Investigation on the contact behaviour of MEMS micromembrane with serpentine hinges

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Abstract. This paper presents the study of micromembranes supported by serpentine hinges. Widely used in microelectromechanical systems as switches or optical micromirrors, these micromembranes are deflected to the substrate in order to close a circuit or to process a signal. The investigated micromembranes are electroplated from gold in different geometrical dimensions. Furthermore, the central plate of micromembrane is suspended by two or four serpentine hinges. The stiffness of micromembranes is given by the geometry of hinges. One of the failure causes of micromembranes, which are directly deflected to substrate, is the adhesion effect between the flexible plate and the substrate. The adhesive force depends on the mechanical restoring force given by the hinges stiffness. In the case of micromembranes for optical applications, one additional stress is provided by temperature. A temperature gradient applied on micromembranes changes the stiffness with influence on the adhesion force. The study of temperature effect on stiffness and adhesion force is performed using an atomic force microscope and a thermal controlled stage. Experimental results of stiffness as a function of temperature are compared to numerical data.

1. Introduction
Microelectromechanical systems (MEMS) find their application in many domains where a miniaturization of products is necessary, such as: automotive and aerospace industry, chemical and bio-medicine, optical applications including displays and wireless communications. MEMS devices include sensors and actuators, switches, microrobots, optical scanners, micromotors, micropumps etc. Numerous bibliographic sources provided by the literature highlights the growing interest of researchers on MEMS generally, respectively of MEMS-based optical applications in particular [1-10]. Over the past decade, the telecommunications have become a strong market for optical MEMS devices. This is due to the explosion of internet network systems through fiber optics, digital scanning systems based on optical mirrors and of switches and transmission systems for the optical signal. In medical devices, micro optical scanners have resulted in three-dimensional scanning endoscopic systems. There are several applications, which include micromembranes as a mechanical flexible component. In pressure sensors, a capacitive micromembrane deflects when the pressure is applied, changing the distance between electrodes and the capacitance. In optical MEMS, micromembranes are used as micromirrors supported by hinges (springs) with high mobility. In an interferometer, the deformation of a micromembrane changes the optical light path and the propagation speed, the result being a phase shift. Micromembrane surface stress sensors in chemical and biological applications are fabricated from thin gold layer. The molecular interaction between probe molecules and target molecules generates a surface stress on the micromembrane. This surface stress causes the structural deflection of micromembrane, which generates the capacitance change in electrical sensing [1, 2].

In optical applications, high mobility micromembrane with optical control ability in different planes is needed. Figure 1 shows two micromembranes used in optical applications with the possibility of orientation of the signal by rotating the micromembrane with 10° (Figure 1a) [11].
These micromembranes are used for optical signal processing by turning the micromembrane and/or its linear movement. In a situation when an optical signal is desired to be orientated in different direction, these micromembranes must be replaced by other micromembrane with different systems of joints which may serve as a disadvantage of the optical quality as well as an increase in costs. Such micromembrane with multiple degrees of freedom can be represented by a micromembrane with serpentine hinges [12] where the hinges are deformed in bending and torsion depending on the applied force. When analysing the stress behaviour of a hinge, the critical issue is to understand how this deflects under the applied loads. Finite element analysis is a useful method to simulate the deflection of micromembrane and to compute the stress in hinges [13].

In RF switches (ohmic switch) a micromembrane is electrostatically deflected down to rest on a thin dielectric metal conductor. Stiction is one of the most important and unavoidable failure problems of micromembranes which deflect to substrate. Stiction is the adhesion of the contacting surfaces due to surface forces (van der Waals, capillary forces, Casimir forces, hydrogen bridging, and electrostatic forces). The restoring force acts against the adhesion force and depends on the micromembrane stiffness. In a stiction failure case, the restoring force of the micromembrane is not enough to remove the flexible plate to its original shape.

