The Response of Micro-scale Devices Subject to High-g Impact Stimuli

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ABSTRACT
Recent advances in MEMS fabrication technology have resulted in a proliferation of microscale mechanical devices, some of which are applied in environments with severe levels of shock. The objective of this paper is to investigate the use of experimental and simulation methods in quantifying the behaviour of representative MEMS devices subject to high-g impact stimuli. Representative micro-cantilevers were analyzed under vibration and shock in order to determine the mechanical properties of single crystal silicon. The characteristic dimensions of the beams were of 100µm in height/width with beam lengths ranging from 5-7mm. Controlled vibration and shock tests were carried out on a modified Hopkinson pressure bar and a vibration table. The experimental approach allowed non-invasive in-situ monitoring of the micro-cantilevers upon impact through Laser Doppler Vibrometry (LDV) and high-speed imaging (HSI). An investigation of the shock response of representative micro-cantilever beams indicates that orientation plays a significant role in their sensitivity to shock due to the planarity of the fabrication technique. Finite element analysis in conjunction with in-situ HSI proved to be a viable non-invasive inverse technique to determine the loci and amplitude of tensile stress within generic micro-scale devices.

KEYWORDS
MEMS, shock, vibration, nano-indentation, finite element analysis

INTRODUCTION
There is a consistent increase in the innovations and applications of miniature, micro- and sub-micron scale devices, however the physical phenomena governing these devices is not fully understood [1]. This is particularly evident in emerging application environments such as military and aerospace, where devices are being subjected to high forces and high strains that can induce mechanical failure at a microscale. Significant improvements in the reliability of MEMS devices have been realized through approaches such as resonance excitation, static deflection loading and design specific on-chip approaches to implement techniques such as electrostatic actuation [2-6]. Developments such as these have equally advanced test procedures and metrology techniques aiding in the correct characterization of material properties and the response of microscale devices. Ozdoganlar et al. [2] investigated a methodology for experimental modal analysis of micro-devices highlighting the deficiency of both test and metrology techniques necessary to quantify the reliability of MEMS. Chang [7] also reported on the importance of reliability in MEMS referencing several commercial applications and telecommunications environments investigated in literature. Even with developments such as these, however, the majority of testing that has been reported in current literature is carried out in static environments where excitation of a given device is relatively deterministic. This trend has partly been due to the limitations of instrumentation and existing techniques but furthermore to enable predictable boundary conditions in static environments which enable higher accuracy when correlating results theoretically [8]. Due to the ongoing commercialization of MEMS, current research emphasis is application and/or device specific, shifting from passive device characterization to active device reliability, as seen with the development of the Texas Instruments Digital Micro-mirror Device [9]. The evident need for reliability characterization of devices - coupled with harsher application environments - has led to a requirement for highly transient dynamic testing of micro-scale devices. There are a select number of methods of producing high amplitude repeatable shock pulses that are capable of exciting micro-scale devices to failure; such as drop tables, ballistics, Hopkinson pressure bars (HPB) and explosives [10-14].
complexity of the test environments for these methods, there are also only a limited range of measurement techniques to realize any quantitative information from a test program. Therefore, when creating a reliability test program, it is necessary to develop measurement techniques that are capable of monitoring the in-situ response of a micro-scale device as well as post analyses techniques to ascertain modes of failure. An inherent advantage of this is the ability to fabricate micro-devices without embedded sensor layers that allow generic characteristics to be quantified for multi-purpose design rules.

When establishing a new test method, material choice and fabrication process also have to be taken into consideration as they play a significant role in the response of a device. Silicon is the dominant fabrication material seen in literature due to its inherent use in MEMS fabrication and also due to the brittle nature of single crystal silicon (SCS) and polycrystalline silicon [8]. Gad-El-Hak [8] proceeds to note that large experimental deviations in basic material properties such a Young’s modulus is due to insufficiently precise models in inverse methods and errors in metrology techniques. Extensive investigation has been carried out in determining the effect of fabrication process on the material properties and it has been shown that different techniques can return different values of Young’s modulus and fracture strength of a device, as seen in Ref. [15]. Research specific to this paper has been carried out on material choice and fabrication process highlighting the effects of each [16]. It was shown that surface flaws from fabrication processes and crystal orientation influenced failure loci and crack propagation direction.

This paper will investigate the effectiveness of high strain rate shock tests on generic SCS micro-cantilevers as a test method for characterizing the response of microscale devices in high strain rate environments. It will also develop metrology techniques for monitoring highly transient events as seen in shock environments. A correlation between the transition from low to high strain rate testing will also be investigated to serve as a supplement to current design rules in predicting the failure modes of devices employed in shock environments.

**FABRICATION PROCESS**

Bulk SCS micro-cantilevers were fabricated from 100mm p-type <100> SCS wafer of 525µm thickness with a primary flat orientation of [110]. The beams had characteristic lengths of 5-7mm with cross sections of 100µm × 100µm. Several of the beams also had proofmasses at the beam tips to influence their response under deflection. Finally each beam type was reproduced with notches of 10% and 40% of beam width to induce failure and/or degradation in the material through stress raisers. Figure 1 shows a front side image of a SCS micro-cantilever sample within a frame for mounting on the test apparatus. The sample shown has 5mm, 6mm and 7mm beams with proofmasses at the beam tips.

![Figure 1. SCS micro-cantilever structure displaying the relative lattice planes and directions](image)

The fabrication process was carried out in 54 run steps consisting of cleaning, inspection and physical steps. A thin film oxide layer was deposited onto the front side and back-side of the wafer and the front-side mask was used to transfer the beam geometry onto the oxide surface by means of photolithography. The patterned oxide layer was then stripped off using reactive ion etching (RIE) and the remaining photoresist was stripped from the front-side. A nitride layer was then deposited both front and back-side by means of low pressure chemical vapour deposition (LPCVD) to act as a barrier for a following potassium hydroxide (KOH) solution wet etch. The back-side mask was then used to pattern photoresist onto the wafer and the oxide/nitride layers were removed using a RIE etch. The remaining photoresist was stripped and a timed anisotropic KOH etch was used to remove 425µm of the SCS to obtain the 100µm beam depth. The nitride layer was then removed and aluminium and polyimide layers were deposited on the back-side to act as an etch stop and support the micro cantilevers while under vacuum respectively. Deep RIE (DRIE) was then used to etch out the beam geometries on the front-side of the wafer. All sacrificial layers were then stripped from the wafer before dicing and cleaning to finish the fabrication process. Table 1 summarises the fabrication procedure into the main physical run steps and shows a wafer cross section during each process step.
Table 1. Fabrication process run steps

<table>
<thead>
<tr>
<th>No</th>
<th>Step</th>
<th>Description</th>
<th>Physical Process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>Variable wet oxide</td>
<td>1µm thick</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Photolithography</td>
<td>8.7µm photosensitive coat - front-side mask exposure</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Shallow oxide etch</td>
<td>Remove oxide to form front-side beam pattern for DRIE</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Photoresist Strip</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>LPCVD</td>
<td>Deposit nitride layer for front-side/back-side KOH protection</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Photolithography</td>
<td>8.7µm photosensitive coat - back-side mask exposure</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Shallow oxide/nitride etch</td>
<td>Remove oxide/nitride to form back-side beam release geometry</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Photoresist Strip</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>KOH etch</td>
<td>back-side KOH wet etch - 425µm depth to define 100µm beam depth</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Nitride removal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Aluminium sputter</td>
<td>6µm Al. sputter on back-side to act as etch stop in DRIE etch</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Polymide support layer</td>
<td>Polymide coat on back-side to support beams under vacuum in DRIE etch</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>DRIE etch</td>
<td>Front-side etch of beam geometry using oxide mask - 100µm depth - 6-10µm/min</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Finishing</td>
<td>Removal of sacrificial layers – Al/nitride/oxide – cleaning</td>
</tr>
</tbody>
</table>

Siemens
SiO₂
Photoresist
Nitride
Aluminium
Polymide

EXPERIMENTATION

This section outlines the progression of experimental and simulation approaches used to characterize the response of the micro-cantilevers. Resonance tests are used at first to characterize the micro-cantilevers in a relatively deterministic environment and provide a basis for developing finite element models. HPB tests are then used to induce high-g impacts on the micro-cantilevers, where experimental data sets are correlated with simulation to determine the stresses present in the micro-cantilevers under deflection.

