POLYMERIC HOTPLATES FOR SENSORS AND ACTUATORS

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Summary: In this communication, we present the fabrication and the characterisation of micro-heating elements made on polyimide sheets and on spin coated polyimide membranes. Different types of polyimide and heater materials were investigated to realise micro-hotplates for gas-sensing and thermal actuating applications. The effects of the type of polyimide used and of the different annealing performed on the mechanical and electrical properties of the metallic heaters were characterised. Using an optimised combination of materials and processes, flexible micro-hotplates on polyimide sheets and on polyimide membranes on silicon were realised and their thermal properties evaluated. Platinum and aluminium micro-heating elements on polyimide exhibited promising characteristics for their integration in low-power gas sensors and thermal actuators.

Keywords: micro-heaters, polyimide, anodic bonding

1. INTRODUCTION

There is a need in the field of Microsystems for low-cost micro-heating elements made in a polymeric technology. Compared to micro-hotplates on silicon with their membranes made of dielectric layers, their fabrication on polymers brings the advantages of simplified processing and an improved robustness and flexibility. These advantages are of interest for the integration of micro-heating elements in devices made of polymers such as in the field of micro-fluidics and for the realisation of flexible and low-cost thermal microsystems such as gas sensors, flow sensors and actuators. In the case of thermal actuators based on the thermal expansion of an actuating material, the use of low-cost robust polymeric micro-heaters would ease the integration of the thermo-expandable material and make the actuating device more compatible with micro-fluidics technology. Finally, flexible low cost gas sensors would be interesting for the integration of gas sensors in radio-frequency identification flexible tags or in textiles. Some work has been previously performed on the integration of heating elements on polyimide, but it was limited in terms of characterisation and gas sensing integration or concentrated on the development of hot anemometers and finger print sensors [1-3].

In this work, we have fabricated and characterised micro-heating elements made on different types of polyimide for applications in the gas-sensing and thermal actuating fields. The evaluation of the processing and the adhesion of different metals on several types of polyimide has been performed. The effect of annealing on the mechanical and electrical properties of the metallic heaters was investigated. From the results of these tests, a set of polyimides and metals have been selected for the realisation of micro-hotplates for gas-sensing and thermal actuating applications. For the gas-sensing applications (up to 350°C), micro-hotplates with platinum heaters and electrodes were made on polyimide sheets and on spin coated polyimide membranes on silicon substrates. In the case of the thermal paraffin actuator (up to 200°C), micro-hotplates with an aluminium heater and aluminium layer for anodic bonding of a Pyrex cavity (to store the paraffin) were made on polyimide sheets. The short time reliability of these micro-hotplates during operation has been characterised. Platinum and aluminium micro-heating elements exhibited promising characteristics for their integration in low-power gas sensors and thermal actuators.

2. DESIGN

There were two specific designs for the micro-heating elements realised on polyimide sheets (Upilex-S, T_g at 500°C), one for a resistive gas sensor and the other one for a the thermal actuator. Figure 1a) illustrates the design for a resistive gas sensor with the platinum electrodes and the heater patterned on the top side and on the bottom side of a 50 µm- thick polyimide sheet, respectively. This design involves simplified processing steps to realise fully flexible micro-hotplates for resistive gas sensors. However, some changes have to be brought to the standard packaging procedure on TO headers to ensure thermal insulation (by suspending the chip) and to be able to contact the heater on the backside of the chip. Another design proposed and presented in Figure 1b) consists in an Upilex sheet on which is patterned a heating element covered by a 10 µm-thick spin coating layer of photosensitive polyimide (PI 2731 from HD MicroSystems, T_g > 350°C) with on top platinum electrodes.

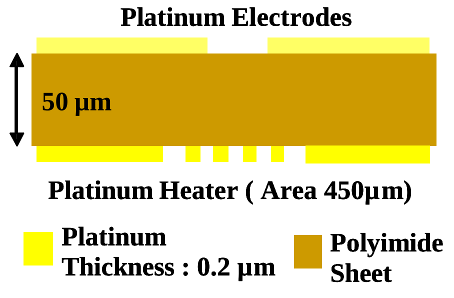


Fig. 1a. Design of the gas sensing structure realised using the both sides of a polyimide sheet.

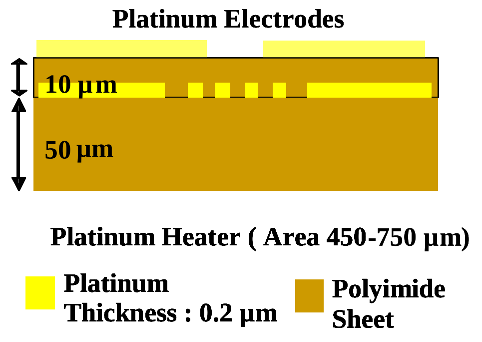


Fig. 1b. Design of the gas sensing structure realised only on the top side of the polyimide sheet.

