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## Low-cost IR system for thermal characterization of electronic devices

### Abstract

In this article, a Low-cost measurement Infra-Red (IR) system for dynamic thermal testing of electronic devices is described. The element is powered by a step-function current and simultaneously temperature is measured by a fast single-detector IR head. The thermal impedance  $Z_{th}(j\omega)$  is calculated using the Laplace transform and the Foster network is to get thermal time constants distribution.

**Keywords:** thermal impedance, Foster network, thermal time constants, temperature measurement.

### 1. Introduction

The thermal characterization of electronic systems can be carried out in steady-state or dynamic conditions. The thermal performance in steady-state conditions is described by thermal resistance while in transient condition by thermal impedance.

There is a standard of measurement the thermal resistance and impedance described in JESD51-1 norm [1]. This standard assumes the power dissipation in the tested device in form of step-function and simultaneous measurement of temperature, typically by a contact sensor. In many practical cases, it is possible to use a sensor inside a Device Under Test (DUT), e.g. the technological diode in MOS or p-n emitter junction in bipolar transistors.

There is a commercial system implementing JESD51-1 standard –Thermal Transient Tester (T3Ster) [2, 3]. It is a professional tool used by many producers of electronic devices and systems. The high price is the drawback of this system.

We propose a low-cost IR system to measure temperature while heating a DUT. The IR system allows registration of temperature on the surface exposed to the thermographic system. The outer surface of a DUT sometimes is far away from the heat source. In this way we estimate the transfer impedance. In order to fulfill the requirements of JESD51-1 standard and measure temperature in or very close to the heat source, using modeling we can calculate the thermal impedance in the proper place in the semiconductor structure.

### 2. Measurement system

The block diagram of the proposed measurement system is shown in Fig. 1. The main element of the system is a single point IR head. This head is equipped with 1 mm<sup>2</sup> MCT photovoltaic cooled detector combined with 4-stage thermoelectric cooler [4, 5]. The detector's spectral characteristic has maximum absorption in MWIR wavelength range at about  $\lambda=5 \mu\text{m}$ . In order to improve sensitivity, the detector is integrated with immersion lens and with external optics it has 36° FOV. The IR head sensor is equipped with a preamplifier which ensures stable operation in wide range of ambient temperature with the highest SN ratio.

In order to power the DUT and to capture the output signal, a dedicated electronic controller was developed. The digital part of the control system was integrated in XC6SLX9 FPGA module [6]. The controller allows transferring data via USB high-speed link. For USBHS interface we applied FT2232H module (FTDI) [7]. FTDI transfers data at the rate up to about 40 Mb/s. In addition, PIC18F4520 microcontroller (MCU) is applied to program the peripherals, mainly ADC using SPI interface [8]. The ADC circuit is composed of ADS7056 and fully differential operational amplifier AD8475. 14-bit resolution ADC can acquire temperature variation with 2.5 MSPS sampling rate.

In addition, the proposed system contains an interchangeable adapter for different kinds of tested electronic devices, such as bipolar and MOS transistors, diodes, resistors, etc. The power controller is based on MAX5354 Digital to Analog Converter (DAC) and MAX44242 operational amplifier (OA). The power dissipated in a DUT is set and controlled by MCU and allows precise synchronization of temperature measurements and power dissipation in DUTs. The block diagram of the developed testing system is shown in Fig. 2.

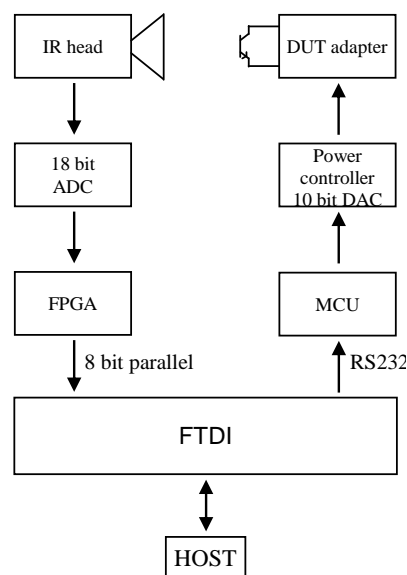


Fig. 1. Block diagram of IR system for thermal characterization of electronic devices

