Resonance Frequency Trimming for MEMS Micro-Mirror Scanner

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Abstract: - MEMS devices with harmonic oscillators resonating at specific frequency are useful in a variety of applications. One of these applications that demands high and accurate resonant frequency is optical scanners for display applications. Due to the large tolerances of MEMS fabrication a calibration is required to achieve accuracy in resonance frequency. In this paper we present a novel technique for frequency trimming and spring stiffness trimming. The proposed technique is one time one direction frequency trimming and is based on anisotropic wet etching process, the same process used for fabrication of the device itself. We also present some preliminary results of resonant frequency of micro-mirror scanner devices for display applications before and after trimming process.

Key-Words: - MEMS, mirror, scanner, resonance, frequency, trimming, calibration, anisotropic, wet, display.

1 Introduction

Electro-optical scanner are most useful devices in many applications such as barcode readers, display devices etc. Some of these applications require high rate optical scanning. Micro-mirrors produced with MEMS technology enables high rate scanning and in particular resonance scanners enable very high rate scanning with very low power consumption. Therefore MEMS micro-mirror devices are promising solution for many optical scanning instruments. However, typical tolerances of fabrication in MEMS technology may be quite large. In some applications such as display applications the exact scanning frequency is crucial. It happens that in display applications the desired scan frequency is very high (in the region of 10 to 40 KHz) and therefore a resonant scanner is a favored option. Because of fabrication tolerances the accuracy of the achieved resonance frequency is lower than needed. To satisfy with the needed resonance frequency accuracy, a calibration process is required.

In this paper we present a novel technique that can be used for resonance frequency trimming by trimming the stiffness of the spring hinges of the resonator. This technique is based on the well known anisotropic wet etching process [1] which is widely used as low-cost fabrication process in MEMS technology. Anisotropic wet etching of silicon selectively etches the material by its crystal planes. During etch process rapidly etched planes (such as <100> and <113> planes) deteriorate faster than the other planes and the slow etched planes (such as <111>) are revealed. In convex corners it is the faster etched planes that are revealed because all planes are available and the etch process proceed in the fastest direction.

The fabrication of the device itself (described in details in [2], [3]) is done by anisotropic wet etching and therefore the trimming process is no different than the fabrication process. The proposed process is a one time trimming technique that enables only a reduction in resonance or in spring stiffness. The suggested trimming technique can be used for trimming resonance frequencies or spring stiffness of devices for applications other than displays as well.

2 Device Description

In order to perform the trimming process, a description of a device should be introduced first. The device under consideration (non limiting example) is a single axis micro-mirror scanner for VGA display applications. The required frequency is about 14 KHz [4] and therefore it is resonantly scanning. The required \( \theta D \) product, the figure of merit of the optical scanner, is about 5 deg:mm [4] equals to 87 Rad\( \cdot \)\( \mu \)m. As illustrated in fig. 1 we calculate the traveling of the micro-mirror tip in order to reach the desired \( \theta D \) product assuming small angles approximation

\[
h = \frac{D}{2} \tan \theta \approx \frac{D\theta}{2}. \tag{1}
\]

Hence \( h \) is about 44\( \mu \)m.
Electrostatic actuation [5] has very low power dissipation but a simple parallel plate electrostatic actuator is not applicable because of the large distance required between plates. Therefore we use a non-parallel plate actuator [6], [7] with triangular prism base electrode as illustrated in fig. 1. The non-parallel plate actuator enables large deflection angles at mirror tip and small air gap near rotation axis. Thus the mirror is actuated to large deflection angles with relatively low operating voltage.

![Fig 1: Illustration of non-parallel plate electrostatic actuated micro-mirror device](image)

The device is combined of two chips: the base chip described in [3] and the mirror chip described in [2]. The two chips are bonded together by flip-chip bonding process. The mirror chip includes the mirror body and the flexure hinges, which together forms the harmonic oscillator and therefore the resonance frequency is determined only by this chip. All further discussion is related only to the mirror chip.

The resonance frequency of the micro-mirror device with rectangular cross section hinges is (after [4]):

\[
f = \frac{1}{2\pi} \sqrt{\frac{K_f}{I_m}},
\]

where the mirror inertia is:

\[
I_m = \frac{1}{12} M(D^2 + t^2),
\]

where \( M \) is the mirror mass, \( D \) is the mirror width, and \( t \) is the mirror thickness, and

\[
K_f = \frac{2K_s G a b^3}{L_f},
\]

\[
K_s = 5.33 - 3.66 \frac{b}{a} (1 - \frac{b^4}{12a^2}), \quad \text{for } a \geq b
\]

where \( 2a \) and \( 2b \) are hinges cross section dimensions, \( G \) is the rigidity modulo of the material, and \( L_f \) is the flexure length.

