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Investigations on thermo-pneumatic volume actuators based on PCB technology

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Abstract

In this paper, four thermo-pneumatic driving concepts for volume actuators based on printed circuit board technology (PCB) are presented. Several experimental measurements have been realised to quantify the power consumption and the behaviour of the actuators for different duty cycles and frequencies. This allows an evaluation of the concepts with respect to an application in micropumps or active valves. Simulations using the finite integration technique (FIT) have been accomplished to calculate the resulting chamber temperature of an actuator if a certain amount of heating power is dissipated in the chamber. The results are validated with measurement data.

Keywords: PCB; Thermo-pneumatic volume actuator; Fluidics; Micropump

1. Introduction

There is an increasing interest for the widespread introduction of cheap fluidic microsystems in laboratory devices in order to decrease the consumption of required resources and probe-material and to reduce analysis time. In biological, medical or chemical sensor devices or apparatus the least amounts of fluids have to be sensed, analysed and actuated [1,2]. For example, the development of a fluidic system for a complex integrated bio-sensor (nutrition of biological cell cultures) is a subject of research at the University of Rostock (Life Support System, Lab On Board) [3].

The PCB technology offers the chance to develop complex integrated fluidic systems without expensive equipment compared to silicon and LIGA technology [4,5]. The technology and the main additional steps to fabricate fluidic elements on PCBs are described in [4].

Several fluidic components based on PCB technology have already been developed. Some examples are: a bubble detector (see Fig. 1a) and a thermo-pneumatic valve introduced in [4,6], a pH-regulation system showed in [7], a pressure sensor described in [3] and a self-filling micropump (see Fig. 1b) presented in [3,5].

Former investigations on thermo-pneumatic actuators have shown that this actuating principle is suitable for silicon micropumps [8]. In this paper, four heating concepts for thermo-pneumatic volume actuators built in PCB technology are described and evaluated. These actuators are needed to drive micropumps or active valves.

2. Working principle of thermo-pneumatically driven volume actuators

One method to drive an actuator is to use the thermo-pneumatic principle. A cavity encloses gas (air) as the working medium (air chamber). The chamber forms a closed thermo-dynamic system. That ideally means no exchange of substances but exchange of energy with environment. An electric heater is implemented in the chamber. By switching on the heater, it dissipates electric power and leads to an increase of temperature in the chamber. Therefore, to refit the thermo-dynamic equilibrium, the pressure of the air chamber rises. Turning off the heater forces the chamber to cool down. Hence, the chamber pressure relaxes. That way, periodically heating of the air leads to a cyclic pressure change in the chamber.

If one border of the chamber is flexible, a changing pressure is able to move that border, and thus, to displace a certain volume of fluid in an opposite pressure chamber. A fluid channel under the pressure chamber then performs the

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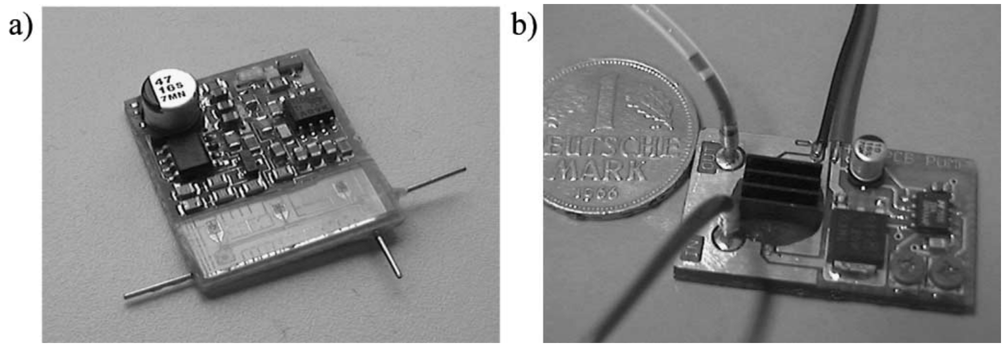

Fig. 1. (a) Bubble detector [4]; (b) delivering micropump based on PCB technology [3,5].

transport of that displaced fluid. This configuration forms a thermo-pneumatic volume actuator. Fig. 2 schematically shows the principle structure of such an actuator built in PCB technology.

