

Gallium arsenide suspended microheater for MEMS sensor arrays

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Abstract This work describes the design, simulation, fabrication and characterization of a TiN/Pt microheater prepared on a GaAs micromechanical structure as a prospective device for micro-electro-mechanical system (MEMS) sensor arrays. Electro-thermal simulation was employed to verify the properties of the designed micro-structure, which confirmed achievement of the operating temperatures in the range from 470 to 600 K with a heating power less than 25 mW. The average temperature gradient in the active area does not exceed 0.6 K/ μm . Fabrication of GaAs suspended membranes was demonstrated, realized in two steps by combination of surface and bulk micromachining. Development and characterization of a microheater on a GaAs membrane is described. The mechanical stability of the heated multilayer membrane structure was tested and satisfactory mechanical stability of the hotplate was confirmed. The power consumption at an operating temperature of approximately 550 K is about 30 mW which is in good agreement with the value of about 22 mW obtained from electro-thermal simulation. The achieved thermal resistance value is 8.43 K/mW.

1 Introduction

Gallium arsenide-based micro-electro-mechanical system (MEMS) devices are an attractive alternative to the well-developed silicon-based MEMS. They can provide the best solutions for micro-optoelectronic applications with a number of material-related and technological advantages over silicon (Hartnagel et al. 1999; Hjort et al. 1996). GaAs-based MEMS are being developed for microsensors and microactuators, such as accelerometers and tunable optoelectronic devices (Chiang et al. 2002). For optical telecommunication applications, GaAs-based optical MEMS require selective deep etching to create microstructures, such as membranes and via holes (Shul et al. 1997). GaAs micromachining is also very interesting for the RF-MEMS field thanks to its potential for easy monolithic integration of micromachined passive circuit elements with active devices manufactured on the same chip (Pantazis et al. 2005). A GaAs suspended microheater for MEMS metal oxide gas sensors can bring a substantial reduction of thermal losses due to removal of the substrate (Hotovy et al. 2006).

Gas sensors often work in the high temperature mode that is required by the chemical reactions between the molecules of the specified gas and the surface of the sensing material. High temperature gradients between the active area and its colder surrounding cause heat losses by conduction through the bulk substrate material, convection in air from all exposed surfaces, and radiation. Power consumption of the gas sensors prepared using the thick layer technology is in the range from 100 to 500 mW due to their excessive thermal mass. If we want to use them in portable applications, these values are still too high. In addition to low power consumption, a uniform temperature distribution is required in the active area to ensure equal

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sensing properties of the whole surface (Cerde Belmonte et al. 2006). Mechanical stability and fast response belong to very important parameters that cannot be neglected. All the above-mentioned requirements are satisfied by micro-mechanical structures in which the sensing layer is placed on a suspended thin dielectric membrane prepared by micromachining process (Aslam et al. 2004; Suzuki et al. 2005; Barconcini et al. 2004).

However, GaAs suspended microheater for MEMS sensor arrays have not been developed yet. In our work, we have described thermal simulation, fabrication and characterization of a microheater structure to achieve low power consumption.

2 Thermal simulations

All three topologies come out from the well-known construction using a thin dielectric membrane. This is suspended using a few microbridges. Thermal properties of three modifications were investigated that differ in the membrane size and the number of microbridges. The whole structure is based on a GaAs substrate with a thickness of 300 μm . The thin dielectric membrane consists of a bilayer structure $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ (800 nm) + GaAs (200 nm). A double serpentine shaped platinum heater is placed on the membrane and covered by a SiC insulating layer with a thickness of 500 nm. The design topologies no. 1 and 2 differed only in the membrane size, which was suspended by six microbridges. The membrane size for the design no. 3 ($150 \times 150 \mu\text{m}^2$) was considered as the smallest possible according to the abilities of the available technology (Fig. 1a). Here, only four suspended microbridges in diagonal direction were used.

Before computer simulation was performed, the thermal properties of the design were forecasted by means of simple calculations. This supposed to evaluate the thermal resistance of each modification. Thermal conductivity of the surrounding air and the membrane were considered to be the main reasons for heat losses. Heat losses due to convection were neglected thanks to the small membrane size. This simplification creates a deviation in the results of about 5% (Cerde Belmonte et al. 2006).

