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# Effect of an External Resonator on the Space Charge Dynamics in a Semiconductor Superlattice

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**Abstract**—The dynamics of a semiconductor superlattice in an external resonator is studied. It is shown that the external electrodynamic system considerably complicates the behavior of the superlattice by exciting random oscillations and leads to additional negative differential conductivity in the *I*–*V* characteristic that is not observed in an autonomous system.

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## INTRODUCTION

Semiconductor superlattices are nanostructures consisting of a number (usually two tens or more) of alternating semiconductor materials with different gaps. They were proposed for the first time by L. Esaki and R. Tsu [1, 2] and independently in [3] as one-dimensional structures for studying various quantum effects related to resonant tunneling and Bloch oscillations. After publication of those original works, various semiconductor superlattices with different electromagnetic properties were proposed and produced. At present, semiconductor superlattices are convenient for studying both processes of physics of condensed matter [2, 4] and various nonlinear phenomena [5–9]. In addition, Bloch oscillations and domain transport in tightly bond superlattices, along with the nonlinear processes associated with them [10], make superlattices promising elements for the generation, amplification, and detection of rf signals of up to several tens of terahertz [11].

To use semiconductor superlattices in rf electronics, it is important to study the interaction between a superlattice and external electrodynamic systems that can be associated with a nanostructure. This problem can be considered in two aspects. First, at high frequencies it is impossible to get rid of spurious capacitances and inductances of superlattice connecting elements (wires, contacts, etc.), which form spurious resonance contours affecting the superlattice. In studying superlattice generation regimes, we must therefore consider the effect of such external spurious contours. Second, as is well known, external electromagnetic systems are often effective for controlling complex nonlinear oscillation processes in the rf range; in particular, the use of additional resonant systems can excite random oscillations in generators, e.g., resonant backward or gyro traveling wave tubes [12]. In this study, we present the results from numerical investigations of the spatial charge dynamics in a semiconductor nanostructure placed into an external high-Q resonator.

## INVESTIGATED SYSTEM AND NUMERICAL MODEL

To describe the collective charge dynamics in a semiconductor superlattice, we use the standard model based on a self-consistent system of Poisson and continuity equations that were numerically integrated. The parameters of the analyzed superlattice were chosen to be similar to those of the superlattices described in [6, 9], where it was assumed that the conducting portion of a mini-zone is divided into $N = 480$ layers with of rather narrow width $\Delta x = L/N = 0.24$ nm.

The change in the charge density in each layer $n_m$ whose right boundary is $x = m\Delta x$ is specified by the discrete analog of the current continuity equation

$$e\Delta x\frac{dn_m}{dt} = J_{m-1} - J_m,\ \ m = 1, \dots N, \quad (1)$$

where $e$ is the elementary charge and $J_{m-1}$ and $J_m$ are the current densities on the left and right boundaries of layer $m$. The current density is determined as

$$J_m = en_m\upsilon_d(\bar{F}_m), \quad (2)$$

where $\bar{F}_m$ is the mean electric field in layer $m$ and drift velocity $\upsilon_d(\bar{F}_m)$ is determined as

$$\upsilon_d = \frac{d\Delta}{2\hbar}\frac{\tau\omega_B}{(1+\tau^2\omega_B^2)}, \quad (3)$$

where $\hbar$ is the Planck constant, $\tau$ is the electron scattering rate, and $\omega_B = eFd/\hbar$ h is the angular frequency of Bloch oscillations of electrons [1, 8].

Electric field $F_m$ at the boundary of layer $m$ can be determined from the Poisson equation, the discrete form of which is

$$F_{m-1} = \frac{e\Delta x}{\varepsilon_0 \varepsilon_r}(n_m - n_D) + F_m, \quad m = 1, \ldots N, \tag{4}$$

where $n_D = 3 \times 10^{22}$ m$^{-3}$ is the doping density in all the layers of the superlattice.