3. Structure of thermo-pneumatic actuators

For measurement purposes, the pressure chambers of the investigated actuators have been left open and the fourth PCB with the fluidic channel has been omitted. So all actuators consist of three patterned PCB layers and one flexible membrane. The thickness of the used PCBs (FR4) is 800 μm. The height of the copper structures measures 70 μm. The membrane consists of a thin polymeric foil (Kapton® or Mylar®), which has a thickness of 8 μm (Kapton®) or 6 μm (Mylar®). A special adhesive technique is utilised to connect the patterned PCBs and the membrane [4]. In order to handle the membrane, it is mounted in a carrying system (clamping rings). This enables the processing of the membrane (cleaning, coating, structuring) and an exact positioning for the connection with the PCBs in a special assembling system. By clamping the membrane in the carrying rings, the membrane gets its intrinsic tension.

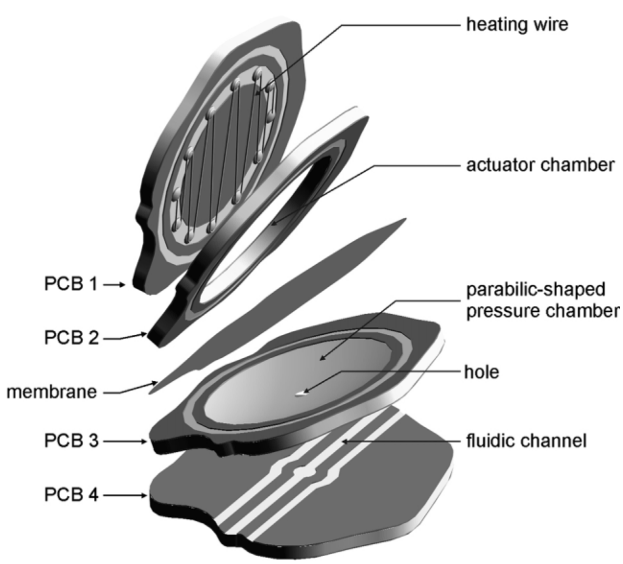

Fig. 2. Scheme of a thermo-pneumatic actuator built in PCB technology.

There are four different concepts for heating the actuator chamber:

1. A copper heater is directly placed on the membrane (thickness 500 nm) (see Fig. 3a). To form the heater, the membrane is coated using thin-film technology (sputtering), photo-lithographically patterned and wet-chemically etched. Because the electric connection of the heater is realised outside the chamber, the heater requires an insulation at the crossover with the PCBs copper sealing rings of the chamber. This is done by placing a thin (8 μm) polymeric slice of Kapton® between the heater and the copper ring on their crossover.
2. A commercially available Constantan® heater wire (70 μm in diameter) is mounted on the bottom of the actuator chamber by manually threading it through small holes and sealing the holes with epoxy. The two ends of the Constantan® wire are soldered on copper pads on the PCB (see Fig. 3b).
3. A heater is formed by direct use of the patterned copper of a PCB (thickness 25 μm) (see Fig. 3c). The patterning of the heater on the PCB is done by photo-lithography and wet-chemical etching (as usually in PCB technology).
4. A cantilever polymeric carrier coated with Constantan® (500 nm Constantan® on 8 μm Kapton®) is soldered on its two ends on the bottom of the actuator chamber (see Fig. 3d). The Constantan® is deposited on the Kapton® membrane using thin-film technology (sputtering). Subsequently, the Constantan® film is patterned by photo-lithography and wet-chemical etching. After mounting the patterned Constantan®-coated membrane on the PCB by soldering it on copper pads on the PCB, the remaining uncoated parts of the membrane are removed by using plasma etching (processing gases: CF_4 and O_2). This is possible due to the resistive effect of metallic structures in this plasma etching process. After these steps a released heater (cantilever) is the result.