The atomic force microscopy (AFM) technique due to force and displacement sensing capabilities has been extensively used for the measurement of mechanical behaviour of flexible microcomponents. The AFM spectroscopy in point is used to deflect the central plate directly to substrate in order to measure the stiffness and the adhesion force.

In some MEMS applications the operating temperature of micromembranes can be significantly higher than the ambient one, for example in MEMS carrying several hundred of mW of power the membrane can reach 200ºC and in a video projector near the incandescent light source can exceed 100ºC. The temperature introduces residual stress and stress gradients that deform the micromembrane but it also decreases the modulus of elasticity of the material with influence on the mechanical response of the system. For reliability design, it is recommended to investigate the structure behaviour under a thermal field including a thermo-mechanical analysis. A thermal phenomenon introduces softening due to Young’s modulus-temperature relation and a thermal relaxation which affects the rigidity of material - less force is needed to deflect the micromembrane if temperature increases, in order to produce the same displacement as at the initial temperature. In a case of a heated micromembrane under bending, the relaxation of Young’s modulus has to be considered. Experimentally, the dependence between the force $F_z$ and the displacement in z-direction of micromembranes as a function of temperature is determined.

This paper presents experimental investigations and numerical analysis performed on micromembranes with serpentine hinges fabricated from gold as described in section 2. The interest is to determine the temperature influence on the mechanical and tribological behaviour of micromembranes. Stiffness and adhesion force are experimentally determined as a function of temperature, work included in section 3 of this paper. In section 4 of the paper, numerical analysis on stiffness is presented and the comparative results are included in section 5. The paper is ended with conclusions.
2. Sample description
The samples for experimental tests are micromembranes gold electroplated with rectangular hinges and different geometrical dimensions as presented in (Figure 2). The samples were manufactured in the Laboratory for Analysis and Architecture of System in Toulouse (France). The material used to fabricate the micromembranes is gold and the structure was fabricated in 10 lithography and deposition steps. The gold material has high thermal efficiency and short thermal time constant of relatively low temperature (< 200°C). The serpentine hinges used in our model to connect the mobile plate of micromembrane to anchors are formed of seven series-connected units. The in-plane displacement of the mobile plate gives extension and compression of each hinges. Out of plane movement of the proof mass performs the bending as well as the torsion of hinges.

![Figure 2. Geometry of micromembranes supported by serpentine hinges [12].](image)

The micromembrane supported by two serpentine hinges (Figure 2) is sensitive to in-plane and out of the plane moments. While the central mass translates at least on one of the in-plane directions, the hinge legs that are directed perpendicularly to the motion direction will be bent, whereas the other legs will be subjected to axial extension and compression in addition to bending. Out of the plane displacement gives bending and torsion of the hinge legs. A simplified analytical formula for the bending stiffness of a micromembrane supported by serpentine hinges when a force is applying on z-direction in the mid-position of the mobile plate (Figure 2), is given in [14]. The model lead to approximate results due to the fact that lengths \( l_1 \) and \( l_4 \) are neglected and the central plate was considered rigid.

In our paper only numerical and experimental analyses were performed. Micromembranes supported by two and four serpentine hinges are investigated in order to estimate the samples’ deflections under a mechanical force as a function of temperature. The thickness of micromembrane is 3µm and the flexible part is suspended at 2µm above a silicon substrate. The gold material is the most used in optical and switching applications. The width of mobile plate is 38µm and the length is 118µm (which define the contact area with the substrate). The mobile plate is supported by two and four serpentine hinges. The hinges have the following geometrical dimensions (Figure 2): width \( w = 6 \)µm, \( l_1 = l_4 = 13 \)µm, \( l_2 = l_3 = 16 \)µm. Hinges with different length \( l \) are used to suspend the mobile plate. The images with the investigated micromembranes are presented in Figure 3. The micromembrane-1 presented in Figure 3a is supported by 2 hinges as the micromembrane-2 (Figure 3b). The difference between them consists of different dimensions \( l \) of the hinges (Figure 2). Micromembrane-1 has the length \( l=14 \)µm and the second micromembrane is characterized by \( l=39 \)µm. The micromembrane-3 and 4 are fabricated with 4 hinges. The length \( l \) of micromembrane-3 (Figure 3c) is 14µm comparatively with micromembrane-4 (Figure 3d) for which \( l=39 \)µm.
3. Experimental stiffness and adhesion force

