Abstract—This paper reports on the use of Raman spectroscopy to characterize the motion of high frequency MEMS/NEMS. The change in Raman signal from a device driven into resonance at 101 KHz was used to indicate the mode shape at that frequency and the strain induced during the oscillation. The results are in good agreement with a finite element model of the structure. The results were also used to predict device failure during excessive vibration.

Keywords—MEMS characterization; Raman spectroscopy; failure analysis

I. INTRODUCTION

Optical characterization techniques are recognized as important in characterizing dynamic micro and nanoscale devices during their development and much progress has been made in recent years on the development of such techniques. For example include utilizing laser vibrometry and optical profilometry as MEMS workstations [1] and constructing a measurement system capable of interferometry, stroboscopic imaging and image processing [2]. Systems such as these are now commercially available for MEMS metrology. However problems with these techniques are that they are limited in frequency to less than 30 MHz (making them unsuitable for characterization of ultra high frequency MEMS resonators) and either require the measurement to be performed along the line of motion (i.e. 1 dimensional) or by utilizing a surface feature (i.e. an edge). These techniques are also used to monitor reliability however they are limited as either the device is designed to fail at a certain point [3] or, for a typical device, they can only give an indication of the mechanism of device failure once it has occurred.

Raman spectroscopy is a technique that is developing in its use to characterize MEMS/NEMS as it may be utilized to give a direct measure of strain in these microstructures. The crystalline structure of silicon results in a sharp triply degenerate Raman peak centered on 520.8cm⁻¹ and whose Raman tensors, \( R_j \), are given by [4]:

\[
TO_x = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & d \\
0 & d & 0
\end{pmatrix}, 
TO_y = \begin{pmatrix}
0 & 0 & d \\
0 & 0 & 0 \\
d & 0 & 0
\end{pmatrix}, 
LO_z = \begin{pmatrix}
0 & d & 0 \\
d & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}.
\]

Strain induced in the lattice breaks this degeneracy and shifts the peaks [5], tension causing the peaks to move to lower wavenumber. This approach was originally used to characterize static strain levels in microstructures either due to doping [6] or loading [7,8] however it can be extended to characterize the motion of dynamic MEMS/NEMS.

As device vibrates, the strains induced within it periodically vary. Figure 1 shows the strain patterns (obtained via finite element analysis) of a silicon device vibrating in various modes. One option to examine this periodicity in strain is by high frequency modulation of the Raman laser synchronized with the motion of the structure. This was demonstrated by Xue et al [9] however this approach is ultimately limited by the laser modulation frequency as a narrow laser linewidth must be maintained for the measurement. The method proposed here uses a continuous laser, thereby circumventing the problem of the modulation. As the structure vibrates, the Raman peak is broadened. A fitting procedure and modeling is then used to determine the strain as a function of time.

For a measure of all the unknown stress states, particular crystal orientations and scattering polarizations must be considered [10]. For this work, the incident laser polarization, \( p_i \), was (100) and all backscattered light, \( p_f \), was collected. The Raman intensity is given by:

\[
I = |p_R R p_i|^2
\]

and so for the geometry used here, only the longitudinal \( LO_z \) peak was observed. A measure of peak shift shows relative levels of strain in the structure. To obtain an absolute value, this shift must be correlated with the actual strain present. The shift in the Raman peak was shown to correspond to the volumetric strain in the unit cell [5]. A four point bending experiment [7] determined this calibration factor to be 5.2x10⁻⁴ cm⁻¹/volumetric µstrain for the \( LO_z \) photon.

II. METHODOLOGY

A series of test structures were designed with fundamental resonant frequencies between 10 KHz to 1 MHz. Designing the test structures within this frequency range allowed comparisons to be made with conventional optical metrology techniques. The devices were asymmetry in their design as this allowed for easy mechanical actuation of in-plane, out-of-plane and twisting modes of vibration via a piezo actuator.

