DESIGN, MODELING AND SIMULATION OF THERMAL MICROACTUATORS

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This paper presents a study of MEMS microactuators with different configurations (U, V and Z). The technological process for these structures was described. The polysilicon thermal microdevices were designed and simulated using COSMOS M Geostar software. The influence of geometric parameters on the performance of the U-shaped and bent-beam microactuators was analyzed. In addition, an investigation has been made on the Z-type microactuator, recently developed in the MEMS field. The simulation result of last one has been compared with those determined by analytical calculation. Interesting conclusions have been inferred regarding under study parameters of the three microactuator shapes.

Keywords: thermal microactuators, MEMS technology, numerical simulation.

1. Introduction

The microactuator is the main part of MEMS structures that provide movement. Compared to other types of actuation in this domain, these thermal microdevices have the following advantages: robust structure, large output forces, easy operation. It is therefore one of the principal choices for operation microdevices [1]. Table 1 presents a comparison between the main types of microactuators [2].

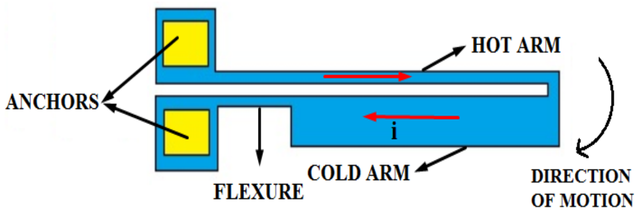

Fig.1 U-shaped thermal microactuator [3, 4]

These microdevices find application in miniaturized surgery, fluidics, robotics and medicine [5].

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Table 1

Comparison between more types of microactuators [2]

Type of microactuator	*Advantages*	*Disadvantages*
Electrostatic	Quick response Low energy consumption	High drive voltage Effect of withdrawal
Electromagnetic	Large forces Low drive voltage	High energy consumption External magnets
Piezoelectric	Quick response Low energy consumption	Hysteresis effect Large inclination angle
Electrothermal	Large scanning angle Easy operation Low drive voltage Large forces	High energy consumption Slow response

Various types of actuation are distinguished: electrostatic, electrothermal, electromagnetic, piezoelectric and others. It has been shown that electrothermal microactuators obtain better displacement results at low voltage than other types. [5]. These MEMS structures are based on thermal expansion and effect of Joule heating. U-shaped microactuator (Fig.1) consists of one narrow (hot) arm, one wide (cold) and the flexure. After heating caused by electricity, a bending moment is formed in the structure of the two arms because of temperature difference between them. So, the device deflects towards the arm with smaller expansion [3]. The other two investigated structures (Fig.2 and Fig.3) are almost identical, but the second is grounded on the flexing of the Z-shaped symmetrical beams induced by the heating to realize the moving of the central element. More precisely, when a current passes through microactuator, the heat is produced along the beam due to Joule heating. Increasing the temperature contributes to the thermal expansion of all parts, especially beams with larger dimensions [6, 7].

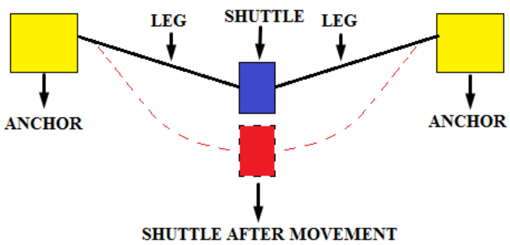

Fig.2 V-shaped thermal microactuator [4,8].

The displacement obtained due to thermal loading of structures is mainly influenced by the material used and their geometry, and it is important to study these influences in order to obtain the desired results for different MEMS applications.

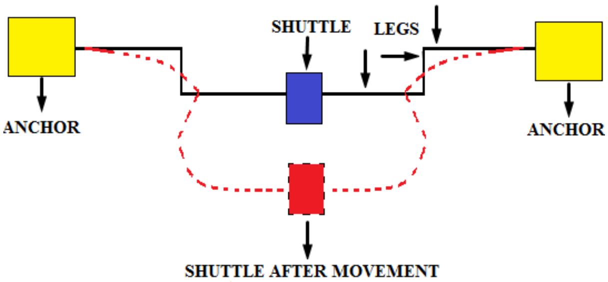

Fig.3 Z-shaped thermal microactuator [6].

