DESIGN AND CHARACTERIZATION OF THERMALLY ACTUATED BIMETALLIC MEMBRANES BY MICHELSON INTERFEROMETRY

DISEÑO Y CARACTERIZACIÓN DE MENBRANAS BIMETÁLICAS ACTUADAS TERMICAMENTE MEDIANTE INTERFEROMETRÍA DE MICHELSON

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ABSTRACT: This paper presents the design and characterization of thermally actuated Al-Si bimetallic membranes. The design was made with the Finite Element Method and was emphasized on optimizing the thickness ratio between the aluminum and silicon layers. The membrane deflection was measured employing the Michelson Interferometer. The experimental process was carried out with square membranes of 5 mm of side length, 10 µm in silicon thickness, and an aluminum thicknesses of 4 and 1 µm. A maximum deflection of 14 µm was obtained for membranes with 4 µm of aluminum thickness, which is consistent with predictions made by numerical calculations.

KEY WORDS: Bietallic effect, micromembranes, interferometry, Finite Element Method

RESUMEN: En el presente trabajo se describen el diseño y la caracterización de membranas bimetálicas de Al-Si, con actuación térmica. El diseño se realizó empleando el método de los Elementos Finitos y se concentró en optimizar la relación de los espesores de las capas de aluminio y silicio. La deflexión de las membranas se determinó aplicando la técnica del Interferómetro de Michelson. En la etapa experimental se utilizaron membranas cuadradas de 5 mm de lado, con un espesor de 10 µm para el silicio y espesores de 4 y 1 µm para el aluminio. La caracterización entregó un desplazamiento máximo de 14 µm para la membrana con 4 µm de Al, lo cual es consistente con los resultados obtenidos numéricamente.

PALABRAS CLAVE: Efecto bimetálico, micromembranas, interferometría, Método de los Elementos Finitos.

1. INTRODUCTION

Most of micro-mechanical actuators in micro-systems correspond to thin film structures which modify their geometrical shapes, such as, for example, sensors with moving membranes or beams, piezoelectric resonators, micro-motors, micro-pumps, valves, cantilevers, and so on [1-8]. The characterization of this kind of micro-structure requires a high-performance measurement system to determine the static and dynamic behaviour of small deflections [9, 10].

The design of microsystems uses simulation tools based on the Finite Element Method (FEM). This method is useful to study components at the physical level [11, 12]. However, FEM analysis is not suitable to carry out the analysis of a whole system. In these cases it is necessary to extract behavioral models which can accurately describe the behavior of the system currently being analyzed [13, 14].

The behavior of linear systems can be represented by an adequate transferring function. However, many microsystems include considerable sources of non-linearity arising from large geometrical deflections in mechanical systems, or from temperature-dependent material properties in thermal problems. When the system behaves in a non-linear manner, it is known that the most accurate linear representation depends on the operating point. In those cases, it can be necessary to extract the transfer function from the analysis of signals in the time domain [15].

This work presents the design and characterization of a thermally actuated Al-Si bimetallic membrane. The design was emphasized on optimizing the thickness ratio between the aluminum and silicon layers. The membrane deflection was measured employing the Michelson Interferometer.

Experiments were carried out with square membranes of 5mm of side length, 10 μm in silicon thickness, and an aluminum thicknesses of 4 and 1 μm, respectively. In the sequel the most relevant results are reported.

2. METHODS AND MATERIALS

2.1. The bimetallic effect

There are many mechanisms of action when building micro-pumps in micro-system-related technologies. One of them, the pneumatic mechanism, consists of using a radiating energy to heat the air molecules enclosed in a sealed cavity in order to increase the internal pressure to cause the membrane deflection [16].

In this work we are interested in the bimetallic effect. It takes advantage of the difference in the mechanical and thermal properties of two different materials. Thus, the radiating energy is absorbed by the surface layer, heating it up, causing the membrane deflection.

Figure 1 shows a cross-section view of the bimetallic membrane. This structure consists of two layers with different materials, aluminum and silicon in this case. Changes in temperature lead to differential rates in thermal strain within the membrane. However, the layers are confined at each interface, and it leads to elastic strains in the films and substrate. In the equilibrium condition, this membrane has no resultant forces or applied moments [17].

