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Spectral Power Density of Current Oscillations in a Semiconductor Superlattice in the Presence of a Tilted Magnetic Field at Various Temperatures

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Abstract—We have studied the spectral power density of current oscillations in a semiconductor superlattice at various applied voltages and temperatures. Special attention is devoted to the effect of a tilted magnetic field on the power density spectrum. On the whole, an increase in the temperature leads to a significant decrease in the spectral power density and total power of current oscillations in the semiconductor superlattice.

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Semiconductor superlattices are complex nanostructures consisting of several thin (on the order of 10 nm) alternating layers of various semiconducting materials [1–3]. These structures were originally proposed in 1969 by Esaki and Tsu [4] for investigation of various quantum-mechanical phenomena related to the resonant tunneling and Bloch oscillations and still serve a unique model object for deeper insight into solid state physics [5, 6] and investigations in the field of nonlinear dynamics [7–13].

The application of constant electric and tilted magnetic fields to a superlattice leads to the formation of electron domains moving along the structure. The passage of these domains via the superlattice leads to the generation of current oscillations in the system. Previously, it was demonstrated [7, 11] that the application of a tilted magnetic field to a superlattice can be used for effective control of the properties of this structure. The present work considers the influence of temperature on the spectral power density of generated current oscillations in a semiconductor superlattice.

Processes in a semiconductor superlattice have been modeled using a system of equations that includes the equation of continuity

$$e\frac{\partial n}{\partial t} = \frac{\partial J}{\partial x}, \tag{1}$$

the Poisson's equation

$$\frac{\partial F}{\partial x} = \frac{e}{\varepsilon_0\varepsilon_r}(n - n_D), \tag{2}$$

and an expression for the current density with allowance for the electron drift velocity [2, 7],

$$J = env_d(F), \tag{3}$$

where t is the current time; x is the coordinate in the direction perpendicular to layers of the superlattice; variables $n(x, t)$, $F(x, t)$, and $J(x, t)$ describe the electron concentration, electric field strength, and current density, respectively; ε_0 and ε_r are the absolute and relative dielectric permittivities, respectively; n_D is the equilibrium electron concentration; v_d is the electron drift velocity calculated for the field F; and $e > 0$ is the electron charge.

The dependences of the electron drift velocity on the electric field were numerically calculated for various temperatures in the framework of a semiclassical approximation described in detail elsewhere [5, 10, 11], including the effect of temperature on the field dependence of the electron drift velocity [11].

Following the approach adopted in [8, 11], we assume that the contacts on the superlattice emitter and collector are ohmic, so that current density J_0 via the emitter is determined by contact conductivity $\sigma = 3788\ \Omega^{-1}$ as $J_0 = \sigma F(0)$. Electric field $F(0)$ can be determined from the boundary condition

$$V = U + \int_0^L F(x)dx, \tag{4}$$

where V is the voltage applied to the superlattice and U describes the voltage drop on the contacts [7].

As was noted above, semiconductor superlattices under the action of an applied electric field admit the