The devices were fabricated from <100> SOI with a 16µm device layer and a 3µm sacrificial oxide layer at the Scottish Microelectronics Centre, Edinburgh. The fabrication process consisted of a lithography step, followed by a DRIE through the device layer and finally a HF etch to remove the sacrificial oxide. 5µm×5µm etch holes were placed every 20µm in the
devices to facilitate the release step. The fabricated devices are shown in Fig. 2.

The experimental setup consisted of a HR800 Jobin Yvon Raman system with a 514nm Ar+ laser source. The device was imaged through a 100X objective, giving a spatial resolution of 1µm. The backscattered signal was directed through the spectrometer before being collected by a CCD camera and saved to a PC. Data points were collected every 0.56 cm\(^{-1}\). The device was mounted on a shear mode piezo actuator to drive the first in-plane mode of vibration. Motorised xy staging was used to allow automated mapping of the device.

Initially, whilst the device was static, a series of Raman spectra were obtained from the root of the device. A Matlab non linear least squares fitting routine was used to fit a Voigt profile to this data, the fitting parameters being Gaussian width, Lorentzian width, peak wavenumber, intensity scaling and background. The device was then driven into resonance with a free end amplitude of 22µm and a sequence of measurements at 2µm intervals were taken at the clamped end of the device, as indicated in Fig. 2. For this data, a profile was constructed from a series of Voigt profiles; each of these Voigt profiles being offset from the unstrained central frequency by \( A_0 \sin(\theta) \) where \( A_0 \) is the maximum peak wavenumber shift during vibration and \( \theta \) ranges from 0 to 2\( \pi \). For this fitting, the Lorentzian width and Gaussian width were held constant with \( A_0 \), peak wavenumber, intensity and background being the fit parameters. Note that the peak wavenumber was fit during this fitting.

![FIGURE 1. FINITE ELEMENT ANALYSIS INDICATING THE STRAIN PATTERNS PRESENT DURING 4 MODES OF VIBRATION.](image1)

![FIGURE 2. THE TEST STRUCTURES WERE DESIGNED FOR EASY MECHANICAL ACTUATION OF ALL MODES. THE STRAIN MEASUREMENTS ON THIS DEVICE WERE TAKEN AROUND THE CLAMPED END. INSERT SHOWS DETAIL OF FILLETING DUE TO FABRICATION TOLERANCES.](image2)
procedure to account for any static strains within the wafer. Fig. 3 shows two Raman spectra, one from a region of low dynamic strain (denoted ‘○’) and one from a region of high dynamic strain (denoted ‘□’). The spread in the profile, $A_0$, was converted from wavenumber to volumetric strain as given in [7].

III. DEVICE MODELLING

A. Analytical

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

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

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 has been used to obtain the approximate expression for the mode shape and natural frequency [11]:

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

By measuring the deflection $v(L)$ at the free end of the cantilever and evaluating $X(L)$ the value of $\lambda$ may be determined. By making use of the Poisson effect, volumetric strain may be calculated from $e = \varepsilon_{ax} + \varepsilon_{gy} + \varepsilon_{gz}$ giving a maximum value of 6800µstrain. This provides a lower estimate for the volumetric strain. The effect of the stress concentration factor, $K_T$, at the root of the cantilever will be to increase the magnitude of the strain components such that $e' = K_T e$, where $K_T$ has the approximate value of 2 [12]. This provides an upper estimate for volumetric strain of 13600µstrain.

B. Finite Element Analysis

For a more detailed modeling of the corner, finite element analysis (using the software package ANSYS) was performed. The device was modeled using a 2D structural solid element. A 1µm fillet radius was used at the clamped end of the device to account for the fabrication tolerances. Figure 4 shows the strain intensity obtained from ANSYS for the device modeled with a vibrating free end amplitude of 22µm. The modeled volumetric strain along the edge of the device increases linearly from 3000µstrain (at a distance of 30µm from the fillet) to 3500µstrain (at 2.6µm) at which point a large volumetric strain concentration develops peaking at 8620µstrain.