This part of article describes surface micromachining, because it was the process used to fabricate the thermal microactuators in this study. The process starts with a silicon wafer. Next, a very thin silicon nitride layer is deposited by LPCVD (low pressure chemical vapor deposition) which acts as an electrical isolation layer. The nitride layer is then patterned. To pattern the nitride layer, a layer of photoresist is deposited. The photoresist is patterned and developed. The areas of photoresist exposed to UV light are chemically removed. This step creates the desired mask of photoresist for the nitride layer. The unprotected (unwanted) nitride is removed by a RIE process (Reactive Ion Etch). Finally, the remaining photoresist is removed in a solvent bath. Next, a silicon oxide is deposited through CVD (Chemical Vapor Deposition), which is used as a sacrificial layer. It is patterned through photo – etching process, too. After that, a polysilicon film is deposited by LPCVD as a structural layer. This polysilicon layer is patterned in the same way as the previous layers. A RTP (Rapid Thermal Process) is used as thermal treatment to release residual and inherent stresses in the polysilicon layer and then hydrofluoric acid is used to corrode the sacrificial layer [9-12].

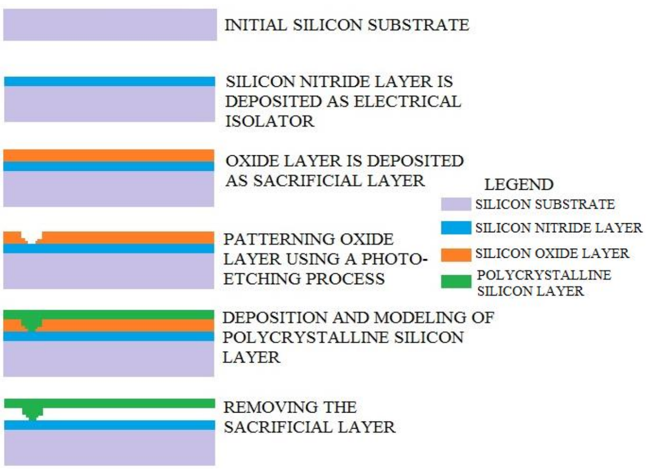

Fig.4 Process for microactuators fabrication

2. Design and modeling of microactuators

The construction of typical U microstructures is shown in Fig.5. U-shaped microactuators are of two types: thermal bimorphs and homogenous. In first case we have two different materials, so with different thermal properties. In the second case the material is the same, so the displacement being obtained due to the different geometries of the beams. In both devices, a bending moment is created in the two beams and the two-arm structure deflects towards the beam with smaller expansion [3]. The other two types (Fig.6) get the moving due to the thermal expansion of the material from the symmetrical beams [4, 6]. Thermal behavior of all investigated structures was simulated using CosmosM software. It is worth mentioning that the figures below being 2D, the thickness (*h*) of the devices is not shown in the sketches.

