УДК 629.3 **doi: 10.26906/SUNZ.2025.1.205-208**

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GENERATION OF SURFACE OSCILLATIONS OF SEMICONDUCTOR STRUCTURES BY CHARGED PARTICLE FLOWS

Abstract. The results of the work determine the degree of influence of flows of charged particles induced by external electromagnetic radiation on the performance of communication equipment. The **aim** is to determine the conditions for the development of hydrodynamic instabilities of electrostatic oscillations in communication system devices containing semiconductor layers surrounded by media with different electromagnetic properties. The following **results** are obtained: A mechanism for the occurrence and development of surface electrostatic oscillation (plasmon) instabilities is proposed under conditions where the interaction of electromagnetic oscillations and a flow of charged particles generated by external electromagnetic radiation is ensured by the presence of a boundary. Specific features of the transformation of the spectral characteristics of the energy of transition radiation associated with the presence of an interface between media with different electromagnetic properties in open-type radiophysical systems are determined. A new physical mechanism for the generation and amplification of surface electromagnetic oscillations by flows of charged particles, the characteristics of which are determined by the properties of the interface between conductive solids, is developed. **Conclusion.** The criteria for the occurrence and development of surface plasmon instabilities associated with the nonequilibrium of electronic systems obtained in the work are realized in conductive solids. Therefore, they can be used in the development of active devices of semiconductor electronics designed to amplify, generate and convert electromagnetic oscillations in the millimeter and submillimeter ranges. The comparative analysis of the increments of beam-plasma instabilities of various branches of electrostatic oscillations during the motion of a particle flow along the normal or along the interface of media, carried out in the work, allows us to solve the problems of optimizing existing mechanisms for amplifying oscillations in structures used in modern radiophysics (MDS, MOS, various types of p-n junctions).

Keywords: beam instability of electrostatic oscillations, semiconductor components, induced current, electromagnetic radiation, surface oscillations.

Introduction

One of the urgent tasks of modern radiophysics is the need to master the submillimeter and short-wave part of the millimeter ranges of electromagnetic oscillations. These ranges are important not only for many technical applications: radar, radio navigation, communication technology, computing technology, but also in biology, medicine, as well as in research in various areas of theoretical physics.

The possibility of mastering this range is impossible without creating appropriate sources of electromagnetic radiation. In solving it, two approaches were determined.

On the one hand, attempts are being made to improve devices that operate in a lower-frequency part of the spectrum, namely, avalanche-transit diodes, microwave transistors, Gunn diodes. These include studies of plasma-wave effects, unstable states and resonances in conducting solids. The results of these studies open up new possibilities for generating oscillations in this range, and also solve problems of radio spectroscopy of solids. On the other hand, research is being conducted aimed at using the laser principle of amplification and generation of electromagnetic waves in the submillimeter range, which is implemented in optics (in semiconductor lasers). A necessary condition for the successful solution of the tasks set is the availability of an appropriate element base created on the basis of materials with predictable parameters.

Modern technology allows creating conductive solid-state structures: semiconductors with a two-dimensional (2D) electron gas, a superlattice, as well as films and structures of the metal-insulator-semiconductor (MIS) type, etc. The study of the electronic properties of ultra-thin layers and plasma oscillations caused by the collective behavior of charges determines the mechanisms of their formation.

Solutions to the issues of interaction of plasma oscillations with flows of charged particles are also important for diagnostics and practical use of conductive solid-state structures (for example, in micro- and nanoelectronics). The fact is that in structures that have submicron dimensions, the ballistic mechanism of charge transfer is implemented. Therefore, they may exhibit instabilities based on the effects of Cherenkov, transition and bremsstrahlung radiation of particles.

In addition, the results of studies of wave processes in a limited semiconductor plasma can be used for contactless methods of diagnostics of electron spectra of charge carriers and surface properties. Finally, new branches of electromagnetic oscillations arise in limited media, as well as a connection between different types of oscillations due to the presence of external boundaries.

This work to a certain extent compensates for the existing gaps in studies of wave processes in semiconductor plasma. It examines the mechanisms of generation of electromagnetic oscillations of the submillimeter and short-wave part of the millimeter ranges, caused by their interaction with flows of charged particles induced by pulsed electromagnetic radiation in semiconductor structures used in modern radio electronics and communication technology.

