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Failure Analysis of Micro-Heating Elements Suspended on Thin Membranes

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Abstract

We report on the degradation of platinum micro-heating elements operating at high temperatures. Devices with platinum heaters suspended on micro-machined dielectric membranes were self-heated at high temperature until failure. Optical and SEM observations combined with mechanical deformation measurements and Thermal Laser Stimulation techniques were used to analyze the failure mechanisms of the micro-heating elements. Platinum atoms migration and breaking of the membrane were two failure modes observed. At high temperature, the migration of the platinum atoms was linked to the mechanical stress in the dielectric membrane. The Thermal Laser Stimulation technique revealed the formation of vertical as well as lateral thermocouples at mechanically deformed areas. One explanation proposed is that those thermocouples are the result of Si diffusion from the Si_3N_4 membrane into the platinum heater as well as electro-stress migration of platinum atoms.

1. Introduction

Over the years, micro-hotplates have shown to be suitable for different transducers, such as in thermal sensors, actuators and gas sensors [1-2]. Depending on the application, different processes have been used to thermally isolate the heating element [2]. Most of the papers published so far on this type of device were focused on the applications. The work reported in the literature on the reliability of micro-hotplates was mainly on polysilicon embedded heaters or based on simulations [3-4].

Failure analysis is a useful method to determine the failure mechanisms, to improve the lifetime of the product, and to develop reliability models to predict how and when failure will occur. In this study several techniques are used to investigate the degradations responsible for the failure at high temperature of platinum micro-heating elements integrated on micro-machined hotplates. In addition to mechanical deformation measurements, optical and SEM observations, the Non-Biased Thermal Laser Stimulation (NB-TLS) technique [5], also known as SEI [6], was used to observe and map thermocouples formed within the micro-heating elements during the ageing process.

2. Experimental Methods

2.1. Micro-hotplate design and fabrication

The micro-hotplates were fabricated on silicon wafers [7]. They consist in a dielectric membrane, in which a platinum heater was embedded (Fig. 1). The heater is made of platinum or platinum-iridium with a tantalum adhesion layer. Two low-stress LPCVD silicon nitride films forms the thermally insulated membrane

(0.25 µm below and 0.5 µm over the heater) of the micro-hotplate. The membrane was released using backside bulk micromachining of the silicon wafer. The membrane has an area of 1.0 × 1.0 mm^2, and the area covered by the double meander heater is of 450 × 450 μm^2.

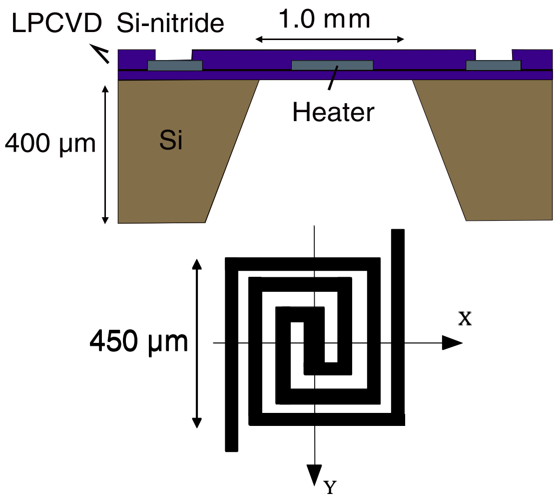

Fig. 1. Schematic cross-section view of a micro-hotplate made of a Pt heater in between two Si_3N_4 thin films (above) and top view of the Pt heating element (below).

2.2. Mechanical deformation test

The membrane deformation was characterized before investigating the degradation mechanisms responsible for the failure of the micro-hotplates when operating at high temperature. The membrane deformation as a function of the input power was measured using an optical profilometer (UBM GmbH).

2.3. Thermal Laser Stimulation

Thermal Laser Stimulation (TLS) consist of scanning a near-infrared laser beam to locally heat absorbing elements of the device under test, such as metallic lines. It modifies the electrical properties of the heated medium, namely its resistivity. It also generates a Seebeck voltage at thermocouples. The Seebeck effect is based on the generation of an electromotive force by temperature gradients at junctions composed of two different materials. The Seebeck voltage induced when one side of a thermocouple is heated is given by:

$$\Delta V = (Q_1 - Q_2)\Delta T = Q_{1-2}\Delta T$$

where Q_1, Q_2 are the respective thermoelectric power of materials and Q_{1-2} the relative thermoelectric power difference of the two materials.

Under non biased conditions, the voltage variations are directly correlated to the Seebeck voltage. It may be monitored at the power supply nodes. Mapping the induced voltage changes at different laser spot location provides precise localization of the thermocouples.

