HEAT TRANSFER IN SILICON MICROMECHANICAL STRUCTURES

PhD thesis

PÉTER FÜRJES

Supervisor: Dr. ISTVÁN BÁRSONY

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1. PREMISES

The technical development and the rapid growth of automation requires devices which are able to control complex systems without human intervention. They collect data from the environment, analyse them, and have to arrive at adequate conclusion in order to do the job committed – in most cases more effectively as a human.

Several sensor structures operate with calorimetric principle at elevated temperature for detection and analysis mass and heat transfer. Due to the convincing experience in microelectronics, device scale of MEMS are also decreasing in order to achieve higher level of integration and better reliability. Therefore, both prediction and verification of operation properties of devices have crucial importance for the final realisation and applicability.

The main target of the research at the Microtechnology and Sensor Laboratory of the Research Institute for Technical Physics and Materials Science are development and manufacturing integrable sensor structures having international interest. My primary work is the optimisation of the operation properties of sensors by exploring the basic physical processes and determining device characteristics. The results were applied in design of three sensor structures: pellistor type gas detector, calorimetric mass flow meter and capacitive porous silicon based humidity sensor structures.

2. TARGETS

Exact description of thermal and flow transport phenomena in the micro devices is essential for the determination of possible applications and operation conditions. Device function can be described and predicted by formation of adequate models and must be experimentally verified by measurements capable to determine physical properties of microscale structures. The knowledge of structural properties, processing technology and applicability of MEMS plays crucial role in the R&D procedure.

Application of the adequate models makes the design steps shorter and easier. The expressive models assist to explore, identify and eliminate technological failures, and also predict the effects of any structural modification. Moreover, an ideal model is a powerful tool for getting acquainted with the physical phenomena taking place in the microstructures.

The validity of the built-up models must be verified by analytical and functional tests. In case of microstuctures with dimensions of 1 to 100 microns the implementation of several methods for thermal characterisation is hardly achievable.

3. STRUCTURES AND METHODS APPLIED

Pellistor type gas sensor array

The adequate knowledge of the thermal properties plays determining importance in the design of a sensor based on the detection of the heat generated by the catalytic oxidation at elevated temperatures. The minimisation of the power dissipation is crucial requirement for detection of combustive gases, where one always must count with the risk of explosion. The thermal phenomena taking place inside and around the microheaters were investigated by the application of theoretical models and experimental measurements, such as in-situ, non contact temperature detection or determination of the infrared emission behaviour by lock-in thermography. Aiming at the enhancement of sensitivity the heat transport phenomena toward and inside the catalyst material were analysed.

Direction dependent calorimetric flow sensor

Thermal and flow processes taking place in and around calorimetric flow meter structures were investigated in order to optimise the geometry of the targeted flow rate and direction sensitive sensor.

Porous silicon based humidity sensor

In development of a capacitive type humidity sensing structure the reduction of response time and heat dissipation were the main targets. The influence of the enhanced thermal isolation was investigated by using various geometry of the integrated heater elements and improvement of the packaging system.

The main elements of the above listed structures are the thermally isolated (by porous silicon or after its removal by the formed air gap) microheaters. These complex layer structures contain heater resistors embedded in dielectric layers. The operation of these devices at elevated temperatures requires a comprehensive knowledge of thermal properties, processes, experimental methods and unique material technologies.

1. Thermal and mechanical behaviour of point size or localised heat sources (microheaters) were modelled – by COSMOS (FEM) and SUNRED (CTM) codes – and investigated for determination of thermal properties and processes taking place during operation.
2. Dynamic and static behaviour of the heat sources was described by analysis of thermal emission of the structure detected by lock-in thermograhy using an IR camera of THERMOSENSORIK Ltd., Erlangen and T3STER-MASTER (NID) code of MICRED Ltd., Budapest.

3. Transport phenomena between and inside the microhotplate and the deposited thick sensing layers were described by comparison of the predicted properties and the results of the electrical and IR measurements.
4. Influence of thermal properties on adsorption and desorption processes take place in porous structures was investigated and an adequate structure was designed to provide the targeted fast recovery of the device.
5. Flow processes around the heat source put in gas flow were investigated and simulated, and the optimum geometric design was determined for a given sensor application.
6. The sensor structures based on the above investigations were manufactured and their applicability and functionality were verified.

4. NEW RESULTS

Heat dissipation phenomena of the localised microscopic heat sources were modelled and experimentally investigated by detecting thermal properties of the structures. The temperature vs. heating power function of the microheater was determined by different measuring techniques. Defects of structural materials arise in processing or during operation were detected by thermo-mechanical simulations. Based on a detailed investigation platinum was proposed for the material of the microfilament.

Thesis 1: I realised and experimentally verified that the deviation between the theoretically calculated and measured conductivity of a single crystalline silicon heater filament suspended by platinum contacts can be ascribed by structural deterioration due to the high temperature. I suggested the application of platinum heater filament in micromechanical systems instead of Si. The Pt-Si contacts are unreliable due to the potential degradation, and proved non-stable even in structures where TiN diffusion barrier was applied. [F.1 – F.3]

The thermal equivalent elements describing the structural details were determined by investigation of the dynamic properties of different structures, and their thermal equivalent circuits.

