ELECTROMAGNETIC COMPATIBILITY OF SEMICONDUCTOR STRUCTURES WITH A TWO-DIMENSIONAL ELECTRON LAYER

Abstract. The subject matter is the mechanisms of interaction of the flow of charged particles with the surface plasmons of a two-dimensional electron layer (2D) due to the action of external pulsed electromagnetic radiation (EMP). The aim is obtaining design relations that determine to what degree the instabilities of natural vibrations of a two-dimensional electronic layer of a semiconductor structure may influence the performance of semiconductor devices. The objectives are a model of occurrence of reversible failures of radio products arising from the transformation of energy of currents induced by external pulsed radiation to excite electrostatic oscillations of a two-dimensional electronic layer of semiconductor structures. The methods used are analytical methods for solving electrodynamics (Maxwell) equations and material equations in the framework of kinetic approach. The following results have been obtained: The mechanisms of interaction of the flow of charged particles with the natural electromagnetic vibrations of a two-dimensional electron gas occurring due to the presence of a potential barrier at the interface have been studied. Investigations of functioning of semiconductor components of radio products (structures with two-dimensional electron gas) under the influence of strong pulsed electromagnetic fields have been carried out. A kinetic equation describing the change in the number of electromagnetic oscillations of such a system has been obtained. The solution of the equation has been found, which allows determining the influence of the barrier on the instability increment of surface vibrations as well as the contributions of the transmitted and reflected components of the particle flux to the increment. Equations for the increment of instabilities allow us to determine the energy loss of the induced currents on the excitation of natural oscillations i.e. the emergence of a mode of oscillation generation, which is characterized by a change in the volt-amper characteristics of radio devices.

Conclusion. A comparative analysis of the instabilities of vibrations of structures with a two-dimensional electron gas has been carried out under conditions when the interaction of waves and particles is random and deterministic. It is shown that the differences in the expressions for increments are associated with a change in the size of the region of interaction of waves and particles. Differences in the influence of the potential barrier on the increment are established in cases where the interaction of surface plasmons and charged particles is determined or has the character of random collisions. The mechanisms of the influence on the boundary of the interaction of surface electromagnetic waves and electrons in the presence of a potential barrier are determined. Intrinsic electromagnetic oscillations of a two-dimensional electron layer are taken as research objects. The results obtained in the work can be used to assess the operability of electronic equipment in millimeter and submillimeter ranges under the influence of pulsed electromagnetic fields.

Keywords: electromagnetic fields; vibrations; semiconductor; kinetic instabilities; potential barrier; flow of charged particles; generation; radiation energy.

Introduction

One of the tasks of electromagnetic compatibility is to determine the mechanisms of occurrence and development of temporary loss of operability of electrical radio devices in the presence of external electromagnetic radiation (reversible failures). The current paper belongs to this field of research. It studies how the flow of charged particles induced by external electromagnetic radiation interacts with the natural vibrations of the semiconductor structure constituting a radio device (surface plasmons of the two-dimensional electron layer (2D)). A solution to this problem allows us to determine the temporal characteristics of the oscillation generation mode (instability increment), i.e. radiation energy.

Switching to the generation mode leads to a distortion of the current-voltage characteristics of the devices (appearance of sections with negative resistance). Thus, the results of this work can be used to quantify the degree the operating characteristics of electronic equipment for millimeter and submillimeter ranges may deviate from the norm under the influence of pulsed electromagnetic fields.