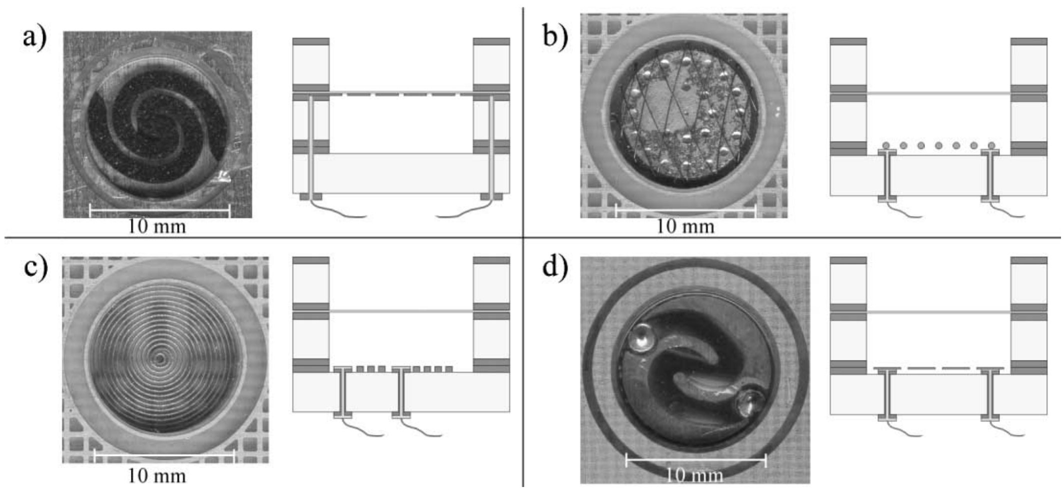

Fig. 3. Photographs and schemes of thermo-pneumatic volume actuators with several heating concepts: (a) copper heater directly placed on the membrane; (b) Constantan® heater wire; (c) copper heater directly patterned on the PCB; (d) cantilever Constantan® heater on a polymeric carrier.

All actuators have the same chamber diameter of 10 mm and use the same membrane material (8 μm Kapton®).

4. Experimental and theoretical characterisation

4.1. Membrane

A sufficient approach for the theoretical dependence of a pressure load p_a on the deflection w for the centre of a circular membrane gives the following equation [9]:

$$p_a = \frac{4d\sigma_0}{R^2}w + \frac{8d}{3R^4}\frac{E}{1-\nu}w^3 \quad (1)$$

where R and d are the radius and thickness of the membrane, respectively; σ_0 the intrinsic tension of the membrane caused by the clamping process, and E and ν the material values (Young's modulus and Poisson's ratio, respectively) of the foil. Fig. 4a shows the good correlation of a calculated and measured deflection versus pressure curve for a 10 mm diameter actuator membrane. The measurement is carried out by using the depth of focus of a microscope and a manometer.

Measurements with a surface profilometer (α-STEP) exhibit that the bulged membrane adapts a paraboloic form (see Fig. 4b). So the displaced volume can be calculated by

$$V = \frac{\pi}{2}R^2 w \quad (2)$$

Assuming air as an ideal gas, a relation between the chamber's increasing mean temperature ΔT and the deflection w of the membrane's centre is given by

$$\Delta T = T_0\left[\frac{(p_a + p_0)}{p_0}\left(1 + \frac{1}{2}\frac{w}{h_a}\right) - 1\right] \quad (3)$$

where p_a is the pressure difference in the actuator chamber (cp. Eq. (1)). T_0 and p_0 are determined by the absolute values of ambient temperature and pressure of the air during the

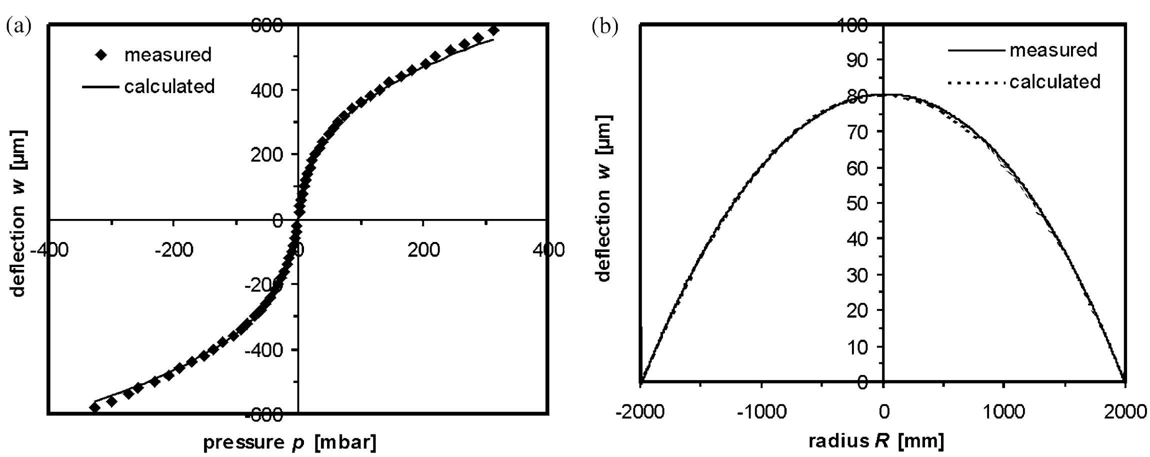

Fig. 4. (a) Calculated and measured deflection vs. pressure difference curve of a 10 mm diameter membrane (for $E = 3$ GPa, $\nu = 0.34$, $d = 8$ μm, $\sigma_0 = 7$ MPa); (b) parabolic shape of a bulged membrane (4 mm diameter, measured and calculated curve).