As described in [2] the cross section of the flexure is hexagonal. In order to find the flexure stiffness we use an approximation of the cross section to a rectangular as illustrated in fig. 2 were the rectangular width is the average width of the hexagon

\[
w_{\text{average}} = \frac{w_{\text{top}} + w_{\text{waist}}}{2}
\]

![Fig 2: Approximation of cross section of hinge by rectangular form.](image)

Assuming that material properties (\( G \) and \( \rho \)) are uniform and constant the resonance frequency is proportional to:

\[
f \propto \sqrt{\frac{K_f}{I_m}} \propto \sqrt{\frac{ab^3 K_s}{L_f D t L (D^2 + t^2)}}
\]

In most cases \( t^2 \ll D^2 \) and therefore \( t^2 \) is negligible. Thus the resonance frequency is proportional to:

\[
f \propto \sqrt{\frac{a b^3 K_s}{L_f t L D^3}}
\]

\( L_f, L \) and \( D \) are large (1mm). Therefore tolerances of microns for these dimensions have minor effect upon the resonance frequency and we will not explore them. One dimension of the hinges of the described device is equal to the thickness of the mirror \( t \) which is the thickness of the wafer. It is either \( 2a \) or \( 2b \) depending if it is the larger or the smaller dimension (respectively) of the hinge cross section. In the case of \( 2b = t \) then

\[
f \propto \sqrt{\frac{b^3 K_s}{L_f t D}}
\]

And in the case of \( 2a = t \) then

\[
f \propto \sqrt{\frac{a b^3 K_s}{L_f t D}}
\]

For example the resonance frequency of a silicon mirror (\( \rho = 2330 \text{ Kg/m}^3 \)) of the size 1mmX1mmX50µm with silicon flexure hinges (\( G = 64 \text{ GPa} \)) of 1mm length from each side of the mirror and hexagonal cross section of 50µm
thickness, 40µm top width and 75µm waist width (in this case \( t \) is smaller than \( w_{\text{waist}} \) and \( 2b=t \)) should have a resonance frequency of

\[ f = 19,581 \text{ Hz} \]  \hspace{1cm} (11)

The same mirror with change of 1µm in thickness of hinges and mirror (\( t=50\pm1\mu m \)) will have a resonance frequency of

\[ f = 19,248\div19,913 \text{ Hz} \]  \hspace{1cm} (12)

The same mirror with change of 1µm in hinges width (\( w_{\text{waist}}=57.7\pm1\mu m \)) will have resonance frequency of

\[ f = 19,270\div19,905 \text{ Hz} \]  \hspace{1cm} (13)

As observed from the results of eq. (11), (12) and (13) although the complicated relations between the dimensions and the frequency the change in frequency is about proportional to the change in dimensions that cause it.

### 3 Trimming method

For applications that can not be tolerant to a wide spread resonance frequencies it is possible to adopt tight fabrication processes. This leads to more complicate fabrication processes and lower yield both contribute to higher fabrication cost of devices. Another solution is to use various techniques for within processing or post processing calibration of resonance frequency. The method suggested in this paper belongs to the within process calibration and offers only one time one direction frequency trimming.

The discussed above hexagonal cross section of the hinges created by the anisotropic wet etching process is the key for the trimming process. As illustrated in fig. 3 the hexagonal cross section has convex corner. These convex corners are rapidly etched under anisotropic wet etching conditions. As the wet etching continues the cross section is deteriorated (fig. 4a. to 4c.) and thus the flexure stiffness is reduced. Due to the change in the hinge's cross section the resonance frequency is also reduced. The same anisotropic wet etching fabrication process used for device fabrication is used for the frequency trimming.

### 4 Experimental results

The device described above was fabricated with low-cost mailer masks. Since tolerances of device dimensions were large, the dimensions were measured after fabrication and expected frequency was calculated. Then the resonance frequency was measured and compared to the calculated frequency.

A trimming process was executed on the measured devices using anisotropic wet etching with KOH and water solution (40% KOH in weight) and isopropanol at 80ºC for 5 minutes. After the trimming process the resonance frequency was measured again. The results of calculations and measurements are in table 1.

In fig. 5 there is a hexagonal cross section hinge captured by S.E.M. in fig. 6 there is a hinge once had a hexagonal cross section after a long trimming process.
Table 1: Calculated and measured resonance frequency of micro-mirror devices before and after 5% KOH 40%wt. +IPA at 80°C trimming.

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<tr>
<td>A1</td>
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<td>A4</td>
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<td>-</td>
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Fig. 5: S.E.M. photograph of cross section of flexure hinges before trimming process.

Fig. 6: S.E.M. photograph of cross section of flexure hinges after long trimming process.

5 Conclusion
In this paper we proposed a novel technique for resonance frequency and spring stiffness trimming. The technique is based on an anisotropic wet etching process, the same process used for the fabrication of the devices themselves. Two devices were fabricated and the suggested trimming technique was demonstrated successfully. Knowing the exact dimension of the resonator it is possible to calculate the resonance frequency with good compliance. A change of over 10% in resonance frequency was demonstrated with only short etching trimming process with anisotropic wet etching process. There was no cause to stop trimming at that point and trimming could go on expanding the range of frequency even further.

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References: