Dynamic characterization of high frequency MEMS/NEMS using Raman spectroscopy

Dewanto R.S., Hedley J., Gallagher B.J., Hu Z.X.
School of Mechanical and Systems Engineering
Newcastle University

Abstract
This paper proposes the development of a Raman spectroscopy system which has capabilities to characterize the motion of high frequency MEMS/NEMS and devices without surface features. Raman spectroscopy is being increasingly used as a technique to characterize such devices to overcome inconveniences of other optical measurement techniques which include laser vibrometer, stroboscopic imaging, interferometry, electronic speckle pattern interferometry, laser holography and blur synthesis. Problems with these techniques are that they are either limited in frequency to less than 30 MHz, require the measurement to be performed along the line of motion or need to utilize a surface feature. A cantilever beam, as the most common basic geometry of a MEMS/NEMS structure is used to evaluate the basic dynamic parameters of a microstructure. Mode shapes of vibration, natural frequencies and strain maps for such structures are determined by using analytical calculations and finite element analysis. A model of a cantilever with large end mass is used to calculate strain components whilst mode shape and natural frequency are obtained using Rayleigh’s calculation method. In addition, a 3D anisotropic structural element is used in Ansys to confirm the analytical calculations. The next step is to design an experiment to verify these models.

1. INTRODUCTION

The importance of suitable optical techniques development for characterization of static and dynamic properties of MEMS/NEMS is acknowledged. Appropriate techniques either in device performance tests, reliability assessments or fabrication problem identifications can assist to faster designs and development times of such devices. General requirements for an optical MEMS characterization system are mentioned by Bossebouf and Petitgrand [1]; these include abilities to perform both static and dynamic measurements as well as out-of-plane and in-plane measurements with a high sensitivity and a large dynamic measurements range.

For the last decade, there has been much effort dedicated on MEMS characterization techniques. Particular advantages of those characterization techniques for dynamic micro and nanoscale devices has been reported by researches, such as high sensitivity
(2), fast and simple characterization (3), direct on wafer testing with a number of single elements in parallel (4), wide measurements range (4-6), and related limitations. Examples include laser Doppler vibrometer (2), stroboscopic phase-shifting interferometer (5), electronic speckle pattern interferometry (4), laser TV holography (6) and blur synthesis (3).

Problems with these techniques are that they are either limited in frequency to less than 30 MHz, require the measurement to be performed along the line of motion, need to utilize a surface feature or not straightforward. In addition, in reliability studies of MEMS/NEMS, these techniques can only give an indication of the mechanism of device failure once it has occurred or limited only applicable to a device designed to fail at a certain point (7).

Raman spectroscopy, which is being increasingly used for MEMS/NEMS dynamic characterization, has capabilities to determine material properties, indicate crystallinity and strain measuring within the lattice. This characterization method had been utilized to measure local mechanical stresses (8-12) and to produce a submicron stress map of a plastically deformed area of a silicon wafer (8). Recently, dynamic stress quantification (9), motion and strain levels measurement (10), mode shape and failure analysis (7) in dynamic micromechanical structures has been shown.

Recent advances in instrument technology have simplified the equipment and reduced the problems substantially. These advances, together with the ability of Raman spectroscopy to examine dynamic structures of MEMS/NEMS, have led to a rapid growth in the application of the technique. In addition, modern Raman spectroscopy is simple, variable instrument parameters are few, spectral manipulation is minimal and a simple interpretation of the data may be sufficient. However, utilizing Raman spectroscopy in this field is an underdeveloped technique, with much important information often not used or recognized (11). The aim of this study is to propose a development of Raman spectroscopy methods to increase its reliability in a high frequency MEMS/NEMS dynamic characterization.

2. BACKGROUND

2.1. Raman Spectroscopy Principles

The phenomenon of inelastic scattering of light was first postulated by Smekal in 1923 and first observed experimentally in 1928 by Raman and Krishnan. Since then, the phenomenon has been referred to as Raman spectroscopy (11).

When light interacts with matter, the photons which make up the light may be absorbed or scattered, or may not interact with the material and may pass straight through it. In Stokes–Raman scattering the incident photons coupled with phonon-induced changes in the polarizability of the solid, causing the scattered photons to lose a quantum of lattice energy or phonon relative to the incident photons. Regarding to the conservation of momentum, only phonons close to the \( \Gamma \)-point of the Brillouin zone are excited in such processes (12). Moreover, the frequency \( \omega \) of the excited
phonons is described as [13]:

\[ \omega = \frac{1}{\lambda_i} - \frac{1}{\lambda_s} \]  

(1)

where \( \lambda_i \) and \( \lambda_s \) are the wavelength of the incident and scattered radiation respectively. The Raman shift is that described as the value of \( \omega \) and is generally have a unit of cm\(^{-1}\). Then the Raman spectrum can be produced as a graph of the scattered intensity as a function of the Raman shift and contains information about the physical and chemical characteristic of the solid. A presence of mechanical stress/strain can cause this frequency of Raman modes to change, and lifts their degeneracy. Tension will change the peaks of Raman shift to a lower wavenumber than the stress free frequency, in contrary a Raman shift higher than stress-free frequency indicates compressive stress [14].

