Modeling of Focused Ion Beam Trimming of Cantilever Beams

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ABSTRACT

A finite element model of the cantilever beam is implemented to include a non-uniform thickness along its length, due to focused ion beam trimming. A quasi-static, iterative approach is used to calculate the cantilever profile for a given bias voltage. Two focused ion beam trimming strategies are compared. The snap-down voltage as a function of milling depth or width is calculated.

Keywords: focused ion beam trimming, cantilever beams, finite element method.

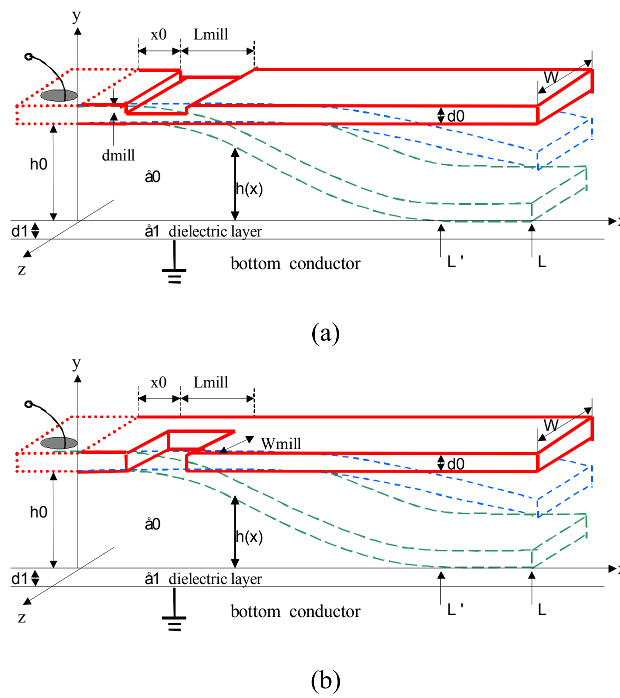
INTRODUCTION

Precision MEMS structures often require trimming by accurate removal of material to adjust the mass, damping, or compliance of the structure. Since material cannot be added back once removed, the position and extent of such trimming cuts must be carefully determined beforehand. Focused ion beams offer the most versatile means for accomplishing this trimming [1]. This work presents a physical device model for a cantilever beam, which includes the effects of focused ion beam trimming cuts as an example of the type of modeling needed for this application.

A finite element model of the cantilever beam is implemented to include a non-uniform thickness along its length. Typical beam geometry is illustrated in Fig. 1. An actual SEM image of a trimmed cantilever beam using focused ion beam is shown in Fig. 2. Due to the highly nonlinear nature of electrostatic actuation, a quasi-static, iterative approach is used to insure convergence. An analytical approximation is used as an initial guess which is input to a quickly converging self-iterating algorithm that equates the electrostatic and mechanical forces on each element of the beam. The results of this model closely match reported measurement data for a cantilever of uniform cross-section [2].

NUMERICAL METHODS

The governing equation for an Euler-Bernoulli beam undergoing small deflection is



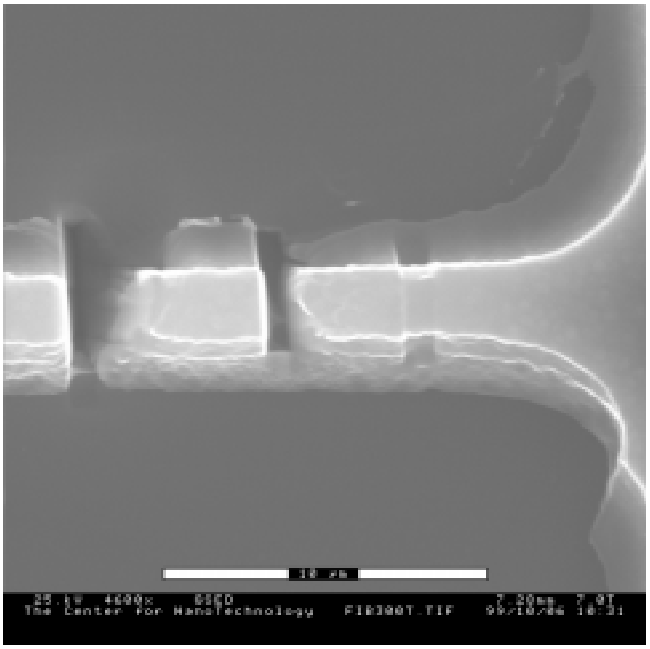
Lmill,Wmill,dmill: milling length, width, and depth
L, W, d0: length, width, thickness of cantilever
h0: initial separation
d1: thickness of dielectric layer
x0: distance from support to milling edge
å0, å1: permittivity in vacuum and in silicon nitride
h(x): deflection profile
V: applied voltage

Figure 1. Geometry of a cantilever with milled cut a)across its width on the top and b)on the side.

