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Noise influence on characteristics of current, flowing through semiconductor superlattice, in high frequency oscillation mode

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Noise influence on characteristics of current, flowing through semiconductor superlattice of nanodevice with prospects of using in terahertz spectroscopy, is examined. It is demonstrated, that the limit voltage, at which the current oscillations start, slightly depends on noise intensity. Oscillation amplitude increases at some noise intensity values for case without magnetic field and in the presence of a tilted magnetic field. At the same time with increase of noise intensity at developed oscillations the basic frequency decreases, while higher harmonics amplitudes can significantly decrease.

Keywords: semiconductor superlattices, microwave devices, high frequency spectroscopy, added noise, spectral analysis.

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Introduction

Nowadays the electronics, that can operate in terahertz (THz) and sub-THz bands, become more relevant in many areas of science, including biophysics and medical applications [1]. Creation of stable communication channels between various devices and THz spectroscopy are becoming the primary areas [2–4]. In these studies the application of devices based on nano- and microstructures as quantum-cascade lasers, devices with electron transfer and other devices, that demonstrate the negative differential conductivity, show good results [5,6]. If due to physical limitations the base frequency becomes less preferable, one of the common methods of oscillation frequency increase is operation with higher harmonics of the base frequency [7,8].

One of the prospective devices, demonstrating the spectrum, containing power harmonics and operating in sub-THz band, is the semiconductor superlattice. Semiconductor superlattices consist of alternate layers of various semiconductor materials (two or more) with various band width [9]. Such periodic structure contributes to minizones forming, where electrons can move along the structure. If product of charge carriers concentration in a device by structure length exceeds the critical value, the negative differential conductivity initiates the formation of distributing charge domains, that can be used for generation or amplification of sib-THz/THz radiation [6,10]. Recently the possibility of external signal amplification due to its synchronization with the base frequency and higher harmonics of current oscillations in the superlattice was demonstrated [11,12]. Such approach increases interest to semiconductor superlattices in terms of high frequency spectroscopy.

At the same time at heterostructure formation the spatial heterogeneities of the superlattice occur inevitably (for instance, random fluctuations of dope concentration [13]), having influence on current, flowing through the semiconductor superlattice. At random nature of heterogeneities occurrence their influence is similar to noise. Along with that, the temperature noise and other noise types are present in current, flowing through the semiconductor superlattice. In the work [14] the model of noise adding to the current, flowing through the semiconductor superlattice, is examined. In it, as well as in some other works [15,16], it is demonstrated, particularly, that noise in some cases does not destroy the current coherent oscillations, but contributes to their generation. This effect is extremely important for spectroscopy tasks, since it allows to operate in the area of high frequencies in the presence of noises, that can not be often suppressed completely. In the above mentioned works the main attention is paid to electron domains dynamics, while in this article it is proposed to study the noise influence on characteristics of current, flowing through the semiconductor superlattice, including oscillation spectrum. Beside that, examination of the case of the presence of the tilted magnetic field, which influence often results in current oscillations stability at external exposure [6,11,12], is also planned.

Model

Current, flowing through the semiconductor superlattice, can be determined by solving the equation system in hydrodynamic approximation [9]: continuity equation, Poisson equation, drift approximation. For numerical simulation convenience, the equations are initially presented in discrete form. At the same time the superlattice is divided into large amount of small layers (about 30−40 layers per structure period) and it is assumed, that inside each layer the electrons density, electric field intensity and current density do not change [6].

For this study the noise is added directly to current density in continuity equation [14,15], after which the equation system, describing the current changes in the superlattice, introduced similar to [6,9], takes the following form:

$$e\Delta x\,\frac{dn_m}{dt} = J_{m-1} + D\xi_{m-1} - J_m - D\xi_m, \quad m = 1\ldots N,$$

$$F_{m+1} = \frac{e\Delta x}{\varepsilon_0\varepsilon_r}\,(n_m - n_D) + F_m, \quad m = 1\ldots N,$$

