MEMS education: design, fabrication, and characterization

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ABSTRACT

For more than two decades, intensive worldwide MEMS research and development have led to widespread applications of MEMS-based devices in consumer, industrial, and military products. Harnessing of MEMS technology enabled the birth of pressure sensors, accelerometers, gyroscopes, print heads, optical switches for rapid communications and, recently, the bio-chips for life science applications. Successful design of a MEMS device requires a high level of fabrication knowledge and a dedicated research effort to find a suitable process sequence for fabricating it and, therefore, demands the personnel with specialized training in leading edge MEMS technologies. The MEMS educational program at WPI provides our undergraduate and graduate students in design and manufacturing engineering with critical high-level skills and knowledge in MEMS technology. The MEMS course curriculum has been developed to build up expertise in MEMS design, analysis, fabrication, and characterization. It also emphasizes hands-on student access to equipment for laboratory experiments and demonstrations, with support of a newly-built cleanroom facilities for silicon-based materials and photolithography, including characterization tools such as SEM, AFM, profilometer, optoelectronic holography (OEH), and optical microscopy. This paper describes MEMS multidisciplinary education at WPI and illustrates it with representative examples.

Keywords: MEMS education, design, fabrication, characterization, OEH.

1. INTRODUCTION

Microelectromechanical systems (MEMS), which has evolved out of the microelectronics industry in the past 30 years, is a new chapter of microelectronics and it is considered a big design and manufacturing field of current interest. In the U. S. applications of MEMS range from pressure sensors in automobile industry, to RF MEMS in wireless communications, to new uses of MEMS as monitoring devices in medical care [1]. Also very significant are micromirrors, such as those produced by Texas Instruments, which are used in projection devices and flat-screen TVs [2]. Such applications depend on cost, size, and user-friendly advantages inherent in MEMS.

MEMS technology essentially shrinks a machine, or an instrument, onto a silicon chip, often adding "smart" capabilities. MEMS allows complex electromechanical systems to be manufactured using batch fabrication techniques, decreasing the cost and increasing the reliability of sensors and actuators to equal those of integrated circuits [3]. MEMS represents one of the fastest-growing technology areas, at this time, but there exist obstacles which hinder even wider applications of MEMS. Companies that wish to explore potential of MEMS have rather limited options for prototyping or manufacturing of devices, and have no capability or have a minimal expertise in microfabrication technology. Few companies will build their own fabrication facilities because of high initial investment. In addition, designers of MEMS need adequate level of fabrication knowledge and a dedicated research effort in order to develop successful processes. Therefore, it is extremely important to carry out fundamental MEMS research and education in universities, at both the undergraduate and the graduate levels, to
students with, at least, fundamentals of all aspects in the development process of MEMS products including, but not limited to, design, analysis, fabrication, packaging, test, and characterization [4].

This paper presents a representative project that our students perform to learn, in a coordinated manner, rudimentary aspects of design, analysis, modeling, fabrication, and characterization of MEMS. In this project (at this time) a surface micromachined (SMM) cantilever is utilized for resistive type RF MEMS switches [5]. Design of a MEMS cantilever is addressed first with electrical and mechanical considerations. Then, fabrication processes are reviewed. Finally, characterization methodologies are presented for determining electrical and mechanical parameters quantifying performance of a finished device.

2. DESIGN OF A MEMS CANTILEVER

Based on their topologies, RF MEMS switches can be grouped into two categories [6]: (1) membrane-type, i.e., capacitive, and (2) cantilever-type, i.e., resistive. In this paper, we consider a cantilever-type RF MEMS switch configuration, Fig. 1. Samples considered herein were fabricated from silicon and have characteristic dimensions of the active length, \( L \), the thickness, \( h \), the width, \( b \), the contact gap distance \( d_g \), and the separation between the electrodes, \( d_o \).