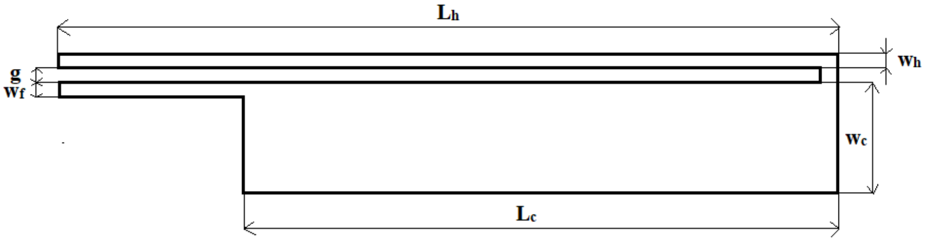

Fig.5 Design of U-shaped thermal microactuator

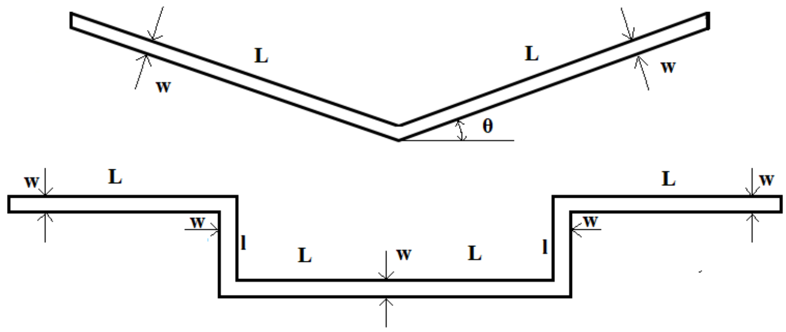

Fig.6 Design of V-shaped and Z-shaped thermal microactuators

The displacement of U-shaped structure can be found using linear Euler-Bernoulli beam–theory [3]. Lobontiu and Garcia [4] also determined the mechanical performances of U and V-type or bent-beam microactuator.

According to Guan and Zhu [6], it can achieve the displacement in the y direction for Z-shaped microactuator:

$$\delta = \frac{12\alpha \Delta T L^3}{l^2 + 6L\left(l + \frac{w^2}{8l}\right)} \qquad (1)$$

The geometric and material [13] characteristics for studied microdevices are shown in Table 2. The dimensions and properties of the structure material were established in correlation with the technology described in previous chapter.

Table 2

Geometric and material properties values for proposed microactuators

U TYPE	**V TYPE**	**Z TYPE**
Length of hot arm L_h=240 μm	Leg length L=100 μm	Long beam L=88 μm
Length of cold arm L_c=200 μm	Leg width w=2 μm	Short beam l=20 μm
Width of hot arm, flexible element, gap, thickness w_h=w_f=g=h=2 μm	Thickness h=2μm	Thickness h=2 μm
Width of cold arm w_c=16 μm	Inclination θ=8°	Beam width w=2.5 μm
Material properties of polycrystalline silicon		
Young's modulus	E[GPa]	160
Thermal expansion coefficient	α [°C^{-1}]	2,6·10^{-6}
Poisson's ratio	ν[-]	0.28

Where ΔT is variation of temperature, the rest is geometric parameters shown in Table 2. Having all calculation data, it results at temperature variation of ΔT=300°C a displacement of 0.579 μm. The determined analytical results will be compared with those numerically simulated from the next chapter.

3. Numerical simulation of under study microactuators

The purpose of this numerical simulation is to see the influence of geometric parameters on the mechanical response of the thermally actuated structures. Besides this, the results of the numerical analysis of Z-shaped thermal microactuator will be compared with the calculated analytical results described in previous chapter. Numerical simulation of these microactuators was performed in Cosmos M Geostar software. It is one of the best choices for finite element method calculations [14, 15]. The first step was to build 3D model of microactuators (Fig.5 and Fig.6) with geometric parameters mentioned in Table 2. Next step is to define element groups (Solid, 8-20 nodes 3D solid element), material properties (in our case – thermal expansion coefficient α, Young modulus E and Poisson's ratio ν) and real constant sets. After that, the parametric meshing is performed on volumes, ending with merging and compressing the nodes. The last steps before the running is the fixing of geometry and the application of load. The load will be thermal (temperature) applied on the volumes. In Fig.7 is shown the simplified sketch of steps for simulating microstructures in Cosmos M Geostar.