A direct measure of strain of a microstructure can be determined using Raman spectroscopy. For a cubic diamond lattice crystalline structure of silicon, Loudon [15] derived three Raman tensors; in a crystal coordinate system \( x = [100] \), \( y = [010] \) and \( z = [001] \) they are given by:

\[
R_x = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & d \\ 0 & d & 0 \end{pmatrix}, \quad R_y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad R_z = \begin{pmatrix} 0 & d & 0 \\ d & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}
\]  

(2)

For back scattering from a (001) surface, \( R_x \) and \( R_y \) correspond to scattering by transverse optical phonons (\( TO \)), polarized along \( x \) and \( y \) respectively, and \( R_z \) corresponds to scattering by longitudinal optical phonons (\( LO \)), polarized along \( z \). For an unstressed condition, the corresponding three degenerate Raman-active optical phonon modes of single crystal silicon have the same frequency of about 520.8 cm\(^{-1}\). Then the total Raman intensity is given by:

\[ I = |p_x R_x p_i|^2 \]  

(3)

Where \( p_i \) and \( p_s \) are the polarizations of the incident laser and the collected scattered photons respectively. All quantitative measure of all unknown stress states can be revealed by evaluating particular crystal orientation and monitoring various scattering polarization [16].

2.2. Raman spectroscopy utilisations for MEMS/NEMS dynamic characterization

The change of Raman shift had been used to characterize static mechanical stresses and strain levels due to microindented [17], external loading [18] or boron doping in silicon wafer [19]. Moreover, by using a four point bending rig to determine the phonon frequency change as a function of wafer curvature strain in one dimensional, a Raman/strain calibration value had been determined. A Raman shift–volumetric
strain response coefficient was determined as $5.2 \times 10^4$ cm$^{-1}$/volumetric strain [18].

Recently Raman spectroscopy method had been extended to measure the dynamic strain. When a device vibrates, the strain within it will vary according to the vibration phase. Unfortunately, MEMS devices like microresonator work at frequency about 10 KHz that in case of a continuous-wave laser, Raman spectroscopy will not be able to collect the information of the dynamic stress at any point perfectly according to 30 ms CCD response time. In order to solve this problem, a high-frequency modulation technique is employed [9]. The Raman laser is modulated in synchronized frequency to the device vibration. However, according to Hedley et al [7] this high frequency modulating method is ultimately limited since a narrow laser linewidth must be maintained for the measurement.

Utilizing laser modulation, Hu et al [10] synchronize the vibrating device and strobe the Raman laser at a fixed phase of motion. Then the induced strain is captured at that phase. To obtain the strain as a function of time of the device, the phase difference between the device motion and the Raman laser is sequentially stepped through $2\pi$. The captured Raman profile at two phases of the device motion and plotted peak positions of complete phases during resonance is showed in figure 1 and figure 2 respectively.

A continuous Raman laser for dynamic characterization of the device has been demonstrated to overcome figured problems in modulated Raman laser [7, 10]. Strain is determined by evaluating the broadening of a Raman profile shown in figure 3 since there are no phase data available in this technique, a fitting procedure and modeling should be used to determine the strain as a function of time.

3. INITIAL SYSTEM DESIGN

To carry out the basic dynamic parameters of a microstructure, a cantilever beam, as the most common basic geometry of a MEMS/NEMS structure is used. Mode shapes of vibration, natural frequencies and strain maps for such structures are determined by using analytical calculation and finite element analysis. The test structures are designed to have resonant frequencies between 10 kHz to 1 MHz. This frequency range will allow comparison with laser vibrometry and dynamic surface profilometry available within the laboratory.

3.1. Analytical Model of MEMS

Derived by Hu et al [10], the cantilever beam model is oriented to such that the length, the width and the thickness of the structure will be associated to $x$-axis, to $y$-axis and to the $z$-axis, respectively. And the point of origin of the coordinate system is situated on the middle clamped end of the structure upper surface as shown in figure 4.

The axial strain in a longitudinal fibre of the cantilever due to in-plane bending is given by $\varepsilon_{xx} = y_0 K$, where $K$ is the curvature of the beam and $y_0$ is the position of the
fibre relative to the neutral axis. For large deflections the curvature of the beam is given by:

\[
K = \frac{v'(x)}{[1 + (x')^2]^{3/2}}
\]  

(4)

Where \(v(x)\) is the in-plane deflection of the neutral axis. Since the beam is driven into resonance at its fundamental natural frequency, the deflection may be written in terms of the fundamental mode shape as \(v(x) = \lambda X(x)\) where \(\lambda\) is the amplitude-scaling factor and Rayleigh’s method [20] has been used to obtain the approximate expression for the mode shape and natural frequency:

\[
X(x) = \left(\frac{L - x}{L}\right)^2 - 3\left(\frac{L - x}{L}\right) + 2
\]

(5)

By measuring the deflection \(v(L)\) at the free end of the cantilever and evaluating \(X(L)\), the value of \(\lambda\) may be determined.

