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To cite this article: A A Imanova *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **537** 032083

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Automation of the design and development stages of semiconductor devices

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Abstract. The scientific article analyzes the thermal conditions of heat transfer in semiconductor devices, developed a calculation algorithm; a computational methodology for printed circuit boards was chosen, and the proposed methods were implemented by the example of printed circuit boards for calculating the thermal conditions of printed circuit boards that are used to implement power semiconductor technology of oil and gas facilities. It has been established that the automation of design of semiconductor elements and devices involves the initial stages of the thermal calculation in order to optimize the placement of elements and devices to improve the weight and size. It is shown that the analytical approach to the selection of elements and devices allows to reduce the preliminary labor costs for layout, as well as to optimize the placement of elements and devices according to the criterion of minimizing the weight and size indicators. Analysis of transient thermal processes on the printed circuit board can significantly improve the quality of the calculation and obtain more reliable results, bringing them closer to the most reliable.

1. The relevance of research

Modern semiconductor devices and equipment that are used in computing, in process control systems and in building pulse-phase control systems for power semiconductor technology. These devices are subject to increased requirements for reliability and weight-size indicators. Usually the reliability indicators of semiconductor devices are determined by their thermal modes of operation. Any short-term excess temperature even in local areas leads to a decrease in service life. On the other hand, the choice of the calculation method plays an important role not only from the standpoint of ensuring accuracy indicators, but it also allows reducing the time for designing and, consequently, reducing the cost price of the device being developed. In connection with the above, the scientific and technical problem of automating the stages of designing semiconductor devices is relevant and requires its solution.

2. Formulation of the research problem

To achieve the goal, the following scientific tasks are solved in the article:

- analysis of thermal conditions of heat transfer in semiconductor devices and equipment;
- development of a calculation algorithm;
- choice of calculation method;
- analysis of the calculation results.



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3. Analysis of thermal regimes of heat transfer in semiconductor devices

To ensure the thermal load of the radio-electronic devices (RED), systems for ensuring the normal thermal regime (SETR) are used, each of which is characterized by structural features, heat removal intensity, technical indicators (mass, dimensions, power consumption, cost, reliability, etc.) [1].

Features of the system's structure are determined by:

- the mode of operation of the system, depending on the ratio of the ambient temperature and the temperature of the RED (heating, cooling, temperature control);
- the nature of the connection of the refrigerant with the external environment (the refrigerant is the external environment, the refrigerant is isolated from the external environment, the combined system);
- mode of operation of the RED (continuous, periodic);
- the method of heat transfer (convection, thermal conductivity, radiation, due to the thermoelectric effect; the combined method);
- by the method of heat absorption (due to thermo-accumulating properties of the environment and materials of construction, due to the thermoelectric effect) [2].

Also, the structure of the SETR is determined by the area of use in which the system works (on Earth, in the atmosphere, in space, stationary, on a moving object, etc.), the level of unbundling of the RED (IC, cell, unit, rack, etc.). etc.), type of equipment (laser, powerful microwave device, high-speed computer, etc.).

If the average ambient temperature is close to normal for the RED, then the system should provide isolation from the effects of rapid changes in ambient temperature. This is achieved by using passive (heat insulation, reflective coatings) or active (heating, cooling, reverse) temperature control systems. If the average ambient temperature is significantly different from the normal for the RED, then systems are used to reduce this difference by additional heating or cooling the RED to the average ambient temperature. Cooling is used in cases where it is necessary to reduce the influence of heat released in the apparatus, to divert the heat flux from the apparatus and then dissipate it. This is accomplished with the help of various cooling systems for which factors such as the method of heat transfer, the type of coolant and its relation to the environment, the operating mode of the apparatus and the method of absorbing heat are important [3].

When designing passive thermostats, it is necessary to take into account that an increase in the thermal resistance of thermal insulation is only advisable to a value equal to the thermal resistance of electrical leads from the thermostatically controlled volume. If temperature fluctuations inside the chamber exceed the permissible value, then a thermal damper should be placed between the chamber and the object of temperature control [4].

Active temperature control makes it possible to maintain the temperature value with the required accuracy, which is especially important for such objects as setting frequency generators. In most cases, an isothermal chamber with an object is thermostated. According to the accuracy of temperature maintenance, there are coarse ($\pm 0.5^\circ\text{C}$), medium accuracy ($\pm 0.1 \dots 0.5^\circ\text{C}$) and precision ($\pm 0.05^\circ\text{C}$) systems of active thermostating of radio electronic devices. The composition of active thermostats includes temperature meters (sensors), heaters (coolers), isothermal chambers, control systems.