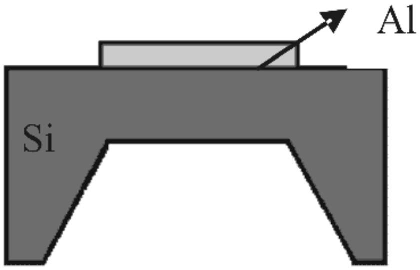

Figure 1. Cross-section view of a bimetallic membrane

The membrane deflection, δ, is given by [18]:

$$\delta = \frac{L_s^2}{8R} \tag{1}$$

Where L_s is the membrane width and R is the effective radius of the deformed membrane.

There are many materials compatibles with the silicon technology like Si_3N_4, SiO_2 and Al, that can be used to fabricate an integrated bimetallic membrane. Table 1 shows the material properties for Al, SiO_2, and Si.

Table 1. Physical constants of Al, SiO_2, and Si

Physical Constants	Symbol	Al	SiO_2	Si
Young's Modulus	E(N/m^2)	$0.7e^{11}$	$0.72e^{11}$	$1.9e^{11}$
Thermal Coefficient	α(°K)$^{-1}$	$23e^{-6}$	$1.83e^{-6}$	$4.68e^{-6}$
Poisson's Ratio	ν	0.30	0.17	0.09
Density	ρ(kg/m^3)	$2.699e^3$	$2.21e^3$	$2.329e^3$
Heat Capacity	c(J/kg °K)	$0.904e^3$	$0.73e^3$	$0.705e^3$
Thermal Conductivity	κ(W/m °K)	$2.37e^2$	$0.014e^2$	$1.56e^2$

When selecting materials to fabricate the bimetallic membrane, Si was the first considered because it is the basic element in microelectronics, and the actuation cavity can be molded by micromachining techniques. Then, Al was chosen as the other material because its thermal coefficient is higher than that of SiO_2, the other available material.

An additional advantage of Al is that it is a good absorber of radiating energy mainly in the infrared (IR) spectrum. Thus, an incident IR radiating beam will be absorbed by the Al layer heating it, originating the bimetallic membrane deflection at the same time [19].

2.2. Experimental setup

Some features of optical measurement techniques are: we get full information of the objects studied, the devices are free from contact, and have high sensitivity. There are some optical methods to measure small deflections of thin membranes such as the Position Sensitive Device, PSD [20], which detects the deviation of laser beam incident on the membrane; another alternative is the Optical Interferometry Technique. In the experimental work the second option was used, as described in Figure 2.

A monochromatic wave, supplied by a He-Ne laser, $\lambda = 0.633$ μm, was employed. A beam-splitter produces the reference and test beams depicted in Figure 2. The last beam goes directly to the target, falling perpendicularly to the membrane.

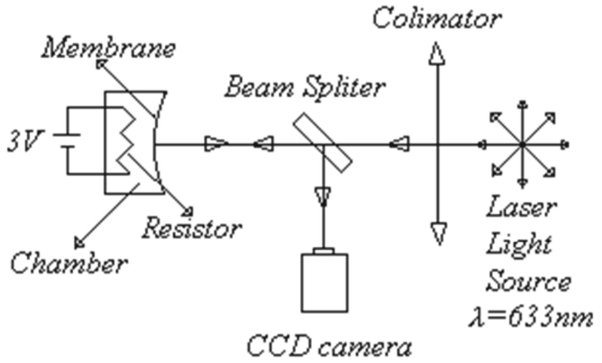

Figure 2. Experimental setup

The membrane deflection produces a difference in the optical paths, which results in a phase difference between the waves; such a difference can be observed as dark and light fringes. As the whole surface is illuminated and each point on the membrane surface presents different deflection values, it results in a two-dimensional image of the interference that can be observed on a CCD camera.

3. RESULTS AND DISCUSION

3.1. Numerical analysis

The ANSYS code was chosen to model the microstructure; it is based on the Finite Element Method (FEM); furthermore, it allows for a static and dynamic analysis of mechanical, thermal, fluidic, and electromagnetic problems [21]. Due to the geometrical symmetry of the structure, the simulation of a quarter of the system suffices to obtain complete information on the bimetallic membrane behaviour as shown in Figure 3.

