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Synchronous Regimes Induced in Semiconductor Superlattices by a Tilted Magnetic Field and External Force

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Abstract—The effect a periodic electric field has on the dynamics of electron domains in a semiconductor superlattice with applied voltage and a magnetic field tilted relative to the superlattice axis is investigated. It is shown that this periodic electric field greatly affects the *I*–*V* characteristic of the superlattice and can induce several interesting phenomena, including the onset of synchronous regimes. The obtained results are compared to the data for a zero tilted magnetic field.

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INTRODUCTION

Semiconductor superlattices are nanostructures formed from several alternating layers of different semiconductor materials. They are capable of displaying some intriguing quantum-mechanical effects in applied electric and tilted magnetic fields. These include the generation of terahertz Bloch oscillations, electron dynamics limitations, negative differential drift velocity, Bloch-cyclotron resonances, and dynamic chaos [1–5]. The autonomous charge dynamics in a superlattice with applied dc voltage and tilted magnetic field has recently attracted great interest from researchers [6–8], while the effect an external ac electric field has on such a system remains poorly studied. In this work, we show that the parameters of an external ac field affect the current flowing through a semiconductor superlattice with applied voltage and a tilted magnetic field. Along with an applied tilted magnetic field, we consider the effect external perturbations have on the charge domain dynamics in a superlattice in a zero tilted magnetic field [9].

NUMERICAL MODEL

To describe the collective dynamics of charge domains in a semiconductor superlattice, we self-consistently solved discrete current density continuity and Poisson equations. A transport miniband with length $L = 115.2$ nm was separated into $N = 480$ layers, each having a width of $\Delta x = L/N = 0.24$ nm, small enough to consider the medium as continuous [7]. Electron density n_m in the mth layer was assumed to be constant within the layer.

The variation in electron density in the mth layer was determined by the discretized current continuity condition

$$e\Delta x \frac{dn_m}{dt} = J_{m-1} - J_m,\ m = 1\ldots N, \tag{1}$$

where $e > 0$ is the elementary charge and $J_{m-1}(J_m)$ is the current density at the left (right) boundary of the mth layer. In the drift approximation and ignoring diffusion, we have current density

$$J_m = en_m v_d\left(\bar{F}_m\right), \tag{2}$$

where v_d determines the electron drift velocity with average electric field F_m in the mth layer [6].

Electric field $F_{m-1}(F_m)$ at the left (right) boundary of the mth layer can be described by the discretized Poisson equation

$$F_{m+1} = \frac{e\Delta x}{\varepsilon_0\varepsilon_r}(n_m - n_D) + F_m,\ m = 1\ldots N, \tag{3}$$

where $\varepsilon_0, \varepsilon_r = 12.5$ correspond to the absolute and relative permittivities, and $n_{D0} = 3\times10^{22}\ \mathrm{m}^{-3}$ is the equilibrium electron density.

We use the ohmic boundary conditions to determine current $J_0 = \sigma F_0$ in a heavily doped emitter contact; electrical conductivity $\sigma = 3788\ \mathrm{S}^{-1}$. Voltage V applied to the device is a global limitation specified as

$$V = U + \frac{\Delta x}{2}\sum_{m=1}^{N}(F_m + F_{m+1}), \tag{4}$$

Here, U is the drop in voltage on the contacts, including the effects of charge accumulation and depletion in the emitter and collector areas. The contact resistance is $R = 17$. With an external force on a semiconductor superlattice, voltage V is determined by the formula

$$V = V_0 + V_m \cos(\omega_e t + \varphi_0), \quad (5)$$

where V_0 is the dc voltage applied to the superlattice, V_m is the amplitude of the external effect, ω_e is the angular frequency of the external force, and φ_0 is the initial phase. The external influence on the superlattice is thus controlled by modulating the voltage applied to the structure. Voltage V_0 is in this case considered to be a control parameter governing the dynamic regime in the autonomous system. The current is calculated as

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

where $A = 5\times10^{10}$ m^2 is the superlattice cross-sectional area [7].

One of the most important characteristics of the above model is the dependence of the electron drift velocity on electric field F. This dependence contains the information needed about the spatial structure (superlattice period d) and energy characteristics of the structure, external magnetic field B, and temperature T. Although such parameters as miniband width $\Delta = 19.1$ meV, magnetic field induction B, and temperature T are not explicitly included in Eqs. (1)–(6) describing the charge domain dynamics in semiconductor superlattices, they were considered in the electric-field dependence of drift velocity v_d.

In our calculations, we used field dependences of drift velocity $v_\mathrm{d}(F)$ obtained using the approach described in [8] at zero temperature ($T = 0$). In a zero magnetic field ($B = 0$), this dependence can be calculated both analytically and numerically. The analytical dependence then takes the form

$$v_\mathrm{d} = \frac{d\Delta}{2\hbar}\frac{\tau\omega_\mathrm{B}}{(1+\tau^2\omega_\mathrm{B}^2)}, \quad (7)$$

where $\hbar$ is Planck's constant, τ is the average time of electron scattering, and $\omega_\mathrm{B} = eFd$ is the angular frequency of electron Bloch oscillations [1, 8]. If the magnetic field is generally $B \neq 0$, drift velocity $v_\mathrm{d}(F)$ can be calculated only numerically [8]. Typical dependences of drift velocity v_d on electric field F in zero ($B = 0$) and nonzero ($B = 12$ T, $\theta = 40°$) magnetic fields are shown in Fig. 1. It is clearly seen that in a zero magnetic field, such a dependence contains only one maximum associated with Bloch oscillations [1, 10]). In a nonzero magnetic field, there are several maxima. The first maximum for the lowest F value is also associated with Bloch oscillations, and the others arise due to the resonant ratio between the Bloch and cyclotron frequencies [8]. These maxima are obviously due to the complex dynamic regimes in semiconductor superlattices.

