MINIATURE ORIGAMI-LIKE FOLDED MEMS TIMU

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ABSTRACT

In this paper, we report implementation of a folded MEMS concept, demonstrating a prototype of Timing and Inertial Measurement Unit (TIMU) in < 50 mm^3 volume. The approach is based on assembling high aspect-ratio single-axis sensors into a 3-D configuration, or folding it into a 3-D prismatic shape, like a silicon origami. The fabrication process permits a significant reduction in size preserving functionality without compromising sensor performance. Fabricated TIMU prototypes feature 3 toroidal ring gyroscopes, 3 accelerometers, and a resonator, thus allowing for miniature self-contained 6-DOF inertial and timing system. Initial characterization confirmed the potential of folded MEMS approach for implementation of low-noise inertial sensors, demonstrating VRW of 0.078 m/s/$\sqrt{\text{h}}$ and bias instability of <0.2 mg for accelerometers, ARW of 0.78 $^\circ/\sqrt{\text{h}}$, and bias instability of <17 °/h for gyroscopes.

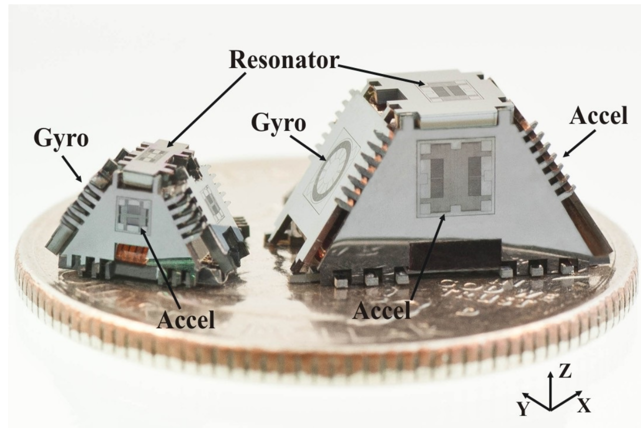

Figure 1: Fabricated TIMU prototypes in 50 mm^3 and 178 mm^3 volume on a quarter US dollar coin. When folded in a 3-D configuration, devices allow for 3-DOF orientation, 3-DOF positioning, and timing data.

INTRODUCTION

Recently, there has been a growing interest in miniaturized MEMS-based Timing and Inertial Measurement Units (TIMUs). MEMS TIMUs have been adopted in consumer electronics, such as mobile phones and gaming devices, as they provide an advantage of small size, low power, and low cost. Improved performance of these devices, in combination with their compact form-factor, enables a wide range of applications, including miniature platforms for personal navigation, small unmanned vehicles, and a broad variety of new applications never-before-envisioned.

Most conventional methods to implement a compact MEMS IMU fall into three general categories. First approach is based on discrete assembly of 6 individual sensors, [1-3]. Using this approach, off-the-shelf single-axis sensors are assembled into a 3-D IMU configuration on macro-scale. Sensors are typically optimized to reject off-axis inputs, allowing for improved IMU performance. However, this approach requires an assembly of 6 separate sensors, resulting in increased size and weight of the system. An alternative method is to fabricate single-axis or multi-axis sensors on a single chip, [4-6]. This approach delivers an advantage of extremely small volume at the cost of potentially increased sensitivity to linear vibrations and cross-axis talk. A third approach for a MEMS IMU involves chip stacking, [7]. The technique is based on a vertical stack bonding of multiple layers of inertial sensors and electronic components. This approach allows for the reduced IMU footprint, however mechanical, electrical, and thermal cross-talk, reliability of bonding, and implementation of interconnects remain to be a challenge.

In this paper, we introduced an alternative method for high-performance miniature TIMU, which combines the advantages of conventional MEMS approaches. We report a TIMU fabrication process based on folding high aspect-ratio single-axis sensors into a 3-D configuration. Our technique enables extreme miniaturization, while ensuring high sensitivity.