The weak Seebeck voltages are best observed when the device under test is not biased. The Non-Biased Thermal Laser Stimulation (NB-TLS) method is applied to observe and map thermocouples within the micro-hotplates at different stage of the aging process. This method is performed with Hamamatsu PHEMOS-1000 Emission Microscopy system. A Stanford Research low noise voltage amplifier is used to pick up the induced Seebeck voltages.

2.4. Electrical characterization during accelerated aging

The micro-hotplate's maximum power leading to breakdown was characterized using the Hewlett Packard 4155A semiconductor parameter analyzer. The devices were submitted to an increasing voltage from 0 to 10 V with a step of 0.05 V and an integration time of 100 ms.

The influence of the nature of the heater material on the reliability of the micro-hotplates was investigated by operating them at high temperatures until failure. They were operated at different powers from 100 to 140 mW (600 to 750°C) and the resistance values of the heaters were monitored (Agilent 34970A data acquisition/switching unit). The visual aspect of the hotplates after failure was inspected with the help of an optical microscope (NIKON) and using scanning electron microscopy (SEM).

3. Results

3.1. Mechanical deformation at high temperature

A threshold input power led to the observation of a mechanical deformation. At the threshold power, two deformation modes of asymmetrical or symmetrical shape could occur. A measurement of the membrane mechanical deformation for the high operating powers studied in this work (100-140 mW) is shown in Fig. 2. A symmetrical mode of deformation with amplitude of few micrometers is observed. The area where the mechanical deformation of the membrane occurs corresponds to the area of the membrane where the heater is located.

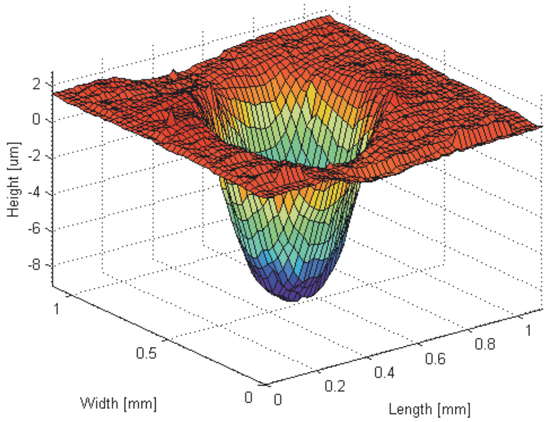

Fig. 2. Deformation of the membrane of the micro-hotplate at a power of 110 mW.

3.2. Non-Biased Thermal Laser Stimulation

Several Non-Biased Thermal Laser Stimulation maps were acquired before and during the aging process. The initial NB-TLS map is shown in Fig. 3a) below. The weak black and white clouds correspond to the voltage variations induced at thermocouples. Those appear after the deposition of the upper silicon nitride film and are most likely due to Si inter-diffusion in Pt. Such inter-diffusion was observed with TEM.

The micro-hotplates are then submitted to a constant 5.8 V voltage, which corresponds to a high operating power of 138 mW, and aged until breakdown. To perform NB-TLS, the voltage source is disconnected and replaced by the Stanford voltage amplifier. The second NB-TLS map shown in Fig. 3b) is acquired after few hours of aging. A change in the micro-hotplate membrane and heater structure can be observed. The black and white signal corresponds to vertical thermocouples. One can suspect a more or less pronounced Si inter-diffusion in Pt depending on the local mechanical stress. The alloy's Seebeck coefficient depends strongly on its composition.

The last NB-TLS map shown in Fig. 3c) is acquired after several hours of aging. It shows the formation of a strong lateral thermocouple at the edge of the heating area, at the intersection of the heater and its interconnection as pointed out by an arrow in Fig. 3c). This thermocouple is most likely caused by an electro-stress migration of platinum atoms. This location corresponds to the edge of the area where the membrane deformation occurs and where the density of current in the heater is the highest (narrower line).

