Optimized Cantilever-to-Anchor Configuration of Buckled Cantilever Plate Structures for Transducer Applications

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Abstract: The mechanical simulation and analysis of the cantilever-to-anchor configuration for an out-of-plane structure used in transducer applications is reported. The polymer-based Buckled Cantilever Plate "BCP" structure, reported here, gives the ability to orient an active device in any angle ranging from 0º to >90º with respect to the substrate, once assembled. Using the Structural Mechanics module of COMSOL® Multiphysics 4.2a, we simulated the mechanical assembly of such structure. In this paper we compare four different cantilever-to-anchor configurations where the cantilever is connected to a square anchor from the bottom (straight cantilever-to-anchor typical configuration), Lateral, Top and Loop configurations. The results of the BCP assembly simulation shows an improvement of the peeling force induced in the anchors in comparison to standard or typical cantilever-to-anchor configuration. The structural variation in these cantilever-to-anchor configurations modify the direction of the reaction forces at the cantilever-anchor interface while performing assembly and at the final lock position of the BCP, leading to a lower pealing force and more reliable anchor performance.

Keywords: MEMS, Microsystems, Transducers.

1. Introduction

In MEMS technology, a wide variety of devices such as accelerometers [1], gas sensors and gyroscopes among others, can benefit from a consistent mechanism to displace them out-of-plane without breaking contact to the substrate, see **Fig. 1**. These devices need to be electrically connected to a power or sensing circuit, which in instance would allow it to communicate to and integrate with other systems. The BCP structure design provides true out-of-plane assembly while preserving a continuous connection to the substrate for routing of electrical lines. Other authors have reported fabrication of the buckled cantilever structures for different purposes, including a three-axis accelerometer [1]. Using SOG as a sacrificial layer [1-4] and a non-photosensitive polyimide PI2611, with thicknesses ranging from 3µm to 7µm by spinning two layers for the latter [1,4]. SU-8 has also been explored as a structural layer [3], but only as a rapid prototyping method and not as the final structural material with attached sensors design using metal layers.

2. Design and Fabrication

In our fabrication process, we use a 200nm SiO_2 layer for anchor adhesion. As the sacrificial layer, 2µm of α-Si layer is deposited on top of the SiO_2. Next steps include the patterning of the dimple and anchor layers with typical photolithography, and dry etching the α-Si using SF_6. The structural layer is then spun, patterned and cured using a photo-definable polyimide (HD-8820), achieving a thickness of 13µm with a single spun layer. After the structural layer is cured a metal layer can be pattern on top of the BCP structure. Finally, the freestanding devices are released using a XeF_2 dry etch to reduce the stiction phenomena between the substrate and the BCP structures. Details of the fabrication process are shown in **Fig. 2**. As shown in **Fig. 3**, the BCP structure design is basically two cantilevers parallel to each other with a connected plate between them.

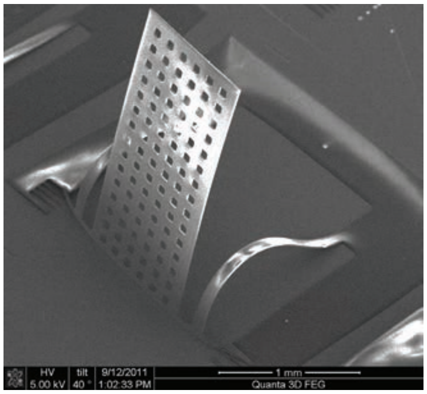

Figure 1 SEM image of an assembled BCP.

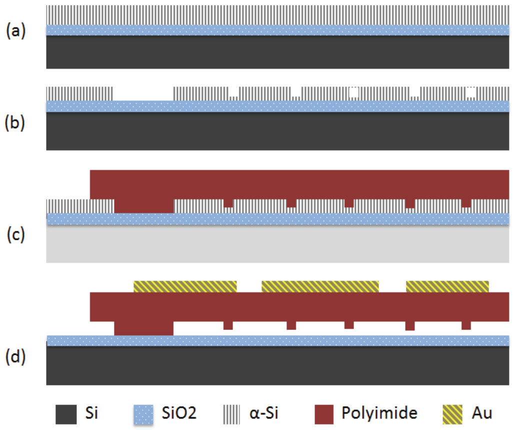

Figure 2 BCP Fabrication Process.