The work considered the mechanisms of interaction of charged particles with surface plasmons of a two-dimensional electron layer (2D), based on the description of the properties of plasmons with the help of kinetic equations. When considering the interaction between electromagnetic waves and charged particles, in addition to the probabilistic approach (kinetic equations), another technique is also used to determine the relationship between the electromagnetic fields of surface vibrations and the wave functions of the flux electrons at the boundary. That technique uses Schrödinger equation and additional (compared to electrodynamics equations) boundary conditions for the perturbed wave functions of the beam electrons. In this case, the amplitudes and phases of the perturbed wave functions of an electron are determined by the already existing amplitude and phase of the plasmon, so the interactions between waves and particles are deterministic. The conditions for the wave functions make it possible to determine the influence the boundary (in particular, the presence of a potential barrier) may have on the magnitude of the instability increment. In the framework of this model, we have studied the mechanisms of excitation of surface plasmons and have developed the equations for the increments of their instability.

We take into account the influence the potential barrier may have not only on the behavior of charged particles of the flow crossing the boundary, but also on the spectral characteristics of electrons of plasma-like
structures. These include, in particular, structures in which the presence of a potential leads to the occurrence of a two-dimensional (2D) electron gas. The interest in two-dimensional systems associated with their unique properties [1] (quantum Hall effect, features of phase transitions) has recently intensified with the advent of the new technologies for creating nanostructures that are promising for solid-state radiophysics [1-3].

**Task solution**

Consider the interaction between plasma oscillations of a two-dimensional electron gas and a stream of charged particles that moves along the normal to the interface [4].

Let there be an infinitely thin layer of electrons at the boundary of two media with different electromagnetic properties. We will describe the behavior of electrons with Schrödinger equation:

$$\frac{\hbar^2}{2m} \Delta \Psi_k + \left[ e_k - V_0 \delta(y) \right] \Psi_k = 0,$$

(1)

where \( U(y) = -V_0 \delta(y) \) is the potential barrier, \( e_k \) - the particle energy; \( m_0 \) - the effective mass.

To find their spectrum, let us represent the particle wave function \( \Psi_k \) in areas \( y < 0 \) and \( y > 0 \) in the following way:

$$\Psi_{1,2} = B_{1,2} \exp(\pm \sqrt{\omega_0^2 + (k_x x + k_z z - e_k t / \hbar)}),$$

(2)

where \( k_x, k_z \) are the components of the wave vector in the direction parallel to the interface;

$$\chi = \left[ \frac{k_x^2 + k_z^2 - (2m/\hbar^2) e_k}{1/2} \right]^{1/2} > 0.$$

At the condition of the equality of the wave functions is satisfied, and the derivatives of the wave functions are discontinuous:

$$\frac{\hbar^2}{2m} \left[ \frac{\partial \Psi_{1k}(0)}{\partial y} - \frac{\partial \Psi_{2k}(0)}{\partial y} \right] = -U_0 \Psi_{1k}(0);$$

$$\Psi_{1k}(0) = \Psi_{2k}(0).$$

(3)

This implies that \( \hbar^2 \chi / m_0 = V_0 \).

The wave function is normalized so that

$$\sum_{k=\infty}^{\infty} \Psi_k^* \Psi_k = N_0 \exp(-2\chi) \left| \Psi \right|; \quad N_0 \right|$$

is the particle density. The frequency of plasma oscillations of 2D electrons is determined by

$$\omega_0^2 = \frac{4 \pi e^2 N_0 d}{m_0 (e_1 + e_2)}; \quad d = \frac{1}{\chi}; \quad \left| \Psi \right| d << 1.$$

(4)

Assuming that \( e_1 = e_0 - \omega_0^2 / \omega_0^2 \), the frequency of surface plasma oscillations has the form

$$\omega_x = \Omega_x / \sqrt{e_1 + e_2}; \quad \Omega_x = \sqrt{\omega_0^2 + \omega_0^2 + \omega_0^2 d / \chi};$$

$$\omega_0^2 = 4 \pi e^2 N_0 / m_0.$$

(5)

After the standard procedure of quantization of the energy of the electromagnetic field of surface plasmons, we obtain the expression for the operator of the vector potential:

$$\hat{A}_a (\vec{r}, t) = \sum_{q=\infty}^{\infty} \sqrt{4 \pi \eta / (V e_0 (e_1 + e_2))} \times$$

$$\left[ \exp(iq \vec{r} / \hbar) (\partial \vec{q} / \partial t) + \partial \vec{q} / \partial t \right] (6)$$

where \( e_1, e_2 \) do not have frequency dispersion.