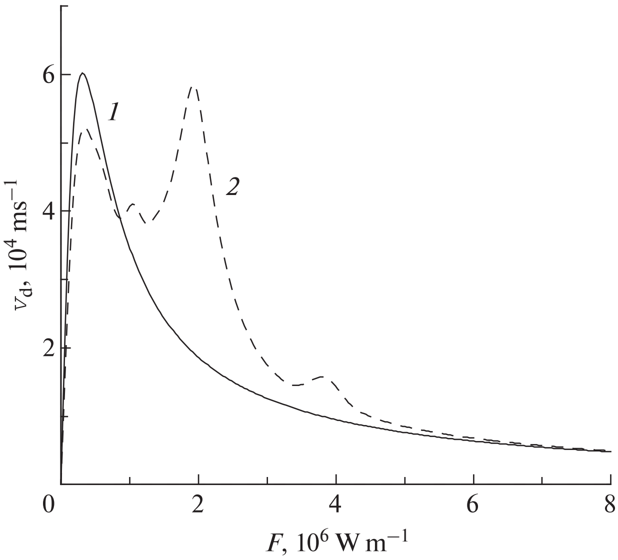

Fig. 1. Drift velocity v_d vs. F, calculated when $B = 0$ (curve *1*, solid line) and $B = 12$ T and $\theta = 40°$ (curve *2*, dashed line) at zero temperature.

RESULTS AND DISCUSSION

If modulation voltage $V_m = 0$, the superlattice can be described by Eqs. (1)–(6). As is well known, the system regimes in this case allow us to observe both the dc current and rf current oscillations, depending on voltage V_0 applied to the device. The moment of current oscillation generation then corresponds to the maximum current in the I–V characteristic. Typical I–V characteristics with and without external forces are presented in Fig. 2: (a) $B = 0$ and (b) tilted magnetic field $B = 12$ T is applied to a superlattice ($\theta = 40°$). We can see that at $B = 0$ with and without external forces, the I–V characteristics exhibit ordinary behavior with one current maximum related associated with single-electron Bloch oscillations in a semiconductor superlattice. When $B \neq 0$, the situation changes. The I–V characteristics then reveal the higher threshold voltage and maximum dc current. Despite the abovementioned differences, the I–V characteristics also have identical brightly pronounced current jumps upon the application of an external force in both a zero and a nonzero magnetic field. These jumps can be attributed to the synchronous regimes observed in a semiconductor superlattice. We may assume the regime to be synchronous when the investigated system oscillates at the frequency of the external force or a multiple of it.

To characterize the regime observed in a semiconductor superlattice, we calculate rotation number $\rho = \omega_e/\omega_0$, where ω_0 is the angular frequency of current oscillations in the superlattice and ω_e is the angular frequency of the external force. When $\rho = 1$, we observe 1 : 1 synchronization in the semiconductor

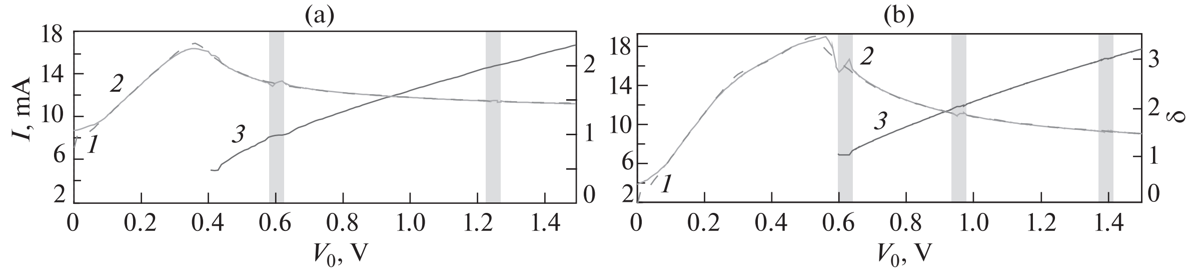

Fig. 2. *I–V* characteristics without (curve *1*) and with (curve *2*) an external effect (V_m = 60 mV and $f_e = f_0$, where f_0 is the current oscillation eigenfrequency in the superlattice). Shown are the calculated dependences of ratio ρ (external force frequency and eigenfrequency) on voltage V_0 applied to the semiconductor superlattice (curve *3*) when (a) B = 0 T and (b) B = 12 T and θ = 40° when T = 0 K.

superlattice. At integer ρ, we have synchronization on harmonics. The rational ρ values correspond to synchronization on subharmonics, while the irrational ones are associated with asynchronous regimes.

Figure 2 shows the dependences of rotation number ρ on voltage V_0 applied to a superlattice (the so-called devil's staircase) in zero and nonzero magnetic fields (curves *3*). Plateaus ρ = 1, 2, ... in the devil's staircase corresponds to synchronous regimes (grey triangles). It is clearly seen that the jumps in the *I–V* characteristics are associated with the onset of the synchronous regime.

CONCLUSIONS

The weak external periodic signal can synchronize electron domain transport in a semiconductor superlattice within a wide range of frequencies of external forces. In both a zero and a nonzero tilted magnetic field, the width of the synchronization region is nearly independent of the ratio between the external frequency and eigenfrequency, which is atypical of the synchronization of periodic oscillations and can be attributed to the rich spectral composition of the current oscillations in an autonomous superlattice.

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