Localized EutecticTrimming of Polysilicon Micro Hemispherical Resonating Gyroscopes

B. Hamelin, V. Tavassoli, F. Ayazi

Abstract—This paper describes a novel technique to permanently tune a frequency mismatch between degenerate modes of a polysilicon micro hemispherical resonating gyroscope (μHRG) caused by fabrication imperfections with the potential to be implemented post-packaging. A systematic trimming algorithm is introduced to compensate for frequency mismatch and mode misalignment based on laser-induced silicon-metal eutectic formation. The stiffness changes are applied to the vicinity of the supporting post at the base of a hemispherical resonator, a region which has not been previously studied for this purpose. Our numerical studies show the four-nodal point elliptical wineglass modes are highly sensitive to strain modifications around the post. The algorithm is developed and proven effective through FEM simulations in COMSOL, where a significant reduction (>10X) of the frequency split of the wineglass modes in an imperfect μHRG has been achieved.

Index Terms—Frequency mismatch, tuning, MEMS.

I. INTRODUCTION

An Inertial Measurement Unit (IMU) consists of accelerometers to measure linear acceleration and gyroscopes to measure angle of rotation [1]. As vital components of IMUs, MEMS gyroscopes are key enabling devices for navigation applications in GPS denied environments. They provide the traditional advantages of MEMS technology, namely small size, weight and power plus cost (SWaP+C). However, high performance MEMS gyroscopes are only achievable when manufacturing imperfections are compensated for. Particularly, structural and material asymmetries can make the resonance frequencies diverge from targeted values and the corresponding modes misaligned [2]. Since such sensors operate based on Coriolis coupling of resonance modes, dynamic tuning or permanent trimming of such mismatches become indispensable.

Several dynamic tuning demonstrations exploited in MEMS resonators and resonant gyroscopes include electrostatic [3] and electro-thermal methods [4–5], which may require high voltages with high stability and excessive power consumption while delivering only a limited frequency tuning range. Trimming approaches such as oxidation [6], change in the device dimensions [7], thermal annealing [8] and mass modification [9] can provide larger frequency shift without requiring active control circuits. However, these approaches may not be mode-selective and typically do not offer a high resolution of frequency adjustment.

An example of a device that requires high resolution frequency adjustment is the Micro-Hemispherical Resonating Gyroscope (μHRG), shown in Fig. 1. Proper operation of this Coriolis-based rotation sensor needs to satisfy two conditions: it should have two modes of vibration (drive and sense) at the same resonance frequency and the antinodes of these modes (locations with maximum displacement) must be aligned with the surrounding electrodes [11]. The degenerate four nodal-point wineglass modes, known as the m=2 modes, often have the lowest frequencies, provide large displacements, are expected to have high-quality factors and in this work are considered as the drive and sense modes. Although the m=2 modes ideally meet the two required conditions, fabrication errors shift the resonance frequencies apart and misalign the two modes with respect to the electrodes. The fabrication errors can range from minute tilting of the post to deviation from a perfect axisymmetric hemisphere. Since the optimum performance of a μHRG is achieved when the device is mode matched, trimming the device to compensate for the frequency split and for the modes misalignment is crucial for proper

Fig. 1. SEM picture of a cleaved polysilicon μHRG with integrated electrodes [11]
While the μHRG along with the novel laser-based, vacuum packaged compatible, post-fabrication trimming method was introduced in [12], this paper provides evidence for the role of the post on the strain energy density distribution and on how the distribution relates to the eutectic trimming operation (section II). Furthermore, frequency trimming as well as mode alignment are discussed (section III). Finally, it is shown that frequency split trimming and mode alignment can both be achieved on the same device through an algorithm (section IV).