Air heat losses are given by the heated area size and also by the topology of the substrate. This influence is especially strong from the backside of the membrane. To derive the air effective thermal resistance a simple simulation was used. A three-dimensional model consisted of a membrane considered to be the bulk heat generator with an input power of 1 mW. The model also involved the substrate and the surrounding air. Assuming the fluid motion to be negligible, air was modelled as a solid on top and bottom of the membrane. The height of the solid was determined after a

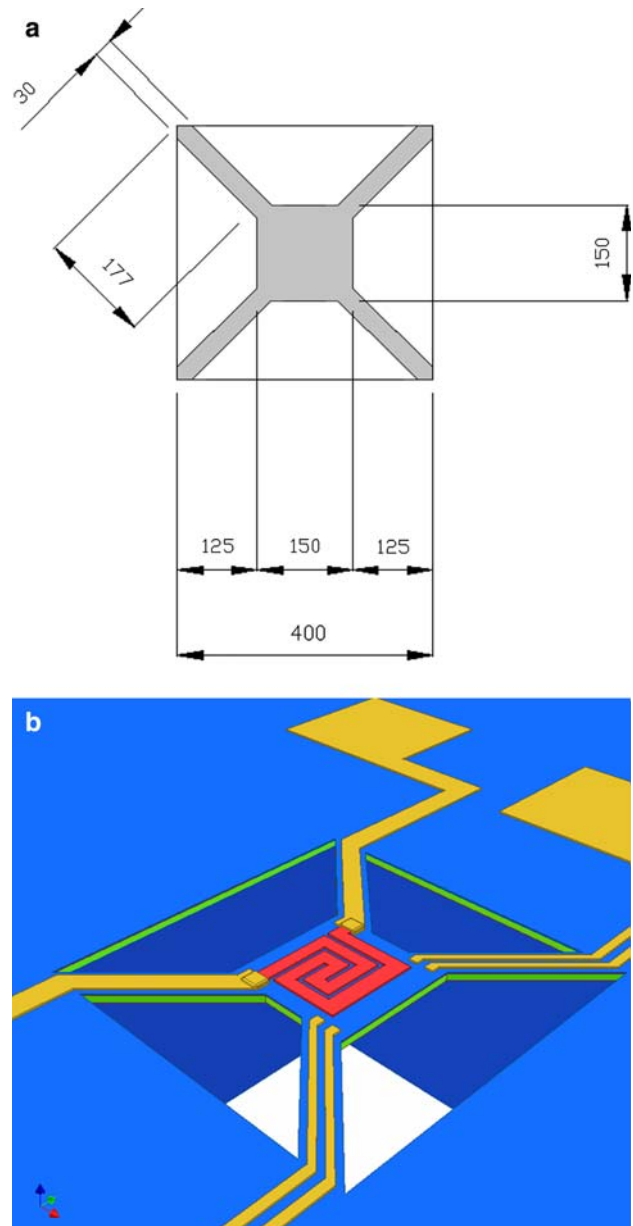


Fig. 1 Detail dimensions in μm (a) and schematic view (b) of the model suspended membrane with a double serpentine shaped heater and metallization

series of simulations in which the air solid height until was increased until reaching the convergence in the heat exchange. The ambient temperature was set to 23°C. Simulation of the air thermal conductivity in design no.1 showed that the temperature increased to 36°C. Hence, the air effective thermal resistance could be expressed using Eq. (1)

$$R_{\text{TH-airref}} = (T_{\text{hot}} - T_{\text{amb}})/P. \quad (1)$$

If it neglects heat losses through the surface of the suspended microbridges, their thermal resistance can be expressed using Eq. (2)

Table 1 Comparison of calculated thermal properties

	Beam thermal resistance (K/mW)	Effective air thermal resistance (K/mW)	Thermal resistance of the structure (K/mW)
Design no. 1	28.34	13.08	8.95
Design no. 2	38.38	15.86	11.22
Design no. 3	70.24	19.48	15.25

$$R_{TH-beam} = l / \sum \lambda_i S_i \tag{2}$$

where l represents the length of the beam, λ_i is specific thermal conductivity, S_i is the cross section area of the layer. The overall thermal resistance of all beams can be calculated as a parallel combination of their respective thermal resistances. This method is used to characterize the thermal properties of each design and the results are shown in Table 1.

