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INFLUENCE OF ELECTROMAGNETIC RADIATION ON THE PERFORMANCE OF SEMICONDUCTOR DEVICES

Abstract. Topicality. The growing level of electromagnetic threats necessitates investigating the failure mechanisms of semiconductor devices used in electronic equipment, particularly under pulsed electromagnetic radiation that can cause both temporary and critical damage to components. **The subject of study** in the article is physical mechanisms of reversible and irreversible failures of semiconductor devices associated with the influence of electromagnetically induced currents on current–voltage characteristics and the development of thermal instabilities. **The purpose of the** article is to develop a physical model of semiconductor device failures and obtain analytical relationships for quantitative assessment of their characteristics under electromagnetic exposure. **The following results** the process of converting the energy of induced currents into intrinsic electromagnetic oscillations and thermal energy of charge carriers was analyzed. A physical model of thermal instability formation leading to secondary thermal breakdown was proposed. Analytical relationships were developed to estimate heat dissipation power and the time required for instability development. Quantitative indicators of reversible failures (changes in current–voltage characteristics) and irreversible failures (thermal breakdown) were determined depending on radiation parameters and material properties. Agreement between calculated and experimental data was demonstrated in terms of the order of magnitude of the critical failure energy. **Conclusion.** The proposed model and derived analytical relationships can be used to determine occurrence criteria and quantitatively predict failures of semiconductor devices under pulsed electromagnetic radiation.

Keywords: electromagnetic radiation, current, voltage, semiconductor structures, thermal instability, critical radiation energy

Introduction

Problem relevance. Experience in operating technical equipment that contains radio and electrical equipment at its core shows that one of the one of the most complex tasks associated with achieving the required level of reliable and high-quality operation of these devices is the problem of ensuring their stable operation in an electromagnetic environment created by sources of natural and artificial origin [1].

The performance of electronic radio equipment (ERE) exposed to electromagnetic radiation (ER) depends to a certain extent on the resistance of its components to this influence. This is explained by the fact that the structural elements of the equipment (housings, casings), due to the presence of, for example, holes or thin walls, are not ideal shields. The external pulsed electromagnetic field, weakened and altered in shape, penetrates the equipment, thereby affecting the functioning of the components and causing dangerous voltages and currents in them and other circuit elements [2].

This, in real operating conditions of ERI as part of equipment, they can be directly affected by electromagnetic fields, transformed in shape and weakened by the screens of the object or equipment units, and pulsed voltages and currents induced by the EMI field on circuit connections and in the products themselves.

Literature review. The expansion of the application areas and the increase in the speed of electronic equipment (EE) leads to the need for an increasing use of components containing semiconductor electronics [3, 4]. This increases the degree of influence of external electromagnetic radiation (EMR) on the performance of EE, to which semiconductor components are highly sensitive.

The wide variety of failures that occur in electronic equipment as a result of external factors are usually divided into reversible and irreversible [2]. Irreversible failures characterize the complete loss of functionality of electronic equipment. They occur when changes in the equipment's internal parameters limit permissible limits (when exposed to external electromagnetic fields, irreversible failures typically result in thermal breakdown of components). A change in the nature of failure is characterized by a temporary loss of functionality, leading to a change in output characteristics.

Most of the available theoretical and experimental results of studies of the influence of EMP on electronic radio products (ERP) relate to the area of irreversible failures [3]. Modeling the mechanisms of interaction of currents and voltages induced by EMP with the processes characterizing the functional purpose of the products is usually carried out within the framework of the theory of circuits with distributed parameters [4]. This approach allows us to evaluate the performance criteria of the product as a whole (for example, to estimate the critical energy characterizing thermal breakdown). At the same time, questions related to the dynamics of the development of processes occurring directly in the semiconductor components of ERP and leading to the occurrence of irreversible failures (in particular, to thermal breakdown) remain open. The fact is that if the EMP is not so powerful (the energy released in the semiconductor structure does not reach the critical level), then the resulting heating of the current carriers does not lead to thermal breakdown (irreversible failure), but has a significant impact on the working (volt-ampere) characteristics of ERP (area of reversible failures).