Thesis 2: By measurement and simulation of thermal properties of different structures I demonstrated, that the pillar shaped mechanical support formed under the microheater is thermally permissible. [F.2, F.3, F.6, F.8, K.14]

The temperature distribution of the structure was ascribed by analysis of thermal equivalent circuit simulations (SUNRED), FEM modelling (COSMOS) and experiments (T3STER-MASTER). The physical phenomena can be qualitatively ascribed by the suggested one dimensional compact thermal model. The temperature dependence of the material properties plays crucial role in the description of the micro size structures.

Thesis 3: I confirmed the applicability of the suggested one dimensional compact thermal model by evaluation of the time constant spectra and structure functions calculated by network identification using deconvolution (NID) method. The applied T3STER device analysed the thermal transients of different structures (suspended, supported by a thin Si pillar and embedded in porous silicon) registered by high resolution lock-in thermography. [F.2, F.3, F.6, F.8, K.14]

Thesis 4.a: By thermal simulation and lock-in thermography analysis of the suspended heaters I demonstrated that the structures show outstanding functional properties for calorimetric applications up to 100-150Hz frequency range. [F.8, K.14]

The effect of the catalyst layer on the thermal behaviour of the device was determined by lock-in thermography and thermal equivalent circuit modelling. The response time of the device is deteriorated by the catalyst layer (t_{90}~32.4ms), however, its functional applicability is unquestionable up to 10Hz frequency range.

Thesis 4.b: By thermal simulations and lock in thermography I qualitatively demonstrated that the 2D phase distribution maps correspond to morphologic and material properties of the 3D structures (for example: catalytic gas sensor). The lock-in thermography analysis complemented by thermal modelling is an outstanding way for non-destructive and quick characterisation of MEMS. [F.8, K.14]

The thermal and mechanical properties of porous silicon layer were investigated by experimental and FEM simulation results. The thermal properties (λ~0.2-50W/Km) of porous silicon layer primarily depend on the morphology and realisation circumstances.

Thesis 5: I optimised the refreshing cycle of passivated porous silicon sensors (for example humidity sensor) by theoretical and experimental investigation of their dynamical behaviour. In case of the structure I designed, the ideal refreshing temperature is 40-45°C, which results in less than one minute recovery time. [F.5]

Thesis 6.a: In the typical size of micro structures (10-100μm) the mass flow processes can be ascribed by low Reynolds-number, therefore, the flow around the devices is laminar. In view of this premise the CFD (computational fluid dynamics) code used widespread to *investigate macroscopic processes can be easily adapted for microsystems to qualitatively describe functional properties of calorimetric devices using temperature independent material constants. [K.9, K.13]*

Thesis 6.b: By calculations and experiments I proved that the process of the physical phenomena differs from that of experienced in macroscopic cases, if the dimensions of the structure are comparable to the thickness of the boundary layers. The similarity theories can be applied by the appropriate physical consideration. [K.9, K.13]

Thesis 6.c: Investigating the heat transfer processes in the calorimetric flow meter I established that heat conduction via the flowing medium plays determining role in microscale structures. The model considers heat conduction phenomena fits more accurately to the experimental results. The dynamical behaviour of the device can be properly calculated by the thermal equivalent circuit I introduced. [K.9, K.13]

5. EXPLOITATION OF THE RESULTS

The optimisation of the novel micromachined silicon devices developed at MFA (integrated micro-pellistor, porous silicon based capacitive humidity sensor, direction dependent calorimetric flow meter) was supported by my results. [F.5, F.6, K.9, K.13]

The success of the following projects was promoted by the work presented:

1. FP5 – SAFEGAS: Sensor array for fast explosion proof gas monitoring (G1RD-CT-1999-00167)
2. German-Hungarian Bilateral Science and Technology Cooperation: Application of porous silicon in sensor technology
   Partner: FH Furtwangen, University of Applied Sciences, Institute of Applied Research – IAF
3. Application of active diamond layer, synthetized by MW-CVD, on thermal mass flow meters - OTKA T034821
4. The origin of electronic noise in semiconductor sensors - OTKA T037706

6. PUBLICATIONS

Publications published in journals:

1. Zs. Vízváry, P. Fürjes, I. Bársony: "Thermomechanical Analysis of Hotplates by FEM", Microelectronics Journal 32 (2001) 833-837 (IF 0,333)

