The control of the frequency of the sub-terahertz source on the semiconductor superlattices for biophysical applications with use the change of the doping density

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ABSTRACT

In the paper we study the possibility to control the frequency of the sub-THz source, based on the semiconductor superlattice by means of optimal spatial distribution of the doping density. We propose the appropriate mathematical model, which allows to describe the collective transport of charge in miniband semiconductor, where the spatial profile of the equilibrium charge density is defined by function. As the example we consider the uniform spatial distribution of doping density, contained local inhomogeneity, caused by local increase of density and described approximately by Gaussian function. We show that such inhomogeneity being placed in different areas of the transport region can affect the dynamics of charge domain, which, in turn, leads to increase (or decrease) of the frequency of current oscillations.

Keywords: semiconductor superlattice,domain transport

1. INTRODUCTION

Teraherz (THz) frequency range is now of the great research interest in the context of biophysical and biomedical applications.[1] This necessitates high quality sources, amplifiers and detectors operating in region of the spectrum. In this context the semiconductor heterostructures represent themselves as the promising solution.[2,3]

The recent advances in the crystal growth technologies enabled high precision control of the properties of the semiconductor heterostructures, which significantly improved the performance of the devices operated in sub-THz/THz frequency range.[4] This promoted the research aimed to optimize the devices design in order to achieve the maximal output of power and frequency.[5–11]

In this respect one of the related task is the analysis of the impact of the profile of doping density on the output characteristics. For example, it was shown that some semiconductor devices, e.g. the Gunn diodes, with the linearly graded doping profiles were shown to demonstrate better performance in power, as compared to the devices with a uniform doping.[12] More complicated configuration of the doping densities may contain a notch, caused, by a thin undoped epitaxial layer between the heavily n-type doped cathode contact and the uniformly n-type doped active transport region. It was found out that such doping profile can lead to a drastic increase of the output power.[13]

In this paper we consider another class of semiconductor structures, namely semiconductor superlattices (SLs).[14] These structures are now of the great research interest from the viewpoint of the prospective application for the microwave generation and amplification in sub-THz/THz frequency range.[15–18] It was shown that the electric field, applied to the superlattice, can lead to a spatio-temporal instability,[19–21] which results in formation

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of the areas with high electron density (charge domains) propagating along the superlattice.[22–25] It was shown that the moving charge domains are able to generate current oscillations with the frequency up to several hundred GHz.[26,27]

The interest to the practical applications of SLs in sub-THz/THz electronics gave rise to the scientific researches aimed to the revealing of the new physical principles of the control and improvement of the output characteristics. In this respect the effect of external circuits, fields, contacts, and load lines on charge transport in SLs [28–30] was studied. Moreover, the possibility to control the charge transport properties of the SL and Gunn devices by manipulation of the emitter boundary condition was discussed in.[31–34] The effects of the doping in the transport region on DC current and electric stability in miniband SLs according to the conventional NL-criterion [35,36] was theoretically studied in Ref.[37] In the recent paper[38] we studied the collective spatio-temporal dynamics of the charge carriers in the GaAs-AlGaAs semiconductor superlattice with the ohmic emitter and collector and described, how the collector dopping density affects the output power of sub-THz current oscillations in the semiconductor superlattices.

Along with the control of the power, control of the frequency of the output oscillations remains very important and less studied. According to this, in the current paper we consider the features of the spatial distribution of the doping density as the factor that affects domain propagation and hence the frequency of the output current oscillations.

2. NUMERICAL MODEL UNDER STUDY

The collective dynamics of the charge carriers in the wide range of semiconductors, including TED devices and miniband superlattices is described by the set of one-dimensional (1D) hydrodynamical equations, which includes Poisson equation

$$\frac{\partial F'}{\partial x'} = \frac{e}{\varepsilon_0 \varepsilon_r}(n' - n'_D). \tag{1}$$

and the current continuity equation

$$\frac{\partial n'}{\partial t'} = -\frac{1}{e}\frac{\partial J'}{\partial x'} \tag{2}$$

Here $n'(x',t')$, $F'(x',t')$, $J'(x',t')$ are, respectively, the volume electron density, electric field and current density, x' and t' — the space coordinate and time, $e > 0$ — the electron charge, $n'_D = 3 \times 10^{22}$ m^{-3} — the n-type doping density in the SL transport region, ε_0 and $\varepsilon_r = 12.5$ are the absolute and relative permittivities, respectively.

