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INFLUENCE OF PULSE ELECTROMAGNETIC RADIATION ON PERFORMANCE OF ELECTRIC RADIO PRODUCTS

Abstract. The **subject matter** is the processes of analysis of the occurrence of reversible and irreversible failures of semiconductor devices under conditions of exposure to electromagnetic radiation. It is shown that the influence of pulsed electromagnetic radiation is accompanied by the emergence of currents in the conductive elements of products and the emergence of their internal fields. The mechanisms for the occurrence of instabilities of natural oscillations of semiconductor components of electrical and radio products, caused by their interaction with flows of charged particles, have been determined. The presence of instabilities of this kind has a significant impact on the spectral (operating) characteristics of electrical radio products. The results obtained in the work make it possible to assess the degree of influence of pulsed electromagnetic radiation on the operating (volt-ampere) characteristics of electrical radio products. The **aim** is a model of the mechanisms of the emergence and development of instabilities of natural oscillations of semiconductor structures, components of electrical radio products (communication equipment), in the presence of currents and voltages induced by pulsed electromagnetic radiation. The implementation of such a model is due to the possibility of transforming the energy of a flow of charged particles induced by external electromagnetic radiation into the energy of natural vibrations of a semiconductor structure, taking into account the properties of the structure itself (size, concentration of free carriers, permeability). The transformation of the energy of currents induced by electromagnetic radiation into natural vibrations of a semiconductor structure is determined by two effects (transition or Cherenkov radiation) depending on the location of the structure relative to the direction of the currents. The **objectives** are: the main electromagnetic effects affecting performance of electrical radio products (ERI) under exposure conditions external pulsed radiation and also indicates characteristic changes ERI parameters that determine their functional purpose, which are a consequence of these effects. The **methods** used are the method of successive approximations over a small parameter, which allows one to determine the spectrum of natural oscillations of a semiconductor device and the mode of their amplification (instability). The following **results** are obtained. The results of studies characterizing the malfunction of electrical radio products under conditions of exposure to third-party electromagnetic radiation are presented, as well as the main parameters characterizing the electromagnetic resistance of electronic devices to the effects of pulsed currents and voltages. The characteristic types of malfunctions of semiconductor devices (SCD), components of electronic components, in areas of irreversible and reversible failures, as well as the levels of intensities and currents of electric and magnetic fields affecting the SPD, separating the areas of reversible and irreversible failures, are given. Using the energy approach, a physical model of the occurrence of one of the types of reversible failures of the semiconductor element base (the appearance of S-shaped sections of current-voltage characteristics) has been developed. This physical model makes it possible to determine the criteria for the electromagnetic resistance of a number of semiconductor devices to the effects of external pulsed radiation and also to obtain calculated ratios for assessing the degree of deviation of the operating characteristics of the PPP from the norm. **Conclusion**. Development of design relationships that determine the modes of amplification (generation) of oscillations of electrical radio products, making it possible to determine the degree of distortion of their current-voltage characteristics (reversible failures) and complete loss of performance (irreversible failures) depending on the parameters of external electromagnetic radiation. The results obtained in the work can be used in the development of amplifiers, generators and frequency converters operating in the millimeter and submillimeter range that are resistant to external electromagnetic radiation. Quantitative estimates of the criterion for reversible failures (instability increments) show that the amount of radiation energy lies within the sensitivity of modern submillimeter radiation receivers and is the cause of failures.

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

Introduction

All types of failures of radio-electronic equipment associated with the influence of third-party factors are usually divided into reversible and irreversible. Most of the available theoretical and experimental results of studies of the influence of electromagnetic radiation (EMR) on radio products belong to the field of irreversible failures, which are characterized by a complete loss of performance

At the same time, the development of interaction mechanisms between currents and voltages induced by electromagnetic radiation and processes characterizing the functional purpose of products is usually carried out within the framework of the theory of circuits with distributed parameters. This approach makes it possible to evaluate the performance criteria as a whole (for example, to estimate the critical energy characterizing thermal breakdown), however, questions related to the determination of various types of electromagnetic interactions occurring directly in the components of the product when exposed to EMR remain open.

The expansion of areas of application and increasing speed of electronic equipment (REE) leads to the need for an increasing use of the element base containing semiconductor electronics products [1]. The increase in the dependence of the performance of component equipment on the influence of electromagnetic radiation is associated with an increase in the complexity of the tasks that are assigned to electrical radio products, which leads to an increase in their sensitivity [1] This increases the degree of influence of external electromagnetic radiation on the performance of electronic devices, to the effects of which semiconductor components have increased sensitivity. At the same time, the probability of reversible failures increases, which are characterized by a temporary loss of performance associated with a distortion of the output characteristics of the device.