![Fig. 1. RF MEMS switch: cantilever configuration, electrical traces were omitted for simplicity.](image)

2.1. Analytical model of a RF MEMS switch

A cantilever of active length \( (L) \) is fabricated parallel to a substrate in such a way that separation between the electrodes (one electrode is on the bottom of the cantilever and the other is on the top of the substrate) \( d_o \) is greater than the contact gap distance \( (d_g) \). The values of \( d_o \) and \( d_g \) are based on a relationship defining instantaneous distance \( (d_o-d_g) \) between the electrodes, as the switch is being activated, and the corresponding value of the activation voltage, \( V(d) \), which is a function of the cantilever deformation \( d \) [7,8], i.e.,

\[
V(d) = (d_o - d) \sqrt{\frac{2kd}{\varepsilon_o \varepsilon_r A_e}}.
\]

In Eq. 1, \( \varepsilon_o \) is the permittivity of free space, \( \varepsilon_r \) is the relative permittivity of the medium between the electrodes, \( A_e \) is the area of the electrodes defined as \( L_e b_e \), and \( k \) is the spring constant of the cantilever defined as

\[
k = \frac{Ebh^3}{4L^3},
\]

where \( E \) is the modulus of elasticity of the material of the cantilever, while \( L, h, \) and \( b \) are its length, thickness, and width, respectively.

2.2. Dynamic response of a RF MEMS switch

Response speed of a RF MEMS cantilever contact can be estimated using fundamental undamped resonance frequency, \( f_o \), defined as [9]

\[
f_o = \frac{1}{2\pi} \sqrt{\frac{L}{L^2} \sqrt{\frac{35 E}{33 \rho g_c}}},
\]

(3)
where $\rho$ is the density of a cantilever material, $g_c$ is the gravitational conversion constant, and other parameters are as previously defined. Phenomenological relationship [10] corresponding to the explicit Eq. 3 is

$$f_0 = f_0(h, L, E, \rho, g_c),$$

(4)

based on which partial differential representation of uncertainty [11], $\delta f_0$, in the resonance frequency can be expressed as

$$\delta f_0 = \left[ \left( \frac{\partial f_0}{\partial h} \delta h \right)^2 + \left( \frac{\partial f_0}{\partial L} \delta L \right)^2 + \left( \frac{\partial f_0}{\partial E} \delta E \right)^2 + \left( \frac{\partial f_0}{\partial \rho} \delta \rho \right)^2 + \left( \frac{\partial f_0}{\partial g_c} \delta g_c \right)^2 \right]^{1/2},$$

(5)

where $\delta$ represents the uncertainties and $\partial$ represents the partial derivatives.

3. FABRICATION OF A MEMS CANTILEVER

Surface micromachining (SMM) is, at this time, one of most popular methods for fabrication of MEMS. It consists of deposition and etching of structural and sacrificial layers (thin films) [1,4]. Simple microstructures (beams, gears, membranes, etc.) and complex microdevices (actuators, motors, and sensors) are fabricated on top of a silicon substrate/wafer. There are three key challenges in fabrication of microstructures using SMM: (1) control and minimization of stress and stress gradients in the structural layer to avoid bending or buckling of the released microstructure [12], (2) high selectivity of the sacrificial layer etchant to structural layers and silicon substrate, and (3) avoidance of stiction of a released microstructure to a substrate.

A representative process for SMM of a cantilever is shown in Fig. 2. A sacrificial layer of SiO$_2$ is deposited on a surface of a silicon wafer. Two layers of poly-Si and ferromagnetic alloy are then deposited and patterned using dry etching. The wafer is etched to remove the sacrificial layer under the cantilever releasing it to let the cantilever be suspended by its anchor, which is attached to the substrate/wafer [3,13].

![Fig. 2. Representative process for surface micromachining of a MEMS cantilever.](image-url)
Control and minimization of stress and stress gradients in a structural layer in order to avoid (or at least to minimize) bending or buckling of a released microstructure is one of the key issues of the SMM fabrication process. There are typically three types of stresses that exist in surface micromachined structures. The first type is a thermal stresses resulting from mismatch of coefficients of thermal expansion (CTE) of materials used. The second type is the residual stress that is inherent in the SMM process; almost all deposition techniques used, at this time, result in inherent residual stresses in films due to fabrication. The third type of stress that could be introduced in thin-film structures is intrinsic stress due to local change of atomic structure because of reaggregation of crystalline grains of materials during deposition.

