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BROAD SIDE LOADED ISOSCELES TRAPEZOIDAL MEMS CANTILEVER BEAM

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ABSTRACT

In this paper we are presenting a design of isosceles trapezium shaped polysilicon cantilever beam at Micro Electro Mechanical Systems (MEMS) level that is highly sensitive for extreme low pressure measurements. Using surface micromachining technique, the design concentrates on optimizing the shape of the rectangular and triangular beam so that the final design provides tradeoff between sensitivity and maximum tolerable pressure. For the applied pressure, this paper concentrates a Finite Element Analysis (FEA) on beam's displacement, distribution of stress along its length using Intellisuite software simulation tool for the trapezoidal cantilever beam. The analysis is also extended to find the maximum tolerable pressure for the trapezoidal beam.

Keywords: MEMS, surface micromachining, FEA.

INTRODUCTION

In today's fast and busy life MEMS devices have dominated the market worldwide possibly making the designs at microscopic level and densely packed together as Compact structures in the field of Engineering and its related disciplines. [1-3] Complexity in design and high fabrication costs of such high ended engineering micro-structures could not obstruct its growth in biomedical, chemical, automobile and aerospace domains because these designs are precise, minute and have a speedy response. One type of MEMS structures is a Cantilever beam that has support at one side to make it rigid and other side being freely moved when loaded with some external phenomena. MEMS cantilever structures are in the order of sub-micron and micron size i.e. approximately 10^{-6}m. [3]Any chemical, biological molecules or physical actions tend to displace the beam. [4] Without any dedicated automatic or hand tool to create, these MEMS structures can be fabricated using several micromachining techniques. MEMS structures are more often sensors or actuators or transducers. These micro-scale level sensors and actuators combined with the interfacing and conditioning circuits bind together and act upon controlling external phenomena that are real word signals. Exploring cause-effect relationship of these signals helps to solve the mystery if science lying behind these actions.

LITERATURE REVIEW

Improvised sensitivity in cantilever beams can be achieved by several methods. One among such methods includes changing the material properties. [5] The first method includes choosing a low young's modulus material for a desired cantilever cross section. A material with low young's modulus property is highly elastic and tends to regain its shape faster. The second method includes selecting piezoresistive materials such as Polycrystalline silicon, Germanium and Nickel which tends to be more flexible. [6] Hence use of piezoresistive materials for designing cantilever beam is encouraged for improving sensitivity as it achieves higher displacement for external physical or bio-chemical phenomena than other materials and deflection detection is also easy in this case. [6] The other method is by introducing Stress Concentration Regions (SCR) along the length of the beam. The introduction of SCR in the beam increases the distribution of stress along the beam which inturn increases sensitivity. [7] Higher sensitivity is also achieved by curtailing the cross section of the cantilever beam. It is very difficult to achieve desired shape at extremely low nanoscale levels. The fabrication process for these very minute structures also is highly expensive. [8] For bio-sensing applications, a method has been proposed to improve the frequency sensitivity on mass loading by optimizing the geometrical constraints of rectangular and V-shaped cantilever beams.
Polysilicon is a brittle material and pure polysilicon MEMS structures do not have a plastic deformation. When the material is stressed beyond Ultimate Tensile Strength (UTS) it will directly undergo fracture. [9] Material properties of Low pressure chemical vapour deposition (LPCVD) based polysilicon is measured using laser interferometry technique which gives approximate value of Young's modulus = 169 Gpa, Poisson's ratio = 0.22 and UTS = 1200 Mpa.

MATHEMATICAL MODELLING

To determine the displacement

When pressure is applied on the face of the cantilever beam it deflects downwards as shown in Figure-1.

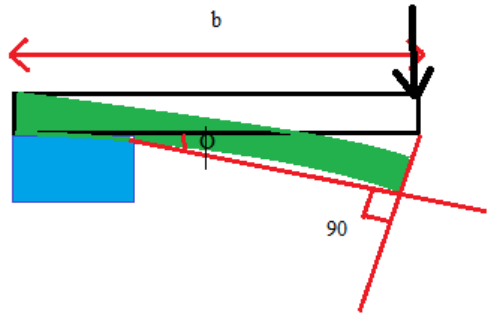


Figure-1. Deflection of the cantilever beam due to applied pressure.

