ON ANALYSIS OF THE ELECTROMAGNETIC RESISTANCE OF RADIOELECTRONIC DEVICES UNDER IMPULSE RADIATION

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The results of investigations on degradation effects in the radioelectronics circuitry under the influence of the high-intensity pulse radiation are given. Analysis of the mechanism of degradation because of shortening the radio pulse radiation wavelength has been carried out. When the wavelength of the object, exposed to the radiation of a centimeter range, exceeds the characteristic size of structural elements, the degradation mechanism is conditioned by the quasi-static effects on the object structure inhomogeneities. The degradation effects manifest themselves in accordance with the concept of a "weak link" and localization damage model. In the case of wavelength shortening, when the characteristic size of the object structure element becomes commensurable with the wavelength, the resonance effect action is more and more increasing. The degradation redistribution occurs according to the field intensity distribution in the resonant regions. The problem of electromagnetic resistance lowering, under conditions of the tendency towards the radio electronics circuitry microminiaturization, is discussed.

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INTRODUCTION

When a probability that the microwave radiation and electromagnetic pulse (EMP) fields have an effect on the elements and units of radioelectronic equipment (REE) is estimated, the three basic problems arise.

First, it is necessary to consider the mechanisms of external magnetic field (EMF) penetration into the interior of the exposed object where the radioelectronic systems (RES) are mounted. Using the known techniques for calculation of the EMP penetration through the orifices, shields, sealing panels, weakly-conducting envelopes one can obtain only crude estimates in the simplest cases. The structure of exposed systems is very complex and in each of cases it is necessary to develop special theoretical models and to carry out an experimental check.

Second, using the known value of EMF and their distribution in the sites of electronic assemblies, it is necessary to determine the amplitudes of voltages and currents inducted by these fields in the electronic units with taking into account the nonlinear signal transformation in the circuit elements (detection, differentiation in the capacitive circuits, excitation of resonant loops etc.)

Third, according to these data one should estimate the energy released in some electronic circuit elements, compare it with the energy which is sufficient for an event of malfunctions or failure in RES elements and determine the most critical damaged circuit elements.

The circuitry of the modern radio electronics and machine-computing technique consists, for the most part, of semiconductor devices. At the same time, just semiconductors show the lowest resistance to the electromagnetic field action. There are data which notify that the malfunction of computer elements occur at an absorbed energy as low as $10^{-9}\ldots10^{-8}$ J, diode zapping in the microwave mixers – at $10^{-6}\ldots10^{-7}$ J, linear integrated circuits – at $10^{-6}\ldots10^{-7}$ J, bipolar transistor circuits – at 10^{-5} J [1 - 4]. In this connection the experimental investigations and simulation of the degradation effects of semiconductors are of current importance. Also, the situation becomes more severe due to the tendency towards microminiaturization of semiconductor elements, use of submicro- and nanostructures, and, on the other hand, to the development of pulsed sources of high-intensity mm radiation.

COMPUTATIONAL PROCEDURE

At present time the damage model is based on the thermal mechanism by which the overvoltage in the junction induces the current which heats the junction to temperature of 150°C. At such values the temperature coefficient for silicon becomes negative, the current and temperature of the junction are avalanche-like increasing. Then the current is splitting into separate local filaments along which a maximum energy releases, temperature reaches the melting point and junction failure occurs. When the temperature in the local semiconductor regions is sharply increasing, the heat transfer goes more slowly and a positive feedback, leading to the heat breakdown, takes place [5].

If the semiconductor heating processes are considered in the general form, one should keep in mind that the thermal damaging process under the energy pulse action can occur in the three thermodynamic regimes.

During the first instants of action, when the heat flow does not propagate yet in the medium surrounding the region with the current heating the junction, the process is of an adiabatic character. At the same time, at a given damage energy $\boldsymbol{W_n}$, the damage power $\boldsymbol{P_n}$ is inversely proportional to the pulse duration $\boldsymbol{\tau}$, i.e. $\boldsymbol{P_n}\tau = const$ (curve 1, Fig. 1).