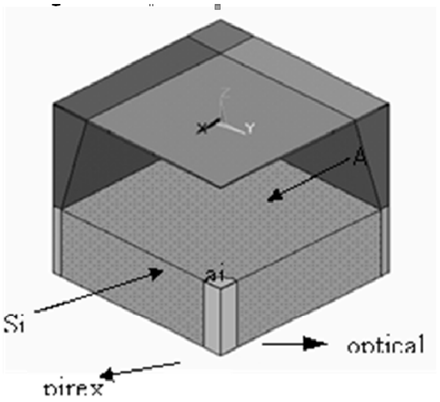

Figure 3. Model of the actuating cavity with a bimetallic membrane. The Si bulk is 250 μm high

All of the bimetallic structures were modelled with 20-Node SOLID elements. Additionally, multi-layer SHELL elements were also applied to the structures of which the upper metal layers were affected by the load (laser light in these case), in an attempt to verify different element models. Some material properties are listed in Table 1.

This model lets us know the mechanical performance of the bimetallic structure with regard to thermal loads applied to the membrane surface. The analysis was carried out considering a square membrane of 5mm in side length, including two layers where the Si supports Al. Thicknesses were selected from 5 to 15 μm in silicon and aluminum thicknesses varying from 0.2 to 15 μm. The optical power used for ANSYS simulations was 10 mW.

Figure 4 shows the FEM analysis results on the bimetallic membrane deflection as a function of the Al and Si thicknesses. As can be observed in Figure 4, there is an optimum relationship between the Al thicknesses for each Si thickness in order to maximize the membrane deflection. In this case, the maximum deflection was 12 μm for 5 μm of each layer. Another important result is that an increment in the total thickness of the membrane produces a decrement in the maximum deflection. Thicknesses below 5 μm for the Si layer were not used for ANSYS simulation because, in practice, membranes of these dimensions become too fragile to be handled.

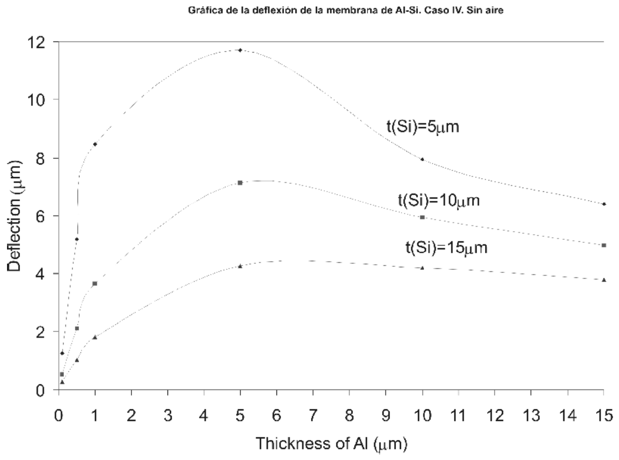

Figure 4. Membrane deflection vs. thicknesses of Al and Si

3.2. Experimental results

The bimetallic membrane has Al on the upper side and Si on the bottom side. The Al thickness is 4 (and 1) μm and the Si thickness is 10 μm. The bimetallic membrane is square and its side length is 5mm. A commercial IR lamp was used for heating the membrane. Results of the deflection measurement of the membrane show interference images like Figure 5. The shape of the rings is due to the fact that the maximum deflection point lies in the center of the membrane. Then, with a TV-video system, we could count them and it was possible to measure the rings' formation time.

Rings appear from the central point of the membrane because it has the highest deflection at any instant of time. In this experiment, the distance between two fringes corresponds to $\lambda/2 = 0.316$ μm, so submicron precision it can be obtained.

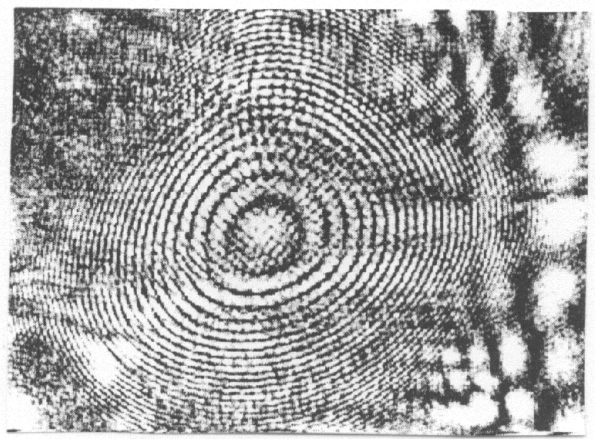

Figure 5. Interference images of deflection

Figure 6 shows the numerical data interpretation of membrane deflection obtained from the interference image for two thicknesses of Al. In the first two minutes the inside-outside rings formation occurred and the positive slope was obtained. Afterwards, the outside-inside rings formation occurred and the negative slope was obtained. From Figure 6 we can obtain 14 μm for the maximum membrane deflection, with 4 μm of Al thickness. Similarly, the maximum deflection for 1 μm of Al thickness membrane is 5 μm at 180 s.