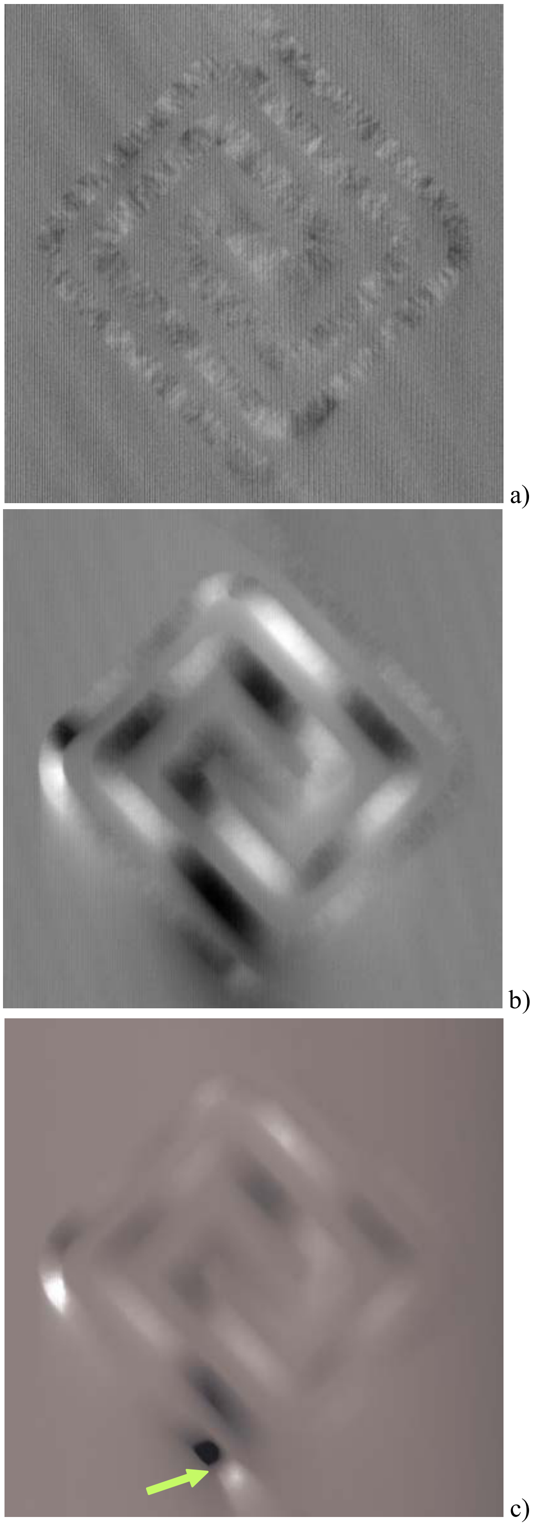

Fig. 3. NB-TLS maps obtained at a) 0h of aging, b) 2h30 of aging and c) 5h00 of aging at a operating power of 138mW.

3.3. Backscattered SEM analysis

Backscattered SEM analysis was performed on the edge of the membrane after the formation of the lateral thermocouple. In the left image of Fig. 4a) we can observe a difference in the membrane composition in four different areas. EDX analysis performed in those areas revealed a migration of Pt atoms at the interface. This aging induced lateral thermocouple of Pt rich element on one side and Pt poor element on the other side explains the Seebeck signal observed in Fig. 3c).

3.4. Micro-hotplate accelerated aging

When the micro-hotplates are aged until failure, two failure modes were observed: breaking of the membrane and electro-stress-migration of the platinum atoms forming the heater. The deformation measurements linked with the NB-TLS maps and backscattered SEM observations indicate that the membrane deformation and the Pt atoms migration are correlated. The same indications are also obtained from the results given by the maximum power test, when the power was ramped up quickly until breakdown. When the failure was not due to the breaking of the membrane, the discontinuity in the heating element was located in a different area, close to the center of the heater. The right image of Fig. 4b) presents a SEM picture taken on a hotplate after its breakdown during the maximum power test. At the center of the heater, part of the silicon nitride covering the heater peeled off and a discontinuity in the heater line occurred, leading to the failure.

The breaking of the membrane happened more often for higher operating powers. For lower operating powers, electro-stress migration of the Pt atoms resulted in a discontinuity in the heating element. During the accelerated aging tests, the platinum heaters with iridium exhibited a longer lifetime than heaters made only of platinum.

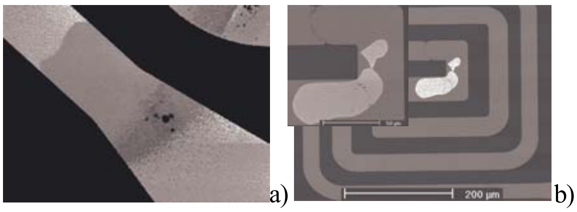

Fig. 4. a) Backscattered SEM image of the micro-hotplate studied by NB-TLS at the edge of the membrane and b) of the full heating area after a quick power ramp up until breakdown.

4. Conclusion

The failure analyses performed on micro-hotplates have demonstrated that the membrane breakdown and the electro-stress migration are the two main causes of failure when operated at high temperature. The Non-Biased Thermal Laser Stimulation method revealed micro-structural changes in the layers composing the membrane of the micro-hotplate. The formation of vertical and lateral thermocouples upon aging can be attributed to Si diffusion from the Si_3N_4 membrane into the platinum heater as well as electro-stress migration of platinum atoms. Those results were correlated with backscattered electron microscopy and EDX results.

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