Resonance Experimental Setup

The resonance testing was carried out on a Polytec Micro-System Analyzer (MSA), as shown in Figure 2. The micro-cantilevers were mounted on a Bruel & Kjaer 4809 electromagnetic shaker which was controlled by an integrated signal generator and power amplifier on the Polytec MSA. The beams were excited with a random burst signal from 100Hz to 100kHz. Out-Of-Plane (OOP) and In-Plane (IP) resonance tests were carried out in a natural damped environment to characterize the beams and correlate them with high strain rate tests. OOP tests were performed using LDV and IP tests were conducted by means of stroboscopy and charged coupled device (CCD) imaging. Multi-point scanning in conjunction with base reference LDV was used to validate mode shapes and distinguish beam resonance from external noise. For clarity, the IP resonance tests were synonymous to the primary shock direction in the HPB tests.

Figure 2. Resonance experimental setup - Polytec MSA
**HPB Experimental Setup**

The micro-cantilevers were mounted in a breakaway fixture on a modified HPB, as in Figure 3. With reference to Figure 3(b), the primary shock direction is from the right to left of the image. The HPB was made of an aluminium incident rod of 19mm diameter and 2.7m length with strain gauges mid-section. This rod was struck at one end by an aluminium striker bar of 19mm diameter and 362mm length. A pressurised gas chamber propelled the striker bar into one end of the incident bar. At this impact point, 2.8mm to 4.4mm thick stationary card was used as a programming material to shape the pulse wave. This generated the desired compression wave that travelled through the incident bar ultimately delivering a shock pulse to the breakaway fixture. The stainless steel breakaway fixture was bonded to the HPB such that it separated from the bar after the initial shock to avoid any additional excitation impulses. The opposing end was threaded for attachment of a Dytran 3200B 80,000g accelerometer. The strain gauge signal was amplified through a Vishay 2110 strain gage conditioner and acquired by a FLUKE PM3394A oscilloscope at 2.5MHz. The accelerometer signal was conditioned through a National Instruments (NI) SC-2345 and acquired by an NI-USB-6251 at 1.25MHz. An IDT MotionPro™ X high speed camera with a Computar TEC-55 telecentric lens monitored the impact event on the cantilevers to verify the temporal point of failure. Xcitex ProAnalyst software Version 1.5.2.3 was used as a motion analysis tool to determine beam resonance and deflection from High Speed Imaging (HSI). Acceleration levels between 10,000g and 40,000g were required to induce failure mechanisms in the micro-cantilevers depending on the beam characteristics. This was achieved by launching the striker bar at a velocity of approximately 11-24m/s. Figure 4 shows characteristic acceleration amplitudes and durations from the strain gauge and accelerometer signals over the 10,000-40,000g input range.

**Simulation**

Finite Element Analysis (FEA) was carried out in an ANSYS simulation environment. Modal analysis was used to correlate against resonance tests to verify appropriate material properties and boundary conditions for relatively deterministic low strain rate testing. Damping was not taken into consideration as the temporal region of interest in HPB tests was of a relatively low magnitude to negate the effects of natural damping. Once accurate material properties and boundary conditions were defined, acceleration traces were taken from HPB tests and 7 point approximations of the initial shock pulse were determined using MATLAB taking into account local maxima and minima. These approximations were then used as input accelerations for the simulation of a beam deflection. These deflections were used to compare against high speed images of beam deflections from HPB tests to evaluate the maximum tensile stresses induced on a cantilever beam under shock stimuli.

