Crosstalk Compensation in Thermal Transient Measurements

Péter G. Szabó, Vladimír Székely

Abstract—Nowadays as the application area of thermal transient testing is advancing further than just being a JEDEC (Joint Electron Device Engineering Council) standard to investigate the thermal behavior of electronic devices, packages etc., the importance of avoiding any disturbances in the measured signal is more relevant. A possible effect that can corrupt the signal is the electrical crosstalk between different parts of the system or between the ambient and the whole system. But if the characteristic behavior of the crosstalk is known then special procedures can be designed in order to clean the corrupted signal from the disturbances. In our paper we present two methods to eliminate the disturbing effects. The first approach is based on polarity inversion while the second utilizes multiple level excitations to manage signal separation. To verify the feasibility of these methods, the procedure is demonstrated on electro-thermal MEMS (microelectromechnical system) devices.

***Index Terms*—Crosstalk compensation; Polarity change; Regression; Thermal transient testing;**

I. INTRODUCTION

Nowadays the importance of thermal transient measurement increases as it became an industry standard to describe the thermal behavior of electronic devices and packagings [1][2]. As its application area is being pushed further to its limits [3][4][5] it has become evident to investigate the applicability, precision and noise sensitivity for measuring other devices, such as electro-thermal microsystems. From the transient temperature response of such a device, its Cauer R-C ladder and other important parameters such as the speed of thermal functional circuits can be derived (Fig. 1). However these microdevices are more sensitive against the disturbances caused by the parasitic elements than the macro scale devices because of their small geometric sizes. This kind of disturbances can be originated from the device itself or from the evaluating electronics. Depending on their location they produce an undesired signal with small or large amplitude in the transient response which could undermine our attempt to create the thermal equivalent circuit of the device. A typical disturbance is originated from the parasitic electrical impedance of the system which time constant is in the range of ms-μs.

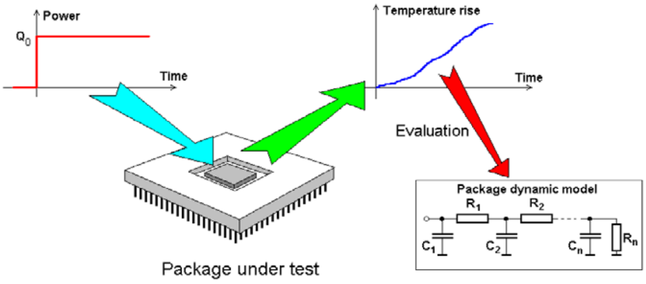

Fig. 1 Concept of thermal transient measurement

By using some special mathematical methods such as linear or square rooted curve extrapolation on the response function the unwanted signal can be filtered, but if the parasitic time constants are in the same range as that of the device then the result of the filtering will be inaccurate.

It is more straightforward to develop a special technique where the separation of the parasitic and the useful signal can be achieved.

In this paper we present two methods to separate the unwanted electric components from the thermal parts in the thermal transient measurements. In the early region of the thermal transient measurement results peaks and other non-linearities may appear in the response function due to the electric coupling between the input and the output nodes which may influence the precision of the measurement. There are a few heuristic solutions where a linear or square function is fitted to the inflexion or minimum point of the temperature rise curves. However these solutions are not adequate when structures with small time constants – for example MEMS – are measured [6][7]. These papers mention a compensation method where the thermal response is separated from the parasitic electric signal at electrostatic resonators. In the measurement setup two independent current sources were used which were utilized in common and reverse mode. As a consequence by measuring the electric resistance of the resonator the end of the electric signal and the beginning of the thermal response have been managed to pinpoint.

Another interesting method developed to filter out the electrical part in thermal transient measurements of HEMT devices was introduced recently where the basic voltage driven setup was replaced by a mixed voltage-current driven setup [8]. The basic idea behind this concept was to prevent the so called drain-lag [9]. Another often used method to separate the electrical and thermal part in the transient response of semiconductor devices is to measure them with higher input amplitudes. This can result in a faster current

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buildup which carries faster electrical transient that can become separable from the thermal transient.

However these methods cannot be used when the response signal is distorted by parasitic crosstalk and neither can it be generalized to be used on other structures. One of the main advantages of our newly developed characterization methods are that they can be utilized when the systems have different layout and work at other multiphysical domains as well. In addition they give the opportunity to minimize or filter out the errors which come from electrical crosstalk by processing the response function recorded at different levels of excitations.