In analytical and numerical studies, it is more convenient to consider the dimensionless analogues of the equations (1) and (2), which can be written in form

$$\frac{\partial F}{\partial x} = \nu(n - 1) \tag{3}$$

and

$$\frac{\partial n}{\partial t} = -\beta \frac{\partial J}{\partial x}, \tag{4}$$

respectively. In Eqs. (3) and (4) $\beta = 0.031$, $\nu = 15.769$ play the role the dimensionless control parameters. The dimensionless variables are connected with the dimension ones as

$$\begin{gathered} x = x'/L', \quad t = t'/\tau', \quad n = n'/n'_D, \\ J = J'/(en'_D v'_0), \quad F = F'/F'_c, \quad F'_c = \hbar/(ed'\tau'), \\ \beta = v'_0 \tau'/L', \quad \nu = L' e n'_D/(F'_c \varepsilon_0 \varepsilon_r), \end{gathered} \tag{5}$$

where $d' = 8.3$ nm and $L' = 115.2$ nm are the period and the length of the superlattice, $\Delta' = 19.1$ meV is the miniband width, $e > 0$ — the electron charge, $F'_c = 3.1725 \times 10^5$ V/m — normalization value of the electric field, The quantity

$$v'_0 = \delta \frac{\Delta' d'}{2\hbar} \frac{I_1(\Theta)}{I_0(\Theta)} \tag{6}$$

determines the maximal possible value of the dimensionless drift velocity, where $\Theta = \Delta'/(2k'_B T')$, $I_{0,1}(x)$ are the modified Bessel functions of the first kind. Parameters $\delta = [\tau'_e/(\tau'_e + \tau'_i)]^{1/2}$ and $\tau' = \delta\tau'_i$ characterize the scattering and depend on the elastic τ'_e and inelastic τ'_i scattering times. In our study we have used $\tau' = 250$ fs, $\delta = 1/8.5$. Here and hereafter the values of the dimension quantities taken from the recent experiments[?,?] have been used.

Within the drift approximation, if there is no external magnetic field and the temperature is close to zero (i.e., $T' \approx 0$ K) the current density is

$$J = nv_d(F). \tag{7}$$

In the miniband semiconductors, in case, when the external magnetic field is absent, according to the semi-classical approach the drift velocity v_d of miniband electrons follows the variation of the electric field F according to the Esaki-Tsu formula

$$v_d(F) = \frac{F}{1+F^2}. \tag{8}$$

The dimensionless voltage $U_{SL} = U'_{SL}/(F'_c L')$ applied to the superlattice is a global constraint given by

$$U_{SL} = \int_0^1 F\,dx, \tag{9}$$

where integration is performed over the dimensionless length of the system under study.

In order to determine the dimensionless current density in the heavily doped emitter contact with the electrical conductivity σ', which according to the recent experiment $\sigma' = 3788$ Sm^{-1} we have used Ohmic boundary conditions

$$J(0,t) = sF(0,t), \tag{10}$$

where $s = \sigma' F'_c/(en'_D v'_0) = 17.6511$ is the dimensionless control parameter corresponding to the electrical conductivity of the emitter contact.

In order to analyze the effect of doping density we rewrite Poisson equation on form

$$\frac{\partial F}{\partial x} = \nu(n - Q(x)), \tag{11}$$

where $Q(x)$ - Gaussian function, which defines the spatial heterogeneity of the equilibrium volume electron density

$$Q(x) = 1 + \mathrm{Exp}(-\frac{x - x*}{2\text{Ø}^2}) \tag{12}$$

Here $x*$ specifies the position of the center of the peak, and Ø controls the width of the "bell".

3. RESULTS AND DISCUSSION

The results of the numerical simulations are shown in the Fig. 1. In Fig. 1, *a* one can see the the dependencies of the output frequency on the location of the heterogeneity, obtained for the Gaussian type heterogeneity with the different width, defined by the value of Ø through Eq. 12. In the current paper we consider heterogeneities of two different width as illustrated in Fig. 1, *b,c*, respectively. Along with the different width, for each type of heterogeneity we consider three different locations, namely, $x_1^* = 0.25$, $x_2^* = 0.25$, $x_3^* = 0.25$ (see profiles 1, 2, 3 in Fig. 1, *b, c*).

Considering Fig. 1, *a* one can see that the maximal frequency of the current oscillations is achieved for the small width of heterogeneity, in case, if latter locates closer to right-hand side of the structure. Having analyzed the spatio-temporal dynamics of charge one can see, that in case, if $x^* = x_1^*$ the domain appears in the vicinity of the heterogeneity (Fig. 1, *d*). When the value of x^* increases, the area of the domain formation becomes close to the right-hand side of the sample, which, in turn, causes the minimal time, which the domain spends on order to travel through the structure (Fig. 1, *e – f*).