Suppose further that an external stream of charged particles (electrons) passes (is injected) through the layer. To find the matrix elements of the Hamiltonian of the interaction of plasmons with this flow, we use the following expression:

$$\tilde{H}^{int} = -\sum_{\rho=1}^{3} \hat{H}_{\rho}^j (\vec{r}, t) \tilde{A} (\vec{r}, t) d^2 r / c,$$

(7)

where \( \tilde{H}_{\rho} = e^2 / (2im) \sum_{j} \left( \hat{\Psi}^{\dagger} \mathbf{P} \hat{\Psi} - \hat{\Psi}^{\dagger} \mathbf{P} \hat{\Psi} \right) \) is the density operator of the total electron current (including incident \( \rho = 1 \), reflected \( \rho = 3 \) and past \( \rho = 2 \) currents; \( m \) is effective mass of the injected electron. Here, the wave function operators have the form:

$$\tilde{H}_{1} = \sum_{k=\infty}^{\infty} \tilde{H}_{1k}^j (\vec{r}, t);$$

$$\tilde{H}_{2} = \sum_{k=\infty}^{\infty} \tilde{H}_{2k}^j (\vec{r}, t);$$

$$\tilde{H}_{3} = \sum_{k=\infty}^{\infty} \tilde{H}_{3k}^j (\vec{r}, t) \sqrt{F} e^{i(k_x x + k_z z)};$$

(8)

where \( \tilde{H}_{\rho k}^j \) are electron creation and annihilation operators while \( F \) is the system volume. The electron dispersion law is assumed quadratic: \( E_k = \hbar^2 (k_x^2 + k_z^2 + k_y^2) / (2m_0) \).

Coefficients \( \alpha_k \) and \( \beta_k \) are found from the boundary conditions for the functions \( \tilde{H}_{1,2,3} \) and have the form:

$$\alpha_k = - \frac{ih \hbar^2 k_y}{m U_0 + ih \hbar^2 k_y}; \quad \beta_k = - \frac{m V_0}{m V_0 + ih \hbar^2 k_y}.$$

(9)

The operator of the energy of interaction of particles with plasmons is written:

$$\tilde{H}^{int} = \sum_{k q} \tilde{W}^{(p)} (\vec{k} \vec{q}) \left( \tilde{a}_{\vec{q}} (t) + \tilde{a}_{\vec{q}}^\dagger (t) \right) \tilde{b}_{\vec{k}} (t),$$

where \( \tilde{W}_{\vec{k} \vec{q}} \) - the matrix element of the interaction Hamiltonian is determined by the expressions:

$$\tilde{W}^{(1)} (\vec{k} \vec{q}) = F \left| F_{k_x + k_y + i(k_x + k_y)} \right|, \quad \tilde{W}^{(2)} (\vec{k} \vec{q}) = F \left| F_{k_x + k_y - i(k_x + k_y)} \right|, \quad \tilde{W}^{(3)} (\vec{k} \vec{q}) = F \left| F_{k_x + k_y - i(k_x + k_y)} \right| \beta_k \beta_k,$$

(10)

(11)

(12)
The kinetic equation takes the form:

$$\frac{\partial N_q}{\partial t} = \frac{2\pi}{\hbar} \sum_{k'} E_{qk'} \left( (N_q + 1) n_{k'}^{(p)} - n_{k'}^{(p)} \right) - N_q n_{k'}^{(p)} \left( 1 - n_{k'}^{(p)} \right) \times \delta (E_{qk'} - E_{qk'} - \hbar \omega_q).$$

(13)

