Effect of geometrical dimensions on the tribomechanical response of a gold micromembrane with bent beam hinges

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Abstract. The scope of this paper is experimental and numerical analysis of micromembranes supported by bent beam hinges fabricated from gold in different geometrical dimensions. The experimental tests are performed using an atomic force microscope in order to determine the micromembrane behaviour under a mechanical force. One of the main application of movable microcomponents is MEMS switching application where the flexible plate is directly deflected to substrate in order to close a circuit. Adhesion between the mobile plate and substrate depends on the roughness of the contact surfaces and is influenced by the micromembrane stiffness based on the restoring force. As the dimensions of hinges increases, the stiffness of micromembrane increases and the adhesion between mobile plate and substrate decreases, respectively.

1. Introduction
The micromembranes are used in Microelectromechanical System (MEMS) to support other components which are regularly rigid or to provide the necessary flexibility in a microdevice that has moving parts. The micromembranes can be used as a flexible component in RF-MEMS switches or in optical applications and consists of a mobile plate that is moved in different planes in response of an acting signal, the anchors that connect the flexible structures to substrate, and the microhinges that connect mobile plate to anchors. The micromembranes can be implemented in a RF switch [1, 2], in different variable capacitors [1], in a pressure sensor [3], mechanical memories [4] or can be the active element in optical applications as a movable micromirror [5].

Essentially springs, the micromembranes are characterized by means of their stiffness, which are derived about the main direction of motion. The micromembrane stiffness is related to the geometry and material properties and is influenced by the geometrical and structural characteristics of hinges. Hinges are deformed in bending or torsion as a function of the applied force and characterizes the mechanical deformability of the micromembranes.

The reliability and lifetime of a system depend on the mechanical and tribological behaviours of the flexible parts but also on the material properties. One of the main failure causes of a micromembrane that is deflected to substrate are excessive stress in hinges and the stiction between the mobile plate and substrate. Stiction is one of the most important and unavoidable failure problems of microcomponents which directly deflect to substrate. Stiction is the adhesion of contacting surfaces due to surface forces (van der Waals, capillary forces, Casmir forces, hydrogen bridging, and electrostatic forces). The restoring force of structure opposite to adhesion force depends on the micromembrane stiffness.
Previous works on micromembranes characterization with rectangular and circular geometry include biaxial stress analysis and Young’s modulus of homogeneous structure [6, 7]. The investigations on micromembranes behaviour by static measurement method - load vs. deflection - or bulge test and blister test techniques have also been already reported [8, 9]. A dynamic technique using a laser vibrometer was also applied for stress analysis to determine the frequency response of vibrating micromembranes [10]. The same dynamic analysis was applied on micromembrane with piezoelectric actuation used in biosensing applications. The resonant frequency of micromembrane was determining in air and deionized water [11]. A method to reduce the out-of-plane micromembrane deflection based on internal stress, maintaining the stiffness of structure was developed using multiple-narrow-beam as hinges [12].

One important characteristic of the micromembranes is their mechanical stiffness [13, 14, 15]. The micromembrane stiffness is related to the material properties and is influenced by the geometrical characteristics of hinges. Hinges are deformed in bending or torsion as a function of the applied force. The micromembrane stiffness is related to the geometry and material properties. For micromembranes supported by bent-beam hinges, their mechanical stiffness depends on the geometrical and structural characteristics of hinges. Hinges are deformed in bending and torsion depending on the applied force. When analysing stress behaviour of a hinge, the critical issue is to understand how this deflects under the applied loadings.

Micromembranes supported by bent-beam hinges with different geometrical dimensions are investigated in this paper. Analytical model for out-of-plane stiffness and numerical analysis (finite element analysis) of the micromembrane behavior is presented in section 2 of paper followed by experimental investigation in section 3. The experimental test implies the deflection of investigated micromembranes under a mechanical force given by the bending deflection of an AFM probe and its stiffness. This section also presents the investigation on the adhesion force between flexible part of micromembranes and substrate. Discussions and conclusions are presented in section 4 of the paper.

2. Theoretical model of stiffness and numerical simulation

The geometry of micromembranes supported by bent-beam hinges is presented in Figure 1. The geometrical configuration of investigated micromembrane is symmetrical, the boundary conditions consisting of fixed anchors and a central force perpendicular to the micromembrane surface.

![Figure 1. Micromembrane’s geometry and loading.](image)

The Castigliano’s second theorem is utilized herein to derive the stiffness of investigated micromembranes and to compute the dependence between applied force and the sample bending deflection. The unitary force is considered to be applied in the mid position of the mobile plate as in the numerical investigation.

