SIMULATION, DEVELOPMENT AND CHARACTERIZATION OF PLATINUM MICROHEATER ON POLYIMIDE MEMBRANE

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Abstract - This study is focused on simulation and development of Pt microheater placed on polyimide membrane prepared by deep front plasma etching into Si substrate. Electro-thermal and electrical simulations by FEM analysis for design optimizing of the Pt microheater were performed. Simulation parameters involved various membrane dimensions (50×50, 150×150 and 300×300 µm²) and ratio between width heater’s lines and spacing between them in the range from 9/3 µm to 18/6 µm. Power consumption, heat losses and uniformity of thermal distribution were determined in the Pt microheater’s structure for different layouts. Results of simulation process showed that optimal size was 150×150 µm² for a 3 µm thick polyimide membrane, where power consumption is 35mW for temperature 350°C. The Ti/Pt microheater was developed on a suspended PI membrane by front side silicon etching. Measured power consumption of the Pt microheater was 42mW for temperature 350°C and thermal time constant was 1.8 ms when temperature increased from 25 to 350°C. It was found a good agreement with the simulation model.

Keywords: microheater, polyimide membrane, FEM simulation, microfabrication, RIE

I - Introduction

Over the past ten years it has been increased interest in study of the microheaters mostly based on silicon technology, plastic foils and ceramics. Their applications are often used in metal oxide gas sensors, flow/wind sensors, humidity sensors and infrared sources [1-4]. A microheaters that emit heat by applying a current to a resistor has the advantage for low power sources [1-4]. A microheaters that emit heat by applying a current to a resistor has the advantage for low power sources [1-4].

Silicon dioxide (SiO₂) and silicon nitride (Si₃N₄) membrane based on silicon wafer were recently replaced by plastics foil - PI. Advantages of using PI material for microheater membrane are particularly lower thermal conductivity, more rugged than oxide or nitrides and therefore their yielding is quite high [3]. PI membrane has good mechanical and thermal properties; furthermore it is easy to control their layer thickness in comparison with oxides or nitrides of silicon [3, 5]. In this way PI membrane becomes perspective issue for future investigations. The electro – thermal simulations can be used to optimize the design of microheaters.

This study is focused on design, simulation and development of Pt microheaters situated on PI membrane prepared by deep front plasma etching into Si substrate. It was designed three layouts with various membrane dimensions and microheater geometry. By using electro-thermal FEM (finite element method) simulations we have optimized the microheater power consumption and the thermal distribution. Transient and electro-thermal characterization of microheater was performed. Obtained simulation results and experimental data of Pt microheaters have been compared.

II - Microheater layout design and FEM analysis

Geometry of double spiral resistor was used for design microheater. For calculation of electrical and electro-thermal properties of microheaters was used simulation tool COMSOL Multiphysics 3.5a based on FEM. Free tetragonal mesh with maximum distance 1.4×10⁻⁷m between the nodes was used for the compute built model in FEM software package. The ambient temperature was set up with the value of 25°C. Thermal distribution on the surface and current density of the designed structure are required in order to establish the geometrical characteristics of the development microheater. Authors [1,6] presented that specific thermal losses by radiation were not used in FEM simulation as a parameter considering the relatively low temperature (300°C) for heating. To improve the accuracy and verification models of designed microheaters, the surface radiation, conduction and convection for surrounding air was included to the solving model. The values of the surface radiation were obtained from [2] and data sheet of PI 2555. Previous results [1] concerned to the membrane thickness optimization showed that total thickness of the PI membrane should be as thin as possible in order to...
minimize the power consumption; however it needs to be taken into consideration also mechanical properties of fabricated membrane. Our simulation analyses are focused only on 3 μm thick PI membrane. Target temperature of simulation process on the top microheaters was set to approximately on the value 350°C by applying bias voltage. Three dimensions (50x50, 150x150, 300x300 μm²) of PI membrane were simulated for comparison of electrical and electro-thermal parameters of microheaters. Thickness 250 μm of the Pt films was used for all suggestions. Designed geometries involved width of the heater’s lines and spacing between them in ratio from 6 μm/2 μm (50x50 μm membrane) up to 30μm/17μm (300x300 μm membrane). This ratio was 3 (9/3, 15/5, 18/6) for 150x150 μm² and was determined based on previous simulations.