Task solution

Let us consider the dispersion characteristics of electrostatic oscillations in a system that is a semiconductor layer (or dielectric) surrounded by semi-infinite media with different electromagnetic properties [5]. To find the spectrum of electrostatic oscillations of a given structure, we will use the following electrostatic equations:

$$rot\vec{E} = 0; \quad (1) \qquad div\vec{D} = 0. \quad (2)$$

The electric induction vector $\vec{D}(\vec{r},t)$ is related to the electric field $\vec{E}(\vec{r},t)$ by the material equation:

$$\vec{D}(\vec{r},t) = \int_{-\infty}^{t} \hat{\varepsilon}(t-t')\vec{E}(\vec{r},t')dt'. \quad (3)$$

We select the reference system in such a way that the y-axis is directed perpendicular to the interface boundaries, and the x,z-axes are parallel to them. The system is assumed to be infinite along the x,z-axis.

Let the plate with $\hat{\varepsilon} = \hat{\varepsilon}_1$ occupy the region –d ≤ y ≤ d; the half-space $-\infty < y < -d$ - is the medium "2" with $\hat{\varepsilon} = \hat{\varepsilon}_2$, , the half-space $d < y < \infty$ - is the medium "3" with $\hat{\varepsilon} = \hat{\varepsilon}_3$.

At the interface boundaries y=±d, the conditions of continuity of the tangential components of the electric field $\vec{E}$ and continuity of the normal components of the induction vector are satisfied. At y = ±∞, the variables included in equations (1)-(2) vanish. We represent the field $\vec{E}(\vec{r},t)$ in the form:

$$\vec{E}(\vec{r},t) = \vec{E}(y)e^{i(\vec{q}\vec{\rho}-\omega t)} \quad (4)$$

Where $\vec{q}$ is the wave vector, ω - is the oscillation frequency, $\vec{\rho} = (x,z)$. Since the medium is assumed to be isotropic, the x-axis can be directed along the wave vector $\vec{q}$. In this case $\vec{E}(\vec{r},t) = \vec{E}(y,x,t)$; $\vec{E} = (E_x, E_y)$. The solution to system (1) - (2) takes the following form:

$$E_x(y) = \begin{cases} a_2 e^{qy}, -\infty < y < -d; \\ a_1 e^{qy} + a_0 e^{-qy}, -d \le y \le d; \\ a_3 e^{-qy}, d < y < \infty; \end{cases} \quad (5)$$

$$E_y(y) = \frac{1}{iq}\frac{\partial E_x}{\partial y}, \to q > 0.$$

The boundary conditions at y=±d give the following dispersion law for the natural oscillations of the system:

$$(\varepsilon_1 + \varepsilon_2)(\varepsilon_1 + \varepsilon_3) = (\varepsilon_1 - \varepsilon_2)(\varepsilon_1 - \varepsilon_3)\exp(-4qd), \quad (6)$$

where $\varepsilon_1(\varpi) = \int_0^\infty \hat{\varepsilon}_i = \hat{\varepsilon}_1(\tau)e^{i\omega\tau}d\tau$ - the permittivity of the i-th medium. For the semiconductor layer it is assumed that: $\varepsilon_i(\omega) = \varepsilon_{0i} - \frac{\omega_{0i}^2}{\omega^2}$, $\omega_{0i}^2 = \frac{4\pi e^2 n_{0i}}{m_i}$, ε_{oi} – dielectric constant of the crystal lattice. n_{oi}, m_i – concentration, effective mass of conduction electrons of the medium. Expressions for ε_i are obtained from the equation of motion of conduction electrons.