Assuming that the particle distribution is described by the expression

$$n_{k'}^{(p)} = (2\pi)^3 n_p \delta(k_x) \delta(k_y - k_p) \delta(k_z),$$

where $$n_2 = \|b_k\|^2 n_3 = \|b_k\|^2 n_1 = k_y = k_0; k_z = -k_0$$ and given the inequality $$\hbar^2 k_y^2 / 2 \gg \hbar \omega_q,$$ we get the following expression for the increment $$\gamma = \frac{\partial N_q}{N_q \partial t} = \frac{\alpha^2}{2k_y} V_0 (1 + R^3 + D^3),$$

(14)

where $$R = \|b_k\|^2$$ is the barrier reflection coefficient for a particle and $$D = \|a_k\|^2$$ is the barrier transmission coefficient for a particle. If we substitute the values $$R, D$$ with $$k_0, \chi$$ in equation (14) and introduce the notation $$\chi^2 / k_y^2 = \eta,$$ we get $$\gamma = \left( \frac{\alpha^2}{2k_y} q_s V_0 / \Omega_s \right) Z,$$

where $$Z = 1 - 3/2 \eta^2 / (1 + \eta)^4.$$ At the same time, from the equation (6) (where $$\chi = 2m_0 U_0 / \hbar^2$$), follows that

$$\gamma = \left( \frac{\alpha^2}{2k_y} q_s V_0 / \Omega_s \right) Y,$$

where $$Y = 1 / (1 + \eta)

Analysis

Thus, the potential barrier manifests itself in a completely different way in cases where the process of interaction of plasmons and electrons is deterministic or has the character of random collisions.

At $$\eta = 0$$ the increments are the same: $$Z = Y = 1.$$ Further, with growth of $$\eta$$, function $$Y$$ decreases and becomes zero with $$\eta \rightarrow \infty.$$ Function $$Z$$ passes through a minimum at $$\eta = 1,$$ and at $$\eta \rightarrow \infty$$ it turns into a unit, i.e. it turns out to be less sensitive to the potential barrier. When finding instability increments from kinetic equations in conditions $$k_y^2 \gg \alpha^2 / V_0^2,$$ we considered only “forward” electron scattering at the surface plasmon potential relative to the particle motion direction and neglected the “backward” scattering. Let us compare the magnitude of the matrix elements for these processes using equation (10).

Consider the factor

$$C = \left( k_y' + k_y' + i(k_y' + k_x') \right) / \left( k_y' - k_y' + i[q_s] \right),$$

at $$F$$ in equation (12). Let us assume that $$k_y = k_0, k_x = 0, k_y' = q_x.$$ The wave vector $$k_y'$$ of an electron scattered forward is equal to $$k_y' = k_0 \pm \omega / V_0.$$ Then we have: $$C_1^2 = 4k_0^2 / \alpha^2,$$ as $$q_s^2 \ll \omega^2 / V_0^2; k_0^2 \gg q_s^2.$$ The wave vector of an electron scattered backward is $$k_y' = -(k_0 \pm \omega / V_0).$$ In this case, we obtain $$C_2^2 = \omega^2 / (4k_0^2 V_0^2).$$ It is clear that

$$C_2 / C_1 = \omega^4 / (16k_0^4 V_0^4) << 1.$$

(15)

In conclusion, we note that if the kinetic energy of an electron is less than the energy of a surface plasmon, then there is a process of absorption of energy of surface vibrations. Let us estimate the decrement of plasmons during their interaction with the monoenergetic flow of charged particles, using equations (8), (9) and neglecting the influence of the potential barrier at the interface. Then the kinetic equation for plasmons has the form:

$$\frac{\partial N_q}{\partial t} = \frac{2\pi}{\hbar} N_0 \sum_{k'} |W|^2 \delta (E_{qk'} - \hbar^2 k_y^2 / (2m) - \hbar \omega_q).$$

(16)