Low uniformity in temperature distribution over the PI membrane for 50x50 μm² was observed. The power consumption of the Pt microheater for this topology was 9.28 mW for temperature 350°C. Temperature uniformity was better in the case of 150x150 μm² (Fig.1) than 50x50 μm² PI membrane. Required temperature of 350°C was reached in the center of microheater with area of 80×120 μm² for 150x150 μm² PI membrane. It can be noted that input part of heater’s spiral long 120 μm as well as output part of heater’s spiral long 130 μm, they both reach temperature in interval from 290 to 335°C, for power consumption of microheater 33.5mW.

Figure 1: FEM simulation of temperature distribution in 150x150 μm² PI membrane with microheater’s ratio 15/5μm, P= 33.5 mW.

PI membrane (300x300 μm²) has similar behavior as 150x150 μm²; however for reaching requested temperature of 350°C it requires higher power consumption (72.3mW) which increases non–linearly with the dimension of membrane. From Fig. 2 it can be seen that requested temperature was reached in 72% of active area of Pt microheater.

Figure 2: Simulated of the temperature distribution in 300x300 μm² PI membrane, P= 72.3 mW.

Electro–thermal FEM simulation of 150x150 μm² of PI membrane for heater’s lines ratio 18μm/6μm is depicted in Fig. 3. It can be seen to improving of temperature uniformity of active area in comparison with 150x150 μm² PI membrane with heater’s lines ratio 15μm/5μm (Fig.1). Requested temperature was reached in 85 % of active area of Pt microheater (Fig.3).

Figure 3: FEM simulation of the thermal distribution in 150μm PI membrane with heater’s lines ratio 18μm/6μm.

Tab. 1 recorded calculated changes of different physical parameters of investigated Pt microheaters. Obtained values of lateral temperature gradient from the center to membrane’s the edge reached values from 0.19 to 0.57 K/μm. It was found that optimal width of heater’s line is 18 μm with temperature gradient 0.18 K/μm; however width line decrease to 15 μm it means 3 times increasing of temperature gradient. The increase of power consumption is low and represents 2.3 mW.

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<tr>
<td>150x150</td>
<td>9/3</td>
<td>0.48</td>
<td>28.7</td>
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<tr>
<td>150x150</td>
<td>15/5</td>
<td>0.57</td>
<td>33.5</td>
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<tr>
<td>150x150</td>
<td>18/6</td>
<td>0.19</td>
<td>35.8</td>
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The influence of thermal losses, which was determined by low electrical resistance of power conductors and also by heat transfer from microheater.
into microbridges is observed (Fig.1 and 2). Input Pt lines situated in microbridges revealed temperature decreasing from thorough membrane edge towards substrate. We can note for comparison that lines of Pt temperature sensor have different behavior from the point of thermal distribution in direction out of membrane. This phenomenon is caused by narrower lines and by the fact that the element is passive. For all investigated dimensions of membrane it was straight forward deduced that the temperature drops down radically at the anchors of the microbridges. This effect is more significant for the bigger dimensions of the membrane. Similar phenomenon was observed in the previous work [1]. When the temperature of the microheater is set to 350°C in the simulation tool, temperature of region non etching PI was near the room temperature for all three dimensions. The values of current density of the heater’s lines have decreasing tendency from $27.405 \times 10^9$ A m$^{-2}$ (50×50 µm$^2$) membrane to $10.027 \times 10^9$ A m$^{-2}$ (300×300 µm$^2$ membrane) with increasing dimensions of the membrane, respectively dimensions of the microheaters. In this study and according to [1], the temperature uniformity was increasing, when the size of the heated area in microheater was increasing, too.

III – Microheater fabrication

One side polished 360 µm thick silicon wafer (100) as substrate was used as carrier for Pt microheater. First, PI 2555 (HD MicroSystems™) was spin-coated at 3000 rpm for 60 s on the substrate, which created a 3 µm thick layer. The PI was cured in a nitrogen atmosphere at an elevated temperature of 390°C for 1 hour. Negative photoresist was spin-coated onto the PI layer and patterned using photolithography through a designed mask for of creation microheaters. Double spiral geometry of microheater was designed, using the results of simulations process in previous chapter. The platinum metal deposition patterning of the microheater was carried out using a dc magnetron sputtering process and lift-off technique. Metal layer of Pt with the thickness of 250 nm was deposited onto the 20 nm thin Ti adhesion layer. Then, Pt temperature sensors (150 nm thickness) were situated near microheater, approximately 10µm. The resulting electrical resistance of the microheaters was 40.4 Ω ± 6.3% and for temperature sensors was changed from 220 to 280 µΩ. 150 nm thick Pt contact pads were used.

