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Model for Studying Collective Charge Transport at the Ohmic Contacts of a Tightly Coupled Semiconductor Nanostructure

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Abstract—A mathematical model for describing the collective dynamics of charge carriers in a semiconductor superlattice with ohmic emitter and collector contacts is proposed. The model is based on a hydrodynamic description of electron transport. The effect the emitter and collector characteristics have on the oscillation regimes observed in this system is analyzed using the proposed approach.

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INTRODUCTION

First proposed in 1970 [1], semiconductor periodic nanostructures (superlattices) are now considered to be one of the most promising systems for generating [2] and amplifying [3] terahertz radiation. It is known that the difference between potentials applied to such a structure creates regions with higher charge carrier density (electron domains) that drift along the superlattice and cause high-frequency oscillations of the current flowing through it [4, 5]. Use of the domain generation regime appears promising due to the possibility of raising the domain recurrence rate to several hundred gigahertz [6] and generating microwave and terahertz radiation at higher harmonics of current oscillations [7].

Experimental and theoretical studies show that an electrodynamic circuit formed by an ohmic emitter and collector contacts influences the nanostructure dynamics in actual systems based on semiconductor superlattices, and the domain transport characteristics are thus considerably altered [7–9]. To be specific, the presence of an external electrodynamic structure translates into the formation of parasitic resonance circuits that can trigger the formation of an additional region of negative differential conductivity [8] and, in certain cases, lead to more complex current oscillation regimes [7, 9].

At the same time, the processes of collective charge transport on the ohmic contacts of a semiconductor structure remain understudied. In most studies, the influence of the contacts is taken into account using an approximative model that allows us to estimate the drop in voltage on these contacts [10]. However, this approach does not allow us to study the influence of the contacts on the characteristics (frequency and power) of the oscillation regime.

In a number of studies dealing with the influence of ohmic contacts on the dynamics of semiconductor superlattices and Gunn diodes, emitter contact is taken into account in the form of a local boundary condition [11] with no consideration for the processes of charge transport through it. The influence of the collector contact on the nanostructure dynamics is generally left unexplored.

However, it is fair to assume that the transition of the domain of a charge formed in a semiconductor superlattice into the heavily doped region of collector contact could greatly influence the domain transport characteristics in the domain generation regime. The problems associated with analyzing the processes on emitter and collector contacts are therefore of interest in the context of both designing devices based on superlattices and revealing and studying the nonlinear–dynamic patterns of collective charge transport in different semiconductor nanostructures.

We analyzed the influence of extended ohmic emitter and collector contacts using a model of collective electron transport based a hydrodynamic description. This work details the basic principles of this approach and the results obtained in studying the spatiotemporal dynamics of charge carrier density and the characteristics of generation as functions of the emitter and collector doping level.

SYSTEM AND MATHEMATICAL MODEL

A semiclassical approach is often used to describe collective charge transport in semiconductor superlattices [12]. In this approach, the motion of the charge carrier and the spatiotemporal dynamics of the electrical field configuration in the structure are calculated using a hydrodynamic model composed of a self-consistent continuity and the Poisson equations

$$\frac{\partial^2 \varphi_{SL}}{\partial x^2} = -\nu(n_{SL} - n_D), \quad \frac{\partial n_{SL}}{\partial t} = -\beta \frac{\partial J_{SL}}{\partial x}, \tag{1}$$

where $\varphi_{SL}(x,t)$ and $n_{SL}(x,t)$ are the distributions of the potential and charge carrier density in the semiconductor structure; $\nu = 15.769$ and $\beta = 0.031$ are dimensionless control parameters; and $n_D = 1.0$ is the dimensionless value of the equilibrium charge carrier density in the semiconductor. The dimensionless values in Eq. (1) are related to the dimensional parameters via the equations

$$n = n'/n'_D, \quad x = x'/L', \quad \varphi_{SL} = \varphi'_{SL}/L'F'_C,$$
$$F'_C = \hbar/(ed'\tau'), \quad t = t'/\tau', \quad J_{SL} = J'_{SL}/(en'_D\vartheta'_0), \tag{2}$$
$$\vartheta'_0 = \delta\Delta' d'/(2\hbar), \quad \beta = \vartheta'_0\tau'/L', \quad \nu = L'en'_D/(F'_C\varepsilon_0\varepsilon'_r).$$

where $n'_D = 3 \cdot 10^{22}$ m^{-3} is the equilibrium charge carrier density; $L = 115.2$ nm and $d' = 8.3$ nm are the length and period of the semiconductor superlattice; $e > 0$ is the electron charge; $\tau' = 250$ fs is the carrier scattering time in the semiconductor; $\varepsilon'_r = 12.5$ is the relative electric permittivity of the material; and $\Delta' = 19.1$ mEv is the width of the energy miniband.