II. INVESTIGATED SYSTEM

Examples of such systems which have small thermal time constants are called Quadratic Transfer Characteristics microsystems [10] or thermal converters [11]. The schematic of the MEMS is shown in Fig. 2. This electro-thermal device contains a dissipating resistance (*R*) which heats up a region *H* of the substrate while a thermocouple array senses the temperature difference between the *H* hot region and the *C* cold side. Since the dissipated heat is related to the square of the V_0 voltage, the T_H-T_C temperature difference and thus the output voltage will be proportional to the square of V_0. Thanks to its operation in multiphysical domains the structure is suitable to be used to identify its thermal and electrical parameters as well.

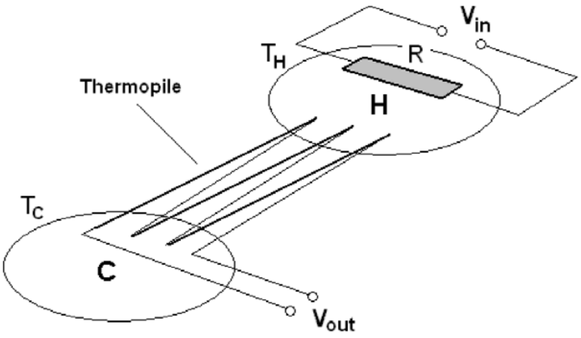

Fig. 2 Principle of the QTC element

The chips which we use were manufactured at TIMA Laboratory [12] by a combination of front-side bulk micromachining and CMOS technology. The previously described circuits which are shown in Fig. 3 were realized on cantilevers for better thermal isolation.

According to [10] [13][14] the time-constants of the cantilever can be calculated as:

$$|\sigma| = \frac{1}{\tau} = (2 \cdot n - 1)^2 \cdot \frac{\pi^2}{4 \cdot R_{th} \cdot C_{th}} + \frac{G_{th}}{C_{th}} \qquad (1)$$

where R_{th} is the thermal resistance, C_{th} is the thermal capacitance, the G_{th} is the parallel conductance of the surrounding air and *n* is an integer giving the n^{th} time constant.

It should be noticed that the system has symmetrical layout and is thermally insensible to polarity change.

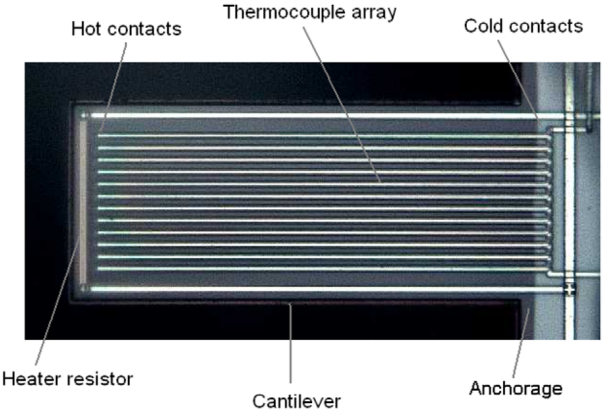

Fig. 3 The investigated microsystem

III. POLARITY CHANGE METHOD

Our first suggested solution for filtering the crosstalk is based on polarity inversion. If we assume capacitive coupling between the input and the output, then the charge movements at dynamic measurements induce a current and with it, a voltage glitch in the output signal. This scenario happens for example at a thermal transient measurement [15]. However the direction of this glitch depends on the polarity of the driving voltage. If the input is driven with positive voltage (compared to ground) then there will be a positive peak in the response function of the thermal transient measurements (Fig. 4). If the input is driven with a negative voltage then a negative peak will arise in the response function (Fig. 5). When evaluating the measurement with the standard method described in section I, these peaks will cause an additional time-constant and will also shift the time constants of the system which are in the same range.

