EXCITATION OF OWN OSCILLATIONS IN SEMICONDUCTOR COMPONENTS OF RADIO PRODUCTS UNDER THE EXPOSURE OF THIRD-PARTY ELECTROMAGNETIC RADIATION

Abstract. The subject matter is the processes of analysis and mechanisms of interaction of EMP-induced currents and voltages with the processes characterizing the functional purpose of radio products, is usually carried out within the framework of the theory of distributed circuits. The presented approach makes it possible to evaluate the performance criteria in general (for example, to evaluate the critical energy characterizing a thermal breakdown), however, issues related to the determination of various types of electromagnetic interactions that occur directly in the components of a product under the influence of EMR remain open. The aim is the possibility of setting up theoretical and experimental studies based on the proposed calculation model for excitation of natural vibrations of a semiconductor structure (experimental growth of amplitude). The parameters of a third-party pulsed electromagnetic field, induced currents and characteristics of semiconductor devices have been established within which the regime of amplification of natural vibrations of a semiconductor structure is observed. The objectives are: mechanisms of interaction of induced currents with surface vibrations of semiconductor components of a radio product under the influence of pulsed electromagnetic radiation. The methods used are: methods of the theory of small perturbations in determining the spectrum of natural oscillations of the system - currents induced by electromagnetic radiation and natural oscillations of the components of the radio product. The following results are obtained: The mechanisms for the appearance of reversible failures of semiconductor components of radio products under the influence of third-party pulsed electromagnetic fields are determined. It has been established that the presence of a current induced by external radiation leads to the establishment of a mode of amplification of natural oscillations of semiconductor components of a radio product (reversible failures). Conclusion. Quantitative estimates of the amplification (generation) modes of oscillations of semiconductor devices, distorting their performance depending on the parameters of external electromagnetic influence, allows developing mechanisms for electromagnetic compatibility of microwave radio products. A comparative analysis of the calculated data obtained in the work can be used in the manufacture of radio devices operating in the millimeter and submillimeter range (amplifiers, generators and frequency converters).

Keywords: induced current; electromagnetic pulse radiation; semiconductor components; surface oscillations; oscillation instability.

Introduction

The types of failures of electrical and radio products in the presence of third-party factors are divided into reversible and irreversible [1, 2]. Irreversible failures occur when the performance of a radio product in the presence of external electromagnetic radiation exceeds the permissible limits and the device completely loses its functionality. Reversible failures are characterized by a temporary loss of performance for the time of exposure to electromagnetic radiation. In the absence of electromagnetic influence, the performance of the product is restored. The existing theoretical and experimental studies of the influence of pulsed electromagnetic radiation on the performance of electrical and radio products are mainly aimed at studying irreversible failures. At the same time, the purpose of these works is to determine the performance criteria in general (for example, the critical energy that determines the thermal breakdown). Questions related to the physical mechanisms of interaction of induced currents and natural oscillations of components usually remain open.

This work belongs to this area of reversible failure research. It studied the influence of currents induced by external electromagnetic radiation on the waveguide characteristics of semiconductor products, leading to the appearance of reversible failures.

Task solution

In [3-7], the collisionless damping of surface plasmons was studied on the basis of the dispersion equation. and it is shown that the damping of oscillations is caused by the transformation of the surface plasmon field into Van Kampen waves. It is shown that this effect leads to a change in the current-voltage characteristics of semiconductor devices (the appearance of regions of negative resistance), i.e. reversible failures.

In the presented work, the mechanisms of attenuation of surface oscillations of semiconductor components of radio products are studied, when their interaction with conduction electrons is in the nature of collisions. Similar effects are realized in the case when the value of the electron concentration of induced currents is much less than the concentration of semiconductor carriers. The kinetic equation for surface oscillations has the form [4]:

$$\frac{dN_{\phi}}{dt} = \frac{2\pi}{\hbar} \sum |W_{k,q,k_2}|^2 \delta(E_1 - E_2 - \hbar\omega_{\phi}) \times \left[(N_{\phi} + 1)N_{k_1} \left(1 - n_{k_2} \right) - N_{\phi}n_{k_2} \left(1 - n_{k_1} \right) \right]$$ (1)

