Measurement of Material Properties of Individual Layers for Composite Films by a Pull-in Method

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Abstract. There has been an increasing need for MEMS devices with composite films in recent years. This paper presents an improved model of pull-in voltage by finite-difference method (FDM) for a composite fixed-fixed beam, which takes influence of lateral residual stresses of each layer into account. Young’s modulus and residual stresses of each layer for composite beam can then be extracted by these pull-in voltages. And fixed-fixed surface machined beams with multi-cup style anchor were fabricated to be suitable to the model of pull-in voltage. Validation and accuracy of the extracting method have been verified by FEM simulation and experiments.

1. Introduction
The mechanical properties of the material used in micromechanical systems (MEMS) fabrication are of fundamental importance. In general, the thin films have different mechanical properties, such as Young’s modulus and residual stress, which are essential parameters for detailed design and analysis of MEMS devices [1]. Hence, the mechanical characterization of the thin films has become one of the most important challenges in micro-technology. The major difficulty encountered in the mechanical characterization of the thin films is that they are not amenable to testing by conventional means because of their size and configuration. An electrostatic pull-in approach allows for easy measurement, uses simply designed test structures that can be microfabricated in-situ alongside other sensors or actuators, and is tractable to well-developed models. Therefore, various novel characterization methods have been developed [2-8]. In comparison with single layer thin films, mechanical characterization of composite films is more challenging because the mechanical properties change from layer to layer [9]. However, for a composite beam, until now a few researches focusing on the composite beam are always assuming the residual stresses released completely along the beam width [10,11]. In fact, the individual layers of the composite beam may have different residual stresses, so the residual stress along the width can not be assumed to be released completely and this phenomenon could be expected to affect the pull-in voltage.

2. Model
2.1. Pull-in voltage of Composite Fixed-Fixed Beam
For a composite fixed-fixed beam, as shown in Figure 1, two layers of the beam are assumed to be conductors. When a DC voltage is applied between the beam and ground, the beam will bend due to the attractive electrostatic force. The length of the beam is $l$. The width, thickness, Young’s modulus, residual stress and Poisson’s ratio of bottom layer film are $b_1, h_1, E_1, \sigma_1, v_1$, respectively. The width, thickness, Young’s modulus, residual stress and Poisson’s ratio of upper layer film are $b_2, h_2, E_2, \sigma_2, v_2$, respectively. $g_0$ is the undeformed gap between the bottom of the beam and the fixed ground plane. $V$ is the applied voltage.

$X$-axis is taken to be the neutral axis. The distance between the neutral axis and the bottom of the beam is $z_c$. According to the static equilibrium condition of the forces, $z_c$ can be determined as follows [8]

$$z_c = \frac{h_1^2 E_1 / (1 - v_1^2) + h_2^2 E_2 / (1 - v_2^2) + h_1 h_2 E_2 / (1 - v_2^2)}{2(h_1 E_1 / (1 - v_1^2) + h_2 E_2 / (1 - v_2^2))}$$

(1)

$$z_0 = -z_c, z_1 = h_1 - z_c, z_2 = h_1 + h_2 - z_c$$

For a differential element in the composite fixed-fixed beam, different from the single layer fixed-fixed beam, the total shear force along x-axial and y-axial, $Q_x, Q_y$, could not be neglected [12]

$$Q_x = \int_{z_0}^{z_1} \tau_{xz_1} dz + \int_{z_1}^{z_2} \tau_{xz_2} dz$$

(2)

$$Q_y = \int_{z_0}^{z_1} \tau_{yz_1} dz + \int_{z_1}^{z_2} \tau_{yz_2} dz$$

(3)

in which shear stress, $\tau_{xz_1}$, $\tau_{xz_2}$, $\tau_{yz_1}$, $\tau_{yz_2}$, of the individual layers are

$$\tau_{xz_1} = \frac{E_1 (z_1^2 - z_0^2)}{2(1 - v_1^2)} \frac{\partial}{\partial x} \nabla^2 w$$