II. STRAIN ENERGY IN MICRO-HRGs

The proposed eutectic trimming technique is founded upon the distribution of elastic strain energy in an anchored resonator, namely a hemispherical shell resonator (HSR) supported on a solid cylinder at the center. The method takes advantage of the fact that controlled modification of the Young’s modulus at strategic locations with high strain energy densities would shift the resonant frequency significantly. An essential requirement for the method to work is that the strategic spots have to reside at different locations on the shell for the two degenerate modes, to ensure that the resonant frequency of each mode can be shifted individually with negligible effect on the other one. Also, these strategic, separated, high strain energy regions must be selectively accessible by a laser used as a heating source.

A detailed discussion which follows, shows that the four nodal-point wineglass modes of an HSR, also known as the m=2 modes, develop high strain energy areas around the support, which satisfy the aforementioned requirements for eutectic trimming.

A. Influence of the post on strain energy distribution

Abundant literature has studied hemispherical shell resonators mathematically and in great detail [13]. But, the equation of motion and the strain energy distribution, to the best knowledge of the authors, are always derived with the assumption of no support. In this work however, finite element method (FEM) is employed to show that a significantly strong strain energy pattern is developed around the post, resulting from the interaction of the resonating shell and the solid support, which are suitable to be used for eutectic trimming.

Fig. 2 depicts plots of the strain energy distribution of the m=2 wineglass mode along a nodal meridian for shells with and without support (green and blue curves respectively), using COMSOL Multiphysics [14] FEM simulations. A hemispherical shell with a radius of 1250μm and thickness of 2μm supported on a solid post with a radius of 150μm is used as typical dimensions for a μHRG. Also, the strain energy distributions in cross-sectional view at the same nodal point are shown in the inset of Fig. 2. The graphs show that although the strain energy distribution is modified only lightly around the top rim, it is significantly changed at the vicinity of the post, exhibiting a peak for the shell with a post. This result can also be confirmed by a semi-analytical expression of the distribution of the strain energy as given in the appendix.

To take advantage of the strain energy density around the support for trimming purposes, strategic spots that offer the greatest trimming range, which will be referred to as eutectic trimming spots, should be looked for. Therefore, characteristics of the energy distribution is further studied through finite element modeling for the m=2 wineglass modes in the following subsections.

B. Strain energy patterns

The analytical description of the mode shapes of a pure hemispherical shell resonator implies that any point on an antinodal meridian would only comprise polar and radial displacements, whereas any point on a nodal meridian would only involve azimuthal displacement [15]. The addition of a solid post ideally enforces the anchored region to be immobile. It is the interaction among atoms belonging to the mobile areas and fixed areas around the post that produces high strain density regions at the nodal and antinodal points as shown in Fig.3.

a. Shape of the post

Finite element analysis shows that distribution of the strain energy depends on the shape of the support. The patterns shown on the right side of Fig. 3 compare the effect of a
square shaped support with that of a circular support on the strain energy distribution around the post which are reflections of the support shapes.

b. Modes of resonance

The strategic eutectic trimming spots for a given mode of vibration have been defined as the locations on the shell where large strain energy densities are developed. Fig. 4 gives an insight on the patterns and polar distributions of strain energy generated at the antinode of the rocking mode, the m=2, 3 and 4 modes. The rocking mode generates the largest amount of strain energy (green curve in Fig. 4), and thus the strategic spots of the rocking mode are the most effective amongst all. Yet, the two degenerate rocking modes have very similar distributions, which implies that they will be equally affected by any stiffness change. Therefore, the resonant frequencies will be strongly shifted during the trimming operation, but the frequency split will not significantly change.

