NOTATION

j, conduction current density vector; **B**, induction vector of magnetic field produced by the conduction current; **E**, electric field strength vector; P_e and P_i, partial pressures of electrons and ions; V_c, macroscopic velocity of plasma motion; V_n, velocity of the neutral component; β, coefficient of friction; $\beta = \frac{m_e}{|e|} \times \left(\frac{1}{\tau_{en}} - \frac{1}{\tau_{in}}\right)$; σ, conductivity: $\sigma = \frac{e^2 n \tau_e}{m_e}$; $\frac{1}{\tau_e} = \frac{1}{\tau_{ei}} + \frac{1}{\tau_{en}} + \frac{m_e}{m_i} \frac{1}{\tau_{in}}$; e, m_e, electron charge and mass; m_i, ion mass; n, electron density, cm^{-3}; $1/\tau_{ei}$, frequency of collisions of electrons with ions; $1/\tau_{en}$ and $1/\tau_{in}$, frequencies of collisions of electrons and ions, respectively, with neutral particles.

LITERATURE CITED

1. A. Kontrovits and H. Jeans, in: Ion, Plasma, and Arc Rocket Engines [Russian translation], Gosatomizdat, Moscow (1961), pp. 112-119.
2. N. M. Kolesnikov, Electrodynamic Plasma Acceleration [in Russian], Atomizdat, Moscow (1971).
3. A. I. Morozov, Plasma Accelerators [in Russian], Mashinostroenie, Moscow (1973).
4. I. F. Kvartskhava, R. D. Meladze, É. Yu. Khautiev, et al., "On the factors limiting plasmoid velocity in plasma guns," Zh. Tekh. Fiz., 36, 759-762 (1966).
5. I. F. Kvartskhava, N. G. Reshetnyak, N. N. Zhukov, et al., "On the fractional mode of plasma acceleration in electrodynamic accelerators," Zh. Tekh. Fiz., 46, 974-980 (1976).
6. H. Alfvén Cosmical Electrodynamics, Clarendon Press, Oxford (1950).

AUTOMATED DESIGN OF A COOLING SYSTEM FOR SEMICONDUCTING MODULES

O. B. Aga, G. N. Dul'nev,
A. A. Perevezentseva, and B. V. Pol'shchikov

UDC 536.241

Thermal and mathematical models of semiconducting modules are proposed and a block scheme for automated design of cooling systems is proposed.

Semiconducting electrical energy transducers (gating devices, rectifiers, semiconducting transistor switches, etc.) are currently widely used in different areas of technology. In addition, as energy use increases, the requirements for efficiency, reliability, and convenience in use of these devices increase. These requirements can be satisfied and development time can be decreased only with the use of automated design systems (ADS). One of the subsystems in ADS is the design of transducers and their cooling systems. In this paper, we describe a technique for automated design of a power semiconducting switch with natural and forced air cooling.

The technical job of designing power semiconducting devices usually includes the following:

type of transistors or other elements used to construct the switch, as well as the auxiliary parts (diodes, thyristors, etc.), the admissible temperature of their p–n junctions, internal thermal resistance between the housing of the device and the crystal or the allowable temperature of the housing with a definite heat load;

operational regime of the device: currents, voltages, time diagram, which permit calculating the intensity of heat losses;

temperature of the surrounding medium;

size requirements for the transducer;

Institute of Precision Mechanics and Optics, Leningrad. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 5, pp. 841-847, November, 1982. Original article submitted July 7, 1981.

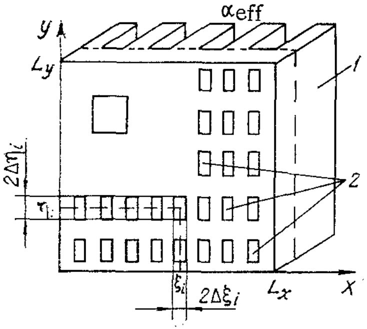

Fig. 1

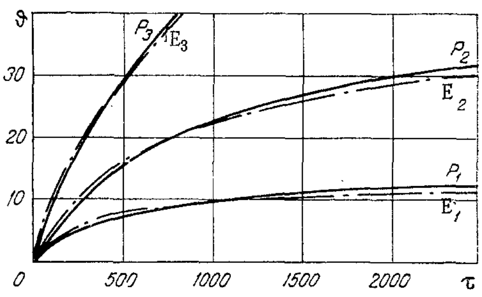

Fig. 2

Fig. 1. Diagram of module construction.

