Thin-film Micro-Heater for Fusion Bonding of Teflon-FEP Foils

Florian EMMERICH[1] *and Stefan CIBA*[1]

[1] Dept. of Engineering, University of Applied Sciences Aschaffenburg, Würzburger Straße 45, 63743 Aschaffenburg, Germany

Florian.Emmerich@h-ab.de

Abstract. *MEMS-based Micro-Heaters, in combination with thin-film temperature sensors, are often used for providing the necessary amount of thermal energy for sensor-applications. In this work, we propose an integrated micro-heater as actuator for fusion bonding of polymers, which can optimize the production process of electret-based micro-energy-harvesters. By adjusting the design parameters of thermoforming-molds, we can implement thin-film micro-heaters that are capable of generating temperatures of above 300 °C for numerous cycles. Utilizing the integrated micro-heater allows local fusion bonding of Fluoroethylenepropylene (Teflon-FEP) foils on a micrometer-scale while reducing unnecessary thermal stress. This is beneficial for the longevity of the micro-energy-harvesters, while simultaneously improving its performance.*

Keywords

Energy-Harvesting, Fusion Bonding, Micro-Heater, SU-8, Teflon-FEP.

1. Introduction

With the progress of silicon micro-electronic-technology, micro-electro-mechanical-systems (MEMS) have found widespread application. The effects of miniaturization reduced power consumption while increasing the mobility of sensors and actuators, opening up a new spectrum of application. Many sensing applications like gas sensors [1] or microfluidic devices [2] are dependent on temperatures far above room temperature, which fueled the development of thin-film based micro-heaters with the capability of integration. Today such heaters can be miniaturized to areas lower than 1 mm² while achieving temperature above 2000 K [3]. The heater material can be chosen from a wide range of metals as aluminium, nickel-chromium, platinum or semiconductors like polysilicon [1]. Furthermore the implementation on flexible polymeric substrates is possible [4], if the maximum operating temperature of the heater is limited below the substrates melting point.

While most applications use micro-heaters as utility for sensing purposes, only few applications, for example inkjet printing [5], use the heaters as an actuator. In this work we propose an integrated micro-heater for fusion bonding of Fluoroethylenepropylene (Teflon-FEP) to improve the production process of electret-based energy-harvesters [6]. This emerging kind of energy-harvester has numerous advantages over non-polymer-based harvesters, as they are flexible, easier to produce and show promising energy-output of almost mW/cm² [7]. Many electret-based harvesters use Teflon-FEP [8], which is an advancement of Polytetrafluorethylene (PTFE, Teflon), having a lower melting point while exhibiting similar electrical and chemical properties [9]. A schematic of such a FEP-based energy-harvester is shown in Figure 1:

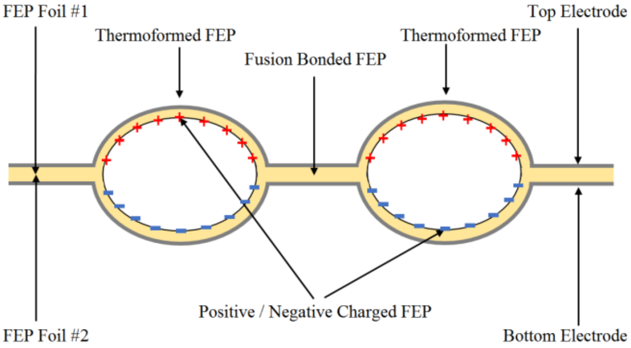


Fig. 1. Schematic of a FEP-based energy-harvester consisting of two thermoformed and fusion bonded FEP-foils.

In short, this kind of energy-harvester consists of thermoformed Teflon-FEP foils, which are fusion bonded in a periodic pattern containing micron-sized cavities. Metallization of both sides will allow applying a high voltage to causes an electric breakdown of the air inside these voids. During breakdown, top and bottom of the cavities are charged with opposite polarities. The inserted charges will be stored for months or years due to the dielectric properties of FEP. Such charged dielectric materials are called electrets. Applying mechanical load on the harvester will induce a change in compensation charges on the electrodes, which can e.g. be used to charge a battery and thus convert mechanical into electrical energy. As this effect is similar to the piezoelectric effect, these energy-harvesters are called piezoelectrets [10]. During the production process, the fusion bonding of the two FEP-foils is a crucial step, as the whole structure is exposed to temperatures above the melting point of FEP of ~270° C [9].