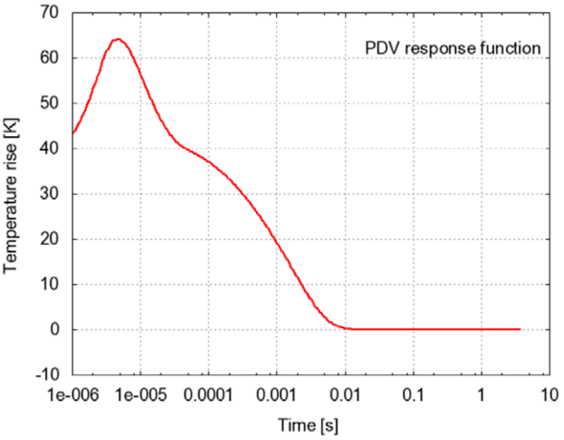

Fig. 4 Response function for positive driving voltage

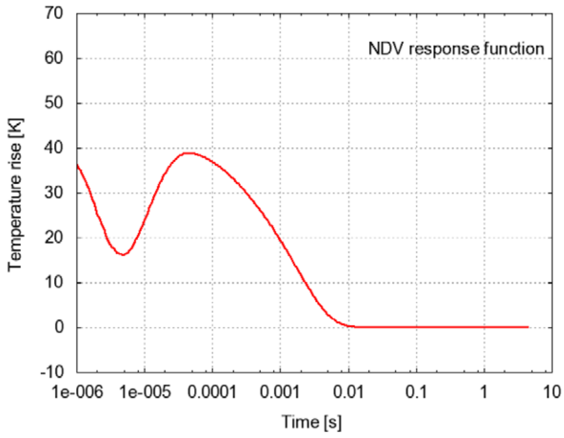

Fig. 5 Response function for negative driving voltage

The effect of polarity change against the direction of the peaks can be used when the results are processed. In theory the peaks have the same amplitude, so if the average of the two response functions is composed along the timeline, then the crosstalk free signal can be obtained. Based on this assumption, if we subtract the signals from each other and divide them by two, then the coupling signal will remain. It is practical to make these modifications in the early steps of the processing, because after this step the evaluation can be continued with the standard thermal transient evaluation methods. A processed but pre-evaluated response function can be seen in Fig. 6 where the unwanted crosstalk has been eliminated and only a small distortion remained in the early part of the response function.

It must be stated that this method can only be used if the investigated device is not sensitive to polarity inversion, but the noise is. For example this method cannot be applied to a diode or to a transistor because these devices behave in an absolutely different manner when their input is driven by positive or negative voltages.

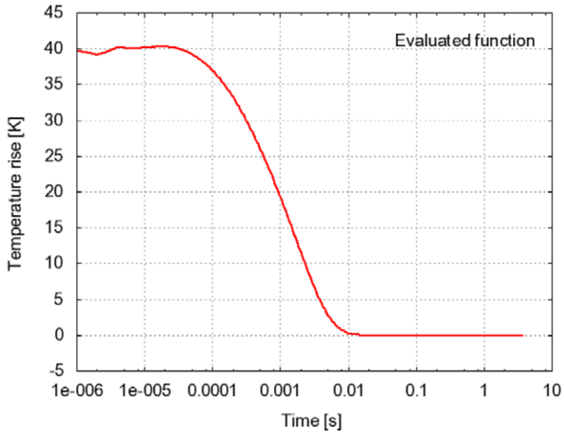

Fig. 6 Processed response function

IV. REGRESSION BASED SIGNAL SEPARATION

As the major part of semiconductor devices show some polarity dependency another method has to be developed which is polarity independent. For this purpose the responses of the devices against different excitations have to be investigated. Since the behavior of the devices, the ambient noises and crosstalks show specific characteristics, they can be separated analytically if the response functions are investigated properly.

As we have seen previously in section II, the effective output signal is proportional to the square of V_0 and as a result of the charge movements the unwanted (capacitive) coupling is in linear relationship with V_0. Let us denote the output signal with S and use a and b to as the intensities of the proportional input components. Throughout the analysis the minimum square approach is used. According to it, the signal which appears at the input of the transient tester is:

$$S = aV_0 + bV_0^2 \tag{2}$$

To estimate the variables a and b, a series of n measurements with different V_0 values are performed (Fig. 7).