The commercial finite element model (FEM) program ANSYS (De Salvo and Swanson, 1979) was employed for the coupled electro-thermal simulation. The three-dimensional model of the structure consisted of the following parts:

- Substrate – GaAs (300 μm)
- Membrane + suspended microbridges – AlGaAs (800 nm) + GaAs (200 nm)
- Heater + metallization – Pt (200 nm), Au (200 nm), respectively
- Insulation layer – SiC (500 nm)
- Surrounding environment – air

The temperature dependence of the thermal conductivity of air and the specific electrical conductivity of metals have also been considered. Pre-simulation of the thermal properties calculation showed, that using design no. 1 and 2 it was possible to achieve the effective thermal resistance as low as $R_{TH1ef} = 8.95$ K/mW and $R_{TH2ef} = 11.22$ K/mW respectively. Only design no. 3 met the initial requirement of $R_{TH} \geq 12.8$ K/mW. Heat conduction to the surrounding air and in the membrane were considered to be the main heat loss factors.

The model structure (Fig. 1b) with a suspended membrane of $150 \times 150 \mu\text{m}^2$ reached the operation temperature in the range from 470 to 600 K using a heating power between 14 and 22 mW (Fig. 2a). A typical thermal resistance value in this case was about 15 K/mW. The temperature gradient in the active area did not exceed 0.6 K/ μm but it should be improved by modifying the heater shape. The current density in the heater is depicted in Fig. 2b. High values up to 5 mA/ μm^2 were achieved. They can bring about degradation of the heater structure due to