The scopes of this analysis are the following: i) to determine the variation of the micromembranes stiffness as a function of temperature; ii) to analyse the temperature influence on the adhesion force between micromembranes and substrate. The experimental tests were done at Technical University of Cluj-Napoca in the Micro and Nano System Laboratory using an AFM XE 70 produced by Park System Co and a temperature controlled heating unit.

![Figure 3. Micromembranes with different hinges: (a) Micromembrane-1; (b) Micromembrane-2; (c) Micromembrane-3; (d) Micromembrane-4.](image)

![Figure 4. AFM experimental curve of micromembrane-1.](image)

An AFM probe with known stiffness is used to bend the flexible plate directly to the substrate. Figure 4 shows the AFM experimental curve of the micromembrane 1 from Figure 3a. During testing the vertical approach of the scanning head and AFM probe toward to the substrate is controlled and the bending deflection of AFM probe is optically monitored. The experimental curve gives the dependence between the displacement of the scanning head and the deflection of AFM probe. The first part (A-B) of the loading curve corresponds to the bending of AFM probe and sample. In the position B the micromembrane comes in contact with the substrate. On the part (B-C) there is bending only of AFM probe. The unloading process starts from position C when the AFM probe is coming in its initial position. As it can be observed on unloading AFM curve, there is a jump (D-E) that is given by the adhesion effect between micromembrane and substrate. The detachment of micromembrane from substrate is delayed due to the adhesion effect. The jump size is proportional to the strength of adhesion between the contacted surfaces. After the contact between micromembrane and substrate is broken in position D the sample and the AFM probe are coming to the initial position. The first part
(A-B) from experimental curve is used to compute the micromembrane stiffness. The detected deflection of the AFM probe multiplies by its stiffness gives the acting force. The difference between the vertical displacement of AFM scanning head and the detected deflection of AFM probe taken from the first part (A-B) of the experimental curve is the micromembrane bending deflection \(Z_{\text{sample}}\). The applied force divided by \(Z_{\text{sample}}\) gives the micromembrane stiffness. During experimental tests, the force is applied in the mid-position of mobile plate as presented in Figure 5 for micromembrane 4 and deflects it directly to substrate.

**Figure 5.** AFM probe in contact with the micromembrane-4.

Using this AFM tests, a stiffness of 64.4N/m is determined for the micromembrane 1, if the force is applied in the mid-position of the mobile plate. The adhesion force between micromembrane and substrate given by the distance between D and E (Figure 4) is 36µN. The same experiment is used to estimate the stiffness of the micromembrane 2 (Figure 3b) with a characteristic length of 39µm of hinges. An out of the plane stiffness of 14.9N/m was experimentally determined if the force is applied in the mid-position of the mobile plate and the adhesion force between flexible plate and substrate is equal to 124µN. For the same contact area from mobile plate and substrate the adhesion force increases if the stiffness decreases, respectively.