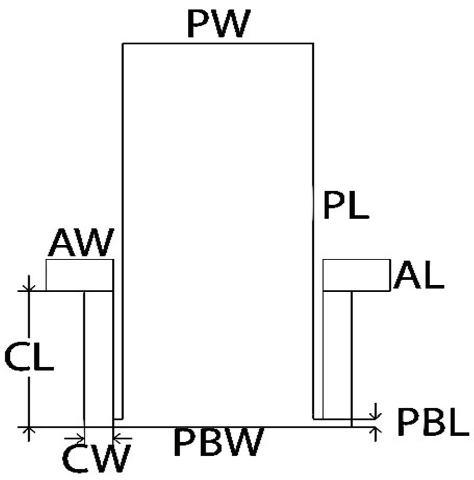

Figure 3 Layout of a BCP where: AL-Anchor Length, AW-Anchor Width, CL-Cantilever Length, CW-Cantilever Width, PL-Plate Length, PW-Plate Width and PBW-Plate Base Width.

The buckled cantilever plate in this out-of-plane structure can be designed to be parallel or perpendicular to the substrate as shown in **Fig. 4A & 4B**. Specific angles can be also achieved by placing the stoppers at a precise distance. Buckled cantilever structures have been also pointed as promising structures capable of thermally insulating different transducer applications from the substrate improving in this way their performance **[2]**. Dimension parameters are to be chosen depending on the desired transducer. By modifying these parameters the structure can achieve distinctive characteristics appropriate to its application. In the following section we will discuss important features that need to be investigated.

Figure 4 A) Lateral layout view of a vertical assembled BCP B) Lateral layout view Assembled BCP with plate parallel to the substrate

3. Mathematical Modeling of BCP

We can understand the mechanical behavior of a cantilever with the aid of Beam Theory. Using beam theory equations we can determine the mode-shape of a buckled cantilever and important features can be investigated. Such features include the cantilever's free end angle and maximum elevation. The cantilever's free end angle will determine the position of a plate mounted between two cantilevers, as show in **Fig. 5 a & b**, while the maximum elevation will indicate the distance of a parallel plate to the substrate where a potential transducer could be mounted between the buckled cantilevers (**Fig. 4B**). Moreover, we can calculate the distance in which such plate should be located to achieve the structure to be parallel to the substrate.

The BCP cantilevers can be modeled as a hinged beam, with one fixed end (anchored) and the other one pined once in its lock position and during assembly. By applying a force and displacing the free cantilever end to its lock position the cantilever will buckle elevating its body positively in the "Z" direction (**Fig. 5a, c & d**).

To determine the buckling load and mode-shape of the cantilever we can use Euler's Column Formula, where the critical load to induce buckling to the cantilever F_{cr} is described as

$$\boldsymbol{F_{cr} = \frac{\pi^2 EI}{(KL)^2}} \quad \textbf{(1)}$$

where,

E : material's Young's Modulus
I : moment of inertia
KL: effective length

The effective length is dependent on the boundary conditions and related to the cantilever's length depending on the conditions of the cantilever ends support.

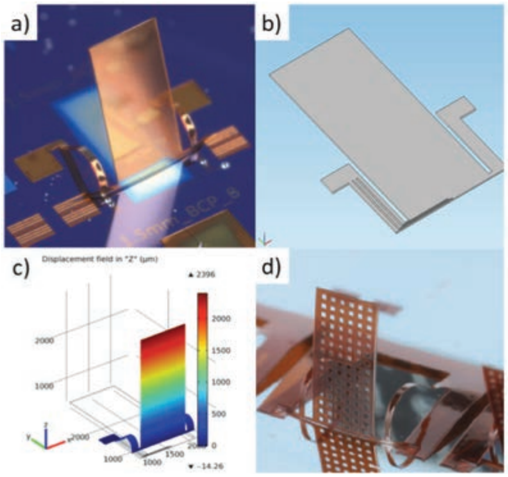

Figure 5 a) Photo of an assembled BCP (Note: "Lateral" anchor configuration) b) Perspective view of a BCP 3D model in rest position c) Simulation of an assembled BCP showing "Z" Displacement. d) Photo of an assembled BCP with Etch Holes (Note: Anchors are failing using the "Bottom" Anchor configuration).

For our case effective length is define as

$$L_{eff} = KL \qquad (2)$$

where,

K : 0.699…
[Constant for a cantilever with one end fixed and the other end pined]
L : the actual cantilever's length

This means that the effective length is shorter than its actual physical length by a factor of 0.699. In [3] the author shows a general solution to the beam-bending differential equation, which is used to solve an axial load on a cantilever, the set of equations are shown below:

Differential equation:

$$EI\frac{d^4y}{dx^4} + F\frac{d^2y}{dx^2} = 0 \qquad (3)$$

General Solution by substituting $k^2 = \frac{F}{EI}$:

$$y(x) = A\sin(kx) + B\cos(kx) + Cx + D \qquad (4)$$

For this solution x is the position along the cantilever and y(x) the cantilever's calculated transverse deflection [3]. Because the BCP is approximated as a fixed-hinged cantilever configuration, we have the following end conditions: $y = \frac{dy}{dx} = 0$ at $x = 0$, and $y = \frac{d^2y}{dx^2}$ at $x = l$, and hence the mode-shape is given by

$$y(x) = \sin(kx) - kl\cos(kx) + kl(1 - \frac{x}{l}) \qquad (5)$$

The equations described in this section are used only to calculate the shape of the cantilever and the important points that are of interest for our problem: highest elevation point along the cantilever and the end angle of the cantilever among other structure's characteristics.

