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Influence of the near-surface regions of the space charge in semiconductor crystals on defect transformation stimulated by action of magnetic fields

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Abstract. The mechanisms of electromagnetic radiation in the near-surface regions of semiconductors depleted of the majority charge carriers under action of magnetic fields, the induction vector of which is parallel to the surface of the crystal, have been analyzed. The relationships for estimating the radiation power of space charge regions have been derived.

Keywords: semiconductor crystal, space charge, magnetic field, bremsstrahlung, cyclotron radiation.

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1. Introduction

In the work [1], a unified mechanism of the effect of electromagnetic and magnetic fields on the defect subsystem in semiconductor structures was proposed. It is based on the idea that a change in the state of defects is caused by resonance phenomena when the frequencies of electromagnetic radiation coincide with the natural frequencies of vibrations inherent to dislocations and clusters of impurity-defect complexes.

When studying the electromagnetic radiation of semiconductor crystals in magnetic fields, it was noted that the presence of regions depleted of majority charge carriers in the near-surface layer of the semiconductor has a significant effect on the radiation intensity [2]. At the same time, in the space-charge region itself under action of a magnetic field two types of electromagnetic radiation are possible.

In the situation where the magnetic field induction vector is directed in parallel to the surface of a semiconductor crystal, then due to the twisting of trajectories typical for charged carriers (we mean electrons by them) in the semiconductor bulk, they cross the space charge region. On the one hand, electrons emit electromagnetic waves as a result of deceleration (acceleration) in the field of electric forces of ionized impurities (in our case, donors).

This radiation is called bremsstrahlung. On the other hand, during rotation, electrons experience acceleration that is constant in its magnitude and directed along the perpendicular to the velocity, and therefore, emit electromagnetic waves with the cyclotron frequency. The presence of a built-in electric field in the space charge region leads to changes in the velocity of charged carriers in the plane of rotation and in the power of cyclotron radiation.

The present work is devoted to studying the electromagnetic radiation from the space charge regions of semiconductors in a magnetic field, which is of interest for understanding their influence on transformation of the defect subsystem in semiconductor structures.

2. Bremsstrahlung of space charge regions of semiconductor crystals in a magnetic field

The bremsstrahlung power of electron P_e is [3]:

$$P_e = \frac{e^2 a^2}{6\pi\varepsilon_0 \varepsilon c^3}, \tag{1}$$

where e is the electron charge, a – acceleration of electron in the electric field of an ionized impurity, ε_0 – electrical constant, ε – dielectric constant of a semiconductor crystal, c – velocity of light.

The bremsstrahlung spectrum is continuous and has an upper limit at the point where the average kinetic energy of electron becomes equal to the energy of a radiation quantum [3]: $\hbar\omega_{\max} = 3kT/2$, where $\hbar$ is Planck's constant, k – Boltzmann constant, T – absolute temperature, $\nu_{max} = \omega_{max}/2\pi$ – maximum value of the electromagnetic wave frequency. At T = 300 K, we have ν_{max} = $9.38 \cdot 10^{12}$ Hz. The power of electromagnetic waves P emitted by N electrons is:

$$P = \frac{e^2 a^2 N}{6\pi\varepsilon_0 \varepsilon c^3}. \qquad (2)$$

Here and in what follows, we mean that N is the number of electrons normalized per unit area of the space charge region, *i.e.*, the density of electrons, then P is the power of electromagnetic waves normalized per unit area. Therefore, to find P it is necessary to determine the quantity of electrons, the trajectory of which crosses the space charge region in the semiconductor, as well as their acceleration.

The electron density is equal to:

$$N = dN_D, \qquad (3)$$

where d is the thickness of layer in the bulk of semiconductor crystal, from which the charge carriers enter the space charge region due to the twisting of their trajectories under the magnetic field action, N_D is the concentration of the donor impurity in the crystal (it is assumed that all donors are ionized). The maximum thickness of the layer d is equal to the diameter of such a circle of rotation of electron, moving along which it will make a full revolution during the time between two acts of scattering (relaxation time). Mathematically, this condition is written as follows:

$$\omega_B \tau = \mu_n B_1 = 1, \qquad (4)$$

where $\omega_B = eB/m_n$ is the cyclotron frequency (angular), B – magnetic induction, B_1 – value of the magnetic field induction B, at which the relation (4) is valid, m_n – effective mass of electrons in the crystal, $\tau = m_n \mu_n / e$ – relaxation time; μ_n – electron mobility.