2. P. Fürjes, Zs. Vizváry, M. Ádám, A. Morrissey, Cs. Dücső and I. Bársony: "Thermal investigation of Micro-filament Heaters", Sensors and Actuators A 99 (2002) 98-103 (IF 0,917)
3. P. Fürjes, Cs. Dücső, M. Ádám, A. Morrissey, I. Bársony: „Materials and Processing for Realisation of Micro-hotplates Operated at Elevated Temperature", Journal of Micromechanics and Microengineering 12 (2002) 425-429 (IF 1,211)
4. E. Lukács, Zs. Vízváry, P. Fürjes, F. Riesz, Cs. Dücső and I. Bársony: "Determination of Deformation Induced by Thin Film Residual Stress in Structures of Millimeter Size", Advanced Engineering Materials Vol. 4 – No. 8 625-627(2002) (IF 0,901)
5. P. Fürjes, A. Kovács, Cs. Dücső, M. Ádám, B. Müller and U. Mescheder: „Porous Silicon Based Humidity Sensor with Interdigital Electrodes and Internal Heaters", Sensors and Actuators B 95 140-144 (2003) (IF 1,44)
6. Cs. Dücső, M. Ádám, P.Fürjes, M. Hirschfelder, S. Kulinyi and I. Bársony: „Explosion-proof Monitoring of Hydrocarbons by Micropellistor", Sensors and Actuators B 95 189-194 (2003) (IF 1,44)
7. H. Csorbai, P. Fürjes, Gy. Hárs, Cs. Dücső, I. Bársony, E. Kálmán, P. Deák: "Microwave-CVD diamond protective coating for 3D structured silicon microsensors", Materials Science Forum 414-4 (2003) 69-73 (IF 0,461)
8. P. Fürjes, Cs. Dücső, M. Ádám, J. Zettner, I. Bársony: „Thermal characterisation of micro-hotplates used in sensor structures, Superlattices and Microstructures, elfogadva (IF 0.859)

Patent:

1. Verfahren zur Herstellung von Feuchtesensoren (Realisation methode for humidity sensors), accepted by the German Patent Office

Publications published in proceedings of conferences:

1. H. Csorbai, P. Fürjes, Cs. Dücső, Gy. Hárs, I. Bársony, P. Deák: „Pinhole free diamond film deposited on monocrystalline silicon by MW-CVD method", Proceedings of the Eurosensors XIV, Copenhagen (2000) 251-252
2. Zs. Vízváry, P. Fürjes, I. Bársony: "Three-Dimensional Finite Element Model for Thermomechanical Analysis of Hotplates" Proceedings of the 6th International Workshop on THERMal INvestigations of ICs and Systems (Therminic), Budapest (2000) 253-257

3. P. Fürjes, Zs. Vízváry, M. Rácz, I. Bársony: "Temperature measurement in micro-filament heater" Proceedings of the 6th International Workshop on THERMal INvestigations of ICs and Systems (Therminic), Budapest (2000) 262-265
4. P. Fürjes, Zs. Vízváry, M. Ádám, Cs. Dücsõ, A. Tóth, I. Bársony: "Processing and characterisation of integrable microhotplates for gas sensing applications" Book of Abstract, First Conference on Microelectronics, Microsystems, Nanotechnology, MMN 2000, Athén (2000)
5. P. Fürjes, Cs. Dücső, M. Ádám, A. Morrissey, I. Bársony: „Materials and Processing for Realisation of Micro-hotplates Operated at Elevated Temperature”, Proceedings of MME 2001, Cork (2001) 191-194
6. P. Fürjes, A. Kovács, Cs. Dücső, M. Ádám, B. Müller and U. Mescheder: „Porous Silicon Based Humidity Sensor with Interdigital Electrodes and Internal Heaters”, Proceedings of Eurosensors XVI, Prague (2002) 525-526
7. Cs. Dücső, M. Ádám, P.Fürjes, M. Hirschfelder, S. Kulinyi and I. Bársony: „ Explosion-proof Monitoring of Hydrocarbons by Micropellistor”, Proceedings of Eurosensors XVI, Prague (2002) 605-606
8. Zs. Vízváry, P. Fürjes: "Thermomechanical Investigation of a Suspended Microhotplate" Proceedings of Third Conference on Mechanical Engineering, Gépészet 2002, Budapest (2002) 302-306
9. P. Fürjes, G. Légrádi, Cs. Dücső, A. Aszódi and I. Bársony: „Modelling and Characterisation of a micro gas-flow sensor”, Proceedings of MME 2002, Sinaia (2002) 157-160
10. Zs. Vízváry, P. Fürjes, M. Ádám, Cs. Dücső and I. Bársony: “Mechanical Modelling of an Integrable 3D Force Sensor by Silicon Micromachining”, Proceedings of MME 2002, Sinaia (2002) 165-168
11. I. E. Lukács, P. Fürjes, Cs. Dücső, Ferenc Riesz and I. Bársony: “Process Monitoring of MEMS Technology by Makyoh Topography”, Proceedings of MME 2002, Sinaia (2002) 283-286

12. P. Fürjes, Cs. Dücső, M. Ádám, Jürgen Zettner and I. Bársony: “Thermal characterisation of Micro-Hotplates Applied in Sensor Structures”, Poceedings of Eurotherm 2003 59-60, Reims (2003)
13. P. Fürjes, G. Légrádi, Cs. Dücső, A. Aszódi and I. Bársony: „Thermal Characterisation of a Direction Dependent Flow-rate Sensor”, Proceedings of Eurosensors XVII 174-175, Guimarães (2003)
14. I. Bársony, P. Fürjes, M. Ádám, Cs. Dücső, J. Zettner and F. Stam: „Thermal response of microfilament heaters in gas sensing”, Proceedings of Eurosensors XVII 510-511, Guimarães (2003)