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This paper, to some extent, addresses the existing gap in this area of research. It proposes a calculation method for assessing the performance of semiconductor devices (regions of reversible and irreversible failures) based on the characteristics of the applied voltage pulse and the parameters of the device itself.

The purpose of the work is to develop a physical model of semiconductor device failures and to form calculation relationships that provide a quantitative assessment of their characteristics under electromagnetic influence.

Main part

The most relevant scenarios involving task offloading mechanisms in the context of cybersecurity are analyzed. In many cases, ensuring secure and uninterrupted service requires the integration of fog computing infrastructure. Critical applications such as intelligent transportation systems, augmented and virtual reality (AR/VR), and healthcare generate vast volumes of sensitive data, which demand low-latency processing and robust data protection. Furthermore, scenarios like video streaming, smart homes, and smart cities also involve the exchange of potentially vulnerable information, making cybersecurity an essential component of system design…

The main criterion for the performance of semiconductor devices in the area of irreversible failures is the critical (threshold) energy released in the device as a result of the action of EMP [1]. Exceeding its value leads to irreversible processes (usually overheating of current carriers (electrons) and, as a consequence, thermal breakdown). For pulse voltages with a pulse duration of $\tau_p \leq 0{,}1$ µs this energy is constant and is called the critical damage energy [2].

Most of the currently used methods for assessing the performance criteria of semiconductor devices under the influence of external electromagnetic radiation [6] define the critical energy W_{cr} that causes product failure by the following relationship:

$$W_{cr} = U_a I_a \Delta t_{min} \tag{1}$$

where – $U_a I_a$ are the avalanche breakdown voltage and current, respectively,

$\Delta t_{min} = \tau_b$ – minimum time of dissipation of induced EMI power (breakdown development time).

The critical pulse energy causing failure of a semiconductor device depends on the time parameters of the applied overvoltage pulse and is determined by the physical and design parameters of the *p-n* junctions and the specific resistances of their high-resistance areas [7].

The universality of the threshold (critical) damage energy of a semiconductor device, as a parameter characterizing its electromagnetic immunity, lies in the fact that these integral characteristics contain both the amplitude and time parameters of the applied voltages and are not strictly limited to a specific source (lightning discharges, static discharges, high-voltage power lines, etc.). Due to the wide variety of failure mechanisms in semiconductor devices, determining the exact damage energy (power) to the device currently presents certain difficulties. However, a number of methods exist for approximate estimates of damage power levels. Among the pioneering works is [8], where the dependence of the specific breakdown power of the current passing through the p-n junction on the pulse duration was obtained experimentally for diodes and transistors ($P_{cr}/S = F(\tau)$, where P_{cr} is the power of the current passing through the cross-section (S) of the p-n junction, at which a catastrophic failure of the diode (transistor) occurs; τ is the duration of the rectangular pulse). The corresponding dependence is widely used in the literature on this problem, is called the Wunsch -Bell dependence (curve) and is shown in Fig. 1. In Fig. 1, the theoretical and experimental dependences of the specific breakdown power on the duration of the applied rectangular pulse are shown in a logarithmic scale [8].

For an analytical description of the experimental data, the authors [8] obtained a semi-empirical formula for the dependence of the specific threshold power ($P/S, kW/cm^2$) of *p-n* junction failures on the pulse duration (t, μs):

$$P/S = K_d \cdot t^{-1/2} \tag{2}$$

where K_d is the degradation coefficient, which was determined on the basis of experimental data.