The radius of circle r, along which a charged particle rotates in a layer of the thickness d under action of the Lorentz force, is:

$$r = \frac{m_n \upsilon_\perp}{eB}, \qquad (5)$$

where $\upsilon_\perp$ is the thermal velocity component perpendicular to the magnetic induction vector, and the average value $\overline{\upsilon_\perp^2}$ for the entire set of electrons has the form [2]:

$$\overline{\upsilon_\perp^2} = \frac{\upsilon_T^2}{2}, \qquad (6)$$

where $\upsilon_T = (3kT/m_n)^{1/2}$ is the mean square velocity of electrons.

Substituting B from (4) into (5) and taking into account (6), we obtain the following expression for the layer thickness $d = 2r$:

$$d = \sqrt{2}\tau\upsilon_T. \qquad (7)$$

Replacing d in (3) with (7), we get:

$$N = \sqrt{2}\tau\upsilon_T N_D. \qquad (8)$$

Note that at the values of the magnetic field induction B, when $\mu_n B < 1$, the number of electrons crossing the space charge region decreases due to their scattering in a layer of thickness d, which is caused by an increase in the radius of the circle of their rotation. In this case, we can assume that

$$N = \sqrt{2}\tau\upsilon_T N_D \frac{B}{B_1}. \qquad (9)$$

Otherwise, when $\mu_n B > 1$, a decrease in the number of charge carriers is a consequence of a decrease in the radius of the circle, along which they move, and

$$N = 2rN_D = \frac{\sqrt{2}\tau\upsilon_T N_D}{\mu_n B}. \qquad (10)$$

The acceleration of electron in the space-charge region during scattering by ionized donor impurities is [4]:

$$a = \frac{Ze^2}{4\pi\varepsilon_0 \varepsilon m_n s^2}, \qquad (11)$$

where Ze is the charge of ion, s – sighting parameter.

The value of the impact parameter will be assumed as half the average distance between donor impurities:

$$s = \frac{1}{2\sqrt[3]{N_D}}. \qquad (12)$$

Then, for the acceleration of electron in the electric field of a donor impurity when Z = 1, one can obtain the following expression:

$$a = \frac{e^2 N_D^{2/3}}{\pi\varepsilon_0 \varepsilon m_n}. \qquad (13)$$

Summing up the equations (2), (8), and (13), one can obtain that the maximum bremsstrahlung power normalized per unit area of the space charge region under fulfilling the condition (4) is

$$P = \frac{\sqrt{2} e^5 \upsilon_T \mu_n N_D^{7/3}}{6\pi^3 \varepsilon_0^3 \varepsilon^3 m_n c^3}. \qquad (14)$$

Thus, the maximum radiation power of electromagnetic waves is the higher, the higher is the mobility of charge carriers, the concentration of ionized donor impurities and the lower the effective mass of electrons in the semiconductor crystal. If the magnetic fields are such that the condition (4) is not fulfilled, then, according to Eqs (9) and (10) and at $\mu_n B < 1$, we have:

$$P = \frac{\sqrt{2} e^5 \upsilon_T \mu_n N_D^{7/3} B}{6\pi^3 \varepsilon_0^3 \varepsilon^3 m_n c^3 B_1}, \qquad (15)$$

respectively, when $\mu_n B > 1$ we get:

$$P = \frac{\sqrt{2} e^5 \upsilon_T N_D^{7/3}}{6\pi^3 \varepsilon_0^3 \varepsilon^3 m_n c^3 B}. \qquad (16)$$

It is quite natural that in both cases the bremsstrahlung powers become lower than those in (14), and in the latter case, the dependence of the power on the mobility of charge carriers disappears, and an inversely proportional dependence on the value of the magnetic field induction appears.

3. Cyclotron radiation of space charge regions of semiconductor crystals

The power of cyclotron radiation for nonrelativistic electron is [5]:

$$P_e = \frac{e^2 \omega_B^2 \upsilon^2}{6\pi\varepsilon_0 \varepsilon c^3}, \qquad (17)$$

where υ is the electron rotation velocity in the plane perpendicular to the magnetic induction vector.