ORIGAMI-LIKE FOLDED TIMU CONCEPT

Folded MEMS TIMU approach is based on double-sided Silicon-on-Insulator (SOI) fabrication process. High aspect-ratio single-axis sensors are created on the device side of the SOI wafer, while metal interconnects and polyimide hinges are formed on the handle side of the wafer, Fig. 2(a). Inertial sensors are intended to be vacuum packaged for improved sensitivity, Fig. 2(b). The TIMU fabrication process is developed so that the sensors can be interfaced with an integrated signal conditioning electronics, Fig. 2(c). Integration with electronics is enabled by introducing the technology of Thru-Wafer Interconnects for Double-Sided (TWIDS) realization of sensors on SOI wafers, [8]. Thru-wafer interconnects provide electrical connection from sensors on the device side of the wafer to Application-Specific Integrated Circuit (ASIC) components on the back side of the wafer. Polyimide flexible hinges are utilized for assembly of the integrated MEMS sensors in a 3-D configuration, or folding in a 3-D shape, Fig. 2(d). Once folded, the sidewalls of the 3-D structure are fused together to maintain the alignment of sensors, [9]. Miniature folded TIMU enables the measurement of 6-DOF motion and

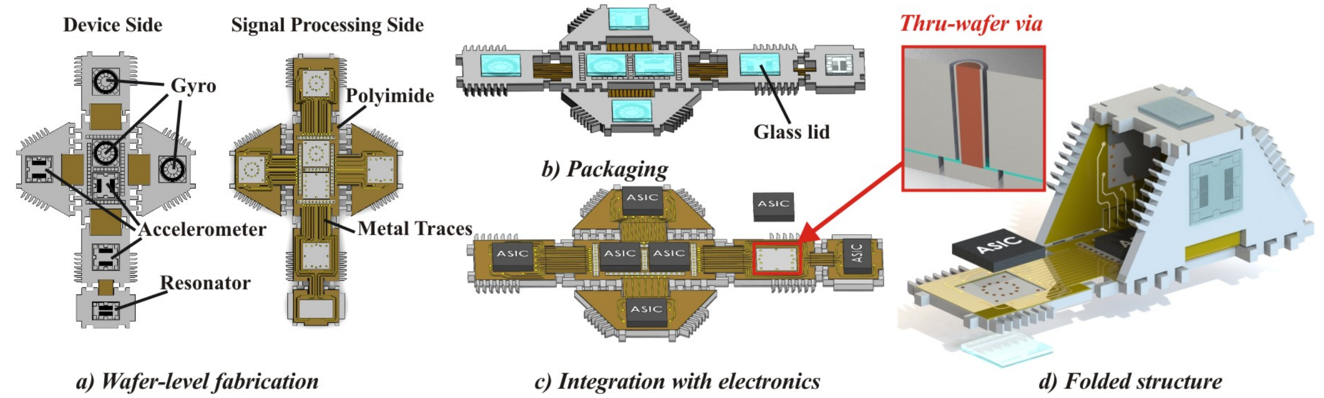

Figure 3: "Origami-like" Folded MEMS process. Double-sided approach enables efficient utilization of the TIMU inner volume.

