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Electromagnetic radiation of semiconductor crystals in crossed electric and magnetic fields

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Abstract. The features of generation of electromagnetic radiation by semiconductor crystals in crossed electric and magnetic fields have been analyzed. Analytical relations for calculating the power of cyclotron radiation have been given. The obtained results are of interest for the purposes of obtaining the sources of electromagnetic radiation in the terahertz frequency range.

Keywords: semiconductor crystal, electric field, magnetic field, cyclotron radiation, terahertz radiation.

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1. Introduction

An actual problem of solid-state electronics is creation of sources of coherent radiation in the far infrared (terahertz) range of electromagnetic waves. To generate terahertz pulses in a wide frequency spectrum up to tens of terahertz, a femtosecond filament in gases, photo-conductive antennas, mechanisms of a built-in near-surface electric field and nonlinear optical rectification, and the photovoltaic Dember effect in semiconductors are used when crystals and gases are irradiated with femtosecond laser radiation [1–13].

Among the well-known solid-state generators of terahertz radiation, the following ones can be distinguished [14–20]: avalanche and Gunn diodes with a radiation frequency up to 1.2 THz, quantum cascade lasers operating in the range up to 5 THz, masers based on hole transitions between Landau levels and on intersubband hole junctions emitting within the range from 1 to 3 THz. The functioning of the latter is due to formation of inverted systems of hot holes in germanium.

An inversion in the distribution of charge carriers appeared due to their dynamic heating and dominant inelastic scattering by optical phonons, when a semi-conductor crystal cooled to temperatures of 4.2 to 30 K was placed in crossed constant and uniform electric and magnetic fields (crossed fields are understood to be those in which the vectors of the electric and magnetic induction fields are mutually perpendicular).

This work is devoted to studying the possibility to obtain terahertz cyclotron radiation by using the semiconductor crystals in crossed electric and magnetic fields at room temperature. The importance of this study is related to at least three factors. First, since the effective mass of charge carriers in semiconductor crystals can be tens and hundreds of the free electron mass, the frequency of cyclotron radiation in accessible magnetic fields can lie in the terahertz range. Second, changing the values of the magnetic field induction enables to provide smooth tuning of the frequency of electromagnetic radiation. Third, due to the fact that semiconductors have rather high dielectric constants, internal reflection of electromagnetic waves takes place in manufacturing the semiconductor structures with a high degree of parallelism of opposite faces. Therefore, the semi-conductor crystal itself acts as a resonator. Thus, due to resonance phenomena, it becomes possible to obtain coherent terahertz radiation of a significant power.

2. Cyclotron radiation of semiconductor crystals in crossed electric and magnetic fields

Let us consider the motion of charge carriers in a semiconductor crystal under the action of crossed constant and uniform electric and magnetic fields. The magnetic field induction values are assumed to be such that quantum effects can be neglected. Let the strength and induction vectors of the electric $\vec{E}$ and magnetic $\vec{B}$ fields, respectively, have one non-zero projection:

$$\begin{cases} E_y = E,\ E_x = E_Z = 0, \\ B_Z = B,\ B_x = B_y = 0, \end{cases} \quad (1)$$

and the coordinates of the charged particle in the initial moment of time are equal to zero.

The motion of a charge carrier, in particular electron, is described by a system of equations [21]:

$$\begin{cases} \dfrac{d\upsilon_x}{dt} + \dfrac{\upsilon_x}{\tau} = \dfrac{e}{m_n}\upsilon_y B, \\ \dfrac{d\upsilon_y}{dt} + \dfrac{\upsilon_y}{\tau} = \dfrac{e}{m_n}E - \dfrac{e}{m_n}\upsilon_x B, \\ \dfrac{d\upsilon_z}{dt} + \dfrac{\upsilon_z}{\tau} = 0, \end{cases} \quad (2)$$

where υ_x, υ_y, υ_z are the projections of vector of the electron drift velocity $\vec{\upsilon}$ on the coordinate axes; e – charge of electron, m_n – effective mass of electron in a semiconductor crystal, $\tau = m_n \mu_n / e$ – relaxation time, μ_n – electron mobility.

