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INFLUENCE OF ELECTROMAGNETIC RADIATION ON RESISTANCE OF SEMICONDUCTOR DEVICES

Abstract. The **subject matter** is the processes of analysis and mechanisms of appearance of instabilities of natural vibrations of semiconductor structures., due to their interaction with flows of charged particles under the influence of external electromagnetic radiation. It is shown that the influence of pulsed electromagnetic radiation is accompanied by the appearance of currents in the conductive elements of products that are capable of exciting natural oscillations of semiconductor components and are the cause of failures of radio products. The **aim** is to develop the theory of collisionless damping of surface polaritons in the classical approximation, as well as to study the mechanisms of collisionless damping of surface plasmons at the boundaries of semiconductor components of radio products under conditions when the temperature of carriers of conducting solids is much lower than the plasmon energy (quantum approximation). The **objectives** are: a kinetic equation describing the change in the number of surface plasmons as a result of their interaction with conduction electrons; obtaining its solution, which determine the decrement of oscillations and the power of spontaneous emission of particles. The **methods** used are: a method of successive approximations for solving the kinetic equations of the charged particle flux - semiconductor structure system within the framework of the quantum approach, when the interaction of waves and particles is in the nature of random collisions and is described by the method of secondary quantization of the system (representation of occupation numbers). The **following results** are obtained: Expressions are obtained for the decrements of surface plasmons in the presence of an infinitely high and infinitely small potential barrier at the interface between media. A kinetic equation is obtained that describes the change in the number surface plasmons as a result of their interaction with conduction electrons; his decisions are given, which determine oscillation decrement. Expressions are obtained for the decrements of surface plasmons at presence of infinitely high and infinitely small potential barrier at the interface between A physical model of the occurrence of reversible failures (effects induced by electromagnetic radiation currents per volt - ampere characteristics of semiconductor devices). The ranges of parameters of the external electromagnetic radiation at which this physical model is realized. **Conclusion.** Calculated relations are obtained that relate the parameters of semi-conductor structures: the concentration of free carriers, permittivity, carrier temperature with the value oscillation decrement in the classical and quantum approximations. The comparative analysis of quantitative estimates of the increments of oscillation instabilities carried out in the work makes it possible to solve the problems of optimizing the operating characteristics of active devices in the microwave range. The results of the work can be used in the development of microwave devices designed to amplify, generate and convert electromagnetic oscillations in the millimeter and submillimeter ranges.

Keywords: flux of charged particles, electromagnetic radiation, semiconductor structures, surface vibrations, increment oscillation instability.

Introduction

The need to master the submillimeter and shortwave part of the millimeter range of electromagnetic oscillations is one of the main problems of modern radiophysics. These ranges are important when conducting research in various areas of theoretical physics, but also in medicine, biology, many technical applications: communication technology, radar, radio navigation, computer technology, etc.

When solving the problem of creating electromagnetic radiation sources of this range, it is necessary to study plasma-wave effects, resonances and unstable states in solids. Interest in them is determined by the search for new possibilities for generating oscillations in this range, as well as by the problems of radiospectroscopy of solids. Obviously, 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 makes it possible to create conductive solid-state structures: films, metal-dielectric-semiconductor (MIS) structures, semiconductors with two-dimensional (2D) electron gas and superlattice, etc. When studying the electronic properties of ultrathin layers and determining the mechanisms of their formation, it becomes necessary to study plasma oscillations due to the collective behavior of charges.

The processes of generation of oscillations in the submillimeter and short-wavelength parts of the millimeter range under the influence of external electromagnetic fields have a significant impact on the performance of semiconductor devices, since the generation mode distorts the current-voltage characteristics of radio products.

This work belongs to this area of reversible failure research. It considers the processes of collisionless damping of surface oscillations, when the interaction of waves and charged particles induced by external radiation is described by the method of secondary quantization of the system and has the character of random collisions. Such interaction of waves and induced currents leads to the appearance of reversible failures of radio products (temporary changes in their performance) and affects their electromagnetic compatibility.

Task solution

The object of the study is the surface oscillations of semiconductor structures included in the composition of electrical and radio products and the mechanisms of their interaction with conduction electrons, leading to damping of oscillations under the influence of an external electromagnetic field.