where $N_{\phi}$ - the number of plasmons in the state; $E_{i,2} = \hbar^2 k_{i,2}/(2m)$ - electron energy; $W_{k,q,k_2}$ - matrix element of electrons between states $k_1 \rightarrow k_2$. The first term on the right side of equation (1) describes the radiation of surface plasmons during the transition of electrons from state to state; the second is the processes of absorption of plasmons during reverse transitions. Plasma medium - a semiconductor structure (medium 1) occupies a region of space $0 \leq y \leq L$
\( (\varepsilon_1(\omega) = \varepsilon_0 - \varepsilon_0^2 / \omega^2 ) \), and areas \( y < 0; \ y > L \) occupies a dielectric (vacuum) \( \varepsilon_2 = \varepsilon_d \).

The penetration depth of the wave field remains small compared to, i.e. the fields are localized at the boundaries independently of each other. We will consider the interaction of electrons and natural vibrations of a semiconductor structure near the boundary.

The Hamiltonian of the interaction of electrons with plasmons, which determines the matrix element \( \delta \), has the form \[5\]:

\[
\hat{H}^{(\text{int})} = -\frac{1}{c} \int \hat{j}(r) \hat{A}(r) dr .
\]

Here the vector potential: \( \text{div} \vec{A} = 0; \ \vec{E} = -\frac{1}{c} \frac{\partial \vec{A}}{\partial t} . \)

It is expressed through the operators of creation and annihilation of vibrations

\[
\hat{a}^{(+)}(t) = \hat{a}(t) \exp(i\omega t); \ \hat{a}^{(-)}(t) = \hat{a}(t) \exp(-i\omega t)
\]

in the following way:

\[
A_q(\vec{r}, t) = \sum_q A_q(\vec{q}) \hat{a}_q \exp(i\vec{q} \cdot \vec{r})
\]

\[
e_{1x} = e_{2x} = \frac{q z}{\sqrt{2}}; \quad e_{1y} = -e_{2y} = \frac{i}{\sqrt{2}}; \quad
\]

\[
e_{1z} = e_{2z} = \frac{q z}{\sqrt{2}}; \quad q = \sqrt{q_z^2 + q_y^2}; \quad
\]

\[
\omega_{-q} = \omega_q; \quad q = -iq \quad y < 0; \quad q = iq \quad y > 0 .
\]

The value is found as a result of quantization of the energy of the plasmon electromagnetic field [5]

\[
\hat{H}^{(\text{cm})} = \frac{\omega_{e}^2}{8\pi c^2} \left[ \hat{\Delta}(\omega, \vec{r}) \right]^2 \frac{d}{d\omega} (\omega \varepsilon_c(\omega)) d\omega .
\]

where integration is carried out over the entire region of plasmon localization. Substituting in (4) \( \left[ \hat{\Delta}(\omega, \vec{r}) \right]^2 \), equating

\[
\hat{H}^{(\text{em})} = \sum \frac{\hbar \omega_{e}}{2} \left[ \hat{a}_q \hat{a}_q^{+} + \hat{a}_q^{+} \hat{a}_q \right],
\]

we get

\[
A_q = \sqrt{4\pi e Q / \left( \varepsilon_0(\omega_{e} + \varepsilon_d) \right)} ,
\]

where \( S \) - surface area of a semiconductor wafer.

The induced current density operator has the form:

\[
\vec{j} = \frac{e \hbar}{2m_0} \left( \hat{\Psi}^{+} \hat{\Psi} - \hat{\Psi} \hat{\Psi}^{+} \right) ;
\]

\[
\hat{\Psi}^{+} = \frac{1}{\sqrt{V}} \sum_k \hat{b}^{+}_k (t) \exp(-i(k_x x + k_y y)) \sin k_y y
\]

\[
\hat{\Psi} = \frac{1}{\sqrt{V}} \sum_k \hat{b}_k (t) \exp(i(k_x x + k_y y)) \sin k_y y
\]

\[
V = SL ; \quad k_y = \frac{\pi}{L} n; \quad n = 1, 2, 3...
\]

where \( b_k^{(+)} (t) = b_k^{(+)} e^{i\varepsilon_F t / \hbar} ; \quad b_k (t) = b_k^{(-)} e^{-i\varepsilon_F t / \hbar} \) - operators of creation and annihilation of electrons with wave vector. Having carried out the integration in the expression (2), we obtain:

\[
H^{(\omega)} = \sum_{k q k_2} W_{k q k_2} b_k^{(+)}(t) (a_q(t) + a_q^{+}(t)) b^+_k(t)
\]

\[
W_{k q k_2} = \frac{2k_1 k_2 (k_1^2 - k_2^2) - W_{0 q x}}{q^2 + (k_2 - k_1 y)^2}
\]

where

\[
W_0 = \frac{2\pi e^2 q_x h^3}{m_0 \varepsilon_0(\varepsilon_0 + \varepsilon_d)} .
\]

Given the law of conservation of energy \( E_2 = E_1 - \hbar \omega_q \) and assuming

\[
q^2 << (k_2 - k_1 y)^2; \quad q << k_y ; \quad q << k_x
\]

we get the following expression for the matrix element:

\[
W_{k q k_2} = \left( \frac{h \varepsilon_F}{m_0 \varepsilon_0} \right)^2 ;
\]

\[
k_y^2 = 2 \varepsilon_0 + \frac{2m_0 q}{\hbar} .
\]

Oscillation decrement \( \gamma = \frac{1}{2N_q} \frac{\partial N_q}{\partial t} \) determined by the processes of stimulated emission and absorption of waves by particles: \( N_q >> 1 \):

Passing in the kinetic equation (1) from summation to integration \( \int_{k_y} = \frac{L}{\pi} \int_{k_y} d k_y \) we get the following expression for the decrement .

\[
\gamma = \frac{W_0 V L}{4\pi^2 m_0 \varepsilon_0^2} \int_{k_y} d k_y k_y^2 \left( n_{k_y}^{(+)} - n_{k_y}^{(-)} \right) .
\]

Consider the case of a Maxwellian distribution of electrons:

\[
n_{k_y} = n_0 \left( \frac{2\pi \hbar^2}{(2\pi m T)^3 / 2} \right) \exp \left( -\frac{\hbar^2 k_y^2}{2m T} \right)
\]

Substituting the values into formula (7) and using the dispersion law of surface plasmons \( \omega^2 = \omega_0^2 \left( \frac{\varepsilon_0}{\varepsilon_0 + \varepsilon_d} \right) \) we get:

\[
\gamma = \frac{\gamma}{\sqrt{\pi}} \frac{q_x y}{T} \left( \frac{T}{\hbar \omega} \right) \left( \exp \left( -\frac{\hbar \omega}{T} \right) - 1 \right)
\]

\[
\times \int_{-\infty}^{\infty} x^2 \sqrt{2 \frac{\hbar \omega}{T} \exp(-x^2)} dx .
\]

It is easy to make sure that the formula (7) in the limiting cases gives the same values of the decrement as the expressions (8). In the case of a degenerate electron gas, the difference \( n_{k_y}^{(+)} - n_{k_y}^{(-)} \) can be represented as \( \frac{\Delta n_{k_y}}{\varepsilon_F} \) where
\[
\frac{\partial n_k}{\partial \epsilon_F} = n_k \delta(\epsilon - \epsilon_F) ; n_k = 1.
\]

As a result of integration (7) we again obtain the expression for in the case of specular reflection of electrons from the boundary.

Thus, the idea of the interaction of surface plasmons and electrons as a collisional process leads to the same results as the method of dispersion relations. In addition, the use of the homogeneous plasma model is valid not only in the classical but also in the quantum approximation.

Equation (1) makes it possible to study the mechanisms of spontaneous emission of particles when \( N_q << 1 \). Consider the radiation created by a single particle moving at a speed. In this case, it follows from equation (1) at
\[
\int_0^\infty \delta(t) dt = 0;
\]
\[
\delta(t) dt = 0;
\]
\[
\delta(t) dt = 0; \quad \delta(t) dt = 0.
\]

Taking into account the condition: \( k^2 > 2m\omega_q / \hbar \), let us determine the power of spontaneous emission of an electron:
\[
\hbar \omega q \frac{\partial N_q}{\partial t} = \frac{4\pi e^2 q^3}{V \omega_0^2}.
\]

If the number of particles in the state is equal, then the right side must be multiplied by this value. Let us compare the radiation power with the value of the energy loss of a particle during its reflection from the interface.

