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Influence of the electromagnetic wave on the transversal conductivity of the graphene superlattice

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ABSTRACT

The transversal conductivity of the graphene superlattice under electromagnetic radiation and constant electric field applied along the superlattice axis was calculated. The cases of sinusoidal and cnoidal electromagnetic waves are considered. Conductivity dependences on the electromagnetic wave amplitude and on the longitudinal electric field intensity were investigated. Such dependences were shown to have the character of oscillations.

1. Introduction

In recent years, the transport properties of graphene-based structures were intensively studied experimentally and theoretically [1–12]. Such investigations are of fundamental and practical interest [13–18]. The remarkable electronic and optical properties of graphene structures are related with its unusual electron spectrum. In [19,20] the quantum theory of the magneto-optical conductivity was developed. The nonlinear electromagnetic (EM) response of the carbon systems to the excitations of different shapes was investigated in [21] where the frequency multiplication effect was calculated. A quasi-classical kinetic theory of the nonlinear EM response of graphene was developed in

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[22–24]. Also in [22–24] the possible applications of the predicted effects for generation of terahertz radiation were discussed. The so-called mutual rectification of the EM waves in graphene was studied in [25–27].

New opportunities for building of the optoelectronic devices can be opened by the predicted nonlinear optical properties of the graphene-based structures. The electron spectrum of the graphene with the additional periodic potential was studied in [28–36]. The band structure of graphene superlattice (GSL) with periodically arranged rows of vacancies and lines of adsorbed hydrogen atoms was calculated in [28,29] correspondingly. In [32] a new method to obtain the superlattice (SL) potential in the graphene was proposed where the last was suggested to be deposited on the periodic substrate h-BN/SiO_2. Dispersion low of GSL was studied theoretically in [32–36].

Intensive investigations of the electronic and optical features of carbon structures (in particularly – graphene structures) with additional SL potential are of interest due to the so-called Bloch oscillator problem [37–39]. Moreover SL is the suitable medium for the formation of the nonlinear and solitary EM waves [40–44]. For instance to form the cnoidal waves and the solitons in the semiconductor SL a relatively small electric fields ($\sim 10^3$ V/cm) in compared with bulk semiconductors [40–42] are required. That is why the structures with SL are of fundamental and practical interest [45–48].

The optical properties of GSL were investigated in [34,35,49–51], where the constant electric current induced in GSL by the EM waves of different polarization was calculated. In [35,50] one of the waves was of cnoidal form. The negative differential conductivity and absolute negative conductivity of the GSL axis was shown to be possible under the simultaneous action of EM wave polarized elliptically and constant electric field applied along the GSL axis.

In [37] the alternate electric field influence on the longitudinal current–voltage characteristics of the semiconductor SL was studied. The GSL current–voltage characteristic along the GSL axis in the presence of the alternate electric field was calculated in [34]. In experiment, however, it is very difficult to orient the electric field vector along the SL axis strictly. There always exists a small transverse component of the applied electric field intensity. The problem of non-coincidence of the electric field intensity with certain crystallographic axis was formulated in [52]. In [53] the dependence of the spectrum of Bloch oscillations on the orientation of an applied electric field was discussed.

Thus, it was of interest to calculate the transversal conductivity of the GSL in the presence of a weak transverse electric field in addition to a strong constant electric field applied along the GSL axis and EM radiation.

The transverse field component can either be related to uncertainly of the field orientation along the GSL axis or it can be specially applied so as to obey certain conditions. Such conditions lead to the constant component of the electric current appearing in the GSL plane transversally to the GSL axis. The dependence of the transversal conductivity on the longitudinal electric field intensity is shown below to have a resonant character.

2. Transversal conductivity of GSL in τ-approximation

GSL is considered to be obtained by a sheet of graphene deposited on a banded substrate formed by periodically alternating layers of SiO_2 and SiC. The layers are arranged so that the hexagonal crystal lattice of SiC was under the hexagonal lattice of graphene. Due to this, in the areas of graphene plane located above the layers of SiC an energy gap $2\Delta = 0.26$ eV arises [2,34]. Let the graphene is located on the plane *xz*. The electron spectrum of GSL has the approximate view [34,35]:

$$\varepsilon(\mathbf{p}) = \sqrt{\varepsilon_0^2 + p_x^2\upsilon_F^2} + \frac{\varepsilon_1^2}{\sqrt{\varepsilon_0^2 + p_x^2\upsilon_F^2}}\left(1 - \cos\frac{p_z d}{\hbar}\right) \quad (1)$$

where $\varepsilon_0 = 0.059$ eV, $\varepsilon_1 = 0.029$ eV, $d = 2 \times 10^{-6}$ cm is the SL period, $\upsilon_F = 10^8$ cm/s is the Fermi surface velocity, *Oz* is the SL axis. The vector potential $\mathbf{A}$ of the EM wave is considered to be applied along the SL axis (Fig. 1). The constant electric field vector is $\mathbf{E} = (E_x, 0, E_z)$. The mean free path of electrons is assumed to be much shorter than the wavelength. This allows us to neglect the coordinate dependence of the EM fields and the distribution function. Under these conditions the electric current