The slope at any point on the deflected beam is given by the first derivative of its displacement axis with respect to the neutral axis while the second derivative gives the radius of curvature. [10] The relation between the Radius of Curvature (D) and the bending moment (B) is given by the relation,

$$B = \frac{yi}{D} \tag{1}$$

where y is the young's modulus of the material and i is the moment of inertia.

[10] The length of the beam (b) and the radius of curvature (D) of the beam is given by the relation,

$$D = \frac{b}{\emptyset} \tag{2}$$

By substituting (2) in (1) we get the value of $\emptyset$ to be,

$$\emptyset = \frac{bB}{yi} \tag{3}$$

[10] The strain energy (E) stored in the beam due to bending is given by

$$E = \frac{1}{2}\emptyset B \tag{4}$$

By substituting (3) in (4) we get the value of E to be,

$$E = \frac{1}{2}\frac{bB^2}{yi} \tag{5}$$

[11]According to Castigliano's first theorem, the partial derivative of strain energy with respect to the moment of force acting on the cantilever beam gives the displacement (x) due to the deflection.

$$\frac{\partial E}{\partial B} = x = \frac{bB}{yi} \tag{6}$$

[11] Also we know moment is the product of Force (F) and distance as indicated in the equation below,

$$B = F * b \tag{7}$$

Substituting equation (7) in (6) we get the value of (x) to be

$$x = \frac{b^2 F}{yi} \tag{8}$$

[11] Since the displacement varies along the length of the beam, the equation (8) can be written as

$$x = \int_0^b \frac{b^2 F}{yi}\, db \tag{9}$$

[11] The displacement due to applied pressure (P) is given by the formula,

$$x = \frac{b^3 PA}{3yi} \tag{10}$$

[12] The area of the trapezoidal cross section (A) is given by,

$$A = \frac{b_1}{2}(p + q) \tag{11}$$

The moment of inertia of the is design is given by,

$$i = \frac{b_2\, t^3}{12} \tag{12}$$

Where$p$, q, b_1, b_2 are indicated in Figure-2, and t is the thickness of the cantilever beam.

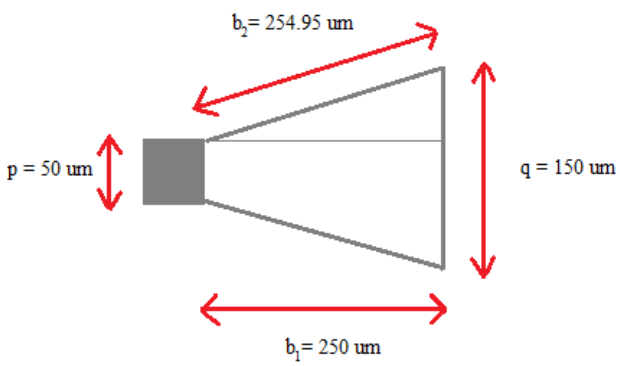


Figure-2. Cross section of the isosceles trapezoidal MEMS cantilever beam.

To determine maximum tolerable pressure

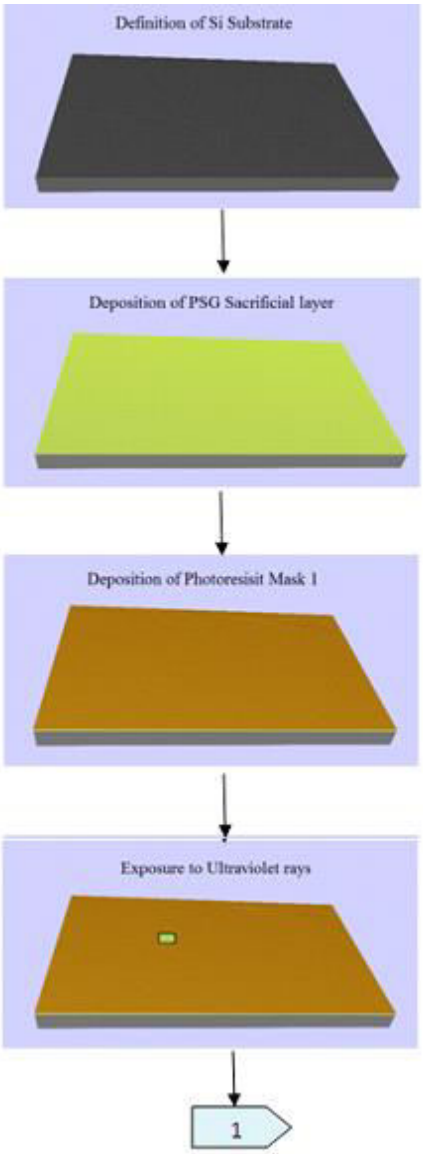
To operate the cantilever beam within the safe limit without any damage, the stresses developed on the cantilever beam should not exceed the UTS for the