The current was determined using the ohmic boundary conditions $J_0 = \sigma F_0$ in a heavily doped emitter with electric conductivity $\sigma = 3788\ \Omega^{-1}$. Voltage $V_{sl}$ applied to the device was determined as

$$V_{sl} = U + \frac{\Delta x}{2}\left(\sum_{m=1}^{N}(F_m + F_{m+1})\right), \tag{5}$$

where $U$ is the drop in voltage on contacts with regard to the formation of layers with enhanced charge concentration near the emitter and reduced charge concentration near the collector of the superlattice [6]. Knowing the current density in each layer, we can calculate the resulting current that flows through the superlattice [10]:

$$I(t) = \frac{A}{N+1}\sum_{m=0}^{N} J_m, \tag{6}$$

where $A = 5 \times 10^{-22}$ m$^2$ is the superlattice cross section. Note that numerical simulations suggest that the superlattice is at low temperatures, so the diffusion component of the current density is ignored.

To simulate the external resonance contour, we use a one-mode approximation; the resonator is described by an equivalent circuit for which the Kirchhoff equations are

$$C\frac{dV_1}{dt} = (I(X_{sl}) - I_1), \tag{7}$$

$$L\frac{dI_1}{dt} = V_{sl} - V_0 - R_1 I_1 + I(V_{sl})R_l, \tag{8}$$

where $I(V_{sl})$ is the current generated by the superlattice. The resonator is characterized by frequency $f_Q$ and factor $Q$.

## SYSTEM DYNAMICS

To study the effect of an external resonator on rf generation, we considered the $I$–$V$ characteristics of a system superlattice in an external resonator at different frequencies of the latter (Fig. 1a). The dependences are typical of superlattices with an Esaki–Tsu peak and a declining segment that reflects negative differential conductivity [1]. Note that there are jumps in the $I$–$V$ characteristic, while the dependence of the autonomous system is smooth. As the resonator frequency rises, the onset of generation shifts toward lower voltages.

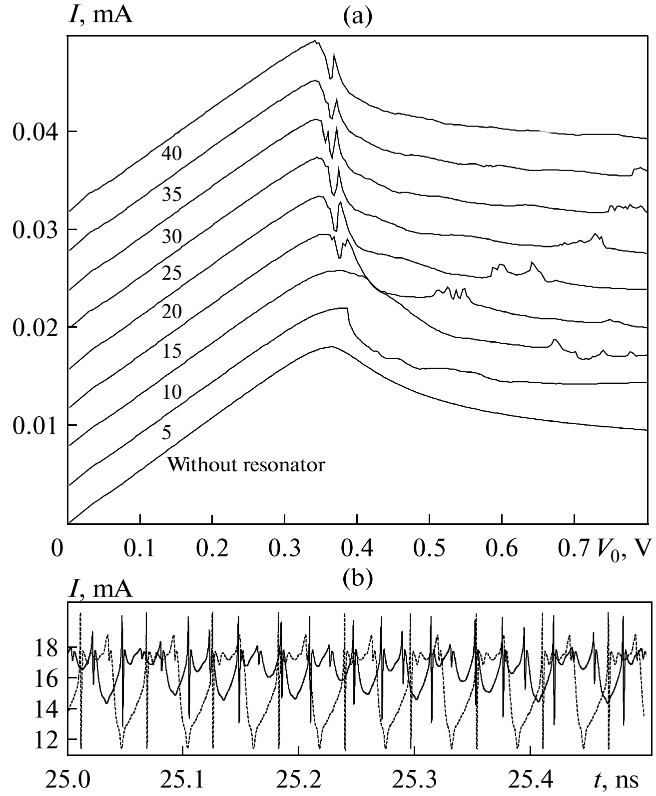


**Fig. 1.** (a) $I$–$V$ characteristics of a superlattice in an external resonator at different frequencies of the latter. The resonator frequency is given under each dependence. For clarity, each subsequent dependence is shifted by 4 mA. (b) Times of current flow at two different supply voltages: the solid line corresponds to voltage $V_0$ = 339 mV; the dashed line, to $V_0$ = 350 mV. The frequency of the external resonator is $f_Q$ = 104.5 GHz and the Q factor is $Q$ = 150.

