THE FIRST SUB-DEG/HR BIAS STABILITY, SILICON-MICROFABRICATED GYROSCOPE

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ABSTRACT

The first sub-deg/hr bias stability gyroscope is fabricated in single crystalline silicon using the SBM (Sacrificial Bulk Micromachining) process. The quadrature error is a major concern in MEMS gyroscopes for high performance. To minimize the quadrature error the fabricated gyroscope has a very flat bottom surface, which gives a highly symmetrical proof mass and springs, which in turn, provides high performance levels with significantly reduced the quadrature error. The fabricated gyroscope has the bandwidth of 58 Hz, and the 4-hr bias stability of 0.3 deg/hr.

Keywords: gyroscope, bias stability, SBM process

INTRODUCTION

Much effort has been expended by various groups to develop MEMS gyroscopes in the past 10 years for tactical-grade navigation and guidance applications. Achieving the tactical grade performance, i.e., resolution and bias stability less than 1 deg/hr, has proven to be a tough challenge, and has not been demonstrated before in silicon MEMS devices. The key in achieving high levels of the bias stability is in minimizing the quadrature error, which requires near perfect device symmetry.

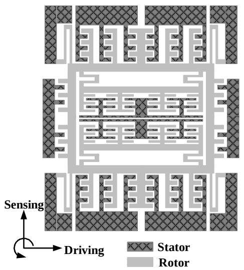
There are three possible causes of the quadrature error, which are asymmetry of the vibrator, unbalance of the stress on beams of the vibrator, and unbalance of the electrostatic force for driving the vibrator. The main cause of the quadrature error was the asymmetry of the gyroscope due to the fabrication imperfection [1]. Many methods have been reported for compensating the quadrature motion. The PI controller based the compensation circuit is used for balancing the gaps between driving combs [2]. The effective mass distribution can be changed by applying different DC bias voltages to the substrate-electrode [1]. The effective spring matrix is controlled by the DC bias voltages of differential interdigitated driving combs [3].

The gyroscope in this paper is fabricated using the SBM process, which is completely free from the

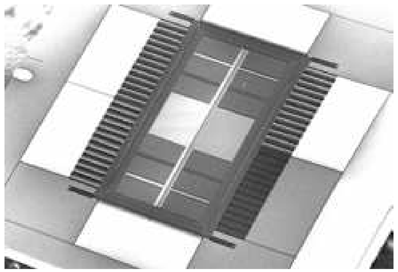
bottom surface fabricated by the SBM process gives near ideal device symmetry preventing the device from the elliptical motion. By the SBM peocess, quadrature error can be significantly reduced. This gives extremely low bias stability.

THE GYROSCOPE WORKING PRINCIPLE AND FABRICATION

The fabricated gyroscope has a decoupled structure between driving mode and sensing mode. Fig. 1 shows the schematic diagram and SEM picture of the fabricated gyroscope. The driving frame and the sensing frame oscillate together in the x-direction. When the Coriolis force induces the y-axis displacement in sensing frame by an external angular motion, the capacitance change due to the displacement is sensed.



(a) Schematic diagram

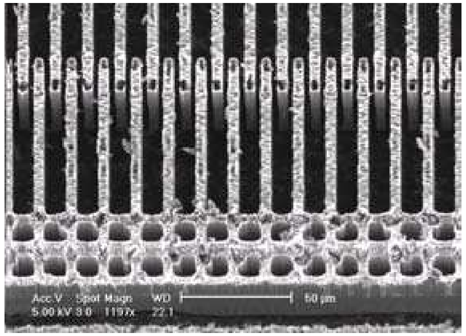


(b) SEM picture

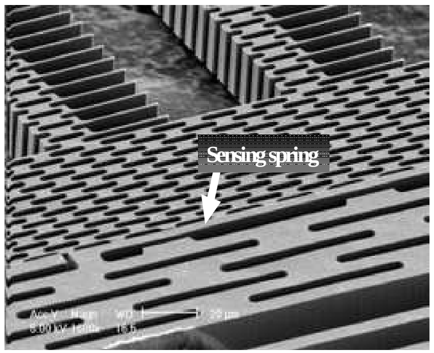
Fig. 1. Schematic diagram and overall view of the

The ideal movement of the driving mass is restricted along the x-direction with no deflection in the y-direction. But in the actual device, the y-direction deflection exists. This is called a quadrature motion. The factors of the quadrature motion are the asymmetry of the springs and the unbalance of the proof mass distribution due to the fabrication [1, 2].