The parametrical bending stiffness expression of micromembrane supported by bent-beam hinges having this particular configuration can be written as follows:
\[
\delta_{1z} = \frac{F}{3} \left[ K_{b,cs} l_1^3 + K_b \left( l_1^2 - l_1^3 + 3l_{13}^2 l_5 - 3l_{13} l_5^2 + l_5^3 \right) + K_c 3 \left( l_1^2 l_2 + l_1 l_4 \right) \right] \\
\frac{-M_0}{2} \left[ K_{b,cs} l_1^3 + K_b \left( l_{13}^2 + l_1^2 + 2l_1 l_5 l_5^2 - l_5^2 \right) + K_c 2 \left( l_1 l_2 + l_1 l_4 \right) \right] 
\]

where:

\[
M_0 = F \frac{K_{b,cs} l_1^2 + K_b \left( l_{13}^2 - l_1^2 + 2l_1 l_5 l_5^2 \right) + K_c 2 \left( l_1 l_2 + l_1 l_4 \right)}{K_{b,cs} 2 l_1 + K_b 2 \left( l_1 + l_5 \right) + K_c 2 \left( l_2 + l_4 \right)},
\]

\[
K_{b,cs} = \frac{1}{E I_{cs}}, \quad K_b = \frac{1}{E 2 I_z}, \quad K_c = \frac{1}{G 2 l_p}, \quad K_c = \frac{1}{G 2 \beta w t^2}, \quad \left( \beta = \beta \left( \frac{w}{t} \right) \right),
\]

\[
\beta = \beta \left( \frac{w}{t} \right); t = 3 \mu m; \beta = \begin{cases} 
0,293 & \text{for } w = 16 \mu m; \frac{w}{t} = 5,3 \\
0,313 & \text{for } w = 32 \mu m; \frac{w}{t} = 10,6
\end{cases}
\]

In these expressions \( I_{cs}, I_z \) are the moments of inertia of the central shaft (mobile plate) and hinges and \( I_p \) is the polar moment of inertia of the hinges given by the micromembrane thickness and widths. The derived parametrical model can be used in further optimizations algorithms of membranes supported by bent-beam hinges.

Finite Element Analysis (FEA) using ANSYS Workbench 13.0 has been applied to simulate the micromembrane displacement under a given force and to compute its stiffness. The analysed samples are electroplated gold micromembranes, one of the most used material from optical and electrical applications. The simulation is performed considering a value of modulus of elasticity of gold thin films equals with 79 GPa. The membranes have a constant thickness \( t = 3 \mu m \) and the flexible part of micromembranes is suspended at 2\( \mu m \) above a silicone substrate.

The geometrical dimensions of samples according to figure 1 are presented in table 1.

| Micromembrane | \( l_1 \) | \( l_2 \) | \( l_3 \) | \( l_4 \) | \( l_5 \) | \( w_{cs} \) | \( w \) |
|--------------|--------|--------|--------|--------|--------|--------|--------|
| S_1          | 87     | 66     | 238    | 72     | 64     | 74     | 16     |
| S_2          | 162    | 66     | 238    | 72     | 64     | 74     | 16     |
| S_3          | 75     | 68     | 254    | 34     | 72     | 74     | 32     |
| S_4          | 149    | 68     | 254    | 34     | 72     | 74     | 32     |

For this analysis, a unitary force is applied in the mid position of the mobile plate and the out-of-plane displacement is simulated (figures 2 - 6). Moreover, considering the applied force and the resulting displacement, the bending stiffness is computed.
Figure 2. Displacement of S1 micromembrane under a unitary force.

Figure 3. Displacement of S2 micromembrane under a unitary force.

Figure 4. Displacement of S3 micromembrane under a unitary force.

Figure 5. Displacement of S4 micromembrane under a unitary force.

A maximum displacement of 525.5 nm is simulated of the investigated S2 micromembrane (Figure 3) for a unitary force applied in the mid-position of mobile plate that gives a numerical stiffness equal by 1.90 N/m. The minimum displacement is obtained for the micromembrane S3 in value of 211.1 nm that corresponds to a stiffness equal by 4.73 N/m.

The same geometrical dimensions and materials constants have been introduced in the expression (1), the obtained stiffness values are presented in table 2. A comparative analysis between the analytical and numerical models reveals a good agreement of stiffness’s values, the relative deviation being under 3%.

Table 2. Stiffness of micromembrane with bent-beam hinges.

| Micromembrane | S1     | S2     | S3     | S4     |
|---------------|--------|--------|--------|--------|
| Stiffness [N/m] analytical | 2.68   | 1.88   | 4.62   | 2.93   |
| Stiffness [N/m] numerical     | 2.69   | 1.90   | 4.73   | 2.97   |

In order to visualize the stress behavior of investigated micromembranes in the case that the mobile central shaft is deflected to substrate, finite element analysis is carried-out. The displacement of mobile central shaft with 2µm (until substrate) is imposed in the software, the equivalent stress (von Mises) distribution is presented in figures 6 - 9 for each investigated micromembrane. It can be noticed that the highest stress undergo the short beams near the anchors and the values are higher for the micromembranes with higher stiffness. Compared with the yield stress of the thin films of gold (~200 MPa) the obtained values (11 – 19 MPa) are small, ensuring a good durability of the micromembranes.
3. Experimental investigations on static response of micromembranes

3.1. Samples description

The samples for experiment are micromembranes electroplated from gold in 10 deposition steps with the geometrical dimensions as presented in table 1. The investigated micromembranes are characterized by different width of hinges. Moreover, the length of the central plate is changed from micromembranes S₁ and S₃ comparatively with micromembranes S₂ and S₄. The optical images of fabricated micromembranes are presented in Figure 10. The gap between central plate and substrate is equal by 2µm.