The micro-hotplate for the thermal actuator is presented in Figure 2. An aluminium film is patterned to define the heating element and the rim for the anodic bonding of the Pyrex cavity on the top side of a 50 µm- thick polyimide sheet.

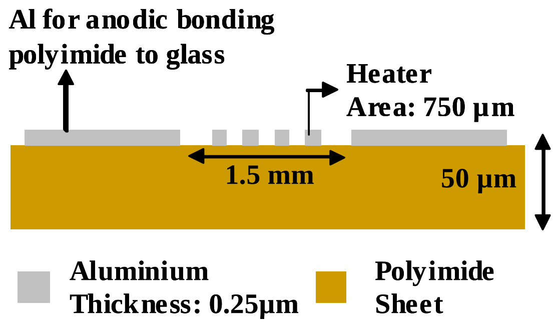


Fig. 2. Design of the micro-heating element structure realised on a polyimide sheet for a thermal actuator.

For both types of devices, a micro-hotplate made of a Pt heating element suspended on a 10 µm-thick polyimide membrane (PI 2731, HD Microsystems) was realised on a silicon substrate (Fig. 3). The cavity in the silicon substrate thermally insulates the heating element and can be used as a chamber to store the paraffin.

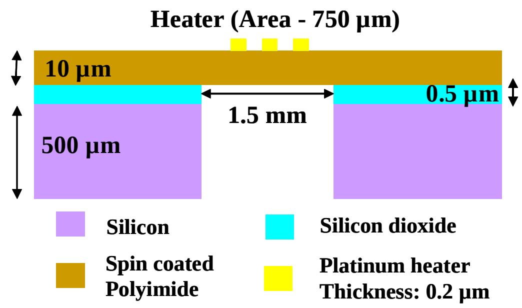


Fig. 3. Design of the micro-heating element structure with a polyimide membrane made on a silicon substrate.

Finally, a photosensitive polyimide film (PI 2731) was also added on top of the heating element of the structure presented in Figure 3 to act as an inter-dielectric layer in between the heater and electrodes to realise complete low-power gas sensor structures.

3. FABRICATION

The processing was simple for the devices realised on polyimide sheets. 50 µm-thick wafers with a diameter of 100 mm were cut in a sheet of Upilex-S. The aluminium and platinum e-beam evaporated heaters (0.15 to 0.25 µm-thick) were patterned using wet chemical etching and lift-off, respectively. The platinum film was deposited directly on the polyimide and on top of thin chromium film (15 nm) used as an adhesion layer. Annealing of the substrates was performed to stabilise the microstructure of the metallic films to be used as heating elements. The annealing was performed in an oven (200 to 350°C, 30 min in air) when there was no subsequent PI film spin coated (Fig. 4). When the spin coated PI (10 µm-thick) was applied over the heater, the latter was annealed during the curing of the PI.

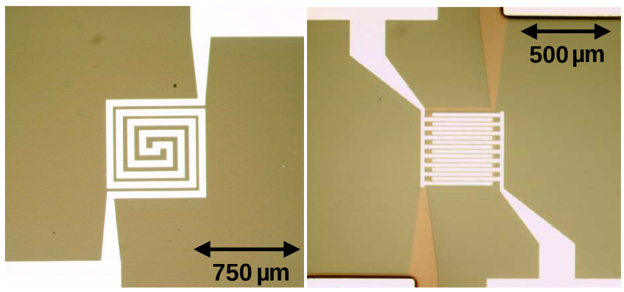


Fig. 4. Micro-heating element structure with a platinum heater on polyimide sheet: (left) heater only, (right) heater + spun PI + Pt electrodes (Fig 1b).

Before curing the polymer was exposed to UV light and developed to pattern windows to access the heater contact pads. The curing of the PI involved temperature ramps from room temperature to a plateau of 200°C and then from 200°C to a plateau a t 350°C that made the PI stable for operation at 400 to 450°C. Platinum electrodes were then patterned on top of the spin coated PI by lift-off (Fig. 4). Figure 5 shows the micro gas-sensing structures fabricated at the wafer level on a polyimide sheet.