If the difference is large between the average temperatures of the medium and the apparatus, then SETR operating in the heating or cooling mode is used. Heating is used for radio electronic devices operating in the northern, high-altitude areas or in open space (in the shade). In other cases, the cooling system is used [5].

The thermal management system may cover individual nodes, blocks or the system. Thus, the liquid power system is often used only for cooling high-power microwave devices in transmitters, and information processing units are not covered by it. Stationary REDs usually have a common SETR.

A substance that removes heat is called a refrigerant. It can be gas, liquid, solid [6]. The environment can be used as a refrigerant (air for low-flying and ground-based facilities; water (for RED installed on

watercraft); RED design materials (when heat is removed due to heat conduction). For air RED, use as a refrigerant environment is meaningless. In combined TP, both environment and other substances act as a refrigerant. Refrigerant insulation allows you to create highly efficient autonomous (for example, aircraft) liquid systems [7].

The operating mode of the equipment affects the thermal mode and the SETR construction. The equipment can operate continuously or intermittently. The continuous operation mode is sometimes short-lived (the RED of the anti-tank missile guidance head).

The capabilities of one or another type of SETR and their design are largely determined by the method of heat transfer (heat exchange): convection, thermal conductivity, radiation. Cooling systems (CS) can be divided into air [8], liquid [9], evaporative [10], conductive, radiation, special and combined. Below we consider in more detail the cooling methods presented in [11].

4. Calculation algorithm

The transfer of heat energy by convection is associated with the movement of a liquid or gaseous medium in contact with a solid (structural element). Heat is transferred during convection both between a solid and a medium, and in the medium itself. Natural convection - is carried out with the free movement of the medium due to the difference in densities of hot and cold areas and forced - when the movement of the medium occurs due to external forces (pump, fan). In zero gravity, there is no natural convection. Convection heat transfer can be enhanced by the absorption of heat during evaporation (evaporation). The transfer of heat by convection is based on Newton-Richmann law:

$$P_{sq} = \alpha S \Delta T,$$

where P_{sq} is the power of the heat flow, W, transferred by convective heat exchange by gas or liquid to the environment or from the environment; α is the heat transfer coefficient by convection from the component to the environment, $W/(m^2 \cdot K)$; S is the surface area of heat transfer, m^2 ; ΔT - overheating of the surface relative to the environment or the environment relative to the surface, K [12].

The values of α are given in table 1. The specific value of α is determined by the physicomachanical and kinematic properties of liquids or gases, the speed of their movement; shape, roughness and dimensions of surfaces in contact with the refrigerant, and so on. For example, about ten physical and geometrical quantities affect the intensity of heat transfer during free convection. On the basis of the similarity theory, physical and geometric parameters can be combined; in this case, the same process can be described using a small number of dimensionless complexes. The most similar dimensionless complexes include the following similarity criteria: Nusselt (Nu), Grashof (Gr), Prandtl (Pr), Reynolds (Re), and others.

Table 1. The values of heat transfer coefficients α , $W/(m^2 \cdot K)$.

The cooling medium, the process	Wednesday movement	
	free	forced
Gas	1...9	9..99
Viscous fluid (oils)	199.299	299...999
Water	199...599	999..2999
Boiling water	499...39999	499...39999
Condensation of water vapor droplets	999...99999	999...99999

Based on the similarity criteria, it is possible to determine the nature of the coolant flow (turbulent, laminar [13]), on which the efficiency of the heat sink (α value) and the noise level caused by the movement of the coolant depend [14].

Air convective heat exchange systems are used in 90 ... 95% of terrestrial RED.

Air cooling systems use air as the coolant; at the same time distinguish free air cooling, internal mixing of air in the device case, free and forced ventilation. [15] a schematically shows free air cooling,

and [16] shows free ventilation. The latter is due to the difference in the density of cold air outside and heated inside the device, while in the case of the device there are special vents.

To intensify air cooling, heat exchangers with a developed surface [17], called radiators, are widely used. When choosing a radiator design should consider the type of production. In a single production, radiators are used that are produced by milling [18], and in mass production can be used injection molding [19] or stamping [20]. The spiral radiator [21] has high efficiency, but low processability due to the difficulty of uniformly soldering the spirals to the plates. The radiators shown in [22], are used abroad (Japan) due to the smaller size and cost of the air-cooling system as compared to the liquid one.

In cases where it is necessary to intensify the heat removal while reducing the noise level, use liquid convection cooling systems. Since the liquid refrigerant has a higher heat transfer coefficient α (due to the large specific heat capacity and density), its speed (and, therefore, noise) can be reduced. However, the absorption of the heat produced by the environment requires, as a rule, the use [23] of liquid-air heat exchangers, which create noise, but are located outside the cooled object. The noise level can be reduced by using liquid-to-liquid heat exchangers (for example, to absorb energy by heating the outboard or tap water).