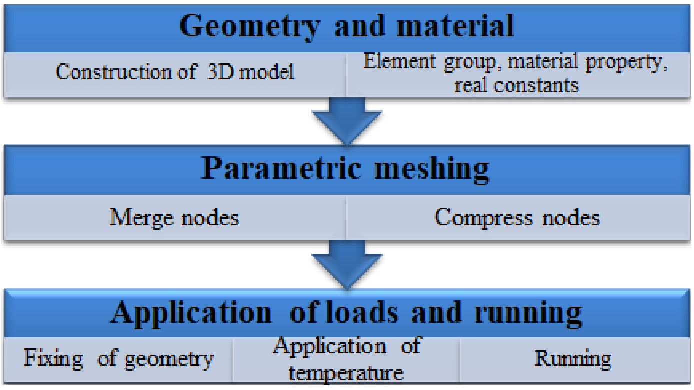

Fig.7 Schematics of numerical analysis steps in Cosmos M Geostar

Following the steps described above, the U-shaped thermal microdevice was succesfully simulated. A temperature difference of 100°C between the hot arm and the cold arm was applied to the structure. Attention should be paid to the temperature difference between the arms in order to have a linear analysis [3]. In our case, for a temperature difference higher than 126°C, a non-linear buckling analysis should be realised to determine the exact microactuator displacement. The deformation of the structure is presented in Fig.8 and at temperature difference of 100°C was obtained a displacement of the beam of 2.524 µm.

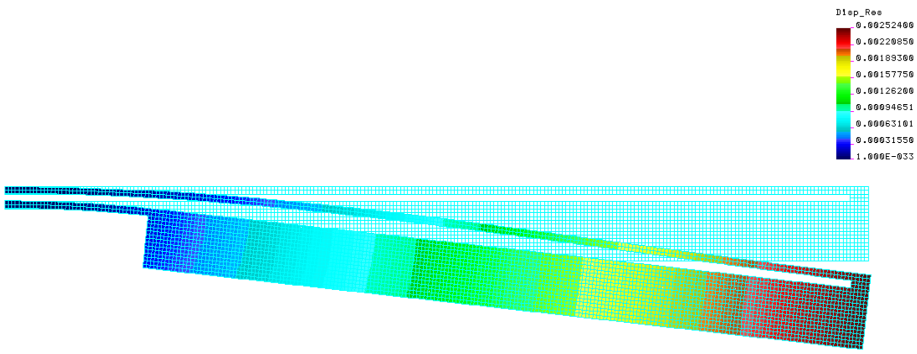
Fig.8 U-shaped thermal microactuator after simulation

Of the three structures, the U-shaped microactuator has the most complex geometry, having the most constructive parameters that can influence beam displacement: length and width of hot arm (L_h, w_h), length and width of cold arm (L_c, w_c), length and width of flexible element (l_f, w_f), gap between arms (g) and thickness (h). Figures 9-11 show graphically the influence of geometric parameters on U-shaped thermal microactuator deflection.

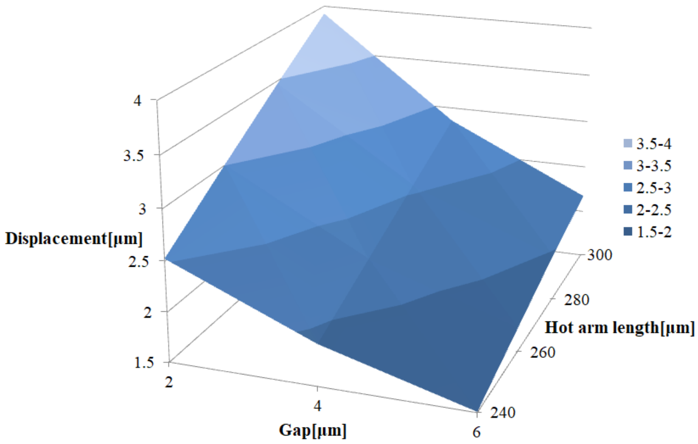

Fig.9 Influence of the gap and the length of the hot arm on the displacement of the U-type microactuator

It must be specified, that at all simulations depending to certain geometric parameters, the other characteristics are the same as in Table 2, apart from the length of flexible element, which will vary with the lengths of hot and cold arms in the corresponding simulations. All investigations of U-shaped structure were realized at the same temperature difference of 100°C.