Fig. 2. Dependence of overheating of the transistor housing on time: E_1, E_2, E_3 are the experimental results; P_1, P_2, P_3 are the computed results. ϑ, °K; τ, sec.

preferability of using cooling systems and its elements;

production scale, cost, etc.

As a base analog, we used the most widely used modular design, consisting of a metallic housing 1 with finning (1 or 2 surfaces) and with elements 2 distributed on the surface (Fig. 1).

Thermal Model. According to the general scheme of the method of modeling by stages [1], it is convenient to perform the analysis as follows: at the first stage, the temperature field of the housing (plates) with the local heat source i is determined, and at the second stage, the heat exchange of a single element j situated on this plate is determined.

The first model consists of a plate 1, whose surface contains local heat sources with power P_i, each of which occupies a rectangular region with dimensions $2\Delta\xi_i$, $2\Delta\eta_i$ with coordinates ξ_i, η_i at the center (Fig. 1); convective–radiative heat exchange between all surfaces and the medium occurs. The stationary temperature field of such a plate is described by the following equation

$$\frac{\partial^2\vartheta_{i\,\mathrm{st}}}{\partial x^2}+\frac{\partial^2\vartheta_{i\mathrm{st}}}{\partial y^2}-\frac{(\alpha_1+\alpha_2)}{\lambda\delta}\,\vartheta_{i\mathrm{st}}=\sum_{i=1}^{n}-1\,\{U_i\}\,\frac{P_i}{4\Delta\xi_i\Delta\eta_i\lambda\delta},$$

$$\vartheta_{i\,\mathrm{st}}=t_{i\mathrm{st}}-t_{\mathrm{m}} \tag{1}$$

with the boundary condition

$$\left[\frac{\partial\vartheta_{i\,\mathrm{st}}}{\partial x}\mp\alpha_{\substack{0\,x\\1\,x}}\vartheta_{i\mathrm{st}}\right]_{x=\left|\substack{0\\L_x}\right.}=0;\quad\left[\frac{\partial\vartheta_{i\mathrm{st}}}{\partial y}\mp\alpha_{\substack{0\,y\\1\,y}}\vartheta_{i\mathrm{st}}\right]_{y=\left|\substack{0\\L_y}\right.}=0. \tag{2}$$

The solution of the system (1) and (2) for the stationary regime is obtained in [2] and permits determining the temperature field at locations where the elements are attached. An approximate nonstationary solution can be obtained using the method of the regular regime [3]:

$$\vartheta_i(\tau)=t_i(\tau)-t_{\mathrm{m}}=\vartheta_{i\,\mathrm{st}}(1-\mathrm{e}^{-m\tau});\quad m=\sigma\psi/C. \tag{3}$$

In our case, we assume $\psi = 1$.

The second model consists of a single body j with uniform temperature field t_j and total heat capacity C_j. The power P_j liberated in the element is expended on increasing its heat content $C_j\dfrac{d\vartheta_j}{d\tau}$ and dissipates from the surface of the housing into the medium $\sigma_c\vartheta_j$; part of the flux $\sigma_{\mathrm{p}}(\vartheta_j-\vartheta_i)$ occurs through the contact thermal resistance R_{p} in the plate, whose temperature is $t_i(\tau)$. Based on the law of conservation of energy, we form the equation

$$C_j\,\frac{d\vartheta_j}{d\tau}+\sigma_{\mathrm{p}}(\vartheta_j-\vartheta_i)+\sigma_{\mathrm{m}}\vartheta_j=P_j;\quad\sigma_{\mathrm{p}}=R_{\mathrm{p}}^{-1} \tag{4}$$