The current density is calculated using the drift approximation

$$J_{SL}(x,t) = n_{SL}(x,t) \times \upsilon_{SL}(F(x,t)), \tag{3}$$

where $\upsilon_{SL}(F_{SL}(x,t))$ corresponds to the dimensionless drift velocity of charge carriers in the semiconductor's superlattice [1]. This dependence can be found using the semiclassical approach in [13], based on the law of motion of individual electrons in the semiconductor's superlattice miniband with allowance for the scattering time [13]. This dependence takes the following form at low temperatures and in the absence of external magnetic fields:

$$\upsilon_{SL}(F_{SL}(x,t)) = \frac{F_{SL}(x,t)}{1 + F_{SL}(x,t)^2}, \tag{4}$$

where $F_{SL}(x,t) = -\partial\varphi_{SL}(x,t)/\partial x$ defines the distribution of the electrical field intensity in the superlattice.

We did also use the hydrodynamic model to simulate the spatiotemporal dynamics of charge carriers on the emitter and collector contacts:

$$\frac{\partial^2 \varphi_C}{\partial x^2} = -\nu(n_C - n_0), \quad \frac{\partial n_C}{\partial t} = -\beta \frac{\partial J_C}{\partial x}, \tag{5}$$

where $\varphi_C(x,t)$, $n_C(x,t)$, and $J_C(x,t)$ are the distributions of the potential, the charge carrier density, and the current density on the semiconductor structure contacts; $n_0 = 3.33$ is the dimensionless equilibrium charge carrier density in these regions. The dimensionless variables in Eqs. (5) are related to the dimensional parameters through Eqs. (2) given above.

The current density on the ohmic emitter and collector contacts is calculated using drift approximation (3). However, Drude's theory states that the drift velocity is in this case governed by the linear law

$$\upsilon_C(F_C(x,t)) = \alpha F_C(x,t). \tag{6}$$

where the dimensionless parameter $\alpha = e\tau'_C F'_c/(\vartheta'_0 m^*)$ depends on the carrier scattering time on contacts τ'_C, and on the effective mass of an electron.

Equations (1)–(6) are complemented by boundary conditions that characterize the fulfillment of the continuity condition at the boundary between the regions of ohmic emitter and collector contacts and the semiconductor's superlattice:

$$\varphi_{SL}(0) = \varphi_{C1}(L_C), \quad \varphi_{C2}(0) = \varphi_{SL}(L), \quad J_{SL}(0) = J_{C1}(L_C), \quad J_{C2}(0) = J_{SL}(L), \tag{7}$$

where $L_C = L'_C/L'$ is the dimensionless contact length; $L'_C = 50$ nm; and $\varphi_{C1}(x,t)$, $\varphi_{C2}(x,t)$, $J_{C1}(x,t)$, and $J_{C2}(x,t)$ correspond to the values of potential and current density at the emitter and the collector, respectively.

The potential difference at the boundaries of the system (superlattice + contacts) is used as a control parameter in this model and is held constant:

$$V = \varphi_{C2}(L_C) - \varphi_{C1}(0). \tag{8}$$

Figure 1 shows a schematic diagram of our model of a superlattice incorporating alternating semiconductor GaAs–AlGaAs layers with ohmic emitter and collector contacts. The parameters of this structure were established in accordance with experimental studies [7, 12].

INFLUENCE OF CONTACTS ON DOMAIN TRANSPORT CHARACTERISTICS

According to the results from experimental studies and numerical modeling of Eqs. (1) and (3)–(8), instabilities develop and domain generation emerges in the studied system upon the application of a certain constant potential difference. Dimensionless poten-

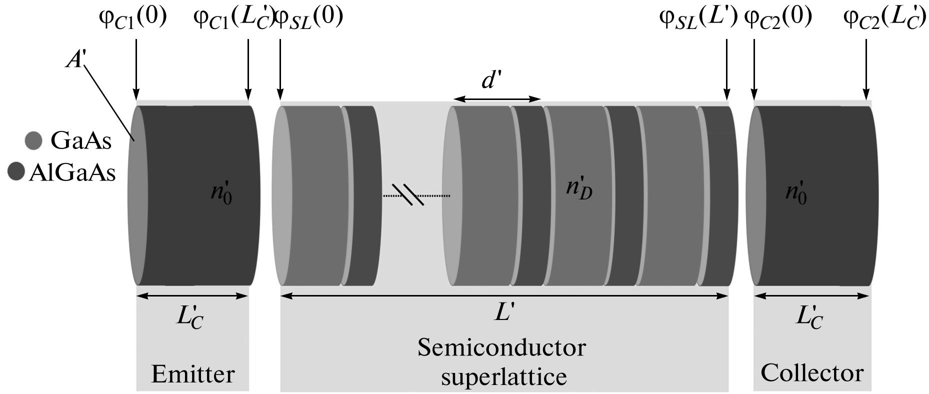

Fig. 1. Schematic representation of a superlattice with period d' and cross-section area A'. The superlattice is composed of semiconductor GaAs–AlGaAs layers with ohmic contacts.