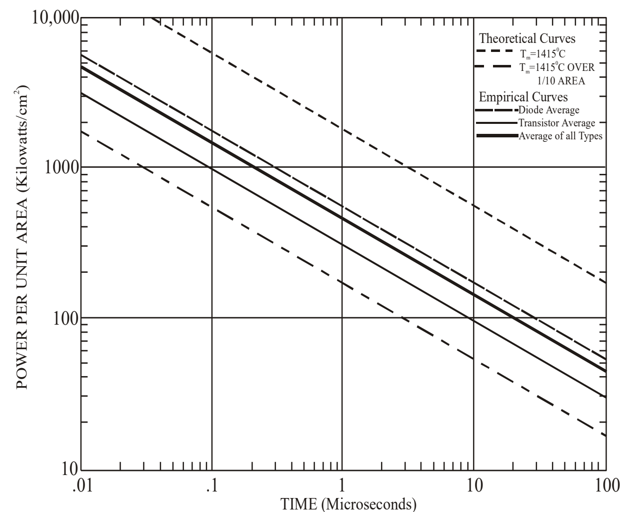

Fig. 1. Dependence of the specific threshold power on the pulse duration (Wunsch -Bell dependence) [8]

Let's consider the most likely mechanism for the influence of externally induced currents and voltages on the performance of semiconductor devices. The study of these currents and voltages allows us to substantiate the proposed calculation model for the development of irreversible failures and define new criteria for assessing the performance of electronic devices. This mechanism is associated with the heating of carriers under the influence of an external electromagnetic field.

This irreversible failure mechanism is associated, in our opinion, with the effect of secondary thermal breakdown, the occurrence of which is the result of localized overheating in the region of the *p-n* junctions. The ability to convert the energy of currents induced by

electromagnetic radiation into thermal energy is due to the very small size of the *p-n* regions. Since the energy is dissipated near the active regions of the *p-n* junctions, heat is generated over a small area, and the temperature can reach values on the order of the melting time of materials for field strengths $E > 100\, kV/m$ and pulse durations of several hundred nanoseconds. This leads to secondary thermal breakdown, which is accompanied by melting of the films created by the metallization and the formation of an arc between the metallized areas.

Currently, an approximate estimate of the damage power of a semiconductor device (the irreversible failure criterion) is commonly used, based on a numerical solution of the thermal conductivity equation. This is achieved using a semiempirical formula for the threshold levels of thermal damage power of a semiconductor:

$$P = K \cdot S \cdot \sqrt{C\lambda\gamma} \cdot (T_m - T_i) \cdot t_n^m, \quad (3)$$

where P is the threshold power level leading to a change in the operating characteristics of the device, K (E) is an empirical constant depending on the design of the device and the amplitude of the pulsed field strength E, S is the heated area, C is the heat capacity of the material, λ is the thermal conductivity coefficient, γ is the density of the material, T_m – the maximum temperature for the device, exceeding which leads to damage to the device, T_i – ambient temperature, t_n – voltage pulse duration, m – a constant determined by the pulse duration.

The magnitude of critical energy causing the loss of the product's functionality (irreversible failures) is thus determined by the following relationship:

$$W_{cr} = R\tau_b, \quad (4)$$

where τ_b is the time of development of secondary thermal breakdown.

In the area of reversible failures, formula (4) requires significant adjustment, since if the EMP is not so powerful (thermal energy W_τ does not reach a critical value W_{cr}), the electron flow generated by heating does not cause thermal breakdown, but it does have a significant impact on the semiconductor's key parameters (conductivity, carrier concentration). This affects the device's output characteristics.

Therefore, to assess the degree of performance of a semiconductor device under conditions of thermal instability, one should use the relation

$$W_\tau = P\tau. \quad (5)$$

At $\tau < \tau_b$ $W_\tau < W_{cr}$ (region of reversible failures).

At $\tau > \tau_b$ $W_\tau = W_{cr}$ (region of irreversible failures).

