Study on the Weak Stress in Flexural MEMS Cantilever

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Abstract. In order to design a better piezoresistive MEMS cantilever beam, especially for cantilever beams that will detect weak forces or will be subjected to weak forces, this paper uses study on the weak stress in flexural MEMS cantilever. The sensor design structure, divided into protective layer, piezoresistive layer, support layer. The protective layer is responsible for protecting the piezoresistive layer so that the varistor is insulated from the outside; the piezoresistive layer is used to make the varistor; the support layer forms the main part of the cantilever beam, the majority of the cantilever beam. This paper has some value for cantilever multilayer structure design and cantilever beam size design.

1. Introduction
In recent years, biomolecules and their unique ability of recognition have been investigated in terms of their mechanical response such as quartz crystal microbalance (QCM) to external forces. Biological or chemical MEMS cantilever biosensors and biochips develop after atomic force microscope (AFM), which is a common feature of methods of mechanical response by applying external force, invention and employ using MEMS technology [1]. The AFM consists of a cantilever with a sharp tip (probe) at its end that is used to scan the specimen surface detected. The cantilever is typically silicon or silicon nitride with a tip radius of curvature on the order of nanometers. When the tip is brought into proximity of a sample surface, forces between the tip and the sample lead to a deflection of the cantilever according to Hooke's law. On this basis, forces that are measured in AFM include mechanical contact forces, Van der Waals forces, capillary forces, chemical bonding, electrostatic forces, magnetic forces, Casimir forces, solvation forces, etc. [2]. And the principle of BioMEMS cantilever biosensor or biochip is that MEMS cantilever surface combines probe molecules after biochemical treatment [3]. While target molecules in the test sample emerge hybridization reaction or other biochemical reactions with probe molecules, the stress on the cantilever surface changes and the cantilever bending deformation occurs, and then it can obtain reaction information through testing deformation of the cantilever [4]. Lang laboratory first reported that they take cantilever into DNA detection in Science 2000 [5]. They converted the weak signals of biochemical reaction to directly and specifically transducer molecular recognition into nanomechanical responses in a cantilever array. MEMS cantilever piezoelectric biosensor is reported most, but the signal is interfered by noise easily and hard to judge whether resonance while instability and detect piezoelectric signal while stability.

In this paper, we study a MEMS cantilever under a concentrated, transverse loading force, which applied at the free end. We often meet this situation in MEMS design. The transverse force loading comprises both longitudinal strains and shear strains. We ignore the shear stress in this paper.
2. Analysis of the stress in flexural MEMS cantilever

Under a transverse loading of a concentrated force at the free end, the torque distribution through the length of the beam is non-uniform—it is zero at the free end and reaches a maximum at the fixed end. At any cross section, the signs of the longitudinal stresses change across the neutral axis. The magnitude of stresses at any point on the cross section is linearly proportional with respect to the distance to the neutral axis. The distribution of stress in MEMS cantilever is described in Figure 1.

![Figure 1. Stress distribution in a uniform and symmetric MEMS cantilever beam](image)

The magnitude of the maximum stress is related to the linear variation of the cross-section with respect to the free end of the distance, reaching the maximum width at the top and bottom ends. In general, the varistor is usually selected in the cantilever beam surface and near the fixed end.

The length of the cantilever beam (L) is that the axis x begins at the free end to the fixed end. The positive stress at any given cross-section (located at axis x) and the distance of the neutral plane (h) is expressed as \( dF(x, h) \). The total reaction torque of the cross-section is that the area integral dA (ie \( dF(x, h) \)) of orthogonal force (normal force) acting on any given area multiplied by the distance between the force and the center of the arm, ie,
\[
M = \int \int_{A} dF(x, h) h = \int_{w_{h - \frac{t}{2}}}^{\frac{t}{2}} \int \sigma(x, h) dA h
\]

Assuming that the magnitude of the stress is linearly related to \( h \), and it has a maximum value \( (\sigma_{\text{max}}(x)) \) on any cross-sectional surface, the moment balance equation at any given cross-section is shown as:

\[
M = \int_{w_{h - \frac{t}{2}}}^{\frac{t}{2}} \sigma_{\text{max}}(x) \frac{h}{t} dA h
\]