Accordingly, the power of cyclotron radiation emitted by electrons of the quantity N in the space charge region of a semiconductor crystal, under the assumption that for the entire set of charge carriers υ is a random quantity, has the form:

$$P = \frac{e^2 \omega_B^2}{6\pi\varepsilon_0 \varepsilon c^3} \sum_{n=1}^{N} \upsilon_n^2 = \frac{e^2 \omega_B^2 N}{6\pi\varepsilon_0 \varepsilon c^3} \sum_{n=1}^{N} \frac{\upsilon_n^2}{N} = \frac{e^2 \omega_B^2 \overline{\upsilon^2} N}{6\pi\varepsilon_0 \varepsilon c^3}, \qquad (18)$$

where υ_n is the value of rotation velocity for n-th electron, $\overline{\upsilon^2}$ – average value of the squared velocity of rotation for the entire set of electrons.

In what follows, like to the previous consideration, we mean that N is the density of electrons, and P is the power of electromagnetic radiation normalized per unit area of the space charge region. Therefore, to find P, it is necessary to know $\overline{\upsilon^2}$. In this particular situation, the trajectories of charge carrier motion under action of the magnetic field lie both in the bulk of semiconductor and in the space charge region. In the bulk, where the electric field is absent, the electron moves along the circle with the velocity $\upsilon_\perp$. In the space charge region, it moves along a complex curve with a rotation velocity that depends on the value of the built-in electric field.

The electric field in the space charge region of semiconductor in the depletion mode is not uniform, and its value $E(x)$ obeys the relation [6]:

$$E(x) = -\frac{\partial\psi}{\partial x} = \frac{2\psi_S}{W}\left(1 - \frac{x}{W}\right), \qquad (19)$$

where x is the coordinate measured from the semiconductor surface, $\psi = \psi_S (1 - x/W)^2$ – potential distribution in the depleted layer, $\psi_S = eN_D W^2 / 2\varepsilon_0 \varepsilon$ – surface potential, W – thickness of the depletion layer.

To simplify the problem, we will assume that electrons move in a uniform electric field. To determine the value of this field, we will use the following approach. Let us estimate the maximum depth l_{max} (measured from the semiconductor surface) of penetration into the space charge region for electron moving in a layer with the thickness d and crossing the boundary of the latter at a right angle with the velocity $\upsilon_\perp$. The l_{max} value can be determined by equating the kinetic energy of electron moving with velocity $\upsilon_\perp$ to the work done by the electric field of the space charge region:

$$\frac{m_n \upsilon_\perp^2}{2} = -e \int_W^{l_{max}} E(x) dx = e\left[\psi(l_{max}) - \psi(W)\right]. \qquad (20)$$

We have

$$l_{max} = W\left(1 - \sqrt{\frac{m_n \upsilon_\perp^2}{2e\psi_S}}\right). \qquad (21)$$

Taking into account (19), as well as the expression for ψ_S, we obtain the electric field value corresponding to l_{max}:

$$E(l_{max}) = \sqrt{\frac{m_n \upsilon_\perp^2 N_D}{\varepsilon_0 \varepsilon}}. \qquad (22)$$

At the same time, even with the determined value $\upsilon_\perp$, the trajectory of the entire set of electrons moving along the circles in a layer with the thickness d crosses the boundary of the space charge region at different angles, depending on the initial position of charge carriers in this layer. The depths of their penetration into the space charge region are also different, and, consequently, the corresponding electric field values are different. Thus, for the entire set of electrons, $E(l)$ is a random variable. We will assume that it obeys a continuous uniform distribution within the range $[0, E(l_{\max})]$. The average value $\overline{E(l)}$ of a uniformly distributed continuous random variable is $E(l_{\max})/2$. Taking into account this statement, as well as the fact that the average value $\overline{\upsilon_\perp^2}$ satisfies the condition (6), as a result of two averaging, we come to the following expression:

$$\overline{E(l)} = \sqrt{\frac{m_n \upsilon_T^2 N_D}{8\varepsilon_0 \varepsilon}}. \tag{23}$$

Since the electric field in the space charge region changes according to the linear law (19), then, when approximating it by a constant field, we will use the value $E = \overline{E(l)}/2$, that is

$$E = \sqrt{\frac{m_n \upsilon_T^2 N_D}{32\varepsilon_0 \varepsilon}}. \tag{24}$$