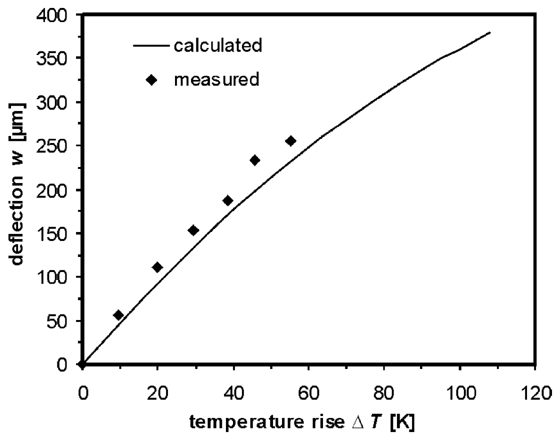

Fig. 5. Dependence of deflection on mean chamber temperature rise of a 10 mm diameter volume actuator and measured deflection at thermal equilibrium (values used for the curve: $E = 3$ GPa, $\nu = 0.34$, $d = 8$ µm, $\sigma_0 = 5$ MPa, $h_a = 800$ µm, $T_0 = 308$ K, $p_0 = 1.013$ bar).

fabrication process, and h_a names the height of the actuator chamber. Fig. 5 depicts the relation in a diagram. The measured values have been obtained at thermal equilibrium. The difference to the theoretical curve must be explained due to the decreasing Young's modulus of the polymeric membrane material as a result of the rising temperature and by thermal expansion of the materials.

4.2. Dynamic behaviour

To observe the displacement behaviour of a dynamically moving actuator membrane, a LASER displacement meter (KEYENCE LK-031) is focused on the centre of the membrane. The exciting of the actuator's heater and the recording of all measured data are done by using a PC (software: LabView®, data acquisition: AT-MIO-16XE-50).

The diagram of Fig. 6 exhibits a typical deflection curve of an actuator measured at a steady-state. The mean deflection $\overline{w}$ (offset) in Fig. 6a (approx. 200 µm) corresponds to a deflection response which will be reached due to a constantly dissipated 1 W heating power (Fig. 6b).

Using the deflection difference Δw (see Fig. 6) with Eq. (2), a volume displacement rate, dV/dt (µl/min), can be defined for the cyclically displaced volume of the membrane in one direction. This yields the maximum theoretical flow rate that will be obtained if the actuator works in a pump without any load.

4.3. Comparison

From the deflection diagrams, the dependence of the volume displacement rate of the several heating concepts on the exciting parameters (duty cycle, frequency, heating power) can be investigated. To compare the several heating concepts, the volume displacement rate has been kept constant at approx. 240 µl/min (using a frequency of 1 Hz, a deflection difference of approx. 100 µm and a membrane radius of 5 mm). Therefore, the mean heating power has been determined for three duty cycles each. As shown in Fig. 7a, the actuators with thin film heaters from concepts (1) and (4) consume the least amounts of heating power.

Further investigations have shown that the bimorph-effect of heater concept (1) cannot be neglected. In an experiment, the actuator chamber has not been closed, so that no pressure could have been built up. The heater then has been excited but, however, a significant membrane movement has been observed. This explains the less required heating power in comparison to the cantilever heater from concept (4). Another drawback of the membrane heater is that if a liquid fluid (e.g. water) comes in direct contact to the membrane, the actuator immediately stops moving because of the small thermal resistance of the thin membrane. This makes this concept unsuitable in micropumps which have to deliver liquids.

The disadvantage of the Constantan® heater wire from concept (2) first is that due to the mounting principle (threading through holes) approx. 30% of the wire lie outside