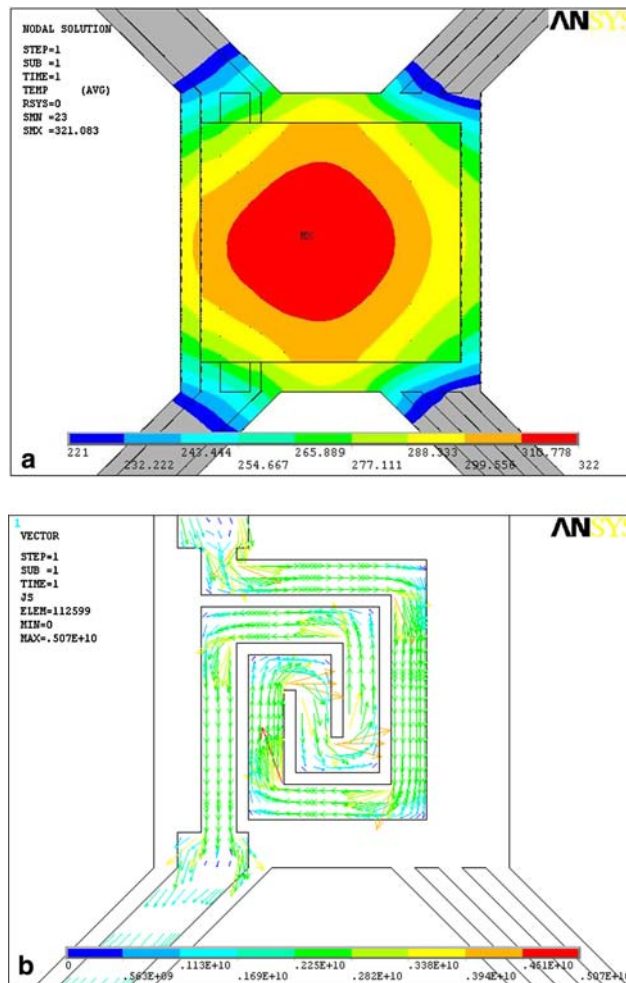


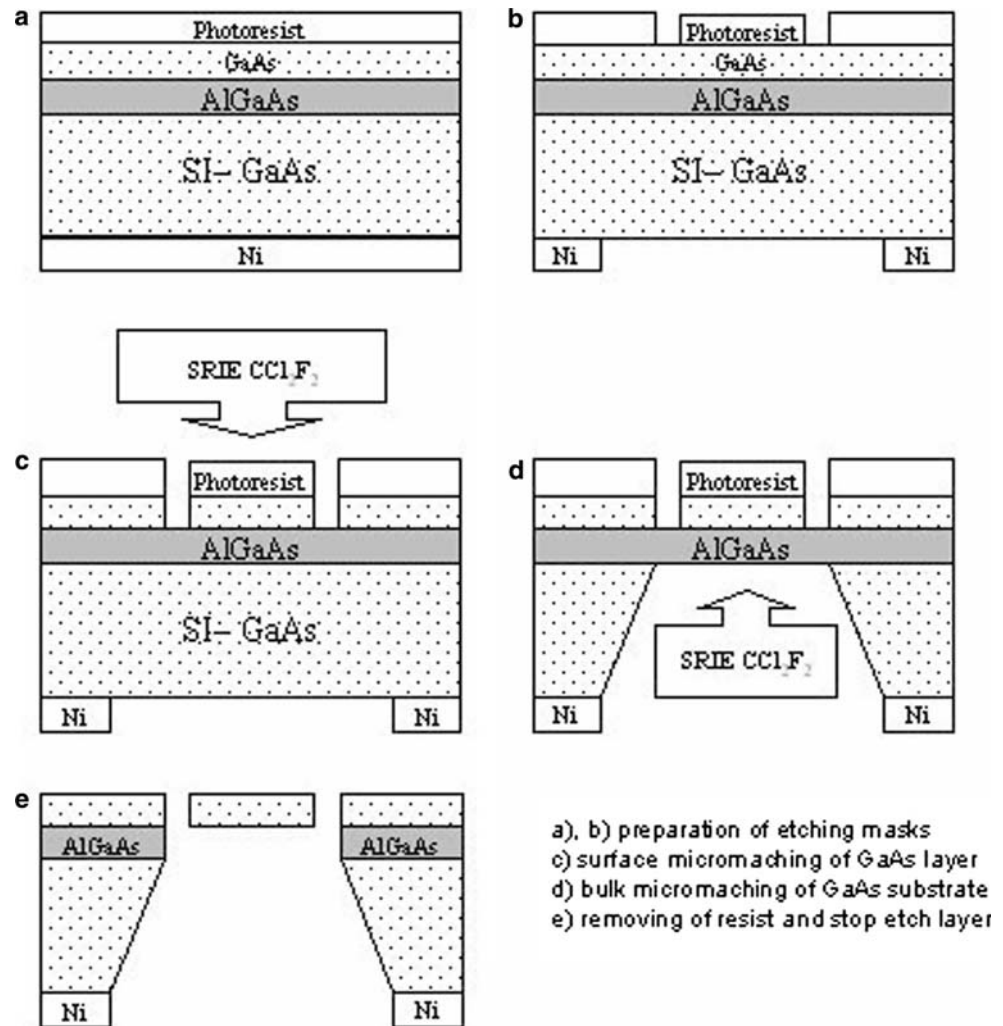
Fig. 2 FEM simulation of the temperature distribution of the microheater (design no. 3, heating power was 22 mW) (a), and current density (A/m^2) in the heater for input voltage 2.85 V (22 mW) (b)

the effect of electro-migration. This problem should be solved using a discontinuous heating mode.

3 Microheater development

In the fabrication of the suspended microheater, the basic steps are to surface and bulk micromachining of GaAs. The GaAs/AlGaAs heterostructure layer system grown by MBE on the GaAs substrate was designed to be used for micromechanical structure fabrication. Figure 3 shows the process sequence of the preparation of the GaAs suspended membranes. In the first step, double-side aligned photolithography was carried out to define the etching masks on both sides of the substrate. After this, highly selective reactive ion etching (SRIE) based on CCl_2F_2 plasma chemistry of GaAs from the front side defined the lateral dimension of the structure. Resist AZ 5214 was used for masking (see Fig. 3a–c).

Fig. 3 The fabrication process flow



The bulk micromachining process started by preparing a Ni mask for backside etching using the lift-off technique. The vertical dimension was defined by deep back side RIE through a 300 μm thick GaAs substrate to the AlGaAs etch-stop layer, hence the structure thickness is precisely determined by the thickness of MBE grown GaAs layer over this etch stop layer. We used again CCl_2F_2 as a process gas (Fig. 3d). Finally, the resist and the etch stop layer are removed (Fig. 3e). Details of the micromachining technology described can be found in (Hascik et al. 1998).