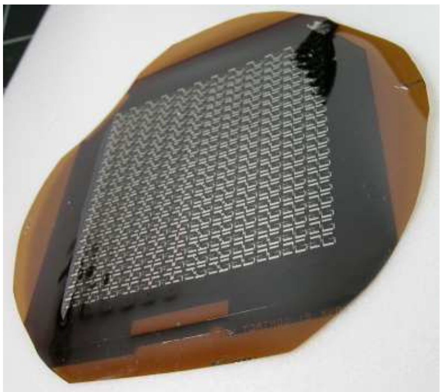
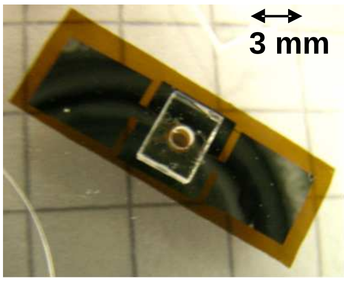


Fig. 5. Micro-hotplates with a platinum heater + spun PI + Pt electrodes on a polyimide wafer.

In the case of the micro-heating element to be integrated in the thermal actuating device, an anodic bonding was performed in between the aluminium layer structured on the polymide sheet (4 x 12 mm^2) and a Pyrex chip (2 x 3 mm^2) with a micromachined cavity to store the paraffin (Fig. 6). The anodic bonding was carried out at a temperature of 320°C and with a voltage of 1 kV between the Pyrex and the aluminium layer. A spin coated PI film could be added on top of the heater if a passivation layer is needed in between the heater and the paraffin. Moreover, the heater could also be patterned on the backside of the polyimide sheet and be made of platinum if a higher working temperature is required.



Fi g. 6. Micro-heating element structure with an aluminium heater on a polyimide sheet anodically to a Pyrex chip.

For the hotplates made on silicon, a thermal oxidation step was first performed. The PI 2731 was spun over the oxide film and cured using the temperature ramp mentioned above. The Pt heater was patterned using a lift-process and annealed in between 200 and 350°C. The polyimide membrane was released using deep reactive ion etching of silicon with the oxide film acting as an etch-stop (Fig. 7). The polyimide membrane could also be used in itself as an etch-stop, nevertheless due to constraint in the type of materials allowed in the DRIE chamber at our Institute, an oxide layer was used to avoid the plasma to be in contact with the polyimide.

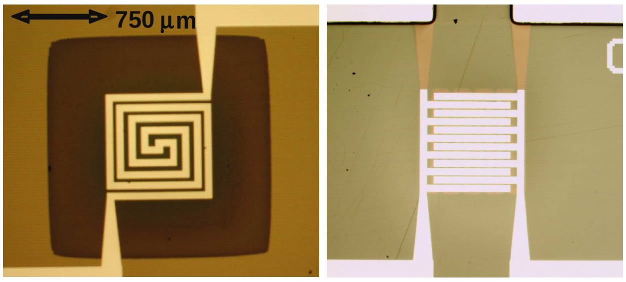


Fig. 7. Micro-heating element structure with a platinum heater on a polyimide membrane made on a silicon substrate: (left) heater only, (right) heater + spun PI + Pt electrodes on membrane (not visible).

4. RESULTS

After being patterned on the Upilex sheets and annealed at 200°C in air for 30 min, the electrical resistance of the aluminium and platinum heaters (0.2 µm-thick, no adhesion layer) were respectively of 27 and 85 ohms. The Pt/Cr heaters (0.15 µm-thick) covered with a spin coated PI film had a resistance of 200 ohms. The use of Cr improved the Pt adhesion.
Temperature coefficients of resistance (TCR) were determined for the Al and Pt heaters made on sheets of polyimide by measuring the variation of resistance when heated at different temperature on a hot chuck. Using these TCR values, a rough estimation of the temperature reached as a function of the power delivered was performed. By ramping up the device voltage by 100 mV every 100 ms until rupture, a maximum power leading to breakdown was defined.

On suspended Upilex sheets with Al heaters (Fig. 2), the maximum temperature of operation of 200°C required for the thermal actuator was reached at about 130 mW with a breakdown power at 375 mW. For the gas sensor structures made on the PI sheets (Fig. 1a), due to their smaller heating area, a temperature of 325°C was reached at 130 mW with a breakdown power at 270 mW. The local degradation of the heater occurred where the current density was the highest and was also related to the deformation of the polyimide sheet when heated (Fig. 8).

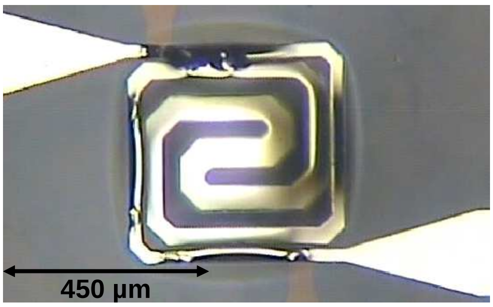


Fig. 8. Image of the Pt heater (Fig. 1a and 4 left) on polyimide sheet when it broke down at 270 mW.