By adjusting the design of a structured photoresist substrate, we present a process to integrate micro-heaters and propose optimal voltages for safe bonding of two FEP foils. This adjustment reduces thermal stress on the complete micro-energy-harvester while improving device-stability and -lifetime.

2. Thin-film micro-heaters

The basic physical principle of micro-heaters is Joule heating, also called Ohmic heating, and was first conducted by James Prescoot Joule in 1841 [11]. Charge carriers, accelerated by an applied voltage, collide inside a conductor with atoms of the crystal lattice, resulting in a random motion according to the applied voltage. This random motion of charge carriers can be considered as heat and is proportional to the applied voltage, as all the electrical energy is converted during the conduction. Basically, every conductor is affected by Joule heating if electric current flows through it. Using long conductors made of thin-metal films, allows the production of heater-designs with defined total resistance in small areas. A schematic of a thin film based micro-heater is shown in Figure 2.

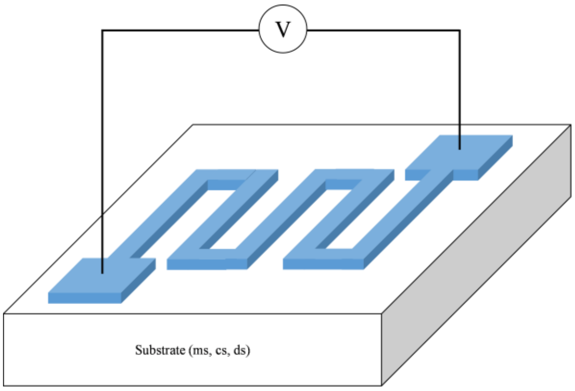


Fig. 2. Schematic of a thin-film micro-heater.

The power P of such a micro-heater can be approximated as:

$$P = {V^2}/{R} = I^2 \cdot R = I \cdot V \tag{1}$$

V represents the applied voltage, I represents the current through the heater and R represents the resistance of the heater. As micro-heaters are usually based on thin-films, the resistance R can be described as:

$$R = \rho \cdot {l}/{A} \tag{2}$$

Here ρ is the specific resistance of the thin-film, l is the length of the conductor and A is the cross-section of the conductor. During heating, the crystal lattice will start to vibrate, resulting in even more collision between charge carriers and atoms. Hence, higher temperatures lead to a higher resistance in the micro-heater. This can be expressed by a temperature dependent specific resistance ρ_T:

$$\rho_T = \rho \cdot \big(1 + \alpha \cdot (T_A - T_R)\big) = \sigma_s \cdot (1 + \alpha \cdot \Delta T) \tag{3}$$

α represents the thermal coefficient of the heater material, T_A the actual temperature and T_R the room or reference temperature. Looking at equation (3) with the fact that α is a positive constant for most metals, yields that the resistance increases with higher temperatures of the heater, resulting in a lower power output. As power is defined as energy per time t, the generated energy E can be expressed as follows:

$$E = P \cdot t = {V^2}/{R} \cdot t \tag{4}$$

As the conductor converts the electric energy to heat Q, the amount of energy, necessary to heat a material to a certain temperature, can be calculated:

$$Q = (m \cdot c) \cdot \Delta T \tag{5}$$

Here m represents the mass of the heated material and c the specific heat capacitance of the heater. During heating, the generated thermal energy will spread in three ways: conduction through surrounding material, convection through air as well as thermal radiation, if the temperature is sufficient. At low temperatures, primarily convection and conduction occur. When a material is affected by a heat source, the resistance against heating up is defined by its total thermal resistance θ:

$$\theta = \left({d}/{A \cdot \kappa}\right) \tag{6}$$

The parameter d represents the thickness of the heated material, A equals the heated Area and κ is the thermal conductivity. A high thermal resistance represents long time delay until the heated material has the same temperature as the heater.

