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Possibility of the effect of absolute negative conductivity in quantum superlattice exposed to the high-frequency electromagnetic radiation

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ABSTRACT

Current density in superlattice placed in quantizing electric field and in high-frequency field of electromagnetic wave was calculated. The calculations were performed by taking into account an inelastic scattering of charge carriers by phonons. Possibility of the effect of absolute negative conductivity, i.e. the effect of appearance of electric current flowing in opposite direction than that of vector of quantizing electric field intensity, was shown. Such effect in graphene superlattices was discussed.

1. Introduction

Last time theoretical and experimental investigations of intensive electromagnetic (EM) field effect on the electric properties of low-dimensional structures with superlattice (SL) are carried out [1–8]. Necessity of such investigations is due to the possibility of using of quantum SL to create the amplifiers and generators of terahertz radiation [2,9,10]. Particular attention is paid to graphene based SL (GSL) [3,11–16]. It is explained by the high mobility of graphene charge carriers in comparison with

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that of bulk semiconductors [17,18]. Non-additivity of the electron spectrum is another feature of GSL. It allows regulating the transversal electric currents by changing of longitudinal voltage [13,15].

Strong electric field applied through the SL axis leads to the radical change in the electron spectrum under certain conditions [19–23]. Namely, continuous spectrum is transformed into a set of equidistant energy levels (it is so called Stark ladder). In Refs. [9,24] the possibilities of using of electronic transitions between Stark ladder levels to generate EM radiation was discussed. Localization of electron wave functions which is induced by the strong electric field and known as Wannier–Stark localization was studied theoretically in Refs. [19–23,25]. Experimentally Wannier–Stark states were observed in Refs. [26–30]. In Ref. [31] Stark quantization in graphene based materials was investigated theoretically.

In Refs. [32,33] the general theory of semiconductor electric conductivity which took into account finiteness of conduction band and electron–phonon interaction was developed. Let us note that electron–phonon interaction in the conditions of Stark quantization was studied in Refs. [4,34]. In Ref. [35] the current density arising through the axis of 2D SL in quantizing electric field was calculated on the basis of the general method developed in Refs. [32,33]. The calculations performed in Ref. [35] showed the possibility of so-called electrophonon resonance (EPR) which was predicted in Ref. [36] for the bulk semiconductors. According to Ref. [35] longitudinal current–voltage characteristic of SL has logarithmic singularities arising due to the electron transitions between Stark ladder levels with phonon involvement.

In Refs. [37,38] the effect of high-frequency (HF) EM radiation with intensity of electric field oscillating perpendicularly to the SL axis on the longitudinal conductivity of 2D SL in quantizing electric field was investigated. Besides, in Ref. [38] the absorption and emission of quanta of the HF field were neglected. In Ref. [37] observation of phenomenon of so-called absolute negative conductivity (ANC) was noted to be possible in narrow-band semiconductors exposed by the HF field. This phenomenon is that the electric current flows along the direction which is opposite to the vector of the intensity of the constant electric field. Presence of the finiteness conduction band both in longitudinal and in transversal directions with respect to constant electric field was the significant circumstance. ANC induced by the HF electric currents was observed experimentally in Josephson junctions [39]. Such effect induced by the EM microwaves in semiconductors in quantizing magnetic field was investigated in Refs. [40,41].

Below the current density induced by the quantizing electric field and the HF field of EM radiation along the axis of quantum SL is calculated. The magnetic field is absent in comparison with [40,41]. The processes of absorption and emission of quanta of the HF field are taken into account in present work. It makes results obtained below different from that of [38]. The condition of appearance of ANC is found and the corresponding current density is calculated.

2. Resonances of the current density in 2D SL in quantizing electric and HF EM fields

Let us consider 2D structure with SL which is in the plane xy so that Ox is the SL axis. In tight-binding approximation electron dynamics in the mini-band of a number of semiconductor SLs is described by the following dispersion law ($\hbar = 1$):

$$\varepsilon_{\mathrm{SL}}(\mathbf{p}) = \frac{p_y^2}{2m} + 2\Delta \sin^2 \frac{p_x d}{2}, \tag{1}$$

where m = const is the constant effective mass corresponding to the electron motion along the direction Oy, Δ is the mini-band semiwidth, d is the SL period, $\mathbf{p}$ is electron quasimomentum. For instance, Eq. (1) describes the electron motion in the mini-band of SL based on GaAs/AlGaAs [1,2,35].

Let structure suggested above is irradiated by the EM wave with intensity of electric field oscillating in the structure plane xy with amplitude E_0 and frequency ω. Moreover the strong electric field with vector of intensity $\mathbf{E}$ is suggested to be applied along the SL axis. For this field the next conditions are performed:

$$\Omega_{\mathrm{B}} \ll \varepsilon_{\mathrm{g}}, \ \Omega_{\mathrm{B}}\tau \gg 1, \tag{2}$$