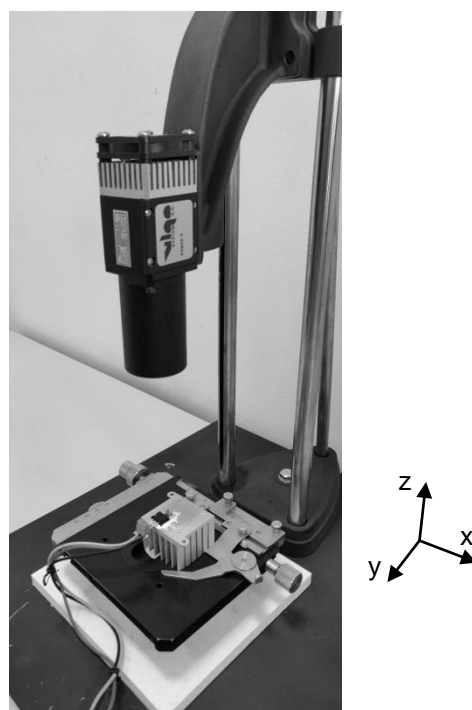


Fig. 2. Measurement IR system for thermal characterization of electronic devices

The Movement of the IR head in the vertical direction ( $O_z$  axis) is realized manually using a photographic stand. In addition, movement in the horizontal directions (in  $Oxy$  plane) is realized using the micrometer table. Furthermore, the micrometer table is realized manually using a photographic stand. The micrometer table is equipped with two handles that enables reliable fixing of the DUT.

The radiation sensor was calibrated using FLUKE 4181 blackbody as shown in Fig. 3 [9].

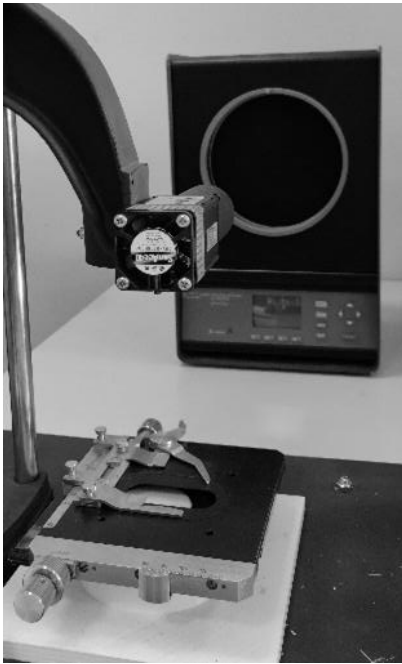


Fig. 3. Calibration of the developed system using a blackbody

Signal from the detector (expressed in millivolts) was registered during 30 seconds for varying temperature values of the blackbody. Then, the registered calibration signals were averaged. The calibration was made in the temperature range (25 – 150)°C. In this stage of the research, calibration is valid for constant ambient temperature  $T_a = 25^\circ\text{C}$ . The calibration curve is shown in Fig. 4. A 4<sup>th</sup> order polynomial was used to approximate the discrete calibration data. The correlation coefficient of this approximation  $R^2$  equals to 0.9996.

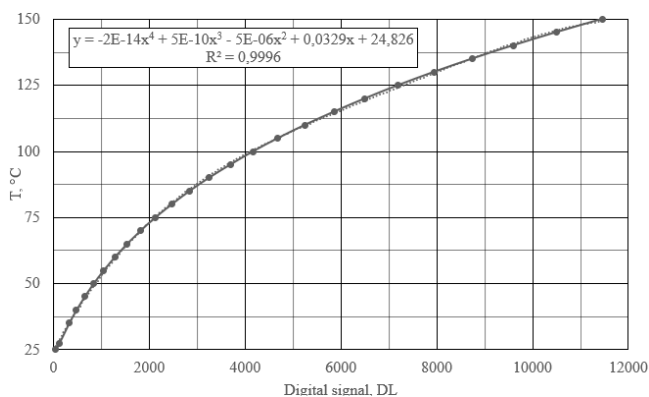


Fig. 4. Calibration curve

### 3. Temperature acquisition software

Two software packages were developed in the research presented in this paper. One of them is *IR Data Logger* written in C# environment and is used to perform high-speed digital data acquisition from the IR head. The main window of *IR Data Logger* program is shown in Fig. 5. This program allows setting the sampling period, total acquisition time and DC current/power supplied to a DUT. At first, the measurement system has to be connected to a computer using USB link. After successful connection and setting the measurement parameters, the system is ready to power a DUT and register temperature response in time. After registration, the measured data are saved to a \*.txt file for further analysis by the signal processing software.