To achieve a uniform temperature distribution above the heater, various designs such as meander-shaped, circular, fan-shaped, square-shaped or power compensated have been examined in the literature [1]. In summary, basic designs as meander or circular heaters do not achieve a uniform temperature distribution and deviate up to 40% over the heater's surface, with a temperature maximum in the middle.

3. Experimental Section

3.1 Substrate preparation

For improving the production process of Teflon-FEP-based energy-harvesters, it is necessary to integrate the micro-heater into the production process of thermoforming-masters. These masters are prepared by spin-coating of 75 µm SU-8-100 negative tone photoresist (MicroChem Corp., Westborough, USA) on a 38 x 38 mm² piece of borofloat glass (Schott Technical Glass Solutions, Jena, Germany). In a later step, trenches are implemented into the photoresist, acting as mold for thermoforming of the FEP foil. During the whole production process temperature is a crucial parameter to guarantee suitable adhesion between the SU-8 and the glass substrate. The entire production process will be published elsewhere [6]. A schematic of a thermoforming-master is shown in Figure 3, where white areas represent the trenches and black areas the SU-8:

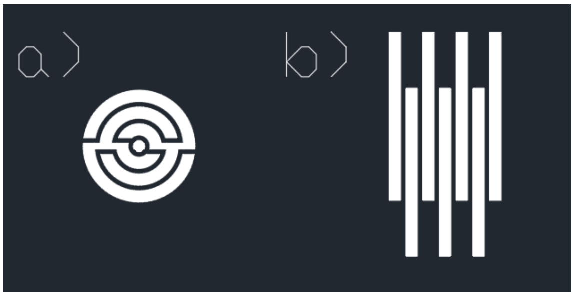


Fig. 3. Schematic of the thermoforming master for a) circular and b) parallel trenches.

3.2 Micro-Heater production

Following the fabrication of the thermoforming-master, the production of the micro-heater was realized. For this purpose a magnetron sputter device Lesker NANO 36 (Kurt J. Lesker Ltd., Sussex, England) is utilized. Onto the whole surface of the master a uniform layer aluminium was sputtered for 12.5 minutes at 200 Watt. Subsequently, the specific resistance $\rho \approx 5{,}3 \cdot 10^{-8}\,\Omega\mathrm{m}$ was measured and the resulting film-thickness of ~105 nm was determined by Atomic-Force-Microscopy.

Past metallization, we used spin coating to apply 1 µm of the positive tone resist AZ701 (Microchemicals, Ulm, Germany) across the substrate. After a 1 minute softbake at 100 °C, we exposed the film with a photolithographic mask, in alignment with the trenches of the master, with a dose of 225 mJ/cm² using a UV-KUB 2 exposure system (Kloe, Montpellier, France). A subsequent post exposure bake of 1 minute at 100 °C was applied before developing the whole sample for 120 seconds in AZ developer (Microchemicals, Ulm, Germany), diluted in a ratio of 1:1 with ultrapure water. Thereafter, the sample was rinsed isopropanol and water and thoroughly cleaned with nitrogen. As a result, all metallized trenches and areas on the sample unnecessary for the heater were blank metal while the remaining areas were covered with the photoresist. The used mask-designs for the photoresist are shown for designs in Figure 4:

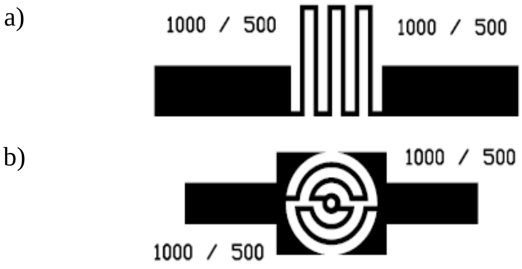


Fig. 4. Photolithographic masks for a) parallel and b) circular micro-heater designs. Using a positive tone photoresist, dark areas will remain on the sample after development. These areas are matched with the thermoforming-master.