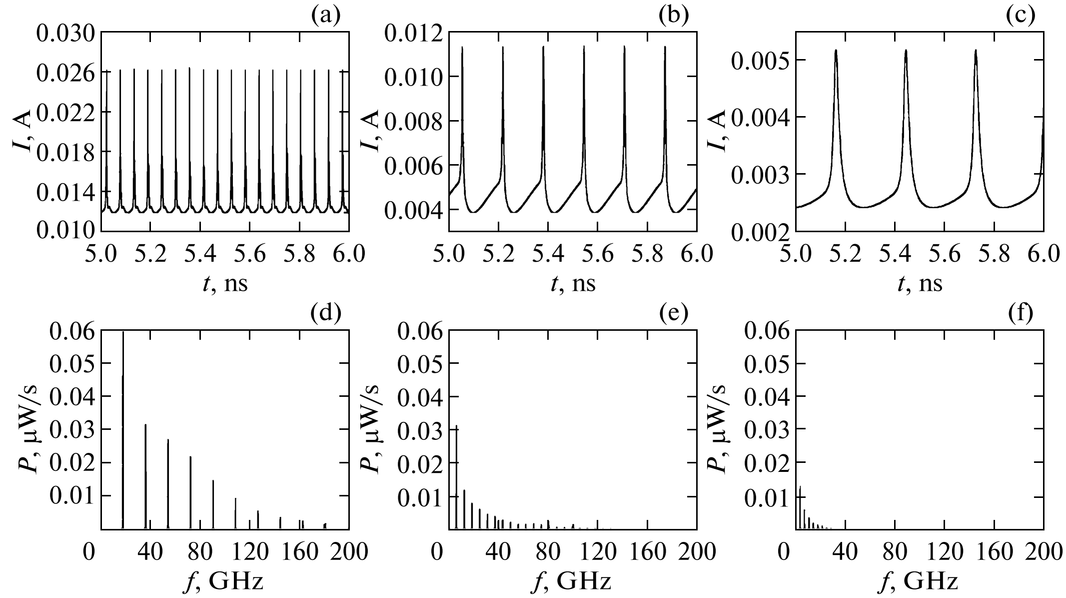

Fig. 1. (a, b, c) Time series of the current passing through a semiconductor superlattice and (d, e, f) corresponding spectral power densities of current oscillations for $V = 0.5$ V in the absence of an applied tilted magnetic field, $\theta = 0°$, and various temperatures: $T =$ (a, d) 4.2, (b, e) 100, and (c, f) 200 K.

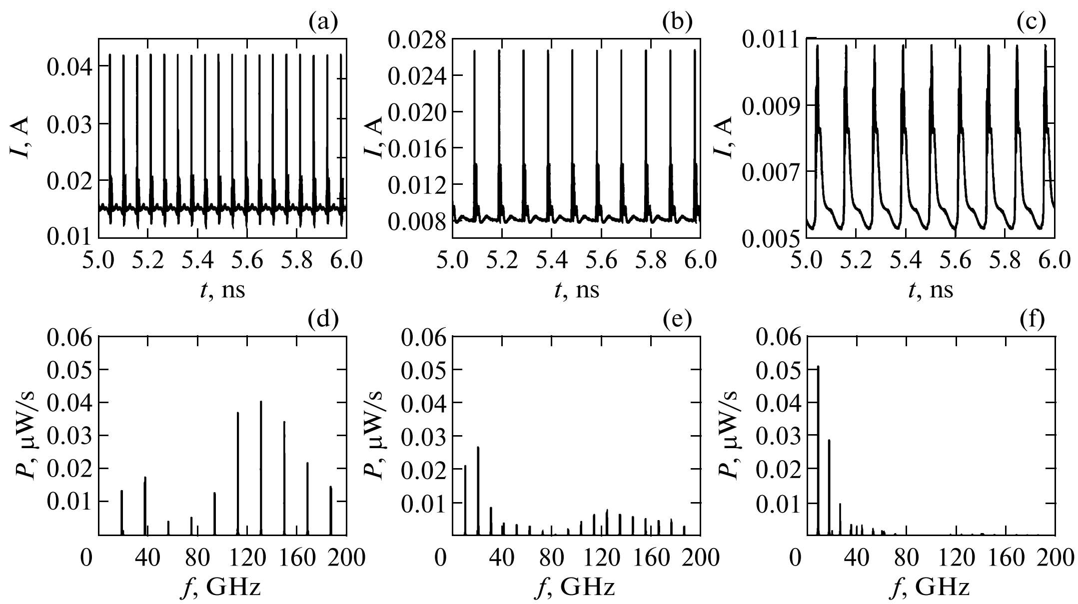

Fig. 2. (a, b, c) Time series of the current passing through a semiconductor superlattice and (d, e, f) corresponding spectral power densities of current oscillations for $V = 0.7$ V in the presence of tilted magnetic field $B = 15$ T, $\theta = 40°$, and various temperatures: $T =$ (a, d) 4.2, (b, e) 100, and (c, f) 200 K.

formation of electron domains, the propagation of which is accompanied by oscillations of the current passing through the superlattice [5, 6]. Figure 1 shows the time series and spectral power densities of current oscillations at fixed values of the voltage applied to the superlattice and various temperatures in the absence of a magnetic field. As the temperature increases (Figs. 1b and 1c), the frequency of domain passage decreases and, as result, the frequency of current oscillations decreases as well [11]. Since the current oscillations possess a rather complicated shape, the spectra contain a large number of harmonics, the power of which decreases with increasing harmonic number. It is evident that the power of all harmonics decreases with increasing temperature. As was mentioned above, the frequencies of harmonics also decrease with increasing temperature.