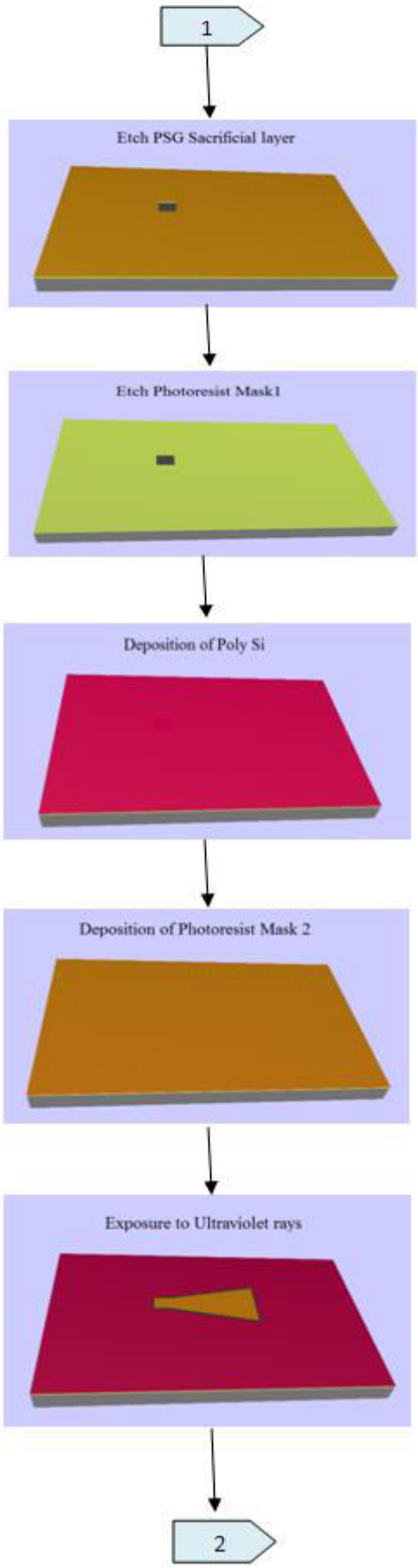
pressure applied. The maximum stress (MTS) developed on the cantilever beam for the applied pressure should be

$$MTS = \frac{1}{2}\,UTS$$

DESIGN USING INTELLIFAB

Surface micromachining technique is followed to achieve trapezoidal cantilever beam design using Intellifab. The advantage of using Intellisuite software package for modeling is it brings out the actual fabrication effects into consideration so that the virtual model will be similar to the actual fabricated design. The design process is indicated in Figure-3 which involves twelve steps from substrate definition to achieve the final design.