$$J_m = en_m v_d(\overline{F}_m), \tag{1}$$

where n_m — charge carriers concentration in m layer, J_m — density of current, flowing through boundary of m layer, F_m — electric field intensity in m layer, $\Delta x = 0.24\,\mathrm{nm}$ — elementary layer width, e — electron charge, N — number of discrete layers, $n_D = 3\cdot 10^{22}\,\mathrm{m}^{-3}$ — equilibrium electrons concentration, ε_0 and $\varepsilon_r = 12.5$ — absolute and relative permittivity. Here D — noise intensity, taken within this article as constant and not depending on current density, ξ_{m-1} and ξ_m — random values with Gauss distribution with single dispersion. Such noise introduction suggests a wide spectrum of noise components in the superlattice without elaboration of their nature; moreover, it allows to consider several noise components in the resulting current, if they follow Gauss distribution.

$v_d(\overline{F}_m)$ in equation (1) — dependence of drift velocity on electric field intensity. This dependence has various forms for various external exposure. However, if the possibility of inter-minizone tunneling is not considered, tilted magnetic field is not introduced and temperature is assumed close to absolute zero, the drift velocity takes rather simple form [9]:

$$v_d = \frac{d\Delta}{2\hbar}\,\frac{\tau\omega_B}{(1+\tau^2\omega_B^2)}, \quad \omega_B = \frac{eFd}{\hbar}, \tag{2}$$

where Δ — minizone width, τ — scattering time, ω_B — Bloch oscillations frequency. In this work, beside this simple case, the presence of the tilted magnetic field with induction of $B = 15\,\mathrm{T}$ and tilt angle of $\theta = 40^\circ$ is examined. Introduction into magnetic field consideration results in the drift velocity profile change and additional resonance peaks appearance [6]. For that case the dependence of the drift velocity on electric field intensity is calculated numerically, as in [6,17].

Noise intensity influence on current characteristics

Application of the semiconductor superlattice with sufficient voltage value to the contacts results in generation of high frequency current oscillations [6,18]. In the experimental works these oscillations (frequency can reach dozens of GHz) are hard to register, but usually the dropping section on volt-ampere characteristic indicates the presence of oscillations [17]. Within numerical simulation, as in this article, the similar result is observed at current averaging by time. Example of time dependence of current and volt-ampere characteristic without tilted magnetic field is presented in fig. 1. Beside the average current the minimum and maximum current values are also showed in the figure with grey color. Such representation gives a lot of information on the main characteristics of current, flowing through the semiconductor superlattice: oscillations frequency, oscillations amplitude, limit value of voltage, at which current oscillation starts, but it makes a diagram rather awkward.

Volt-ampere characteristics for various noise intensity values for cases without magnetic field and in the presence of the tilted magnetic field are presented in fig. 2. It should be noted, that in the presence of the tilted magnetic field the volt-ampere characteristics change significantly. Value of voltage, at which generation starts, increases, as the frequency and amplitude of generation [6,17]. At the same time the oscillations form also significantly changes — they become highly non-linear. It was demonstrated earlier, that in the presence of the tilted magnetic field the semiconductor superlattices are more resistant to external exposure influence [6,11,12].

For noise, added to current, the following patterns are observed. Small values of noise intensity slightly influence the volt-ampere characteristics. When noise intensity exceeds some limit, the influence becomes significant. In the presence of the tilted magnetic field, that is expected, the higher value of intensity is required for the changes of volt-ampere characteristics to become significant. Limit value of voltage, at which the current oscillation starts, hardly changes in the presence of noise for the case without magnetic field and changes only at high noise intensities in the presence of the tilted magnetic field. The average current increases under noise exposure, if noise intensity is sufficient.

There is another important difference of the case without noise from the case with the presence of noise, added to current. At low voltage values without noise the volt-ampere characteristic is a linear dependence. However, under exposure of the added noise, it can be seen, that for low voltage values the average current increases, the dependence becomes non-linear. This is because the added noise results in generation of higher frequency, but less powerful oscillations at small voltage values. With voltage increase this generation stops, and by means of symmetry of Gauss distribution the average current value becomes equivalent to the case without added current. However, at significant noise intensity in case of the tilted magnetic field the difference between the case with noise and without it remains until the limit value. It is possible, that this exactly