The same AFM test is also used to measure the stiffness of micromembranes 3 and 4 supported by four serpentine hinges for a force applied in the mid-position of mobile plate, as presented in Figure 5. The geometrical dimensions of hinges are the same as those previously described for the micromembranes supported by two hinges. Experimentally, a bending stiffness of 127.5N/m is determined for the micromembrane 3 and it is 26N/m for the micromembrane 4. The adhesion force between mobile plate and substrate of micromembrane 3 is 1.27µN and for the micromembrane 4, with smaller value of stiffness, for the same contact area, the adhesion force increases to 78.2 µN. These preliminary tests were done at room temperature (20ºC) and a humidity equal to 40%RH. Moreover, the temperature effect on stiffness and adhesion force is investigated. During experimental tests, the following temperatures 20 ºC, 40 ºC, 60 ºC, 80 ºC and 100 ºC are applied directly on substrate with the help of a temperature controlled heating unit. In order, to limit the thermal effect on the AFM tip (Si\(_3\)N\(_4\)), after each measurement, the AFM scanning head is moved to the zero position that is the initial starting location of measurements. The AFM probe used in our experiment has the tip height of 25µm. So, the cantilever of AFM probe that is optically monitored during scanning is suspended at 25µm above the sample that reduces the influence of temperature on the AFM probe. The experimental stiffness of the micromembrane 1 decreases with 4.1% if the micromembrane operates at 100ºC, instead of 20 ºC. In the same way, the adhesion force increases but not significantly. For the micromembrane 2, the stiffness increases with 3.3% if temperature increases from 20 ºC to 100 ºC. The small influence of temperature is determined for the micromembrane 3 as its stiffness changes only with 0.05%. For the micromembrane 4 the stiffness is modified with 4.1%. Because the stiffness of the structure is not strongly influenced by temperature, the adhesion forces is not significantly changed. Based on this investigations, the temperature has a small influence on stiffness and adhesion force that making these micromembranes with serpentine hinges suitable for MEMS applications where a temperature gradient occurs.
4. Numerical simulations of stiffness for different temperatures
A numerical analysis of micromembranes stiffness was performed by Finite Element (FE) method using the thermo-mechanical module in ANSYS Workbench 13 software. During the virtual tests, a thermal gradient is applied on the micromembrane and a mechanical force is used to bend the mobile plate toward the substrate. Using the same geometrical dimensions as in the experiments, the samples were modelled and their response (out of plane deflection) for a given temperature and a central force was computed. The own weight of the mobile plate upon the hinge deformation is very small and has been neglected. The simulation consists of two steps: first, only the temperature was increased with no mechanical load; in the second step, the temperature was kept constant and a mechanical load was applied in the central position of the mobile plate. The stiffness calculation took into account only the out of plane deflection due to mechanical force, thus, from the total deflection, those due to temperature increase were extracted. The Young's modulus of the investigated samples used in the FEA, according to the literature (www.totalmateria.com; http://silicon.mhopenge.ml1.net/Silicon/), are 79GPa for gold and 169GP for silicon. The thermal expansion coefficients (CTE) considered in these simulations were: 14×10^{-6} [1/°C] for gold and 2.1×10^{-6} [1/°C] for silicon. The CTE values were considered constant in the temperature range from 20 °C to 100 °C. In Figure 6, the total deflections (thermal & mechanical) of the investigated micromembranes for a temperature change of 20°C (from 20°C to 40°C) and a 1µN central force are shown.

![Figure 6. Out of plane deflection of micromembranes due to change in temperature from 20°C to 40°C and applied central concentrated force (1µN): (a) Micromembrane- 1; (b) Micromembrane- 2; (c) Micromembrane- 3; (d) Micromembrane- 4.](image)

5. Results and discussions
Comparative results (numerical vs. experimental) for out of the plane stiffness of the investigated micromembranes as a function of temperature are included in table 1. Table 2 presents the experimental results of the adhesion force between flexible plate and substrate for the investigated micromembranes for different temperatures. The tests were done with a mechanical force applied in the mid-position of mobile plate. In order to measure the adhesion force, the micromembrane is directly deflected to substrate with a controlled AFM force. The materials in contact are the
micromembrane material (gold) and its substrate (silicon). In order to determine the temperature effect on stiffness and adhesion, a thermal controlled stage was used. During tests, the temperature increases until 100°C.