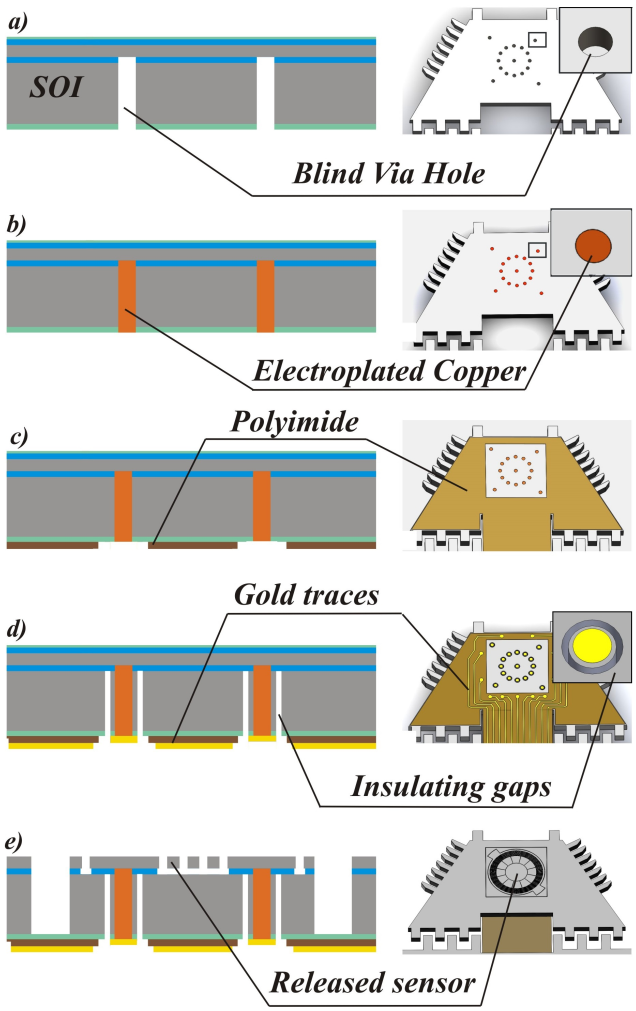

Figure 2: 6-Mask wafer-level fabrication process for double-sided TIMU with thru-wafer interconnects.

time. In addition, an efficient utilization of the TIMU inner volume is achieved by integration with electronics.

FABRICATION

Manufacturing process for Folded TIMU involves inertial sensors fabrication, forming flexible hinges, and defining electrical interconnects to each of the sensors in the sensor cluster. In the first step of the process, thru-wafer interconnects are fabricated using seedless copper electroplating method. First, a 5 μm thick SiO_2 hard mask is deposited on the handle side of the SOI wafer. The mask is used for the Deep Reactive-Ion Etching (DRIE) of blind via holes. This is followed by removing of buried oxide layer inside the via holes to permit electrical contact with a highly doped silicon device layer, Fig.3(a). Sonic-assisted copper electroplating is utilized to fill the via holes with metal, Fig. 3(b). This method allows for ultra-low resistance voids-free features. Electrical resistance across the vertical connection of less than 0.5 Ohm was demonstrated for the 60 μm diameter via holes, [10]. The wafers are then lapped to remove the excessive copper and to prepare the surface for the next lithography step. Once thru-wafer interconnects are defined, polyimide layer is deposited, photo-lithographically patterned, and cured for 1 hour at 375 °C temperature, Fig. 3(c). Metal traces are then created on top of the polyimide, using electron beam evaporation for deposition of a 500 $\mathring{A}$ adhesion layer of chrome, and 5000 $\mathring{A}$ layer of gold, followed by a metal lift-off process, Fig. 3(d). Next, 35 μm donut-shaped gaps are etched around the copper filled vias in order to provide insulation, Fig. 3(d). Top-side processing involves etching of sensor features and thru-wafer etching, which is necessary for separation of the TIMU panels for subsequent folding in a 3-D configuration, Fig. 3(e).

In the described process flow, the sensor features are etched in the final step using the SiO_2 hard mask. This eliminates a need for sensors protection during the thru-wafer etch and allows to avoid aggressive cleaning after the fabrication is complete. To release the devices, the underlying buried oxide is etched using vapor HF.

Fabricated TIMU prototypes feature 3 toroidal-ring gyroscopes, 3 accelerometers, and a resonator, Fig 5. However, other types of inertial sensors can be fabricated in the introduced process. After the fabrication is complete, the TIMU

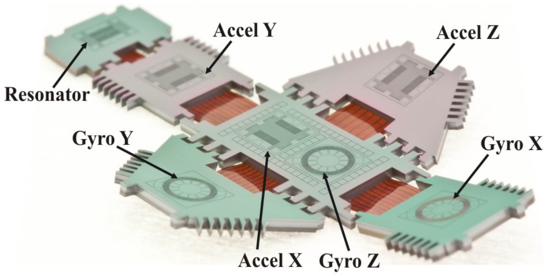

Figure 4: Fabricated unfolded structure, featuring 3 ring gyroscopes, 3 accelerometers, and a resonator.

devices are folded into a 3-D configuration, Fig. 1.