Note too the considerable significant dip in the $I$–$V$ characteristic near $V_0 \approx 370$ mV, when the resonator frequency approaches that of the superlattice's natural vibrations at this voltage ($f \approx 17$ GHz). Note that this dip remains virtually stationary upon a further rise in resonator frequency and corresponds to the onset of generation in a system with a low-frequency resonator. This effect is due to the high-Q resonator favoring generation at lower voltages since the resonator frequency and the domain repetition rate match. The latter drops with rising voltage, along with the drift velocity of electrons. Figure 1b shows the times of oscillations in the current generated by the superlattice at two different supply voltages before and after the dip and with the resonator tuned to frequency $f_Q$ = 104.5 GHz ($Q$ = 1500). We can see that the frequency of generation before the dip is much higher than after it; the amplitude displays an inverse dependence, indicating considerable rearrangement of the domain motion.

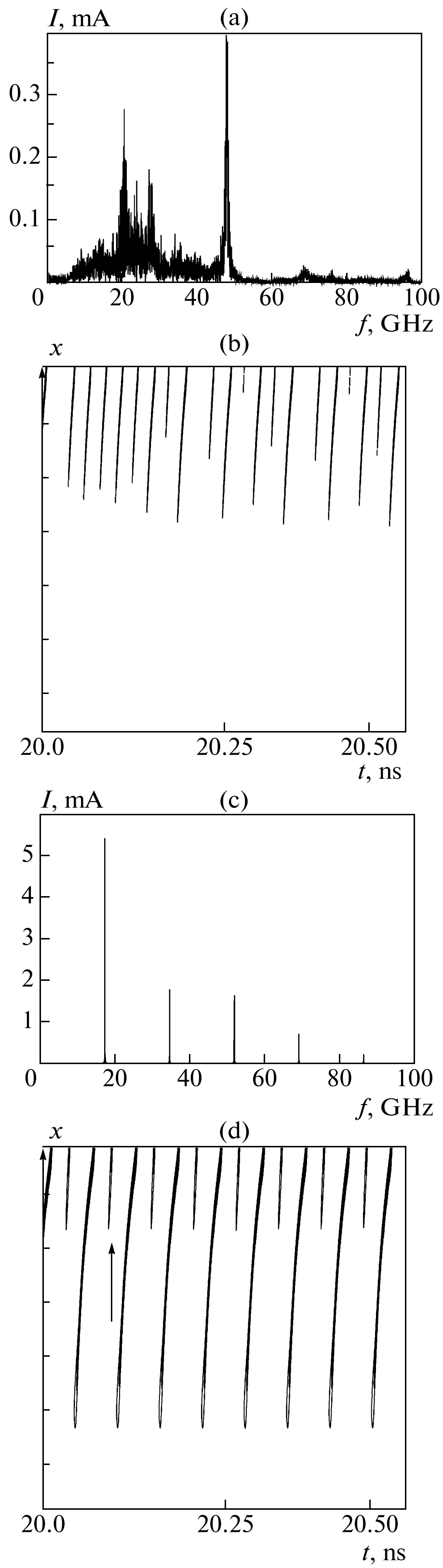


**Fig. 2.** (a, c) Spectra and (b, d) space-time distribution of a charge in the superlattice layers at supply voltages (a, b) $V_0 =$ 339 mV and (c, d) $V_0 = 350$ mV. The external resonator frequency is $f_Q = 104.5$ GHz and the Q factor is $Q = 150$.