Table 1. Out of the plane stiffness [N/m] as a function of temperature.

| Temperature [°C] | Membrane 1 | Membrane 2 | Membrane 3 | Membrane 4 |
|------------------|------------|------------|------------|------------|
|                  | Na         | E b        | Na         | E b        | Na         | E b        | Na         | E b        |
| 20               | 63.90      | 64.40      | 15.35      | 14.90      | 130.82     | 127.50     | 28.80      | 26.00      |
| 40               | 63.42      | 63.71      | 15.40      | 15.12      | 130.84     | 127.42     | 30.59      | 26.20      |
| 60               | 62.89      | 62.92      | 15.45      | 15.20      | 130.89     | 127.66     | 30.72      | 25.89      |
| 80               | 62.17      | 62.24      | 15.50      | 15.38      | 130.89     | 127.81     | 30.10      | 26.38      |
| 100              | 62.09      | 61.75      | 15.55      | 15.42      | 131.20     | 128.06     | 30.65      | 27.13      |

*a* Numerical results / b* Experimental results

Table 2. Experimental results of adhesion force [µN].

| Temperature [°C] | Membrane 1 | Membrane 2 | Membrane 3 | Membrane 4 |
|------------------|------------|------------|------------|------------|
| 20               | 36.0       | 124.0      | 1.27       | 78.20      |
| 40               | 38.2       | 122.8      | 1.27       | 76.80      |
| 60               | 40.0       | 122.2      | 1.30       | 76.20      |
| 80               | 40.5       | 121.6      | 1.32       | 77.10      |
| 100              | 40.2       | 121.1      | 1.46       | 76.72      |

The coupling of the strain field to a temperature field provides an energy dissipation mechanism that allows for the system to relax. In the case of the investigated micromembranes under out-of-the-plane displacement, the relaxation strength/stress to be considered is influenced by the modulus of elasticity. A thermal gradient applied on the structure decreases both the modulus of elasticity and stiffness. On the other hand, the temperature gradient applied on the structure introduces a thermal prestress in hinges that increase the stiffness. These two aspects are considered in the investigated samples. As for the micromembranes with higher stiffness the thermal prestress given by the thermal dilatation of hinges is smaller than that of the micromembrane with less stiffness. In this case the thermal relaxation of the modulus of elasticity is considered as the reason for stiffness decrease. For micromembranes with smaller stiffness, the thermal prestress is significant and the stiffness given by the structure geometry is increased based on an additional thermal stiffness.

6. Conclusions
This paper presents the analysis of thermal effect on stiffness and adhesion force of micromembranes with serpentine hinges. Depending on their application, micromembranes with different sensitivity can be obtained by changing the number of hinges and their geometrical configurations. Micromembranes with two and four hinges were investigated in order to evaluate their static response under a mechanical load and a thermal gradient. The AFM spectroscopy in point was used to measure the stiffness and adhesion force between mobile plate and substrate. The force was applied in the mid position of mobile plate and it deflects it directly to substrate. The same force was used for all investigated micromembranes. Because the dimensions of mobile plate are the same for all micromembranes, the contact areas with substrate are equal and the roughness of micromembranes should be in the same range. The adhesion force is mainly influenced by the restoring force of micromembranes from substrate, this force depending on the membrane stiffness. Micromembranes with higher stiffness are accompanied by smaller values of adhesion forces comparatively with micromembranes with smaller stiffness. Increasing the temperature, the stiffness as well as the
adhesion forces are modified. Experimentally, the dependence between force and displacement of micromembranes can be determined as a function of temperature and the Young’s modulus – temperature dependence can be estimated. Temperature introduces an additional prestress of structure given by the thermal dilatation of hinges that increases the stiffness especially for micromembranes with small initial stiffness. The experimental results of stiffness as a function of temperature are compared to the numerical values and these are in good agreement. Comparing to with micromembranes supported by the other geometry of hinges, the micromembranes with serpentines hinges provide a compensation of thermal effect with small influence of stiffness and on adhesion, thus, these micromembranes being suitable for applications where a thermal gradient occurs.

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