tial difference (8), corresponding to the origin of instability V^*, is roughly equal to 1.5 in this structure. We used the constant potential difference $V^* \approx 2.5$ in this work to analyze the influence of the emitter and collector parameters on the current oscillation characteristics. This value corresponds to a developed domain transport regime. Equilibrium charge carrier density n_0 served as a physical parameter characterizing the contacts.

Figure 2 shows the results from numerical modeling of Eqs. (1) and (3)–(8), which describe the collective dynamics of charge transport in the superlattice and on the emitter and collector contacts. Figure 2a shows the dependence of the frequency of current oscillations arising in the system (the rate of domain recurrence) on the charge carrier density on the contacts. The solid curve represents the frequencies at various charge carrier densities on the collector contact (the charge carrier density on the emitter n_0^E remained constant at 3.33). The dashed line in turn corresponds to variations in the n_0^E parameter at a constant charge carrier density on the collector: $n_0^C = 3.33$.Figure 2b shows the dependences of dimensionless power P/P_0 of current oscillations (P_0 corresponds to the oscillation power at $n_0^C = 1.0$ and $n_0^E = 3.33$) on the charge carrier density on the emitter (dashed curve) and the collector (solid curve). It can be seen that varying the charge carrier density on the collector significantly influences the power of current oscillations. It also follows from Fig. 2a that changes in power are accompanied by changes in the frequencies of the observed oscillations. It should be noted that this emitter parameter has almost no effect on the domain generation characteristics. The oscillation frequency and power are in this case determined by the collector contact parameter and are not altered when the n_0^E value is changed. Figure 2c shows the time representations of current oscillations corresponding to a constant value

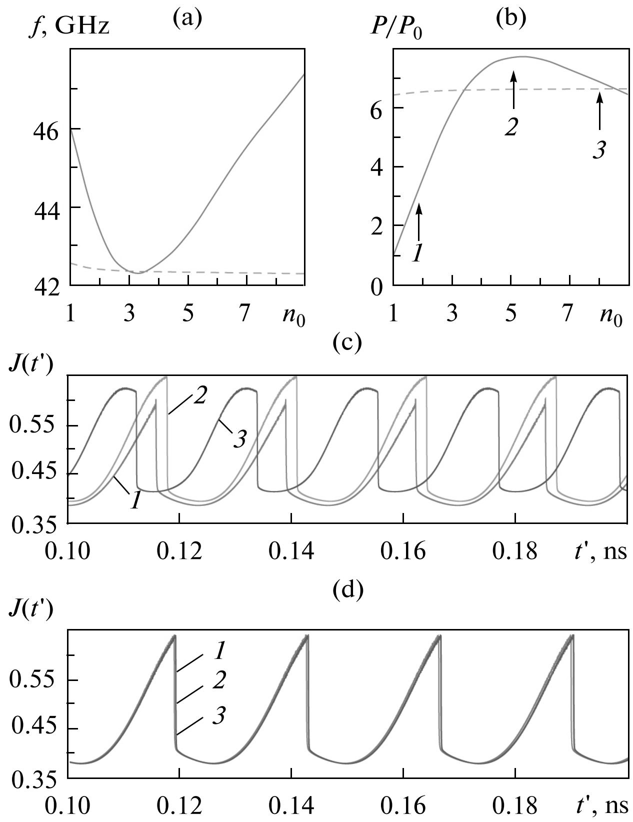

Fig. 2. Dependences of (a) the frequency of oscillations of current flowing through a superlattice and (b) the dimensionless oscillation power on the dimensionless equilibrium charge carrier density on the collector (solid curve; charge carrier density on the emitter $n_0^E = 3.33$) and the emitter (dashed curve; charge carrier density on the collector $n_0^C = 3.33$). Times of current oscillations are shown that correspond to (c) at a constant charge carrier density on the emitter and different charge carrier densities on the collector ($n_0^C = 2.0$ (curve *1*), $n_0^C = 5.0$ (curve *2*), and $n_0^C = 8.0$ (curve *3*)) and (d) a constant charge carrier density on the collector and different charge carrier densities on the emitter ($n_0^E = 2.0$ (curve *1*), $n_0^E = 5.0$ (curve *2*), and $n_0^E = 8.0$ (curve *3*)).