By choosing appropriate deposition and doping parameters, stress and stress gradients in thin films can be controlled and minimized. In the process of growing silicon dioxide, slow deposition is required in order to minimize stresses in thin films. For deposition of polysilicon, appropriate “growth” rate needs to be chosen to minimize internal stresses and prevent bending and buckling (ideally, polysilicon thin film will be stress free or have a tensile internal stress). Deposition is performed using low pressure chemical vapor deposition (LPCVD). Requirements on deposition rate, thickness, and stress controls lead one to analysis of mechanical properties and film morphology. Morphological range is controlled by deposition and nucleation conditions. Calculations based on single-crystal data and texture functions indicate that fine-grained, randomly oriented films are needed to attain isotropic mechanical properties. This requirement restricts film growth conditions for amorphous-polycrystalline boundary, or for LPCVD silicon, to a temperature range from 575°C to 610°C. Optimization of mechanical properties of thin films is achieved via flow, pressure, and temperature control. This requires fast measurement and control methods. Furthermore, in the final process of removing silicon dioxide and releasing the thin film membrane, in order to avoid bending down or sticking of a membrane to substrate, the poly-Si membrane with internal stress that makes it bend (i.e., curve) up during drying can be used. An alternative is to use a rough polysilicon which does not stick. Both solutions lead to specific mechanical properties of the polysilicon membrane which might not be optimal from the operating requirements standpoints [1].

To consider control of a built-in strain in deposited thin films, maximum membrane deflection \(d\) for a loaded plate, which is subjected to built-in strain, is a nonlinear function of the pressure \(p\), the strain \(e\), the length \(l\), the thickness \(h\), the modulus of elasticity \(E\), and the Poisson’s ratio \(\gamma\), and can shown to be [1, 14]

\[
d = \frac{l^4 (1 + p^2) \gamma f(e)}{E h^2}.
\]  

If the strain field is compressive (i.e., \(e < 0\)) bending and buckling may occur. If the field is tensile, membrane deflections will be reduced for a given pressure. Compressive polysilicon can be converted to tensile polysilicon via annealing which converts thin films to a fine-grained form (this involves a volume contraction which causes the tensile field).

4. CHARACTERIZATION AND ANALYSIS OF MEMS CANTILEVERS

Education in analysis and characterization of MEMS addresses measurement and testing of MEMS components for determining electrical and mechanical characteristics, and reliability and failure analysis to study performance of MEMS components. Measured results are correlated with analytical and computational results, subject to corresponding uncertainty analysis for determining performance of a specific component.

4.1. OEH characterization of strain/deformation of MEMS cantilevers

Characterization of strain/deformation in surface micromachined MEMS cantilever is based (in our approach to education) on optoelectronic holography (OEH) methodology, which provides quantitative real-time whole field imaging and allows measurements of displacements and deformations with sub-micrometer accuracy [15-17].

The OEH configuration, Fig. 3, leads to formation and acquisition of phase stepped interference images, and processing of these images to obtain displacements and deformations of objects that are being investigated [18].
In Fig. 3, a laser beam is directed into an acousto-optic modulator (AOM) and then into a single-mode optical fiber. Output of the fiber is collimated by a collimating illumination lens subsystem (C). Resulting light field is then divided into reference and object beams by a beam splitter (BS). A reference component, produced by the BS, is directed towards a PZT actuated phase step mirror (M) and back to the beam splitter. The object component is directed towards the object (O), which in this case is a MEMS cantilever being studied, and is reflected back to the beam splitter. The two beams recombine at the BS and are imaged by a long working distance microscope objective (L) onto a sensing element of a CCD camera, which records resulting interference patterns. The patterns are transferred to a system computer for subsequent image processing and quantitative analysis.

Therefore, from an observation point, two intensity distributions, transmitted by the long working distance microscope (L) are viewed: one of light reflected from a MEMS and the other arising from reflection off the reference mirror. These two light beams recombine and interfere with one another and the resulting interference intensity patterns are acquired by the camera (CCD), and can be expressed as

$$I_i(x,y) = 2I_0(x,y)[1 + \cos(\phi(x,y) + \theta_i)], \quad i = 1,2,\ldots,5, \quad \theta_i = \frac{(i-1)\pi}{2},$$

(7)

where $I_i(x,y)$ is the light intensity at each pixel of the $i$th image, $I_0(x,y)$ is the average light intensity, $\phi(x,y)$ is the unknown phase, and $\theta_i$ is the known phase step introduced between successive interferograms in a given recording sequence.