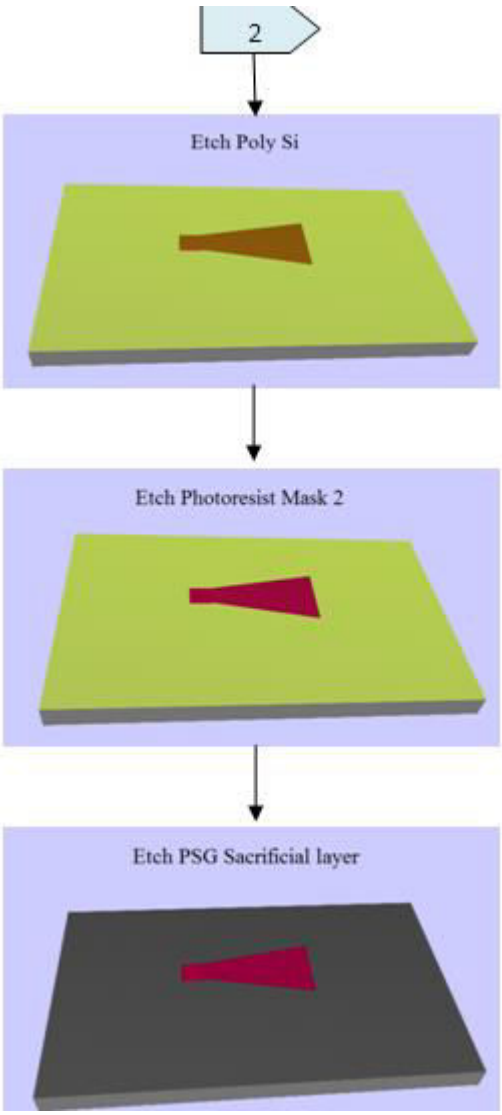


Figure-3. Process flow for cantilever beam.

With substrate excluded, the back view of trapezoidal cantilever beam whose thickness is 1um is shown in Figure-4 whose support area at the bottom is indicated in red and the dimensions are also specified.

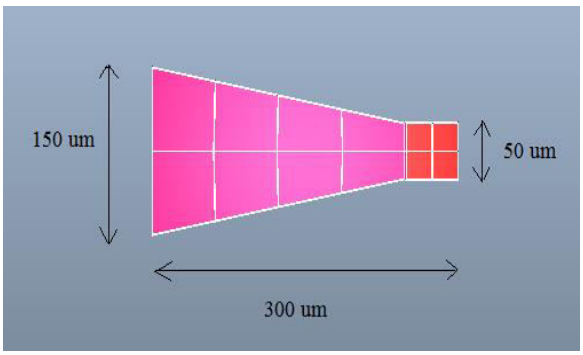


Figure-4. Back view of isosceles trapezoidal MEMS Cantilever beam.

The masks used for trapezoidal cantilever beams are shown in Figure-5 and Figure-6, which are designed using Intellimask. These masks are used in photolithography process. The Mask 1 is used to create support area for the beam while Mask 2 is used to achieve the desired profile of the cantilever beam.

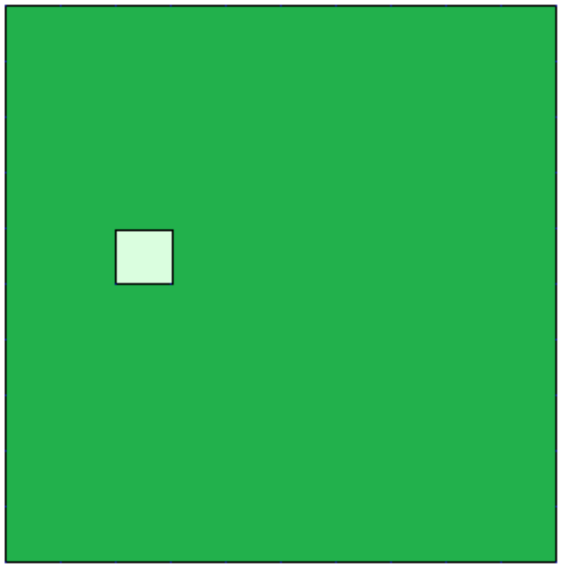


Figure-5. Layer of Mask 1.

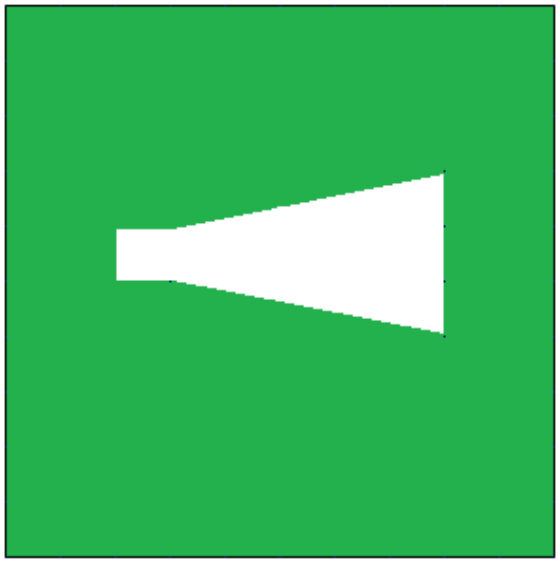


Figure-6. Layer of Mask 2.