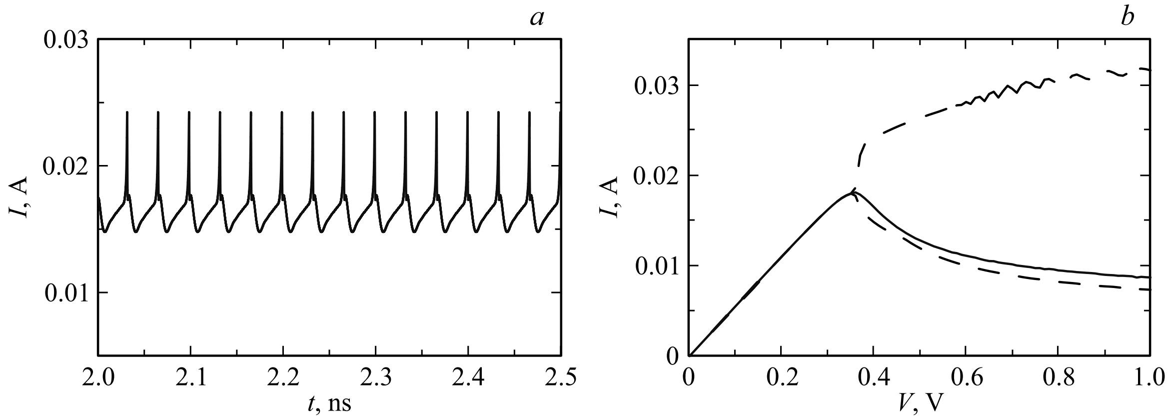

Figure 1. (*a*) Time dependence of current, flowing through the semiconductor superlattice, for case without noise and magnetic field at voltage of $V = 0.4\,\mathrm{V}$. (*b*) Dependence of average (solid line), maximum and minimum (dashed line) current, flowing through the semiconductor superlattice, on voltage, applied to the structure.

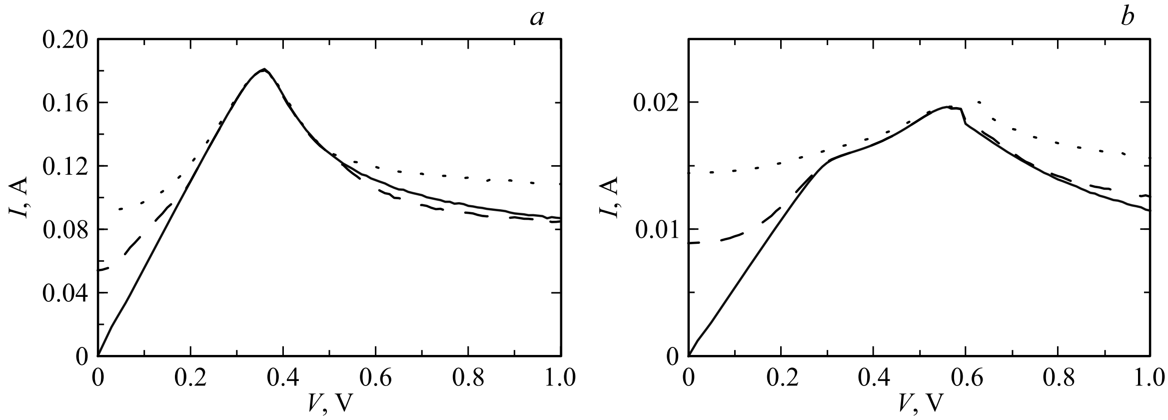

Figure 2. Dependence of the average current, flowing through the semiconductor superlattice, on voltage, applied to structure, for various values of noise intensity. Solid line — $D = 0\,\mathrm{A\cdot m^{-2}}$, dashed line — $D = 3.6\,\mathrm{A\cdot m^{-2}}$, doted line — $D = 7\,\mathrm{A\cdot m^{-2}}$. *a* — case without magnetic field, *b* — case with magnetic field.