According to Eq. 7, a recording sequence consists of 5 interferograms between which phase steps of $\pi/2$ radians are introduced. These phase steps are applied in the reference beam with the mirror M, between acquisition of sequential images. The images in a given sequence record the same state of a MEMS cantilever being studied, the only parameter that varies is $\theta_i$, which changes in a stepwise fashion.

For determination of deformations from the sequence of images described by Eq. 7, optical phase is computed as

$$\phi(x,y) = \arctan\left\{\frac{2[I_4(x,y) - I_2(x,y)]}{2I_4(x,y) - I_2(x,y) - I_5(x,y)}\right\}.$$

(8)

Equation 8 yields spatial distribution of wrapped phase. This wrapped phase-map is then unwrapped to produce a continuous phase-map at each point on a studied MEMS cantilever. The continuous phase can, in turn, be used to determine spatial distribution of differences in the optical path, $OP(x,y)$, traversed by the object and reference beams, i.e.,

$$OP(x,y) = \frac{\lambda}{2\pi} \phi(x,y),$$

(9)
where $\lambda$ is the wavelength of the illumination light used in a specific OEH setup.

Finally, using Eq. 9, deformations $z(x,y)$ of a MEMS cantilever can be determined to be

$$z(x,y) = \frac{OP(x,y)}{2}.$$  \hspace{1cm} (10)

Equation 10 yields spatial distribution of deformations of a MEMS cantilever beam.

### 4.2. Determination of material properties

Measurement of properties of MEMS materials is a very important issue and can be solved using the OEH methodology. In this paper, we use prismatic cantilever beam-like samples, Fig. 4, which are excited dynamically to vibrate at their resonance frequencies. Then, we record OEH images of resonating test samples. Finally, using these images and the parameters defining experimental conditions under which the images were recorded, we determine the modulus of elasticity of materials out of which the samples were made [19].

![Fig. 4. Geometry of test samples used in this study.](image)

It can be shown [13] that the modulus of elasticity ($E$) of a material can be determined to be

$$E = 4\pi^2 \frac{f_i^2 L^4 m}{\beta_i^4 I},$$  \hspace{1cm} (11)

where the subscript $i$ indicates the mode number, $f$ is the resonance frequency, $L$ is the active length of a sample, $m$ is the mass per unit length of a sample, $I$ is the area moment of inertia, and $\beta$ is the parameter characterizing the specific mode with the first three being as follows:

$$\beta_1 = 1.8751,$$

$$\beta_2 = 4.6941,$$

$$\beta_3 = 7.85476.$$  \hspace{1cm} (12)

The mass per unit area, appearing in Eq. 11, is defined as

$$m = \rho A \equiv \rho bh,$$  \hspace{1cm} (13)

where $\rho$ is the material density, while $b$ and $h$ are the width and thickness, respectively, of a test sample, Fig. 4. Furthermore, the area moment of inertia is defined as

$$I = \frac{bh^3}{12},$$  \hspace{1cm} (14)

with $b$ and $h$ as defined above.
Since all parameters used in Eqs 11, 13, and 14 have tolerances, or uncertainties, associated with them, the resulting $E$ will also have an uncertainty, $\delta E$. This overall uncertainty in the modulus of elasticity can be determined by, first, writing fundamental equations, corresponding the Eqs 11, 13, and 14, as

$$E = E(f, L, m, \beta, l),$$  \hspace{1cm} (15)

$$m = m(\rho, b, h),$$  \hspace{1cm} (16)

and

$$I = I(b, h),$$  \hspace{1cm} (17)

respectively. Then, the RSS-type uncertainty [10,11] in $E$ can be determined by differentiation of Eq. 15 to obtain

$$\delta E = \left[ \frac{\partial E}{\partial f} \delta f + \left( \frac{\partial E}{\partial L} \delta L \right)^2 + \left( \frac{\partial E}{\partial m} \delta m \right)^2 + \left( \frac{\partial E}{\partial \beta} \delta \beta \right)^2 + \left( \frac{\partial E}{\partial l} \delta l \right)^2 \right]^{1/2},$$  \hspace{1cm} (18)

where $\delta f$ indicates uncertainties in the primary parameters while $\delta m$ and $\delta l$ are defined, based on Eqs 16 and 17, as

$$\delta m = \left[ \left( \frac{\partial m}{\partial \rho} \delta \rho \right)^2 + \left( \frac{\partial m}{\partial b} \delta b \right)^2 + \left( \frac{\partial m}{\partial h} \delta h \right)^2 \right]^{1/2}$$  \hspace{1cm} (19)

and

$$\delta l = \left[ \left( \frac{\partial l}{\partial b} \delta b \right)^2 + \left( \frac{\partial l}{\partial h} \delta h \right)^2 \right]^{1/2},$$  \hspace{1cm} (20)

respectively.