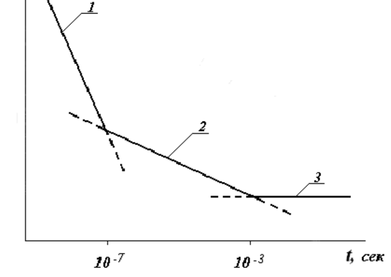


Fig. 1. Model approximation of the semiconductor junction damage energy threshold as a function of time: 1 – adiabatic region; 2 – Wunsch-Bell region; 3 – thermal equilibrium region

Such mode exists for $\boldsymbol{\tau << c/\lambda q}$, where λ is the heat conductivity coefficient; $\boldsymbol{c}$ – specific heat capacity of the material, and $\boldsymbol{q}$ – characteristic size of the element. The estimations for the RES semiconductor elements show the values of the order of $\boldsymbol{\tau} \leq 10^{-7}$ s. In this mode at $\boldsymbol{P \geq P_n}$ the junction burnout can occur until the released heat energy begins to diffuse into the material surrounding this junction. The ultimate energy for the junction failure, is determined as $\boldsymbol{W_n \approx mc(T_n - T_n)}$; where $\boldsymbol{m}$ is the junction element mass; $\boldsymbol{T_n}$ – initial junction temperature; $\boldsymbol{T_n}$ – junction melting temperature.

At the relatively low power levels the thermal equilibrium (see curve 1, Fig. 1) can be established before the release of the ultimate energy $\boldsymbol{W_n}$ in the junction, that is necessary for the junction heating up to the melting temperature $\boldsymbol{T_n}$. These conditions are reached during the time of the order of $10^{-5}\ldots10^{-4}$ s and the damages are not observed regardless of the pulse duration.

There is a Wunsch-Bell region [6] (see curve 2, Fig. 1) where the heat energy released in the semiconductor junction is partially absorbed by the surrounding medium. This region is characterized by the relation $\boldsymbol{P_п}\tau^{-1/2}=const$. Basing on the theoretical thermodynamic model and experimental result generalization the authors of [6, 7] have obtained the semiempirical formula relating the absorbed radiation power flux density with the exposure time and temperature change in the junction

$$P/S = \left(\pi\lambda\rho C_\rho\right)^{1/2} \cdot \left(T_\kappa - T_n\right)^{-1/2} \cdot \tau^{-1/2}\,, \qquad (1)$$

where P is the absorbed power; S – junction area ($10^{-1}\ldots10^{-4}$ cm^2); λ – heat conductivity coefficient; ρ – semiconductor density; C_ρ – specific heat capacity τ – pulse duration.

Equation (1) is a base for the most of linear semiconductor damage models. As a result of solving the heat conduction equation in the linear approximation in [8] the expression was obtained for the time dependence of the thermal damage for the *p-n* semiconductor junction

$$P = \frac{P_0}{1 - t/t_f}\,, \qquad (2)$$

where $t_f = \left(\dfrac{d}{\pi}\right)^2 \dfrac{C_p\rho}{\lambda}$, d is the thickness of the semiconductor structure (here of the *p-n* junction).

The mechanism of microwave radiation effect on the semiconductors is different for different frequency regions. For the short-wave radiation with $f \geq 10^{12}$ Hz an essential significance belongs to the resonant absorption mechanism by which the electrons can get into the conduction zone where the photons, having the energy exceeding the forbidden region width, are absorbed. The frequency range, for which this mechanism is important, is determined by the characteristic values of the forbidden region width $\varepsilon_g \sim 10^{-2}\ldots10$ eV. The conductivity, being increasing in this case, when the element is loaded by the operating voltage, can lead to the malfunction or failure of the circuit. The dependence of the electromagnetic resistance of radioelectronic devices on the radiation effect frequency is investigated quite insufficiently. Most of the known publications deal with analysis of the degradation in the REE elements and components, evaluation of semiconductor junction damage energy thresholds, development of degradation effect models [1 - 10]. Essential attention is given to the processes in the transistors being main elements of the discrete and integrated circuitry [6, 11 - 13].