with initial conditions

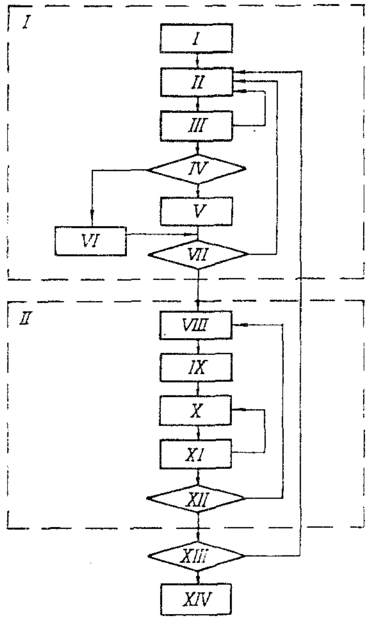

Fig. 3. Block diagram of the thermal design of the module: I) formation of program complex; II) calculation of L_x, L_y, δ, α_{eff}, t_m, λ; III) positioning of elements; IV) check of the possibilities of using the unified base; V) determination of the optimal profile, flow rate, etc.; VI) unified base; VII) analysis of the results of design at level I: VIII) choice of type of connection and definition of the thermal criterion; IX) formation of the program complex; X) calculation of the necessary thermal resistance contact; XI) determination of the structural and technological parameters; XII) analysis of the results of design at level II; XIII) analysis of the design result; XIV) determination of the sensor adjustment temperature.

$$\vartheta_j(0) = t_j(0) - t_m = 0. \tag{5}$$

The solution of Eqs. (4) and (5), substituting (3), has the form

$$\vartheta_j = \frac{\sigma_p}{\sigma_p + \sigma_m}\vartheta_{ist}\,(1 - e^{-m\tau}) + \frac{P_j}{m_0 C_j}(1 - e^{-m_0\tau}) + \frac{\sigma_p}{\sigma_p + \sigma_m}\vartheta_{ist}\,\frac{m}{m_0 - m}\,(e^{-m_0\tau} - e^{-m\tau});\quad m_0 = \frac{\sigma_p + \sigma_m}{C_j}. \tag{6}$$

The computational method proposed contains errors caused by the assumptions that the initial temperature field of the housing is regular and that the temperature field of the element is uniform. In order to estimate the magnitude of the error, we studied the temperature fields of such devices experimentally. The structure of the devices was similar to that shown in Fig. 1; the temperatures measured with the help of thermocouples were compared with the results of calculations using Eq. (6). The maximum disagreement between the computed and experimental values was found from the equation

$$\delta' = \frac{|\vartheta_E - \vartheta_c|}{\vartheta_E}\cdot 100\ \%$$

and, as follows from Fig. 2, did not exceed 15% and did not exceed the limits of error of the experiment.

Module Design Technique. The thermal criterion is the allowable temperature of the crystal t_{p-n}, related to the temperature of the housing t_{jst} and the power in the element P_j as follows:

$$t_{j\text{st}} = t_{p-n} - R_{\text{in}} P_j. \tag{7}$$

The design is conducted sequentially on both levels of the hierarchy (Fig. 3). First, the plate with its cooling system is examined and then the method for attaching elements to it. Both operations are iterative and can be repeated several times. We shall represent the temperature of the housing as follows:

$$t_{j\text{st}} = \Delta t + t_{i\text{st}} + t_{\text{m}}. \tag{8}$$

The magnitude of the maximum permissible temperature of the plate $(t_{ist})_{perm}$ at the location at which the elements are attached is the thermal criterion for design at the first level. At the second level, the magnitude of overheating Δt, owing to the contact thermal resistance, is the criterion for choosing the method for attaching separate devices.

The first operation (block I) consists of forming the complex of programs for calculating t_{ist} and t_{jst}.

Next (block II), the most preferable geometrical (L_x, L_y, δ, ξ, η) physical (α_{eff}, λ) parameters of the construction are determined (α_{eff} is the coefficient of heat transfer from the plate to the surrounding medium, determined by the efficiency of the finned surface; $\alpha_{eff} = \alpha_1 + \alpha_2$ [4]). In order to solve this problem, algorithms for calculating the temperatures t_{ist} and the effective heat transfer coefficients α_{eff}, numerical optimization methods, a dialogue process of working with the computer using a display, and a choice of radiator designs that are manufactured commercially are used. The geometrical parameters (volume, dimensions) are used as the optimization criteria. In this case, the temperature t_{ist} must correspond to the permissible temperature $(t_{ist})_{perm}$ with a fixed approximation, i.e., $t_{ist} \to (t_{ist})_{perm}$.

