Infrared system for thermal resistance measurement of microobjects

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Abstract. The original measuring system and method of temperature fields measuring of integrated circuits chips for controlling of thermal resistance between a chip and its case under production conditions is presented. The infrared system allows temperature measuring over the range (40–150)°C, and also allows to spot small gains of IC chips temperature around 1°C. The developed system based on infrared microbolometric matrix and allows controlling of integrated circuits chips temperature fields with the high spatial resolution up to 15 microns.

1. Introduction
The IR system and method of measuring of thermal resistance between an integrated circuits chip and its case under production conditions is presented.

The developed system based on infrared microbolometric matrix allows integrated circuits chips temperature fields controlling with the high spatial resolution up to 15 microns. The system allows temperature measuring over the range (40–150)°C, and also allows to spot small gains of IC chips temperature around 1°C at various operating modes. The instrumental error of temperature measuring does not exceed ±0.5°C for a blackbody model. For determination of thermal resistance in the system included special bulk copper heat load that provides IC case temperature stabilization in range (40–160)°C at drift less than ±0.1°C.

The system consists of the opto-electronic block with a microbolometric matrix, the infrared objective with precision fluid-flow temperature stabilization of the case, the heat load with adjustable temperature and the fluid-flow thermostat with the solid-state cooling medium.

2. Principle of operation
The infrared pyrometry system for temperature distribution measuring of microcircuit chips with micron resolution is developed on the basis of a microbolometric matrix. The principle of temperature measurement is based on spectral separation of a portion of thermal radiation from the entire flow of thermal energy emitted by a heated body using wideband interference filters. The microbolometric matrix on amorphous silicon, which has a maximum sensitivity in the infrared range of 8 to 12 microns converts this radiation into analog signal. This signal after amplification is fed to a 16-bit analog-to-digital converter and then digital code after sensitivity correction and bad pixels replacing is transmitted via USB interface to the PC.

The method for determining junction-to-case thermal resistance of microcircuits and semiconductor devices, based on measuring 2D temperature fields of the top surface of ICs die...
at a fixed case temperature was implemented. Junction-to-case thermal resistance $R_{thJC}$ is originally defined for devices with nearly perfectly one-dimensional heat flow. In such a case it can be defined simply [1] as:

$$R_{thJC} = \frac{(T_{chip} - T_{case})}{P_W}, \quad (1)$$

where $T_J$ means the temperature of the junction at a certain powering, $T_C$ the temperature of the case and $P_W$ the power dissipated at the junction layer of IC chip. This quantity is the preeminent figure in product datasheets concerning the thermal properties.

3. Temperature measurement method

A photodetector (microbolometric matrix) records an electric signal that is proportional to thermal radiation intensity of the object and which can be calculated by integrating the radiation intensity within the solid angle $\omega$ and in the spectral range $\lambda_1-\lambda_2$, taking into account the geometric factor of the optical system. The spectral range is determined by the IR filters, spectral sensitivity range of the microbolometric matrix, the optical properties of the intermediate medium and the object under investigation. Obviously, in the process of measuring the solid angle remains constant, therefore, if we ignore the effects of second order of smallness, such as the temperature dependence of the indicatrix of the object radiation or errors due to inaccurate focusing, the integral over $\omega$ will be included in the conversion factor of the system $K$. The expression for the signal measured by the IR system can be written in the following form:

$$U(T) = K \int_{\lambda_1}^{\lambda_2} \epsilon_{\lambda,T} C_1 \lambda^{-5} \left( \exp\left(\frac{C_2}{\lambda T}\right) - 1 \right)^{-1} d\lambda =$$

$$K \epsilon_{\lambda_1-\lambda_2,T} \int_{\lambda_1}^{\lambda_2} C_1 \lambda^{-5} \left( \exp\left(\frac{C_2}{\lambda T}\right) - 1 \right)^{-1} d\lambda, \quad (3)$$

where $K$ is the system conversion factor, $\epsilon_{\lambda,T}$ is the spectral emissivity, $\epsilon_{\lambda_1-\lambda_2,T}$ is the effective emissivity, $C_1$, $C_2$ is the first and second radiation constants. The system calibration equation can be written as:

$$\frac{1}{T_{pyr}} = \sum_n A_n f(U)^n, \quad (4)$$

where $n = 3$, $A_n$ – coefficients are found by the ordinary least squares (OLS) method during calibration via reference blackbody model.