The constants a_i are related to each other by the following relationships:

$$a_2 = \frac{2\varepsilon_1 a_1}{\varepsilon_1 + \varepsilon_2}; \quad a_0 = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2}a_1 e^{-2qd};$$

$$a_3 = \frac{2\varepsilon_1}{\varepsilon_1 + \varepsilon_3}a_1 e^{-2qd}. \quad (7)$$

For large wave numbers (*qd*>>1) we obtain two independent solutions: $\varepsilon_1 + \varepsilon_2 = 0$ и $\varepsilon_1 + \varepsilon_3 = 0$ and describing surface plasma oscillations on isolated boundaries $y = \pm d$ of media "1-2" and "1-3". In the opposite limiting case (d→0) we have plasma surface oscillations on the boundary of media "2" and "3" ($\varepsilon_2 + \varepsilon_3 = 0$). For small but finite *qd*, plasma oscillations also arise in the layer $\varepsilon_1(\omega) = 0$.

From equation (6) it follows:

$$\varpi_{1,2}^2 = \frac{\Omega_1^2}{2}\left\{1 + \frac{\alpha+\beta}{2} \pm \sqrt{\left(1+(\alpha+\beta)/2\right)^2 - 2\times \frac{\alpha+\beta+(1+\alpha\beta)th2qd}{1+th2qd}}\right\}. \quad (8)$$

Here $\varepsilon_{01} = \varepsilon_{02} = \varepsilon_{03} = \varepsilon_0$; $\Omega_i^2 = \varpi_{0i}^2/\varepsilon_0$; $\Omega_2^2 = \alpha\Omega_1^2$; $\Omega_3^2 = \beta\Omega_1^2$; α and β; are real numbers expressing the relationship between the concentrations of charge carriers in different media. An example of such a system is, for example, "R - P"- transitions at y = ±d.

It is interesting to note one circumstance related to the symmetry of the system. If we put in expression (6), then it splits $\varepsilon_3 = \varepsilon_2$ into two independent equations:

$$(\varepsilon_1 + \varepsilon_2) = \pm(\varepsilon_1 - \varepsilon_2)\exp(-2qd) \quad (9)$$

The equation with the "+" sign describes oscillations with a symmetric distribution of the tangential component of the field in the layer $E_x(-d) = E_x(d)$, the second - with an antisymmetric one. If medium "1" is a dielectric with $\varepsilon_1 + \varepsilon_d$, and where second is a semiconductor $\varepsilon_2 = \varepsilon(\varpi)$, where $\varepsilon(\omega) = \varepsilon_0 - \varpi_0^2/\omega^2$, then the spectra of symmetric and antisymmetric oscillations have the following form:

$$\varpi_1(q) = \frac{\omega_0}{\sqrt{\varepsilon_0 + \varepsilon_d thqd}} \quad (10)$$

$$\varpi_2(q) = \frac{\omega_0}{\sqrt{\varepsilon_0 + \varepsilon_d cthqd}} \quad (11)$$

On the contrary, in the case of $\varepsilon_1 = \varepsilon(\varpi)$ and $\varepsilon_2 = \varepsilon_d$ the spectrum of symmetric oscillations is described by formula (11), and antisymmetric ones by formula (10). For the metal-insulator-semiconductor structure $\varepsilon_2 \to \infty$, $\varepsilon_1 = \varepsilon_d$, $\varepsilon_3 = \varepsilon(\varpi)$, there is only one branch with the dispersion law:

$$\varpi(q) = \frac{\omega_0}{\sqrt{\varepsilon_0 + \varepsilon_d cth2qd}} \quad (12)$$

Let us now consider the interaction of the flow of charged particles with the oscillations of the electric field in these structures. Let the flow of electrons with density n_0 and velocity v_0 move in the medium "1" ($\varepsilon_1 = \varepsilon_d$) along the X-axis (in the final formulas we can always put

$(\varepsilon_d = 1)$. At the boundaries $y = \pm d$ the normal component of the induction vector undergoes a discontinuity caused by the occurrence of surface charges. Thus, from the Poisson equation, at $y = d$ it follows that the boundary condition takes and is written as follows:

$$\varepsilon_d E_y(d+0) - D_y(d-0) = 4\pi\varepsilon \int_{d-0}^{d+0} n dy . \quad (13)$$