To determine the spectrum of natural (surface) oscillations and decrements of their collisionless damping at the boundary of two semi-infinite media under conditions of neglecting the effect of delay of the electromagnetic field, we use the following system of equations:

$$\begin{gathered}\operatorname{rot}\vec{E}(x,y,t)=0;\\ \vec{E}(x,y,t)=\vec{E}(\omega,q_x,y)e^{i(q_x x-\omega t)};\\ \vec{E}(\omega,q_x,y)=(E_x,E_y,0);\end{gathered} \quad (1)$$

$$\begin{gathered}\operatorname{div}\vec{D}(\omega,x,y)=0;\\ \vec{D}(\omega,x,y)=\varepsilon_0(y)\vec{E}(\omega,x,y)+\frac{4\pi i}{\omega}\vec{j}(\omega,x,y);\end{gathered} \quad (2)$$

$$\varepsilon_0(y)=\begin{cases}\varepsilon_{01}, & y>0;\\ \varepsilon_{02}, & y<0;\end{cases}\quad \vec{E}=\begin{cases}\vec{E}_1, & y>0;\\ \vec{E}_2, & y<0;\end{cases}$$

$$\vec{j}=\begin{cases}\vec{j}_1, & y>0;\\ \vec{j}_2, & y<0\end{cases}$$

with boundary conditions at y = 0: the continuity of the tangential components of the electric field E_x and the normal components of the electric induction D_y.

Let us consider the attenuation of surface plasmons at the boundary of two media, which, at a temperature $T = 0$, are characterized by dielectric permittivity.

$$\varepsilon_i=\varepsilon_{0i}-\frac{\omega_{0i}^2}{\omega^2}.$$

If the media are separated by an infinitely high potential barrier $\omega_{01}\neq\omega_{02}$, , then the electromagnetic properties of such a semi-limited medium are identical to the properties of an infinite one, and the particles experience elastic (mirror) reflection from the barrier on both sides. The results obtained in [3] in the classical approximation for a plasma–dielectric interface (nonabsorbing medium) can be extended to the case of two plasma-like media separated by a dielectric layer whose thickness is small compared to the wavelength.

Based on the model of a homogeneous medium, we will assume, as in the case of a cold plasma, that both media are unlimited, and the fields and currents in each of them satisfy the boundary conditions on the plane $y=0$ and decrease at $y\to\pm\infty$. Obviously, such a model is quite justified if the boundary is transparent for particles, those. the height of the potential barrier is small compared to the particle energy. Then the equation for the conduction current can be written as:

$$\vec{j}(\omega,\vec{r})=-\frac{e^2 n_0}{mc}\vec{A}(\omega,r)+\vec{j}'(\omega,r)\,. \quad (3)$$

Here, $\vec{A}(\omega,\vec{r})=\frac{c}{i\omega}\vec{E}(\omega,\vec{r})$ is the vector potential, $n_0=\sum\rho_k^0\psi_k^*(\vec{r})\psi_k(\vec{r})$ is the equilibrium concentration of electrons ρ_k^0, their equilibrium distribution function, $\psi_k(\vec{r})=V^{-1/2}\exp(ik\vec{r})$ is the wave function of an electron with the dispersion law, $E_k=\hbar^2k^2/(2m)$, V is the volume of the medium,

$$\vec{j}'(\omega,\vec{r})=\sum\rho_{kk'}(\omega)\vec{j}_{k'k}(\vec{r})$$

is the conduction current due to transitions of electrons between states k and k' $(k_z=k'_z)$ due to their inelastic scattering on the potential

$$\vec{A}(\omega,\vec{r})=\vec{A}(\omega,q_x,y)\,e^{i(q_x x-\omega t)}$$

(hereinafter, for definiteness, we assume that is the perturbed off $q_x>0,\omega>0)$, $\rho_{kk'}^0(\omega)$ - diagonal correction to the equilibrium distribution function of particles, determined from the equation of motion for the density matrix [2]:

$$\begin{gathered}\rho_{kk'}(\omega)=\frac{\rho_k^0-\rho_{k'}^0}{\hbar(\omega_{kk'}-\omega^*)}H_{kk'}(\omega);\\ \omega_{kk'}=\frac{\hbar(k^2-k'^2)}{2m};\\ \omega^*=\omega+i\upsilon,\quad \upsilon\to 0,\end{gathered} \quad (4)$$

where $H_{kk'}=\frac{ie\hbar}{2mc}\int\psi_k^*(\vec{r})(\vec{A}\nabla+\nabla\vec{A})\psi_{k'}(\vec{r})d\vec{r}$ is the matrix element of the Hamiltonian of the interaction of electrons with an electromagnetic field;

$$\vec{j}_{kk'}=\frac{ie\hbar}{2m}\left\{\nabla\psi_{k'}^*(r)\psi_k(\vec{r})-\psi_{k'}^*(r)\nabla\psi_k(\vec{r})\right\} - \quad (5)$$

is the matrix element of the particle current density operator. The result $\vec{j}'(\omega,\vec{r})$ is converted to the following form:

$$\vec{j}'(\omega,\vec{r})= =-\frac{1}{\hbar c}\sum\begin{pmatrix}\vec{j}_{k'k}(\vec{r})\cdot\frac{(\rho_k^0-\rho_{k'}^0)}{\omega_{kk'}-\omega^*}\times\\ \times\left[H_{kk'}^s(\omega)+\int\vec{j}_{kk'}(\vec{r})\vec{A}(\omega,\vec{r})d\vec{r}\right]\end{pmatrix}, \quad (6)$$

where $H_{kk'}^s=\frac{ie\hbar}{2mc}\int\begin{pmatrix}dxdz\psi_k^*(x,0,z)\psi_{k'}(x,o,z)\times\\ \times\left[A_y(\omega,x,+0)-A_y(\omega,x,-0)\right]\end{pmatrix}$.

In expression (3) for the total current, the first term determines the frequency of surface plasmons, and the second determines their damping.

Substituting further $\vec{j}(\omega,\vec{r})$ into equation (2) and taking into account equation (3), we obtain:

$$\begin{gathered}\frac{\partial^2A_x(\omega,x,y)}{\partial y^2}-q_x^2A_x(\omega,x,y)=\\ =-\frac{4\pi iq_xc}{\omega^2\varepsilon(\omega)}\operatorname{div}\vec{j}'(\omega,x,y);\end{gathered} \quad (7)$$

$$\varepsilon(\omega)=\begin{cases}\varepsilon_1(\omega), & y>0;\\ \varepsilon_2(\omega), & y<0\end{cases}.$$

The solution of equation (7) must be sought by the method of successive approximations, since the oscillation damping decrement is small compared to their frequency. We find for $\varepsilon(\omega)\neq 0$ the following expressions for the potential in each of the media, assuming, in the first approximation, the right side equal to zero:

$$\begin{aligned} &y>0, \quad A_{1x}(y)=A_1\,e^{-q_x y}, \quad A_{1y}=iA_{1x}(y); \\ &y<0, \quad A_{2x}(y)=A_2\,e^{-q_x y}, \quad A_{2y}=-iA_{2x}(y). \end{aligned} \tag{8}$$

Taking into account the fact that the normal component $\vec{A}(y)$ experiences a discontinuity in the plane $y=0$, we continue the potentials, respectively, to the half-spaces

$$y<0 \; u \; y>0{:}A_x(-y)=A_x(y);$$
$$A_y(-y)=-A_y(y).$$

Substituting the values $\vec{A}(\omega,\vec{r})$ in formula (3), after replacing the summation $\sum_k$ with integration $\frac{V}{(2\pi)^3}\int d\vec{k}$. and, integrating over the entire space $\vec{r}$, we obtain

$$\vec{j}'(\omega,\vec{r})=\frac{e^2\hbar A\,e^{iq_x x}}{2(2\pi)^4 m^2 c}\times$$
$$\times\int\left(\begin{array}{c}\frac{d\vec{k}dk'_y}{\omega_{kk'}-\omega^*}(\rho_k^0-\rho_{k'}^0)(\vec{k}+\vec{k}')\times \\ \times\left[1-\frac{k^2-k'^2}{q_x^2+(k_y-k'_y)^2}\right]e^{i(k_y-k'_y)y}\end{array}\right). \tag{9}$$

At this point $k'_x=k_x-q_x, \quad k'_z=k_z$.

