EPITAXIALLY-ENCAPSULATED POLYSILICON DISK RESONATOR
GYROSCOPE

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ABSTRACT
We present a 0.6 mm diameter, 20 μm thick epitaxially-sealed polysilicon disk resonator gyro (DRG). High Q (50,000) combined with electrostatic mode-matching and closed-loop quadrature null performed by dedicated electrode sets enables a scale-factor of 0.286 mV/(°/s) and Angle Random Walk (ARW) of 0.006 (°/s)/√Hz. Without precise control of temperature, the minimum Allan deviation is 3.29 °/hr.

INTRODUCTION
Due to their small size, low power consumption, and low cost to manufacture, MEMS gyros present a promising alternative to currently available high-performance gyros. In order to be useful for inertial navigation in GPS-denied environments, however, they must achieve high sensitivity, while maintaining high stability in terms of bias drift and scale factor. Key performance criteria for gyros include angle random walk (ARW), bias stability and scale-factor stability. Low ARW requires low noise and therefore high quality factor (Q), however stable scale-factor can only be achieved in a gyro with high frequency stability, as the gyro’s scale-factor depends on the oscillation frequency.

This paper concerns a disk resonator gyro (DRG) that is fabricated using high-temperature, ultra-clean epitaxial polysilicon encapsulation, resulting in a resonator in which the frequency stability is dominated by temperature sensitivity of -26 ppm/°C [1]. This process also provides high Q, resulting in high performance in an extremely small resonator volume. The DRG design is attractive because, like a ring gyro, it has an inherently symmetrical structure, but maintains a larger modal mass and therefore is capable of increased strain energy density in comparison with a ring [2]. Here, high Q (50,000) is achieved through the center-anchored DRG design, and through hermetic encapsulation resulting in pressure less than 1 Pa [3]. Fabricating the device from polysilicon allows mode-matched operation in the 2θ vibration mode unlike gyros fabricated in [100] crystalline silicon [4].

DEVICE DESIGN & OPERATION
Nominal design parameters of the DRG are summarized in Table 1. An SEM image of the device is shown in Figure 1, along with a block diagram of the sensor operation. As shown in the figure, the device has 24 electrodes which are connected into four sets that enable driving and sensing of the two elliptical 20 vibration modes (referred to as mode A and mode B) as well as four sets of electrodes used for electrostatic mode matching and quadrature nulling [5] [6]. Transcapacitance amplifiers are used for capacitive sensing of the drive and Coriolis sense axis motion with a resolution of approximately 0.38 pm/√Hz, and with differential measurement implemented on the sense axis. The Brownian-noise limit of the device is 0.46 pm/√Hz. Closed-loop amplitude control of the drive axis oscillation is implemented using a digital PLL and PID controller (HF2LI, Zurich Instruments), while the Coriolis sense axis output is operated open-loop using the same instrument to demodulate the in-phase component of the motion signal.

Electrostatic mode-matching is performed to maximize the scale-factor and a separate set of tuning electrodes is operated in closed loop to null mechanical quadrature resulting from anisoinertia and anisoelasticity.

Figure 1: Top: SEM image of the device, showing epitaxial encapsulation layer. Bottom: System diagram. Tuning electrodes at 0° and 45° are used to match the resonant frequencies of the drive and sense axes, and electrodes at ±22.5° are used to null quadrature. Closed-loop control of the drive-axis oscillation amplitude is implemented using a digital PLL. The sense axis output is IQ demodulated with the in-phase signal used as the rate output, and the in-quadrature signal used to null quadrature.
Gyro frequency response measured using a swept-frequency sinusoidal rate input. The extracted 3 dB bandwidth is 4 Hz and \( Q \) is 48,000.

The frequency response before and after mode-matching is shown in Figure 2. The initial frequency mismatch is 135 Hz, and the residual mismatch, due to temperature drift between sweeps, is less than 0.5 Hz. Because the 3 dB bandwidth of the device is 4 Hz, the residual mismatch, at 10% of this value, is insignificant.

Closed-loop quadrature null is achieved using a second PID controller that adjusts the voltage applied to the quadrature null electrodes. In addition to reducing mechanical coupling between the two axes of the gyro, maintaining the correct quadrature null is necessary in order to achieve mode-matching [5]. Control gains must be selected to ensure low bandwidth for the quadrature nulling loop, as a large bandwidth can result in suppressed rate signal. The effect of quadrature null on frequency split is demonstrated in Figure 3, where the frequency split between the two axes of a tuned gyro is seen to increase as the quadrature nulling voltage is perturbed from its optimal value, 8.44 V. When the gyro is well-tuned, the two resonances are difficult to distinguish, but from theoretical calculations, it is clear that even a small perturbation from optimal quadrature null produces a small frequency split.