The disturbed concentration n of beam electrons is related to the velocity $\vec{v}$ by the equations of hydrodynamics:

$$i(\varpi - qv_0)n = iqn_0 v_x + \frac{\partial}{\partial y}\left[n_0(y)v_y\right]; \quad (14)$$

$$(\varpi - qv_0)\vec{v} = i\frac{e}{m}\vec{E} . \quad (15)$$

Using (14), (15), after integrating over the transition layer (13) we find:

$$\varepsilon_d E_y(d+0) - D_y(d-0) = \frac{\omega_b^2 \varepsilon_d}{(\varpi - qv_0)^2} E_y(d+0) . \quad (16),$$

Where $\varpi_b = \left(4\pi e^2 n_0 / m\right)^{1/2}$ is the plasma frequency of the beam electrons. Let us further assume that $\varepsilon_2 = \varepsilon_3 = \varepsilon(\omega)$. In other words, there is a gap in the semiconductor plasma through which a flow of charged particles passes. In this case, in the dispersion relations (9), it is necessary to replace ε_1 with $\varepsilon_d - \omega_b^2/(\omega - qv_0)^2$. As a result, we obtain:

$$\left[\omega^2 - \omega_1^2(q)\right](\omega - qv_0)^2 = \frac{\omega_b^2\omega^2}{\varepsilon_0 cthqd + \varepsilon_d}; \quad (17)$$

$$\left[\omega^2 - \omega_2^2(q)\right](\omega - qv_0)^2 = \frac{\omega_b^2\omega^2}{\varepsilon_0 thqd + \varepsilon_d} . \quad (18)$$

We obtain the solution of equation (17) using the approximation of low beam density $\omega_b^2/\omega_0^2 \ll 1$ [7]. Assuming ω_b=0, we define two independent solutions:

$$\omega = \omega_1(q) . \quad (19)$$

$$\omega = qv_0 . \quad (20)$$

The first characterizes the already known natural oscillations of the system in the absence of a beam, the second – oscillations in a beam with low density. Taking into account the finite density of beam electrons leads to a change in frequencies and the emergence of instability (the Akhiezer and Feinberg mechanism). Under the conditions of Cherenkov resonance, when the frequencies and wave numbers of both branches coincide, the oscillation increment γ has a maximum value:

$$\frac{\gamma}{\omega_1} = \frac{\sqrt{3}}{2}\left(\frac{\omega_b^2 thqd}{2\omega_0^2}\right)^{1/3} . \quad (21)$$

The magnitude of the instability γ increment characterizes the oscillation generation mode since it determines the exponential growth of the amplitude ***E*** of the electromagnetic fields of radiation of semiconductor devices with time:

$$E \approx \exp(+\gamma t); \;\; \gamma = 1/\Delta t_{ei} ,$$

where Δt_{ei} – the time of effective interaction of induced currents and natural oscillations of the semiconductor structure (the time it takes a particle to pass through the semiconductor layer).

The relative increment for antisymmetric oscillations with a frequency $\omega = \omega_2(q)$ is found in a similar way. It differs from formula (21) by replacing th *qd* with cth *qd*. For small qd, the relative increment for a branch $\omega_1(q)$ is proportional to $(qd)^{1/3}$, and for a branch $\omega_2(q)$ it turns out to be significantly larger and proportional to $(qd)^{-1/3}$. This is due to the fact that the perturbed electron density in the flow is localized at the boundaries and therefore the interaction of space charge waves is more effective with antisymmetric plasmons.

The interaction of an electron beam with plasma oscillations was experimentally studied in indium antimonide and germanium [9, 10] in the millimeter and submillimeter ranges. Due to the high frequency of electron collisions ν, the weak coupling condition is realized in the experiment, where $\Delta\omega < \nu$, where $\Delta\omega$ is the change in the frequency of natural oscillations in the presence of a beam. Therefore, compensation of the wave amplitude attenuation is observed due to the energy of the particle flow.