The fields created by the particle will be described by the following equations:
\[
\text{rot} \; \vec{E}(r,t) = 0;
\]
\[
\text{div} \; \vec{D} = 4\pi \varepsilon_0 \delta(x)[\delta(y-v_0 t) + \delta(y-v_0 t)] \delta(z);
\]
\[
\vec{D}(r,t) = \int_0^t \delta(t-t') \vec{E}(r,t') dt'; \quad y > 0.
\]
\[
\text{rot} \; \vec{E}(r,t) = 0; \quad \text{div} \; \vec{D} = 0; \quad \vec{D}(r,t) = \varepsilon_0 \vec{E}(r,t); \quad y < 0.
\]

The Fourier components of the electron field have the following form:
\[
\vec{E}(r,t) = \sum_{q_x, q_z} \int_{-\infty}^{\infty} \vec{E}(\omega, q_y, y) e^{i(q_y - \omega t)} d\omega;
\]
\[
q = \sqrt{q_x^2 + q_z^2},
\]
\[
E_x(\omega, q_y, y) = \frac{i e q_y v_0 \cos(\omega v_0 / y)}{\pi^2 \varepsilon(\omega) S[\omega^2 + q_y^2 v_0^2]},
\]
\[
E_y(\omega, q_y, y) = \frac{i e \omega \sin(\omega v_0 / y)}{\pi^2 \varepsilon(\omega) S[\omega^2 + q_y^2 v_0^2]},
\]
\[
\varepsilon(\omega) = \int_0^\infty \varepsilon(\tau) e^{\omega \tau} d\tau.
\]

Further
\[
\varepsilon(\omega) = \varepsilon_0 - \omega_0^2 / \omega^2; \quad \omega^2 > q^2 v_0^2.
\]

To these fields it is necessary to add free fields, which are solutions of homogeneous equations (11) in media “1” - “2”:
\[
E_x(\omega, q_y, y) = A_1 e^{-\omega t}, \quad y > 0;
\]
\[
E_y(\omega, q_y, y) = \frac{i q}{q_x} A_1 e^{-\omega t}; \quad y > 0;
\]
\[
E_x(\omega, q_y, y) = A_2 e^{\omega t}, \quad y < 0.
\]
\[
E_y(\omega, q_y, y) = -i \frac{q}{q_x} A_2 e^{\omega t}; \quad y < 0.
\]

From the boundary conditions we find:
\[
A_1 = \frac{i e q v_0}{\pi^2 \varepsilon(\omega) [\varepsilon(\omega) + \varepsilon_d]};
\]
\[
A_2 = \frac{\varepsilon(\omega)}{\varepsilon_d} A_1.
\]

The normal component of the electric field in medium “1” has the form:
\[
\vec{E}_n(\vec{r},t) = -\frac{8\pi e v_0}{S(\varepsilon(\omega) + \varepsilon_d)} \times \sum_{q_y, q_z} \frac{q}{q_x} e^{i q_y \omega \sin(\omega t)} \times t > 0;
\]
\[
\vec{E}_n(\vec{r},t) = 0; \quad t < 0.
\]

**Analysis**

The energy loss of a particle for the excitation of a surface plasmon per unit time \( \frac{\partial \varepsilon}{\partial t} \) is determined from the equation of motion:
\[
\frac{\partial \varepsilon}{\partial t} = e v_0 \varepsilon_y.
\]

In this formula, one should substitute the value of the field at the point where the particle is located
\[
x = 0; \quad y = v_0 t; \quad z = 0.
\]

Next, it is necessary to average the expression for the energy loss over the time of flight by the particle of the region of interaction with the wave in the forward and backward directions: \( \tau = 2L / v_0 \).