Here, the matrix element $$|W| = |W_{kqk}| |W_{kqk}|$$ can be set equal to $$2F,$$ since the wave vector of a scattered electron $$k_y' = \pm k_x$$ is the largest term in the equation (16). Substituting the value $$|W|^2$$ in (16) and replacing the summation with integration, we get the following decrement:

$$\gamma = -\alpha^2 / \Omega_s q_s / \Omega_s.$$

(17)

where $$k_\pm = \sqrt{k_0^2 + 2m_0 \omega / \hbar}.$$

It can be seen that with growth of $$k_0,$$ the absolute value of the decrement also decreases and turns to zero approaching a certain threshold value $$k_0^2 > 2m_0 \omega / \hbar.$$ Further increase of $$k_0$$ changes the sign of $$\gamma$$ and the increment at $$k_0^2 \gg 2m_0 \omega / \hbar$$ takes on the following form: $$\gamma = \alpha^2 / \Omega_s q_s / \Omega_s.$$

For the development of instability, it is necessary that $$\gamma$$ exceed the attenuation of plasmons since the electrons may scatter on various objects (impurities, phonons, etc.) The attenuation of plasmons caused by these processes equals to $$\nu / 2$$ where $$\nu$$ is the highest characteristic electron pulse relaxation frequency. In addition, it is necessary that the mean free path of electrons in the flow exceed the penetration depth of the surface plasmon.

The numerical estimates for the heterostructure $$Al_{x}Ga_{1-x}As - GaAs - Al_{x}Ga_{1-x}As$$ with a two-dimensional electron gas at the interface at $$k_0^2 \gg 2m_0 \omega / \hbar$$ are as follows: At $$\Omega_s = 10^{12} \text{ s}^{-1},$$

$$d \sim 2 \cdot 10^{-7} \text{ cm}; q_x \approx 10^5 \text{ cm}, V_0 \sim 10^7 \text{ cm}, \omega_0 / \Omega_s \approx 0.1$$
the increment reaches the value of 0.1Ω, which is greater than \( v \leq 10^{11} \text{s}^{-1} \).

**Conclusions**

1. We have studied the mechanisms of interaction between a flow of charged particles and natural electromagnetic oscillations of a two-dimensional electron gas, occurring due to the presence of a potential barrier at the interface. As a result, we have obtained a kinetic equation that describes the change in the number of electromagnetic oscillations of such a system; we also provide an equation for the increment of the instability of the oscillations.

2. A kinetic equation has also been obtained that describes the change in the number of surface plasmons during their interaction with the flow of charged particles crossing the interface between the media having inhomogeneous potentials. We have provided a solution for the equation, which allows determining the influence the barrier may have on the instability increment of surface vibrations as well as the contribution to the increment resulted from the transmitted and reflected components of the particle flux.

3. We have determined the mechanisms through which the boundary influences the interaction of surface electromagnetic waves and electrons in the presence of a potential barrier. We used surface plasmons and intrinsic electromagnetic oscillations of a two-dimensional electron layer as research objects.

4. We also present a comparative analysis of the instabilities of these types of oscillations in conditions where the interaction of waves and particles is random or deterministic. It is shown that the differences in the expressions for increments are associated with a change in the size of the region of wave-particle interaction. Differences in the effect of the potential barrier on the increment are established in cases where the process of interaction between surface plasmons and charged particles is deterministic or has the character of random collisions.

**References**

1. Averkov, Yu.O. and Yakovenko, V.M. (2009), “Transitional radiation of a modulated electron beam crossing a wire screen”, *Radiophysics and electronics*, vol. 14, No. 3, pp. 337-343.

2. Averkov, Yu.O. and Yakovenko, V.M. (2009), “Excitation of surface electrostatic waves in semi-bounded layered superconductors by a nonrelativistic electron beam”, *ZhTF*, vol. 79, No. 5, pp. 87-94.