The next operation (block III) is related to the positioning of the elements. It can be completed with the help of special machine methods, as well as in the simplest case manually using dialogue systems. It should be noted that the operations (blocks II, III) are closely related to one another and are completed in such a way so as to satisfy the thermal, weight-dimension, and other technical and economical requirements.

The operation in block IV is related to the choice of the commercially manufactured element base. It is realized based on the definite, in block II, magnitude of the effective heat transfer coefficient α_{eff}. In our case, this is a search for a radiator with the required profile. If there is no appropriate radiator, then the geometry of the profile is determined for subsequent preparation of the radiator.

At the second level of the hierarchy, a method is sought for attaching elements and the structural-technological parameters for attaching elements to the plate (type of connection, screw tightening moment, required roughness of the contact surfaces, etc.). For this purpose methods for calculating a contact thermal resistance [5, 6] and algorithms in trial and error methods realized on a computer are used.

Design Results. The proposed system for automated design was used to calculate and design structures and cooling systems of several tens of variants of semiconducting switches; we shall present some examples.

It is necessary to choose a construction of a semiconducting switch with free and forced ventilation. The switch consists of 50 transistors and a single auxiliary diode. The power between the transistors and the diode can be distributed arbitrarily, so that in this work, we examine three variants of the distribution: in the first variant, all the power is uniformly distributed between the transistors $(\sum_{i=1}^{50} P_{tr\,i} = 200$ W), and there is no liberation of heat in the diode; in the second variant, heat is liberated in all transistors and the diode in the same manner, i.e., $\sum_{i=1}^{50} P_{tr\,i} = 100$ W, P_d = 100 W; in the third variant, all power is dissipated in the diode $(\sum_{i=1}^{50} P_{tr\,i} = 0$, P_d = 200 W). The permissible temperatures of the transistor housings are 100°C and that of the diode is 165°C. In examining structural variants with forced cool-

TABLE 1. Design Results

Form of convection	Free			Formed					
Temp. of medium, °C	50			30					
Charac. of the medium	Temperature head $\Delta T = 50$ K			Velocity of air flow V = 2 m/sec					
Form of radiator	Pronged			Pronged			Pronged		
α_{eff} of radia., W/(m^2 · °K)	59			230			38		
Height of prong (fin), mm	14						12,5		
Diameter of prong (thickness of fin), mm	2						1,5		
Distance between prongs (fins), mm	6,6						10		
Plate dimensions $L_x \times L_y$, mm	242×244			114×130			242×244		
Power distribution variants	1	2	3	1	2	3	1	2	3
Overheating of housing of most highly heated transistor, °K	50,7	35,7	29,1	46,6	38,6	37,2	68,0	52,3	46,5
Overheating of diode housing, °K	19,0	96,0	114,4	21,2	100,7	125,7	34,2	105,3	134,0

ing, the velocity of the air is assumed to equal V = 2 m/sec, while its temperature is t_m = 30°C. The temperature of the medium for the case of free convection is t_m = 50°C. After analyzing different variants, it was proposed that the construction be formed into two levels. The scheme for placing the elements in levels is given in Fig. 1. All geometrical and thermophysical parameters and their values, as well as the values of the overheating obtained in this case, are presented in Table 1.

The elements are attached with screws with the following structural and technological parameters: tightening moment $2.5 \cdot 10^{-2}$ kg/m; number of screws per transistor l = 2; height of microroughness of the structural surfaces, h_{av} = 30 μm; chassis material, AL2. The magnitude of the contact thermal resistance of the plate is R_d = 0.6 K/W for the diode and R_{tr} = 2.8 K/W for the transistor.

The advantage of the technique proposed for analyzing the temperature field and designing the setup lies in the comprehensive inclusion of a large number of different parameters and characteristics, such as the operational regimes and cooling regimes of the device, dimensions and construction, positioning of elements and methods for attaching them to the chassis.

Thus using the principle of modeling in stages and the proposed procedure for the calculations, the temperatures of the housings of the elements of semiconducting modules operating in the stationary state can be determined with a small amount of computer time and with accuracy satisfactory for engineering calculations. This permits using the proposed procedure in a system for automated design at the analysis stage of the design being developed. The potential for using the stage by stage procedure for modeling and designing devices should also be noted, since it is applicable to the analysis of the temperature fields of structures at any level of the hierarchy.