The heater structure was of double spiral type and it was situated on a thermally isolated $150 \times 150 \mu\text{m}^2$ suspended membrane using four microbridges. A 20 nm thick TiN adhesion layer followed by 200 nm of Pt was deposited by magnetron sputtering and lift-off technique. The resulting resistance of the heater was in the range from 63 to 71 Ω . After annealing at 400°C, stabilization of the electrodes was achieved. After this process, the micromachined substrate was diced, the chips were mounted on TO package and four wire bonds (two for the microheater contacts and

two for the temperature sensor contacts) were realized. The fabricated structure is shown in Fig. 4. The cavity under the microheater structure through GaAs substrate was $400 \times 400 \mu\text{m}^2$. The SEM micrograph (Fig. 5) shows the bulk etching of back GaAs wafer through the Ni mask.

In our experiments, the optimal etching conditions were found for preparing 2 μm thick suspended membranes for the MEMS sensor arrays. The etch rate was about 2 $\mu\text{m}/\text{min}$, the selectivity to the sputtered Ni etch mask better than 2,000 and to the AlGaAs stop-etch layer better than 1,000 when using a pressure of 18 Pa and rf power 150 W. Our experimental results agree with conclusions of Chiang et al. 2002 who report on deep anisotropic etching of GaAs with chloride-based chemistry.

4 Device electro-thermal testing

For testing purposes, the microheater was powered up with a variable voltage of 0 to -3 V source using a probing

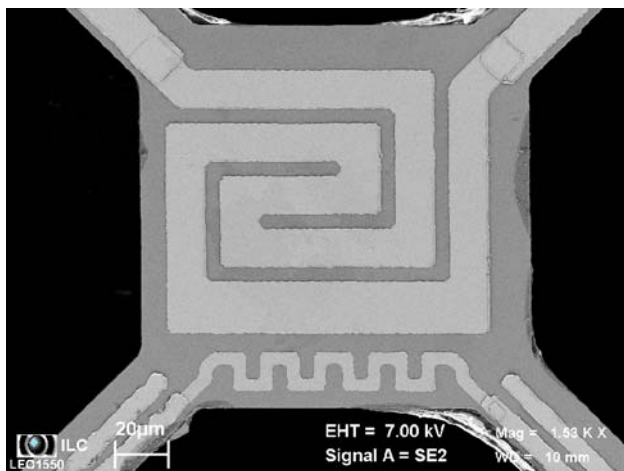


Fig. 4 SEM image of a suspended TiN/Pt microheater

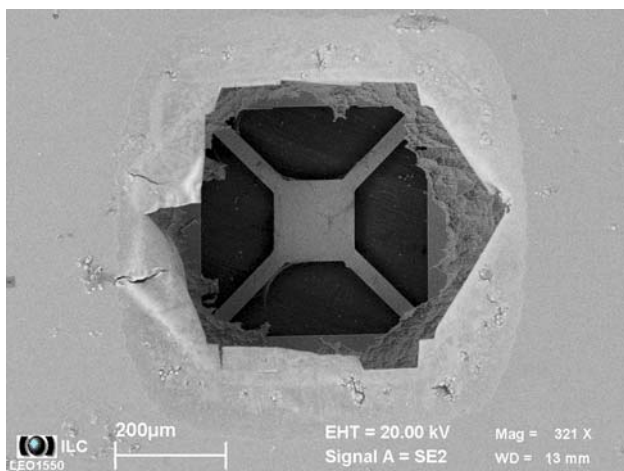


Fig. 5 SEM view of bulk etched GaAs window $400 \times 400 \mu\text{m}^2$

system. I–V measurements were performed using an automatic measurement system consisting of AgilentVee Software environment and KEITHLEY 237 and 238 Source Measure Units. The temperature sensitivity of TiN/Pt thin film temperature sensor was investigated in the first stage. The I–V curve of the temperature sensor at constant current biasing was used to convert the temperature into voltage. Figure 6 shows the measured voltage response to the temperature at constant current biasing of 3 mA. As expected, very good linearity in the sensor voltage response was observed.