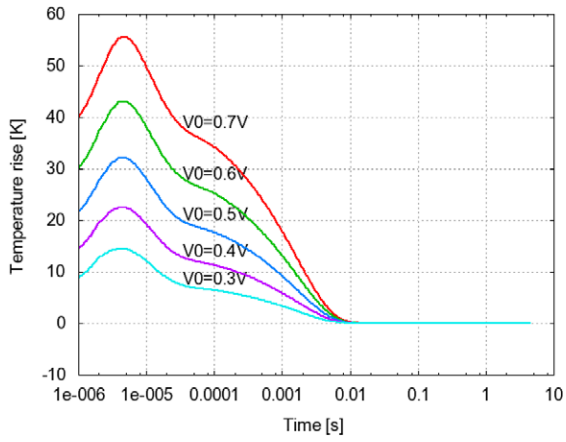

Fig. 7 Measured response functions for different V_0 values

Let us assign an e matching error for our calculations:

$$e = \sum_{i}^{n} \left(a \cdot V_{0i} + b \cdot V_{0i}^2 - S_i\right)^2 \tag{3}$$

where all the summations are over the available recordings for different V_0 values. To find the minimum of this error, (3) has to be derived with respect to variables a and b and the result should be equal to zero:

$$\frac{\partial e}{\partial a} = 2 \cdot \sum_{i}^{n} \left(a \cdot V_{0i} + b \cdot V_{0i}^2 - S_i\right) \cdot V_{0i} = 0$$

$$a \cdot \sum_{i}^{n} V_{0i}^2 + b \cdot \sum_{i}^{n} V_{0i}^3 - \sum_{i}^{n} S_i \cdot V_{0i} = 0 \tag{4}$$

and

$$\frac{\partial e}{\partial b} = 2 \cdot \sum_{i}^{n} \left(a \cdot V_{0i} + b \cdot V_{0i}^2 - S_i\right) \cdot V_{0i}^2 = 0$$

$$a \cdot \sum_{i}^{n} V_{0i}^3 + b \cdot \sum_{i}^{n} V_{0i}^4 - \sum_{i}^{n} S_i \cdot V_{0i}^2 = 0 \tag{5}$$

These equations constitute the following linear system of equations for a and b variables:

$$\begin{aligned}\sum V_{0i}S_i &= a\sum V_{0i}^2 + b\sum V_{0i}^3\\ \sum V_{0i}^2 S_i &= a\sum V_{0i}^3 + b\sum V_{0i}^4\end{aligned} \qquad (6)$$

This system of equations has to be solved for a and b. The amplitude of the component depending linearly on V_0 is given by a while b gives the amplitude of the component proportional to the second power of V_0. After solving the equations a vector is obtained for a and b. If V_0 and V_0^2 are multiplied by them accordingly, then the data in Fig. 8 is obtained. It can be seen that the glitch and the useful signal are detached effectively in the range above 5 µs.

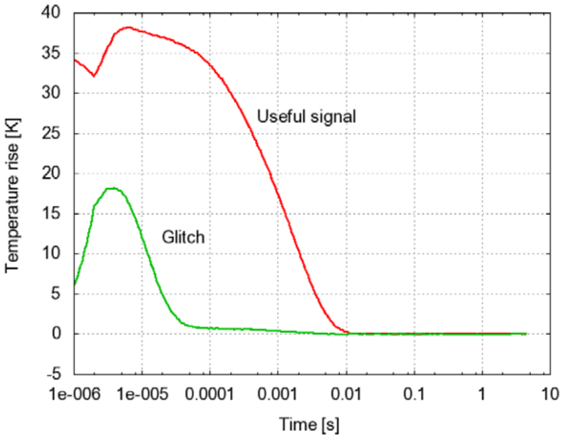

Fig. 8 Separated components

As this method is based on the differences of the signal components on different signal levels, it can be implemented when the system can only be driven by unipolar signals. As a consequence it can be used to analyze the components of devices with pn junctions. Since for example diodes have such junctions and parasitic elements such as serial resistors, their influence can be calculated by analyzing the response signals of the device under different excitations.

V. EFFECT OF ADDITIONAL UNKNOWN COMPONENTS

The primary condition of the adaptability of the regression based signal separation technique is to know the major characteristic components of the analyzed system and those of the parasitics. However it is nearly impossible to know all the components of an element and it's still worth investigating which components can be neglected because of their relatively low coefficient. For example the examined microsystems have temperature dependent components which result in V_0^4, V_0^6, V_0^8… elements [10]. The evident question emerges: which component can be neglected? Beside the influence of external noises other undesired effects such as temperature dependent material properties can also affect the separation.

For our analysis a general case is investigated when it is not known which component is neglected. Therefore a random noise or component is added to a generated response function and we investigate its effect on the separation. In order to examine the rate of the degradation in the accuracy, several sets of virtual measurement data are generated in the first step. In each set a glitch which is proportional to the V_0 parameter is inserted, next to the useful signal which is proportional to the square of V_0. The amplitude of the glitch is either positive or negative. These virtual data functions are presented in Fig. 9 for a few V_0 values.