One of the reasons for the occurrence of reversible equipment failures is caused by a change in the current-voltage characteristics of semiconductor devices - the appearance of areas with negative resistance in the forward current sections. The appearance of such areas is associated with the establishment of a mode of amplification of natural oscillations of the semiconductor structure - the possibility of transforming the energy of a flow of charged particles induced by external electromagnetic radiation into the energy of natural oscillations of the semiconductor structure. The increase in oscillations is characterized by an exponential increase in the amplitude of oscillations, i.e. their instability [3].

This work to a certain extent compensates for the existing gap in the research of reversible failures of this kind. It examines the interaction of flows of charged particles induced by pulsed electromagnetic radiation with wave processes in semiconductor structures used in modern radio electronics.

Task solution

The area of irreversible failures of semiconductor components of electrical and radio products has been studied in quite detail, both experimentally and theoretically [1]. The currently used methods for assessing the durability criteria of semiconductor devices in this failure region when exposed to external pulsed electromagnetic radiation (EMR) [2-3] consider in this capacity the value of the critical energy $W_{кр}$, exceeding which leads to a complete loss of performance (energy characterizing thermal breakdown. At the same time, to calculate currents and voltages induced by EMR, $W_{кр}$ which determine and arise directly in semiconductor components inside electrical and radio products, a transmission line model (generalized telegraph equations) is traditionally used. In this case, the components of electrical radio products are considered as linear circuits containing R, L, C - elements and include sources of currents and voltages caused by external electromagnetic influence. The circuit equations are solved in the frequency domain, and the inverse Fourier transform is used to move to the time domain [1]. It should be noted that semiconductor devices (SPDs) and integrated circuits (ICs) are most sensitive to the influence of external electromagnetic fields. Therefore, the main influence on the performance of this kind of electrical and radio products is exerted by voltages induced by external radiation. Irreversible failures of these products are usually associated with electrical (the magnitude and distribution of currents in the device structure, leading to breakdown) and thermal (an increase in the temperature of individual sections of the structure up to) [2].

This approach has a number of significant limitations and does not take into account effects that can affect the performance of semiconductor devices in the field of reversible failures, which does not allow reliably assessing the criteria for electromagnetic resistance [2]. These limitations are due to the fact that when analyzing reversible (short-term) failures in the performance of semiconductor devices, it is necessary to take into account the following factors of third-party electromagnetic influence [8]:

- dimensions (dimensions) of semiconductor components of ERI;
- time characteristics of the electromagnetic pulse (duration pulse rise and fall);
- constructive arrangement of installation of circuits relative to the shielded housing of the electrical radio product;
- orientation of the components of the semiconductor structure and vectors of the electric and magnetic pulse field;

It should be noted that the characteristic types of malfunctions of semiconductor devices (SCD), components of electrical and radio products, they depend on the levels of electric and magnetic fields of the applied pulse. So for the fields $E < 100$ *кВ/м*; $H < 600$ *А/м* – as a rule, reversible failures occur; otherwise, irreversible failures occur.

When determining electromagnetic immunity criteria, these factors cannot be fully taken into account within the framework of transmission line theory.

In particular, [1] the theory of long lines is limited to the low frequency range - the sizes of the structures under study are an order of magnitude smaller than the wavelengths. This limitation makes it impossible to describe the processes of interaction of radiation-induced currents with physical processes occurring directly in semiconductor components and determining their performance under conditions where the dimensions of the structures are comparable to the wavelengths.

In addition, transmission line theory generally assumes that all applied pulse energy is released at the critical circuit element, and the load is matched to the line. However, as a rule, the load is not matched over the entire frequency range and the low-power critical element is not located directly at the input, but after several passive elements capable of absorbing part of the radiation energy. Therefore, to determine the criteria for the occurrence of reversible failures (temporary loss of performance) within the framework of the theory of transmission lines, it is necessary to calculate the transient process for each specific device circuit.

Finally, the approach used (one-dimensional approximation) does not take into account the effects associated with the spatial limitation of semiconductor products and their location in relation to the direction of the applied pulse field (the orientation of the electromagnetic field and the direction of the vectors of operating currents and voltages in the components of the radio product themselves).

When considering the physical mechanisms of the occurrence of reversible failures of semiconductor components of radio products, this work proposes a more rigorous methodology based on the use of a complete system of electrodynamics (Maxwell) equations, supplemented by material equations for the media that compose semiconductor devices, and boundary conditions that make it possible to determine the relationship between the quantities induced by external pulse of currents with the own electromagnetic fields of semiconductor devices. This approach makes it possible to study the processes of interaction of electromagnetic oscillations and induced currents directly in semiconductor components, which are not possible to describe within the framework of transmission line theory.

