.\right. \\
&+ \left.\left. \mu_{ni,j} e^{\varphi_{i,j} + V_{ni,j}} \theta\left(\Phi_{ni,j+1} - \Phi_{ni,j}\right)\right) \frac{\Phi_{ni,j+1} - \Phi_{ni,j}}{\Delta y_j} - \right. \\
&- \left(\mu_{ni,j} e^{\varphi_{i,j} + V_{ni,j}} \theta\left(-\Phi_{ni,j} + \Phi_{ni,j-1}\right) + \right. \\
&+ \left.\left. \mu_{ni,j-1} e^{\varphi_{i,j-1} + V_{ni,j-1}} \theta\left(\Phi_{ni,j} - \Phi_{ni,j-1}\right)\right) \frac{\Phi_{ni,j} - \Phi_{ni,j-1}}{\Delta y_{j-1}} \right] - G_{i,j} + R_{i,j} \Bigg\},
\end{aligned} \tag{6}$$

where *i, j* are the indexes of coordinate grid points; *m* is the index of time grid points; Δx_i, Δy_j are the coordinate grid steps; Δt_m is the *m*-th time grid step; $\varphi_{i,j}$ are the node values of the potential in the *m*-th instant of time; $\Phi_{ni,j}$ are the node values of the exponent of Fermi qasi-level in the *m*-th instant of time; $n_{i,j}$ are the node values of the electron density in the *m*-th instant of time; $V_{ni,j}$ are the node values of the heterostructure potential in the conduction band in the *m*-th instant of time; $\mu_{ni,j}$ are the node values of the electron mobility in the *m*-th instant of time; $N_{EFi,j}$ are the node values of the effective concentration of impurities in the *m*-th instant of time; $G_{i,j}$ are the node values of the generation rate of the carriers in the *m*-th instant of time; $R_{i,j}$ are the node values of the recombination rate of the carriers in the *m*-th instant of time; $n^*_{i,j}$ are the node values of the electron density in the (*m*+1)-th instant of time; θ is the Heaviside step function.

The presence of the Heaviside function in finite-difference continuity equation (6) is caused by the application of the upwind scheme.

We used the following standard formulation of the Dirichlet boundary conditions assuming the infinite recombination velocity at the ohmic and Schottky barrier contacts [7]:

$$\varphi = \varphi_T \ln\left(\frac{\frac{N_{EF}}{2} + \sqrt{\left(\frac{N_{EF}}{2}\right)^2 + n_i^2}}{n_i^2} \right) + U(t); \tag{7}$$

$$\varphi = \varphi_T \ln\left(\frac{\frac{N_{EF}}{2} + \sqrt{\left(\frac{N_{EF}}{2}\right)^2 + n_i^2}}{n_i^2} \right) + U(t) - \varphi_0; \tag{8}$$

$$\Phi_n = \exp\left(-\frac{U(t)}{\varphi_T} \right), \tag{9}$$

where $U(t)$ is the bias voltage applied to the contact at the moment t; φ_0 is the Schottky barrier height; n_i is the intrinsic carrier concentration; (7) and (9) are the boundary conditions for ohmic contacts; (8) and (9) are the boundary conditions for Schottky barrier contacts.

The boundary conditions on the free from the contacts boundaries of the structure is expressed as follows:

$$\frac{\partial \varphi}{\partial \xi} = 0; \qquad \frac{\partial \Phi_n}{\partial \xi} = 0, \tag{10}$$

where ξ is the normal to the boundary surface.

The initial conditions were defined as the results of numerical solution of the stationary system of equations corresponding (5)–(10).

4. RESULTS OF NUMERICAL MODELING

Figure 2 shows two-dimensional spatial distributions of the electron density in the heterostructure presented in Figure 1,b. Table 1 shows the values of the main parameters of considered heterostructure. We have calculated these results applying the developed model (5)–(10) and numerical modeling technique.

Table 1. The values of the main parameters of microwave switcher heterostructure

The main parameters and its values	
Parameter	*Value*
Thickness of the barrier layer *n*-$Al_{0.3}Ga_{0.7}As$	60 nm
Thickness of the *i*-$Al_{0.3}Ga_{0.7}As$ spacer	5 nm
Thickness of the undoped layer *i*-GaAs	400 nm
Impurity concentration in the barrier layer *n*-$Al_{0.3}Ga_{0.7}As$	10^{18} cm^{-3}
Impurity concentration in the regions of ohmic contacts	10^{18} cm^{-3}
Gate length and distance between gates	500 nm