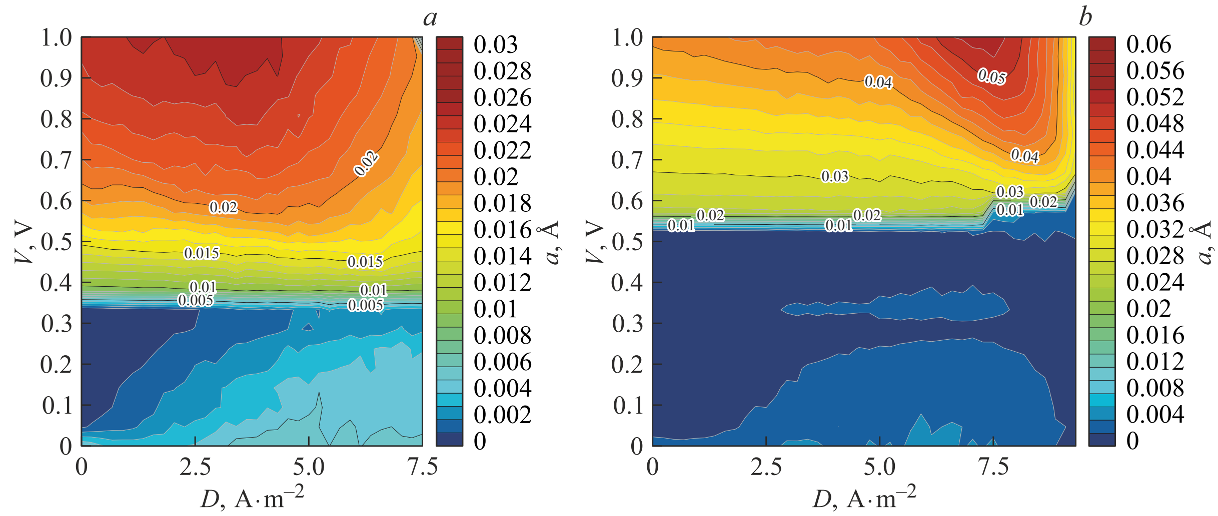

Figure 3. Dependences of oscillations amplitude of current, flowing through structure, on voltage, applied to superlattice, and noise intensity. (*a*) Case without magnetic field, (*b*) case with magnetic field.

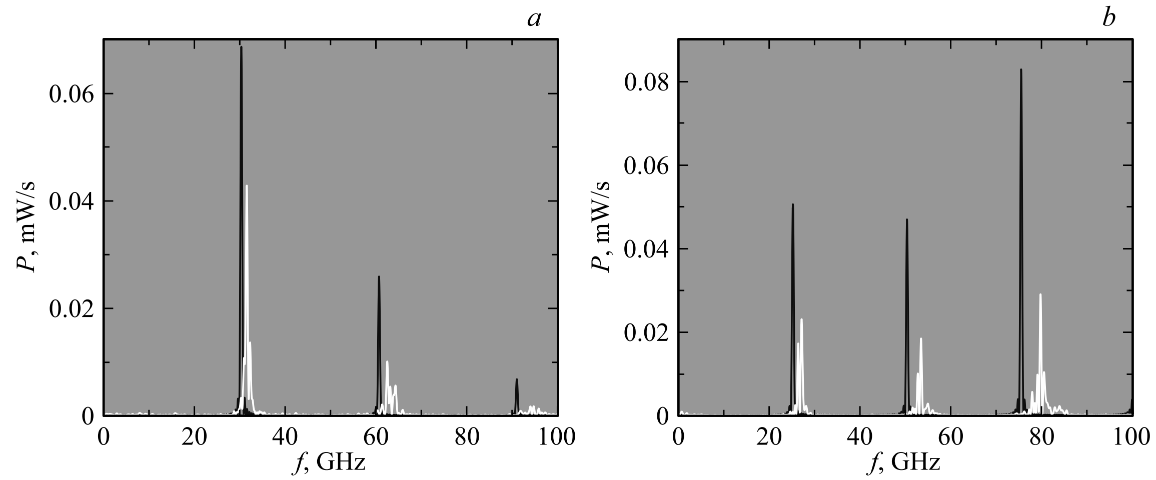

Figure 4. Spectral densities of current oscillations power at various parameters of magnetic field and voltage, applied to the semiconductor superlattice, for cases without added noise (black line) and with added noise with intensity of $D = 7.5\,\mathrm{A \cdot m^{-2}}$. (*a*) Case without magnetic field, (*b*) in the presence of magnetic field. (*a*) $V = 0.4\,\mathrm{V}$, (*b*) $V = 0.6\,\mathrm{V}$.

results in increase of voltage value, at which the drop on volt-ampere characteristic is observed.