In the time intervals between two successive scattering events, the system of equations (2) can be written as:

$$\begin{cases} \dfrac{d\upsilon_x}{dt} = \dfrac{e}{m_n}\upsilon_y B, \\ \dfrac{d\upsilon_y}{dt} = \dfrac{e}{m_n}E - \dfrac{e}{m_n}\upsilon_x B, \\ \dfrac{d\upsilon_z}{dt} = 0. \end{cases} \quad (3)$$

We will assume that in the initial time electron has one non-zero velocity component: $\upsilon_y(0) = \upsilon$, $\upsilon_x(0) = \upsilon_z(0) = 0$. Then the trajectory of the charged carrier is a two-dimensional curve lying in the X0Y plane, which is the solution of the system of equations:

$$\begin{cases} \dfrac{d\upsilon_x}{dt} = \dfrac{e}{m_n}\upsilon_y B, \\ \dfrac{d\upsilon_y}{dt} = \dfrac{e}{m_n}E - \dfrac{e}{m_n}\upsilon_x B. \end{cases} \quad (4)$$

This time curve is a trochoid, that is, between two successive scattering events, the electron motion trajectory is a superposition of two motions [22]. The first one is movement along a circle in the X0Y plane with the parameters [22]:

$$\upsilon_r = \left[\upsilon^2 + \left(\frac{E}{B}\right)^2\right]^{1/2}, \quad (5)$$

$$\omega_B = \frac{eB}{m_n}, \quad (6)$$

where υ_r is the linear velocity of the electron movement along a circle, ω_B is the cyclotron frequency of electron rotation. The second one is a rectilinear movement along the 0X axis at a constant velocity υ_{sl} [22]:

$$\upsilon_{sl} = \frac{E}{B}. \quad (7)$$

From (5) and (7), it follows that $\upsilon_r >> \upsilon_{sl}$. It means that the trajectory of a charged particle is described by the trochoid that has loops.

In electric fields such, when the relationship between the drift velocity of charged carriers υ and the electric field strength $\upsilon = \mu_n E$ is fulfilled, we have:

$$\upsilon_r = E\left[\mu_n^2 + \frac{1}{B^2}\right]^{1/2}. \quad (8)$$

If in this case the magnetic field induction is such that $\mu_n^2 >> B^{-2}$, then

$$\upsilon_r = \mu_n E, \quad (9)$$

which means that the linear velocity of electron along the circle is equal to its drift velocity.

In strong electric fields, the drift velocity υ_E is a complex function of E. At high electric field strengths, it becomes equal to the saturation velocity. Moreover, in semiconductors, where intervalley transitions take place in the field dependence of the drift velocity of charge carriers, rather extended sections with negative differential mobility are observed.

In particular, for GaAs the intervalley transitions of electrons occur at the drift velocities of $2.2 \cdot 10^5$ m/s and electric field strengths of $3.2 \cdot 10^5$ V/m. In what follows, we will consider electric fields with the strength less than that at which intervalley transitions of charged carriers are observed.

For strong electric fields, the relation (5) can be written as:

$$\upsilon_r = \left[\upsilon_E^2 + \left(\frac{E}{B}\right)^2\right]^{1/2}. \quad (10)$$

For $\upsilon_E^2 >> (E/B)^2$

$$\upsilon_r = \upsilon_E, \quad (11)$$

that is, the linear velocity of the charge carrier along the circle is equal to its drift velocity.