It is important to note that the comparative analysis of data on the effects of microwave radiation and EMR fields of ultrashort-pulse duration allows one to find a close similarity in both the damage character and general features of degradation effects in REE and its components. At the same time, the process of electromagnetic radiation interaction with REE is considered in the antenna model conception, when the exposed object is a receiving antenna, in which the loads are the REE internal structure elements, first of all, semiconductor devices [14]. Figs. 2-5 show the main types and specific of the degradation effects in REE and its components.

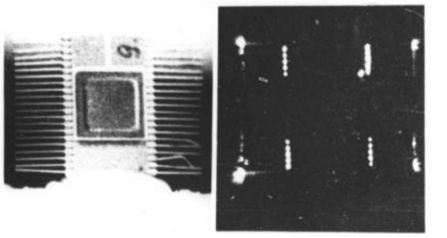


Fig. 2. Degradation of the 1-st level

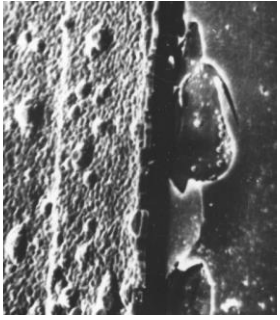
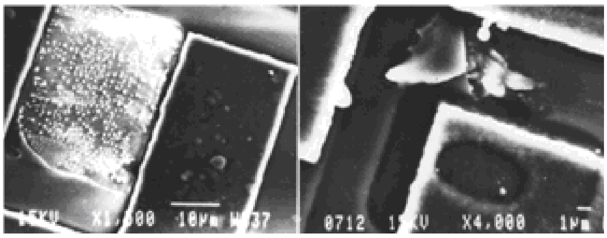
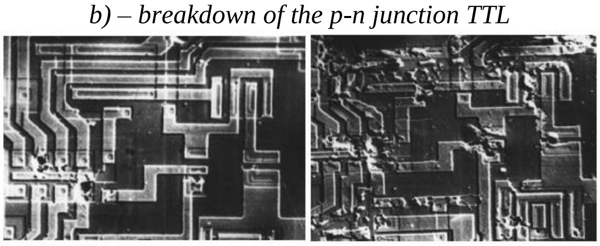


Fig. 3. Degradation of the 2-nd level



a *b*

Fig. 4. Degradation of the 2-n level:
a) – evaporation of the film resistor TTL;
b) – breakdown of the p-n junction TTL



N=1 *N=10*

Fig. 5. Development of the radiation-induced defect formation processes

In this conception the REE resistance problem under the action of mm microwave radiation is significantly complicated [15]. Besides, the sizes of receiving antennas, formed by the REE structural elements, become not only commensurable with the wavelength but can exceed it. This leads to the interference effect arising in the REE interior, forming the very nonuniform field distribution, producing the regions of increased field intensity in which the semiconductor elements can be arranged.

The microwave radiation effect on the REE components can have a double manifestation. As is shown in [15], when silicon substrates are directly irradiated with short microwave radiation pulses, $\tau = 15$ ns, $\lambda = 8$ mm, there is observed the change in the characteristics of impurity clusters, as well as in the lifetime and mobility of carriers in the superconductor, that is accompanied by the change in the semiconductor structure reflection coefficient. In its turn, this can cause the change in the amplitude and frequency-time parameters of the integrated microcircuits or in the sensitivity and lag of optoelectronic devices.