EXPERIMENTAL CHARACTERIZATION

TIMU prototypes in <50 mm^3 volume with all 7 sensors operational were demonstrated, thus confirming feasibility of the proposed fabrication approach, Fig. 5. Frequency domain characterization showed resonant frequency of the resonator at 5.57 kHz and resonant frequencies of 3 accelerometers spaced at 640, 648 and 670 Hz. Characterization of toroidal ring gyroscopes co-fabricated on the TIMU sidewalls revealed frequency splits of 10 Hz, 35 Hz and 220 Hz at the center frequencies of 14 kHz, 15 kHz, and 15.9 kHz, correspondingly, with a Q-factor of 27 in air and 50,000 at 1 mTorr vacuum. Bias instability of less than 0.2 mg and velocity random walk (VRW) of 0.078 m/s/$\sqrt{\text{h}}$ were demonstrated for X, Y, and Z accelerometers, [11].

The toroidal ring gyroscope integrated on the TIMU folded structure is comprised of an outer anchor that surrounds the device, a distributed ring structure, and an inner electrode assembly, Fig. 6(a), [12]. The suspension system consists of sixteen 10 um thick concentric rings, connected to each other using spokes between the rings. The distributed support structure decouples the vibrational motion of the innermost ring from the substrate, effectively minimizing the anchor loss. The inner electrode assembly comprises 12 radial electrodes used as a forcer and as a pick-off for each mode. The device is designed to operate at resonant frequency of 14 kHz in n=3 wineglass mode, which is inherently robust to fabrication asymmetries. The gyroscope architecture provides an opportunity to reorder the fundamental wineglass modes. In this implementation, n=3 mode has the lowest stiffness among all wineglass modes, potentially allowing for the improved vibration immunity, Fig. 6(b) and (c).

Dynamic response of the toroidal ring gyroscope was tested using the capability of Ideal Aerosmith 2102 Series Two-Axis Position and Rate Table System, allowing to produce a rotation with programmed sinusoidal angular acceleration. Electrostatic actuation and capacitive detection were employed for gyroscope operation. The gyroscope was excited with a constant DC voltage of 34.5 V and AC voltage generated by a Phase Locked Loop (PLL), Fig. 7. A carrier of 1.9 Vrms at 100 kHz was applied to the proof mass, resulting

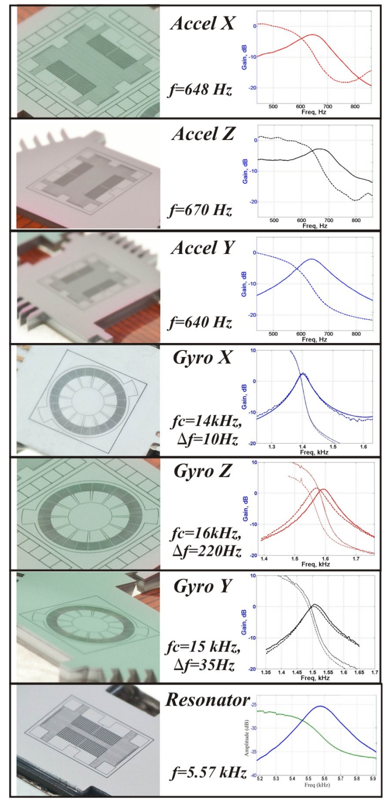

Figure 5: Freq. sweeps of 3 accelerometers, 3 gyroscopes, and a resonator implemented on the same TIMU device.