Then the average particle energy losses per unit time for excitation
\[
\text{The average particle energy loss per unit time for excitation} \; q \text{- harmonics of the plasmon field takes the form:}
\]
\[
\frac{\partial \varepsilon}{\partial t} = -\hbar \omega q \frac{\partial N_q}{\partial t}.
\]

Thus, the loss of particle energy (spontaneous emission of a surface plasmon) arises as a result of the transformation of the Van Kampen wave incident on the
boundary into the plasmon field. Knowing the expression for the matrix element, one can estimate the integral of collisions of electrons with surface plasmons and find the change in the number of electrons $n_{k1} = n_{k0} \delta_{k1k0}$ capable of $k_0$ upon their transition to the state $k$ as a result of spontaneous emission of surface plasmons ($N_q \to 0$).

As a result, we get:

$$\frac{\partial n_{k0}}{\partial t} = -n_{k0} \frac{4 \pi e^2 q N_0}{V \omega_0^2 \hbar \omega_q} \frac{1}{\kappa^2} \frac{\partial n_k}{\partial t} = -\frac{\partial n_{k0}}{\partial t}. \quad (18)$$

The electron energy loss in this case during the transition is equal to:

$$E_0 \frac{\partial n_{k0}}{\partial t} + F q N \frac{\partial n_k}{\partial t} = (E_0 - E) \frac{\partial n_{k0}}{\partial t},$$

where

$$E_0 - E = \hbar \omega q, \quad \frac{\partial n_{k0}}{\partial t} = -\frac{\partial N_q}{\partial t}.$$

Let us give quantitative estimates. For a wafer with transverse dimensions $a = 10^{-1}$ cm, with current density $j \sim 100$ A/cm$^2$, ($v_0 = 3 \times 10^9$ cm/s, $n_0 \sim 10^{11}$ cm$^{-3}$) energy loss for surface plasmon excitation ($\omega \sim 10^{10}$ s$^{-1}$, $q \sim 3$ cm$^{-1}$) equal $|\frac{de}{dt}| \sim 1 \mu$W.

For modern semiconductor components of radio products, such losses are quite detectable and can cause reversible failures (the appearance of segments of current-voltage characteristics with negative resistance).

### Conclusions

The mechanisms of attenuation of surface electromagnetic oscillations in semiconductor components of electrical and radio products based on the concepts of Van-Kampen waves are determined. It is shown that the damping of oscillations of this kind is due to the fact that oscillations excite Van Kampen waves at the media interface, which are modulated by the surface wave field and carry the field energy deep into the medium.

A kinetic equation has been 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.

The presented approach makes it possible to evaluate the performance criteria of electrical radio products and solve issues related to the description of various kinds of electromagnetic interactions that occur directly in the components of the product when exposed to pulsed radiation.

Quantitative estimates of amplification (generation) modes of oscillations of semiconductor devices, distorting their performance depending on the parameters of external electromagnetic influence, allows developing mechanisms for electromagnetic compatibility of microwave radio products.

### References


Возбуждение собственных колебаний полупроводниковых комплектующих радиоизделий при воздействии стороннего электромагнитного излучения

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Аннотация. Предмет исследования – процесс анализа механизмов взаимодействия наведенных ЭМИ токов и напряжений с процессами, характеризующим функциональное назначение радиоизделий, обычно проводится в рамках теории цепей с распределенными параметрами. Представленный подход позволяет оценить критерии работоспособности в целом (например, оценить критическую энергию, характеризующую тепловой пробой), однако вопросы связанные с определением различного рода электромагнитных взаимодействий, протекающих непосредственно в комплектующих радиоизделий, остаются открытыми. Цель исследования — возможность постановки теоретических и экспериментальных исследований на основе представленной расчетной модели возбуждения собственных колебаний полупроводниковой структуры. Использованы следующие методы: методы теории малых возмущений, спектр анализа, метод анализа и синтеза систем.

Выводы. Количественные оценки режимов усиления и генерации в радиоизделях при воздействии стороннего электромагнитного излучения. Определены механизмы появления обратных отказов изделий полупроводниковых комплектующих радиоизделий в условиях воздействия импульсного электромагнитного излучения. Использованы следующие методы: методы теории малых возмущений. Определены механизмы возникновения обратных отказов полупроводниковых комплектующих радиоизделий в условиях воздействия импульсного электромагнитного излучения. Использованы следующие методы: методы теории малых возмущений.

Ключевые слова: наведенный ток; электромагнитное импульсное излучение; полупроводниковые комплектующие; поверхностные колебания; неустойчивость колебаний.