In turn, the value υ_r defines the power P_e of the electron cyclotron radiation at the frequency ω_B [23]:

$$P_e = \frac{e^2\omega_B^2\upsilon_r^2}{6\pi\varepsilon_0\varepsilon c^3}, \quad (12)$$

where ε_0 is the electrical constant, ε – permittivity of a semiconductor crystal, c – speed of light. For the power P of cyclotron radiation of a semiconductor crystal, the following relationship can be written [23]:

$$P = \frac{e^2 \omega_B^2 \upsilon_r^2 n S d}{6\pi \varepsilon_0 \varepsilon c^3}, \quad (13)$$

where n is the concentration of free electrons in semiconductor, S – area of the radiating surface in the semiconductor crystal, d – thickness of the radiating layer of the crystal (the length of the semiconductor crystal face along the OZ direction).

Due to absorption of electromagnetic radiation by free charge carriers, the thickness of the radiating layer must satisfy the relation $d << \alpha_e^{-1}$, where α_e is the absorption coefficient of free charge carriers. With this choice of the radiating layer thickness, we can approximately assume that there is no absorption of electromagnetic waves in it on free charge carriers. The expression for the absorption coefficient has the form [23]:

$$\alpha_e^{-1} = \frac{c \bar{n} \varepsilon_0 \left[1 + (\mu_n B)^k\right]}{\sigma}, \quad (14)$$

where $\bar{n}$ is the real part of the complex refraction index, $\sigma = e\mu_n n$ – specific electrical conductivity of the semiconductor, k is the exponent depending on the type of semiconductor crystal (in particular, for InSb and Ge crystals $k = 2$, and for GaAs $k = 3$ [23]). In the practically important case of large B values corresponding to terahertz frequencies $\nu_B = \omega_B / 2\pi$, the inequality $(\mu_n B)^k >> 1$ is fulfilled. Accordingly, (14) is transformed into [23]:

$$\alpha_e^{-1} = \frac{c \bar{n} \varepsilon_0 (\mu_n B)^k}{\sigma}. \quad (15)$$

The real part of the complex refraction index $\bar{n}$ has the form [24]:

$$\bar{n} = \sqrt{\frac{\varepsilon}{2}\left[1 + \sqrt{1 + \left(\frac{\sigma}{\varepsilon_0 \varepsilon \omega_B}\right)^2}\right]}. \quad (16)$$

Let us analyze two limiting cases [24]. When $(\sigma / \varepsilon_0 \varepsilon \omega_B) >> 1$, we get:

$$\bar{n} = \left(\frac{\sigma}{2\varepsilon_0 \omega_B}\right)^{1/2}. \quad (17)$$

If $(\sigma / \varepsilon_0 \varepsilon \omega_B) << 1$, then

$$\bar{n} = (\varepsilon)^{1/2}. \quad (18)$$

With an increase in the frequency of electromagnetic radiation in semiconductors, strong absorption by the characteristic phonons and their combinations takes place. Thus, undoped GaAs crystals have good transmission in the terahertz frequency range up to $3 \cdot 10^{12}$ Hz. In conclusion, we note the following facts:

1. An important parameter of electromagnetic radiation is the width of the spectral line. Narrow spectral lines of cyclotron radiation occur when charge carriers in crossed magnetic and electric fields make at least one convolution between two successive scattering events. This is achieved by applying magnetic fields to the semiconductor structure, which satisfy the condition: $\omega_B \tau = \mu_n B \geq 2\pi$. As it follows from the said above, this condition underlies formulas (9) and (15).

2. Generation of cyclotron radiation is possible in continuous and pulsed modes. The choice of a mode is defined by the concentration of free charge carriers in the semiconductor crystal, in other words, by the electric currents flowing in it, causing the latter to heat up. In the continuous generation mode, to prevent formation of the Hall electromotive force (emf), which compensates the action of the Lorentz magnetic force, it is necessary that the length of the semiconductor crystal face along the OX axis be significantly greater than that along the OY axis (unlimited sample).

