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Characterization and modelling of electrothermal microsystems

Ph.D. Thesis Booklet

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1 Premise to research

Throughout my Ph.D. research I've dealt with the characterization, modelling and measurement techniques of various electrothermal microsystems which are embedded in today's modern sensor units. In my experiments I've studied in detail the heat transfer and conduction processes within micro and macro size objects, the secondary effects in the microsystems which have significant impact on the operation and the physical cross-effects in the micro-electromechanical systems (MEMS) which are responsible for the operation of sensors and actuators. I've also dealt with eliminating electrical measurement errors in small (µm) sized systems by using unconventional measurement methods. In the last few years I've worked in numerous national and international projects (PATENT DfMM, NanoPack, Eniac SE2A), the results of which contributed to the efficiency of my work.

In the last decades, similarly to the integrated circuits, the sensor and actuator systems undergone a major size-decrease. The precise IC manufacturing technologies presented a good base for the semiconductor sensors. Although the processes can not be applied in the same form, the techniques and devices can be utilized after modifications. It is also remarkable that there is one order of magnitude difference in size between the semiconductor sensors and integrated circuits. As a consequence the companies that use cheaper and less advanced manufacturing equipments can become competitive against the better sponsored concurrence. So in this field the European companies and institutes can overcome their US based rivals just as the Hungarians can overcome their Western European competitors.

The heart of the cutting edge sensor and actuator systems are the tiny so called micro-(opto)electromechanical systems (M(O)EMS). These are basically $1\ mm - 1\ \mu m$ long devices, that produce an electrical signal for a circuit or actuate their environment by utilizing their electromagnetic, optical, chemical, thermal or mechanical properties. Today their biggest field of application is transportation safety, where the most sophisticated systems can be found in automobiles and avionics. Beyond these, they can also be found in fire alarm systems, fingerprint readers, computer subsystems. Numerous research institutes are trying to achieve their own results which can be used in medical applications that were previously unrealizable. The relevant research fields in this area are the artificial implants (artificial eye, cochlear implant), biometric systems (blood-sugar measurement pulsoximetric) and the Lab-on-a-chip systems where multiple laboratory functions are realized on a single chip. At the same time they can be used for military and law enforcement tasks and because of that many research institutes are supported by the army and ministry of war.

Before the MEMS-es are built into a sensor system which is being used daily, they have to go through a number of design and development processes and first of all experiments. To design a device one has to be aware of their detailed operation for which it is essential to have adequate and precise physical and behaviour models. To define the material and physical parameters test structures are manufactured in the early phases of the design process, which can be optimized according to the results of the characterizations. In my research I've dealt with electrothermal teststructures. I've paid great attention to model these systems precisely and to elaborate proper characterization techniques. There are also notable demands to measure and identify the possible errors and malfunctions of the completed devices and microsystems which are already used in the industry. Besides the design for testability (DfT) concepts it is essential to have measurement techniques and circuits which help to determine whether our structures work according to the specifications. When designing the measurement strategy extra attention must be paid to external noises which can suppress the signal and the measurement itself as it can alter the operation.

As a summary it can be stated that when a microsystem is being designed it is extremely important to have models and characterization processes which help the designer to develop the optimal device that complies to the specifications. In addition, the operation of the completed device, the later improvement and the failure mechanisms must be monitored which demands new type of measurement methods. Because of these reasons it is highly important for MEMS to consider and to treat these topics with the utmost importance. In my dissertation I would like to present the results and concepts of my research in order to provide theoretical and practical principles for these issues.

1.1 Objectives of the research

One of the main objectives of my doctoral research is the characterization and modelling of quadrature transfer characteristics (QTC) MEMS elements in order to gain a deep insight to their function. Because today in the early phase of sensor design before they reach the mass production state or the daily usage a precise description is needed of the expected behaviour of the device in order to know the major effects which have a significant impact on the operation. For these purposes, various test structures are being used which help to optimize the fabrication and they can be useful to give development advises to avoid unexpected effects. In the later phases of the design process when the functionality of the microsystem has to be simulated together with the evaluation electronics it is a must to have an equivalent circuit model which describes the hole system simultaneously. To create the optimal device it is crucial for these equivalent circuits to include all the parameters that were extracted by the measurements and have an affect on the functioning. During my work I've performed the characterization steps for a special kind of microsystem: the quadrature transfer characteristics (QTC) MEMS by taking into to consideration these criterions.

