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Reliability Analysis of Electrical Engineering Power Semiconductor Devices

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Abstract—A new approach to predicting reliability indices based on the numerical analysis of nonuniform temperature fields of power semiconductor devices (PSDs) is presented. Thermal analysis of the power diode module is carried out in a two-dimensional formulation with junction temperature $T_{\text{junc}} = 125°C$. The finite difference method is used to solve the differential equation of heat conduction. During the numerical experiments, the ambient temperature (from 25 to 45°C) and dimensional orientation of the diode module vary. It was found that the temperature difference is more than 100°C. To analyze the reliability indices of the diode module, two mathematical models, Arrhenius and multiplicative (statistical), are selected. 1t is found that raising the ambient temperature from 25 to 45°C approximately halves the reliability indices of the power diode module. The vertical orientation of the module reduces the heat transfer and causes an increase in the failure rate indices to 10% under natural convection for $T_{\text{amb}} = 25°C$. When the diode module is lowered, the reliability indices drop by 18%, all other things being equal. The largest differences in the estimates of the reliability of PSDs are observed at a lower location of the diode assembly. For example, the failure rate for the Arrhenius model was 325 times higher than that of the multiplicative model for an ambient environment of 45°C. The necessity of taking into account the real unsteady temperature fields to increase the prediction reliability resource of PSDs is shown.

Keywords: power semiconductor device, reliability prediction, thermal condition, nonuniform temperature fields, failure rate

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Operation of power semiconductor devices (PSDs) is a global trend in developed countries in the field of electrical power engineering [1, 2]. The wide nomenclature of PSDs allows one to apply such devices in electrical power engineering, electric vehicles, mechanical engineering, and metallurgy. More than 70% of the generated electric power is further converted with use of semiconductor devices [1, 3]. In Russia, this share is less than 30%. The increase in the number of PSDs in various areas of life can significantly improve the energy efficiency and, at the same time (upon achieving the world index) save 12–15% of all electric energy generated in Russia [1–4].

Contemporary PSDs can formally be divided into two groups [1]. The first group of devices, which is primarily used for converting large capacities, involves diodes and thyristors. The second group of devices, which are used in the range of medium and small capacities, represents the field and gate-modulated bipolar transistors.

The application of power semiconductor devises relates to significant constraints [1–5]. On the one hand, the vast majority of such devices are developed in a climatic design TCC (temperate and cold climate) with the extreme ambient temperature during operation up to +45°C. On the other hand, the temperature field is the considerably unsteady process and the temperature differences of the device may reach 20–30 K [6]. It is also known that temperature instability leads to self-heating and degradation of semiconductor structure devices [7].

When the temperature of semiconductor devices increases for every 10 K (in the working range of temperatures), the failure rate quite often more than doubles [8]. The effect of reducing operational reliability with increasing temperature is observed not only in PSDs, but, for example, in transformers. It was found that the service life of the latter decreases by 2.5% on average at the ambient temperature increase by 10 K. Moreover, taking into account the large energy payback time, reliability analysis should be performed after the rated product life [9].

It can be concluded that prediction of reliability at all stages of the life cycle of electrical power devices should be based on an analysis of thermal modes of their operation. The current methods for the electrical

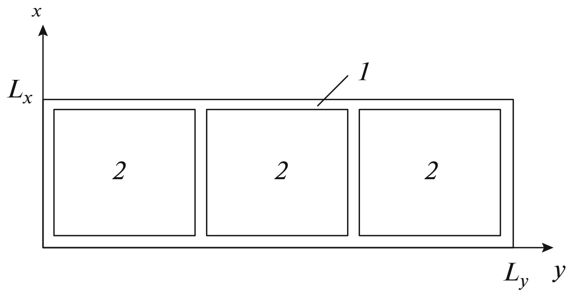

Fig. 1. The geometry of the solution area ((*1*), (*2*) are the areas with different thermal-physical characteristics).

energy thermal analysis rely on modeling with the use of various software packages (for example, Flow Vision) or monitoring and diagnostics software [9]. Other approaches are also known: methods of thermal resistance [10], quantitative thermography [11], and thermal monitoring [12]; the finite element method; and finite-difference methods that take into account natural convection together with heat sink radiation in stationary and cyclic modes of operation [13].

Reliability analysis of the power plants is usually carried out on the basis of a priori information [12, 14] using probabilistic simulation techniques [15]. For example, the main parameters in assessment of the reliability of the thyristor group of a semiconductor switch that is part of the powerful phase rotators are taken to be average times of no-failure operation and the first precautionary disconnection [16].