(4)

$$\tau_{xz_2} = \frac{E_2 (z_2^2 - z_1^2)}{2(1 - v_2^2)} \frac{\partial}{\partial x} \nabla^2 w$$

(5)
\[ \tau_{y_1} = \frac{E_1(z^2 - z_1^2)}{2(1 - v_1^2)} \frac{\partial}{\partial y} \nabla^2 w \]

(6)

\[ \tau_{y_2} = \frac{E_2(z^2 - z_2^2)}{2(1 - v_2^2)} \frac{\partial}{\partial y} \nabla^2 w \]

(7)

Since both ends are fixed, axial stretching of the beam will yield when the beam bends. Then the differential equation of the composite fixed-fixed beam under an electrostatic load is obtained, by taking the shear force into account [12] [13]

\[
\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} - (\sigma_1 h_1 + \sigma_2 h_2) \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right) - \left[ \left( E_1 h_1 \right) \frac{1}{1 - v_1^2} + \left( E_2 h_2 \right) \frac{1}{1 - v_2^2} \right] \frac{1}{2l} \int_{-l/2}^{l/2} \left( \frac{\partial w}{\partial x} \right)^2 \, dx \frac{\partial^2 w}{\partial x^2} \\
+ \left[ \left( E_1 h_1 v_1 \right) \frac{1}{1 - v_1^2} + \left( E_2 h_2 v_2 \right) \frac{1}{1 - v_2^2} \right] \frac{1}{2l} \int_{-l/2}^{l/2} \left( \frac{\partial w}{\partial x} \right)^2 \, dx \frac{\partial^2 w}{\partial y^2} + f_e(x, y) = 0
\]

(8)

where \( w \) is the displacement of the beam at \((x, y)\).

Accounting to Ref [8], \( f_e(x, y) = \frac{\varepsilon_0 V^2}{2(g_0 - w)^2} (1 + 0.65 \frac{g_0 - w}{b}) \), \( \varepsilon_0 \) is permittivity of vacuum, \( b \) is the width of the beam electrode, here, since the beam is assumed to be a conductor, \( b = b_1 \).

The boundary conditions are

\[
w(x, y) \big|_{y = -l/2} = 0, w(x, y) \big|_{y = l/2} = 0, \left. \frac{\partial w(x, y)}{\partial x} \right|_{x = -l/2} = 0, \left. \frac{\partial w(x, y)}{\partial x} \right|_{x = l/2} = 0, \left. \frac{\partial^2 w(x, y)}{\partial y^2} \right|_{y = -b/2} = 0, \left. \frac{\partial^2 w(x, y)}{\partial y^2} \right|_{y = b/2} = 0
\]

Combining Eqs.(2),(3),(8), pull-in voltage of the composite fixed-fixed beam can be obtained by the numerical calculations. The accuracy of the differential equation was verified by Coventor Ware. The error is no more than 10%. Figure 2 shows the pull-in voltage as a function of residual stress of bottom layer film. Here, the width of the beam is 12µm, the undeformed gap is 2.0µm, Young’s modulus and Poisson’s ratio of the bottom layer film are 180GPa, 0.23, respectively, Young’s modulus, residual stress and Poisson’s ratio of the upper layer film are 53GPa, 18MPa, 0.3, respectively.

![Figure 2. Pull-in voltage vs. residual stress of the bottom layer film](image-url)
2.2. Extraction of Material Properties

Since the pull-in voltage is dependent of material properties and geometries of the beam, the Young’s modulus and residual stress of each layer of the composite beam can be extracted by using of a set of pull-in voltages. In this paper, two kinds of beam with different lengths should be designed, and each kind of beam with the same length needs two different types: one has the same width of each layer while the other only has one layer (width of the other layer is zero). 4 pull-in voltages can be measured from these 4 beams. Then, 4 equations can be obtained as follows

\[
\begin{align*}
V_{PI1}(E_1, \sigma_1) - V_{PI1} &= 0 \\
V_{PI2}(E_1, \sigma_1) - V_{PI2} &= 0 \\
V_{PI3}(E_1, E_2, \sigma_1, \sigma_2) - V_{PI3} &= 0 \\
V_{PI4}(E_1, E_2, \sigma_1, \sigma_2) - V_{PI4} &= 0
\end{align*}
\]

(9)

where \(E_1, E_2, \sigma_1, \sigma_2\) are the Young’s modulus and residual stress of each layer to be extracted, \(V_{PIi}(i=1, 2, 3, 4)\) are the function of \(E_1, E_2, \sigma_1, \sigma_2\) given by Eq.(9), \(V_{PIi}(i=1, 2, 3, 4)\) are the measured pull-in voltages. Material properties can be calculated by using the Newton iteration and least-square method.