Another goal of my research was to separate the unwanted electrical components and the thermal response in thermal transient measurements. The problem raised with the measurement of the microsystems because in the early phase of thermal transient testing as a consequence of electrical couplings spikes and other components can appear in the response function which influence the accuracy of the measurements. The currently available solutions where linear or rooted fitting were done at the inflexion or minimum points of the curves are not satisfactory, when structures with small time constants e.g. MEMS are being measured. With the help of my newly developed method it is possible to filter out or minimize the error by using multiple excitation impulses.

2 Applied instruments and test methods

Even at the early stages of my work it was evident that one of the main fields of my research would be the electrothermal modelling and measurement technologies so I studied about the thermal behaviour of different microsystems and microelectronics elements and the related physical cross-effects. With the help of the knowledge acquired from the scientific journals and books I have developed analytical methods to check the measured results.

I studied electrothermal modelling strategies and the implementation possibilities of my model into circuit simulators with extra attention. I examined the analogy between the physical cross-effects and the thermal parameters against the electrical components in order to obtain the appropriate equivalent circuit.

During my research I acquainted with complex mathematical methods which allowed me to process the results correctly. Besides the academic preparation, I also learnt to use special instruments and unconventional equipments such as the T3ster (Thermal Transient Tester) and the Alcatel RF sputtering equipment and its vacuum system. The way conventional instruments affect the DUT (device under test) also had to be investigated.

For analysis and verification purposes I used different kinds of mathematical and simulator programs. As my work progressed I learnt to use the MATLAB and the SUNRED programs on a professional level and I also begun to use the ANSYS Multiphysics and the products of

Mentor Graphics for simulation (Eldo, Flotherm) and for processing (T3Ster-Master, EZwave). I interpreted and checked my results with the powerful help of these softwares.

3 New theoretical results

3.1 First thesis

I have developed a new characterization method for experimental and theoretical analysis of QTC (quadrature transfer characteristics) thermoelectric MEMS elements. Beyond the basic effects I determined the impact of the secondary effects and of the scaling phenomenon and I developed the essential measurement methods.

1.1. I have investigated the deflection of the QTC elements from the ideal characteristics. I have determined that as a consequence of temperature dependency the resulting non-linearities generates even-numbered harmonics in the spectrum. Based on these I have made suggestions to maintain the prescribed distortion level.

1.2. I have determined both experimentally and analytically that the heating current which flows through the heating resistors embedded in the microsystem induces Peltier effect on the aluminium and polysilicon contacts. The effect can generate heat up to 10 % of the full magnitude, which changes the symmetrical heat distribution and affects the operation of the device. I have stated the construction principles to avoid the disturbances. I have also pointed out that with symmetrical layout the effect does not influence the operation.

1.3. I have investigated the behaviour of electrothermal microsystems in vacuum and under normal atmospheric conditions. I have demonstrated that on a given thermal range if a gaseous material surrounds the structure it alters the behaviour and the transfer characteristics of those microsystems which have a thermally isolated part apart from the silicon substrate. The gas represents a parallel heat flow path. By using the transmission line theory I have analytically

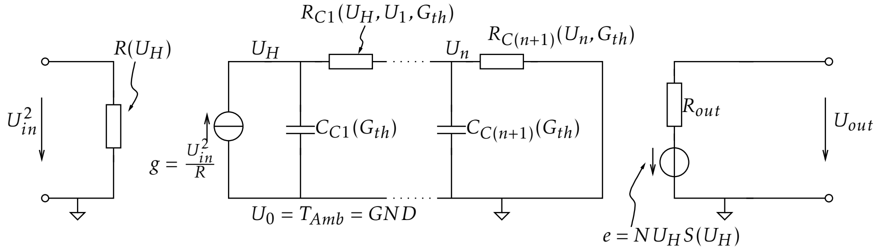

Figure 1: Equivalent circuit of the QTC MEMS

demonstrated the shifting of the thermal time constants of the QTC elements as a consequence of the presence of the air. The shifting has also been demonstrated experimentally with thermal transient testing.