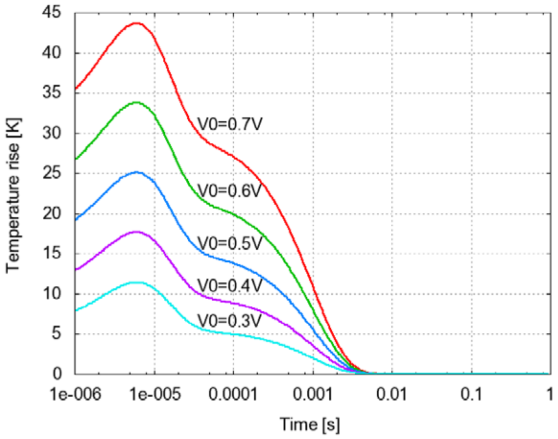

Fig. 9 Set of noiseless virtual data

In the generated functions the glitches corresponding to the crosstalk are described with

$$V_{glitch} = V_0\left((1-\exp(-t/\tau_1)) - (1-\exp(-t/\tau_2))\right) \qquad (7)$$

where $\tau_1 = 4\cdot 10^{-6}$ s and $\tau_2 = 10^{-5}$ s while the useful signal is generated by using

$$S_{useful} = V_0\left(1-\exp(-t/\tau_u)\right) \qquad (8)$$

with $\tau_u = 10^{-3}$ s. It should be noticed that exponential functions are used to describe the transient behaviors, because of their capacitive characteristics. At the glitches there are rising and falling exponential functions with different time-constants to model the charge buildup and the useful signal is described with a single stage RC ladder which yields an exponential function with one time-constant. To model the unknown components a *psr [0,1)* pseudo-random noise value multiplied by the virtual signals was added to the original signal

$$Noise = \left(S_{useful} + V_{glitch}\right)\cdot psr\cdot nl \qquad (9)$$

where *nl* is the noise level. It can be noticed that this noise is proportional to the virtual signal. This means that it has a maximum value when the corresponding signal is at its highest point and its value is zero when the signal reaches its minimum. According to (7)(8)(9) Fig. 10 show the generated signals where *nl=5 %*.

After utilizing the regression based separation technique the resulting signals can be observed in Fig. 11. It is clearly visible that for *nl=5 %* reduced effectiveness is found. In order to gain a deeper insight the results are investigated in the time-constant spectrum. The noisy useful signal in Fig. 12 contains additional time constants compared to the pure useful signal which has only one time constant. These extra time constants make difficult to distinguish the signal from some noisy components.