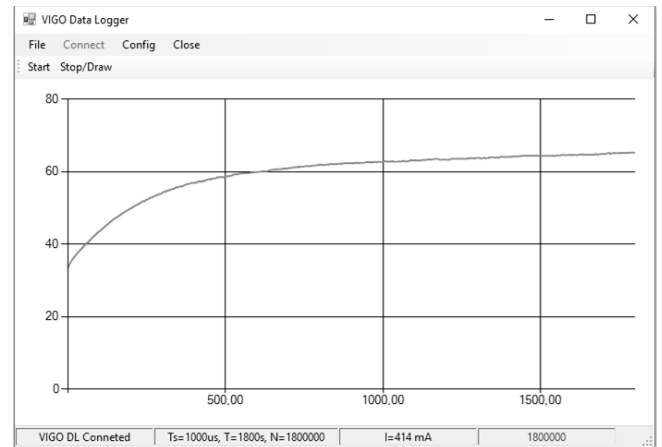


Fig. 5. The measurement window of the temperature acquisition program

### 4. Measurement method

A new method for thermal characterization of electronic devices was implemented. A thermal model in frequency domain of the multilayer structure of a DUT was elaborated. This 1D model calculates the thermal impedance of an electronic device in the form of the Nyquist plot [10, 11].

$$Z_{th}(x, j\omega) = \frac{T(x, j\omega)}{P(x, j\omega)} \quad (1)$$

where  $x$  is a position in the multilayer structure the thermal impedance is considered.

For a step-function power dissipated in a DUT the thermal impedance is calculated using the Laplace transform for  $s=j\omega$  [12, 13].

$$Z_{th}(j\omega) = \frac{j\omega}{P_0} \int_0^{\infty} T(t) e^{-j\omega t} dt \quad (2)$$

Next, knowing the thermal impedance presented in frequency domain, the thermal time constant distribution is estimated using *tfest* function in-built in the MATLAB program. The time constant distribution  $R(\tau)$  is in fact the impulse response  $h(t)$  of a thermal dynamic system. Using  $h(t)$  it is possible to get the thermal response for any power  $P(t)$  by performing convolution  $T_{model}(t) = h(t) * P(t)$ .

Using the analogy between thermal and electrical phenomena, time constant distribution  $R(\tau)$  can be represented by a Foster network.

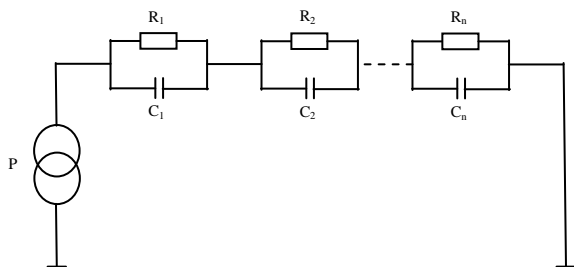


Fig. 6. Equivalent Foster network of thermal multilayer structure

Having the identified parameters of the Foster network, it is possible to get the step-function thermal response directly.

$$T(t) = P_0 \sum_{i=0}^{\infty} R_i \left[ 1 - \exp\left(-\frac{t}{\tau_i}\right) \right] \quad (3)$$

where:  $R_i$ ,  $\tau_i = R_i C_i$  – thermal resistance and time constant of  $i$ -th layer of a DUT.

It has to be underlined that Foster network has no physical meaning. Therefore, it is worth to use the Cauer RC network that can be constructed directly from the Foster one.

Simultaneously with modeling, temperature evolution in time is measured on the outer surface of the case  $T(t)$  by the IR head. Then, temperature variations obtained from the model and the measurements are compared. The difference between them is a measure of disparity and is used for tuning the model until simulated and measured temperature is matched.

One should notice that because temperature is measured on the upper surface of the case of an electronic device, the simulations have to be performed for the same place, and in consequence we get transfer thermal impedance.