Additionally, Figure 6 shows that the best performance, with the same optic power, is obtained for the 4 μm of Al thickness membrane, which is approximately 50% higher than the 1 μm Al thickness.

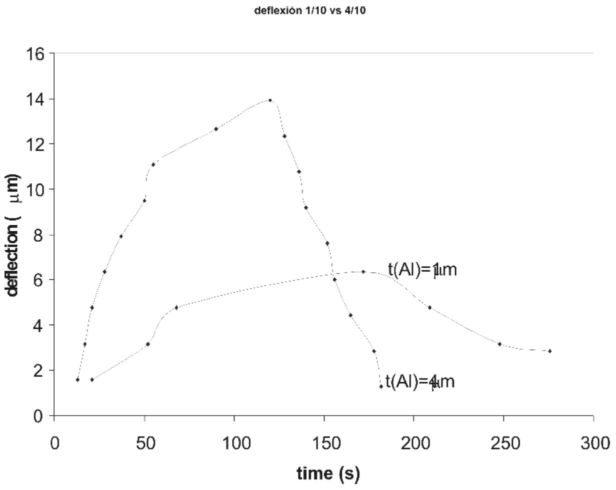

Figure 6. Numerical data interpretation

Figure 7 shows the deflection versus response time for the bimetallic membrane of 4 μm of Al thickness with different distances of optic power. As it can be seen, if the optic power is near to the membrane surface, radiation absorption is greatest and the membrane's performance is better (time response is shorter and deflection is greatest).

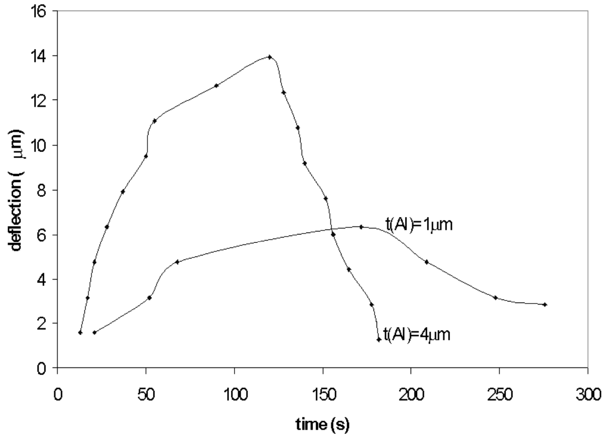

Figure 7. Deflection vs. time with different distances with the same optic power

As it can also be seen, deflection decreases exponentially with the distance of the power source as in Figure 8 [22].

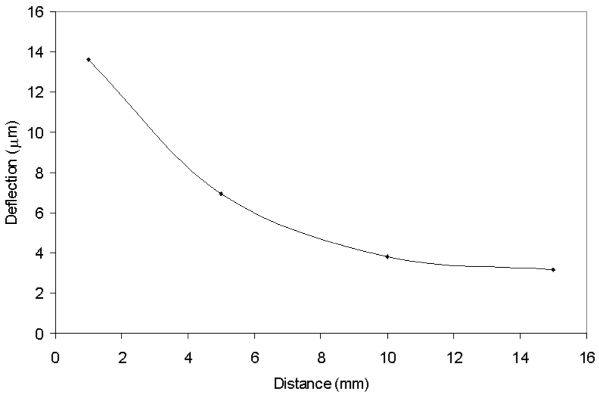

Figure 8. Deflection vs. distance with the same optic power

4. CONCLUSIONS

In this work we present the ratio optimization between Al and Si layer thicknesses of a square membrane designed to operate under the bimetallic effect. An important result of the FEM analysis is that an increment in the total thickness of the membrane produces a decrement in the maximum deflection.

The experimental process was carried out with square membranes of 5mm of side length, 10 μm of silicon thickness, and an aluminum thicknesses of 4 and 1 μm, respectively. A maximum deflection of 14 μm was obtained for membranes with 4 μm of aluminum thickness, which is consistent with predictions made by numerical calculations.

The Michelson Interferometer was employed to measure the membrane deflection as a function of the optical power applied. This technique allows for the characterization of static and dynamic behaviors with submicron resolutions.

6. ACKNOWLEDGEMENTS

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