IV. RESULTS

A map of the measured volumetric strain was constructed, as shown in Fig. 5, with values ranging from 0 to 3300µstrain. The map, as compared with Fig. 1, clearly indicates an in-plane mode of vibration with a high strain concentration at the fillet. This course mapping shows reasonable agreement with the calculated values. To map the location of possible device failure, a higher spatial resolution Raman map was recorded, as shown in Fig. 6, in the location of the fillet. A maximum strain of 4600µstrain was measured. This is well below the modeled

![FIGURE 3. A MEASUREMENT OF THE BROADENING OF THE Raman PROFILE IS USED TO DETERMINE THE INDUCED STRAIN IN THE DEVICE DURING RESONANCE. MEASUREMENTS SHOWN TAKEN FROM POINTS HIGHLIGHTED IN THE INSET. THE SOLID LINES INDICATE THE FITTED PROFILE.](image)

![FIGURE 4. FINITE ELEMENT ANALYSIS WAS USED TO MODEL THE INDUCED VOLUMETRIC STRAIN WITHIN THE DEVICE WHILST IT WAS DRIVEN AT RESONANCE.](image)
value however the Raman signal is the sum of a 1µm diameter area from the focused laser. By considering a 1µm×1µm area of the finite element calculation around the fillet, the average modeled value of volumetric strain is 5360µstrain which shows much better agreement. The predominant error in the model is from the experimental determination of the amplitude of vibration, this was estimated from a visual blurring of the image during resonance and determined to be 22±2µm. The limit of detection of the broadening of the Raman peak was estimated from the variation in the fitting parameters from unstrained regions of silicon and found to be 30µstrain. The results are summarized in Table 1. It should also be noted the difficulty in determining the precise fillet geometry for the model, this highlights the importance of verifying actual device performance experimental.

As a final experiment, the device was over-driven to induce failure, the failure point occurring as shown in Fig. 7. The failure occurred at the high strain point induced in the fillet region during vibration, as indicated by modeling and the Raman measurements. Note that due to device symmetry, the dislocation may have initiated at either the top or bottom surface of the device. A Raman mapping of each face would be required to predict the precise initiation point.

### Table 1. Comparison of the Experimentally Determined Values Compared with the Model Values. The relatively large error associated with the theoretical values is due to the difficulty in determining amplitude of vibration.

<table>
<thead>
<tr>
<th>Method</th>
<th>Frequency (KHz)</th>
<th>Volumetric strain (µstrain)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical</td>
<td>103.8</td>
<td>6800 ± 620</td>
<td>Rayleigh's method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13600 ± 1240</td>
<td>Concentration factor included</td>
</tr>
<tr>
<td>Finite</td>
<td>97.0</td>
<td>5360 ± 490</td>
<td>1µm² average</td>
</tr>
<tr>
<td>element</td>
<td></td>
<td>8620 ± 780</td>
<td>Peak value</td>
</tr>
<tr>
<td>Experimental</td>
<td>101.3</td>
<td>4580 ± 30</td>
<td>Calibrated from [7]</td>
</tr>
</tbody>
</table>

FIGURE 5. MEASURED STRAIN MAP OF FIRST IN-PLANE MODE. BLACK CROSSES, INDICATING MEASUREMENT POINTS, HAVE A 2µm SPACING.

FIGURE 6. A HIGH RESOLUTION MEASURED STRAIN MAP OF THE FILLET. BLACK CROSSES, INDICATING MEASUREMENT POINTS, HAVE A 500nm SPACING.

FIGURE 7. THE DEVICE FRACTURED DURING EXCESSIVE VIBRATION. POINT OF FAILURE, INDICATED BY THE INSERT, WAS AT THE PREDICTED HIGH STRAIN LOCATION.
V. CONCLUSIONS

This work has demonstrated the utilization of Raman spectroscopy for the characterization of MEMS devices. The technique may be used to determine natural frequency, mode shape and strain contours within the device as it vibrates thereby giving an indication of possible locations of device failure. The results presented here have a measurement resolution of 30 µstrain and, most notably, the technique has an unlimited frequency range making it the first optical characterization technique suitable for ultra high frequency MEMS resonators. As devices become smaller, material homogeneity becomes more critical. This technique is suitable for mapping any inhomogeneity within a device. The technique may be extended to Raman SNOM for higher spatial resolution.

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REFERENCES