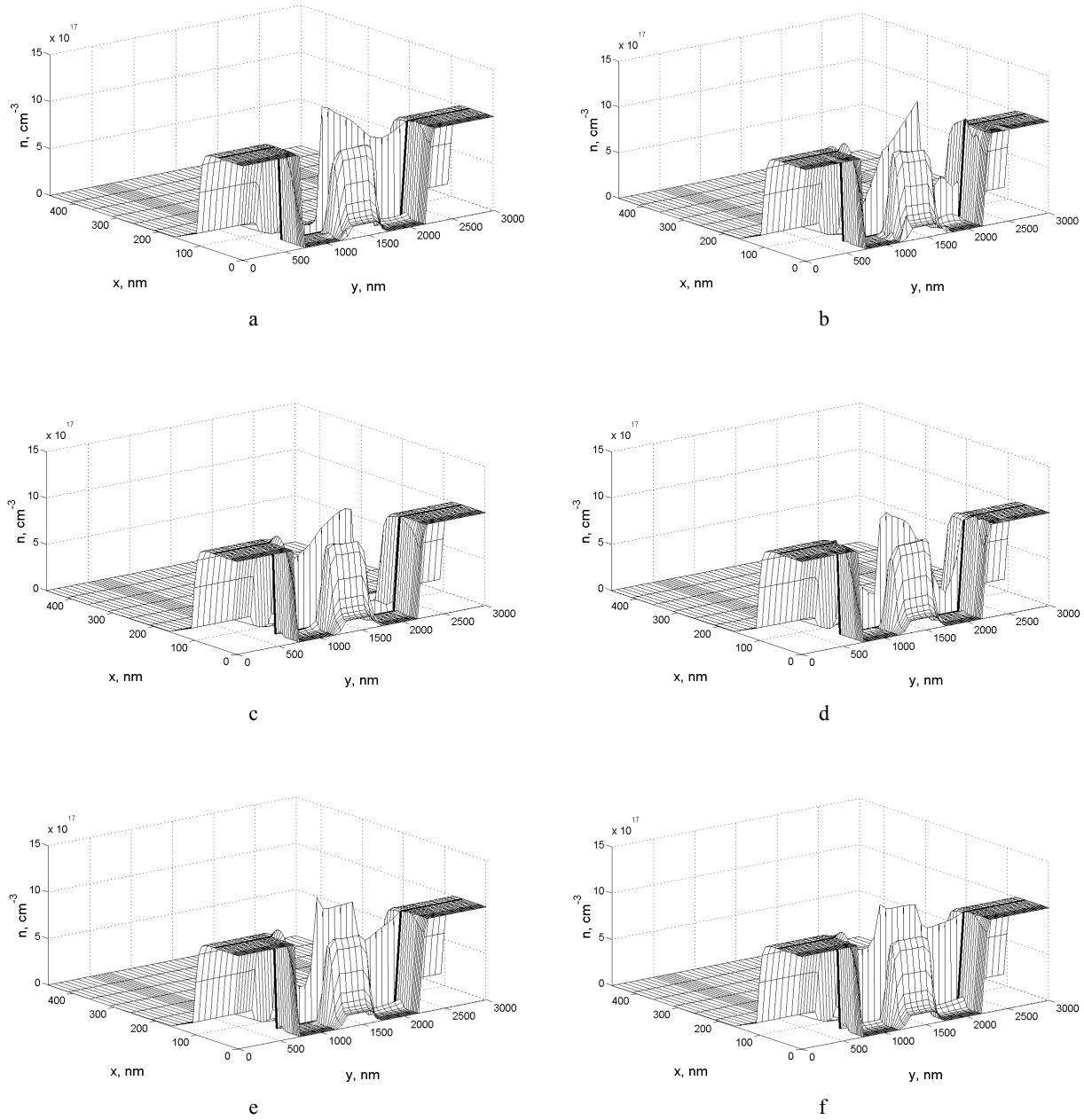

Figure 2. The spatial distributions of electron density in microwave switcher in the moments of transient process $t = 0$ (a), $t = 0.05$ ps (b), $t = 0.1$ ps (c), $t = 0.15$ ps (d), $t = 0.25$ ps (e) and $t = 0.5$ ps (f)

Figure 3 shows the dependencies on time of two-dimensional electron gas layer density averaged on the length of the first gate (n_{S1}) and on the length of second one (n_{S2}). These dependencies were computed by integration of electron density spatial distributions presented in Figure 2 for antiphase (in the time interval 0 to 0.2 ps) and in-phase (in the time interval 0.2 to 0.5 ps) control signals $U_{IN1}(t)$, $U_{IN2}(t)$ on the first and second gates of the microwave switcher.