The volumetric strain then is given by:

\[
\varepsilon = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}
\]

(6)

in which the Poisson’s ratio is used to calculate the remaining principle strain components. Then a similar argument will be applied to out-of-plane motions.

### 3.2. Finite Element Analysis

Finite element analysis by using ANSYS are performed either to confirm the value of analytical calculation of the model or to make numerical data available for further experiment works.

Natural frequencies of cantilever beams, which have been determined from modal analysis for every geometry and dimensions, will be used to actuate the devices in harmonic analysis. Magnitudes of the harmonic analysis actuating force are chosen therefore such value will deflect the end tip of the models at about 22 \(\mu\) m from its rest position. Maps of strain intensity resolved from these simulations will become a reference for Raman laser measurement points and the volumetric strain will be calculated from these results.

An anisotropic solid elastic 3D element type is used to perform out-of-plane simulations. In simulations, the device is actuated in same directions via its fixed clamp as it will be performed in the experiments.
3.3 Result and discussion

Finite element analysis indicating natural frequencies of the device is shown in the table below:

Table 1. The 5 natural frequencies of the device

<table>
<thead>
<tr>
<th>Natural frequency</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>62750</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>83952</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>0.19724E+06</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>0.55625E+06</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt;</td>
<td>0.73115E+06</td>
</tr>
</tbody>
</table>

These natural frequencies of such device geometry meet the required range that either comparison using conventional optical measurement or twisted mode of motion can be performed. The strain pattern present during 5 modes of vibration can be seen in figure 6.

In the in-plane simulation, the model is actuated to y-direction at its 1<sup>st</sup> natural frequency. The strain intensity of the device is linearly increased. The increment is started from a 30 μm distance in x-direction from the fixed end clamp in upper and surface of 4397 μ strain to a maximum strain intensity of 8700 μ strain at 3 μm distance. A harmonic drive force of 1.1 x 10<sup>-5</sup> N is applied to the device to oscillate it at amplitude of 21.3 μm.

Moreover, in the out-of-plane simulation, the device is actuated to z-direction at its 1<sup>st</sup> natural frequency; the strain intensity of the device is linearly increased. The increment is started from a 30 μm distance in x-direction the fixed end clamp in the upper and lower surface of 4396 μ strain to a maximum strain intensity of 8700 μ strain 3 μm distance. Figure 6 shows the pattern of the maximum strain intensity. To deflect the device free end at maximum value of 21.3 μm, a harmonic drive force of 1.9 x 10<sup>-7</sup> N is applied.

Both in-plane and out-of-plane actuation drives the device to produce maximum strains intensity in the same positions but have different values of 1.1 x 10<sup>-5</sup> N and 1.9 x 10<sup>-7</sup> N to deflect the free end to the same magnitude of 23.1 μm.

Since the maximum strain intensity is occurred on both upper and lower surface around the fixed end of the device, dislocation may be initiated either the top or bottom surface. A Raman mapping of each face would be required to predict the precise initiation point.
3.3. **Description of the system**

An arrangement of a ‘superhead’ FHR1000 from Horiba Jobin Yvon Raman system will be used to perform the experiment. A Lynx tunable Littrow external cavity diode laser from Sacher Lasertechnik together with an MLD1000 as its controller are used to produce a tuned of 632.8 nm beam which will be directed to the ‘superhead’ using two mirrors. To focus this laser light to a spot size of 4 μm, a 50x long working distance objective is used.

To actuate the device to move either in-plane or out-of-plane a piezo disk from Morgan Matroc is utilized. The device signal driver will be amplified using a TEGAM Model 2350 high voltage amplifier. It will also need additional circuitry to protect from voltage spikes. Using a XYZ staging for attaching the device makes positioning and laser focusing available. Camera systems within the superhead allow beam position visualization. Using a liquid nitrogen cooled CCD, the Raman signal is returned into a spectrometer through an optical fiber.

Schematic arrangement of this system can be seen in figure 5.
LIST OF REFERENCES


FIGURES

Figure 1. Raman profile obtained at two phases of the device’s motion

Figure 2. Peak position of the silicon Raman peak during resonance.
Figure 3. Raman profile broadening taken from points highlighted in the inset [7].

Figure 4. Schematic model of the device
Figure 5. Schematic of the experimental setup for the modulated Raman measurements

Figure 6. Maximum strain intensity at 1st mode vibration
Figure 7. Strain pattern indicated present during 4 modes of vibration