### Table 1: Device Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Height</td>
<td>20 µm</td>
</tr>
<tr>
<td>Electrode gap</td>
<td>1.5 µm</td>
</tr>
<tr>
<td>Effective mass</td>
<td>1.95 µg</td>
</tr>
<tr>
<td>( f_n ) (mode A, B)</td>
<td>264.040 kHz, 264.175 kHz</td>
</tr>
<tr>
<td>( Q ) (mode A, B)</td>
<td>60.2k, 58.6k</td>
</tr>
</tbody>
</table>

## RESULTS & DISCUSSION

### Scale factor and bias instability

Following tuning, rate testing was conducted using a rate table (Aerosmith 1291BR) with a maximum rotation rate of 500 °/s. The gyro’s output maintains a linear response for rate inputs up to 500 °/s, showing a scale-factor of 0.286 mV/(°/s). The open-loop rate-axis frequency response, shown in Figure 4, was measured by applying sinusoidal rate inputs at frequencies from 0.25 Hz to 8 Hz and measuring the amplitude of the response. A fit to the frequency response resulted in \( Q = 48,000 \) and a 3 dB bandwidth of 4 Hz, in rough agreement with the open-loop frequency response presented in Figure 2.

The Allan deviation of the zero-rate output (ZRO) was measured using the setup shown in Figure 1, but only minimal temperature control (resulting in measurable fluctuations in operating frequency) and no temperature compensation was implemented. As shown in Figure 5, a bias instability of 3.29 °/hr and ARW of 0.006 (°/s)/√Hz are achieved. The measured ARW is in good agreement with the value predicted from theoretical and measured Brownian noise.

### Temperature compensation of scale factor

The open-loop scale factor from rate to displacement is

\[
SF_{\text{rate}} = \frac{2cm\omega_m x_A Q_B}{k_B},
\]

where \( c = 0.8 \) is the angular gain, \( m \) is the modal mass, \( x_A \) is the drive axis displacement amplitude, and \( Q_B \) and \( k_B \) are
the quality factor and stiffness of the sense axis, respectively. As the device temperature changes, the stiffness and quality factor both change, resulting in large variations in scale factor. The temperature coefficient of $Q$ is $-0.54\%/°C$ for this temperature range, dwarfing the temperature coefficient of $k_B$, $-0.068\%/°C$. The temperature dependence of scale factor without compensation is $-0.524\%/°C$, as shown in Figure 6. Fortunately, since the driven axis of the gyro is operated in a closed loop, it is straightforward to measure changes in the gain of this axis (which is proportional to $Q_A/k_A$) by measuring changes in the drive amplitude required to maintain constant displacement amplitude. Assuming that $Q_B/k_B$ tracks $Q_A/k_A$, the measured drive axis gain was used to compensate the scale factor, reducing the temperature dependence of the scale factor to less than $0.1\%/°C$. The residual temperature dependence is likely due to variations in the mode-matching.

**Drive amplitude-dependent ARW and bias instability**

As shown in Eq. (1), the scale-factor is proportional to drive-axis amplitude, $x_d$. Therefore, both bias instability and ARW can be reduced by increasing $x_d$, assuming that this increase does not affect the offset or noise at the gyro’s output. However, amplitude-dependent nonlinearity of the drive axis resonator, illustrated in Fig. 7, has two effects on the amplitude dependence of ARW and bias instability. First, examining the dependence of scale factor on drive amplitude, shown in Figure 8, it is apparent that the scale factor increases linearly with drive voltage until $v_c = 37\, mV$ is reached, at which point its dependence is sub-linear and increases in drive voltage have a diminishing effect on scale-factor.

A second and more important effect is that operating the resonator above $v_c$ results in increased noise and instability in the gyro output at both short and intermediate integration times. The dependence of ARW and bias instability on drive amplitude was characterized by collecting ZRO and performing Allan deviation tests for varying drive amplitudes. Figure 9 shows that as the drive voltage increases, bias instability initially drops as expected, however, after $v_c$ is reached, a steep increase in bias instability occurs. Beyond this point, the bias instability is somewhat unpredictable, but never drops...
below the value achieved at \( v_c \). The measured scale factor from Figure 8 was used to compute the expected ARW at each drive voltage assuming that the noise is constant. This curve, plotted along with the experimental ARW data in Figure 10, shows that the two curves begin to diverge when the drive voltage exceeds 55 mV, indicating that the output noise is increasing at these voltages.

The increase in bias instability and ARW at large drive amplitudes is attributable to increased noise produced by the resonator. This noise is analogous to the increased phase noise that is observed in micromechanical oscillators operated above the threshold of nonlinearity [7].

CONCLUSIONS
This paper demonstrates an encapsulated polysilicon disk resonator gyro which, despite its small resonator volume, is capable of achieving an ARW of 0.006°/s/√Hz, a scale factor of 0.286 mV/(°/s), and bias instability of 3.29°/hr. These results are enabled by high \( Q \) and careful mode-matching and quadrature null. Because the sense axis is operated open-loop, temperature dependence of \( Q \) and stiffness result in variations in the scale factor. This temperature dependence can be compensated using measurements of the drive axis gain, reducing the scale factor variation to less than 0.1%/°C. The dependence of ARW and bias instability on the drive axis oscillation amplitude was characterized. Amplitude-dependent nonlinearity of the drive-axis resonator was found to result in increased noise in the gyro’s output at large oscillation amplitudes. As a result, the ARW and bias instability were found to decrease with oscillation amplitude until the threshold of nonlinearity was exceeded, after which both ARW and bias instability were found to increase.

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REFERENCES

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