![Figure 3. HPB experimental setup – (a) HPB apparatus (b) breakaway, micro-beam frame and accelerometer (c) schematic diagram of experimental setup](image)

![Figure 4. Characteristic shock acceleration pulses taken from accelerometer and strain gauge signals](image)
RESULTS AND DISCUSSION

Due to the planarity of the fabrication processes, inherent with all MEMS fabrication, the beams were designed with a primary test direction in mind. Cantilever bases were rounded in the primary shock direction to avoid stress raisers, which can lead to erroneous material characterization as seen in literature [15].

The beam structures as seen in Figure 1 were analyzed under resonance to investigate the natural damped frequencies of the beams. The first approach carried out was to correlate the IP and OOP techniques of the Polytec MSA with geometrically similar micro-cantilevers. While the IP results corresponded to OOP results, they were consistently lower with divergence in resonant frequencies mainly attributed to surface topographies from fabrication processes, as reported in [16], and geometry discrepancies such as the presence of notch and proofmass. The OOP technique demonstrated much higher capabilities detecting torsional mode shapes and resonances in excess of 90kHz. Table 2 lists the data sets from several resonance tests carried out to correlate IP and OOP test methods. The HPB column in Table 2 lists the resonant frequencies taken from samples subsequent to HPB tests, as described below. The mode numbers in Table 2 refer to the mode shape detected in the respective planes, e.g. the 91.18kHz resonance was the 4th resonance/mode shape identified by the OOP technique.

<table>
<thead>
<tr>
<th>Beam Characteristics</th>
<th>OOP (kHz)</th>
<th>IP (kHz)</th>
<th>HPB (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 5mm length, 100µm x 100µm, proofmass, no notch, 1st mode</td>
<td>3.56</td>
<td>3.49</td>
<td>3.57</td>
</tr>
<tr>
<td>2 6mm length, 100µm x 100µm, proofmass, no notch, 1st mode</td>
<td>2.62</td>
<td>2.52</td>
<td>2.58</td>
</tr>
<tr>
<td>3 7mm length, 100µm x 100µm, proofmass, no notch, 1st mode</td>
<td>2.02</td>
<td>1.94</td>
<td>1.98</td>
</tr>
<tr>
<td>4 5mm length, 100µm x 100µm, no proofmass, 40% notch, 1st mode</td>
<td>5.43</td>
<td>5.09</td>
<td>-</td>
</tr>
<tr>
<td>5 5mm length, 100µm x 100µm, proofmass, no notch, 2nd mode</td>
<td>29.23</td>
<td>26.94</td>
<td>-</td>
</tr>
<tr>
<td>6 7mm length, 100µm x 100µm, proofmass, 40% notch, 4th mode</td>
<td>91.18</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

HPB tests were carried out on similar beams to those tested under resonance to verify the use of HSI as a quantifiable metrology technique. Beam resonance was inferred from a HSI data set for a given acceleration input using the motion analysis software. Figure 5 is a graph highlighting the resonances of 5mm, 6mm and 7mm micro-cantilevers as determined by the motion analysis software over a period of 4ms. Inset is an image of a micro-cantilever frame and breakaway fixture at just over 400µs after a 12,500g amplitude 220µs duration acceleration pulse. This image illustrates the out of phase oscillation of the beams due to their relative resonant frequencies.

The device was tested under resonance in the Polytec MSA subsequent to the HPB tests and the resonant frequencies for the 5mm, 6mm and 7mm beams were 3.57kHz, 2.58kHz and 1.98kHz respectively, as listed in Table 2. This verified the accuracy of the motion analysis software as a measurement tool.

![Figure 5. Resonant frequencies of 7mm, 6mm and 5mm cantilevers with HSI inset](image-url)
In addition, it was observed that the resonant frequencies of beams that were subject to HPB tests went through an increased frequency shift. This can be seen comparing the bold values highlighted in Table 2 and was also evident in supplemental tests. This indicated a change in material properties and/or the occurrence of a change in dimensional properties such as fracture initiation or surface flaw growth. This preliminary observation requires further quantification to warrant its significance in predicting the onset of failure in micro-cantilevers under shock stimuli.