3. Averkov, Yu.O., Bass, F.G. and Yakovenko, V.M. (2009), “Excitation of surface excitations in semi-bounded solids by a non-relativistic electron beam”, *TT*, vol. 51, No. 1, pp. 57-64.

4. Kravchenko, V.I., Yakovenko, V.I. and Losev, F.V. (2009), “The influence of semiconductor components of electrical radio equipment”, *News of NTU “KhPI”*, NTU “KhPI”, Kharkiv, No. 11, pp. 62-69.

5. Beletsky, N.N., Khanika, S.I., Yakovenko, V.I. and Yakovenko I.V. (2010), “Interaction of surface plasmons with flows of charged particles passing through the boundary”, *ZhTF*, vol. 80, No. 4, pp. 120-125.

6. Khankina, S.I., Yakovenko, V.M. and Yakovenko, I.V. (2011), “Electronic states on an uneven surface of a solid body”, *PNT*, vol. 37, No. 11, pp. 1148-1155.

7. Kravchenko, V.I., Korobko, A.I. and Yakovenko I.V. (2014), “The influence of external electromagnetic factors on the waveguide characteristics of semiconductor components of radioelectronic equipment”, *Bulletin of NTU “KhPI”*, No. 21, pp. 79-84.

8. Kravchenko, V.I. and Yakovenko, I.V. (2014), “Failure mechanisms of semiconductor components of radio electronic components under the influence of external electromagnetic radiation”, *Bulletin of NTU “KhPI”*, No. 21, pp. 84-88.

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Електромагнітна сим'я множини напівпровідникових структур з двовимірним електронним шаром

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Анотація. Предметом вивчення є процес аналізу механізмів взаємодії потоку заряджених частинок з поверхні плацентами двовимірного електронного шару (2D), які виникають внаслідок впливу імпульсних електромагнітних випромінювань (EMV). Метою є вивчення розрахункових співвідношень, що визначають ступінь впливу нестійкостей власних коливань двовимірного електронного шару напівпровідникових структур на працездатність випромінювання випромінювання випромінювання випромінювання.

Об’єктом дослідження є: модель вивчення обміну відомих випромінювань, які виникають внаслідок взаємодії енергії випромінювання з двовимірним електронним шаром в напівпровідниковах структурах. Використовувані методи: аналітичні методи рішення рівнянь електродинаміки (Максвелла) і математичних рівнянь в рамках кинетичного підходу.

Отримані наступні результати: Досліджено механізми взаємодії потоку заряджених частинок з власними коливаннями двовимірного електронного шару, виникнення якого обумовлено нестійкістю потоку заряджених частинок на поверхні плацент частинок.

Проведені порівняння існуючих методів оцінки працездатності радіоелектронної апаратури "міліметрового і субміліметрового діапазонів" в умовах кинетичного підходу.

Ключові слова: електромагнітні поля; коливання; напівпровідник; кинетичні нестійкості; потенційний бар’єр; поток заряджених частинок; генерація; енергія випромінювання.

潦  электротехнічна структури з двовимірним електронним шаром

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Annotation. The subject of the study is the process of analysis of mechanisms of interaction of the charged particle flux with the surface plasma of a two-dimensional electronic layer (2D), which are formed as a result of the influence of impulse electromagnetic radiation (EMR). The goal is to obtain analytical relationships that determine the degree of influence of two-dimensional electronic layer plasma instabilities on the performance of semiconductor structures.

The object of investigation is: a model of the influence of EMR, formed as a result of the interaction of energy of EMR with a two-dimensional electronic layer of semiconductor structures. The methods used: analytical methods for solving Maxwell's equations and mathematical equations in the framework of a kinetic approach.

The obtained results: The mechanisms of interaction of the charged particle flux with the surface plasma of semiconductor structures are investigated, the results of which are used to estimate the performance of semiconductor structures.

The key words: electromagnetic fields; vibrations; semiconductor; kinetic instabilities; potential barrier; flux of charged particles; generation; energy of EMR.