NOTATION

j, element situated on the plate; i, point on the plate at the location of attachment of the j-th element; t_m, temperature of the medium; t_{ist}, ϑ_{ist}, stationary temperature and overheating of the plate at the point of attachment of the j-th element; δ, thickness of the plate; λ, coefficient of thermal conductivity of the plate material; P_j, total power of the j-th element; P_i, part of the power of the i-th element passing through the contact thermal resistance into the plate; α_1, α_2, heat transfer coefficients on the basic surfaces of the plate; α_{0x}, α_{1x}, α_{0y}, α_{1y}, heat transfer coefficients on the end faces of the plate; L_x, L_y, plate dimensions; n, number of elements on the plate; $1\{U_i\}$, trace using a step function of a discrete heat source; τ, time; $t_j(\tau)$, $\vartheta_j(\tau)$, temperature and overheating of the plate at the point of attachment of the j-th element at time τ; m, rate of heating of the plate; C, total heat capacity of the structure (plate + elements); ψ, criterion for uniformity of the temperature field, equal to the ratio of the average surface temperature of the plate to its average volume temperature; σ, thermal conductivity from the plate to the medium; σ_m, σ_p, thermal conductivities from the housing of the element to the medium and into the plate; ϑ_j, average surface overheating of the element housing in the nonstationary state; m_0, rate of heating of the element; R_{in}, internal thermal resistance between the crystal and the element housing.

LITERATURE CITED

1. G. N. Dul'nev, B. V. Pol'shchikov, and A. Yu. Potyagailo, "Algorithm for modeling heat transfer processes in complex radioelectronic complexes," Radiotekhnika, 34, No. 11, 16-21 (1979).
2. G. N. Dul'nev, B. V. Pol'shchikov, and E. S. Levbarg, "Temperature field for plates with local heat source and heat transfer at the end-faces," Voprosy Radioelektron., Ser. TRTO, No. 1, 98-103 (1976).
3. G. N. Dul'nev and E. M. Semyashkin, Heat Transfer in Radioelectronic Devices [in Russian], Énergiya, Moscow (1968).
4. L. I. Roizen and I. N. Dul'kin, Thermal Calculation of Finned Surfaces [in Russian], Énergiya, Moscow (1977).
5. G. N. Ddul'nev, Yu. P. Zarichnyak, and B. V. Pol'shchikov, "Investigation of methods for regulating the thermal resistance between elements with contacts," Vopr. Radioelektron., Ser. TRTO, No. 2, 118-125 (1977).
6. V. N. Popov, Heat Transfer in the Contact Zone of Dismountable and Nondismountable Connections [in Russian], Énergiya, Moscow (1971).

USE OF CLASSICAL STEFAN PROBLEM FOR INITIALIZING SOLUTION IN THE NUMERICAL PREDICTION OF FREEZING

V. M. Gorislavets and V. A. Mitrokhin

UDC 536.421.4

The exact solution of the classical Stefan problem is examined from the point of view of using it as an "initial solution" in numerical solutions of appropriate problems.

The classical Stefan problem is taken to mean the self-similar one-dimensional problem of freezing or melting of a homogeneous isotropic medium with constant boundary conditions [1].

The solution of such a problem can be represented in the form

$$T_u(z,\ t) = T_w + \frac{T_f - T_w}{\operatorname{erf}\left(\frac{\beta}{2\sqrt{a_u}}\right)} \operatorname{erf}\left(\frac{z}{2\sqrt{a_u t}}\right), \tag{1}$$

$$T_v(z,\ t) = T_0 - \frac{T_0 - T_f}{\operatorname{erfc}\left(\frac{\beta}{2\sqrt{a_v}}\right)} \operatorname{erfc}\left(\frac{z}{2\sqrt{a_v t}}\right), \tag{2}$$

$$\zeta(t) = \beta\sqrt{t}. \tag{3}$$

The coefficient of proportionality β, characterizing the velocity of the phase transition

Kiev Branch of the All-Union Petroleum and Gas Scientific-Research Institute on Construction of the Main Pipelines. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 5, pp. 847-850, November, 1982. Original article submitted July 7, 1981.

0022-0841/82/4305-1304$07.50