A High Aspect-Ratio Polysilicon Vibrating Ring Gyroscope

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ABSTRACT

This paper presents the fabrication and testing of a high aspect-ratio 80 μ m tall polysilicon ring gyroscope (PRG) fabricated using a new *dry-release* poly-silicon MEMS technology. This single-wafer technology is capable of producing electrically isolated vertical electrodes as tall as the main body polysilicon structure (50 to 100's μ m tall) with various size air-gaps ranging from sub-micron to tens of microns. An open-loop sensitivity of 200 μ V/deg/sec in a dynamic range of ± 250 deg/sec was measured under low vacuum level for a prototype device tested in hybrid format. The resolution for a prototype sensor with a quality factor (Q) of 1200, drive amplitude of 0.15 μ m, and sense node parasitic capacitance of 2pF was measured to be less than 1 deg/sec in 1Hz bandwidth. Elimination of the parasitic capacitance and improvement in the quality factor of the ring structure will improve the resolution to 0.01 deg/sec in 1Hz bandwidth. Three hundred microns long clamped-clamped beam resonators fabricated in this technology have shown measured quality factors as high as 85,000 in 1mTorr vacuum.

Keywords: Gyroscope, high aspect-ratio, silicon micromachining, vibratory gyroscope, yaw rate sensor.

INTRODUCTION

High-performance microgyroscopes [1] are needed in many applications, including inertial navigation, control, and defense/avionics/space. The first nickel *vibrating ring* gyroscope was presented at the 1994 Hilton Head Workshop [2]. The vibrating ring gyroscope, shown in Fig. 1, consists of a ring, eight semicircular support springs, and drive, sense and control electrodes that are located around the structure. The ring is electrostatically vibrated into its first flexural mode with fixed amplitude. When the device is subjected to rotation around its normal axis, Coriolis force causes energy to be transferred from the first mode to the second flexural mode, which is located 45° apart from the first mode, causing amplitude to build up proportionally in the latter mode; this build-up is capacitively monitored. This device provides a number of advantages, including excellent mode matching, high-resolution, low zero-rate output, and long-term stability. The technological requirements for improving gyroscope performance and the scaling limits of ring gyroscopes were previously presented at MEMS 98 conference [3]. This paper reports the fabrication and testing of a high aspect-ratio (20:1), 80 μ m tall, 1.1mm in diameter polysilicon ring gyroscope (PRG) fabricated using a new *dry-release* poly-silicon MEMS technology [4]. This all silicon single-wafer technology is capable of producing electrically isolated vertical electrodes as tall as the main body structure (50 to 100's μ m tall) with various size air gaps ranging from sub-micron to tens of microns. It provides all the features required for eventual realization of "inertial-grade" micromachined gyroscopes and other MEMS devices.

Figure 1: Structure of a vibrating ring gyroscope.

FABRICATION TECHNOLOGY

Figure 2 shows the fabrication process flow for the high aspect-ratio dry-release poly-silicon technology. First, a thin layer of LPCVD silicon nitride is deposited and patterned to serve as an isolation dielectric layer underneath the electrode bonding pads. Deep trenches with straight sidewalls (90° $\pm$ 1°) are then dry etched into a low-resistivity silicon substrate using the STS Silicon Deep Reactive Ion Etcher (DRIE). Trenches with smooth and straight sidewalls are needed to eliminate void formation in the polysilicon beams which will be formed by back-filling these trenches. Mechanical structures are created by refilling trenches with polysilicon deposited over a sacrificial oxide layer. The structural polysilicon layer has to be doped to lower its electrical resistance. Doping with boron is preferred over phosphorous due to the fact that the etch rate of boron-doped poly is much less than the etch rate of phosphorous-doped poly in the HF:H₂O (1:1) solution, leaving the poly beams intact after relatively long HF release step.

Silicon sense electrodes *as tall as the ring structure* are released from the substrate using a *dry directional/isotropic SF₆ silicon etch* performed in an STS etcher. This dry release step consists of a deep, directional etch (depth of the trenches + 20 μ m) followed by an isotropic SF₆ silicon etch. The sacrificial oxide layers are then etched away in HF:H₂O (1:1) solution to create submicron capacitive air gaps between the sense-electrodes and the ring structure.

This technology has been employed to fabricate a number of thick polysilicon vibrating shell gyroscopes [4] with silicon electrodes as tall as the shell structures. Figure 3 shows the SEM view of an 80 μ m tall, polysilicon ring gyroscope. The ring is

1.1mm in diameter and the diameter of the support post is 120 μ m. The width of the ring and support springs is 4 μ m. Sixteen electrodes are evenly located around the structure; they are approximately 60 μ m tall and 150 μ m long and are separated from the ring by a 1.4 μ m capacitive air-gap. Figure 4 shows close-up of a silicon electrode as tall as the main body structure separated from 80 μ m thick polysilicon ring by 1.4 μ m air-gap created through sacrificial oxide etching. The silicon is anchored on top to the supporting polysilicon layer, which is in turn anchored through the isolating nitride layer to the substrate. Vertical polysilicon stiffeners (trench-refilled) are also incorporated in the structure of the electrodes to improve rigidity.