On the other hand, the short-pulse radiation action on the conducting elements in the REE structure (metallization, conductor line, equipment wires) is accompanied by the induction in them of a high-frequency current, which flows through the nonlinear elements (transistor, diodes) and enriches itself with impact frequency harmonics and their combinations with frequency components of the signals circulating in REE. This is resulting in data corruptions and additional heat loads onto the semiconductor components that can lead to the irreversible failure [16]. At frequencies of 37.7 and 75 GHz the aluminum skin-layer thickness is 0.43 and 0.31 μm, respectively. Therefore, the current, induced in the metallization, will heat it that may cause the thermal melting and partial damage of the SiO_2 protective layer on the surface of the integrated circuit chip or printed-circuit board.

Besides the irreversible thermal damages, the electromagnetic action leads to the distortion of semiconductor device characteristics. The nonlinearity parameters of the volt-ampere characteristics (VAC) of semiconductor devices are calculated by the following procedure. The current flowing through the nonlinear element under action of voltage u can be represented in the form of the Taylor expansion.

$$i(u) = i_0 + Su + S'u^2 + \ldots + S^{(k-1)}u^k , \quad (3)$$

where i_0 is the constant current component in the operating point $u = U_0$, and the quantities

$$S = \left.\frac{di}{du}\right|_{u=U_0}, \quad S' = \left.\frac{d^2 i}{du^2}\right|_{u=U_0}, \quad S^n = \left.\frac{d^n i}{du^n}\right|_{u=U_0} \quad (4)$$

are the slope of VAC and its derivative, respectively.

If the instantaneous voltage is an actually harmonic function

$$u = U_m \cos \omega t , \quad (5)$$

then the substitution of (5) into (3) permits to obtain the set of equations for calculation of the harmonic current components $A_{m1},\ldots A_{m5}$, corresponding to the frequencies $\omega \ldots 5\omega$, from which the following equation are obtained

$$\begin{cases} S = \dfrac{1}{U_m}\left(A_{m1} - 3A_{m3} + 5A_{m5}\right) \\ S' = \dfrac{1}{U_m^2}\left(A_{m2} - 4A_{m4}\right) \\ S'' = \dfrac{24}{U_m^3}\left(A_{m3} - 5A_{m5}\right) \\ S''' = \dfrac{192}{U_m^4} A_{m4} \\ S^{(IV)} = \dfrac{4800}{U_m^5} A_{m5} \end{cases} . \quad (6)$$

Thus, the transit VAC of a bipolar transistor in the circuit with a common emitter is described by the equation given in [17]

$$i_k = I_{k0}\left\{\exp\left[\frac{q\left(u_b - i_b r_b'\right)}{kT}\right] - 1\right\}, \quad (7)$$

where I_{k0} is the reverse (uncontrolled) current of the collector junction; $q = 1.6\times10^{-19}$ C – electron charge; u_b – base voltage; i_b – base current; r_b' – volume base resistance; $k = 1.38\times10^{-23}$ J/K – Boltzmann constant; T – temperature.

Equation (7) represents an implicit function since for the collector and base currents the following relation takes place

$$i_k = \beta i_b, \quad (8)$$

where β is the base current amplification.

Using the data reported in [18] we obtain the Tailor expansion of VAC (5) in the form

$$\begin{cases} S = \dfrac{a i_k}{1 + a b i_k} \\ S' = \dfrac{2a^2 i_k}{(1 + a b i_k)^3} = \dfrac{2a}{(1 + a b i_k)^2} S \\ S'' = \dfrac{4a^3 i_k (1 - a b i_k)}{(1 + a b i_k)^5} = \dfrac{4a^2 (1 - a b i_k)}{(1 + a b i_k)^4} S \\ S''' = \dfrac{4a^4 i_k \left(2 - 7abi_k + 3a^2b^2i_k^2\right)}{(1 + a b i_k)^7} = \dfrac{4a^3 \left(2 - 7abi_k + 3a^2b^2i_k^2\right)}{(1 + a b i_k)^6} S \\ S^{(IV)} = \dfrac{4a^5 i_k \left(4 - 33abi_k + 47a^2b^2i_k^2 - 12a^3b^3i_k^3\right)}{(1 + a b i_k)^9} = \\ = \dfrac{4a^4 \left(4 - 33abi_k + 47a^2b^2i_k^2 - 12a^3b^3i_k^3\right)}{(1 + a b i_k)^8} S \end{cases} , \quad (9)$$

