SIMULATION OF THE THERMAL MECHANISM IN SEMICONDUCTORS UNDER ACTION OF PULSED ELECTROMAGNETIC FIELD

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The paper presents a model taking into account the time character of heat localization and distribution in semiconductor devices unlike the classical Wunsch-Bell linear model describing the thermal mechanism of EM-radiation action on REA. The classification of action levels is given. The nonlinear model permitting to determine the time boundary of heat propagation in the semiconductor device is presented. In the time range $t>t_{cr}$ a uniform volumetric heating of the object takes place, and for $t<t_{cr}$ there is a heat localization in the range of energy release due to the lag of the heat dissipation process behind the energy input process. Taking this into account one determines the energy leading to irreversible results of action. The model allows one to determine the feeblest aspects of REA.

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1. INTRODUCTION

Experimental studies of the electromagnetic stability of radio-electronic apparatus (REA) are concerned with the methods of destructive control under which in the objects the irrevercible processes take place that makes impossible their further use. In some cases the results of such investigations have a unreasonably high cost. One of possible ways to reduce the expenses is the mathematical modeling of the processes of failure in REA elements and components and construction of the experimental device capable to reproduce the acting electromagnetic pulse that permits to decrease considerably the number of experiments [1,2]. In the paper the authors consider the main aspects of modeling of the thermal mechanisms taking place in radio-electronic components under action of electromagnetic fields (EMF) of a short duration.

The processes taking place in REA are identical to the processes of elastic strain: elastic strain– REA failures occur in the time of pulse action t_p; residual strain – REA failures are much longer than the time of pulse action t_p "glare", and catastrophic processes when burning of REA element occurs.

2. MAIN PART

As is known, to consider the processes taking place in REA under action of pulsed EMF the classical linear Wunsch-Bell model (W-B model) is used [2]. It makes it possible to calculate the threshold power of failure (TPF) in semiconductor devices at pulses of duration $t \geq 10^{-8}$ s. Extension of the time region, for which the linear thermal model is valid, allowed one to obtain the general expression for TPF in the form [3]

$$P_n = \frac{P_0}{1 - e^{-t/t_c}}, \qquad (1)$$

where P_0 is the minimum threshold power of failure; t_c is the critical duration of failure pulse.

Parameters of the model P_0 and t_c have a certain physical meaning, So, from (1) it follows that $P_p \longrightarrow P_0$, i.e. TPF tends to the value of a minimum threshold power as the duration of action increases. The value t_c has a meaning of a time constant of thermal process duration and is the characteristic of the object being affected, i.e. it shows the time limit beginning from which one should take into account the time lag (inertia) of thermal processes. In the range of times $t > t_c$ there is a uniform volumetric heating of the whole object, and for $t<t_{cr}$ there is a heat localization in the range of energy release due to the lag of the heat dissipation process behind the energy input process. The values P_0 and t_c calculated in the Sestroretsky model [4] are expressed in terms of the thermal-physical parameters of the semiconductor:

$$P_0 = \frac{\pi^3}{8} \frac{\kappa_T S T_{max}}{d}, \qquad (2)$$

$$t_c = \frac{C_p \rho}{\kappa_T} L^2 = \frac{L^2}{D_{th}}, \qquad (3)$$

where C_p, ρ, κ_T are the thermal capacity, the density and the heat conduction of semiconductor material, respectively; T_{max} is the maximum temperature of the semiconductor overheat at which the loss of physical properties takes place Generally as T_{max} one chooses a melting temperature of material (for silicon T_{max}=1415 C°).L is the characteristic size of the energy release region; D_{th} is the coefficient of thermal diffusion.

The results of calculations for silicon of [4], lead P_0 to the form $P_0 = 2.67\, T_{max}S/d$ [Вт], where S and d are the cross-section and the length of the semiconductor specimen.

The known results of calculations of failure characteristics (constant of failure in semiconductor devices $B_1 = \sqrt{\pi \kappa_T \rho C_\rho}$) and the results of testing the stability of REA components are given in table 1 [2,5,6,7].