The current resulting from the transition of an electron from a state k to a state k' with the emission of a quantum $\hbar\omega$ of an electromagnetic field is determined by a term proportional to ρ_k^0 ,. In this case, one can perform integration k'_y, over taking $k_x>>q_x$, $\omega>>q_x v_x$ into account the contributions of the poles

$$k_y'^2=k_y^2-\frac{2m(\omega+i\upsilon)}{\hbar}.$$

The term $\rho_{k'}^0$ determines the current associated with the transitions of electrons from state k' to state k upon absorption of energy $\hbar\omega$. This current is determined by the poles $k_y^2=k_y'^2+\frac{2m(\omega+i\upsilon)}{\hbar}$ when integrated over k_y.

As a result of integration, we get:

$$\vec{j}'(\omega,\vec{r})=\frac{-ie^2\omega A\,e^{iq_x x}}{(2\pi)^3\hbar c}\times$$
$$\times\left\{\int\left(\begin{array}{c}\frac{d\vec{k}(\vec{k}+\vec{k}_-)\rho_k^0}{k_y^-(k_y-k_y^-)^2}\left[1-\frac{\hbar(k_y-k_y^-)^2}{2m\omega}\right] \\ \exp\left\{i\left[k_y-k_y^-+i\delta_-\right]y\right\}\end{array}\right)-\right. \tag{10}$$
$$\left.-\int\left(\begin{array}{c}\frac{d\vec{k}(\vec{k}+\vec{k}_+)\rho_k^0}{k_y^+(k_y-k_y^+)^2}\left[1-\frac{\hbar(k_y-k_y^-)^2}{2m\omega}\right] \\ \exp\left\{i\left[k^+{}_y-k_y+i\delta_+\right]y\right\}\end{array}\right)\right\}.$$

Here $y<0,\; k_y^{\pm}=\sqrt{k_y^2\pm\frac{2m\omega}{\hbar}}>0,$

$\vec{k}_{\pm}=(k_x,k_y^{\pm},k_z),\; \delta_{\pm}=\frac{m\upsilon}{\hbar k_y^{\pm}}.$

It can be seen that the current $\vec{j}'(\omega,\vec{r})$, arising as a result of electronic transitions between states k_y and k'_y is an infinite set of spatial harmonics with a period $\frac{2\pi}{\left|k_y-k_y^{\pm}\right|}$, depending on the frequency of the field and the momentum of the particle, with an amplitude decreasing from the boundary as $\exp(-\delta_{\pm}\left|y\right|$.

Such harmonics (in the classical limit $k_y^2, k_y'^2>>2m\omega/\hbar$) are known as "Van Kampen waves", whose phase velocity is equal to the velocity of the particle. The potential excited by the current $\vec{j}'(\omega,x,y)$ is found by substituting (6) into equation (7).

$$A'_x(\omega,q_x,y)=\frac{i\alpha(\omega,q_x,y)}{\varepsilon(\omega)}A;$$
$$A'_y(\omega,q_x,y)=\frac{A}{q_x\varepsilon(\omega)}\frac{\partial\alpha}{\partial y}(\omega,q_x,y);$$
$$\alpha(\omega,q_x,y)=\frac{e^2q_x m}{\pi^2\hbar^2}\times$$
$$\times\left\{\int'\left(\begin{array}{c}\frac{\rho_k^0 d\vec{k}}{k_y^-(k_y\mp k_y^-)^4}\left[1-\frac{\hbar(k_y\mp k_y^-)^2}{2m\omega}\right]\times \\ \times\exp\left\{i(k_y\mp k_y^-\pm i\delta_-)y\right\}\end{array}\right)-\right. \tag{11}$$
$$\left.-\int'\left(\begin{array}{c}\frac{\rho_k^0 d\vec{k}}{k_y^+(k_y\mp k_y^+)^4}\left[1-\frac{\hbar(k_y\mp k_y^+)^2}{2m\omega}\right]\times \\ \times\exp\left\{i(\pm k_y^+-k_y\pm i\delta_+)y\right\}\end{array}\right)\right\}.$$

The upper signs before $k_y^{\mp}$ and $\delta_{\mp}$ refer to the half-space, the lower ones $y>0$, respectively, to the half-space $y<0$.

