APPLICATION OF METHODS OF COMPUTATIONAL IR THERMOGRAPHY IN COMPUTER-ASSISTED SYSTEMS FOR DESIGN OF RADIO-ELECTRONIC APPARATUS

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The technical means and methods making it possible to perform nondestructive checking of reliability and to obtain a thermally optimal arrangement of the heat-emitting elements in radio-electronic equipment, on the basis of both expert assessment of the temperature fields of the operating equipment and the use of the local heat-transfer coefficient as a criterion, are examined.

Existing systems for computer-assisted design of radio-electronic apparatus (REA) are, as a rule, oriented toward forming electronic schemes with topologically optimal electric circuits. The separate components of the microelectronic device are arranged on the board automatically or semiautomatically in an interactive mode so as to minimize the length of the current-carrying conductors. The reliability of the REA designed can be improved with the help of information about the thermal state of the components at the stage of design of the board topology.

Wide adoption of multilayered boards makes it possible to develop REA with thermally optimal mutual arrangement of components on a board, taking into account the specific conditions of heat exchange with the surrounding medium. Lowering the temperature of the active components of the REA makes the physicochemical processes resulting in the failure of REA less intense. Indeed, for integrated circuits failures are caused primarily by processes governed by corrosion owing to the effect of moisture, electromigration, electrocorrosion, and degradation of conductors. The lower reliability of REA is explained by higher temperature of the components in the static or transitional operating modes; in most cases this can be explained by incorrect choice of electric conditions and poor layout of the boards in the REA or of the cooling system [1].

In order to predict failures in REA it is necessary to know the temperature distribution on the surface of the boards at an arbitrary moment in time. To this end, laborious measurements of the temperature of separate components are usually performed using both contact and no-contact methods. The small size of the components makes it difficult to place on them contact sensors; in addition, a sensor operates in this case as a heat sink, which introduces errors in the measurements.

The methods of computational IR thermography can be effectively employed to increase the reliability and lifetime and to determine the probable reasons for failures and defects in complicated microelectronic apparatus. These methods make it possible to investigate, on the basis of analysis of the spatial distribution of the temperature over the entire surface of electronic boards, the operating temperatures of REA. The use of IR systems for monitoring the temperatures makes it possible to study the change in the temperature accompanying transient processes, for example, at the time the apparatus is switched on and off, when there is a high probability that the chosen temperature regime will be destroyed [2]. Reliable information about the temperature fields of electronic components can be obtained only by taking into account the emissivity of different components in the spectral wavelength range corresponding to the sensitivity of a particular IR recording system. This makes it difficult to employ published reference data, which, as a rule, are of an integral character. There are two methods for determining the emissivity experimentally with the help of systems of computational IR thermography: recording the spatial distribution of IR radiation from an isothermal surface of the radio-electronic board under study or recording external IR radiation reflected from the surface of interest.

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The determining criterion of the thermal regime, in addition to the temperature, is the effective heat-transfer coefficient of separate microelectronic components. In contrast to the temperature, this coefficient characterizes not only the operating regime of the components, but also the optimality of their mutual arrangement.

Identical microelectronic components operating in an identical regime but having a high effective heat-transfer coefficient will have a lower temperature. For this reason, it is important to determine the actual heat-transfer coefficients of the components of a geometrically complicated REA under real operational conditions. In order to determine the spatial distribution of the heat-transfer coefficient over the surface of a board it is necessary to know not only the absolute surface temperatures of the components themselves but also the temperature and velocity of the air flow cooling the REA. For this it is necessary to do the following:

Position in the plane of the board a small mirror reflector and a source of IR radiation at distances of up to 1 m;

Record the IR image of an operating board with signal amplitude

$$A(x,\ y)=\int\limits_{\lambda_1}^{\lambda_2}\varepsilon(\lambda)\,d\lambda\int\limits_{\lambda_1}^{\lambda_2}b_0(x,\ T)(\lambda,\ T)\,d\lambda; \tag{1}$$

Record the IR image of an operating board illuminated with an external source of radiation:

$$B(x,\ y)=\int\limits_{\lambda_1}^{\lambda_2}(1-\varepsilon(\lambda))\,d\lambda\int\limits_{\lambda_1}^{\lambda_2}b_1(\lambda,\ T)\,d\lambda+A(x,\ y) \tag{2}$$

and, separate an element B_m corresponding to the surface of the reflector:

$$B_m=\int\limits_{\lambda_1}^{\lambda_2}b_1(\lambda,\ T)\,d\lambda; \tag{3}$$

Calculate the effective emissivity of the elements of the image using the Kirchhoff approximation:

$$\int\limits_{\lambda_1}^{\lambda_2}\varepsilon(x,\ y)\,d\lambda=1-(B(x,\ y)-A(x,\ y)/B_m; \tag{4}$$