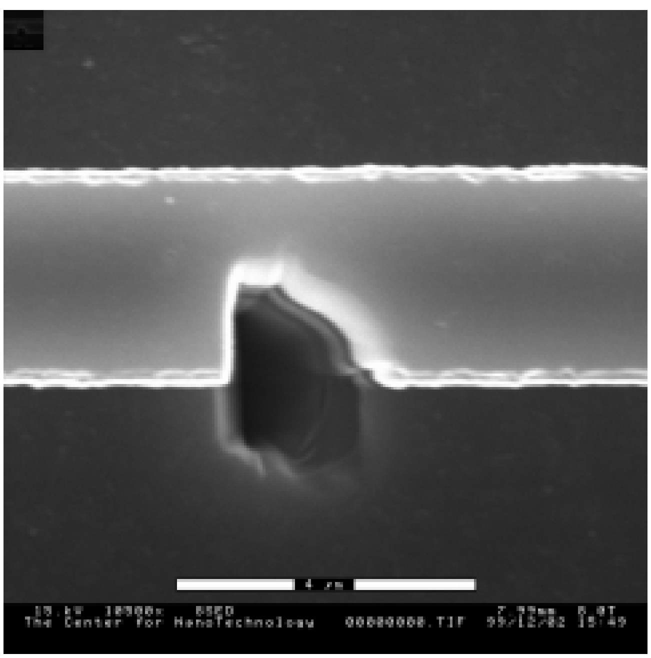
$$Ei \frac{d^4 v}{dx^4} = -q(x) \,, \tag{1}$$

where E is Young's Modulus, I is the cross-sectional area moment of inertia equaling $\frac{Wd_0^3}{12}$, and $v(x)$ is the deflection profile from equilibrium due to loading $q(x)$. The large ratio of length L over initial gap distance h_0 used in this model meets the small deflection criteria of Euler-Bernoulli beams, even after snap-down.

The electrostatic loading per unit length *q(x)* is given by the attractive forces between two capacitor plates



(a)



(b)

Figure 2. SEM images of a mill cut a)on the top and b) on the side of a cantilever using a focused ion beam.

$$q(x) = -\frac{V^2 W\varepsilon}{2[h(x)]^2}\left(1 + \frac{0.65h(x)}{W}\right), \tag{2}$$

where V is the bias voltage between the cantilever and the ground plane, and *h(x)* is the height of the cantilever above the ground plane. The first term on the right is the familiar capacitor plates attraction force. The second term on the right is to compensate for fringing-field effects. *h(x)* is the unknown profile, and is given by

$$h(x) = h_0 + v(x), \tag{3}$$

(Note that the beam bends downward, hence *v(x)* is negative).

By inspecting equations (1)-(3) one can see that the differential equation is highly nonlinear due to the fact that the electrostatic force is inversely proportional to the square of the separation. To solve for the profile *h(x)* an iterative, quasi-static approach is used. First the initial gap is used to calculate uniform loading for the whole beam, for a given bias voltage V. From this loading a beam profile is calculated. The new beam profile, now a function of x, is then used to recalculate the loading. The process is repeated until convergence takes place, i.e. when two successive iterations give nearly identical profiles. Convergence takes place at the equilibrium profile when the electrostatic force balances the mechanical restoring force of the beam. If a bias voltage greater than the snap-down voltage of the beam is used, the beam profile will bend downward until stopped by the ground plane.

The beam profile is calculated using two different methods: numerical integration (NI) and finite element method (FEM). In the NI method the differential equation is numerically integrated to find shear forces, bending moment, slope, and finally deflection profile. At each integration step appropriate boundary conditions are applied. For the FEM method the beam is divided into small beam elements. The global stiffness matrix and force vector are then assembled and inverted to find the deflection profile. A good introduction to the FEM method is given by Lepi [3].

The results given by NI and FEM are almost identical. They both agree well to interferometric measurement data reported by Jenson [2]. The NI method has the advantage of easy implementation for a milled cantilever. However, the FEM method is valuable later on when we want to study the beam profile after it has snapped down. Fig. 3 illustrates how fast the iterations converge even for the case when the beam is biased near the snap-down voltage.