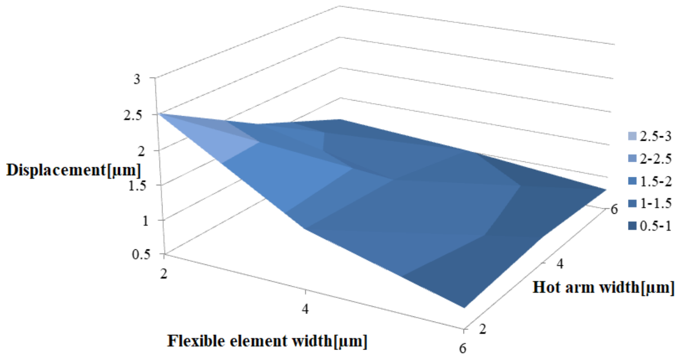

Fig.10 Influence of the widths of flexible element and hot arm on the displacement of the U-type microactuator

It can be seen that the displacement substantially increases with the growth of length of the hot arm and decreases with the growth of the gap (Fig.9). Also the widths of hot arm and especially of flexible element greatly influence the displacement results (Fig.10). In order to have bigger mechanical performances, the widths of hot arm and flexible element should be as small as possible. The variations of geometric parameters of cold arm do not significantly change the deflection results (Fig.11). The displacement increases with the width of cold arm and decreases with the length, but this is due to the fact that the length of the flexible element decreases with the increase of cold arm length. The thickness does not intervene in change of displacement results of structures.

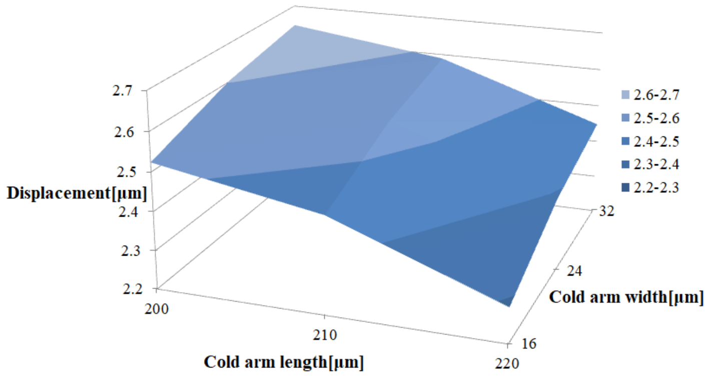

Fig.11. Influence of the length and the width of the cold arm on the displacement of the U-type microactuator

The other two types are simpler from a constructive point of view. At variation of temperature of 300°C, the V-shaped thermal microactuator develops a displacement of 0.553 µm (Fig.12). With regard to the Z type microactuator, it was obtained a displacement of 0.6 µm at variation of temperature of 300°C (Fig.15).

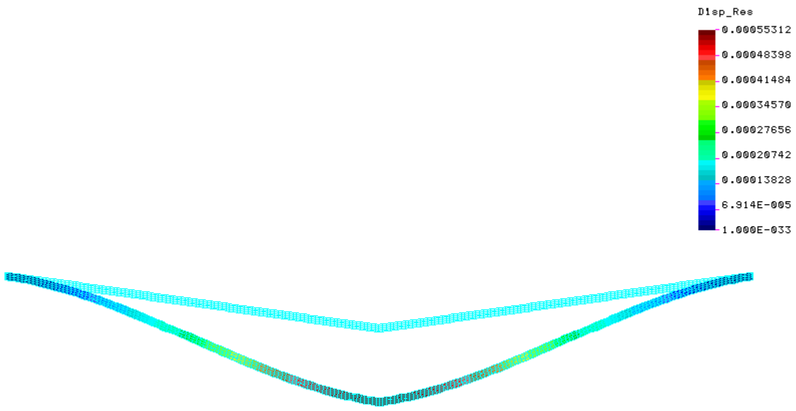

Fig.12 V-shaped thermal microactuator after simulation

Geometric parameters that can influence the mechanical performance of V-shaped microactuator are: leg length (*L*), leg width (*w*), inclination angle (θ) and thickness (*h*). These microactuators were simulated varying the angle of inclination (8° to 12°) and leg length (from 100 to 140 microns), the other parameters being the same in Table 2. Figure 13 shows the behavior of the displacement in function of these characteristics, where it can be observed that the increasing of inclination angle leads to decreasing of displacement. On the other hand, the displacement increases with the growth of leg length. It seems that the angle of inclination is the most important parameter that influences the displacement, the variation of which leads to major changes of its results.