[24] and, shows the RED, the internal volume of the body which is filled with liquid, washing the surface of the boards, chassis, parts, etc. In this case, heat exchange between these elements and the liquid can occur as in normal conditions (free and forced convection), and when boiling liquid. Heat can be removed from the heated fluid by using a coolant-immersed coil with heat transfer fluid or heat exchangers installed on the housing of the apparatus. [25] shows schematically liquid and evaporative cooling systems in which heat exchange between heat sources P and liquid occurs under conditions of forced convection in a closed loop. Heat is removed from the circuit by means of a heat exchanger T , and the movement of a liquid is carried out by means of a supercharger N . In [26] graphically shows the forced cooling of devices placed in a liquid.

Liquid SETR are complex systems, which makes them expensive to manufacture and operate. Nevertheless, these systems are widely used in on-board radio electronic systems, since the specific gravity of the best aircraft liquid SETR is 9 ... 11 kg per kilowatt of output power. The refrigerant in liquid systems can be isolated from the cooled elements and transported using pipelines [27] or directly wash the cooled elements. The cooling liquid in which the elements are immersed must have a number of properties: chemical inertness with respect to metals and dielectrics (approximately the same as inert liquefied inert gases); small and relatively stable in the entire temperature range of dielectric constant ($\varepsilon = 1.6 \dots 1.9$); small losses ($\tan \delta < 2 \cdot 10^{-3}$) in the frequency range up to 500 MHz; high electrical strength (up to 200 kV / cm) at boiling points that do not deteriorate after repeated electrical breakdowns; thermophysical properties, better than transformer oils and silicone fluids. Today, organofluorine liquids (freons) satisfy these requirements to the greatest extent. In addition, freons allow to heat at relatively low temperatures (due to the low boiling point). In systems with an isolated liquid coolant, water, ammonia and others are used, sometimes ethylene glycol is used as a refrigerant. These fluids can also be used for evaporative condensation systems [28].

The general advantage of liquid and evaporative systems is the constant temperature of the cooling medium. However, if the temperature exceeds a certain critical value, then a continuous film of vapor forms at the wall and the efficiency of the heat sink drops. The heat sink deteriorates in the presence of a laminar film during the flow of the coolant. The use of various convection heat sink systems is illustrated by the diagram presented in [29], where the overheating ϑ_c of the element surface relative to the environment is plotted along the ordinate axis and the heat flux density q along the abscissa axis.

[30] presents two types of areas: in one it is possible to recommend the use of any one cooling method (not shaded: 1 - free air, 3 - forced air, 5 - forced evaporative); in the other, it is possible to use two or three methods of cooling (shaded: 2 - free and forced air, 4 - forced air and liquid, 6 - forced liquid and free-water evaporative, 7 - forced liquid, forced and free evaporated, 8 - free forced and free evaporative, 9 - free and forced evaporative).

The upper curves in [31] are usually used to select the cooling of large elements - large lamps, magnets, chokes, etc. The lower curves are used to select the cooling system of blocks, racks, etc., performed on discrete and microminiature elements.

If the RED indicators fall into the shaded area (it is possible to use two and three cooling methods), then the task of choosing the cooling method is complicated and more detailed calculations are required.

5. Mathematical design model

Thermal conductivity - the molecular transfer of heat in a continuous medium, due to the temperature difference. In RED, the thermal conductivity of solids (supporting structures) is widely used. The RED blocks (especially the airborne ones) have a high-volume fill factor and rather small internal channels for conveying heat.

Conductive cooling system - a cooling system using the phenomenon of thermal conductivity as the main mechanism for transferring thermal energy from sources to heat sinks located on the periphery of the device [32].

For a planar construction, the transfer of heat using thermal conductivity following the generalized Fourier law can be described by a linear equation:

$$P_H = K_H S \Delta T,$$

where P_H is the heat flux transmitted by heat conduction, W; K_H is thermal conductivity; S is the cross-sectional area of the heat flux, m²; ΔT is the temperature difference between the two sides of the wall, K.

For a flat wall W/(m² · K):

$$K_H = \lambda / \delta,$$

where δ is the thickness of the structural element of the wall through which the heat flux passes (the length of the heat sink bus), m; λ is the thermal conductivity coefficient of the wall material, W/(m·K).