SIMULATION AND ANALYSIS

The static analysis is performed using Thermo-Electro-Mechanical (TEM) module by applying pressure along the broad side of trapezoidal cantilever beam. For applied pressure of 0.001 Mpa, the displacement profile for trapezoidal beam is shown in Figure-7, which indicates the displacement will be more at the free end of the cantilever beam that is shown in dark blue colour. The stress distribution for the applied pressure of 0.001 Mpa is shown in Figure-8 where stress will be more in the dark red area near the support of the beam.

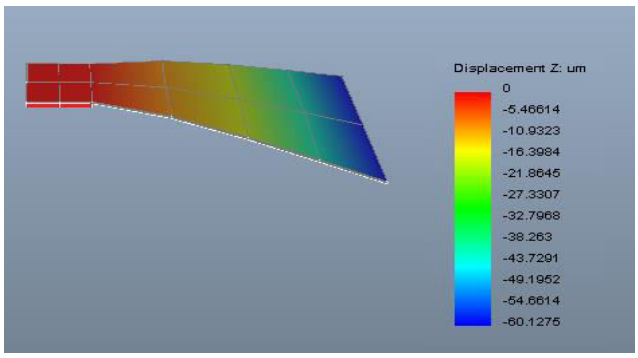


Figure-7. Displacement profile of the cantilever beam.

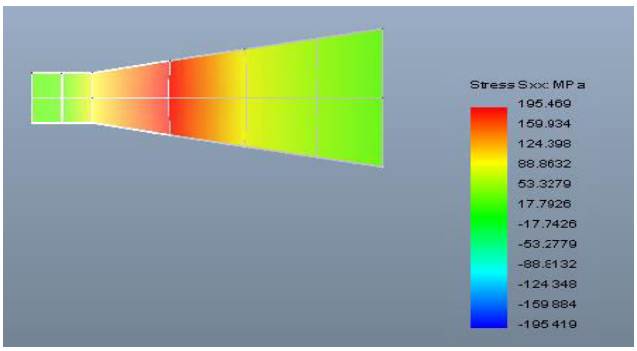


Figure-8. Stress profile of the cantilever beam.

For different applied pressure values Table-1 shows tabulated values of maximum displacement at the free end and maximum stress value near the boundary for trapezoidal cantilever beam.

Table-1. Table indicating displacement and stress component for different applied pressure values.

Pressure applied P (Mpa)	**Simulated displacement values x** (um)	**Displacement value calculated using formula** (um)	**Maximum value of stress** (Mpa)
0.0001	6.01275	6.26646	19.5469
0.0002	12.0255	12.5329	39.0937
0.0003	18.0383	18.7994	58.6406
0.0004	24.051	25.0658	78.1875
0.0005	30.0638	31.3323	99.9668
0.0006	36.0765	37.5987	117.281
0.0007	42.0893	43.8652	136.793
0.0008	48.102	50.1317	156.375
0.0009	54.1148	56.3981	175.922
0.001	60.1275	62.6646	195.469
0.002	120.225	125.329	390.937
0.003	180.383	187.994	586.257
0.00307032	184.661	192.4	599.999

The UTS of polysilicon is material is 1200 Mpa. The cantilever beam can be stressed to a maximum of 599.999 Mpa. Beyond this stress limit it may undergo fracture under practical conditions. In trapezoidal cantilever beam shown in Figure-9, this stress limit is achieved for an applied pressure if 3069.54 Pa. In rectangular cantilever beam shown in Figure-10, this stress limit is experienced for a pressure of 5486.45 Pa. The rectangular cross sectional beam can withstand high pressure when compared with the trapezoidal cross section.

