Increase of The Power and Frequency in The Semiconductor Sandwich Heterostructures

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***Abstract*—We considered the nonstationar charge transport through the nanoscaled heterostructrure, consisting of the muniband semiconductor superlattices (SL), divided by the layers of heavy doped semiconductor. We demonstrate that compared with the regular SL, such design provides simultaneously the significant increase of both the output power and the frequency of the produced current oscillation.**

I. INTRODUCTION

The semiconductor superlattices, consisting of the alternating layers of the different types of semiconductor, were shown to exhibit the nonstationar charge transport, accompanied by the moving charge domains, producing the high frequency current oscillations [1].

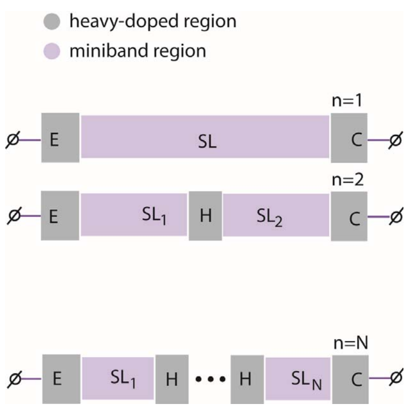

Fig. 1. The schematic illustration of the semiconductor sandwich heterostructure. SL_i - the areas of the miniband semiconductor, E and C correspond to emitter and collector, respectively, H_i - heavy doped layers. n defines the order of the structure.

The dynamics of the charge domains could be controlled by means of the external magnetic fields and the resonant systems, and represented itself as the promising background for sub-THz generation [2].

From one hand, the frequency of the current oscillations, taken place in the autonomous SL is limited by the maximal drift velocity of miniband electrons and, therefore, the maximal frequency can be obtained in the relatively short sample. From the other hand, the short SL produces the very low-power generation [3] and in this case the stack of SLs is required. At the same time, use of stack is also problematic due to the occurrence of the low-frequency parasitic resonant circuits, which are caused by the wires and limited the generation frequency.

In order to escape the limitations, described above, we propose the specific design of the semiconductor device, based on the miniband semiconductor superlattice, namely, the semiconductor sandwich heterostructure. The principal design of the device is shown schematically in Fig. 1. It consists of the identical superlattices (SL_i), devided by the layers (~50 nm) of the heavy-doped (~10^{23} m^{-1}) semiconductor (H_i). Here n corresponds to the order of the structure and defines the number of isolated miniband regions.

II. RESULTS

The collective charge transport through the proposed heterostructure was analyzed numerically with the help of the hydrodynamic model [4], based on the semiclassical approach and Drude theory.

In the framework of this model the spatio-temporal dynamics of the volume electron density $n(x,t)$ and the electric potential $\phi(x,t)$ is described by self-consistent set of the current continuity equation and Poisson equation.

$$\frac{\partial^2\phi}{\partial x^2} = -\frac{e}{\varepsilon_0\varepsilon_r}(n-n_0), \qquad \frac{\partial n}{\partial t} = -\frac{1}{e}\frac{\partial J}{\partial x}, \tag{1}$$

where e is the electron charge, ε_0 and ε_r are absolute and relative permittivities, respectively. The set of the equations (1) is valid for both the miniband regions (SL_i), contact regions (E, C) and the regions of the heavy doped semiconductor (H_i). For these region the values of the n-type doping density n_0 are taken as n_0=n_D =3x10^{22} m^{-3} (for region of the miniband transport) n_0 =10^{23} m^{-3} (for heavy doped layers and contacts).

Within the drift approximation [5], the current density in the area of the miniband semiconductor is given by

$$J_{SL} = en\frac{\delta\Delta d}{2\hbar}\frac{eFd\tau_{SL}/\hbar}{1+(eFd\tau_{SL}/\hbar)^2}, \tag{2}$$

where Δ=19.1 meV is the miniband width, τ_{SL} = 250 fs is the scattering time, d=8.3 nm - period of the superlattice, δ=0.12 - coefficient, reflecting the contribution of elastic and inelastic scattering.

In the region of the Ohmic emitter (E), collector (C) and the heavy doped layers (H_i) the current density $J_{C,E,H}$ is defined, according to the Drude model, as [6]

$$J_{C,E,H} = \frac{e^2 n\tau_{C,E,H}}{m^*}F, \tag{3}$$

where $\tau_{C,E,H}$ = 90 fs. In both cases $F = -\partial\phi/\partial t$ is the value of electric field, distributed over the miniband and heavy-doped regions of the structure. The Eqs. (1)-(3) are supplemented by the boundary condition

$$\phi(L) - \phi(0) = \int_0^L F(x)dx, \qquad (4)$$

which defines the voltage, applied to the heterostructure. Here the intergration is performed over all the system length $L = n*L_{SL} + L_C + L_E + (n\text{-}1)*L_H$. Here L_{SL} and L_H are the length of the miniband transport region and the heavy doped layer, respectively. L_E and L_C correspond to the length of the emitter and collector contacts.