After temperature calibration of the temperature sensor (Fig. 6) it is possible to evaluate the electro-thermal conversion efficiency of the microheater that fulfils the role of the so-called thermal converter device. We changed the power dissipated in the microheater as a product of voltage and current. The temperature sensor was operating at constant current biasing ($I_{TS} = 3 \text{ mA}$), so the temperature

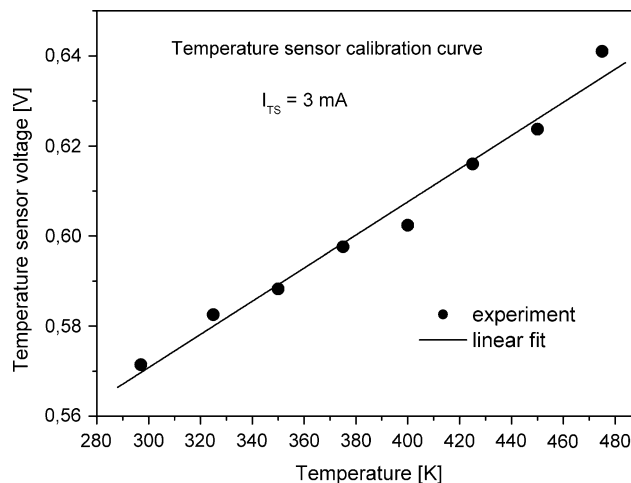


Fig. 6 Temperature sensor calibration curve

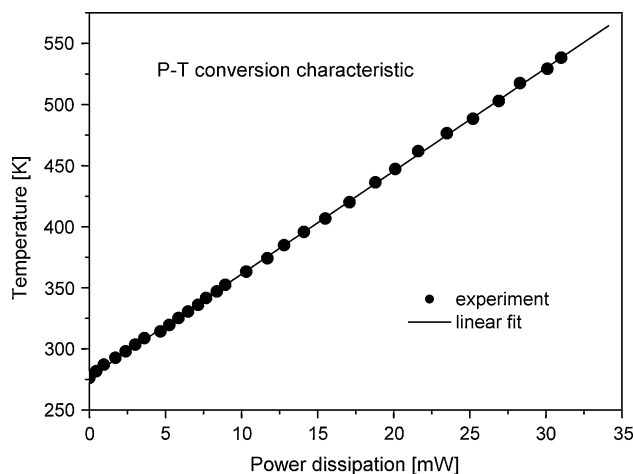


Fig. 7 Power consumption vs. the variation of the microheater temperature

sensor voltage response to the power dissipation was measured immediately.

The linear fit performed on the temperature sensor calibration curve in Fig. 6 allows making a transition of the temperature sensor voltage directly to the temperature. Finally, Fig. 7 shows the so-called power-to-temperature (P–T) conversion characteristic that can be used to evaluate the conversion efficiency of the device. There is also a very good linearity in the P–T conversion. After fitting the measured data by linear regression ($T = 276.878 + 8.4346 P$) it is clear that the thermal resistance R_{TH} defined as $\partial T/\partial P$ is virtually constant in the range of applied power dissipation (measured temperature range). R_{TH} achieves the value of 8.43 K/mW. So, the temperature increase in the sensor active area on the level of 550 K (predicted operating temperature of gas sensor) can be achieved at power consumption about 30 mW. It can be seen that this measured value of the power consumption is in accordance with the

expected value from the electro-thermal simulation (22 mW).

5 Thermomechanical stability of the device

The membrane-like structure of the micro-hotplate platform for the MEMS sensor arrays is a complicated multilayer structure composed of a variety of materials with different thermomechanical properties. It leads to a strong tendency to be deformed at any change of temperature and, regarding the relatively high exploitation temperature range up to 550 K, this factor has to be considered. The membrane remains flat under tension from the upper metallic layer that tends to shrink after its deposition and subsequent cooling down. The structure as a subtle element is forced to deform and vibrate under smallest mechanical activation or using electric feeding thermally activation. After starting the power, the excitation of central deflection and resonant vibrations appears immediately.

To observe the vibration of the micro-hotplate element, the Laser Doppler Vibrometer (LDV) was used. The LDV system Polytec OFV-303 is a point-like contactless vibrational sensor with a laser beam focused on a spot area of about 5 μm in diameter. In the experiment a simple optical setup was adjusted with a possibility of angle-resolved movement of the specimen and direct laser beam focusing on the measured point of the membrane structure with microscopic observation of the position.