According to Fig. 4, the wineglass m=2 mode generates the second largest strain energy density, but since it generates less strain energy than the rocking mode, the trimming sensitivity is smaller. The same conclusion applies to the m=3, 4 and higher order modes. Based on FEM simulations, these modes (m>2) develop much smaller strain energy densities making them not the suitable candidates for eutectic trimming (the frequency shifts are lower than the numerical error of around 0.1 Hz). Furthermore, according to Fig. 3, the strain energy for the two degenerate m=2 modes are distinct, since the colors indicating the maxima do not coincide. Therefore, it is possible to shift the frequencies independently, and increase or decrease the frequency split between the two m=2 modes by controlling local stiffness modifications.

c. Fine and coarse trimming regions

The strain energy distribution is not constant over the thickness of the shell as shown in Fig. 5. For example the largest amount of strain energy is produced at the backside of the shell, at antinodal locations. The plots shown in Fig. 5 also suggest that although the nodes of one of the m=2 modes and the antinodes of the other m=2 mode are located in the same azimuthal regions, the strain energy patterns generated by the nodes and antinodes are not at all the same near the post. Therefore, the locations of strategic eutectic trimming spots for the nodes and those for the antinodes are different; the nodes generate spots that are further away from the post compared to the spots generated by the antinodes as shown in Fig. 5. Furthermore, the antinodes generate eutectic trimming spots with larger strain energy densities than what nodes do. Therefore, the most sensitive locations for eutectic trimming (the spots that generate the largest frequency shifts, suitable for coarse trimming) correspond to the backside of the shell, at the anti-nodal locations on the shell-post edge.

C. Eutectic trimming spot dimensions

In Fig. 6 the strain energy distribution is given with the polar angle for different support sizes. The peaks of the graphs represent the maximum energy developed at the proximity of the support, and the results imply that the peaks are approximately developed around the same polar angle away from the post for different support sizes. Furthermore, the
widths of the peaks, which can be interpreted as the sizes of effective trimming regions, are also about the same for the given range of support sizes. However, the maximum strain energy density, which represents the total strain energy developed around the post vary with the support size.

The top curve in Fig. 7 (green triangles) depicts the dependence of maximum strain energy density developed around the post on support size. In accordance with the results given in Fig. 6, larger strain energies correspond to bigger support sizes, approximately showing an exponential dependence. The lower curve in Fig. 7 (orange diamonds) gives the frequency split caused by stiffness change on the effective trimming spots. The fact that larger frequency shifts are generated for larger support sizes, confirms that the sensitivity of trimming areas are higher for larger posts. Therefore, although a larger post does not create larger eutectic trimming regions, it does create trimming spots that are more sensitive to stiffness modification, and can potentially provide larger frequency shifts.

III. LOCALIZED EUTECTIC TRIMMING

Eutectic trimming of microresonators using Joule heating has been previously reported by our group [16-17]. Laser-based eutectic trimming is based on stiffness modification and can be done over the entire resonate body or only at targeted locations. This technique builds on the well-established area of eutectic wafer bonding for MEMS fabrication and packaging [18].

To realize eutectic trimming, a thin layer of trimming material such as gold or aluminum is deposited on the resonator surface, and is thermally forced to diffuse into the device to create eutectic bonds with the bulk material (i.e. polysilicon) [19], at locations where the temperature reaches a target value [20]. The stiffness modification and the resultant frequency shifts are functions of the size and the location of these eutectic bonds. The minimum temperature needed for formation of eutectic bonds (i.e. the eutectic temperature) can be significantly lower than the melting temperatures of both materials. The thermal budget for eutectic trimming is thus much smaller compared to laser ablation trimming methods.

Although Joule heating has been proven to be a practical technique to provide the needed energy for formation of eutectic bonds, this heating method suffers a drawback that makes it unsuitable for trimming gyroscopes. Trimming down the frequency split of a gyroscope is intended to shift the drive and sense frequencies to a target value. When a current flows through the resonator body, the device heats up due to the Joule effect and the eutectic bonds are formed only at the locations that reach the eutectic temperature. Since the two frequencies need to be shifted independently of one another, the modes must have different sensitivities to the trimming operation. However, the thermal distribution of Joule heating is independent from vibrational mode patterns; therefore the formation of the eutectic bonds may not trim down the frequency split (i.e. $f_{drive} - f_{sense}$) of a gyroscope.

