UDC 621.396.6

D.B. Kucher[1], S.V. Taranenko[1], L.V. Litvinenko[1], T.V. Zontova[2]

[1] *Sevastopol National Technical University, Sevastopol*
[2] *Nakhimov Naval Academy, Sevastopol*

THE MODELING OF THERMAL DAMAGES IN SEMICONDUCTOR DEVICES DUE TO VARIOUS FORM OF PULSED ELECTROMAGNETIC RADIATION

The methodology of analysis of thermal degradations in semiconductor devices due to various form of electromagnetic radiation is presented. The proposed methodology is based on volumetric thermal model. The dependence of the normalized temperature for the investigated pulse is constructed.

Keywords: *semiconductor device, pulsed electric overload, effect of degradation.*

Introduction

At the present time the developers are placing more attention to electromagnetic compatibility and electromagnetic stableness in the design of radio-electronic equipment (REE). First of all, due to the increase in capacity of the modern equipment, the influence of its fields on the sensors of systems increases and can lead to degradation effects. The continuous development and implementation of nanotechnology leads to miniaturization of REE elements and, therefore, increase the level of their sensitivity.

The degradation effects associated with excessing tolerance of thermal mode lead to irreversible damage to the elements and are the most common cause of failure of REE. A thermal overload usually associated with poor electrical modes of operation of semiconductor devices and components of REE, which the most susceptible to the influence of external factors.

In the analysis of the degradation effects in elements of REE arising from the action of pulsed energy overload, the main task is to predict the response of the object to the impact of current and voltage given intensity. It is necessary to take into account the thermophysical parameters of the object, i.e. how much energy is dissipated in its structure during the the impact and required energy to realize the degradation effects.

In this paper, the proposed is technique of analysis of thermal degradation mechanism for semiconductor devices due to pulsed electrical overloads resulting exposure to electromagnetic radiation (EMR) of short duration based on the volumetric thermal model.

The main part

The volumetric thermal model of analysis of degradation effects in semiconductors is an extension of the classical linear thermal Wunsch-Bell (WB) model, described in [1] for the three-dimensional case. This model allows us to determine the temperature rise in the semiconductor crystal with typical dimensions of a, b, c by the action of the electrical overload [2,3].

Expression for calculation of the normalized temperature at any "t" point in time is:

$$f(t)=\frac{T(t)-T_i}{T_f-T_i}=\int_0^t P(\tau)\frac{d}{d(t-\tau)}\left[\frac{1}{P_0(t-\tau)}\right]d\tau . \quad (1)$$

In this expression, $P_0(x)$ is the time dependence of the threshold power degradation under the action of an electrical overload in the form of a rectangular pulse, $P(\tau)$ – power absorbed by the semiconductor crystal, T_i, T_f – initial and final temperature of the material, respectively. Taking into account the dependencies presented in WB-model one can put the equation (1) as

$$f(t)=\frac{1}{2Sw_B}\int_0^{t_f} P(\tau)\frac{1}{\sqrt{t_f-\tau}}d\tau , \quad (2)$$

where t_f – the time needed to implement the thermal overload, S – area of transition, $w_B = B_3\cdot(T_f - T_i)$ – WB-constant, $B_3=\sqrt{\pi k_T \rho C_p}$ – the constant value determined by the thermophysical constants of material, k_T, C_p, ρ – specific thermal conductivity, heat capacity and density of the semiconductor.

For the range of short-pulse electrical overloads ($\tau \le 10^{-8}$s) the expression for generalized temperature can be written as follows:

$$f(t)=A\int_0^t P(\tau)d\tau , \quad (3)$$

where $A=\frac{1}{SB_2(T_f-T_i)}$ – constant value.

Thus the temperature is equivalent to a pulse energy of electrical overload. Also, the maximum temperature is always achieved at the trailing front of the pulse during short-pulse overloads [3]. This is the result of adiabatic heating process.

In [4] there are time dependences of the normalized damage temperature f(t) in semiconductor devices for typical current pulses during electrical overload which equal to energy of following form: rectangular, exponential with a *τ*/5 time constant, sinusoidal and triangular shapes (fig. 1).