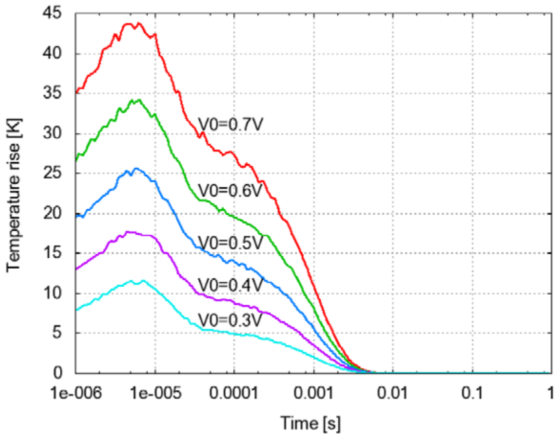

Fig. 10 Noisy signals with nl=5%

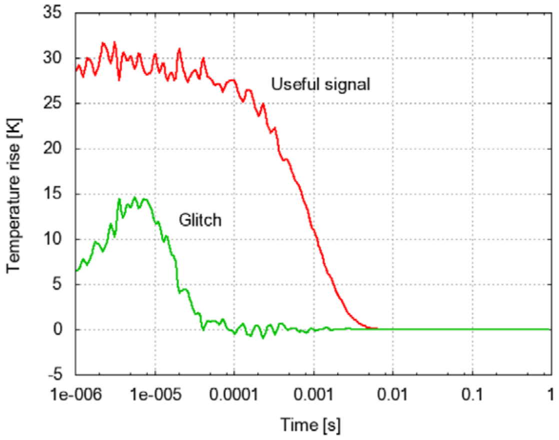

Fig. 11 Separated noisy signals with nl=5%

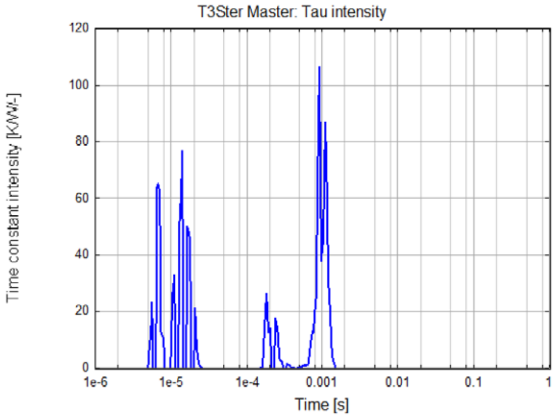

Fig. 12 Time-constant spectrum of the useful signal with nl=5%

However, when the *nl* - noise level- is decreased below 1 % then the separation could still be effective (Fig. 13). The magnitudes of the additional time-constants which can be observed in Fig. 14 are decreased as well.

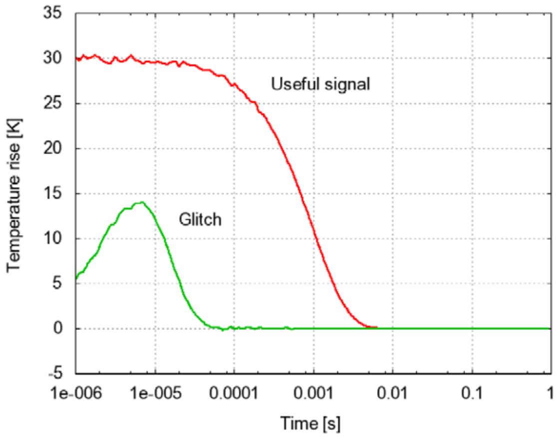

Fig. 13 Separated noisy signals with nl=1%

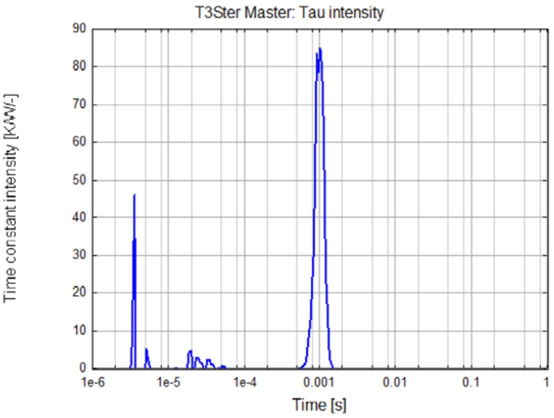

Fig. 14 Time-constant spectrum of the useful signal with nl=1%

This means that if the effects of the excess components of the response are below 1 % then they can be neglected in the separation process, but if their ratios exceed a certain level then the validation of the regression based separation becomes questionable.

VI. CONCLUSIONS

The presented case study shows new compensation techniques to improve the efficiency of thermal transient measurements in special microsystems. These methods are based on the analysis of the response signal either if the polarity of the excitation is changed or using a set of response signals recorded with different levels of driving voltage. Both methods are suitable to separate the useful and spurious signal components if their dependences on the excitation levels are known. Besides the use of similar type of microsystems, further fields of applications can be examined. For example it can be tested on semiconductor devices and microsystems which utilize other types of physical crosseffects.

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Dr. Vladimír Székely - Professor emeritus, member of Hungarian Academy of Sciences - received the electrical engineering degree from the Technical University of Budapest, Hungary, in 1964. He joined the Department of Electron Devices in that year. He was Head of Department between 1990 and 2005. Currently he is professor emeritus of Budapest University of Technology and Economics. His first research area was the theory of Gunn devices. His later research interests are mainly in the area of computer aided design of integrated circuits, with a particular emphasis on circuit simulation, thermal simulation, and device modeling. He conducted the development of several CAD programs in the field of integrated circuit design and simulation. Another area of his technical interest is computer-graphics and image-processing. He has been engaged in the investigation of thermal properties of semiconductor devices and integrated circuits for the last 30 years. This resulted in the development of novel thermal based IC elements and thermal IC simulator programs. Vladimír Székely has published his theoretical and practical results in more than 380 technical papers and 12 books or book-chapters.