The maximum pull of the cantilever occurs at the fixed end \( (x = L) \). Generally, the only interest is the maximum pull value and the pressure value of the fixed end in the design. According to the total torque, the maximum tension expression is

\[
S_{\text{max}} = \frac{M(x) t}{2EI} = \frac{FLt}{2EI}
\]

3. Multilayer Piezoresistive MEMS cantilever Structural Design

The varistor has a fixed length and width, and if the resistance is formed by doping the silicon beam, the piezoresistive element will be located below the upper surface (Figure 2-a). If the resistance is the formation of deposited polysilicon or metal layers, the surface of the piezoresistive element is above the upper surface (Figure 2-b). In both cases, the resistors begin at the root of the cantilever beam. Assuming that the piezoresistive resistor is thin in the vicinity of the upper surface of the cantilever and is shorter than the length of the cantilever beam, the resistance of the resistor can be approximated by the formula (3).
any advantage over fabrication because they exhibit relatively weak impedances and also require a longer processing time (doping or deposition).

In this paper, the composite multi-layer cantilever beam sensor is applied for structure design, divided into protective layer, piezoresistive layer and support layer. The protective layer is responsible for protecting the piezoresistive layer so that the varistor sensor is insulated from the outside; the piezoresistive layer is used to make the varistor; the support layer forms the main part of the cantilever beam, i.e., the majority of the cantilever beam.

The four completely identical cantilever beams are taken as a group, with reference to the characteristics of the universal glass biochip, each homologous gene needs to be tested for repeated gene array measurements. Therefore, at the same time, the four cantilever beams are assigned to each group, and each group is used to measure the same gene. One of the cantilever beams in each group is used as the beam to be tested and the other is the same cantilever beam as the reference beam. A symmetrical Wheatstone bridge circuit is formed with four identical varistors, two of which are located at the same position on the tested beam and the reference beam respectively, and the other two on the substrate. The presence of factors such as external ambient noise, interference, thermo-mechanical vibration noise, or temperature changes may cause deformation of the cantilever beam, which can eliminate the signal error caused by the reference beam.

In the analysis of this paper, the effect of shear, residual stress, manufacturing process on cantilever beam is neglected, and the electrostrictive force is also neglected. Assuming that each layer is fully elastic, the thickness of the cantilever showed in Figure 3 is much smaller than the bent z-direction displacement of the cantilever caused by the pressure, so only the force of the vertical x and y-direction plane can be considered.

![Figure 3. Multi-layer cantilever beam diagram](image)

4. Simulation of weak stress in flexural MEMS cantilever
The simulated cantilever beam uses silicon as the material, the cantilever beam size is 400μm × 100μm × 10μm, the left end is fixed, and the right end is free. The parameters of silicon are: Young's modulus $E = 170 \times 10^9$Pa, Poisson's ratio $\nu = 0.28$, density $\rho = 2329$kg / m$^3$. The gravity of the cantilever itself results in cantilever beam stress, the application of COMSOL Multiphysics (Femlab) simulation obtains:

The simulation of the cantilever beam stress caused by the gravity of the cantilever beam is shown as below in Figure 4.

The simulation of the displacement of the cantilever beam due to the gravity of the cantilever beam is shown as below in Figure 5, and the software is shown as exaggerated deformation.
The stress equipotential surface of the cantilever beam caused by the gravity of the cantilever beam to be simulated is shown in Figure 6.

Its maximum value is on the outside of the fixed end, and the free end of the above figure is enlarged as shown in Figure 7.

The partial amplification of domain of fixed end is shown in Figure 8.
It can be seen that the stress in the cross section of the cantilever beam is also stratified, and it will be greater when the stress goes outside.

5. Conclusion

This article studied the weak stress in flexural MEMS cantilever, which can be used on biosensors or biochips, and even on inertial navigation devices. In the case of MEMS cantilever beam (which will impose a weak force) design, according to the analysis of this paper, MEMS cantilever beam can be designed as the optimal multi-layer structure, and can be designed as the optimal size.

Reference

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