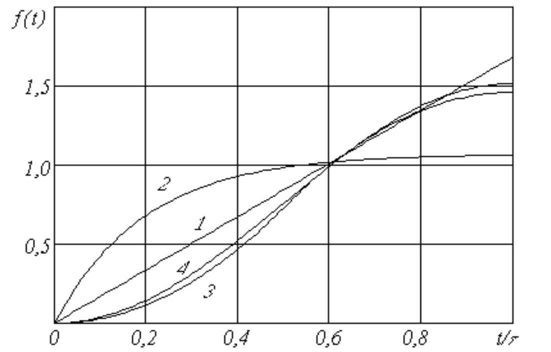

Fig. 1. The dependences of the normalized damage temperature f(t) (reverse bias of p-n junction mode) for short-pulses current of electrical overload: 1 - rectangular shape, 2 - exponential shape with a *τ*/5 time constant,3 - sinusoidal shape,4 - triangular shape.

As a result of the dependence analysis it is established that for a rectangular pulse the function f(t) is monotonic and the maximum temperature is reached at the end of the pulse. At the same time a maximum temperature can be achieved in the beginning or in the middle of the pulse for non-uniform heating by the complex shape pulses. In the case of exponential pulse, the most of the energy is concentrated near the leading front and the warming rate in the beginning is much higher than with other forms of pulses, but the achievement of high temperatures is limited due to rapid reduction of pulse power over time [4].

However, in practice these pulses rarely affect to the REE in the form they were generated. This is due to the fact that the EMR pulses are distorted in shape and amplitude attenuated while passing to the sensitive elements of the equipment through the antenna and feeder unit (AFU), power systems, grounding and protective casing screens [5,6].

Let's consider the case of exposure by the EMR exponential form with a duration = 2 ns on the REE input circuits. The time dependence of the pulse EMR coming to the AFU load has the form (see Fig. 2):

$$U_{out}(t) = \frac{U_{max}R_l e^{-\alpha t}\cdot \sinh(kt)\cdot\left(2-CaR_l a_1 - CaR_r a_1\right)}{2\cdot k\cdot Lr\left(1+Ca\cdot Lr\cdot a_1^2 - Ca\cdot a_1\cdot\left(R_r+R_l\right)\right)} - \frac{U_{max}R_l\cdot Ca\cdot a_1\cdot\left(e^{-a_1 t}-e^{-\alpha t}\cosh(kt)\right)}{1+Ca\cdot Lr\cdot a_1^2 - Ca\cdot a_1\cdot\left(R_r+R_l\right)}, \quad (4)$$

where U_{max} – the pulse amplitude, $a_1 = 0{,}7/\tau_i$ – the coefficient defined by exposure time, Ca – the antenna capacity to ground, Lr – inductance which appears with a capacity of antenna resonant circuit at first resonance frequency, R_f – radiation resistance, R_l – the load resistance, $\alpha = \left(R_l + R_r\right)/\left(2\cdot Lr\right)$ – coefficient taking into account the parameters of the antenna,

$$k = \sqrt{\frac{Ca\cdot R_r^2 + 2\cdot Ca\cdot R_r\cdot R_l + Ca\cdot R_l^2 - 4\cdot Lr}{4\cdot Ca\cdot L_r^2}}.$$

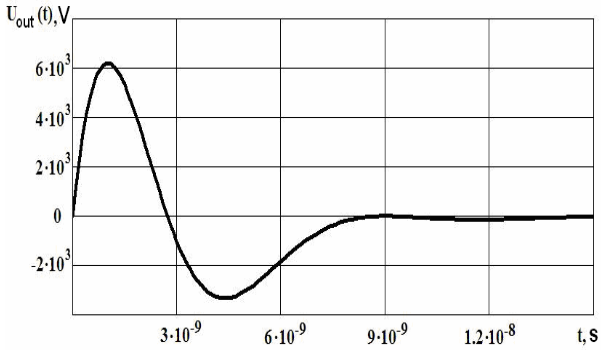

Fig.2. Time dependence shape of EMR pulse coming to the AFU load

Thus, the EMR exponential pulse significantly changes its shape on the way through the antenna-feeder circuit, and it becomes a damped sinusoid (Fig. 2). This is due to resonance phenomena in the antenna and feeder causing oscillatory process at passing the signal. The volumetric thermal model will be applied to analyze the phenomena occured when the EMR pulse with the form shown in Figure 2 is exposed to a semiconductor crystal of germanium (Ge).