Thus, the object of research in this work was not considered circuits with lumped parameters, but limited conducting (semiconducting) media from which the components of electrical radio products are composed.

The results of this work to a certain extent compensate for the existing gaps in the research of one of the types of reversible failures - distortion of the volt-ampere characteristics of semiconductor devices under the influence of third-party electromagnetic radiation.

The reason for the occurrence of such distortions in the operating characteristics of devices is, in our opinion, the possibility of transforming the energy of currents induced by external EMR into the energy of the own electromagnetic oscillations of radio product components. In this case, the induced currents lose their energy by emitting natural oscillations of the semiconductor structure, and an increase in the forward current is accompanied by a voltage drop. Thus, an area with negative resistance appears on the current-voltage characteristic.

Surface waves existing at the boundaries of conducting solids were considered as a channel for transmitting the energy of currents induced by external radiation to semiconductor components.

The choice of surface oscillations as a channel for transmitting the energy of external radiation is not accidental - this type of waves is localized near the interfaces between media that compose semiconductor devices, so they transfer the energy of external electromagnetic fields more efficiently than volumetric oscillations [9].

The radiation mode (oscillation generation) in semiconductor devices usually manifests itself in the section of its current-voltage characteristic (volt-ampere characteristic), having a negative differential resistance (NDR) ($R = \frac{\Delta U}{\Delta I} < 0$). In this case, the induced current (electron flow induced EMR in a semiconductor device) loses part of its energy ($W_{EL} < 0$); while the current increases ΔI accompanied by a voltage drop ΔU. The appearance of such deviations in the current-voltage characteristics characterizes one of the possible mechanisms of reversible failures.

Therefore, as an energy criterion for assessing the electromagnetic resistance of semiconductor devices in this region of reversible failures, the value of the emission energy of natural surface oscillations of semiconductor devices, caused by their interaction with induced external EMR currents, was considered $W_{rad} = W_{EL}$

$$W_{rad} = I_I U_I \Delta t_{ei} . \quad (1)$$

Thus, the value W_{rad} determining the degree of deviation of the current-voltage characteristic, is a quantitative characteristic of this type of reversible failure.

Where $I_I ; U_I$ - induced current and voltage, respectively, Δt_{ei} - time of effective interaction of induced currents and natural oscillations of the semiconductor structure.

In this work, we investigated two possible mechanisms for converting the energy of moving charges (EMR-induced currents) into the energy of surface plasmons of semiconductor components of radio products - the effects of Cherenkov and transition radiation (the corresponding mutual configuration of the vectors of the strengths of the acting electric field and the direct current of the semiconductor device (diode) are shown in Fig. 1.)

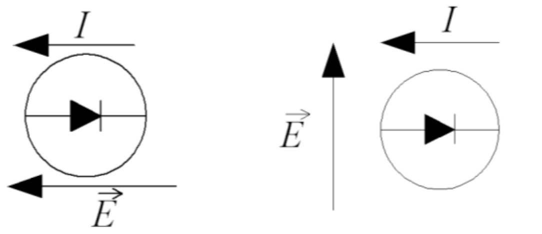
The first mechanism for transforming the energy of moving charges into vibration energy, considered in the work, is the Vavilov-Cherenkov radiation effect. (Cherenkov radiation) [5].

It is realized when induced currents move along the boundary of the semiconductor structure, and the phase velocity of the surface wave is equal to the velocity of charged particles (Fig. 1.2. - a). Under conditions of such resonance, the energy of induced currents (flow of charged particles) is transformed into the energy of natural oscillations of the ERE components and the oscillation generation mode is also established in the semiconductor device.

Another mechanism (transition radiation) is realized when the induced current (direction of the electric field strength vector of the acting external pulse) is perpendicular to the interfaces of the solid structure (semiconductor device) (Fig. 1.-b) and consists of the following [10].

When a charge moves in a material medium, the electromagnetic field it creates is determined not only by the magnitude of the charge and its speed, but also by the dielectric properties of the medium. If these properties change when a charge crosses the interface between media (semiconductor structure) at a constant speed, then the field created by the charge changes, part of the field is torn off from the particle and can be radiated into space. The resulting radiation is called transition radiation. As a result, when a stream of particles induced by an external electromagnetic field passes through a semiconductor structure, a continuous process of converting the energy of charges into the energy of natural oscillations of the field occurs. i.e., the oscillation generation mode is established in the structure.