Figure 6. Equivalent stress distribution of S₁ micromembrane.

Figure 7. Equivalent stress distribution of S₂ micromembrane.

Figure 8. Equivalent stress distribution of S₃ micromembrane.

Figure 9. Equivalent stress distribution of S₄ micromembrane.

Figure 10. Micromembranes S₁, S₂, S₃ and S₄ for experimental tests
(the dimensions are conforming to figure 1 and table 1)
3.2. AFM tests on micromembranes
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. The tests were performed in ambient condition at a relative humidity of 40% and a temperature of 20°C. A mechanical force given by the bending deflection of AFM probe and its stiffness is applied in the mid-position of the mobile plate and deflect it directly to substrate. The AFM probe used in experiment is NSC35B with a stiffness of 14N/m (provided by manufacturer). The scopes of experimental tests are: to determine the dependence between the applied force and the micromembrane deflection that provide information about the bending stiffness; to analyse the adhesion effect between investigated micromembranes and substrate.

![Figure 11. AFM probe in contact with micromembranes S1 and S3.](image)

As a function of geometrical configuration of samples different responses of micromembranes are obtained. Figure 11 shows the AFM probe in contact with the S1 and S3- micromembranes fabricated in different width of hinges. The spectroscopy in point of AFM provide information about the vertical approach of the AFM scanning head together with AFM probe toward to sample while the deflection of AFM probe is monitored.

![Figure 12. AFM experimental curve of S1- micromembrane (red line corresponds to loading and the blue curve is for unloading step).](image)

The experimental AFM curve taken on S1- micromembrane is presented in figure 12. The first part (1-2) of the loading curve corresponds to the bending of AFM probe and sample. In the point 2 the micromembrane comes in contact with substrate. After this position, only the AFM probe is bending. As it can be observed on unloading AFM curve, there is a jump (3-4) given by the adhesion effect between micromembrane and substrate. The detachment of micromembrane from substrate is delayed due to the adhesion effect that gives that jump in the AFM probe deflection. The jump size is proportional to the strength of adhesion between contacted surfaces. After the contact between
micromembrane and substrate is broken in position 4 the sample and AFM probe are coming to the initial position. The first part (1-2) is used to compute the micromembrane stiffness. The detected deflection of AFM probe multiply with 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 (1-2) of experimental curve represents the micromembrane bending deflection ($Z_{\text{sample}}$). Based on the AFM tests, dependence between the applied force and the deflection of micromembranes can be obtained as presented in Figure 13 for $S_1$- micromembrane, and the stiffness can be determined.

![Figure 13. Deflection of $S_1$- micromembrane versus applied force.](image)

The same AFM test is used for all investigated micromembranes. As a function of geometrical dimensions different responses of micromembranes are obtained. The tests were performed 5 times for each sample and the average results are presented in table 3.

| Micromembrane | $S_1$ | $S_2$ | $S_3$ | $S_4$ |
|---------------|------|------|------|------|
| Stiffness [N/m] | 2.6 | 1.8 | 4.6 | 2.9 |
| Adhesion force [nN] | 69 | 28.5 | 80 | 61.5 |

4. Conclusions
The effect of geometrical dimensions on static response of micromembrane with bent-beam hinges is analysed in this paper. The interest was to determine the stiffness of micromembranes under a mechanical load and the adhesion effect between the mobile plate and substrate. For adhesion analysis the flexible plate of micromembranes were deflected until substrate. The experimental results performed by AFM were validated by analytical and numerical analyses. A comparative analysis between the analytical, numerical and experimental values of micromembranes stiffness is graphically presented in figure 14.

The equivalent (von Mises) stress values were computed by considering that the micromembranes are deflected to the substrate. The highest stress is observed in the short beams connected to the anchors, the values being higher for the micromembranes with higher stiffness. The obtained stresses related to the yield stress of their material are small ensuring the requested reliability of the micromembranes.
The stiffness has influence on adhesion based on the restorative force of micromembrane. As temperature increases, stiffness decreases and adhesion force increases respectively. Depending on MEMS application, micromembranes with different sensitivity can be obtained by changing the geometrical dimensions of hinges.

5. References

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