This transfer thermal impedance does not meet the requirement of the standardized thermal measurements of electronic devices. Due to this fact, we propose to use the model mentioned above to recalculate thermal impedance in the place where the heat source is located. Therefore one needs an optimization procedure for adjustment of thermal and geometrical parameters of the multilayer structure model.

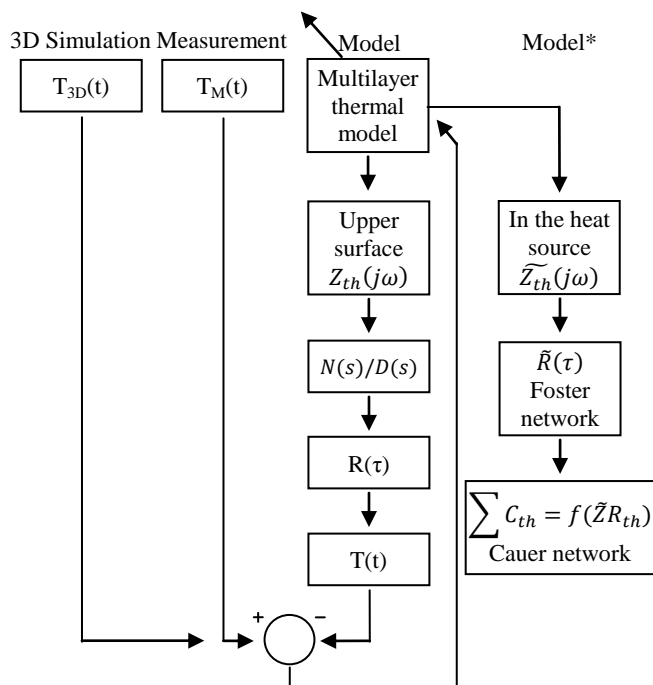


Fig. 7. Block diagram of the proposed method for thermal characterization of multilayer electronic devices

The model is semi-analytical [13]. For each layer the solution of heat transfer equations is analytical, and in order to combine a few layers together, we need boundary and interface conditions. They allow presenting the whole model in form of linear equations set. This set is solved numerically, using e.g. Least Square Method. The block diagram of the proposed method is presented in Fig. 7.

### 5. Signal processing software

The second software package developed in the presented research is the program *IRTherm* written in the MATLAB environment for advanced signal processing. The main window of it is shown in Fig. 8.

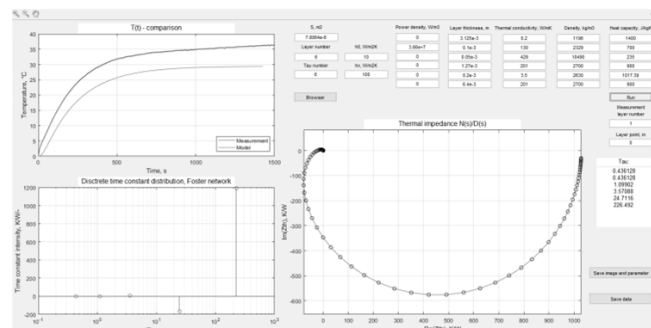


Fig. 8. The simulation program during selection of the parameters

The program *IRTherm* allows loading the registered temperature signal from *IR Data Logger* package. The developed program provides couple of functions listed below.

- Setting values of parameters that are necessary for simulation. The list of parameters is given in table 1.
- Selection of simulation points in any place for any layer where the thermal impedance is calculated. User enters the layer's number and the coordinate within the layer.
- Display of obtained thermal impedance (Nyquist plot) and values of thermal time constants.
- Saving results and obtained characteristics to \*.csv file
- Saving graphics to \*.jpg file.
- Saving entered parameters to \*.txt file

Tab. 1. Parameters of model of multilayer electronic structure [Fig. 9]

Symbol	Unit	Parameter
$S$	$m^2$	cross sectional surface
$h_0$	$W/m^2K$	heat transfer coefficient on the upper
$h_n$	$W/m^2K$	heat transfer coefficient on the bottom of the heat sink
$d_i$	$m$	$i$ -th layer's thickness
$k_i$	$W/(m \cdot K)$	thermal conductivity of $i$ -th layer
$\rho_i$	$kg/m^3$	density of $i$ -th layer
$c_{pi}$	$J/kgK$	specific heat of $i$ -th layer
$q_{vi}$	$W/m^3$	power density of $i$ -th layer

The *IRTherm* program operation consists of several steps. First step **Measurement** is to load the measurement data from IR head for further processing. The data from *IR Data Logger* is kind of a reference and it is used in the optimization procedure.