It should be noted that recent experimental studies of transition radiation serve as the basis for the development of new methods for diagnosing flows of charged particles with high energy and, in addition, for solving problems of generation and amplification of electromagnetic oscillations [9]. The effect of transition radiation determines the mechanisms of excitation of a wide variety of modes of semiconductor structures, so it becomes possible to transfer the energy of surface vibrations across the boundary, for which it is opaque in the absence of induced currents (i.e., exposure to external radiation).



a – Cherenkovsky radiation b – Transitional radiation

Fig. 1. Location of the applied electric field strength $\vec{E}$ and relative to forward current $\vec{I}$ semiconductor device (diode)

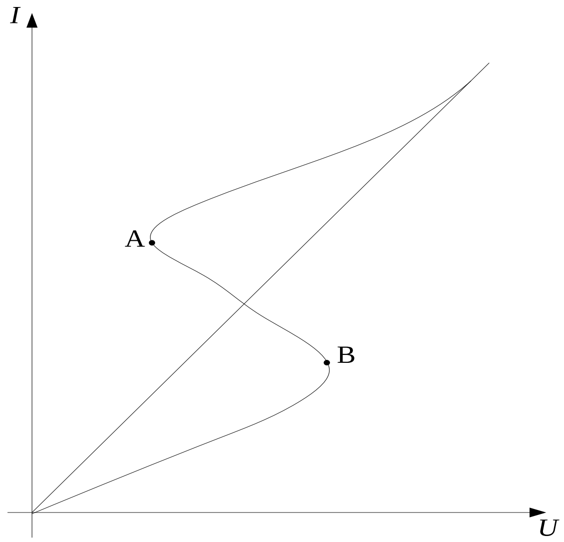


Fig. 2. Current-voltage characteristics of a semiconductor diode: CVC in the absence of external EMR; CVC in the presence of external EMR (reversible failure) (section AB)

Analysis

This mechanism of reversible failures (the appearance S - shaped volt-ampere characteristics of the direct current of the device (Fig. 2.) is realized in conditions where the amplitude strengths of the electric voltages E and magnetic H fields affecting the semiconductor radiation structure are in the range $E < 100\frac{kV}{m}$; $H < 600\frac{A}{m}$ [2].

In the case when the amplitudes of the strengths of the acting strength fields exceed the specified limits, the development of irreversible failures of the device is observed (thermal breakdown followed by melting and burnout of metallization and contact tracks [9].

The authors [7–8] solved a number of problems of interaction between waves and EMR-induced currents in semiconductor structures, which makes it possible to quantify the induced currents and voltages, as well as the time of effective interaction of the induced currents with the intrinsic fields of semiconductor structures. These quantities characterizing the radiation energy (the degree of deviation of the current-voltage characteristic from the norm) were determined within the framework of the theory of beam instabilities, since the oscillation generation mode is characterized by an exponential increase in the amplitude of the electro-magnetic fields of radiation from semiconductor devices:

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

Here γ - instability increment, its value is determined by the parameters of the induced currents and the semiconductor device (concentration of current carriers and their speed).

Thus, solving problems of the emergence and development of beam instabilities in semiconductor structures (determining the growth rate of instabilities) allows you to build a physical model of the occurrence of one of the types of reversible failures of semiconductor devices under the influence of third-party electromagnetic radiation.

Using this model in [6-11], quantitative characteristics of the electromagnetic resistance of radio products were obtained (radiation energy value W_{rad}) in the field of reversible failures. Under conditions where the amplitude of the external pulsed electric field strength $E_0 \approx 15\, kV/m$, pulse duration $\Delta t_{imp} \approx 500ns$, then the magnitude of the radiation energy of natural vibrations of solid layered structures - ΔW_{rad} amounts to $\approx (10^{-7} - 10^{-8})wt$, those. with the sensitivity of modern microwave radiation receivers [7] ($10^{-10}\, wt$) is quite detectable and is the cause of reversible failures.

Conclusion

The main types of failures of electrical and radio products under the influence of pulsed electromagnetic radiation (reversible and irreversible failures) are given.

The results of studies characterizing the malfunction of electrical radio products under the influence of third-party electromagnetic radiation are presented, as well as the main parameters characterizing electromagnetic resistance to the effects of pulsed currents and voltages.

The main electromagnetic effects that affect the performance of radio products under external influence are presented, and characteristic changes in the parameters of radio products that determine their functional purpose, which are a consequence of the occurrence of these effects, are indicated.