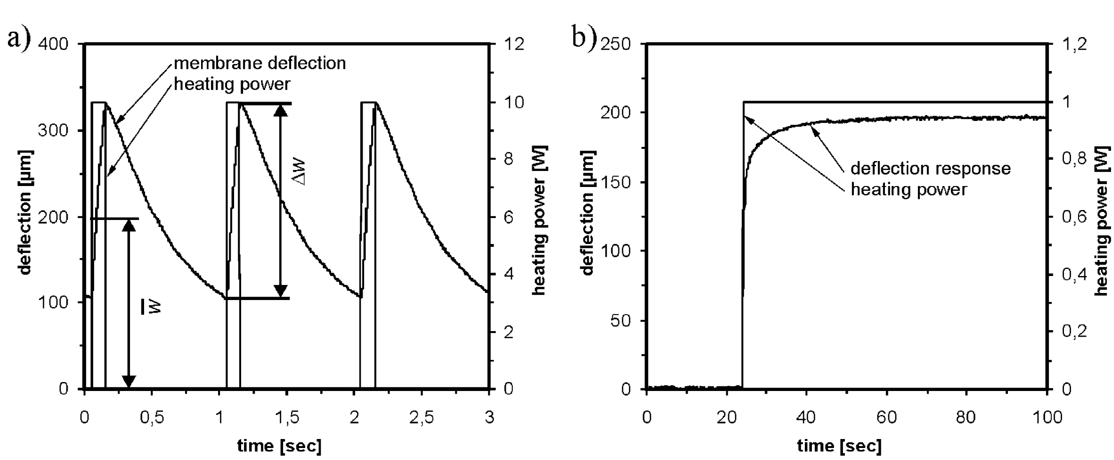

Fig. 6. (a) Typical movement of an excited actuator membrane (heater type: Constantan® wire; exciting frequency: 1 Hz; duty cycle: 0.1; max power: 10 W; mean power: 1 W); (b) deflection response on a heating power step (1 W).

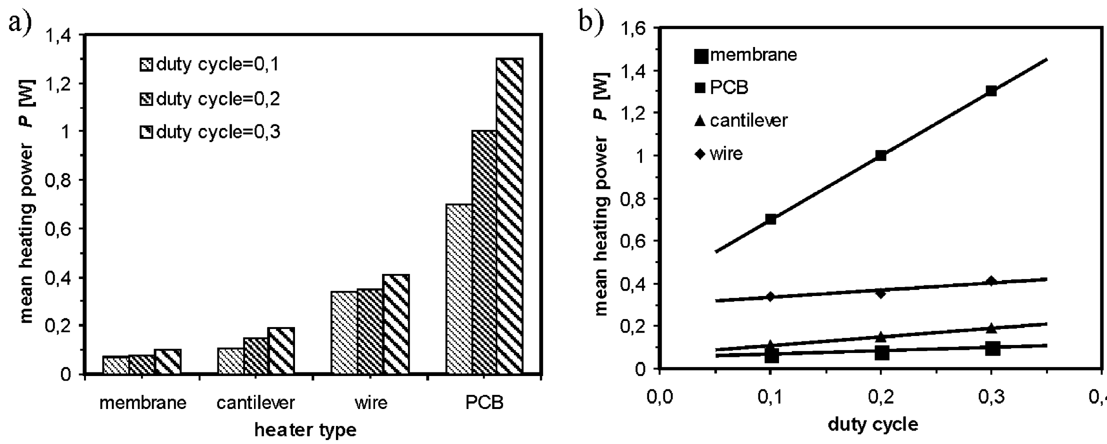

Fig. 7. Comparison of the several heater types, all for the same volume displacement rate of approx. 240 μl/min.

the actuator chamber and thus yield no heating contribution for the air in the chamber. Another disadvantage is the difficulty to automate the fabrication process. The advantage of the wire is its robustness. A long-term test of an actuator with a Constantan® heater wire (frequency: 1.5 Hz; mean power consumption: 1.4 W) has been running since May 1999 and has not been finished up to the time that this article was written (up to now: 11 months with approx. 42 million cycles with a deflection difference of approx. 190 μm). This promises a high working reliability of such a concept.

The simplest way to build an actuator in PCB technology is to use the patterned copper from the PCB as the heating wire (concept (3)); no additional process steps are required; this actuator can be built very cheap. But there are two significant drawbacks. The first is the huge heating power needed to obtain an adequate volume displacement because of the tight contact of the copper heater to the PCB (the copper is usually laminated on the PCB); the second drawback is that with the copper from the PCBs only small heater resistances can be realised.

Although the fabrication of an actuator with heater concept (4) is more complicated and needs more process steps. This concept has the potential for fabricating actuators in quantities since the processes can be automated and batched. But there are no experiences concerning the long-term behaviour of the heater.

A common factor to all heating concepts is that smaller duty cycles require less heating power for the same volume displacement rate. Fig. 7b shows an approximately linear dependence for the measured region.