- a) Deposit and pattern the isolating nitride layer;
b) dry etch deep trenches to define the main body structure.

- c) Deposit LPCVD sacrificial oxide and dope surface of the oxide; d) refill trenches with LPCVD polysilicon; e) etch back poly; f) pattern oxide; g) deposit, dope and pattern poly.

- h) Deposit and pattern Cr/Au;
i) SF₆ dry directional etch + undercut and release electrodes;

- j) Etch the sacrificial oxide and completely release structures.

Figure 2: Fabrication process flow for the six-mask, high aspect-ratio dry-release poly-silicon MEMS technology.

Size of the air-gaps in this technology is not limited to sub-micron levels. Larger air-gaps can be realized with polysilicon trench-refilled electrodes. Larger air-gaps are defined by the distance between two adjacent trenches that form the parallel plates of a capacitor. The silicon between these trenches is then directionally etched in the STS machine during the deep release step. If the spacing is so small that etch openings cannot be placed between adjacent trenches, then the silicon between the two trenches is protected with resist on the top but undercut at the bottom and the sides during the deep release step. This narrow piece of silicon which is held by the oxide on the sidewall of trenches will then fall into the HF:H₂O solution during the sacrificial oxide etch. Figure 5 shows the SEM view of wide

capacitive gaps (10-20 μ m) with polysilicon electrodes fabricated using this technology.

Figure 3: SEM view of a prototype 1.7mm $\times$ 1.7mm polysilicon ring gyroscope fabricated through this technology. The dry-release process was entirely carried in the STS machine.

Figure 4: Close-up of a released sense electrode separated by 1.4 μ m air-gap from the vibrating ring. Each sense electrode is 60 μ m tall. Ring and springs are 4 μ m wide and 80 μ m tall.

Figure 5: Various size air gaps from sub-micron to tens of micron.

This technology provides several important features required for high-performance microgyroscopes. First, the height of the polysilicon main body structure “and the electrodes” can be increased to 100’s μm using DRIE. Second, since the body to sense-electrode gap is defined by the thickness of the sacrificial layer, it can be reduced to sub-micron level; *these two factors together will significantly increase the sense capacitance and hence the sensitivity*. Third, the ring to drive-electrode spacing can be made arbitrarily larger than the ring to sense-electrode spacing to achieve larger drive amplitude and in turn, reduce the noise floor. Fourth, improved long-term stability and temperature sensitivity is obtained due to the all-silicon feature of this technology.

TEST RESULTS

An 80 μm tall prototype polysilicon ring gyroscope was tested open loop under vacuum. The sensor chip was connected in hybrid format to an NMOS source-follower buffer chip, as shown in Fig. 6, to measure ring vibrations. The low-impedance output signal of this buffer chip was then amplified off-chip using discrete amplifiers. Drive and control circuitry needed for tuning and open or closed loop operation of the ring gyroscope were implemented off chip using discrete components.

Electronic tuning is an attractive feature of the ring gyroscope. Any frequency mismatch between the sense and drive modes is electronically compensated using tuning electrodes around the structure. By matching the drive and sense mode frequencies, sensitivity is amplified by the Q of the structure. The frequency of the flexural mode of a prototype device is measured to be $\sim 28.3\text{kHz}$ (with 7V bias applied to the ring) which agrees well with calculation and ANSYS simulation results. As shown in Fig. 7, drive and sense mode frequencies of the ring gyro were 63Hz apart due to imperfections. The balancing voltages required to null this 63Hz of frequency split between the modes were only $\pm 0.9\text{V}$. After balancing, the two peaks merge together and the sense and drive mode frequencies become equal. We have also been able to balance ring structures with up to 1kHz of frequency split ($f_0=28\text{kHz}$) by applying less than 6 Volts tuning voltages to the balancing electrodes. Small capacitive gaps (1.4 μm) have indeed shifted the tuning voltages down to CMOS acceptable levels, increasing the tuning capability.

The measured Q of 1.1mm, 80 μm -thick ring structure was $\approx 1000\text{-}2000$. This is much smaller than anticipated due to excessive

Figure 6: Hybrid attachment of the sensor chip to the buffer chip.

anchor and bulk losses (voids inside the poly beams). Modified devices with solid post design are expected to have higher Q in the range of 10,000-20,000 and hence higher sensitivity. 80 μm tall, 300 μm long clamped-clamped beam micromechanical resonators fabricated in this technology have shown quality factors as high as 85,000 in 1 mTorr vacuum [4].