A physical model of the occurrence of one of the types of reversible failures of semiconductor components of radio products (the appearance of S-shaped sections of current-voltage characteristics) is substantiated. It is based on the process of converting the energy of currents induced by external electromagnetic radiation into the energy of natural oscillations of the semiconductor structure (establishing the mode of generating natural oscillations). This physical model makes it possible to determine the criteria for the electromagnetic resistance of a number of semiconductor devices to the effects of external pulsed radiation and also to obtain calculated relationships for assessing the degree of deviation of the operating characteristics of semiconductor devices from the norm.

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Вплив імпульсного електромагнітного випромінювання на працездатність електрорадіовиробів

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Анотація. Предметом досліджень є процес аналізу появи оборотних та незворотних відмов напівпровідникових приладів за умов впливу електромагнітного випромінювання. Показано, що вплив імпульсного електромагнітного випромінювання супроводжується виникненням струмів у провідних елементах виробів та виникненням внутрішніх полів. Визначено механізми виникнення нестійкостей власних коливань напівпровідникових комплектуючих електрорадіовиробів, які зумовлені їхньою взаємодією з потоками заряджених частинок. Наявність нестійкостей такого роду істотно впливає на спектральні (робочі) характеристики електрорадіовиробів. Отримані в роботі результати дозволяють оцінити ступінь впливу імпульсного електромагнітного випромінювання на робочі (вольт-амперні) характеристики електрорадіовиробу. **Метою статті** є розробка моделі механізмів виникнення та розвитку нестійкостей власних коливань напівпровідникових структур, що комплектують електрорадіовироби (апаратуру зв'язку), за наявності струмів та напруг, наведених імпульсним електромагнітним випромінюванням. Реалізація подібної моделі обумовлена можливістю трансформації енергії потоку заряджених частинок, наведеного зовнішнім електромагнітним випромінюванням, в енергію власних коливань напівпровідникової структури з урахуванням властивостей самої структури (розмірами, концентрацією вільних носіїв, проникністю). Трансформація енергії наведених електромагнітним випромінюванням струмів у власні коливання напівпровідникової структури визначається двома ефектами (перехідного чи черенківського випромінювань) залежно від розташування структури щодо напрями струмів. **Задачі дослідження**: основні електромагнітні ефекти, що впливають на працездатність електрорадіовиробів (ЕРВ) в умовах впливу зовнішнього імпульсного випромінювання, а також зазначені характерні зміни параметрів ЕРВ, що визначають їх функціональне призначення, які є наслідком даних ефектів. **Використовувався метод** послідовних наближень за малим параметром, що дозволяє визначити спектр власних коливань напівпровідникового приладу та режим їхнього посилення (нестійкості). The following **results** are obtained. Наведено результати досліджень, що характеризують порушення функціонування електрорадіовиробів за умов впливу стороннього електромагнітного випромінювання, а також основні параметри, що характеризують електромагнітну стійкість ЕРВ до впливу імпульсних струмів та напруг. Наведено характерні типи порушень функціонування напівпровідникових приладів (НПП), комплектуючих ЕРВ, в областях незворотних та оборотних відмов, а також рівні напруженостей та струмів, що впливають на НПП електричних та магнітних полів, що розділяють області оборотних та незворотних відмов. З використанням енергетичного підходу розроблено фізичну модель виникнення одного з видів оборотних відмов напівпровідникової елементної бази (поява S – образних ділянок вольт – амперних характеристик). Дана фізична модель дозволяє визначати критерії електромагнітної стійкості низки напівпровідникових приладів до впливу зовнішнього імпульсного випромінювання, а також отримувати розрахункові співвідношення для оцінки ступеня відхилення робочих характеристик НПП від норми. **Висновки.** Розробка розрахункових співвідношень, що визначають режими посилення (генерації) коливань електрорадіовиробів, що дозволяють визначати ступінь спотворення їх вольт - амперних характеристик (зворотні відмови) та повної втрати працездатності (незворотні відмови) залежно від параметрів зовнішнього електромагнітного випромінювання. Результати, отримані в роботі, можуть бути використані при розробці стійких до впливу зовнішнього електромагнітного випромінювання підсилювачів, генераторів та перетворювачів частоти, що працюють у міліметровому та субміліметровому діапазоні. Кількісні оцінки критерію оборотних відмов (інкрементів нестійкостей) показують, що величина енергії випромінювання лежить у межах чутливості сучасних приймачів випромінювання субміліметрового діапазону і є причиною відмов.

Keywords: напівпровідникові комплектуючі, наведений струм, електромагнітне випромінювання, нестійкість коливань, поверхневі коливання.