To investigate the dependence of the volume displacement rate on the mean heating power consumption, the duty cycle has been kept constant at 0.1. This has been done for three frequencies each. Fig. 8 depicts the measurement results. As can be seen, the efficiency of the actuators rises with increasing frequency. This can be explained due to the decreasing heating time per cycle (same effect as the duty cycle in Fig. 8).

But in order to increase the flow rate of a micropump, it is not effective just to increase the exciting frequency because the deflection difference Δw of the membrane rapidly decreases in this case (see Fig. 9). Though, for successfully pumping, a significant volume displacement of fluid is essential to drive the valves and to tolerate gas bubbles.

4.4. Simulation

In order to investigate the thermal behaviour of the actuators, simulations using the finite integration technique (FIT) implemented in the simulation package MAFIA [10] have been realised. MAFIA is mainly used for solving electromagnetic field problems. Furthermore, it has a module for the solution of the three-dimensional instationary heat equation with heat sources either spatially distributed by the effect of electromagnetic field losses or located at the borders of the calculation grid.

A preliminary simulation with the entire cylindrical geometry of both pressure and actuator chambers, embedded in PCB layers, showed that there is only a small influence of the vertical chamber walls on the average air temperature in the pressure chamber. This is due to their small surface compared with that of the chamber's lids. For that we decided to perform the calculations as for an infinitely expanded chamber cross-section in a quasi-one-dimensional manner, having only a minimal 2×2-grid in the cross-sectional plane. This made it possible to discretise even the very thin membrane foil with an adequate number of mesh points while keeping the problem within reasonable numerical effort (calculation times below 1 h).

In order not to need a calculation of the current distribution in advance, we located the heat source at one vertical boundary plane of the calculation volume. Therefore, it was necessary to split the calculation volume into two parts above and below the heater. These parts were calculated separately. The continuity of the temperature at the heater plane was maintained afterwards exploiting the linearity of the heat equation by scaling both temperature

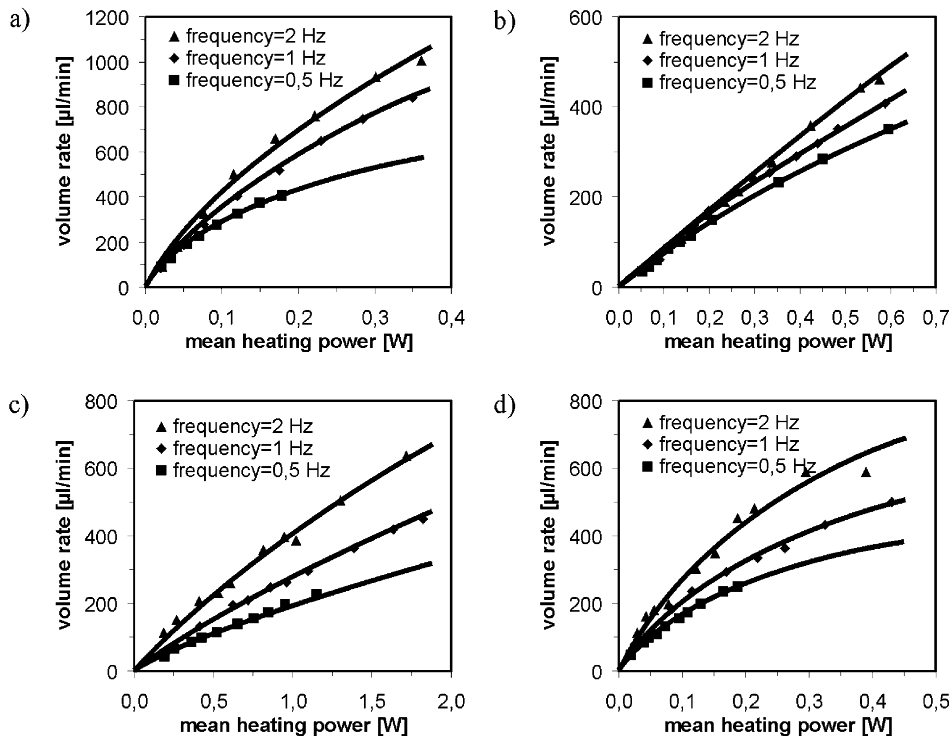

Fig. 8. Volume displacement rate as a function of mean heating power consumption for three different frequencies each: (a) copper heater direct on the membrane; (b) Constantan® heater wire; (c) copper heater direct on the PCB; (d) cantilever Constantan® heater on a Kapton® carrier.

distributions appropriately to each other and to the total heater power.