The mode shapes, $z_i(x)$, are described by [10]

$$z_i(x) = \cosh \left( \frac{\beta_i}{L} x \right) - \cos \left( \frac{\beta_i}{L} x \right) - \gamma_i \sinh \left( \frac{\beta_i}{L} x \right) - \sin \left( \frac{\beta_i}{L} x \right),$$  \hspace{1cm} (21)

where $\gamma_i$ for the first three modes is defined as

$$\gamma_1 = 0.734096,$$

$$\gamma_2 = 1.018467,$$

$$\gamma_3 = 0.9999224.$$  \hspace{1cm} (22)

### 4.3. Computational solution

Computational solution is based on FEM formulation, which can be expressed as [20]

$$\{F\} = [K] \{r\},$$  \hspace{1cm} (23)

where $\{F\}$ is the vector of global nodal forces, $\{r\}$ is the vector of global nodal displacements, and $[K]$ is the assembled system global stiffness matrix [20,21], which results in a number of matrix operations and calculations.
4.4. Experimental solution

Experimental solution, in this study, is obtained using optoelectronic holography (OEH).

In order to determine the modulus of elasticity \((E)\) optoelectronic holography (OEH) was used in this study. OEH images of test samples under a variety of loading conditions were recorded, from which deformations as functions of position on the sample, subjected to a specific load condition, were determined.

The deformations, determined experimentally with nanometer accuracy, were then correlated with the computationally obtained results. The degree of correlation was based on the analytical model of the corresponding uncertainties. This model builds on partial differential equations relating specific material property to the sample geometry, its dimensions, boundary conditions, loading conditions, and fabrication tolerances. In this way, we determine the material properties with high accuracy and precision, using micron-sized samples, and also estimate how good these properties are.

4.5. Results and discussion

The test samples were made using MEMS fabrication methodology. The active length of the samples ranged from 100 \(\mu m\) to 450 \(\mu m\). Typical analytically determined resonance frequencies for these samples, as functions of length along the sample, are shown in Fig. 5. For measurements performed during this study, the test samples were excited at frequencies up to 2 MHz.

![Fig. 5. Resonance frequencies, MHz, for the first two modes.](image)

Representative results from analytical, computational, and experimental investigations, for the 300 \(\mu m\) long samples, resonating at 157 kHz and 970 kHz, are shown in Figs 6 and 7, respectively.

Based on the results shown in Figs 6 and 7, as well as on other similar results for different test conditions than those used to produce Figs 6 and 7, the average modulus of elasticity of the test sample material was determined to be 160 GPa. Then, using the uncertainties in the parameters defining Eq. 11, the overall uncertainty in the modulus of elasticity was determined, from Eq. 18, to be

\[
\delta E = \pm 1.8 \text{ GPa}.
\]  

Therefore, relative, percentage overall uncertainty, \(\%\delta E\), was calculated to be 1.1\%. It should be noted that these results relate only to the samples and the test conditions used in this study. Other samples and/or other conditions may lead to different results. The methodology should be investigated to determine influence, if any, of test conditions on the results [22].
This paper addresses a sequence of courses relating to education of design, fabrication, and characterization of MEMS, with a typical project considering a dynamics of cantilever contacts for resistive MEMS switches [9]. MEMS education involves analytical, computational, and experimental investigations, and our students are expected to attend lectures, conduct computational simulations, perform laboratory experiments, document their results, and prepare a project report. More complicated MEMS components/systems will be introduced in the future for students to develop analytical and computational models, optimize fabrication processes, and characterize finished products using the state-of-the-art (SOTA) experimental and computational techniques.

5. CONCLUSIONS AND FUTURE WORK

6. REFERENCES

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