Figure 8 shows the response of a prototype ring gyroscope to a 5Hz sinusoidal input rotation rate with peak-to-peak amplitude of 120 deg/sec. Figure 9(a) shows the response of a prototype device to input rotation rates up to ± 250 deg/sec in a 5Hz bandwidth. It should be noted that this measurement was carried out under poor vacuum level and the quality factor was about 250 which is much less than the actual Q of the ring structure under high vacuum. This drop in the quality factor reduces the open loop output signal by a factor of 5-8. Also, the output signal has been further reduced due to large parasitic capacitance in the output sense node. The parasitic capacitance associated with the hybrid connection (C_{imp} of the buffer + capacitance of bonding pads and wirebonds) have been measured to be around 2pF total. This large capacitance has degraded the output signal by an additional factor of 5. The sensitivity of a prototype device under poor vacuum ($Q \approx 250$) and large parasitics ($C \approx 2\text{pF}$) was measured to be 200 $\mu\text{V}/\text{deg/sec}$.

Figure 7: Electronic balancing of the ring gyroscope. (a) *Before balancing*: Two flexural resonant peaks of a prototype ring gyroscope have different frequencies ($\Delta f=63\text{Hz}$ for $f_0=28\text{kHz}$). (b) *After balancing*: two peaks merge together and the frequencies become equal.

Figure 8: Response of a prototype single ring gyroscope to a 5Hz sinusoidal rate with a peak-to-peak amplitude of 120 deg/sec.

Another set of measurements was taken under improved vacuum levels. The Q was measured to be ≈ 1200 after balancing. Figure 9(b) shows the response of the sensor to rotation rates in the range of -20 deg/sec to 20 deg/sec. The resolution was measured to be ≈ 1 deg/sec. This resolution for a Q of 1200 and parasitic capacitances of 2pF is in agreement with theory. The resolution of the sensor is currently limited by the noise from the circuitry. Elimination of parasitic capacitances and improvement in Q will reduce the resolution to 0.01 deg/sec in 1Hz bandwidth, which is the Brownian noise floor for the single ring polysilicon gyroscope with a drive amplitude of $0.15\mu\text{m}$ (Table 1). By increasing the drive amplitude to $1\mu\text{m}$ in an asymmetric polysilicon ring gyroscope design, a minimum detectable signal of 5×10^{-3} deg/sec (18 deg/h) in a 10Hz bandwidth can be achieved.

CONCLUSIONS

This paper presents the fabrication and testing of a high aspect-ratio $80\mu\text{m}$ tall polysilicon ring gyroscope fabricated using a new *dry-release* poly-silicon MEMS technology. An open-loop sensitivity of $200\mu\text{V}/\text{deg}/\text{sec}$ in a dynamic range of ± 250 deg/sec was measured under low vacuum level for a prototype device tested in hybrid format. The resolution for a prototype sensor with a quality factor (Q) of 1200, drive amplitude of $0.15\mu\text{m}$, and sense-

node parasitic capacitance of 2pF was measured to be less than 1 deg/sec in 1Hz bandwidth. Elimination of the parasitic capacitance and improvement in the quality factor of the ring structure will improve the resolution to 0.01 deg/sec in 1Hz bandwidth.

Table 1: Specifications and calculated performance of the polysilicon vibrating ring gyroscope.

Design Parameter	Target Value
Material Quality Factor	20,000
Ring Diameter	1.1 mm
Sense Electrode Gap Spacing	$1.4\mu\text{m}$
Ring and Springs Width	$4\mu\text{m}$
Height of the Ring Structure	$80\mu\text{m}$
Support Post Diameter	$120\mu\text{m}$
Height of Each Electrode	$60\mu\text{m}$
Resonant Frequency	27.3 kHz
Interface Circuit Input Noise (V_n)	$1\mu\text{V}/(\text{Hz})^{0.5}$
Parasitic Capacitance ($C_{\text{device}} + C_{\text{pad}}$)	500 fF
Polarization Voltage (V_p)	7V
Drive amplitude	$0.15\mu\text{m}$
Brownian Noise Floor	$0.01\text{ deg/sec}/(\text{Hz})^{0.5}$
Min. Detectable Signal (10Hz BW)	0.04 deg/sec

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Figure 9: (a) Measured rate results obtained from a prototype ring gyroscope in a 5Hz BW, range= ± 250 °/sec; (b) Measured rate results obtained from a prototype ring gyroscope in a 5Hz BW, range= ± 25 °/sec.