To create a mesh of out-of-plane vibration amplitudes, the microhotplate area was mapped point-by-point by repeated thermal initiation. The initiation pulse shape is in Fig. 8, where also the thermally excited oscillation of the micro-hotplate in one of the measured points is shown. The values of vibration amplitudes are scaled in $\mu\text{m/s}$. Vibration in the measured point is non harmonic, thus there is a superposition of higher order vibration modes.

The spectral distribution of the oscillations can visualize the components of this complicated dynamic movement, where single resonant mode frequencies characterize the natural as well as harmonic multiples of the different parts of micro-hotplate element (see Fig. 8). Figure 9 shows the vibration composition in the corner of the central hotplate island area at the “cold” state, thus at room temperature 300 K. The same point was observed after heating the micro-hotplate to a temperature of 350 K. The spectral distribution in this case identified the lack of higher order modes. Such an effect results from a considerably smaller compliance when the micro-hotplate element is heated. Moreover, under these conditions the central deflection of the micro-island exceeds several micrometers, furthermore at the maximum exploitation temperatures of the hotplate the vibration amplitudes

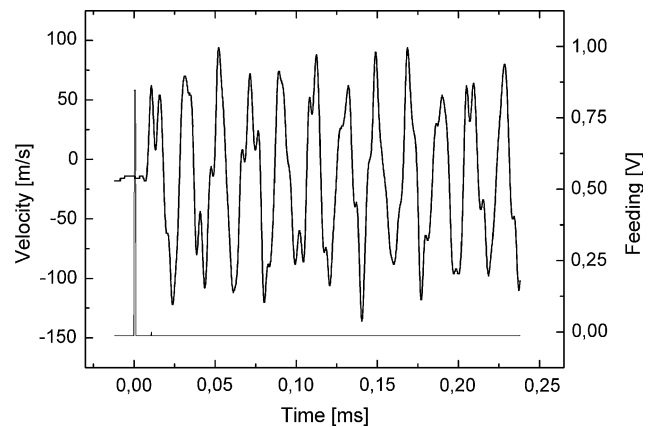


Fig. 8 Excitation pulse shape and excited mechanical vibration of the membrane micro-hotplate element

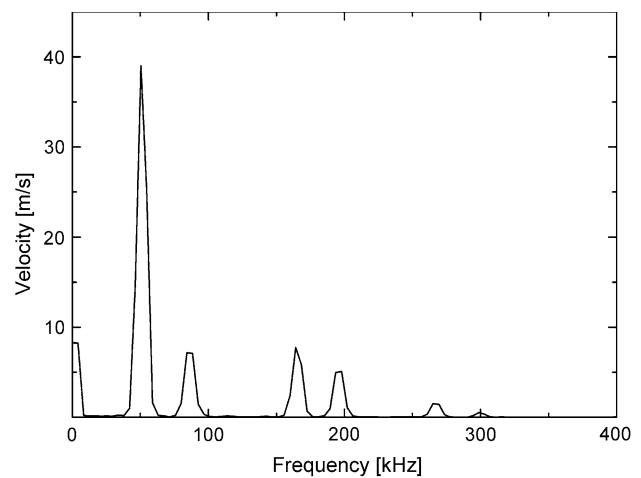


Fig. 9 The spectrum of the vibration response of the element at room temperature conditions

exceed 30–40 μm . The static thermally induced central deflection reached approximately the same values. Nevertheless, even such a deflection of the structure did not influenced the functioning of the device negatively.

6 Conclusions

In this paper, a TiN/Pt microheater prepared on a GaAs micromechanical structure has been fabricated, thermally simulated and characterized as a prospective device for MEMS sensor arrays. Both the suspended membrane ($150 \times 150 \mu\text{m}^2$) and the four microbridges were made of a 2 μm of GaAs and the heater element and temperature sensor were made of platinum. The properties of the micromechanical structure were verified using electro-thermal analysis. It was found that the temperature of the heater on GaAs membrane could be raised to 550 K at a

very low power consumption about 30 mW. This measured value confirmed the value of about 22 mW expected from electro-thermal simulation. Satisfactory mechanical stability of the multilayer structure of the device at highest values of micro-hotplate heating was approved by mechanical testing.

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