As shown above, a generalized temperature is calculated according to the equation (3) for the short-pulse range of electrical overloads ($\tau_i \le 10^{-8}$ s).

We can substitute in (3) the dependence of the instantaneous power which absorbed by the semiconductor crystal and receive:

$$f(t) = \frac{1}{SB_2\left(T_f - T_i\right)}\int_0^t \left(i\left(\tau_i\right)\cdot U_j + i^2\left(\tau_i\right)\cdot R_b\right)d\tau_i \quad (5)$$

where S – area of p-n junction, B_2 – a constant determined by the thermophysical material constant, T_i, T_f – the initial temperature and the melting temperature of the semiconductor, respectively, $i(\tau_i)$ – dependence for the given shape of the current which is acting on the p-n junction, U_j – voltage at the depleted range, R_b – quasi-neutral range resistance, R_j – depletion range resistance.

The integral of the instantaneous power in equation (5) is the energy which is dissipated in the environment for time interval $[0,t]$, i.e.

$$f(t) = \frac{W_n(t)}{SB_2\left(T_f - T_i\right)}. \quad (6)$$

We can obtain the following expression for the generalized temperature with the account of EMR pulse shape which acting on the p-n junction (4):

$$f(t) = \frac{A \cdot U_j \cdot U_{max} \cdot e^{-\alpha t} \cdot \sinh(kt)}{2 \cdot k \cdot Lr} \times \left[2t + x \cdot \ln(t - x) - \ln(x) \cdot (2x - 1)\right], \qquad (7)$$

where $x = 0.7 \cdot Ca \cdot (R_f + R_1)$ – constant which is depending on the parameters of the antenna, the other notations are adopted in (2), (3), (4), (5).

The normalized temperature dependence f(t) for the current pulse which generated by passing the exponential EMR through the antenna-feeder circuit (see Fig. 2), is shown in Fig. 3.

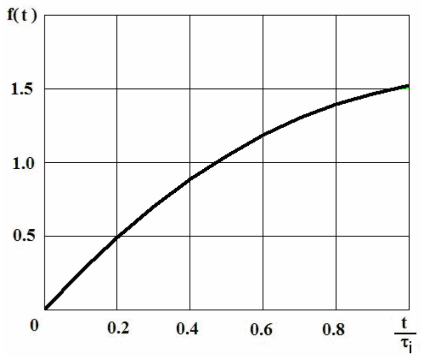

Fig.3. The f(t) normalized temperature dependence for the EMR pulse (reverse bias p-n junction mode)

Analyzing this dependence, it can be concluded that the maximum temperature is reached at the trailing front of the pulse during the short-pulse overload ($\tau_i \leq 10^{-8}$ s) due to adiabatic heating process.

The comparison of the normalized temperature dependence which shown in Fig. 3 with the dependence which is obtained in [4] allows one to note that for the pulses of exponential, triangle, rectangular, and sinusoidal shapes (Fig. 1):

1) The f(t) function is monotonic for a rectangular pulse. The maximum temperature is reached at the end of the pulse, but the beginning temperature levels are not high.

2) The exponential shape pulse causes the intense temperature rising at the beginning of the impact, as it has the most steep front as compared to other types of intervention. However, it is characterized by low levels of temperature on the rest of the time interval.

3) The sine and triangular shape pulses are characterized by a rather high intensity of the temperature influence on the trailing front of the pulse and the slow increase in temperature along the front, compared to the exponential one.