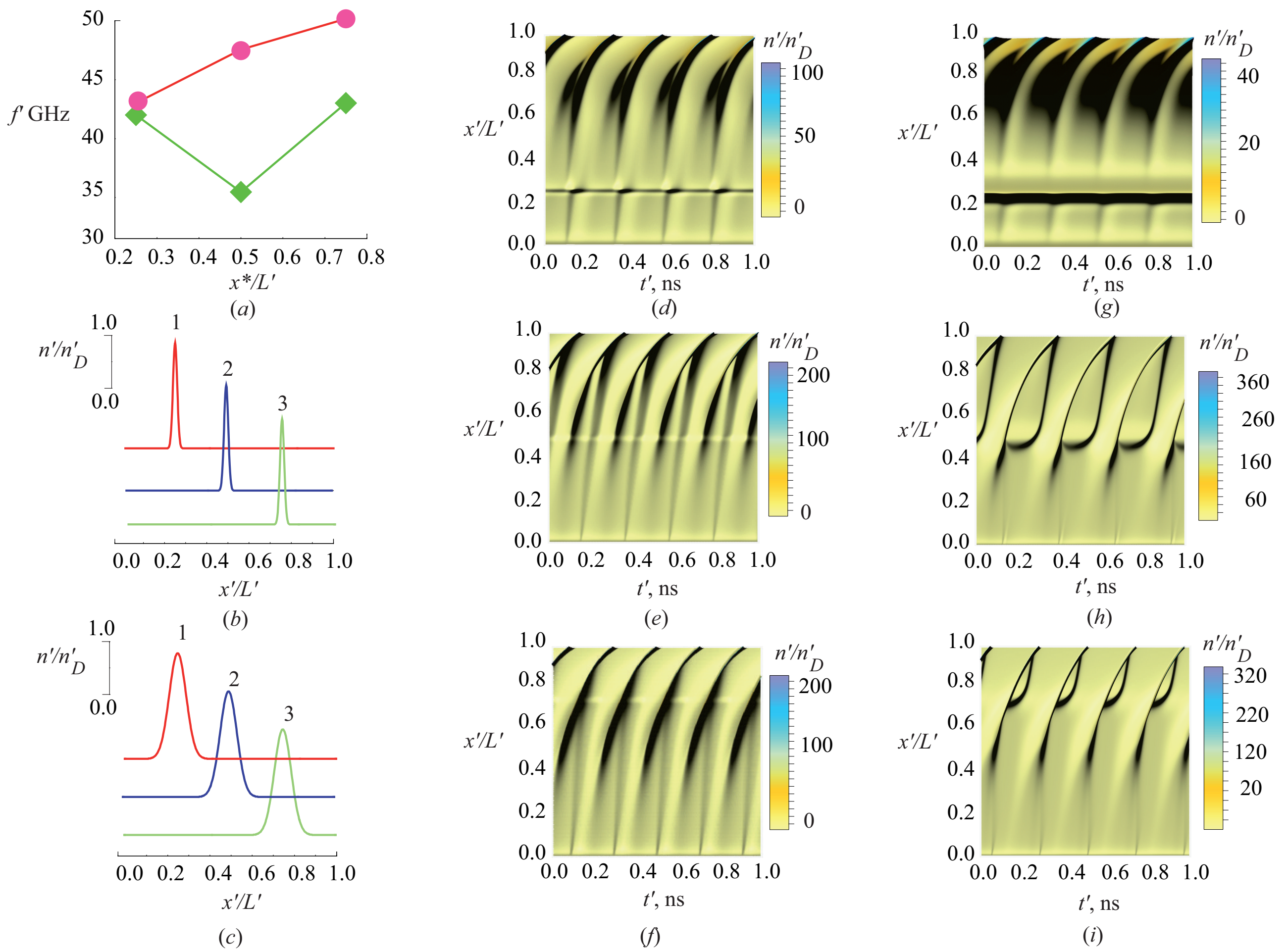

Figure 1. (a) dependencies of the frequency of output current oscillations on the location of heterogeneity, obtained for the heterogeneities of different width; (b, c) the spatial distributions of the equilibrium volume electron density, contained heterogeneity, caused by local increase of charge density, described by Gaussian function (12); (d-i) spatio-temporal dynamics of charge, corresponded to different location (each row) and width (each column) of the heterogeneity. Left column (d-f) corresponds to the small width of the heterogeneity (see panel (b)), right column (g-i) — to the high width of the heterogeneity (see panel (c))

In case of the high width of the heterogeneity the area of the domain formation becomes close to the right-hand side of the structure similarly to the case, considered above. At the same time, the high amount of charge carriers in this area leads to the formation of the additional domains (Fig. 1, h, i). It can be seen from Fig. 1, h, that appearance of such domains affects the trajectory of the main domain and results in the decrease of its velocity. As the result, the frequency of output oscillations decrease for $x^* = X_2^*$ and for the high width of the heterogeneity (Fig. 1, h). According to Fig. 1, i the further increase of the x^* results in the decrease of the time, for which the additional domain exists. In this case the frequency of the current oscillations starts to increase (Fig. 1, i).

4. CONCLUSION

We have considered the spatial profile of the equilibrium volume density of the charge carriers in miniband semiconductor superlattice as the factor which affect the transport of electron domain and, by this, the frequency of the output oscillations in sub-THz frequency band. It has been found that the spatially inhomogeneous profile, namely, contained the local increase of doping density, can result either in increase, or decrease of the frequency, depending on the location and dimensions of the heterogeneity. As the example we have demonstrated the change of the output frequency in the range 35 GHz — 50 GHz for the miniband GaAs superlattice, considered in recent experiments.[39] We believe that the same phenomena can be observed in the wide class of the structures, where the charge carriers exhibit the negative differential drift velocity e.g. strongly-coupled semiconductor superlattices, Gunn devices, the silicon-based structures with natural superlattice, which are of the great interest as the prospective sources for sub-THZ and THz radiation. The obtained results, being taken into account at the design stage of the electronic devices, may cause the significant improve of its frequency characteristics, which, in turn, has the important meaning for the possible biophysical applications.[40,41]

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