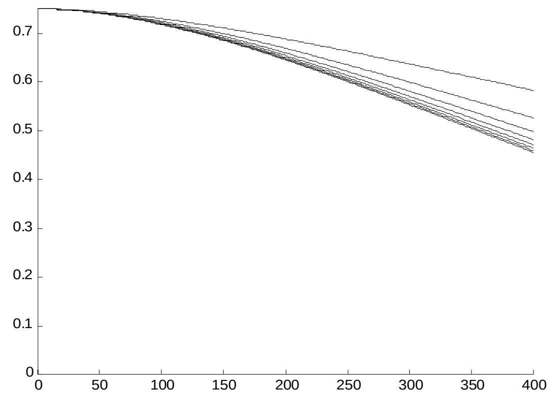


Figure 3. The algorithms are quickly convergent considering the highly non-linear nature of electrostatic actuation. The voltage used is near the snap-down voltage.

APPLICATION TO BEAM TRIMMING

The model described above is modified to study beams with non-uniform thickness or other structural deformities. Focused ion beam trimming could be used to accurately remove material in MEMS devices to adjust the mass, damping, or compliance. Since trimming is irreversible, good prediction of device characteristics is required beforehand.

The case study is a cantilever beam with length L=400µm, width W=20µm, initial thickness d_0 =2.5µm, and gap spacing at support h_0 =0.75µm. The beam, shown in Fig. (1a), is milled from the top with a mill length L_{mill} =20µm and distance from support x_0 =20µm.

The thickness d_0 of the beam is no longer uniform, and needs to be changed to a function in x. To observe changes due to trimming, the snap-down voltage of the beam for various cut depths is monitored. As the beam is cut further down, the flexural rigidity EI of the beam at the cut decreases, the beam becomes weaker and snaps down at a lower bias voltage. Fig. 4 compares the profiles of two beams, one without a cut and one with a cut for the same applied bias voltage. The one with a cut deflects approximately 30 percent more at the tip for any given voltage.

Fig. 5 shows the snap-down voltage as a function of the milling depth. It is surprising to see that the snap-down voltage does not change much until the cut depth is around 70 percent of the total thickness. This is because the flexural rigidity EI varies as the cube of the thickness.

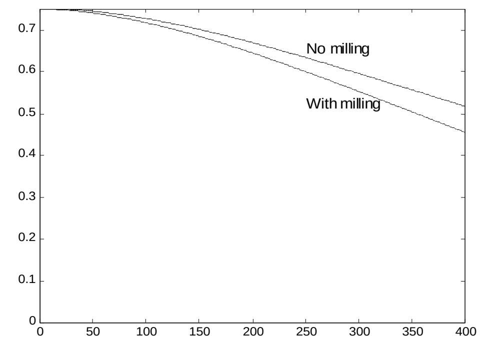


Figure 4. Deflection profiles of uniform and milled cantilevers. Milling depth d_{mill}=2µm.

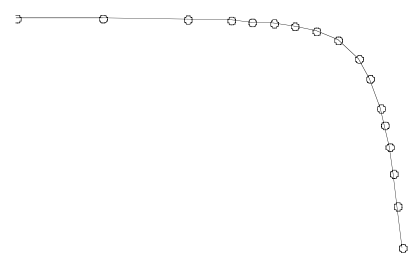


Figure 5. Cantilever snap-down voltage as a function of milling depth for a top cut.

Side cuts, as shown in Fig. (1b), were also examined. Virtually no changes in the beam's deflection profile were observed. The changes in the snap-down voltage were very small, as shown in Fig. 6, even for cuts of up to 90 percent of the beam's width. This is because the flexural rigidity EI varies only proportionally to the width of the beam.

CONCLUSION

A rapidly self-converging numerical integration approach to calculate the deflection profile of a cantilever beam under electrostatic loading has been developed. The method has been validated by FEM simulations with excellent agreement. The model has been applied to study the effect of focused ion beam trimming on cantilever beams, where the resulting beams have non-uniform cross-sections.

The capability to predict device behavior prior to trimming is essential to the economical production of highly accurate MEMS components. The model can easily be modified to study other effects.

Figure 6. Cantilever snap-down voltage as a function of milling width for a side cut.

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REFERENCES

[1] J. Melngailis, C. R. Musil, E. H. Stevens, M. Utlaut, E. M. Kellogg, R. T. Post, M. W. Geis, and R. W. Mountain, "The Focused Ion Beam as an Integrated Circuit Restructuring Tool," *J. Vac. Sci. Tech. B*, vol. 4, no. 1, pp. 176-180, Jan./Feb. 1986.

[2] B. Jensen, M. de Boer, and S. Miller, "IMAP: Interferometry for Material Property Measurement in MEMS", *Proc. 1999 MSM Conf.*, pp. 206-209, San Juan, Puerto Rico, Apr. 19-21, 1999.

[3] Steven M. Lepi, *Practical Guide to Finite Elements: A Solid Mechanics Approach*. New York: Marcel Dekker, Inc., 1998.