Gyroscope trimming calls for a different heating method to keep the advantage of a low thermal budget while being also mode selective. In the proposed heating approach, a laser beam heats certain spots on the device locally as shown in Fig. 8. Although the experimental setup complexity increases compared to Joule heating, laser heating offers substantial advantages. Most importantly, the user can aim the laser beam on any accessible location on the device to selectively modify the stiffness. Consequently, using a laser provides the possibility of substantially changing the resonance frequency of one mode while having negligible effect on the resonant frequency of the other mode. As mentioned before, not all gyroscope modes can be trimmed by a laser-based eutectic technique; the degenerate modes are required to develop strain.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SUMMARY OF TRIMMING EFFECTS</th>
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<tbody>
<tr>
<td><strong>Low frequency mode</strong></td>
<td><strong>High frequency mode</strong></td>
</tr>
<tr>
<td>Node at fine trimming location</td>
<td>Antinode at coarse trimming location</td>
</tr>
<tr>
<td>Antinode at coarse trimming location</td>
<td>Node at fine trimming location</td>
</tr>
<tr>
<td><strong>Increase E</strong></td>
<td><strong>Increase frequency split</strong></td>
</tr>
<tr>
<td>Fine trimming</td>
<td>Coarse trimming</td>
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<tr>
<td>Increase frequency split</td>
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<tr>
<td><strong>Decrease E</strong></td>
<td><strong>Increase frequency split</strong></td>
</tr>
<tr>
<td>Increase frequency split</td>
<td>Fine trimming</td>
</tr>
<tr>
<td>Increase frequency split</td>
<td>Coarse trimming</td>
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energy distributions with orthogonal high/low energy patterns and also high strain energy locations should be selectively accessible by the heat source as described in previous section.

A. Frequency trimming

Based on the analysis presented in previous sections, the wineglass (m=2) mode of a μHRG develops effective eutectic trimming areas around the post with high strain energy densities for one mode and low strain energy for the other one. Additionally, a large strain energy difference befits coarse trimming, whereas a small strain energy difference is suitable for fine trimming.

The strain energy patterns shown on the right side of Fig. 9 indicate that there are two sets of locations around the post where large differences between the energy densities of the two modes are developed. These two sets of locations around the post are shown on the left side of Fig. 9. A thick (respectively thin) ring around the metal’s name represents a location that provides a large (respectively small) difference of strain energy. Accordingly, the regions around the post can be classified into two categories: one that provides large strain energy differences, which will be referred to as coarse trimming locations and another that provides smaller differences, which will be referred to as fine trimming locations. Table 1 summarizes these definitions and conclusions.

B. Misalignment trimming

For maximum gyroscope sensitivity, the nodes and antinodes of the degenerate modes must be aligned with the center of the drive (actuation) and sense electrodes. Localized eutectic trimming has the capability to reduce the mode misalignment, which for example can be caused by minute tilting of the post [11]. Our FEM analysis shows that both four-node wineglass modes are equally sensitive to any stiffness variation applied to locations around the post halfway between the nodal and anti-nodal points. And, that misalignment trimming can be done at these locations with small effect on the frequency split. In Fig. 10, the Young’s modulus is modified at non-optimal locations where the modes are realigned: the low frequency m=2 mode was aligned from 130° direction to the 95° direction. Due to the non-optimal condition of this example, the frequency split is also affected and increases from 0.2Hz to 2.5Hz for a Young’s modulus variation of only 20GPa. In the next section, the same device will have its mode realigned by using optimal locations for the trimming operation and the frequency split will not increase as much.

C. Choice of trimming material

Since this paper focuses on the trimming of a polysilicon μHRGs, gold and aluminum are considered as candidates for trimming material because they offer specific advantages when forming eutectic bonds with polysilicon. Gold-silicon has a low eutectic temperature (363°C) compared to gold’s melting temperature (1063°C). The Young’s modulus of gold-silicon eutectic compound is higher than that of polysilicon [16]. Aluminum-gold has a eutectic temperature (577°C) that is close to aluminum’s melting temperature (660°C), and a reduced Young’s modulus compared to silicon [21].

In the proposed method, aluminum-silicon eutectic bonds are formed at the trimming spots of the higher frequency mode (Fig. 9), which would reduce the Young’s modulus from 160GPa (polysilicon) to 80GPa (aluminum-silicon eutectic). Although this stiffness reduction decreases both m=2 frequencies, the higher frequency will be more sensitive to that stiffness modification, because of the location of the trimming spots, and therefore the frequency split will be reduced. Similarly, the formation of gold-silicon eutectic bonds at the trimming locations of the low frequency wineglass mode reduces the frequency split.

IV. TRIMMING ALGORITHM

A simple and efficient frequency trimming algorithm is devised and is shown in Fig. 11. The first step is to find effective trimming locations around the post; an area which is usually not accurately known since the post is not visible from the top. This will be done through a repetitive process which
can be turned into an automated operation.

A. Finding the trimming locations

The laser is initially aimed at a location as close as possible to the center of the post from the top. Weak laser shots are aimed on the μHRG to create localized eutectics bonds, and the frequency split is recorded at each step. The trimming locations can then be found by studying the frequency split evolution. Increasing the step resolution assures that all the trimming locations are visited.

The laser scans around every trimming location to map more precisely the frequency split reduction with spatial stiffness modification. Laser shots will start creating eutectics in the middle of the post where the frequency split is not affected and then will be aimed outwards in the polar direction, until the location limits are found.

B. Eutectic trimming flowchart

If the measured frequency split does not meet the requirements, then the algorithm (Fig. 11) continues to the next trimming location and creates more eutectic bonds until the frequency requirements are met or until there is no further reduction. In the latter case, the algorithm will proceed to the next trimming spot. If the frequency split requirements are met (Δf < Δf1), the algorithm will then trim misalignment by visiting the misalignment trimming locations. The algorithm will loop back to do frequency trimming if the frequency split does not meet its requirements anymore. The algorithm converges when the device is trimmed both for frequency split and misalignment or when all the trimming locations are used.

C. Results

Fig. 12 shows the automatic eutectic trimming of a μHRG resulting from an FEM simulation. To simplify the numerical analysis, a uniform Young’s modulus across the thickness of the shell is assumed. We consider the diameter of the effective trimming area to be 20μm for a shell with a 1mm diameter which is 2μm thick. An initial frequency split of 40Hz between the m=2 elliptical modes is reduced to 0.1Hz before alignment trimming. The four strong variations of the frequency split (graph in Fig. 12) are due to trimming operation on the coarse trimming locations (blue spots in the top-right image of Fig. 12). As shown in Fig. 13, the modes are then aligned (the same device features as Fig. 9), but this time the frequency split is at least kept 10 times smaller than its initial value.

The best locations for mode alignment are the locations where both modes develop about the same strain energy. In Fig. 13, the frequency split only increases up to 1.5Hz for a Young modulus variation of 80GPa. In Fig. 9, where non-optimal locations have been chosen, the frequency split increases up to 2.5Hz for a variation of the Young’s modulus of only 20GPa. The insets of Fig. 10 and Fig. 13 show where the mode alignment locations are compared to the frequency trimming locations.

And since there are no regions where both modes develop the exact same strain energy, the frequency split will always increase during the mode alignment step. If the increase in
frequency split is too large (Δf > Δf₁), then the algorithm suggests that device would need to be trimmed again.

V. CONCLUSION

A potentially post-fabrication trimming method for μHRGs is introduced for the first time based on localized stiffness modification by formation of eutectic bonds. A laser is used as the heat source on trimming locations to form the silicon-metal bonds. Modal frequencies are shifted by permanently modifying the stiffness of the device at target locations.

The eutectic trimming locations for the four-nodal point wineglass modes of polysilicon μHRGs are described. The presented laser-based technique take advantage of a new trimming area, namely around the support at the base of the μHRG. To the best of our knowledge there is no report on trimming of HRGs at the post, as mass trimming is usually done around the rim.

The formation of silicon-metal bonds can potentially have an impact on the thermo-elastic dissipation (TED) and therefore may limit the Q_{TED}. Future work will also aim at such undesirable effects which will be monitored and examined during the eutectic trimming operation.

APPENDIX

The exact calculation of the strain energy distribution when a spherical post is taken into account is very challenging. Also a semi-analytical approach is facing convergence challenges at the post and will require very large computation power if the post is not considered cylindrical. A numerical estimation of the strain energy as a function of the polar angle was obtained following the approach described in [16].

Let \( u_r, u_\theta, u_\phi \) be the displacement components in the \( r, \theta, \phi \) directions

\[
\begin{align*}
  u_r(\varphi, \theta, t) &= U_r(\theta) \cdot \cos(n\varphi) \cdot \sin(\omega t) \\
  u_\theta(\varphi, \theta, t) &= U_\theta(\theta) \cdot \sin(n\varphi) \cdot \sin(\omega t) \\
  u_\phi(\varphi, \theta, t) &= U_\phi(\theta) \cdot \cos(n\varphi) \cdot \sin(\omega t)
\end{align*}
\]

In the case of a perfect hemisphere, with no post, then the exact equations for the 2n-nodal wineglass mode [15], with D constant:

\[
\begin{align*}
  U_r(\theta) &= -D(n + \cos(\theta)) \cdot \tan^n(\theta/2) \\
  U_\theta(\theta) &= D \sin(\theta) \cdot \tan^n(\theta/2) \\
  U_\phi(\theta) &= D \sin(\theta) \cdot \tan^n(\theta/2)
\end{align*}
\]

In cylindrical coordinates \( (z, \theta, \varphi) \), \( \theta_0 \) is the polar angle defining the intersection between the cylindrical post and the hemispherical shell. In the absence of a post, \( \theta_0 = 0 \),

### TABLE III

Comparison of FEM and semi-analytical strain energy distribution for m=2 wineglass mode along a meridional direction

<table>
<thead>
<tr>
<th>Polynomial degree in ( z ) and</th>
<th>Finite element plot</th>
<th>Semi-analytical plot</th>
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<tr>
<td>(6,6)</td>
<td><img src="image" alt="No post" /></td>
<td><img src="image" alt="No post" /></td>
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<tr>
<td>(5,10)[15]</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Polynomial degree in ( z ) and</th>
<th>Freq. 1</th>
<th>Freq. 2</th>
<th>Freq. 3</th>
<th>Freq. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(6,6)</td>
<td>0.0513</td>
<td>0.901</td>
<td>1.01</td>
<td>1.102</td>
</tr>
<tr>
<td>(5,10)[15]</td>
<td>0.053</td>
<td>1.02</td>
<td>1.036</td>
<td>1.185</td>
</tr>
</tbody>
</table>
otherwise $\theta_0 > 0$. The shell is clamped at $\theta = \theta_0$ and free at $\theta = \frac{\pi}{2}$. The displacement components in the spherical coordinates $(U_\theta(z, \theta), U_\phi(z, \theta), U_r(z, \theta))$ are approximated with polynomials functions of increasing order. The polynomial's coefficients are extracted from the solution of the Eigen value problem in the Rayleigh-Ritz method. The convergence of the first five normalized frequencies, in the case of a perfect shell with no post, is compared with published results [16], in table 2.

The plots of the strain energy distribution of the $m=2$ wineglass mode in the polar direction is shown in Table 3. This semi-analytic plot indicates that the strain energy of the $m=2$ mode is significantly influenced by the post.

ACKNOWLEDGMENT

This work was supported by the DARPA Microsystems Technology Office, Microscale Rate Integrating Gyroscope (MRIG) program under contract #HR0011-00-C-0032 led by Northrop Grumman Corporation.

REFERENCES


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