Related publications: [S1, S2, S3, S4]

3.2 Second thesis

I have developed a component level equivalent circuit to model the behaviour of QTC elements. The base of the model is an RC network which describes the thermal structure of which elements have been derived by deconvolving the time-constant spectrum which is the result of transient measurements. The electrothermal coupling can be described with driven sources. By using this model the operation of the QTC MEMS can be observed with circuit simulators.

2.1. I have built the temperature dependency into the model. The parameters were obtained by measuring a test structure.

2.2. I have built the influence of the surrounding gas into the model by using the experimental data obtained in thesis 1.3.

Related publications: [S1, S2, S3, S4]

3.3 Third thesis

I have developed a new measurement and processing method to decrease the electrical coupling and crosstalk between the input and output in thermal transient measurements.

3.1. I have demonstrated experimentally that if the transient measurement of the QTC elements is done with normal and inverted polarity then the crosstalk can be eliminated in the processing phase. I have determined that this method can be used when the devices are not sensitive to polarity inversion.

3.2. I have developed a polarity independent method to eliminate the crosstalk of quadrature transfer characteristics elements in transient measurements. The method separates the useful signal from the crosstalk components by utilizing different excitation impulses.

Related publications: [S5]

Not related publications: [S6, S7, S8, S9, S10, S11, S12]

4 Utilization of the results

Although the results of my Ph.D. research are based on a specific electrothermal microsystem it describes similar microsystems efficiently. In the first thesis of my dissertation during the characterization of QTC elements I have managed to reveal the impact of the temperature dependent components on the basic elements. These results can be used on systems which consist of the same building blocks. I have determined that as a consequence of the current, the Peltier effect which builds up on contacts with materials of different Seebeck constants influences the heat distribution. According to these I have stated construction principles which help to avoid the influence on the operation. Another important topic of my work is the statement I've made about the surrounding gas when I have built in its effect into the analytical calculations. It's use as a parallel heat conduction path in the calculus was not typical, but based on my results the required corrections become possible which increase the accuracy of the characterizations. The modelling technique in my second thesis can also be used in similar microsystems. The equivalent circuit is fully compatible with the state of the art circuit simulators and it is applicable to simulate the microsystem and the evaluation circuit simultaneously.

Finally, it can be stated that the measurement and processing methods presented in the last chapter of my work are not only help the characterization of electrothermal MEMS with small time-constant but application possibilities can be defined to improve the characterization of other semiconductor sensors and microelectronic devices.

Scientific Publications

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[S2] Péter G. Szabó, Vladimír Székely. Investigation of parallel heat flow path in electro-thermal microsystems. *Microsystem Technologies*, 17(8):533–541, 2011.

[S3] P. G. Szabó, V. Székely. Characterization and Modeling of an Electro-thermal MEMS Structure. *Collection of Papers Presented at the Symposium on Design, Test, Integration and Packaging of MEMS & MOEMS (DTIP'08)*, pages 350–354, 2008.

[S4] Péter G. Szabó, Vladimír Székely. Investigation of Parallel Heat-flow Path in Electro-thermal Microsystems. *Collection of Papers Presented at the Symposium on Design, Test, Integration and Packaging of MEMS & MOEMS (DTIP'10)*, pages 215–220, 2010.

[S5] Péter G. Szabó, Vladimír Székely. Crosstalk Compensation in Thermal Transient Measurements. *Proceedings of the 16th International Workshop on THERMal INvestigation of ICs and Systems (THERMINIC'10)*, pages 24–27, 2010.

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[S11] V. Székely, P. G. Szabó. Blind tracing of mechanical movement in electrostatic MEMS structures. *Collection of Papers Presented at the Symposium on Design, Test, Integration and Packaging of MEMS & MOEMS (DTIP'10)*, pages 39–43, 2010.

[S12] B. Németh, P. G. Szabó, V. Székely. Design, Simulation and Measurements of MEMS Test Structures. *Proceedings of the 6th Electronic Circuits and Systems Conference (ECS'07)*, pages 49–54, 2007.