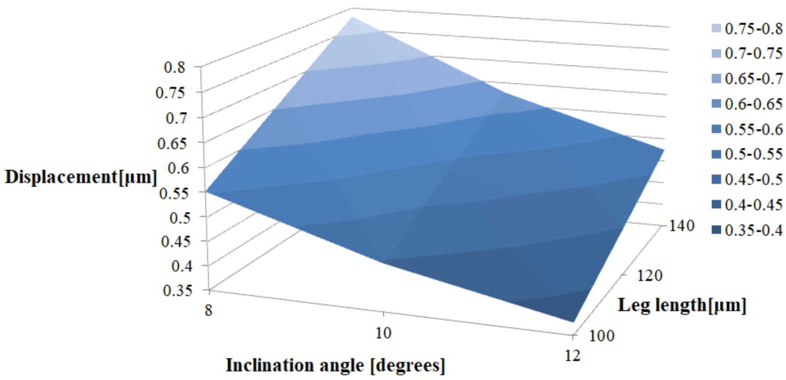

Fig.13 Influence of the inclination angle and leg length on the displacement of the V-type microactuator

In the same way the microstructure was analyzed when the width and thickness varied, this time the angle of inclination and leg length being constant (Fig.14).

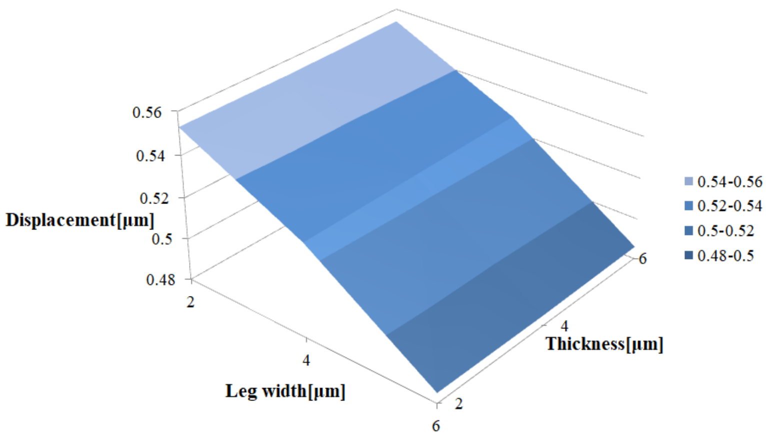

Fig.14 Influence of the leg width and thickness on the displacement of the V-type microactuator

The leg width (*w*) does not greatly affect the displacement; this one decreasing insignificantly with increasing of leg width. The influence of thickness (h) is almost null.

In the Z type microactuators the following parameters were analyzed: short beam length (*l*), long beam length (*L*), beam width (*w*). Thickness, like in the other structures, does not influence the performance of the structure. Fig.16

shows the comparison between the analytical model and the numerical model up to 300° temperature variation, obtaining very close results, the relative error to the temperature variation of 300 ° C being about 3.7%.

Fig.15 Z-shaped thermal microactuator after simulation

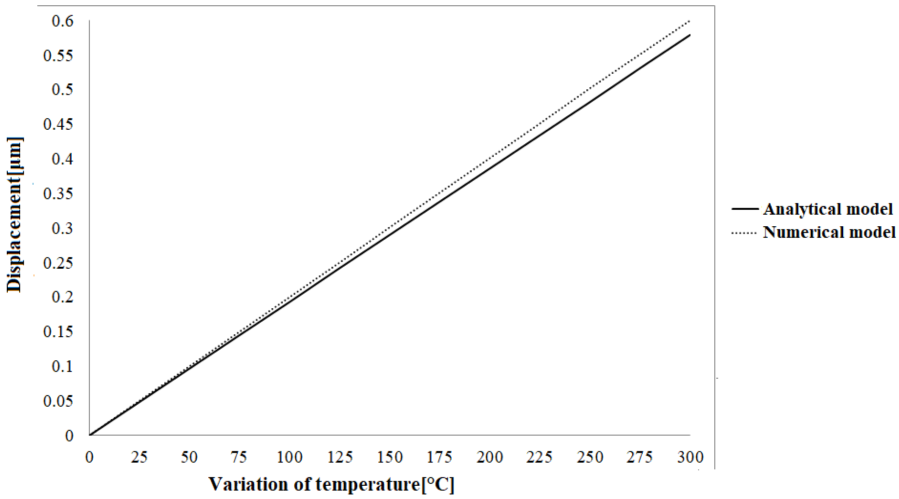

Fig.16 Comparison between analytical and numerical models of Z-shaped thermal microactuator