Volt-ampere dependences, presented in fig. 2, give some understanding on noise influence on current, flowing through the semiconductor superlattice. However, such understanding lacks accuracy and does not have much information on oscillations amplitude. For that purpose the two-parameter dependences of current oscillations amplitude on voltage and noise intensity $a(V, D)$ for cases without magnetic field and in the presence of the tiled magnetic field are showed in fig. 3 with color.

From the oscillations amplitude dependence it is seen, that, despite the oscillations amplitude is not zero at significant noise intensities before the limit value, the oscillations amplitude is still significantly less, than for oscillations after the voltage limit value. At the same time at high voltage the distinct growth of amplitude can be observed at moderate values of noise, added to current. In case without magnetic field the biggest amplitude growth occurs at noise intensity value of $D = 2.5\,\mathrm{A \cdot m^{-2}}$. While in the presence of the tilted magnetic field the biggest amplitude is observed at noise intensity of $D = 7.5\,\mathrm{A \cdot m^{-2}}$. At the same time the amplitude can increase almost by 20% under noise influence.

Noise intensity influence on spectral characteristics of current oscillations

In case without noise, if there is no magnetic field, the spectrum consists of the base frequency and multiple harmonics, divisible by it. The higher the harmonic frequency, the lower the spectral power density (fig. 4, *a*, black lines). In the presence of the tilted magnetic field at some voltages due to complication of oscillations type the situation is possible, when the spectral power density of divisible harmonics is higher, than at the base frequency (fig. 4, *b*, black lines) [11]. Also, usually in the presence of the tilted magnetic field the frequency and amplitude of oscillations are higher, than in the case without magnetic field.

At some voltage values, close to the limit of the oscillations generation start, for both cases with magnetic field and without it, the oscillations frequency slightly increases at noise adding, while spectral power density significantly decreases. Interesting to note, that at the same time the base frequency and harmonics present not just one peak on dependence of the spectral power density on frequency, but several adjoining peaks. The similar pattern is observed both in the case without magnetic field and with the presence of the tilted magnetic field. At the same time at the presence of magnetic field the situation, when the spectral power density of one of the divisible harmonics is higher, than at the base frequency, remains.

It is also important to note, that the spectral power density of divisible harmonics in case without magnetic field decreases at noise adding so much, that almost disappears, resembling a small splash. In case with the tilted magnetic field the spectral power density of the divisible harmonics remains almost on the same level, as for the case without noise adding.

Conclusion

In this work the influence of noise, added to current, on amplitude and spectrum of its oscillations in the semiconductor superlattices is studied in detail. Both cases - without magnetic field and in the presence of the tilted magnetic field were examined. It is demonstrated, that noise influence can result in oscillations amplitude increase. At the same time, the noise of significant intensity should be added to current to make significant noise influence on volt-ampere characteristic. Beside that, for small voltage values the noise induces current oscillations with extremely low amplitude.

For the spectral power density of current oscillations it is demonstrated, that with the noise intensity growth the oscillations frequency slightly increases at the start, and then decreases. In the presence of noise for small voltage values the base frequency and divisible harmonics present not one, but several adjoining peaks of the spectral power density. Values of the spectral power density decreases with divisible harmonics frequency growth, disappearing almost completely. In the presence of the tilted magnetic field the frequency change becomes more noticeable, while the values decrease of the divisible harmonics spectral power density is not observed.

The observed results are of interest for high frequency spectroscopy, since they demonstrate the resistance of oscillations of current, flowing through the semiconductor superlattice, to noises, thus allowing to use these oscillations as the source of coherent electromagnetic waves. Even at significant intensity of noise, added to current, the generation of electron domains, providing the current oscillations with stable spectra, continues in the superlattice. In case of external resonator use for operation with higher harmonics for frequency increase, the case with the tilted magnetic field is of great interest, since in the presence of magnetic field the values of spectral power density of higher harmonics remain significantly high.

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Conflict of interest

The authors declare that they have no conflict of interest.

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