Analysis of statistical information is a common method of prediction of the reliability indices of power plants [12, 14–16]. However, such methods have a number of significant constraints due to not only possibly insufficient information on the PSD operation modes and conditions, as well as storage, but also the standards of sampling of devices for testing [9, 17] and, with great likelihood, the absence of unit analogs in the development of new devices for a particular industry. The assumption of stationary modes of the devices and operation conditions is also not always appropriate [5]. For example, the change of the temperatures of PSDs in time can be up to a factor of 30 or more [13].

Another approach to the prediction of the reliability of power plants based on the physics of failures, rather than on statistical–probabilistic analysis, is proposed in [18]. However, analysis of the physics of failures is usually carried out without taking into account the spatial distribution of temperature changes in time of the researched units [18].

The purpose of the present article is to analyze the failure intensities of a typical PSD on the basis of numerical simulation of an unsteady nonuniform temperature field, when several heat sources are locally distributed under conditions of natural convection with different spatial configurations of the studied unit and the working ambient temperatures.

FORMULATION OF THE PROBLEM OF ANALYSIS OF THE PSD THERMAL MODE

Analysis of the thermal operation mode was conducted on the basis of standard electrical engineering in relation to a simple device that is the power diode module with junction temperature $T_{\text{junc}} = 125°\text{C}$ (Fig. 1).

Numerical simulation of the temperature field was carried out in a nonuniform plate with dimensions L_x and L_y along the x and y axes:

$$x \in [0;\ L_x];\ \ y \in [0;\ L_y], \tag{1}$$

where x and y are the coordinates.

It was assumed that the model (plate) includes areas with different thermal-physical characteristics. In three areas (area *2*, Fig. 1), local heat generation of the given rate Q occurs. The boundary conditions of the third form (combined thermal transfer) are specified on the edges of the plate.

The thermal-physical parameters of the simulated plant are presented in Table 1.

The following key assumptions are used in the problem formulation.

—That the thermal-physical characteristics of materials do not depend on the temperature.

—That the thermal contact at the borders between the areas (1, 2) is considered ideal.

In this formulation, the problem is reduced to a solution of the two-dimensional unsteady heat conduction equations:

$$\begin{gathered} C(x,y)\rho(x,y)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(x,y)\frac{\partial T}{\partial x}\right) \\ +\frac{\partial}{\partial y}\left(\lambda(x,y)\frac{\partial T}{\partial y}\right) + \frac{Q(t,x,y)}{Sh} + \frac{\alpha(T)(T_{\text{B}} - T)}{h} \\ + \frac{\varepsilon_{\text{red}}\sigma\left(T_{\text{B}}^4 - T^4\right)}{h}, \end{gathered} \tag{2}$$

Table 1

Area	Density, kg/m^3	Specific heat C, J/(kg K)	Heat conductivity λ, W/(m K)	Material
1	1200	1000	0.3	Plastic
2	2300	900	3	Metal–ceramic

where c is the specific heat, ρ is the density, T is the temperature, t is the time, λ is the heat conductivity coefficient, Q is the heat source, S is the source area, h is the plate thickness, α is the coefficient of convective heat exchange with the external environment, T_B is the ambient temperature, σ is the Stefan–Boltzmann constant, and ε_{red} is the reduced emissivity factor of the plate and the environment.

The fourth and fifth summands in the right part of Eq. (2) take into account the flow of thermal energy to the external environment due to the convection and radiation heat transfer mechanisms.

Upon setting the initial conditions, it was believed that the PSD temperature at the initial time is uniformly divided:

$$T\big|_{t=0} = T_0(x, y), \tag{3}$$

where T_0 is the initial temperature.

The convection and radiation heat transfers are considered in the boundary conditions:

$x = 0,\ y \in [0, L_y]$:

$$-\lambda \frac{\partial T}{\partial x} = \alpha(T)(T_B - T) + \varepsilon_{red}\sigma\left(T_B^4 - T^4\right); \tag{4}$$

$x = L_x,\ y \in [0, L_y]$:

$$\lambda \frac{\partial T}{\partial x} = \alpha(T)(T_B - T) + \varepsilon_{red}\sigma\left(T_B^4 - T^4\right); \tag{5}$$

$y = 0,\ x \in [0, L_x]$:

$$-\lambda \frac{\partial T}{\partial y} = \alpha(T)(T_B - T) + \varepsilon_{red}\sigma\left(T_B^4 - T^4\right); \tag{6}$$