In comparison to the other study [1-3,6], only front side bulk micromachining of the silicon substrate was used to release the Pt microheater. Al film (thickness 150 nm) was served as a mask for deep front side etching of silicon. The PI windows were opened using RIE in oxygen atmosphere. In order to obtain etching parameters high lateral etching rate was observed at low operational pressure from 3 to 15 Pa in room temperature. The front side of silicon was realized by RIE in SF$_6$ plasma at the total working pressure 10 Pa and a fixed RF power of 150 W. Vertical etching rate of silicon (100) was determined on the value 45 µm/hour and lateral etching rate was 37.5 µm/hour. Total etching time was about 2 hours to what allowed to release of PI membrane. Then, Al mask was removed from top side device using wet etching in HCl for 1 min. The complete schematically cross-sectional view of fabricated Pt microheaters is shown in the Fig. 4. Fabricated Pt microheater was observed using scanning microscopy (SEM) depicted in Fig. 5.

![Figure 4: Schematically cross-sectional view of Pt microheater with illustrated under-etching of PI membrane.](image)

IV – Microheater characterization

Temperature dependences of microheaters were measured in the range of 25÷200°C in the fanned convection oven. From this measurements were calculated temperature coefficients of resistance (TCR) and were changed in the range of 1570÷1625×10$^{-6}$ K$^{-1}$. Average value of TCR was $1600 \times 10^{-6}$ K$^{-1}$. Microheaters elements were bonding and wired on the TO–4 package for characterization of electrical and electro-thermal parameters. Electrical measurements were performed at standard room conditions. I–V curves of the Pt microheaters were measured using source measure unit - Agilent B2902A and multimeters - Agilent 34410A. The power consumption of the Pt microheater was calculated from I–V measurements using TCR. Fig.6 shows the dependences of relations between temperature and power consumption; electrical resistance and power consumption. There is a good linearity in the P-T conversion characteristics and P–R characteristic. Measured power consumption of the
microheater was 42 mW for the temperature 350°C. It was obtained slightly higher power consumption in comparison with the result of simulation.

Temperature distribution on PI membrane was investigated using the Pt temperature sensors situated close to the heater approximately 10µm. Fig. 7 shows only the small differences between the measured and simulated thermal distribution over the PI membrane. Temperature was linearly decreased with increasing distance from centre of heater. On the edge of membrane was temperature below 50°C. Temperature dramatically decreases to on value 45°C in microbridges. Temperature non–etching area of PI was approximately RT from simulation.

For uniformity heated of active layer is desirable extracted temperature gradient very low. Lateral temperature gradient on top PI membrane was measured by Pt temperature sensors. It was determined on value 0.586 K/µm which is in good agreement with the value 0.57 K/µm obtains from simulation process for this type MEMS structure. Thermal resistance was calculated from linear regression P-T conversion characteristic and achieved value of 7.638 K/mW.

In order to determine the transient parameters of the heating elements were measured the pulse rising time of heating the microheaters (thermal time constant – TTC). It takes around 1.8 ms to heat the Pt microheater from temperature 25°C up to 350°C, so the thermal inertia is very low. Rising edge is fluent at heating from the room temperature to the reached temperatures. Tab. 2. shows TTC of the Pt microheaters between the different heating temperatures.

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<tr>
<th>Initial temperature [°C]</th>
<th>Reached temperatures [°C]</th>
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<tr>
<td></td>
<td>100</td>
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<tr>
<td>25°C</td>
<td>400 µs</td>
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<td>100°C</td>
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<td>200°C</td>
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V - Conclusion

The electrical and electro - thermal properties of the Pt microheaters were simulated by FEM software. It was found that optimal distribution of temperature for (150×150 µm²) PI membrane is in proportion 18µm/6µm. Based on electro – thermal simulations were designed Ti/Pt microheaters on 150×150 µm² PI membrane with 4 microbridges which was fabricated by deep front side RIE in SF₆. Fabricated Pt microheaters exhibited by good electro-thermal conversion parameters and excellent mechanical integrity. Measured power consumption of the microheater was 42 mW and it revealed a very short response time of 1.8ms for the temperature 350°C. A good agreement was obtained between the simulated and the measured parameters of Pt microheater.

Acknowledgment

The work was supported by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and of the Slovak Academy of Sciences, No. 1/1106/12, by the Slovak Research and Development Agency under contract No. APVV-0199-10 a by PPP program of DAAD 50755098.

References