Thus, the condition for the occurrence of thermal instability can serve as a criterion for the electromagnetic stability of irreversible failures [6]. The mechanism for its development is due to the fact that the induced electromagnetic current in the *p-n* junction generates heat under reverse bias voltage. An increase in reverse voltage causes an increase in the junction temperature, which in turn leads to an increase in the reverse current, thus creating a section with negative differential resistance on the volt-ampere characteristic. This effect allows us to establish a relationship between the induced electromagnetic current and reverse voltage distortion.

The section of the volt-ampere characteristic with negative differential resistance is characterized by the value V_R – the voltage range for thermal instability development. When exposed to external electromagnetic radiation, the device does not fail, but the type of negative differential resistance characterizes the amplitude and duration of the pulse of the influencing field.

Table 1 shows the section of the reverse branch of the volt-ampere characteristic of the diode (D312A – germanium, mesadiffusion, pulse, voltage pulse amplitude range $E \approx 160 - 200\, kV/m$ [9].

Table 1 – **Reverse branch of the volt- ampere characteristic during thermal instability (diode D 312 A)**

Temperature t^0C T_0	Reverse current density $I_R(mA/sm^2)$	Reverse voltage $V_R(V)$
20	0,3	12,3
30	0,4	45,5
40	0,8	68,2
50	1,2	58,4
60	3,2	43,1
70	4,5	41,3

In the work [11] the dynamics of changes in the volt-ampere characteristics of semiconductor devices (MOS structures) were determined:

at the first stage, current instability is observed at voltages close to the level of avalanche growth of the number of carriers,

at the second stage, switching occurs from the high to the low voltage region,

at the third stage, a sharp increase in current is observed with a small increase in voltage,

the fourth stage corresponds to the failure of the device.

The first three stages define the area of reversible failures ($\tau < \tau_b$) the fourth – irreversible ($\tau > \tau_b$).

It should be noted that, to date, only voltage levels corresponding to the fourth stage (irreversible failures) have been experimentally studied in detail [10]. However, the influence of induced EMI currents can affect the volt-ampere characteristics of this type of devices already at the first stage – the avalanche growth of carriers. The occurrence of distortions in the volt-ampere characteristic in this case is associated with temperature instability. When a sufficiently powerful voltage pulse is applied to the transistor, causing a secondary breakdown, the latter occurs with some time delay. This time is called time of secondary breakdown (thermal instability) [10]. This time – τ characterizes reversible failures. When τ failures τ_b become irreversible and the device completely loses its functionality.

Table 2 – **Dependence of the breakdown turn-on time of the structure *Si – Au – Ge* from the power of the applied pulse at different temperatures**

Temperature t^0C T_0	Turn-on time τ	Pulse power $P(W)$
100	10^{-4}	6,1
	$5{\cdot}10^{-4}$	5,3
	$7{\cdot}10^{-4}$	3,2
50	10^{-4}	7,2
	$6{\cdot}10^{-4}$	5,5
	$8{\cdot}10^{-4}$	4,1
20	10^{-4}	8,3
	10^{-4}	7,1
	10^{-4}	5,2

Table 2 [11] shows the dependence of the τbreakdown turn-on time on the power of the applied pulse voltage at different ambient temperatures T_0. For a certain turn-on time, τthere is a breakdown turn-on temperature T_τ, which should be understood as the temperature of the "hot spots" at the moment preceding the secondary breakdown. This value T_τ is related to the pulse power P and the ambient temperature T_0 by the following relationship:

$$T_0 - T_\tau = C_1 P, \tag{6}$$

where C_1 is a constant.

At a fixed temperature, the ratio between the pulse power and the thermal instability on-time is approximately:

$$\tau \approx \exp\left(-C_2 P\right), \tag{7}$$

where C_2 is a constant.