The time dependences of TPF are given in Fig.1 where the points with the abscissas $t=t_c$ are marked with arrays.

Type of semiconductor device	Value of B_1, [kW·µs^{0,5}·cm^2		
	Minim value	Max value	Typical value

Diodes:			
rectifier diodes	0.5	20	3
commutating diodes	0.01	1.0	0.1
stabilitrons point diodes	0.1	10	10
RF	$5\cdot10^{-4}$	0.1	0.01
Transistors:	$3\cdot10^{-4}$	$3\cdot10^{-2}$	$3\cdot10^{-3}$
high-power	0,2	0,5	1
low-power	$3\cdot10^{-3}$	2	0,1
switching	0,02	0,3	0,1
gerrmanium	0,02	1,0	0,2
IS (input-casing signal)	$3\cdot10^{-4}$	0,2	0,1

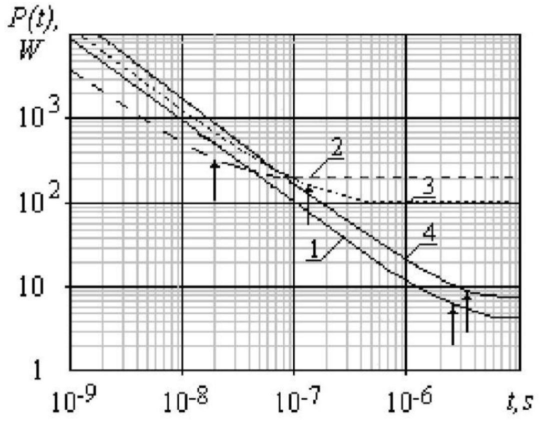

Fig.1. Threshold power of action as a function of the time:
1–P_0=1.5 mW; t_c=2.5 ms; 2–P_0=0.8W; t_c=0.125 ms;
3– P_0 =10 W; t_c=20 nc;
4 – P_0; t_c =3.33μ s

When calculating the threshold energy of failure by the pulsed EMF one should take into account that Equation (1) describes not an instantaneous value but the value of the threshold power level at different time values necessary for realization of the action effect. Then the energy W_n is expressed via the product, not the integral, i.e.

$$W_n = \frac{P_0 t}{1 - e^{-t/t_c}},$$

Dependence of the threshold energy of failure (TEF) on the time of pulsed EMF action is given in Fig.2. It is seen that in the region of small times TEF tends to $W_n = P_0 t_c$ that is a low energy limit of the thermal model of failure. However, this value is not absolute energy limit, as it is known [7.8] that at subnanosecond duration of actions there begins to develop a nonthermal mechanism of failure the characteristic times of which are considerably less than the time of thermal relaxation of a semiconductor (for example, the characteristic time of the nonthermal process can be the change of the dielectric permeability or specific conductivity of material [8].

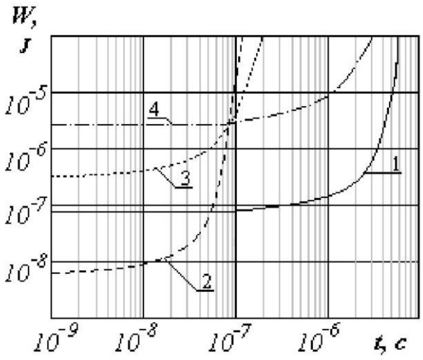

Fig.2. Dependences of the threshold energy of failure (4) (parameters corresponds to the plots of fig.1)

3. DISCUSSION OF RESULTS

So, the duration of action $t=t_c$ is a critical point of the choice of a minimum action duration for development of the thermal mechanism of failure. When the time of action duration increases, the character of the dependence is determined by the value t_c. Thus, for curve 1 and 4 the threshold energy of failure remains almost constant if t changes by three orders of magnitude. However, the failure power also increases by three orders with time decreasing (Fig.1, curves 1,4). From this the important conclusion follows that shortening of the action duration with simultaneous increase of the power does not lead to the significant gain in the energy threshold of failure. At the same time, it is known that realization of nanosecond ultra-high-power electromagnetic radiation sources constitutes a rather complicated engineering problem. So, as an estimation of the time of required electromagnetic action duration one may consider the value t_c. Exceeding of this value leads to the zone of the constant power of failure.