To solve the asymmetry of springs and the unbalance of the proof mass distribution due to the roughened bottom surface, the gyroscope is fabricated by using the SBM process which makes the bottom surface even. In SOI process, the footing is inevitably caused as shown in Fig. 2(a). The footing makes the bottom surface rough. The roughened bottom surface is the factor of the asymmetry of springs and the unbalance of the proof mass distribution. In the anisotropically wet etching step of the SBM process, the roughened bottom surface is flatten as shown in Fig. 2(b) [5]. Therefore, we expect the lower quadrature error. The thickness and the sacrificial gap of the fabricated gyroscope are 40 μm and 20 μm, respectively.



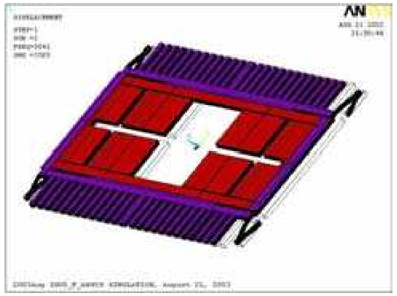
(a) Backside view of the roughened surface using SOI process



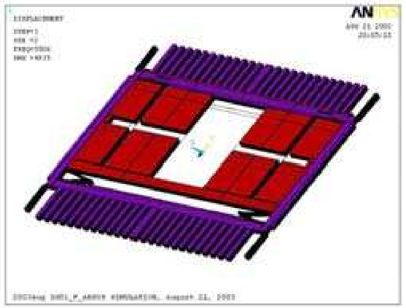
(b) Backside view of the flat surface using the SBM process

Fig. 2. SEM pictures of the fabricated gyroscope

The modal analysis results are shown in Fig. 3. The driving mode and the sensing mode are designed to have the resonant frequency of 5.040 kHz and 5.506 kHz, respectively. The sensing mode resonant frequency is nearly matched to the driving mode resonant frequency by applying DC tuning voltage.



(a) 1st mode (driving mode)



(b) 2nd mode (sensing mode)

Fig. 3. Modal analysis results

EXPERIMENTAL RESULTS

The schematic diagram of sensing electronics is shown in Fig. 4. Two differential sensing electrodes of the gyroscope are connected to the negative input terminals of the charge amplifier. The DC bias voltages for the frequency matching between the driving and sensing frequency are applied to the positive terminal of the charge amplifier, and also applied to the sensing electrodes via virtual ground of the charge amplifier. The proportional voltage to the capacitance in the sensing electrode is produced in the charge amplifier. The output signals from the charge amplifier are amplified by the differential amplifier, and demodulated by the analog multiplier. The demodulated signal is low-pass filtered, and the rate signal is finally obtained.

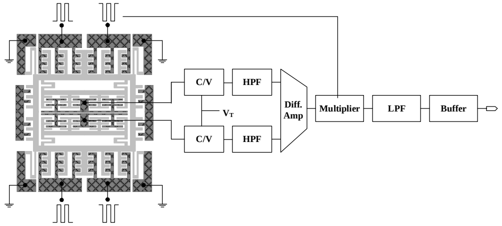
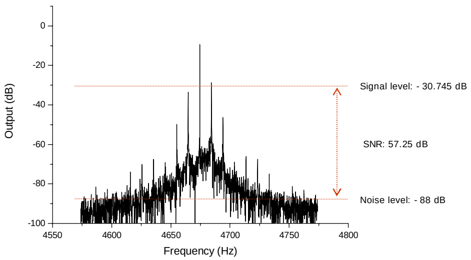
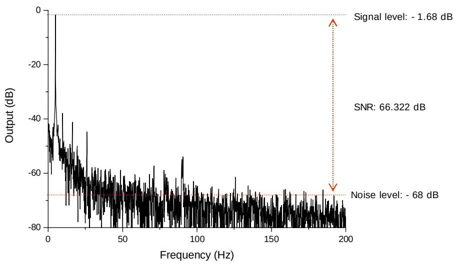