$y = L_y,\ x \in [0, L_x]$:

$$\lambda \frac{\partial T}{\partial y} = \alpha(T)(T_B - T) + \varepsilon_{red}\sigma\left(T_B^4 - T^4\right). \tag{7}$$

The convective heat transfer coefficient depends on the temperature and is found for each point of the surface:

$$\alpha(T) = \left(1.42 - 1.4 \times 10^{-3} T_{av}\right) N \left(\frac{T - T_B}{L}\right)^{1/4}. \tag{8}$$

The above coefficient of surface emissivity of the device and the environment is determined by the following ratio [13]:

$$\varepsilon_{red} = \left(\frac{1}{\varepsilon_s} + \frac{1}{\varepsilon_{amb}} - 1\right)^{-1}. \tag{9}$$

When solving differential equation (2) with the initial (1), (3) and boundary (4)–(6) conditions, the finite difference method was used [19]. To solve the differential analogues of the two-dimensional equations, the coordinate split scheme was used [20]. The solution of the resulting one-dimensional differential equations was carried out in two stages.

—An iterative cycle was constructed in relation to the nonlinear boundary conditions (radiation heat exchange with the external environment).

—The linear system of equations was solved at each step of the iteration cycle by the sweep method using the implicit four-point difference scheme.

FORMULATION OF THE PROBLEM OF PREDICTING THE PSD RELIABILITY INDICES

To analyze the reliability of the diode module, the Arrhenius [8] and multiplicative model [17] mathematical models were selected.

The multiplicative model is

$$\lambda_S = \lambda_b K_M K_F K_K K_S, \tag{10}$$

where λ_b is the base failure rate of the power unit, K_M is the mode factor depending on the electrical load and temperature, K_F is the coefficient of functional specificity of the operation mode of the device, K_K is the coefficient of the quality level of the device, and K_S is the coefficient of operation mode stiffness.

The validity of the selection of (10) results from the experimental and theoretical research on the reliability and analysis of the reasons for failures of electronic and radio devices (ERDs) [17]. It should be noted that the basic failure rate used in mathematical models of type (10) in determining the reliability of ERDs are given for the temperature of +25°C and do not take into account, for example, the spatial heterogeneity of temperature fields both inside and outside the devices.

According to [17], semiconductor devices that do not have an SHF range undergo parametrical failures in 80% of cases. They are caused by the physicochemical processes of degradation (aging) of the semiconductor device structure. As is known, the speed of aging (the accumulation of degradation states) depends not only on the initial state of the PSD, but also on the modes of electric load and the operation and storage temperature conditions [9, 17, 18]. Therefore, analysis of the reliability indices for the typical electrical power devices (namely, the diode module) was also based on a mathematical model for which the temperature is the relevant factor [8].

According to the Arrhenius model, the failure rate exponentially depends on temperature [8]:

$$\lambda_A(T) = C \exp\left(\frac{-E}{kT}\right), \tag{11}$$

where C is a constant, E is the activation power, and k is the Boltzmann constant.

The temperature used with (11) was determined according to the results of the solutions of two-dimensional unsteady heat conduction equation (2) with the corresponding boundary conditions.

An isolating metal–ceramic base through which the heat sink (area *2*, Fig. 1) is set up is a characteristic

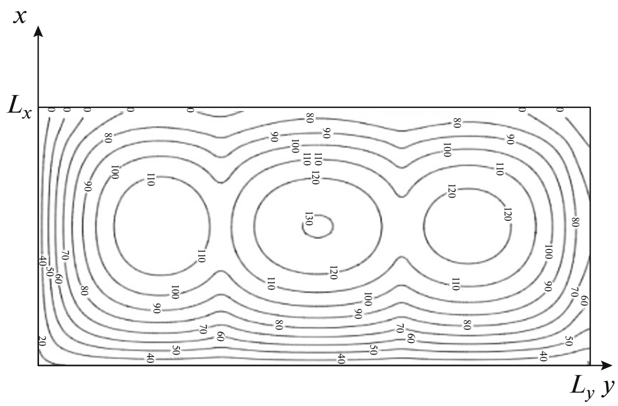

Fig. 2. The temperature field of the simulated unit.