In the last step, the whole sample was etched in aluminium etchant (Microchemicals, Ulm, Germany) (1-5% HNO3, 65-75% H3PO4, 5-10% COOH, diluted in water). The typical etch rate at room temperature is 50 nm/min, resulting in an etch time of 3 minutes to fully etch the aluminium layer. Subsequently, the photoresist was removed in pure AZ 100 remover (Microchemicals, Ulm, Germany) for 3 minutes and thoroughly cleaned with ultrapure water, isopropanol and nitrogen to remove all residues. The completed micro heater on a thermoforming master is shown in Figure 5:

Fig. 5. Photograph of a completed micro-heater implemented on a thermoforming master. The micro-heater is matched between the trenches with big electrodes at both ends for easy electrical contacting.

4. Results and Discussion

In this study, various heaters with circular and square shaped designs were produced. For each heater design, the length of the heating element was measured. The resistance of the heaters was approximated with equation (2), using the experimentally determined specific resistance. The resulting resistance values were measured using a digital multimeter. These findings are summarized in Table 1:

Type	Conductor Width in µm	Conductor Length in mm	Calculated Resistance in Ohm	Measured Resistance in Ohm
Square	500	72.5	73.2	76.5
Square	250	131.6	265.7	305.2
Square	125	261.6	1056.4	975.2
Circular	500	54.8	55.3	53.4
Circular	250	98.8	199.5	208.3

Tab. 1. Evaluation of conductor length, calculated resistance and measured resistance for different heater designs.

As seen in Table 1, the resulting resistances are in good agreement with the expected values. Deviations between calculated and measured values can be explained by contact resistance as well as non-uniformity of the thickness due to different positions of the sample in the sputtering chamber.

For fusion bonding we stacked two FEP-50A foils with a thickness of 12.7 µm (Lohmann Technologies, Milton Keynes, England) on top of a heater and applied a static force of 50 kPa on the stack, guaranteeing good contact between both foils. Various supply voltages were applied in dependence of the heater design. In general, the heating power for a given voltage is higher for low resistances, as shown by equation (1). Exemplary, the circular design with a conductor width of 500 µm created a clean bond between the two foils at a voltage of 15 V during 30 seconds. A typical bonding result using a circular heater is shown in Figure 6:

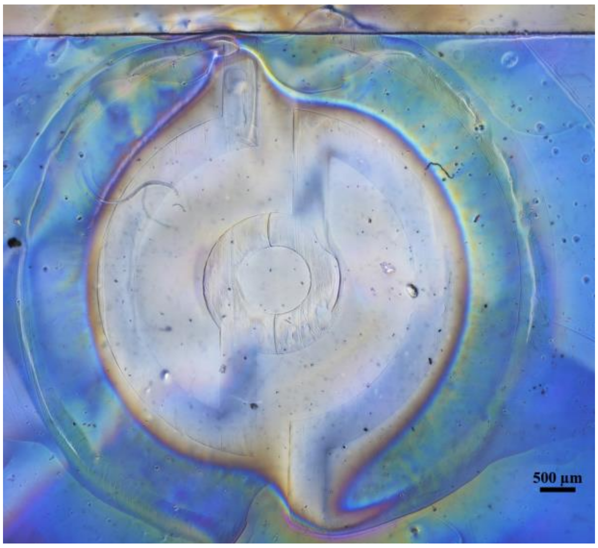


Fig. 6. Micrograph of two fusion bonded Teflon-FEP-foils. The bonded parts are visible through different transmission properties of the bonded FEP.

In Figure 6 it is clearly visible that both foils melted according to the heater layout. Pull tests revealed, that the bonded areas have almost the same tensile strength as the base material. As expected, the bonding in the outer areas of the heater did not show the same results as in the middle, because of the non-uniform heat distribution. Heater designs with a higher resistance needed higher voltages and longer heating times.

The SU-8 thermoforming-masters with integrated micro-heater did not change in size or color during the heating process. This could happen during conventional heating of the whole master of up to 280 °C, making it impossible to reuse the master. All heater designs were tested and did not show any wear-down during 10 heating cycles.

5. Conclusion and Outlook

Fusion bonding of two Teflon-FEP-foils using an integrated micro-heater was considered theoretically and practically by means of various prototypes. An aluminium thin film micro-heater was produced by a process consisting of magnetron sputtering, photolithography and wet-chemical etching. The produced heaters generated temperatures of up to 300 °C without damaging the foil or the thermoforming master.