Analysis

Let us present quantitative estimates of the conditions of resonant (Cherenkov) interaction of surface plasmons with flows of charged particles induced by external electromagnetic radiation, i.e. the possibilities of their generation (amplification) in currently used microwave semiconductor devices. The frequency of surface plasmons for typical values of semiconductor structures used in modern radio electronics is $\omega_s \approx 10^9 - 10^{11} s^{-1}$. The drift velocity of carriers for fields in the range of amplitudes of electric E and magnetic H field strengths acting on the semiconductor structure of radiation is $E < 100\, kV/m;\; H < 600\, A/m$ consists $v_{\partial p} \approx 10^{-7} - 10^{-9}\, sm/s$. Therefore, the conditions of resonant interaction of waves and particles (equality of the phase velocity of the wave v_ϕ and the drift velocity of $v_\phi = \omega_s/q \approx v_{\partial p}$ the particles of the induced current are fulfilled for millimeter (submillimeter) wavelengths $\lambda = 2\pi/q \approx 10^{-1} - 10^{-3} sm$. Thus, the proposed physical model of the emergence of conditions for the generation (amplification) of oscillations is realized for most semiconductor devices used in modern radio electronics since their dimensions are within 10^{-1} – 10^{-3} sm.

Conclusion

The conditions for the development of hydrodynamic instabilities of electrostatic oscillations in communication system devices containing semiconductor layers surrounded by media with different electromagnetic properties are determined.

The problem of the development of the initial perturbation of the charged particle flow, the appearance of which is caused by the action of external electromagnetic radiation, when it passes through the interface of media with different electromagnetic properties, is solved.

Determination of the mechanisms of collisionless attenuation of surface electrostatic oscillations and the conditions of its reversal associated with the interaction of waves and flows of charged particles at the boundary of conducting solids.

Expressions are obtained for the increments of hydrodynamic beam instabilities in semiconductor structures and structures with ballistic charge transfer.

Ratios are obtained that connect the characteristics of semiconductor structures and the parameters of charged particle flows, ensuring the occurrence of unstable states similar to the Akhiezer-Fainberg instability.

A new physical mechanism for generating and amplifying surface electromagnetic oscillations by flows of charged particles, the characteristics of which are determined by the properties of the interface between conducting solids, has been developed. Specific features of the transformation of the spectral characteristics of the energy of transition radiation associated with the presence of an interface between media with different electromagnetic properties in open-type radiophysical systems have been determined.

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Received (Надійшла) 25.11.2024
Accepted for publication (Прийнята до друку) 26.02.2025

Генерація поверхнівних коливань напівпровідникових структур потоками заряжених часток

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Анотація. Результати роботи визначають рівень впливу потоків заряджених частинок, наведених зовнішнім електромагнітним випромінюванням, на робочі характеристики засобів зв'язку. **Мета статті** – визначення умов розвитку гідродинамічних нестійкостей електростатичних коливань у пристроях систем зв'язку, що містять напівпровідникові шари, оточені середовищами з різними електромагнітними властивостями. The following **results** are obtained: Запропоновано механізм виникнення та розвитку нестійкостей поверхневих електростатичних коливань (плазмонів), в умовах, коли взаємодія електромагнітних коливань та потоку заряджених частинок, створюваних зовнішнім електромагнітним випромінюванням, забезпечується наявністю кордону. Визначено специфічні особливості трансформації спектральних характеристик енергії перехідного випромінювання, пов'язані з наявністю межі поділу середовищ з різними електромагнітними властивостями у радіофізичних системах відкритого типу. Розроблено новий фізичний механізм генерації та посилення поверхневих електромагнітних коливань потоками заряджених частинок, характеристики яких визначаються властивостями межі розділу твердих тіл, що проводять. **Conclusion.** Отримані в роботі критерії виникнення та розвитку нестійкостей поверхневих плазмонів, пов'язані з нерівноважністю електронних систем, реалізуються у твердих тілах, що проводять. Тому вони можуть бути використані при розробці активних пристроїв напівпровідникової електроніки, призначених для посилення, генерування та перетворення електромагнітних коливань міліметрового та субміліметрового діапазонів. Проведений у роботі порівняльний аналіз інкрементів пучково-плазмових нестійкостей різних гілок електростатичних коливань при русі потоку частинок за нормаллю або вздовж межі розділу середовищ, дозволяє вирішувати завдання оптимізації існуючих механізмів посилення коливань у структурах, що використовуються в сучасній радіофізиці (МДП, МОП, різних p-n переходів).

Ключові слова: пучкова нестійкість електростатичних коливань напівпровідникові комплектуючі, наведений струм, електромагнітне випромінювання, поверхневі коливання.