The width (*w*) is even less significant in affecting the results of the displacement compared to V shape (Fig.17). The most important parameters have been proved to be the lengths of the beams, especially the short ones. In order to have bigger displacements, the short beam (*l*) must be as small as possible and the long beam (*L*) as large as possible (Fig.18). The displacement increases with the *L / l* ratio, but the MEMS domain being with the miniaturization tendency, the long beams do not have to be greatly increased.

By comparing Fig.13 with Fig.18, we can draw the conclusion of an analogy between the angle of inclination (θ) of V-type microactuators and the short beam (*l*) of the Z-type, the two characteristics having a very similar influence on the displacement of the structure.

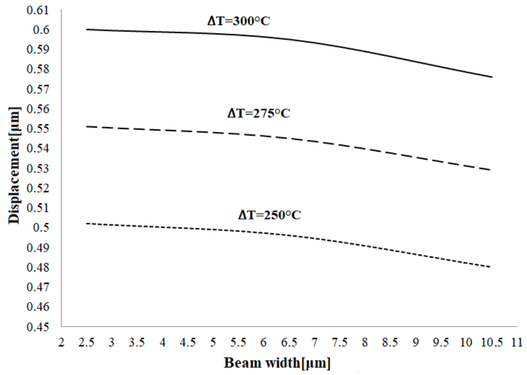

Fig.17 Influence of the beam width on the displacement of the Z-type microactuator

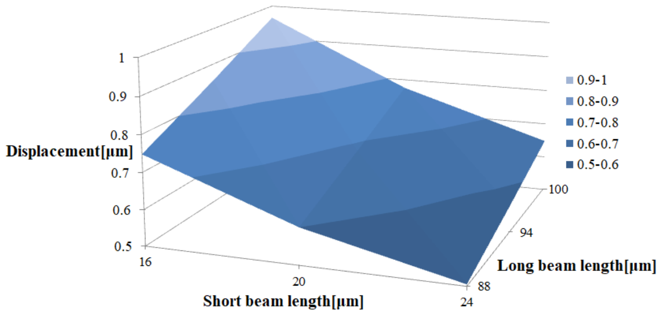

Fig.18 Influence of the lengths of short beam and long beam on the displacement of the Z-type microactuator

4. Conclusions

It was performed a numerical simulation of displacement of three different types of thermal microactuators: U-shaped, V-shaped or bent beam microactuator and Z-shaped. These microactuators mentioned above were simulated in Cosmos M Geostar software to study and highlight how the geometric parameters of the structures influence the displacement results, obtaining interesting conclusions. It has been demonstrated that the change in the thickness of all investigated structures almost does not affect the result of displacement. In U-type microactuators the most important parameters that change the displacement value are the gap, the length and width of the hot arm and also of the flexible element. Structures V and Z are very similar, even an analogy can be made between the angle of inclination of V-type and the length of the short beam of Z-type, both of which most influence the displacement of the structures. The analytical result of Z-type displacement has been compared with simulation getting very close results. Analyzing all geometric parameters and taking into account the tendency of miniaturization of MEMS structures, it can be concluded that microactuators with the proposed material and size values are acceptable and can be designed and used. This type of microactuators has superior characteristics compared to other types of actuation; in addition, the fabrication is simple and not expensive. It is noticeable that these MEMS structures develop large displacements on this scale making them right one of the main choices for actuating in this area in continuous development. In a future research it is desired to extend the study of geometric and material parameters considered for these microactuators and their dynamic behavior.

R E F E R E N C E S

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