Intersection of TEF curves in plots 1 and 2 allows one to determine definitive conclusions on the electromagnetic stability of a complicated system.

So, if the dependences in Fig.2 characterize TEF of elements or components of the system, then the point of their intersection characterizes the critical value of the action duration and the value of TEF at which the failure of some elements can take place, and, consequently, the failure of the whole system will be more probable. Note also, that in the case of transition from the time region on the left from the point of intersection of TEF curves to the right region, the relation between TEF elements (compare curves 2 and 3) changes. It is conditioned by the mechanism of the heat conductivity of structure elements 2 and 3 in the region of large and small times and by the values of initial TEF at $t \approx 0$. On the left from the intersection point the heat conductivity has not time yet for compensation of the initial difference at values W_0, even despite some increase of the action duration with corresponding PTF decrease in Fig.1. In transition across the intersection point the heat conductivity becomes the determining mechanism of energy distribution in the structure of elements, and for failure of the element 3 characterized by the higher value of the coefficient of thermal diffusion D_{th} a higher energy value is required at one and the same time t.

4. CONCLUSIONS

In the paper the problems of modeling the thermal mechanism of REA failure under the actions of short electromagnetic pulses are considered. The limiting estimations of the optimum duration of the pulse action during which failures occur are obtained at radiation source powers realized. The further shortening of the action duration and increasing of the action power result in the development of the nonthermal mechanism of failure.

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МОДЕЛИРОВАНИЕ ТЕПЛОВОГО МЕХАНИЗМА В ПОЛУПРОВОДНИКАХ ПРИ ВОЗДЕЙСТВИИ ИМПУЛЬСНЫМ ЭЛЕКТРОМАГНИТНЫМ ПОЛЕМ

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В работе, в отличие от классической линейной модели Вунча-Белла, описывающей тепловой механизм влияния ЭМ-излучения на РЭА, предлагается модель, учитывающая временной характер локализации и распространения тепла в полупроводниковых приборах. Дается классификация уровней воздействия. Приводится нелинейная модель, которая позволяет определить временную границу распространения тепла в полупроводниковом приборе. В диапазоне времен t>tkp имеет место однородный объемный разогрев объекта, а при t<tkp происходит локализация тепла в области энерговыделения вследствие запаздывания процесса теплоотвода от процесса энерговвода. Исходя из этого, определяется энергия, приводящая к необратимым результатам воздействия.

Модель позволяет определить наиболее слабые места РЭА и позволяет упростить экспериментальные испытания элементной базы и РЭА в целом.

МОДЕЛЮВАННЯ ТЕПЛОВОГО МЕХАНІЗМУ В НАПІВПРОВІДНИКАХ ПРИ ДІЇ ІМПУЛЬСНИМ ЕЛЕКТРОМАГНІТНИМ ПОЛЕМ

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В роботі, на відміну від класичної лінійної моделі Вунча-Белла, яка описує тепловий механізм впливу ЕМ-випромінювання на РЕА, пропонується модель, що враховує часовий характер локалізації та розповсюдження тепла в напівпровідникових пристроях. Дається класифікація рівнів впливу. Приводиться нелінійна модель, яка дозволяє враховувати часову межу розподілення тепла в напівпровідникових пристроях. В масштабі часу $t>t_{кр}$ має місце однорідний об'ємний розігрів об'єкту, а при $t<t_{кр}$ має місце локалізація тепла внаслідок запізнення процесу тепловідводу від процесу енерговводу в області енерговиділення. Виходячи з цього визначається енергія, що приводить до незворотних наслідків дії.

Модель дозволяє визначити найбільш слабкі місця РЕА і дозволяє спростити експериментальні випробування елементної бази РЕА в цілому.