Uncertain constants A_1 and A_2 can be eliminated by means of boundary conditions and obtain a dispersion equation:

$$\begin{aligned}&\varepsilon_1(\omega)\left[1+i\frac{\alpha_2(\omega,q_x,0)}{\varepsilon_2(\omega)}\right]+ \\ &+\varepsilon_2(\omega)\left[1+i\frac{\alpha_1(\omega,q_x,0)}{\varepsilon_1(\omega)}\right]=0.\end{aligned} \tag{12}$$

Hence, when $\left|\frac{\alpha(\omega, q_x, 0)}{\varepsilon(\omega)}\right| << 1$ we get:

$$\omega_s = \left(\frac{\omega_{01}^2 + \omega_{02}^2}{\varepsilon_{01} + \varepsilon_{02}}\right)^{1/2};$$

$$\Delta\omega_s = \frac{i\omega_s}{2} \frac{\left[\alpha_1(\omega, q_{x,} 0) + \alpha_2(\omega, q_{x,} 0)\right]}{\varepsilon_{01} + \varepsilon_{02}}.$$

Analysis

Let us now find the damping decrements in various physical situations. In the case of a Maxwellian distribution of electrons

$$\rho_k^0 = \frac{(2\pi\hbar)^3 n_0}{(2\pi m T)^{3/2}} \mathrm{e}^{-\frac{\hbar^2 k^2}{2mT}}$$

expression for $\alpha(\omega, q_x, 0)$ can be converted to the following form:

$$\alpha(\omega, q_x, 0) =$$

$$= \sqrt{\frac{2}{\pi}} \frac{\omega_0^2 q_x \upsilon_T T}{\hbar\omega^4} (\mathrm{e}^{-\frac{\hbar\omega}{T}} - 1) \int_{-\infty}^{\infty} (x^2 + \frac{\hbar\omega}{T})^{\frac{1}{2}} x^2 \mathrm{e}^{-x^2} dx.$$

At this point, we get:

$$\alpha = -2 \frac{\omega_0^2 q_x \upsilon_T}{\omega_s^3} \sqrt{\frac{T}{2\hbar\omega_s}}, \quad \frac{\hbar\omega_s}{T} >> 1;$$
$$\alpha = -2 \sqrt{\frac{2}{\pi}} \frac{\omega_0^2 q_x \upsilon_T}{\omega_s^3}, \quad \frac{\hbar\omega_s}{T} << 1. \quad (13)$$

At the boundary of two plasma media separated by an infinitely high potential barrier, the expressions for the decrement take the form:

$$\Delta\omega_s = -i \frac{q_x}{\sqrt{2\hbar\omega_s}} \frac{\sum \omega_{0i}^2 \upsilon_{Ti} T_i^{1/2}}{\sum \omega_{0i}^2};$$
$$(14)$$
$$\Delta\omega_s = -\sqrt{\frac{2}{\pi}} i q_x \frac{\sum \omega_{0i}^2 \upsilon_{Ti}}{\sum \omega_{0i}^2}; \quad i = 1, 2 \ldots$$

In the case of an infinitely small barrier:

$$\omega_{01} = \omega_{02}, \quad \varepsilon_{01} \neq \varepsilon_{02}, \quad \omega_s = \omega_0 \sqrt{\frac{2}{\varepsilon_{01} + \varepsilon_{02}}} \;-$$

the oscillation decrements are respectively equal to:

$$\Delta\omega_s = -i q_x \upsilon_T \sqrt{\frac{T}{2\hbar\omega_s}}; \quad \hbar\omega_s >> T;$$
$$\Delta\omega_s = -\sqrt{\frac{2}{\pi}} i q_x \upsilon_T; \quad \hbar\omega_s << T. \quad (15)$$

A comparative analysis of the experimental [11] and calculated data obtained using the damping decrement values (14) – (15) shows that the radiation energy for most semiconductor devices [2] (diodes) in the presence of external electromagnetic radiation (electric field strength amplitude $E < 100 \frac{\kappa B}{м}$, pulse duration $\Delta t_{imp} \approx 10^2 - 10^3 нс$) is determined by one order of magnitude and has general trends of change depending on the values

$$\Delta W_{RAD} \approx 10^{-7} - 10^{-9} \, Joules$$

of the physical parameters of the component materials and the acting voltage pulse.