Reconstruct from A(x, y), including ε(x, y), the absolute temperature taking into account the selective character of the sensitivity of the IR system, as described in [2, 3], or estimate the temperature with the help of the formula

$$T(x,\ y)=k\sqrt[4]{A(x,\ y)/(\sigma S)}, \tag{5}$$

where k is determined by the geometry of the experiment;

Place a metal-coated polymer film directly next to the board and measure the spatial distribution of the temperature of an airflow, in a manner analogous to that described above. In this case, the metal coating will prevent heating of the film by the radiation flux from the REA, and analysis of the temperature distribution will make it possible to determine unequivocally the effectiveness of the cooling system employed;

Measure the temperature distribution T'(x, y) along the film, heated by an electric current, when the plate is switched off and the cooling system is switched on;

Measure the temperature distribution T''(x, y) along the film, heated by an electric current, when both the plate and cooling system are switched off;

Calculate the spatial distribution of the velocity of the air flow V(x, y) according to the formula

$$V(x,\ y)=kh_f(T(x,\ y)-T_a(x,\ y))(\overset{a}{c}_\rho\overset{a}{\rho}(T''(x,\ y)-T'(x,\ y)))^{-1}; \tag{6}$$

Determine, assuming the air flow is laminar and uniform, the local values of the heat-transfer coefficient, using the previously obtained data and a priori information about the electronic components using the formula

$$\alpha_k(x, y) = \frac{P}{(T(x, y) - T_a(x, y))S}; \tag{7}$$

And, display the computational results in the form of isolines or multidimensional projection on a screen of a color monitor or with the help of a plotter on paper.

The approach described above makes it possible to use the method of computational IR thermography not only for diagnostics of the electronic apparatus, but also for nondestructive testing. On the basis of the experimental data it is possible to optimize the thermal operating regimes of the REA, using as the criterion the maximum increase of the heat-transfer coefficient.

Another promising direction of investigation is to use systems of computational IR thermography for calculating the predicted reliability of complicated electronic circuits [4].

Since the reliability of microelectronic components is significantly determined by temperature-dependent chemical reactions occurring in them, the temperature and time dependence of the reliability can be described by Arrhenius' equation

$$\frac{dx}{dt} = -kf(x) = -A\exp(-\Delta E/RT)f(x). \tag{8}$$

The lifetime t_e, which corresponds to fixed maximum values of x_e, is determined with T = const by the expressions

$$\log t_e = k + \Delta E/RT, \tag{9}$$

$$t_e = \exp(k + \Delta E/RT). \tag{10}$$

The use of a system of computational IR thermography makes it possible to construct, from the results of temeprature measurements, two-dimensional fields characterizing the reliability of a part. Analysis of the obtained spatial distribution of the temperature over the surface of boards in the REA makes it possible to reject electronic components whose surface temperature gradient exceeds 20% of the maximum temperature. Experiments show that such components have the lowest operating lifetime, probably because of the destructive effect of thermal stresses; this is confirmed by results of thermal cycling of parts.

Thus the integrated application of methods and apparatus of computational IR thermography in designing REA makes it possible to develop designs with optimal thermal operating regimes, high reliability, and long operating lifetime.

NOTATION

Here A(x, y) and B(x, y) are the amplitude of the television signal, corresponding to an element of the iamge with the coordinates (x, y); λ is the wavelength of the recorded radiation; $\varepsilon(\lambda)$ is the spectral emissivity; $\varepsilon(x, y)$ is the integrated emissivity of an element of the image with coordinates (x, y); $b_0(\lambda, T)$ is the distribution of the radiation density of the recorded surface; $b_1(\lambda, T)$ is the distribution of the radiation density of the external source; B_m is the intensity of the television signal, corresponding to the spectral reflector; T(x, y) is the surface temperature; σ is Boltzmann's constant; k = const determines the geometry of the experiment; $T_a(x, y)$ is the local temperature of the airflow; $T'(x, y)$ and $T''(x, y)$ are the values of the local temperature of the film; V(x, y) is the velocity of the airflow; h_f is the heat-transfer coefficient; c_{ρ}^a is the heat capacity of air; ρ^a is the density of air; $\alpha_k(x, y)$ is the local heat-transfer coefficient; P is the thermal power emitted by an electronic component; S is the effective surface area of the electronic component (the area of an element of the image); A and k are the effective chemical-reaction constants; x is a parameter with respect to which the temperature-induced degradation of the characteristics of the REA occurs; ΔE is the activation energy of the reaction; R is the universal gas constant; f(x) is the concentration function; t is the reaction time; and t_e is the operating lifetime, which corresponds to fixed limiting values.

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