Two different arrangements were studied numerically: the copper heater laying directly on the PCB (concept (3)) and the cantilever heater located 100 µm above the actuator chamber's bottom (concept (4)). Fig. 10 shows the simulated temperature distribution after a 100 ms long heating interval for both arrangements. The pressure chamber was assumed to be air-filled which made it easy to compare with membrane deflection experiments shown in Fig. 11.

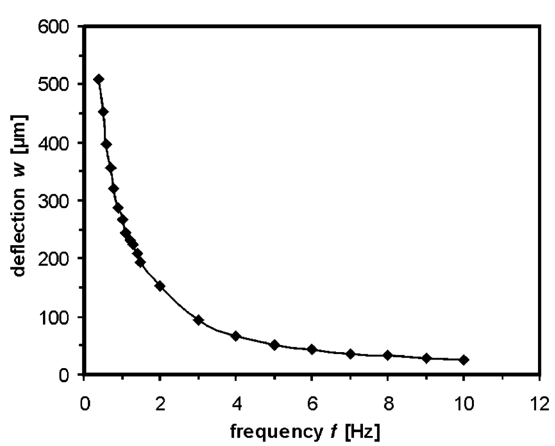

Fig. 9. Typical membrane deflection difference versus exciting frequency curve (heater concept (2) with a duty cycle of 0.1 and a constant mean heating power of 1 W).

As it is shown, there is a linear temperature decrease through both chambers if the heater is located directly at the PCB (see Fig. 10a). It has different slopes above and below the membrane, which represents an heat transfer resistor. The linear dependency above the heater indicates an almost stationary situation, whereas the PCB below the heater is not levelled out after the heating interval. The situation is similar for the elevated heater (see Fig. 10b): both air volumes show linear dependencies, while the temperature dependence in the lower PCB layer has a curved shape. The temperature in the PCB layer located above the chambers behaves similar, but on a temperature level to low to be observed in the graphs.

In this simulation, only a single heat interval is considered. The cool-down time and a temperature pile-up during numerous cycles are omitted. From experimental experience this seems to be a reasonable approach.

The simulation yields a mean temperature rise in the actuator chamber of 41.0 K with 10 W heating power for concept (3) and of 62.5 K with 2.5 W heating power for concept (4). Using Eq. (3), this corresponds to an estimated membrane deflection of 175 µm (concept 3)) and 250 µm (concept (4)). To validate the results obtained from the simulation, the deflection response of the membrane on a 100 ms heating power step has been observed for the heater concepts (3) and (4). Fig. 11 shows the curves.

The measured deflection values of 140 µm (Fig. 11a) and 210 µm (Fig. 11b) correlate well with the theoretical results. There are only moderate deviations of 25% (concept (3)) and 19% (concept (4)), respectively.

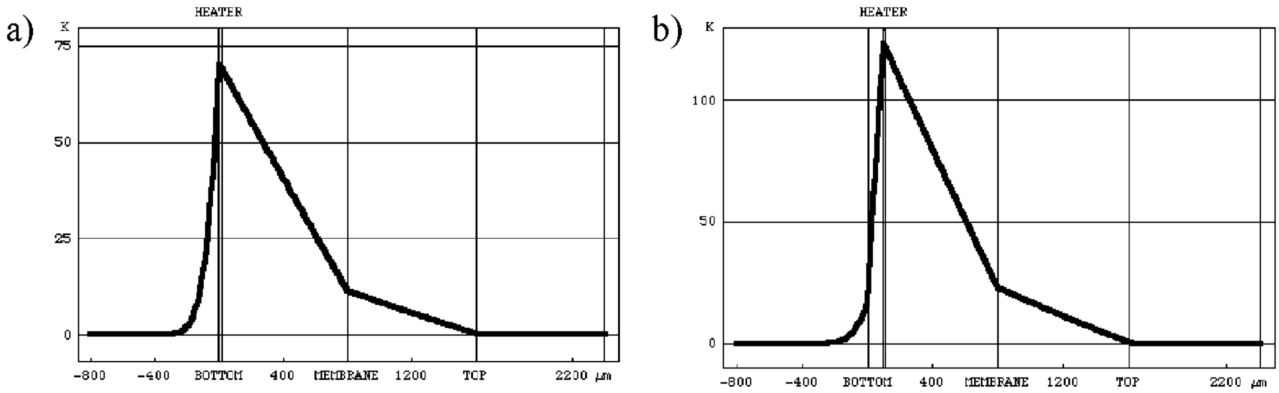

Fig. 10. simulated temperature distribution after a 100 ms long heating interval (a) copper heater direct on the PCB; (b) cantilever Constantan® heater on a Kapton® carrier.