where $a = \dfrac{q}{kT}$, $b = \dfrac{r'_b}{\beta}$, and coefficients $p_i = S^{(i)} / S$ are the VAC nonlinearity parameters [19].

CONCLUSIONS

High-frequency current harmonics are sources exciting the radiation which can aggravate the problems of electromagnetic compatibility of the radioelectronic equipment.

The conclusion of this study is that the radiation of mm range has a negative action on the REE electromagnetic resistance as a result of the enhanced radiation penetrability, as well as, because of effects which arise in semiconductors at frequencies commensurable with characteristic frequencies of the electron-atom interaction in the crystalline lattice. An essential attention should be given to the amplitude and frequency modulation of the actuating signal.

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К АНАЛИЗУ ЭЛЕКТРОМАГНИТНОЙ СТОЙКОСТИ РАДИОЭЛЕКТРОННЫХ ПРИБОРОВ ПРИ ВОЗДЕЙСТВИИ ИМПУЛЬСНОГО ИЗЛУЧЕНИЯ

Ю.Ф. Лонин, А.Г. Пономарев, В.И. Чумаков

Приведены результаты исследований деградационных эффектов элементной базы радиоэлектроники при воздействии импульсного излучения высокой интенсивности. Проведен анализ механизма деградаций при укорочении длины волны радиоимпульсного излучения. Показано, что в условиях воздействия излучения сантиметрового диапазона, когда длина волны излучения превышает характерный размер структурных элементов объекта воздействия, механизм деградаций обусловливается квазистатическими эффектами на неоднородностях структуры объекта. Деградационные эффекты проявляются в соответствии с концепцией «слабого звена» и локализационной модели повреждений. При укорочении длины волны, когда характерный размер элемента структуры объекта становится соизмерим с длиной волны, все более начинают сказываться резонансные эффекты. При этом деградации перераспределяются в соответствии с распределением напряженности поля в резонирующих областях. Обсуждается проблема снижения электромагнитной стойкости в условиях тенденции микроминиатюризации элементной базы радиоэлектроники.

ДО АНАЛІЗУ ЕЛЕКТРОМАГНІТНОЇ СТІЙКОСТІ РАДІОЕЛЕКТРОННИХ ПРИЛАДІВ ПРИ ДІЇ ІМПУЛЬСНОГО ВИПРОМІНЮВАННЯ

Ю.Ф. Лонін, А.Г. Пономарьов, В.І. Чумаков

Наведено результати досліджень деградаційних ефектів елементної бази радіоелектроніки при впливі імпульсного випромінювання високої інтенсивності. Проведено аналіз механізму деградації при скороченні довжини хвилі радіоімпульсного випромінювання. Показано, що в умовах впливу випромінювання сантиметрового діапазону, коли довжина хвилі випромінювання перевищує характерний розмір структурних елементів об'єкта впливу, механізм деградації обумовлюється квазістатичними ефектами на неоднорідностях структури об'єкта. Деградаційні ефекти проявляються відповідно до концепції «слабкої ланки» і локалізаційної моделі ушкоджень. При скороченні довжини хвилі, коли характерний розмір елемента структури об'єкта стає порівняним з довжиною хвилі, все більше починають позначатися резонансні ефекти. При цьому деградації перерозподіляються відповідно до розподілу напруженості поля в резонуючих областях. Обговорюється проблема зниження електромагнітної стійкості в умовах тенденції мікромініатюризації елементної бази радіоелектроніки.