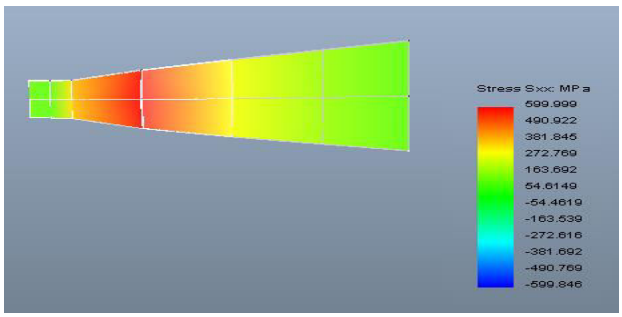


Figure-9. Stress profile for maximum pressure that trapezoidal beam can withstand (Top View).

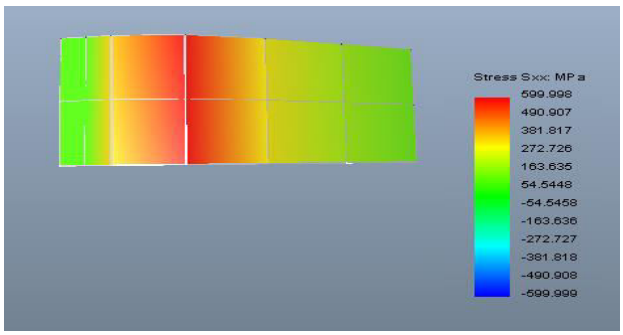


Figure-10. Stress profile for maximum pressure that rectangular beam can withstand (Top View).

The displacement at the free end for the applied pressure of 3069.54 Pa for trapezoidal and rectangular cross sectional beams are shown in Figure-11 and Figure-12. This illustrates for the same applied pressure, sensitivity is comparatively higher for trapezoidal cross sectional beam in comparison with rectangular beam having same thickness and length.

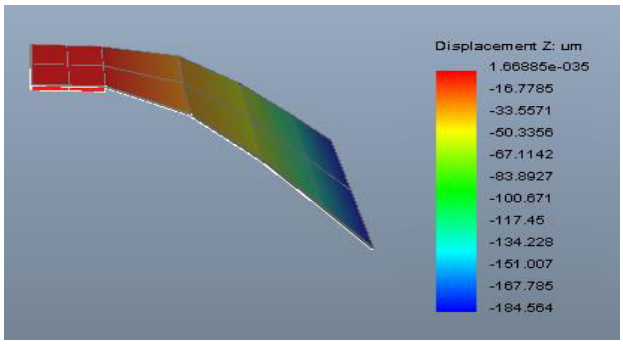


Figure-11. Displacement profile for the applied pressure of 3069.54 Pa for trapezoidal beam.

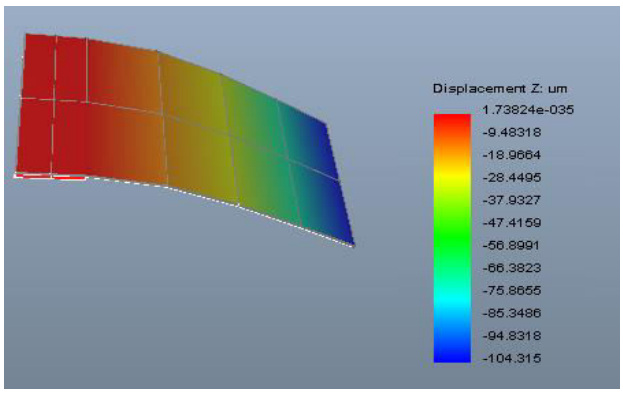


Figure-12. Displacement profile for the applied pressure of 3069.54 Pa for rectangular beam.

RESULTS

The simulated results of isosceles trapezoidal polysilicon cantilever beam shows, it is highly sensitive for extreme low pressure measurements. Stress distribution along the length of the beam illustrates the cantilever beam experiences high stress in the area adjacent to the support and decreases as moving towards the free end. The maximum pressure that the cantilever beam can withstand is 0.00307032 Mpa. This optimized design provides good tradeoff between sensitivity and maximum tolerable pressure.

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