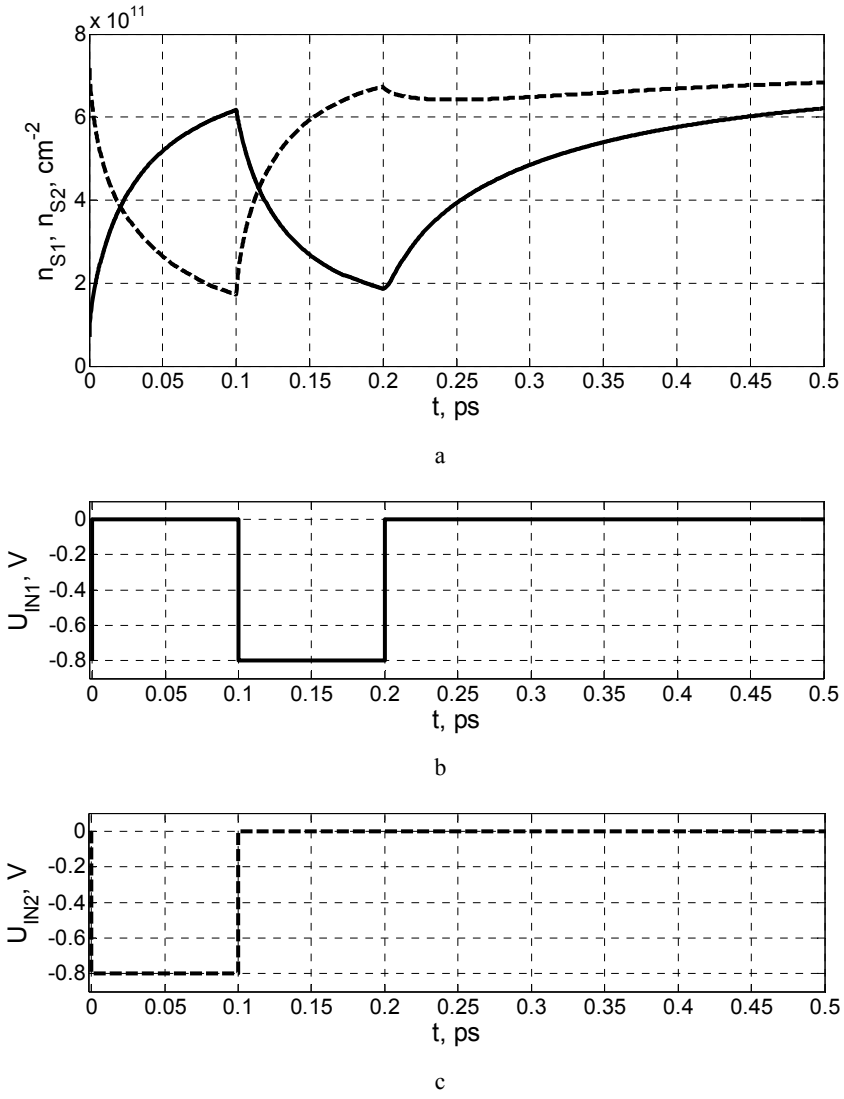

Figure 3. Dependences on time of average over the gate length electron layer densities $n_{S1}(t)$ and $n_{S2}(t)$ (a) for antiphase (in the time interval 0 to 0.2 ps) (b) and in-phase (in the time interval 0.2 to 0.5 ps) (c) control signals $U_{IN1}(t)$ and $U_{IN2}(t)$ on the first and second gates of the microwave switcher

The results of numerical modeling in Figure 3 show that the total number of electrons in the active region of the microwave switcher remained practically unchanged in the process of spatial rearrangement under the influence of antiphase control signals on the gates. This fact is confirmed by symmetry of the dependencies on time of the averaged two-dimensional electron gas layer density under the first gate and under the second one in the time interval 0 to 0.2 ps.

According to the results shown in Figure 3, under the influence of antiphase control signals on the gates an amplitude of the average 2DEG layer density changing riches up to 70% of the difference between the electron layer densities corresponding the stationary state in less than 0.1 ps, even with relatively large gate length of 500 nm.

In contrast, in-phase changing of the control voltages $U_{IN1}(t)$ and $U_{IN2}(t)$ in the interval of 0.2 to 0.5 ps, leading to a significant change in the total number of electrons in the active region of microwave switcher, more than three times increases the duration of the active phase of transient process.

5. CONCLUSION

The obtained results of numerical modeling show that even with relatively large gate length of 500 nm the switching time of the microwave switcher using the principles of electron density maximum spatial rearrangement three times less (up to 0.1 ps) compared to the switching based on the traditional principles.

The considered results of numerical modeling were obtained without taking into account the parameters of external circuits of microwave switcher. These parameters can be considered in the process of circuit modeling.

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