3. Use of COMSOL Multiphysics

We have used COMSOL Multiphysics software package as an aid to investigate more complicated characteristic of the BCP structures, such as reaction forces, principal stresses and total displacement between others. In order to reduce the peeling force induced at the anchors, the set of four cantilever-to-anchor configurations, shown in **Table 1**, were evaluated at the point of vertical assembly (90º). By using the Structural Mechanics module in COMSOL® Multiphysics 4.2a, we were able to calculate the stresses and displacements (**Fig. 5c**)

Table 1 Anchor configurations for the Buckled Cantilever Plates.

Cantilever-to-Anchor Configuration Types	**Finite Element Simulation of the Anchor Geometry**			
	 **"Bottom"**	 **"Lateral"**	 **"Top"**	 **"Loop"**
Simulated Assembly Distance	650μm	650μm	830μm	850μm
Simulated Pealing Force at 90°	$-1.4558e^{-4}$ N·m	**$-2.4498e^{-5}$ N·m**	$-3.236e^{-5}$ N·m	$-3.825e^{-5}$ N·m
% Reduction	Reference	**83%**	78%	74%

of the assembled microstructure as well as the peeling forces acting at the anchors (**Fig. 6**). These forces are of great interest to us due to its important relation to the assembly yield. These variables were parametrically evaluated with respect to the "assembly distance" of the free moving bottom edge of the structure. As described in the fabrication process polyimide was chosen as the structural layer, we simulated the structures using this polymer, **Table 2** enlist this material physical properties.

Table 2 Simulated Material Properties

Property	**Value**	**Units**
Density (ρ)	1300	kg/m3
Young's Modulus (E)	3.1e9	Pa
Poisson's Ratio (ν)	.34	1
Heat Capacity (C_p)	1100	J/(kg*K)
Conductivity (k)	0.15	W/(m*K)

In this paper we define the peeling force at the anchor as the reaction force in the "z" direction, which is induced by the cantilever beam when buckled. The other force components in the "x" and "y" directions were evaluated but are not of relevance for this study as their values are a couple of orders of magnitude weaker and act over a relative big surface area. In COMSOL there are different ways to compute reactions forces. However, this analysis uses the predefined variables for the forces and moment as described in the COMSOL Multiphysics User's Guide. **Fig. 6** shows the sum of the nodal values over the specific cantilever-to-anchor configuration interface. Note that the direction of the reaction force at the edge of the anchor is opposite to the peeling force that will make the anchor fail **Fig. 5d.** The results revealed a reduction in the induced force at the anchor interface of 83% compared with the standard cantilever-to-anchors reported [1-4]. In addition our simulations match the predicted value of the assembly distance stated in [4], in which the vertical position of the plate is achieved at approximately one third of the cantilever's length. In the "Top" and "Loop" anchor configurations, these distances are bigger due to the deflection of their loop shape connection and material's properties.

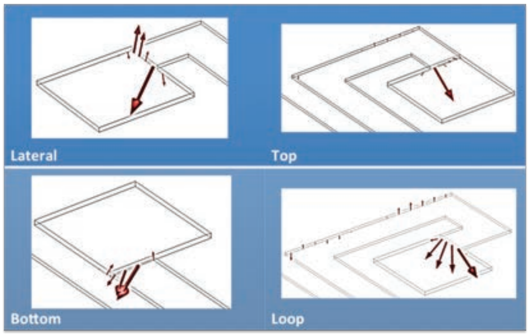

Figure 6 Sum of nodal values for each cantilever-to-anchor configuration.

7. Conclusions

The cantilever simulations for the displacement and mode-shape results match the predicted values using the equations presented in [3]. We have demonstrated an optimized cantilever-to-anchor configuration that reduces the peeling force at the anchors-cantilever interface of a buckled cantilever plate structure by 83%. By using the best cantilever to-anchor configuration, out of the four evaluated in this paper, the reliability of these structures will increase making them more resistant to their most common failure mode.

8. References

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