As expected, a better thermal insulation was provided to the Pt heater by the thermally isolated spin coated polyimide membrane on silicon (Fig. 3), with a temperature of 325°C reached at 70 mW and a breakdown power of 240 mW. For the complete gas sensor structure, the addition of an extra polyimide layer led to an increase of the power to a value of 82 mW to reach an operation temperature of 325°C. The temperature as a function of the dissipated power in the heating element for both types of structures is presented in Figure 9. The temperature was measured using a micro-thermocouple (Type S: Pt / Pt-10%Rh with a diameter of 1.3 µm) [4].

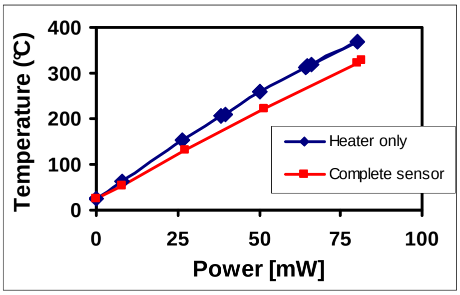


Fig. 9. Temperature at the centre of the membrane as a function of the input power for Pt heaters on polyimide membrane spin coated on silicon.

These measurements coupled with thermal FEM simulations on CoventorWare allowed to determine the thermal conductivity of the PI film, estimated at 0.3 W/mK, and to simulate an optimised heater geometry to obtain a homogeneous temperature distribution over the heating area (Fig. 10).

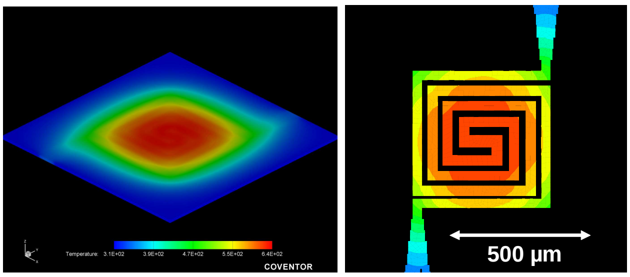


Fig. 10. Temperature distribution (at 640 K) of over the polyimide membrane for an optimised heater design.

The main failure mechanism was related to the breakdown of the heating element due to the mechanical deformation of the membrane and to the higher mobility of the polymeric chains at temperatures closed to the glass-transition temperature of the polyimide film (Fig. 11).

The polyimide micro-hotplates on Upilex (Figs 1a and 1b) and on silicon withstood an annealing in air at 450°C. Complete gas-sensing structures were drop coated with SnO_2 and annealed in air at 450°C (Fig. 12). Gas measurements are under progress. Upilex sheets with aluminium heaters had their bonded Pyrex cavity successfully filled with paraffin and actuators with large deformations (> 100 µm) were realised. These devices will be presented elsewhere.

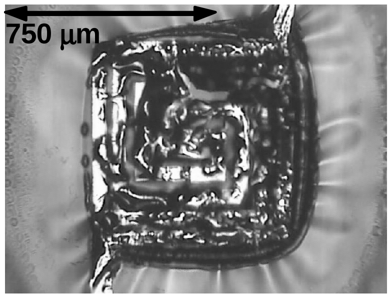


Fig. 11. Image of the Pt heater (Fig. 3 and 7 left) on a spin coated polyimide membrane on Si when it broke down at 240 mW.

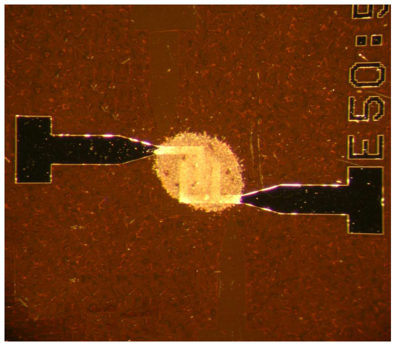


Fig. 12. Image of a drop coated gas sensing structure on an Upilex sheet (design Fig 1a), electrodes on the top side as seen on the picture, heater on the backside.

5. CONCLUSION

Platinum and aluminium micro-heating elements on polyimide exhibit promising characteristics for their integration in low-power gas sensors and thermal actuators. Relatively high temperature can be reached with low-power consumption. The short time reliability of these micro-hotplates during operation has been characterised. The main failure mechanism was related to the breakdown of the heating element due to the mechanical deformation of the membrane and to the higher mobility of the polymeric chains at temperatures closed to the glass-transition temperature of the polyimide film.

Acknowledgements

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