3. Experiments and Testing

Test structures were fabricated in IME of PKU by surface micromachining technology. Fabrication process is shown in Figure 3. The top layer is Al, and the bottom layer is polysilicon. 5 kinds of fixed-fixed beam with different lengths (300µm, 420µm, 550µm, 700µm, 850µm) were fabricated. The undeformed gap is 2.0µm, the width and thickness of polysilicon are 20µm, 2µm, respectively, the width and thickness of Al are 20/0µm, 0.8µm, respectively. For surface machined beams with non-ideal compliant supports are not suitable for the model, here multi-cup style anchor were fabricated. Parts of test structures are shown in Figure 4. Multi-cup style anchor is shown in Figure 5.

![Figure 3. Fabrication process](image)

![Figure 4. Parts of test structures](image)

![Figure 5. Multi-cup style anchor](image)

The experiment set-up for the pull-in measurement is shown in Figure 6. A TZ-103 Manual Probe Station and a HP4145B Semiconductor Parametric Analyzer were used to measure pull-in voltages of the test structures. The HP4145B was programmed to slowly ramp the voltage at 1 volt/second over a specified voltage range until pull-in was detected on the HP4145B I/V screen output interface as a sudden step in the current. One measured pull-in voltage by HP4145B Semiconductor Parametric Analyzer is shown in Figure 7. Figure 8 is the measured pull-in voltages of the beam whose widths are both 20µm of two layers. The ramp speed of 1 volt/second is slow enough to insure no dynamic effects during the bending of the test structures. The test structures were maintained in their static regime during the voltage ramp.
By using of geometric dimensions and measured pull-in voltages, the Young’s modulus and residual stresses are solved simultaneously by Eqs.(8),(9). For the beams with two different lengths, there are four corresponding test structures. The measured four pull-in voltages are used to extract the Young’s modulus and the residual stresses of each layer. In our design, there are beams with four different lengths, and hence, there are six different sets of pull-in voltages. The results are as follows: the Young’s modulus of polysilicon is 165GPa±5GPa, the residual stress of polysilicon is 38MPa±2MPa, the Young’s modulus of Al is 55GPa±3GPa, the residual stress of Al is 7.7MPa±3MPa.

The optical method was used to measure the maximum displacement of the composite fixed-fixed beam. Figure 9 is the fringe projection figure of the beam by Micro Fringe Projection System, Figure 10 shows the bending of the beam when a DC voltage of 22v was applied to a bilayer fixed-fixed beam with the length of 550µm.
When the same voltage was applied to the same test structure, the maximum displacement of the beam (0.25µm) was simulated by Coventorware with the measured material properties, the error between the optical method (0.24µm) and simulation result is 4.2%.

According to the obtained Young’s modulus and residual stress, residual stain of polysilicon is about: $230 \times 10^6$, compared with the residual stain of polysilicon read by bent beam (See Figure 11) fabricated in the same process: $220 \times 10^6$, they agree with each other well.

![Figure 11. The bent beam](image)

### 4. Conclusions

This paper presents an extended model of pull-in voltage by finite-difference method (FDM) for a composite fixed-fixed beam, which can solve the influence of residual stress along beam width to the pull-in voltage. Then Young’s modulus and residual stresses of each layer for composite beam can be obtained by sets of fixed-fixed beams. And fixed-fixed surface machined beams with multi-cup style anchor were fabricated to improve boundary condition. Validation and accuracy of the extracting method have been verified by FEM simulation and experiments.

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