Fig. 4. Schematic diagram of the sensing electronics

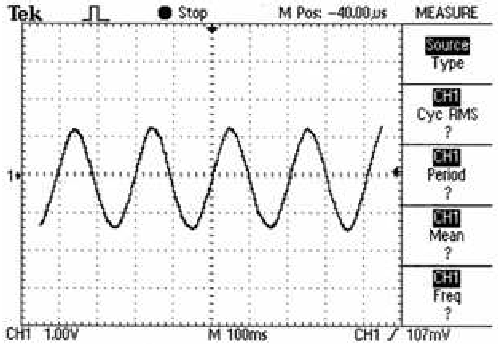
The fabrication gyroscope is tested in a 10 mTorr vacuum chamber, which is installed on a rate table. Fig. 5 shows the modulated output spectrum and demodulated output spectrum when 10 deg/sec, 5 Hz input rate is applied. The measured NER (Noise Equivalent Resolution) is 0.0048 deg/sec. Fig. 6 shows the frequency response of the fabricated gyroscope. The measured bandwidth is 58 Hz. Fig. 7 shows the measured output as a function of the input angular rate. The range is over ± 70 deg/sec, and the output linearity is 0.5 %FSO. Fig. 8 shows the time domain output with zero applied rate input, and the 4-hr bias stability is calculated to be 0.3 deg/hr.



(a) Modulated output spectrum



(b) Demodulated output spectrum



(c) Demodulated output spectrum in time domain

Fig. 5. Output spectrum when 10 deg/sec, 5 Hz angular rate input.

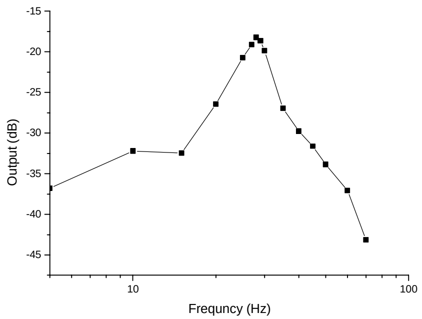


Fig. 6. Measured bandwidth of the fabricated gyroscope

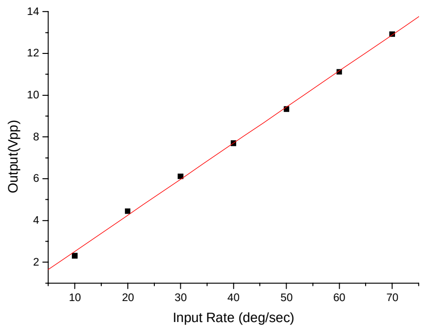


Fig. 7. Output versus angular-rate input

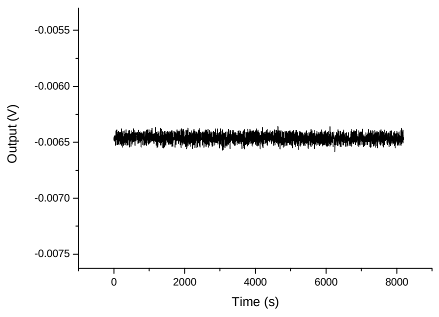


Fig. 8. Time domain output with zero applied rate input

CONCLUSION

The first sub-deg/hr bias stability gyroscope is fabricated in single crystalline silicon using the SBM process, which has the flat bottom surface. The quadrature motion of the device is minimized by near perfect device symmetry. Therefore, the notchless, flat bottom surface fabricated by the SBM process gives near ideal device symmetry preventing the device elliptical motion, and thus, the quadrature error is significantly reduced.

The performance of the fabricated gyroscope is experimentally evaluated. The measured NER (Noise Equivalent Resolution) is 0.0048 deg/sec, and the measured bandwidth is 58 Hz. The 4-hr bias stability is calculated to be 0.3 deg/hr. The SBM process is suitable for fabricating the high-performance gyroscope without the compensating the quadrature motion.

ACKNOWLEDGEMENTS

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