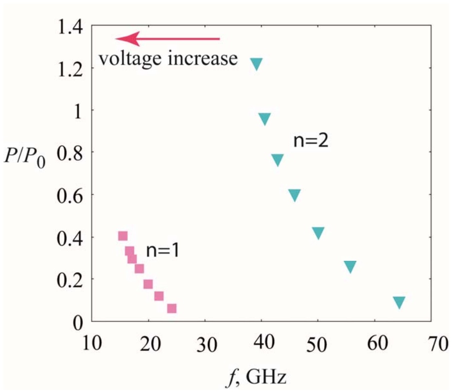

Fig. 2. The frequency-power characteristics of the regular SL (solid squares) and the sandwich structure, contained the heavy-doped layer in the middle (*N*=2) (solid triangles), obtained for the same range of the applied voltage.

The results are shown in Fig 2. The solid squares correspond to the frequency-power characteristics of the regular SL, while the solid triangles illustrates the same feature of the sandwich structure, which contains two identical superlattices (n=2), divided by the heavy-doped layer. One can see that, compared with the regular SL, the considered sandwich structure of the same whole length provides simultaneously the significant (up to three times) increase of both the output power and the frequency of the produced current oscillations due to the synchronization of the domains, travelling in the superlattices.

In order to explain the observed effect, in Fig 3. the current oscillations are shown with the spatio-temporal evolution of the charge (the trajectory of the travelling domain is shown by the dots). One can see that the domain in regular superlattice (Fig 2. *d*) spends more time to reach the collector area, compared to the domain, travelling through the miniband area of the sandwich heterostructure. This results in the decrease of the frequency of the induced current oscillations, which take place, when the domain comes to the collector.

At the same time, the amplitude of the individual domain in the sandwich structure (Fig 2. *b*) becomes much lower, which, in the ordinary case, have to cause the decrease of the oscillation power. However, the domains, travelling in the different parts of the heterostucture, exhibit the synchronous dynamics due to the applied boundary condition (4). It makes the domains to reach the boundaries of the miniband regions simultaneously and contribute to the amplitude of the current impulse.

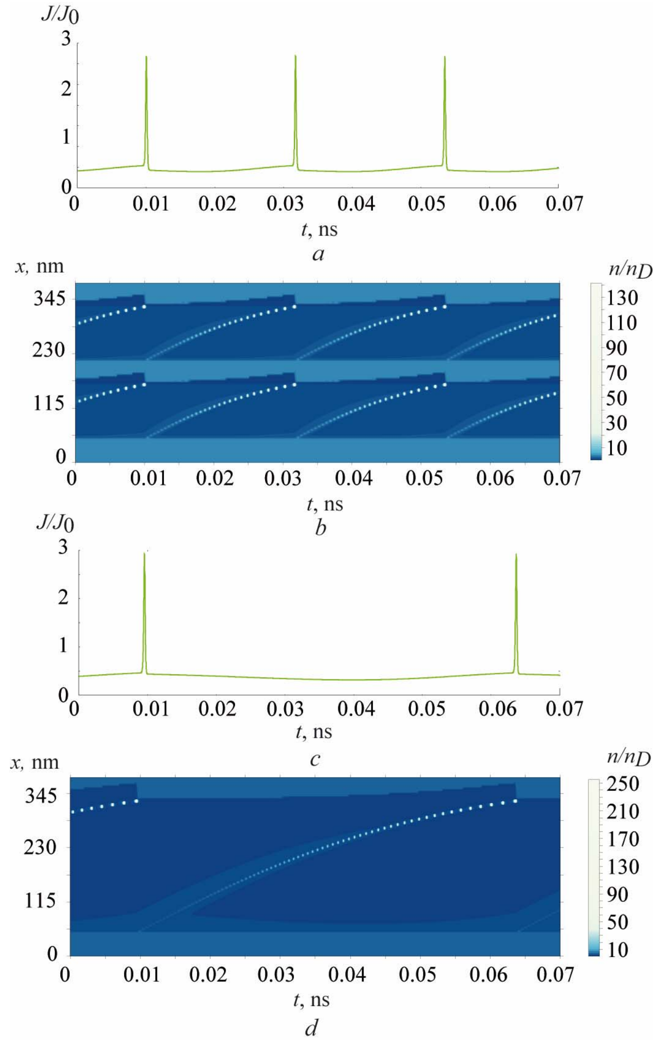

Fig. 3. The current, flowing through the heterostructure and the spatio-temporal dynamics of the volume electron density, corresponded to the sandwich heterostructure (n=2) (*a, b*) and the regular superlattice of the same length (*c, d*).

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