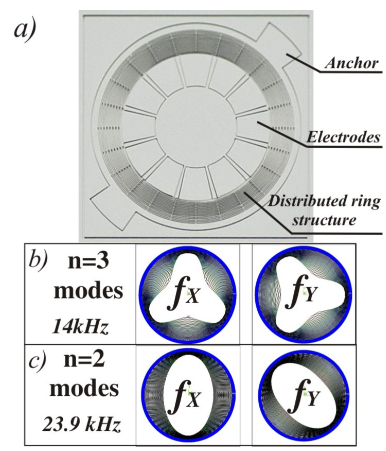

Figure 6: Toroidal ring gyroscope implemented on TIMU. Design permits ordering the fundamental wineglass modes.

in the amplitude modulation of the sensor output. A low-noise fully input/output differential amplifier (Texas Instrument Op. Amp. THS4131) was used in a transimpedance configuration in order to convert motional current to voltage, as well as to increase the signal-to-noise ratio. The output signal is then demodulated to reveal the low frequency changes in capacitance. The amplitude of the drive-mode motion was stabilized, using an Automatic Gain Control (AGC). All loops

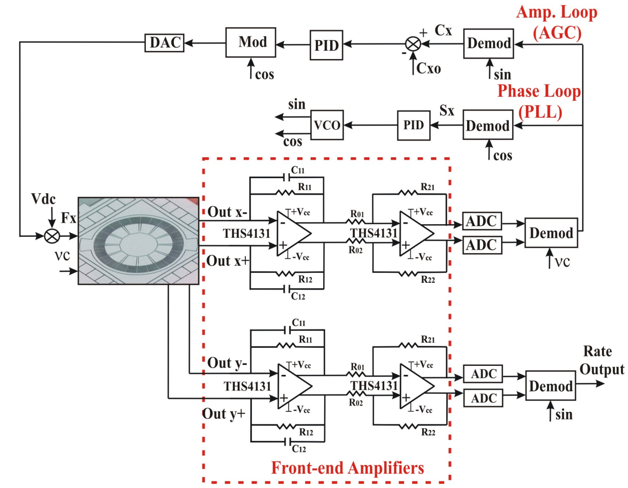

Figure 7: Signal detection schematics for characterization of gyroscopes.

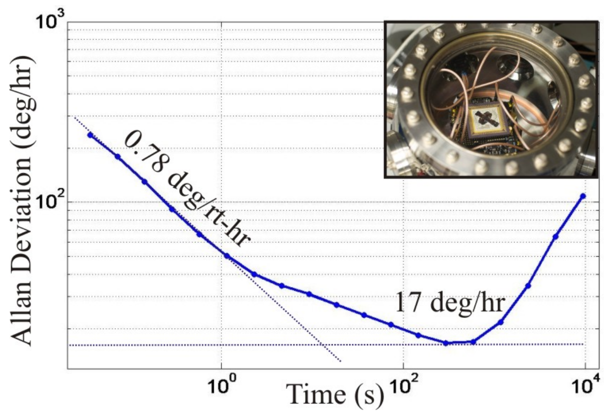

Figure 8: Allan deviation of gyroscope output, showing bias stability of <17 deg/h and ARW of 0.78 $deg/\sqrt{h}$.

were realized using a Zurich Instruments HF2LI digital lock-in amplifier. Initial gyroscope characterization was performed in an open loop configuration without mode-matching of the device. Rate table experiment revealed the gyroscope scale factor of 1.1 mV/(deg/s). The Root Allan Variance Analysis (r-AVAR) was used for identification of random noise characteristics. Experimental characterization of the toroidal ring gyroscope in vacuum demonstrated ARW of 0.78 $°/\sqrt{\text{h}}$ and bias instability of 17 °/h, Fig. 8.

CONCLUSIONS

A Folded MEMS method for realization of TIMU has been presented in this paper. The process combines advantages of conventional IMU approaches and a compact form-factor, allowed by MEMS technology. The approach is based on folding high-performance single-axis sensors into a 3-D configuration. Thru-wafer interconnects enable efficient utilization of the TIMU inner volume, which can be potentially interfaced with integrated signal processing electronics. 50 mm^3 TIMU prototype that contains three gyroscopes, three accelerometers, and a resonator have been successfully fabricated, and all seven sensors have been implemented and demonstrated to be operational. Characterization of gyroscopes revealed ARW of 0.78 $°/\sqrt{\text{h}}$ and bias instability of 17 °/h. These results demonstrate the feasibility of the Folded MEMS fabrication process to provide a technological platform for 3-D sensor configuration.

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