3. It is also recommended to apply ohmic contacts on the crystal faces, to which electrons move along the trochoid, shunting the Hall emf. It is possible to use a Carbino disk, in which the Hall emf is absent, since the electric field has a radial component. In fact, it means that this disk is an unlimited sample. In the pulse mode of electromagnetic radiation generation, in addition to the noted approaches, it is possible to use semiconductor crystals with a face length along the OX axis much greater than $\upsilon_{sl} \Delta t$, where Δt is the duration of applied electrical voltage pulse.

4. The obtained analytical relations enable to calculate the power of intrinsic (free) electron cyclotron radiation by semiconductor structures in crossed electric and magnetic fields. They do not take into account the effect of its significant increase due to the fact that the semiconductor crystal itself can act as a resonator. As noted above, with a high degree of parallelism of the opposite faces of the latter, due to resonance phenomena, it becomes possible to obtain sufficiently powerful coherent terahertz radiation.

3. Calculation of the parameters inherent to cyclotron radiation of semiconductor structures

Let us calculate the power of intrinsic cyclotron radiation (excluding resonance effects) of n-GaAs with free electron density $n = 10^{20}$ m^{-3} in crossed electric $E = 2 \cdot 10^5$ V/m and magnetic $B = 5$ T fields. The values of semiconductor material parameters used in the calculations: $\mu_n = 0.85$ m^{2}V^{-1}s^{-1}; $\varepsilon = 12.9$; $m_n = 0.063 m_0$, and m_0 – mass of electron.

In accordance with (6), the cyclotron frequency $\omega_B = 1.38 \cdot 10^{13}$ Hz, that is $\nu_B = 2.22 \cdot 10^{12}$ Hz. In view of the fact that $(\sigma/\varepsilon_0 \varepsilon \omega_B) = 8.6 \cdot 10^{-3} << 1$, then according to the expression (18), $\bar{n} = 3.59$. Since $(\mu_n B)^k = 77 >> 1$ ($k = 3$), the calculation according to formula (15) gives the following value: $\alpha_e^{-1} = 5.5 \cdot 10^{-2}$ m. Let's take $d = 1.1 \cdot 10^{-3}$ m as the thickness of the radiating layer. At $E = 2 \cdot 10^5$ V/m for *n*-GaAs, the relation $\upsilon = \mu_n E = 1.7 \cdot 10^5$ m/s is approximately fulfilled. Since in the expression (8) $\mu_n^2 = 0.72 >> B^{-2} = 0.04$, then $\upsilon_r = \upsilon = 1.7 \cdot 10^5$ m/s. Then for the power of intrinsic electron cyclotron radiation (13), normalized per unit area of the radiating surface of the semiconductor crystal, we have $P/S = 0.26$ W·m^{-2}.

4. Conclusions

The power of intrinsic cyclotron radiation by semiconductor structures in crossed constant and uniform electric and magnetic fields is a parabolic function of the linear velocity of charge carrier movement along the circle. In its turn, the linear velocity of the electron movement along this circle is defined by its drift velocity, and, consequently, by the strength of the electric field in the semiconductor crystal.

On the other hand, the power of electromagnetic radiation is a power function of the magnetic field induction, and hence, the cyclotron frequency. The results obtained in this work are promising for the purposes of generating terahertz radiation. Since the semiconductor crystal itself can act as a resonator, it becomes possible to obtain sufficiently powerful coherent electromagnetic radiation in the terahertz frequency range.

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Authors' contributions

Milenin G.V.: conceptualization, writing – original draft, validation, writing – review & editing, methodology.

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Електромагнітне випромінювання напівпровідникових кристалів у схрещених електричному та магнітному полях

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Анотація. Проаналізовано особливості генерації електромагнітного випромінювання напівпровідниковими кристалами у схрещених електричному та магнітному полях. Наведено аналітичні співвідношення для розрахунку потужності циклотронного випромінювання. Отримані результати становлять інтерес з метою отримання джерел електромагнітного випромінювання терагерцового діапазону частот.

Ключові слова: напівпровідниковий кристал, електричне поле, магнітне поле, циклотронне випромінювання, терагерцове випромінювання.