The integrated micro-heater described in this work represents a significant improvement to the production process of micro-energy-harvesters. Reduced thermal stress on the foils, which is significant during normal fusion bonding, will improve the overall performance and longevity of such energy-harvesters.

Further work will focus on redesigning the thermoforming-master. The creation of more elaborate heater geometries, will yield a more uniform heat distribution across the whole heater, instead of a hot-spot inside the middle. Additional optimization will involve the usage of different materials, as Nickel-Chromium. A Finite-Element-Simulation of the whole structure will also be performed to find an optimal heating time / voltage combination for each heater design. This can cause a reduction of the heaters power-consumption, by modifying the substrate and minimizing the thermal losses.

Acknowledgements

The research described in this paper was supervised by Prof. Dr.-Ing. C. Thielemann, BioMEMS Lab, UAC Aschaffenburg and financially supported by the Bayerisches Staatsministerium für Bildung, Kultus, Wissenschaft und Kunst in the frame of ZEWIS.

References

[1] BHATTACHARYYA, P., Technological Journey Towards Reliable Microheater Development for MEMS Gas Sensors: A review *IEEE Transactions on Device and Materials Reliability* 2014, vol. 14, no. 2, p. 589-599.

[2] DARHUBER, A., VALENTINO, J., TROIAN, S., WAGNER, S., Thermocapillary Actuation of Droplets on Chemically Patterned Surfaces by Programmable Microheater Arrays *Journal of Microelectromechanical Systems* 2003, vol. 12, no. 6, p. 873-879.

[3] WEIR, S. T., JACKSON, D. D., FALABELLA, S., SAMUDRALA, G., VOHRA, Y. K., An electrical microheater technique for high-pressure and high-temperature diamond anvil cell experiments Review of Scientific Instruments 2009, vol. 80, 013905.

[4] HAN, J., TAN, Z., SATO, K., SHIKIDA, M., Thermal characterization of micro heater arrays on a polyimide film substrate for fingerprint sensing applications *Journal of Micromechanics and Microengineering* 2005, vol. 15, p. 282-289.

[5] MILLS, R., Ink jet printing: past, present and future. In IS&T: Recent progress in ink jet technologies 1996, Ed. Rezanka and Eschbach, Springfield, IS&T.

[6] EMMERICH, F., THIELEMANN, C., to be published 2017.

[7] ZHANG, X., PONDROM, P., WU, L., SESSLER, G. M., Vibration-based energy harvesting with piezoelectrets having high d31 activity *Applied Physics Letters* 2016, vol. 108, p. 193903 (4pp).

[8] ZHANG, X., SESSLER, G. M., XUE, Y., XINGCHEN, M., Audio and ultrasonic responses of laminated Fluoroethylenepropylene and porous polytetrafluoroethylene films with different charge distributions Journal of Physics D: Applied Physics 2016, vol. 49, 205502 (8pp).

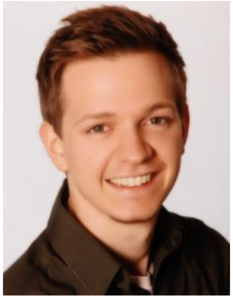
[9] CHEMCOURS Teflon FEP Film Properties.

[10] HILLENBRAND J., SESSLER, G. M., High-sensitivity piezoelectric microphones based on stacked cellular polymer films *Acoustical Society of America* 2004, vol. 116, no. 6, p. 3267-3270.

[11] JOULE, J. P. On the heat evolved by metallic conductors of electricity, and in the cells of a battery during electrolysis *Philosophical Magazine Series 3* 1841, vol. 19, no. 124, p. 260-277.

About Authors

Florian EMMERICH was born in Aschaffenburg. After his Bachelor degree in Industrial Engineering and his Master degree in Electrical Engineering at the UAC Aschaffenburg he started his Ph. D. in Electrical Engineering at the Technical University Darmstadt. His research is focused on micro- and nano-sized electrets, atomic-force-microscopy and the miniaturization of micro-energy-harvesters.



Stefan CIBA was born in in Erlenbach. After receiving his Bachelor of Science degree from the Heilbronn University he started his Master degree in Electrical Engineering at the UAC Aschaffenburg. His current research focuses on development and improvement of micro-energy-harvesters.