Thus, we will assume that electrons move in the space charge region in mutually perpendicular uniform electric and magnetic fields. The trajectory of motion of charge carriers between two successive acts of scattering is a two-dimensional curve called a trochoid. That is, the motion of a particle is a superposition of motions of two types: the motion along the circle, the plane of which is perpendicular to the vector of magnetic induction, as well as the rectilinear motion of the circle center with the constant velocity *E*/*B* perpendicularly to the vectors of the electric field and magnetic field induction. The linear velocity of the charge carrier motion along the circle is:

$$\upsilon^2 = \left(\upsilon_{\perp x} - \frac{E}{B}\right)^2 + \upsilon_{\perp y}^2, \tag{25}$$

where $\upsilon_{\perp x}$ and $\upsilon_{\perp y}$ are the initial values of the $\upsilon_\perp$ projections on the coordinate axis in the plane perpendicular to the magnetic induction vector, when electron crosses the boundary of the space charge region ($\upsilon_\perp^2 = \upsilon_{\perp x}^2 + \upsilon_{\perp y}^2$).

For the entire set of electrons, the values $\upsilon_{\perp x}^2$ and $\upsilon_{\perp y}^2$, like to $\upsilon_\perp^2$, are random values, in so doing $\overline{\upsilon_{\perp x}^2} + \overline{\upsilon_{\perp y}^2} = \overline{\upsilon_\perp^2}$, and the mean values $\overline{\upsilon_{\perp x}}$ and $\overline{\upsilon_{\perp y}}$ due to the equality of the directions of all velocity projections $\upsilon_\perp$ on the coordinate axis in the plane perpendicular to the magnetic induction vector are equal to zero: $\overline{\upsilon_{\perp x}} = \overline{\upsilon_{\perp y}} = 0$. Then, taking into account (25) and (6), for the average linear velocity of movement along the circle, we can write the relation:

$$\overline{\upsilon^2} = \frac{\upsilon_T^2}{2} + \left(\frac{E}{B}\right)^2. \tag{26}$$

Substituting (26) into (18), one can obtain the expression for the cyclotron radiation power normalized per unit area of the space charge region:

$$P = \frac{e^2 \omega_B^2 N}{6\pi\varepsilon_0 \varepsilon c^3}\left[\frac{\upsilon_T^2}{2} + \left(\frac{E}{B}\right)^2\right]. \tag{27}$$

The first term in the square brackets of (27) characterizes the power of electromagnetic radiation of thermal charge carriers plasma of semiconductor crystal in a magnetic field. Analysis of this phenomenon was carried out in [2]. The second term describes the emissivity of electrons in the space charge region of semiconductor in mutually perpendicular magnetic and electric fields.

When the condition (4) is fulfilled, taking into account (8), it can be obtained an expression for the maximum radiation power normalized per unit area:

$$P = \frac{\sqrt{2} e^3 \upsilon_T N_D B}{6\pi\varepsilon_0 \varepsilon c^3 m_n}\left[\frac{\upsilon_T^2}{2} + \left(\frac{E}{B}\right)^2\right]. \tag{28}$$

When the values of the magnetic field induction do not satisfy the condition (4), then taking into account (9) and (10), it can be obtained that for $\mu_n B < 1$:

$$P = \frac{\sqrt{2} e^3 \upsilon_T N_D \mu_n B^3}{6\pi\varepsilon_0 \varepsilon c^3 m_n B_1}\left[\frac{\upsilon_T^2}{2} + \left(\frac{E}{B}\right)^2\right], \tag{29}$$

and for $\mu_n B > 1$

$$P = \frac{\sqrt{2} e^3 \upsilon_T N_D B}{6\pi\varepsilon_0 \varepsilon c^3 m_n}\left[\frac{\upsilon_T^2}{2} + \left(\frac{E}{B}\right)^2\right]. \tag{30}$$