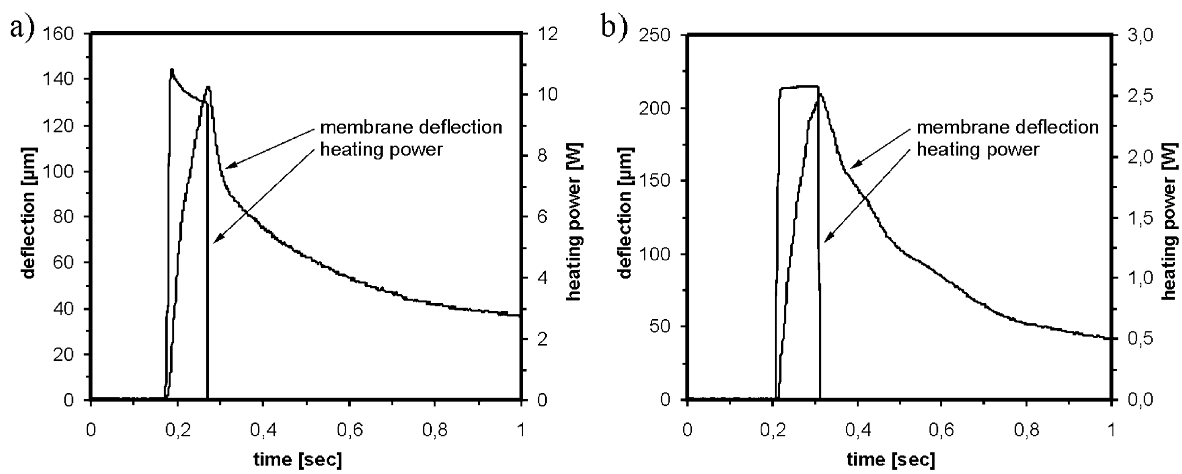

Fig. 11. Membrane deflection response on a 100 ms heating power step: (a) copper heater direct on the PCB; (b) cantilever Constantan® heater on a Kapton® carrier.

As shown in Fig. 11a, the heating power does not keep constantly. This is because of the temperature dependence of the copper and a constantly applied heating voltage ($P = U^2/R$). The heater of concept (4) consists of Constantan® which shows a negligible temperature dependence (see Fig. 11b).

5. Conclusions

The investigations of the several heating concepts show that effective actuators can be built in PCB technology. High volume displacement rates (up to 1000 μl/min) with large membrane deflections and moderate power consumption are properties of the presented PCB actuators. That is why these actuators seam to be suitable for application in micropumps.

The use of an commercially available Constantan® wire as the actuator heater is advantageous concerning the long-term behaviour. If another mounting process for the wire can be established, this concept will be favoured. The copper heater patterned from the PCB (concept (3)) is the simplest and cheapest but yields a too small efficiency. Heater concept (1) only functions with gaseous fluids, and thus, it is unsuitable for micropumps which have to deliver liquids. A cantilever heater (concept (4)) is effective but needs more fabrication steps. If batch processing is used, this problem can be overcame. But at this time, no long-term experiences of this heating type are existing.

Concerning the simulation, we consider the approach as sufficient for modelling the actuator setup, since there remain uncertainties about material constants used in the simulation and taking into account that (small) cooling effects near the chamber side wall have been neglected.

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Biographies

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Hans-Walter Glock has been working as a Scientific Assistant since 1998 at the Department of Electrical Engineering of Rostock University. He received his PhD degree in 1997 in the area of high-frequency measurement techniques applied to particle accelerator structures. His main interests are the development of field solving methods and their use for various applications.

Lienhard Pagel has been Professor in Microsystems and Director of the “Institute of Electronic Appliances and Circuits” at the University of Rostock since 1994. Prior to this, he worked in research and development in the semiconductor industry for 10 years. Since 1994, his main topic has been the realisation of microfluidics systems in PCB technology.

Stefan Richter was born in 1970 in Chemnitz, Germany. He studied Electrical Engineering at the Universities of Jena and Chemnitz. In 1996, he received the Dipl.-Ing. degree from the Chemnitz University of Technology and started his scientific career as a Research Assistant at the Department for Microsystems and Precision Engineering of the same university. In 1999, he joined a Graduate College at the University of Rostock, where he works on PCB-based micro-fluidic systems.