To study this effect in more detail, we examine the spectrum and space–time domain dynamics at two different supply voltages (Fig. 2). The spectrum in Fig. 2a illustrates the regime in effect before rearrangement of the domain motion ($V_0 = 339$ mV). The spectrum corresponds to the developed random oscillations of the space charge in the superlattice and has many peaks at a frequency of 20–30 GHz; the most intense harmonic frequency is ~50 GHz. The space-time charge distribution (Fig. 2b) reflects the random dynamics: domains follow irregularly, and the charge concentrations differ strongly. As the voltage rises to 350 mV, the domain dynamics in the semiconductor superlattice are rearranged: in the spectrum in Fig. 2c, we observe a simple periodic regime. There is only the reference frequency and its harmonics; the base generation frequency falls to 18 GHz and the amplitude of the spectral components grows by a factor of more than 10, relative to the case of a lower applied voltage. It can be seen in Fig. 2d that this transition is related to the stabilization of the space-time tableau: the motion becomes regular and the charge concentration in the domains grows. Note that there are small charge clusters (marked with an arrow) that follow with high velocity between the high-concentration domains.

These effects allow us to conclude that the external high-Q resonator favors the second negative differential conductivity segment in the $I–V$ characteristic of the superlattice and, as a consequence, forces generation at lower supply voltage, due to the excitation of domains with low charge concentrations that move fast through the superlattice space and are characterized by rf voltage oscillations in the resonator. In this case, we can increase the rate of domain motion by increasing the resonance frequency of the electrodynamic system. This regime is characterized by a high base frequency and a low-power radiation noise spectrum. Electron transport changes as the voltage rises to the generation threshold of the superlattice's natural vibrations. The charge concentration in the domain grows, substantially reducing the next domain, which is transformed into the fast electron cluster shown by the arrow in Fig. 2d. As a result, the reference generation frequency shifts to 20 GHz and the oscillation power grows rapidly.

## CONCLUSIONS

The dynamics of a semiconductor superlattice in an external high-Q resonator was studied. The $I–V$ characteristics were determined and the behavior of the superlattice at different resonator frequencies was investigated. It was shown that when the resonator frequency exceeds the frequency of the superlattice natural vibrations, there is an additional negative differential conductivity segment in the $I–V$ characteristic due to the excitation of charge domains by rf voltage oscillations in the resonator. This effect is of interest both in fundamental studies of semiconductor nanostructures and in using superlattices for the generation of microwave and terahertz oscillations.

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## REFERENCES

1. Esaki, L. and Tsu, R., *IBM J. Res. Develop.*, 1970, vol. 14, no. 1, p. 61.
2. Tsu, R., *Superlattices to Nanoelectronics*, New York: Elsevier, 2005.
3. Ovsyannikov, M.I., Romanov, Yu.A., Shabanov, V.H., and Loginova, R.G., *Fiz. Tekhn. Poluprovodn.*, 1970, vol. 4, no. 12, p. 2225.
4. Shik, A.Ya., *Fiz. Tekhn. Poluprovodn.*, 1974, vol. 8, p. 1841.
5. Bonilla, L.L. and Grahn, H.T., *Rep. Prog. Phys.*, 2005, vol. 68, p. 577.
6. Fromhold, T.M., Patane, A., Bujkiewicz, S., et al., *Nature*, 2004, vol. 428, p. 726.
7. Balanov, A.G., Fowler, D., Patan'e, A., et al., *Phys. Rev. E*, 2008, vol. 77, no. 2, p. 026209.
8. Selskii, A.O., Koronovskii, A.A., Hramov, A.E., et al., *Phys. Rev. B*, 2011, vol. 84, p. 235311.
9. Balanov, A.G., Greenaway, M.T., Koronovskii, A.A., et al., *JETP*, 2012, vol. 141, no. 5, p. 863.
10. Wacker, A., *Phys. Rep.*, 2002, vol. 357, no. 1, p. 121.
11. Waschke, C., Roskos, H.G., Schwedler, R., et al., *Phys. Rev. Lett.*, 1993, vol. 70, p. 3319.
12. Nusinovich, G.S., Vlasov, A.N., and Antonsen, T.M., *Phys. Rev. Lett.*, 2001, vol. 87, no. 21, p. 218301.

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