Second step **Model** is to calculate temperature in a given point in the structure for assumed parameters in each layer –  $S$ ,  $d$ ,  $\lambda$ ,  $\rho$ ,  $c_p$ , for given convection coefficients  $h_0$ ,  $h_n$  and power densities  $q_v$ . This step can be repeated sufficient number of times with different values of thermal and geometrical parameters to get agreement of measured and modeled temperature.

After matching results for experiments and modeling, third step **Model\*** can be executed to change the simulation point to one corresponding to the heat source in electronic device.

In order to validate the proposed algorithm, the data from the measurement can be replaced by results of 3D modeling using commercially available software. In this research we intend to perform the similar procedure of signal processing using data from 3D commercial package for physical simulations – COMSOL [14]. We use this software as a reference to compare the results with our simplified modeling. The block diagram of program operation is shown in Fig. 7.

## 6. Exemplary results

Let us consider a bipolar power transistor placed on a heat sink where the constant power starting in time  $t_0 = 0$ , is dissipated  $P(t) = P_0 \cdot 1(t)$ . In consequence, the temperature rises above ambient  $T(t)$  and is registered by the IR head.

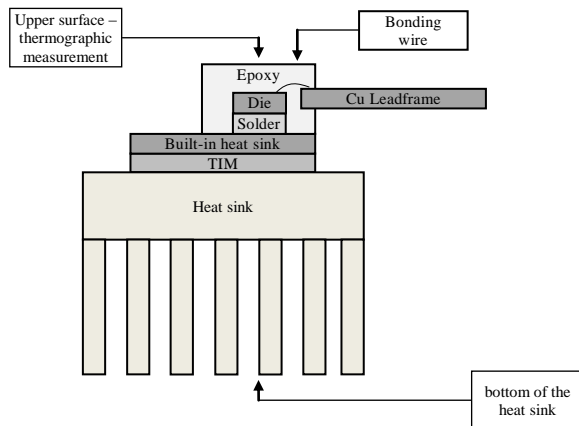


Fig. 9. Cross section of tested object

The cross-section of the power element is presented in Fig. 9. As assumed, it is the multilayer structure with different thickness and thermal parameters of each layer.

In the study we used BD911 BJT transistor in the TO220 case placed on a heat sink. The thermal parameters are determined analyzing heat flow from the semiconductor die to the heat sink and ambient. Fig. 9 shows the tested structure. In order to model correctly the power transistor, we defined Foster network with  $n=5$  layers. The following components are included in the model: die, solder, in-built heat sink, Thermal Interface Material (TIM) and radiator (main heat sink).

The exemplary temperature rise in different layers of the transistor is shown in Fig. 10. A delay is visible for temperature measured at the epoxy surface about 3 mm away from the heat source. It results in getting transfer thermal impedance and does not meet the requirements of the standard [1]. Therefore for further analysis we take the temperature in the die obtained from the model.

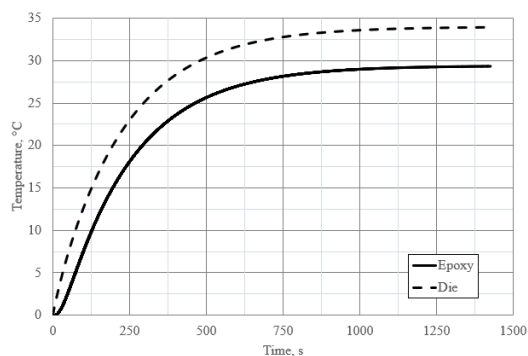


Fig. 10. Modeled temperature in the die and measured temperature at the upper epoxy surface for BD911 transistor

## 7. Conclusions

In this paper we present a low-cost IR measurement set-up and software for thermal characterization of electronic devices using thermal impedance in frequency domain and thermal time constant distribution. Developed system can be used in both industrial and scientific applications. The proposed system is equipped with single-detector cooled MWIR IR head which allows sampling temperature at the rate of about 10  $\mu$ s.

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