From expressions (6) and (7) follows the equality for the secondary breakdown turn-on time

$$\tau \approx \exp\left(-{}^{C_1}/_{C_2}\left(T_0 - T_\tau\right)\right). \tag{8}$$

Breakdown switch-on T_τ temperature depends on various parameters and the geometry of the devices. For most silicon diodes and transistors, the temperature T_τ corresponds to the temperature at which the concentration of carriers of the intrinsic material is equal to the concentration of the impurity in the collector [12] Hot spots are usually located near the center of the device. The value T_τ varies depending on the concentration of impurities in the collector, and the ratio of the constants ${}^{C_1}/_{C_2}$ is determined by the geometry of the device [12]. Therefore, the breakdown turn-on time varies greatly depending on the type and operating mode of the transistor (diode).

Outside the region of unstable currents, the voltage across the device drops sharply, and during the second stage, the resistance of the hot spots decreases sharply. In the third stage (the low-voltage stage), the semiconductor is at a high temperature and, near the breakdown points, becomes an intrinsic semiconductor [11].

With further increase in current, the breakdown points begin to melt and the fourth stage occurs – destruction of the device. Time τ_b characterizes precisely this region – the region of irreversible failures. To determine the degree of deviation of the volt-ampere characteristics using this technique, it is necessary to evaluate the components at each of the previous stages of discharge τ depending on the amplitude and duration of the acting EMI.

Discussion and analysis of the results obtained

In progress [2] conducted experimental research influences pulsed e electromagnetic radiation on the current-voltage characteristics of semiconductors devices: planar silicon barrier diode Schottky 2D 922 V and epitaxial silicon diode KD 409 A in the range currents and voltages characterizing reversible failures (absence of thermal breakdown). It was established that impact external pulsed electromagnetic field (amplitude tension electric field – $E = 10 \div 30\, kV/m$, duration impulse $\Delta t_p \approx 500ns$) leads to the emergence sections of the volt-ampere characteristics of diodes with negative resistance. On these areas the increase in forward current in the range $\Delta I = 5 \div 10mA$ accompanied by a voltage drop in the range: $\Delta U = 500 \div 2000mV$ (areas generation fluctuations).

How it is known [1] that the generation mode in semiconductor devices occurs in the direct current sections of the volt-ampere characteristics with negative resistance $R = {}^{\Delta U}/_{\Delta I}$. In the generation mode (instability own fluctuations semiconductor device) induced current (flow induced electrons external radiation) loses Part his own energy ΔW_{el} to excite electromagnetic fluctuations semiconductor structures with energy radiation ΔW_R ($\Delta W_{el} < 0$, $\Delta W_R > 0$, $\Delta W_R = \Delta W_{el}$). Thus, growth amplitudes voltage within $E = 10 \div 30\ kV/m$, is accompanied by an increase in energy radiation within $W_R = 10^{-10} \div 10^{-7}J$ (region of reversible failures) [2].

Further increase amplitudes within $E = 40 \div 80\ kV/m$ led to an increase energy radiation within $W_R = 10^{-6} \div 10^{-4}J$. When the amplitude of the EMI disturbance exceeded level $E > 90\ kV/m$ semiconductor diodes lost performance, fell on c t thermal breakdown, and energy radiation reached critical levels level $W_{cr} \approx 10^{-3}J$ [2].

In our opinion, the excess level $E > 40\ kV/m$ characterizes the area of development thermal instability when electronic the flow induced by the EMI is lost Part his own energy ΔW_{el} to warm up the media W_τ. Moreover, the area $E = 40 \div 80\ kV/m$ refers to the first three stages development of thermal breakdown $\tau<\tau_{пр}$ (reversible refusals), and excess $E > 80\ kV/m$ to the fourth stage $\tau < \tau_b$, when the semiconductor device is losing performance (irreversible) refusals) ($W_\tau = W_{cr}$).

Quantitative assessments thermal radiation power P (f.(3)) and time development thermal instability τ (f.(8)) showed that existing experimental [1] and obtained in this work settlement data are determined by one order of magnitude – for the first three stages thermal instability stages $W_R = 10^{-6} \div 10^{-4}J$, (reversible failures) for the

fourth stages $W_{cr} \approx 10^{-3} J$ (irreversible refusals).