Following the verification of the motion analysis software a second test was carried out focusing on the deflection of the beams due to the initial shock pulse. A significant amount of trial and error was required to optimise the HSI data acquisition as an increase in spatial resolution inversely affected the temporal resolution. Figure 6 shows a deflection set for a micro-cantilever frame under a 27,114g amplitude 150μs duration acceleration shock. Tests carried out at higher accelerations initiated failure in the cantilevers. The images were captured at 21400fps which yields 46.7μs per frame and the spatial resolution was calculated at over 60μm per pixel. The motion software tool calculated the horizontal offset of each beam using a base reference point. Initial offsets caused by camera tilt as seen in frame 1 were used to correct the displacements giving a maximum deflection of 931μm, 1426μm and 1959μm for the 5mm, 6mm and 7mm beams respectively. The 5mm beams maximum deflection was observed in frame 3 and the 6/7mm beams maximum deflection was observed in frame 4.

The acceleration trace can be seen in Figure 7 with an overlaid 7-point approximation for the finite element simulation. Using FEA, behavioural models were developed to predict the deflection and consequently the maximum tensile stress of the micro-cantilevers. A density of 2330kg/m³, Poisson’s ratio of 0.28 and Young’s moduli of 130GPa and 167GPa for SCS was taken from literature [8]. The Young’s moduli values are indicative values taken from several SCS characterization approaches in literature that relate principally to the this research e.g. similar crystal orientation. Maximum deflections of cantilevers were derived for each beam for both values of Young’s modulus to indicate the sensitivity of deflection to a variation in modulus. For the devices tested, nano-indentation of the SCS substrate yielded Young’s moduli of approximately 120-130GPa while modal analysis simulation of data sets in Table 1 yielded approximately 155GPa.

Figure 8 shows the correlation between the deflections and maximum tensile stresses from the motion analysis software and the simulations. From Figure 8 (a) the actual cantilever deflections lie between the deflections of the two behavioural models which validates the FEA. From this the maximum tensile stress was taken from...
each beam length and plotted in Figure 8 (b). The upper and lower data sets act as bounding limits for the maximum tensile stress seen in the actual cantilevers. The beam sets analyzed here began to fail as acceleration amplitudes approached 30,000g for the current test configuration, this indicates that the bounding limits of the 7mm beam in Figure 8(b) are within proximity of the fracture strength of the micro-cantilevers as this beam saw the largest deflections.

CONCLUSION
The experimental approach in this paper verified conventional OOP LDV resonance tests with IP stroboscopic imaging. This IP technique was then used to validate the motion analysis software against deterministic resonance tests. Ultimately, the motion analysis tool was then used in combination with HSI and FEA to predict the deflection and thus maximum tensile stresses present in the micro-cantilevers. The values found correlated with what is reported in literature, demonstrating the viability of HSI and FEA as non-invasive techniques in determining material properties of micro-device materials.

- The primary resonant frequencies of the investigated micro-cantilevers ranged from approximately 2kHz to 3.5kHz.
- The OOP resonance technique identified resonances and their associated mode shapes in excess of 90kHz.
- The IP resonance technique correlated well with OOP results for primary resonances with variance attributed to discrepancies in geometry and fabrication techniques.
- The correlation of HPB and IP results for tested and untested beams detected a 40Hz to 80Hz increase in resonance on HPB tested beams.
- FEA of micro-cantilever resonance and deflection comparisons calculate the Young’s modulus of the cantilevers at approximately 155GPa.
- The beams tested in this paper deflected up to 1959μm under the initial shock pulse which generated a tensile stress in excess of 1GPa at the base of the beams.

Further investigation is required on FEA as an inverse technique to quantify maximum tensile stress of a beam under shock induced deflection; specifically the sensitivity of deflection in relation to the key material properties. Further investigation is also required to determine the significance of the frequency shift observed in HPB tested micro-cantilevers.
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