4) The researched pulse shape (see Fig. 2) is characterized by a slow increase of temperature along front compared with the exponential. Nevertheless, there is a more intense rise in temperature than for sinusoidal, rectangular and triangle factors (see Figure 1). This is due to the presence in researched pulse the both properties: exponential and sinusoidal exposure.

Conclusions

Consequently, the pulse which is generated during the passage of the exponential EMR through the antenna-feeder circuit will be more dangerous for the sensitive elements of the REE than the pulse shape shown in [4], because there is intensive rising of the temperature along the front. This temperature rising contributes to the rapid heating of the p-n junction, causing its degradation effects. Thus due to the high temperatures on the trailing front of the impact the relaxation process does not occur, i.e. semiconductor does not cool down to the initial temperature.

References

1. *Wunsch D.S. Determination of threshold failure level of semiconductors diodes and transistors due to pulse voltage / D.S Wunsch, R.R .Bell // IEEE Trans. on Nuclear Sci. - 1968. - Vol.15. - P.244 - 259.*

2. *Dwyer V.M. Thermal failure in semiconductor devices / V.M Dwye., A.J. Franklin, D.S. Campbell // Solid State Electronics. - 1990. - Vol.33.- P. 553 - 560.*

3. *Dwyer V.M. Electromagnetic discharge thermal failure in semiconductor devices / V.M.Dwyer, A.J .Franklin, D.S .Campbell // IEEE Trans. on Electr. Dev. - 1990. - Vol.37(11) - P. 2381 - 2387.*

4. *Chumakov V.I. Methods of modeling the thermal failures in semiconductor devices / V.I. Chumakov // Radio electronics and informatic. – 1999. - №2 - P.31 - 37.*

5. *Bludov S.B. The generation of high-power microwave pulses of ultrashort duration and the impact on electronic equipment / S.B. Bludov, N.P. Gadetsky, I.I. Magda etc. // Plasma Physics. – 1994. -, v.20. - issue 7,8. - P. 712 - 717.*

6. *Brigidin A.M. The research of susceptibility in semiconductor devices and integrated circuits to the effects of HF and VHF interferences / A.M. Brigidin, N.I. Listopad, N.A. Titovich, G.I. Yasyulya // Technology and Electronics. Repub. Interagency. Sat scientific. works. - Minsk: Higher School. – 1990 - Issue 1 - P. 115 - 119.*

Поступила в редколлегию 27.06.2013

Рецензент: д-р техн. наук, проф. И.Л. Афонин, Севастопольский национальный технический университет, Севастополь.

МОДЕЛИРОВАНИЕ ТЕПЛОВЫХ ПОВРЕЖДЕНИЙ ПОЛУПРОВОДНИКОВЫХ ПРИБОРОВ ИМПУЛЬСНЫМ ЭЛЕКТРОМАГНИТНЫМ ИЗЛУЧЕНИЕМ РАЗЛИЧНОЙ ФОРМЫ

Д.Б. Кучер, С.В. Тараненко, Л.В. Литвиненко, Т.В. Зонтова

Приведена методика анализа тепловых деградаций полупроводниковых приборов при воздействии электромагнитных излучений различной формы на основе объемной тепловой модели. Построена зависимость нормализованной температуры для исследуемого импульса тока.

Ключевые слова: *полупроводниковый прибор, импульсные электрические перегрузки, деградационный эффект.*

МОДЕЛЮВАННЯ ТЕПЛОВИХ ПОШКОДЖЕНЬ НАПІВПРОВІДНИКОВИХ ПРИЛАДІВ ІМПУЛЬСНИМ ЕЛЕКТРОМАГНІТНИМ ВИПРОМІНЮВАННЯМ РІЗНОЇ ФОРМИ

Д.Б. Кучер, С.В. Тараненко, Л.В. Литвиненко, Т.В. Зонтова

Наведено методику аналізу теплових деградацій напівпровідникових приладів при впливі електромагнітних випромінювань різної форми на основі об'ємної теплової моделі. Побудована залежність нормалізованої температури для досліджуваного імпульсу струму.

Ключові слова: *напівпровідниковий прилад, імпульсні електричні перевантаження, деградаційний ефект.*