When measuring the temperature of real bodies, it is necessary to make corrections to the emissivity, i.e. need to know $\epsilon_{\lambda_1-\lambda_2,T}$. The expression for the calculation of $\epsilon_{\lambda_1-\lambda_2,T}$ can be written as:

$$\epsilon_{\lambda_1-\lambda_2,T} = \frac{\int_{\lambda_1}^{\lambda_2} \lambda^{-5} \left( \exp\left(\frac{C_2}{\lambda T_{pyr}}\right) - 1 \right)^{-1} d\lambda}{\int_{\lambda_1}^{\lambda_2} \lambda^{-5} \left( \exp\left(\frac{C_2}{\lambda T}\right) - 1 \right)^{-1} d\lambda}. \quad (5)$$

When calculating the emissivity, equation (4) is solved for $T_{pyr}$. Then for the found value of $U$ at a given object temperature $T = T_0$, the emissivity is calculated. Then one can measure the true temperature of the object in a given temperature range, for example, around $\pm(10-30)^\circ C$ of $T_0$, at which $\epsilon_{\lambda_1-\lambda_2,T}$ was determined (5). This is based on the fact that the emissivity of a silicon chip in the IR ranges changes, as a rule, only slightly. For example, black acrylic paint, which is used for thermal testing of IC chips, has an emissivity of $\epsilon \approx 0.8$, which changes by 0.04 in the temperature range of $40-120^\circ C$ [2]. This introduces an additional error in determining the temperature in the range of $40-120^\circ C$ less than $1^\circ C$. 


4. Technical characteristics and design of the IR system

The image of the object is formed in the plane of the microbolometric matrix using a special infrared lens with an aspheric optical element. The lens magnification is $1:7$, which provides a spatial resolution of about 15 microns. The measured signal from the microbolometric matrix largely depends on the matrix temperature and on the background temperature. Therefore, when developing the system, a thermostat was created for the matrix. The matrix was dismantled from the standard housing and placed on a copper plate that served as a heat sink. At the other end was installed thermal cooler. The assembly of the matrix and the temperature sensor was insulated. By adjusting the temperature of the cold junction of the thermal cooler, the thermostat was adjusted according to the signal from the temperature sensor. The developed precision pulse-width modulator maintained the matrix temperature at a level of $16 \pm 0.01^\circ C$.

The calibration of the system is performed in the temperature range of $35–150^\circ C$ with a step of about $10 ^\circ C$ along the reference blackbody model with an aperture of at least 38 mm. Calibration coefficients are then calculated and written to a file. Calibration error does not exceed $\pm 0.5^\circ C$ in such temperature range.

5. Results of measurement

The IR system is designed to measure 2D temperature fields of IC chips in mode of measuring the relative temperature increment when changing the modes of operation of the test chip. Such measurements are carried out in two stages. At the first stage, temperature field of the chip is measured while the case of IC is fixed on the isothermal radiator and the supply voltage is not applied to the chip. So, in the absence of heat sources, it can be assumed that the temperature distribution of the chip surface is uniform, and the temperature of the chip can be equated to the temperature of the isothermal radiator [2]. According to this assumption, it is possible to

![Figure 1. Temperature field measured during IC chip testing.](image)
calculate the effective emissivity field at each point of the micro-object and use this data at the second stage of measurements.

At the second stage of measurements the supply voltage is applied to the chip and the field of the increment temperature is measured taking into account the emissivity measured at the first stage. Figure 1 shows the temperature difference field measured during the test of the chip in the operating mode at the power consumption of 1.16 watts.

The figure shows that in test mode the IC chip is heated non-uniformly, near the power supply pads and near of protective diodes placement there is maximum heat dissipation and the maximum temperature increment is $6.0 - 7.4 \degree C$. In center of the chip and away from the power pads, the temperature increment is smaller and amounts to $4.1 \degree C$ and $3.2 \degree C$, respectively. For example, the figure shows the measurement results of chip heating in a test mode without a blackening coating that commonly used to increase silicon IC chip emissivity during testing. The effective emissivity $\epsilon_{1-2,T}$ at the point with coordinates $X = 91$, $Y = 180$ is $0.258$, and the measured value of the temperature increment is in good agreement with measurements at neighboring points with emissivity of $0.4 - 0.47$. Calculation of thermal resistance $R_{th-JC}$ at the hottest spot gives $6.3 \degree C/W$.

6. Conclusion
The IR system based on a microbolometric matrix was developed and tested for measuring temperature fields of IC chips under thermal testing. The system allows measuring temperature fields in the range of $40 - 150 \degree C$, effective emissivity and temperature increment fields. The temperature increment field that is temperature difference between the IC chip in the operating mode and in quiet state is used to calculate junction-to-case thermal resistance. During the design of IR system, the problem of the stability of temperature measurements was solved by reducing the influence of the thermal background during long-term measurements. Tests have shown that the IR system allows one to measure temperature increment less $1 \degree C$, and also to detect defects caused by errors in IC chip design or chip mounting and which lead to local overheating of the surface.

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