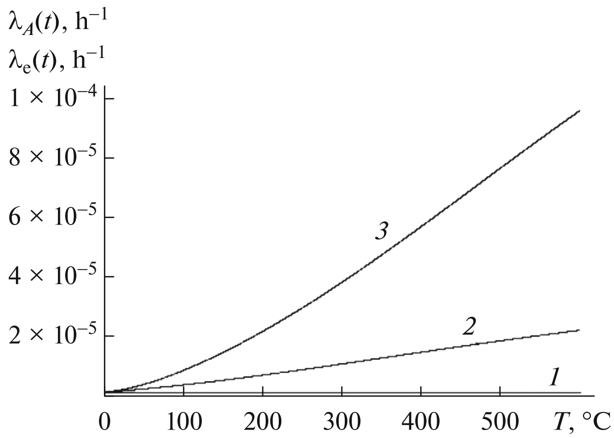

Fig. 3. The PSD failure rate at ambient temperature T = 25°C and t = 600 s ((*1*) is the multiplicative model (10), (*2*) is the Arrhenius model (at T_{av}), and (*3*) is the Arrhenius model (at T_{max}).

structural feature of a diode module (Fig. 1). Therefore, analysis of the reliability indices of the SPP (models (10) and (11)) was conducted for three possible variants of spatial configuration of the diode module in typical operating conditions at the rectifier operating mode of the device. The ambient temperature changed in the range of 25—45°C.

RESULTS AND DISCUSSION

The characteristic form of the temperature field of the simulated unit (diode module) at ambient temperature T = 25°C at time t = 600 s is shown in Fig. 2.

The present thermal field of a PSD is typical for the given initial conditions and operation mode. Analysis of heat conduction over the surface of the module (Fig. 1) shows that the temperature of the most heated area (Fig. 2) is 5–10°C higher than T_{junc}. The temperature field of the device is significantly nonuniform and characterized by considerable gradients. Therefore, prediction of a PSD using the Arrhenius model is appropriate for the average (T_{av}) and maximum (T_{max}) temperatures of the investigated unit.

The results of numerical simulation of reliability (failure rate) indices of an SPP are given in Fig. 3. The behavior of failure rate $\lambda_A(t)$ indicates not only significant differences in the reliability estimates of models (10) and (11), but also a high degree of dependence of the prediction Arrhenius model (curves *2* and *3*, Fig. 3) of the calculated (accepted) temperature.

The analysis of the curves shows that the numerical values $\lambda_A(T_{max})$ calculated by the Arrhenius model (11) are 141 times greater than those obtained by multiplicative model (10) for a working time of 600 s and ambient temperature of 25°C. For the average temperature on the device the reliability index is less by 27 times. The ratio of failure rates by the Arrhenius model λ_A (T_{max}) to $\lambda_A(T_{av})$ was 5.2 with all factors being the same.

Obviously, when the temperature in the range of PSD working temperatures (for example, in case of an increase in the ambient temperature) rises, the failure rate of the devices should grow or the reliability indices should decrease. For instance, the latter must affect the service life of electrical power equipment and reliability of system operation.

Table 2 gives the results of numerical analysis of PSD reliability indices for three ambient temperatures T_B and the spatial configurations of the module. When the failure rate was determined, mode coefficient K_M corresponded to 50% of the maximum electrical load [17].

The greatest differences in the estimates of the PSD reliability index are observed when the heat removal surface of the diode assembly is located lower. For example, at an ambient temperature of 45°C, the failure rate by the Arrhenius model is 325 and 75 times higher for maximum and average PSD temperatures, respectively. Increasing the temperature from 25 to 45°C leads to growth of the failure rate by approximately half for T_{max} and more than half for T_{av}. It should be also noted that the failure rate under conditions of natural convection is 10 and 18% higher with the vertical configuration of the diode module and the lower location of the heat removal surface in comparison with the upper location for T_{amb} = 25°C.

The significant differences in the reliability estimates have several causes.

—Significant heterogeneity of the temperature field of the simulated electrical power devices (owing to the local heat sources).

—Basic failure rate (λ_b in Eq. (10)) used in the estimate λ_E is defined for T_{amb} = 25°C.

—With increasing T_B, convective heat transfer rate decreases, which causes even greater heterogeneity of the temperature fields with a corresponding increase

Table 2

Ambient temperature, °C	Ratio between the failure rate by the Arrhenius model at T_{max} (numerator) and T_{av} (denominator) and the failure rate by the multiplicative model		
	horizontal		vertical
	up	down	
25	141/27	127/34	155/30
35	198/42	238/51	217/46
45	273/62	325/75	297/68

of the maximum and mean temperatures for the device.

CONCLUSIONS

(1) Using the multiplicative model in determination of PSD failure rates results in significant improvement in the service life of the device.

(2) Prediction of the PSD reliability indices should be carried out on the basis of an analysis of real unsteady nonuniform thermal conditions of the device.

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