Obtained in the work settlement the relations (f.(3) f.(4) f.(5) f.(8)) allow evaluate quantitative characteristics (reversible – deviation of volt-ampere characteristics and irreversible – secondary thermal breakdown) failures semiconductor devices depending on the parameters electromagnetic radiation and physical properties materials, components radio product.

Comparative analysis results existing experimental research reversible and irreversible refusals and numerical ratings received calculated by way of the present work, showed adequacy proposed physical models mechanisms influences pulsed electromagnetic fields for performance semiconductor devices.

Conclusions

1. A physical model is proposed for the occurrence of reversible and irreversible failures of semiconductor devices caused by the influence of electromagnetic radiation (EMR)-induced currents on the operating characteristics of the devices and the development of thermal instabilities leading to secondary thermal breakdown. This model is based on the mechanism for converting the energy of external EMR-induced currents into the energy of natural electromagnetic oscillations and the thermal energy of the carriers of semiconductor components of radio devices.

2. In progress received settlement ratios for evaluation thermal radiation power and time development thermal instability allowing evaluate quantitative characteristics of reversible (change in volt-ampere characteristics) and irreversible (secondary thermal breakdown) failures semiconductor devices depending on the parameters electromagnetic radiation and physical properties materials, components radio product.

3. Quantitative assessments energy causing refusal products showed that existing experimental and obtained in the present work, calculations data are determined by one order of magnitude. Areas reversible failures $W_R = 10^{-6} \div 10^{-4} J$, in the area of irreversible failures $W_{cr} \approx 10^{-3} J$.

4. Results from the comparison analysis existing experimental research and numerical ratings received calculated by way of the present work, showed adequacy proposed physical models and possibility use the calculation relationships obtained on its basis to determine the criteria for the occurrence and quantitative characteristics of failures of semiconductor devices under conditions of exposure to pulsed electromagnetic radiation.

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ВПЛИВ ЕЛЕКТРОМАГНІТНОГО ВИПРОМІНЮВАННЯ НА ПРОДУКТИВНІСТЬ НАПІВПРОВІДНИКОВИХ ПРИЛАДІВ

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Анотація. Актуальність. Зростаючий рівень електромагнітних загроз вимагає дослідження механізмів відмов напівпровідникових приладів, що використовуються в електронній апаратурі, зокрема, під впливом імпульсного електромагнітного випромінювання, яке може спричинити як тимчасове, так і критичне пошкодження компонентів. **Предметом дослідження** у статті є фізичні механізми оборотних та незворотних відмов напівпровідникових приладів, пов'язані з впливом електромагнітно-індукованих струмів на вольт-амперні характеристики та розвитком теплових нестабільностей. **Метою статті** є розробка фізичної моделі відмов напівпровідникових приладів та отримання аналітичних співвідношень для кількісної оцінки їх характеристик під впливом електромагнітного випромінювання. **Були отримані наступні результати.** Проаналізовано процес перетворення енергії індукованих струмів у власні електромагнітні коливання та теплову енергію носіїв заряду. Запропоновано фізичну модель формування теплової нестабільності, що призводить до вторинного теплового пробою. Розроблено аналітичні співвідношення для оцінки потужності тепловіддачі та часу, необхідного для розвитку нестабільності. Визначено кількісні показники оборотних відмов (зміни вольт-амперних характеристик) та незворотних відмов (термічного пробою) залежно від параметрів випромінювання та властивостей матеріалу. Узгодженість між розрахунковими та експериментальними даними була продемонстрована з точки зору порядку величини критичної енергії руйнування. **Висновок.** Запропонована модель та отримані аналітичні залежності можуть бути використані для визначення критеріїв виникнення та кількісного прогнозування відмов напівпровідникових приладів під впливом імпульсного електромагнітного випромінювання.

Ключові слова: електромагнітне випромінювання, струм, напруга, напівпровідникові структури, теплова нестабільність, критична енергія випромінювання