The reciprocal of K_H is called thermal resistance (m² · K / W):

$$R_H = 1/K_H = \delta / \lambda.$$

Heat conductivity coefficients of various materials are shown in [33]. If the wall is multi-layered and flat, then the total thermal resistance of thermal conductivity:

$$R_{H\Sigma} = \sum_1^n \delta_i / \lambda_i,$$

And thermal conductivity:

$$K_{H\Sigma} = \frac{1}{R_{H\Sigma}} = \left(\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \dots + \frac{\delta_n}{\lambda_n} \right)^{-1},$$

If the thermal contact from the outer sides of the thin-walled structure is carried out using convection, then instead of thermal conductivity K_H , heat transfer coefficient is used in the calculations:

$$K_{HC} = \left(\frac{1}{\alpha_1} + \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \dots + \frac{\delta_n}{\lambda_n} + \frac{1}{\alpha_2} \right)^{-1},$$

where α_1 and α_2 are the heat transfer coefficients by convection from one and the second side, W/(m²·K).

When constructing the thermal circuit of the device, the value called the specific thermal resistance (K / W) is used:

$$R = R_H / S = \delta / (\lambda \cdot S),$$

where S is the cross-sectional area through which the heat flux spreads. Specific thermal resistance characterizes, for example, the thermal parameters of an integrated circuit (IC) body. So, for ceramic

cases $R = 30 \dots 40 \text{ K / W}$ for plastic $R = 55 \dots 60 \text{ K / W}$, that is, the temperature difference for plastic cases with the same IC power is twice as high.

In some cases, to build a thermal circuit, it is necessary to know the contact thermal resistance of R_{CHR} . Its value depends on the combination of materials in thermal contact, specific load, surface roughness of the contact pair [34].

Contact thermal resistance (K / W) is determined by the formula:

$$R_C = R_{CHR}/S.$$

For a more efficient heat dissipation in the RED, materials with high thermal conductivity (aluminum, copper, ceramics) are used, measures are also taken to eliminate air gaps in the places of thermal contacts (using thermal paste), reduce roughness, increase the area of thermal contact, increase contact force (using fastening screw or staples) [35].

6. Calculation results

The proposed computational model allowed us to estimate the dependence of the temperature regimes for semiconductor devices, the arrangement of which is organized according to the classical scheme.

Figure 1 shows a graph of the temperature dependence of the superheat temperature of a resistive heater.

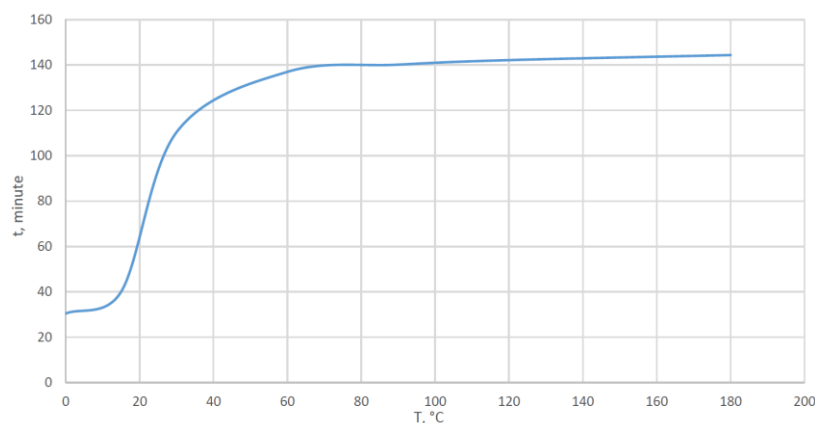


Figure 1. Graph of temperature versus time.

Analysis of thermo photographs of the radiator allows us to conclude that its temperature in all the indicated modes did not exceed 70°C . Analysis of the calculation results showed that with an acceptable heating temperature of 90°C , more compact placement of semiconductor elements and devices on the printed circuit board is allowed.

7. Conclusion

1. Automation of the design of semiconductor elements and devices at the initial stages involves the implementation of thermal calculation in order to optimize the placement of elements and devices to improve the weight and size parameters.

2. Analytical approach to the selection of elements and devices allows to reduce the preliminary labor costs for prototyping, as well as to optimize the placement of elements and devices according to the criterion of minimizing the weight and size parameters.

3. Analysis of transient thermal processes on a printed circuit board can significantly improve the quality of calculation and obtain more reliable results, bringing them closer to the most reliable.

4. The obtained calculations were successfully applied to the calculations of the thermal conditions of printed circuit boards, which are used to implement the power semiconductor technology of oil and gas facilities.

Acknowledgement

South Ural State University is grateful for financial support of the Ministry of Education and Science of the Russian Federation (grant No 13.9662.2017/BP).

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