In conclusion, we note that the condition for the predominance of cyclotron radiation over bremsstrahlung or *vice versa* is satisfying the following requirements for the values of the magnetic induction, respectively: $B > B^*$ or $B < B^*$. Moreover, B^* is defined by the relation $F_L = F_C$, where $F_L = e\upsilon B$ is the Lorentz force ($\upsilon = \sqrt{\overline{\upsilon^2}}$); $F_C = e^2/4\pi\varepsilon_0\varepsilon s^2$ is the force of the Coulomb interaction of electron with an ionized donor impurity, *i.e.*,

$$B^* = \frac{e N_D^{2/3}}{\pi\varepsilon_0\varepsilon\left(\frac{\upsilon_T^2}{2} + \frac{E^2}{B^2}\right)^{\frac{1}{2}}}. \tag{31}$$

4. Calculation of the power of electromagnetic radiation

Let us estimate the power of electromagnetic radiation from the space charge region in the *n*-GaAs-based semiconductor structures. Let $N_D = 10^{22}\,\text{m}^{-3}$, B = 0.2 T. The values of parameters used in these calculations are as follows: $m_n = 0.063 m_0$ (m_0 is the mass of free electron), $\mu_n = 0.7\,\text{m}^2\text{V}^{-1}\text{s}^{-1}$, ε = 12.9, $\upsilon_T = 4.4\cdot 10^5\,\text{ms}^{-1}$ [7]. Since, according to (4), B_1 = 1.43 T ($B < B_1$), then to calculate the power of bremsstrahlung and cyclotron radiation, we use the expressions (15) and (29). Accordingly, we have the power values $3.2\cdot 10^{-5}$ and $2.9\cdot 10^{-5}\,\text{W}\cdot\text{m}^{-2}$, *i.e.*, they are close, but bremsstrahlung is somewhat dominant. This fact follows from (31), since B^* = 0.22 T.

5. Conclusion

In the near-surface regions of semiconductors depleted of the majority charge carriers under action of magnetic fields, the induction vector of which is parallel to the crystal surface due to the twisting of trajectories typical for motion of charged carriers from the semiconductor bulk to the space charge region, both bremsstrahlung of electrons rotating around ionized impurities and cyclotron radiation are observed. Depending on the values of the magnetic field induction, one or another radiation mechanism dominates. The bremsstrahlung power is determined by such parameters of a semiconductor material as the mobility and effective mass of charge carriers, as well as the concentration of ionized impurities in the crystal. The power of cyclotron radiation, in addition to the semiconductor parameters, depends on the values of induction and those of mutually perpendicular magnetic and electric fields in the space charge region.

The obtained results make it possible to estimate the intensity of the electromagnetic radiation from the space charge regions of semiconductor crystals being in magnetic fields. They are of interest for understanding the mechanisms of the magnetic field effect on transformation of a defect subsystem in semiconductor structures.

References

1. Milenin G.V., Red'ko R.A. Transformation of structural defects in semiconductors under action of electromagnetic and magnetic fields causing resonant phenomena. *SPQEO*. 2019. **22**, No 1. P. 39–46. https://doi.org/10.15407/spqeo22.01.39.
2. Milenin G.V., Milenin V.V., Red'ko R.A. Cyclotron radiation of semiconductor crystals. *SPQEO*. 2018. **21**, No 1. P. 54–57. https://doi.org/10.15407/spqeo21.01.054.
3. Panofsky Wolfgang K.H., Philips Melba. *Classical Electricity and Magnetism*. 2nd ed. Addison – Wesley Publishing Company, Inc., 1962.
4. Longmire Conrad L. *Elementary Plasma Physics*. Intersci. Publ. Division of Willey, 1963.
5. Bekefi G. *Radiation Processes in Plasmas*. John Willey and Sons, Inc., 1969.
6. Sze S.M. *Physics of Semiconductor Devices*. Willey, 1981.
7. www.ioffe.ru/SVA/NSM/Semicond/GaAs/index.html/

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Вплив приповерхневих областей просторового заряду у напівпровідникових кристалах на деформаційне перетворення, стимульоване дією магнітних полів

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Анотація. Проаналізовано механізми електромагнітного випромінювання у приповерхневих областях напівпровідників, збіднених основними носіями заряду під дією магнітних полів, вектор індукції яких паралельний поверхні кристала. Отримано співвідношення для оцінки потужності випромінювання областей просторового заряду.

Ключові слова: напівпровідниковий кристал, просторовий заряд, магнітне поле, гальмівне випромінювання, циклотронне випромінювання.