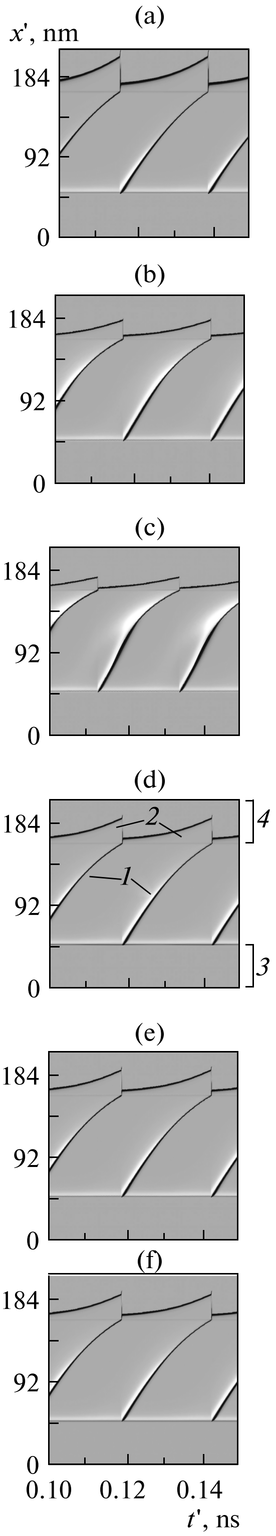

Fig. 3. Spatiotemporal dependences of charge carrier density (in domain (*1*) and region of depletion (*2*)) in the semiconductor structure that correspond to different carrier densities on collector contact (*4*) ((a) $n_0^C = 2.0$, (b) $n_0^C = 5.0$, and (c) $n_0^C = 8.0$) and the emitter contact (*3*) (d) $n_0^E = 2.0$, (e) $n_0^E = 5.0$, and (f) $n_0^E = 8.0$).

of $n_0^E = 3.33$ and different values of n_0^C: $n_0^C = 2.0$ (curve *1*), $n_0^C = 5.0$ (curve *2*), and $n_0^C = 8.0$ (curve *3*). It can be seen that the current oscillation amplitude grows when the charge carrier density on the collector contact is raised to $n_0^C = 5.0$. When n_0^C is raised further, the oscillation amplitude is reduced (curve *3*). The time representations of oscillations corresponding to different charge carrier densities on the emitter are almost identical (Fig. 2d). Curves *1*, *2*, and *3* in Fig. 2d correspond to a constant value of $n_0^C = 3.33$ and the equilibrium charge carrier densities on the emitter $n_0^E = 2.0$, $n_0^E = 5.0$, and $n_0^E = 8.0$, respectively.

The spatiotemporal dependences of the charge carrier density are plotted in Fig. 3 to illustrate the charge transport processes in the studied structure. Figures 3a–3c correspond to a constant charge carrier density on the emitter $n_0^E = 3.33$ and different carrier densities on the collector: $n_0^C = 2.0$ (Fig. 3a), $n_0^C = 5.0$ (Fig. 3b), and $n_0^C = 8.0$ (Fig. 3c). It can be seen that a domain (*1*) starts to form in the semiconductor superlattice near the emitter, and a region of depletion (*2*) appears on the collector at that moment. As the domain moves toward the structure's collector, its amplitude rises dramatically, and the collector contact's region of depletion grows larger. When the domain reaches the collector region, it expands rapidly on the ohmic contact and is dissolved. The region of depletion recovers, and a new domain is formed in the emitter region.

It can be seen from Fig. 3 that an increase in the charge carrier density at the collector results in a reduction in the collector depletion region, accompanied by an rise in the charge domain amplitude. In addition to this, the trajectory of domain motion in the semiconductor's superlattice region is warped at $n_0^E > 5.0$ (Fig. 3c). It should be noted that the analyzed domain transport regime is not accompanied by disturbances in the charge carrier density on the emitter. This explains the weak dependence of the generation characteristics on the emitter contact parameters (Figs. 3d–f).

CONCLUSIONS

A mathematical model for studying the processes in a semiconductor superlattice with extended ohmic emitter and collector contacts was proposed. The model is based on the principles of hydrodynamic description of electron transport. The spatiotemporal dynamics of the charge carrier density in such a structure and the dependence of its current oscillations on the equilibrium charge carrier density on the emitter and collector contacts were analyzed using the proposed approach. It was shown that a change in the level of collector doping substantially alters the current oscillation power, while the emitter doping level has almost no effect on the domain transport characteristics. Our results could help to solve practical problems related to modeling and analyzing the dynamics of systems based on superlattices. The proposed model could also find use in analyzing sandwich-type structures that contain alternating layers made from different semiconductor materials and metals.

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