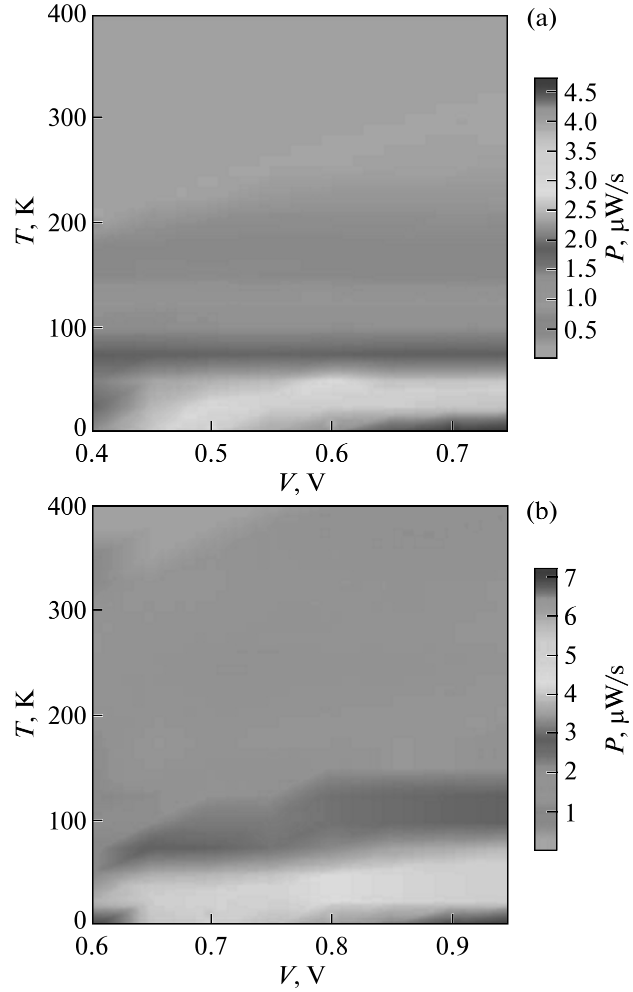

Fig. 3. Dependence of the total power of current oscillations in a semiconductor superlattice on the temperature and applied voltage (a) in the absence of magnetic field ($\theta = 0$) and (b) in the presence of a tilted magnetic field $B = 15$ T at $\theta = 40°$.

A somewhat different situation is observed when the semiconductor superlattice is exposed to a tilted magnetic field. Figures 2a–2c show the time series of the current at various temperatures in this case. The frequency and amplitude are significantly higher than those in the absence of the field [11]. In addition, the character of oscillations also significantly changes: in the tilted magnetic field, the shape of oscillations becomes more complicated. As can be seen, the oscillations are characterized by several maxima. Accordingly, Figs. 2d–2f show that the power of higher harmonics in the presence of a tilted magnetic field can be greater than the power of the main harmonic. At low temperatures (T = 4.2 K), the maximum power is observed for the sevenths harmonic, while the second harmonic is most powerful at $T = 100$ K. With a further increase in the temperature, the maximum power is observed for the main harmonic. In addition, comparison of Figs. 2e and 2f shows that the power of the main harmonic at $T = 200$ K is significantly higher than that at T = 100 K, while the power of higher harmonics (except the second one) at the greater temperature decreases.

Analysis of the obtained results poses a question concerning the behavior of the total power of current oscillations in the superlattice with increasing temperature. For calculations of the total power, the spectral power density was calculated over the entire frequency range. Figure 3 shows plots of the total power of current oscillations as a function of the temperature and voltage applied to the semiconductor superlattice. As can be seen for any voltage in the absence of a tilted magnetic field, an increase in the temperature is accompanied by a decrease in the power of current oscillations, while the presence of a tilted magnetic field makes local growth in the power of oscillations with increasing temperature possible.

Thus, it can be concluded that an increase in the temperature in semiconductor superlattices leads to a decrease in the spectral power density and frequency of current oscillations. It has been found that, in the presence of a tilted magnetic field, the power of higher harmonics can exceed that of the main harmonic. With increasing temperature, this effect vanishes and changes to a monotonic decrease in the power of harmonics with increasing number, analogous to the behavior observed in the absence of a magnetic field.

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