Conclusions

The mechanism of interaction of conduction electrons of a semiconducting medium with surface vibrations is considered, when the interaction of waves and charged particles induced by external radiation is in the nature of random collisions and is described by the second quantization method.

Based on it, a physical model of the occurrence of reversible failures is implemented as a consequence of the influence of currents induced by electromagnetic radiation per volt - ampere characteristics of semiconductor devices.

A kinetic equation is obtained that describes the change in the number of surface plasmons as a result of their interaction with conduction electrons; its solutions are given, which determine the decrement of oscillations and the power of spontaneous emission of particles.

Expressions are given for the decrements of surface plasmons in the presence of an infinitely high and infinitely small potential barrier at the interface between the media.

Calculation relations are obtained that relate the parameters of semiconductor structures: the concentration of free carriers, dielectric permittivity, carrier temperature with the magnitude of the oscillation decrement in the classical and quantum approximations.

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Вплив електромагнітного випромінювання на стійкість напівпровідникових приладів

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Анотація. Предметом дослідження є процес аналізу та механізми появи нестійкостей власних коливань напівпровідникових структур, обумовлених їх взаємодією з потоками заряджених частинок в умовах впливу зовнішнього електромагнітного випромінювання. Показано, що вплив імпульсного електромагнітного випромінювання супроводжується виникненням струмів у провідних елементах виробів, здатних збуджувати власні коливання напівпровідникових комплектуючих та бути причиною відмов радіовиробів. **Метою статті** є розробка теорії беззіткувального згасання поверхневих поляритонів в класичному наближенні, а також дослідження механізмів беззіткувального згасання поверхневих плазмонів на межах напівпровідникових комплектуючих радіовиробів в умовах, коли температура носіїв твердих тіл набагато менше енергії плазмону (квантове наближення). **Цілі такі**: кінетичне рівняння, що описує зміну числа поверхневих плазмонів внаслідок їх взаємодії з електронами провідності; отримання його рішення, що визначають декремент коливань та потужність спонтанного випромінювання частинок. **Методи, що застосовувались при дослідженні**: метод послідовних наближень розв'язання кінетичних рівнянь системи потік заряджених частинок – напівпровідникова структура в рамках квантового підходу, коли взаємодія хвиль та частинок носить характер випадкових зіткнень та описується методом вторинного квантування системи (подання чисел заповнення). **Отримано такі результати**. Отримано вирази для декрементів поверхневих плазмонів за наявності нескінченно високого та нескінченно малого потенційного бар'єру на межі розділу середовищ. Отримано кінетичне рівняння, що описує зміну числа поверхневих плазмонів у результаті взаємодії з електронами провідності; наведено його рішення, що визначають декремент коливань. Отримано вирази для декрементів поверхневих плазмонів за наявності нескінченно високого та нескінченно малого потенційного бар'єру на межі розділу середовищ. Обгрунтовано фізичну модель виникнення оборотних відмов (вплив наведених електромагнітним випромінюванням струмів на вольт – амперні характеристики напівпровідникових приладів). Визначено області параметрів зовнішнього електромагнітного випромінювання, за яких реалізується дана фізична модель. **Висновки.** Отримано розрахункові співвідношення, що зв'язують параметри напівпровідникових структур: концентрацію вільних носіїв, діелектричну проникність, температуру носіїв з величиною декременту коливань у класичному та квантовому наближеннях. Проведений у роботі порівняльний аналіз кількісних оцінок інкрементів нестійкостей коливань дозволяє вирішувати завдання оптимізації робочих характеристик активних приладів НВЧ –діапазону. Результати роботи можуть бути використані при розробці приладів НВЧ – діапазону призначених для посилення, генерації та перетворення електромагнітних коливань міліметрового та субміліметрового діапазонів.

Keywords: потік заряджених частинок, електромагнітне випромінювання, напівпровідникові структури, поверхневі коливання, інкремент нестійкості коливань.