Origami-like Folded MEMS for Realization of TIMU: Fabrication Technology and Initial Demonstration

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***Abstract*—This paper reports a prototype of miniature, <50 mm^3, Timing and Inertial Measurement Unit (TIMU), implemented utilizing a Folded MEMS concept. The approach is based on a wafer-level fabrication of high aspect ratio single-axis sensors, interconnected by flexible polyimide hinges, and then folded into a 3-D configuration, typically in a shape of cube or prism. Co-fabricated thru-wafer interconnects enable interfacing sensors on the device side of the TIMU with signal conditioning electronics potentially integrated inside a folded 3-D structure. We report a TIMU prototype with all 7 sensors operational, thus demonstrating a feasibility of the proposed fabrication approach. In this paper, we emphasize the characterization of the low-noise accelerometers, implemented on the TIMU sidewalls, demonstrating VRW of 0.057 $m/s^2/\sqrt{h}$ and bias instability of <0.2 mg.**

INTRODUCTION

Miniaturized MEMS-based Timing and Inertial Measurement Units (TIMUs) is currently an active area of developments. The reduced Cost, Size, Weight, and Power (C-SWaP) high-performance MEMS TIMU chip is a desirable solution for miniature platforms, including those needed for personal navigation and unmanned air/underwater vehicles.

There are currently two main fabrication approaches for implementation of MEMS-based TIMU: a discrete assembly of 6 individual sensors [1-4] and implementation of all 6 sensors on a single chip [5-7], Fig.1. In conventional approaches three gyroscopes and three accelerometers are combined in a single unit, allowing for high-performance position and orientation measurements. However, this approach requires six separate sensors, which generally increases the size and weight of the system. For example, utilizing the discrete assembly approach, a tactical grade IMU has been demonstrated by Honeywell in 82 cm^3 volume (HG 1930 in Fig.1) and a near-tactical grade IMU by Sensonor in 37 cm^3 volume (STIM 300 in Fig.1). In contrast, utilizing a single chip approach, very small volume IMUs have been reported at consumer grade performance. For example, IMU in 22 mm^3 volume has been demonstrated by ST Micro, (LSM 330DLC in Fig.1). Despite a significant progress towards the high performance MEMS TIMUs, made by both commercial institutions [1-7] and academia [8], realization of tactical grade devices in a compact form factor remains a challenge.

In contrast to solutions currently available on the market, our method is based on wafer-level fabrication of high aspect-ratio single-axis sensors and then folding them into a 3-D configuration. This permits a significant reduction in TIMU size, without compromising in sensor performance, [9-12]. In this work, we report the most recent developments in the "origami-like" MEMS paradigm, demonstrating a <50 mm^3 TIMU with 7 single axis high-aspect ratio sensors and thru-wafer interconnects.

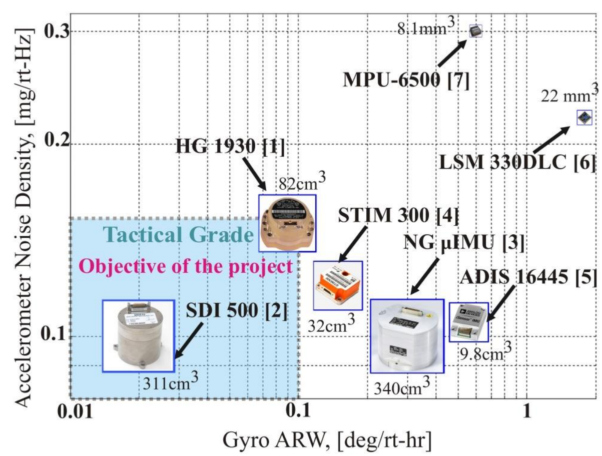

Fig. 1. Commercial MEMS IMUs Performance

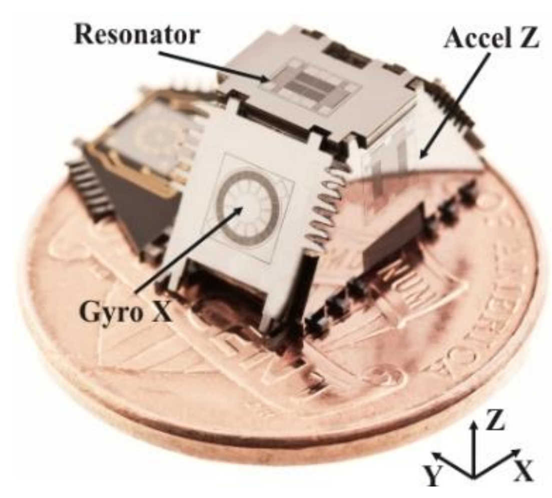

Fig. 2. Fabricated TIMU prototype folded in a 3D configuration, allowing for 6-DOF orientation, positioning data, and timing.

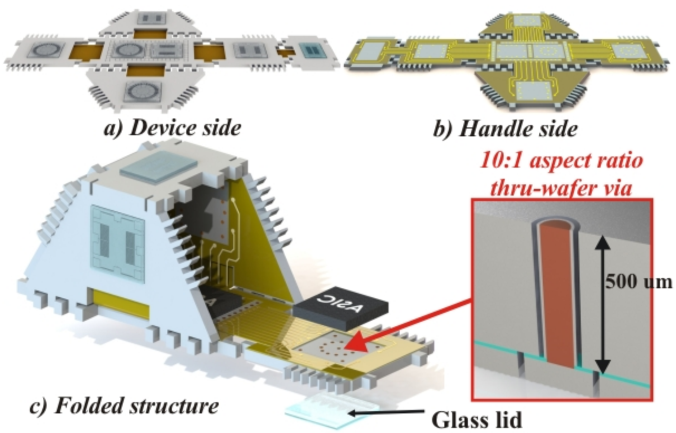

Fig. 3. Double-sided MEMS "origami-like" TIMU integrated with high aspect-ratio thru-wafer interconnects.

"Origami-like" Folded TIMU Concept

Folded MEMS TIMU approach is based on fabrication of flat structures with high performance single-axis sensors on the device side of the SOI wafer and metal traces on the handle side, Figs. 3 a) and b). Polyimide flexible hinges connect the device panels, allowing for assembly of the integrated MEMS sensor cluster in a 3-D configuration, or folding in a 3-D shape. Folded TIMU enables the measurement of 6-DOF motion and time. Co-fabricated silicon latches are strategically located along the edges of each panel and assure the rigidity of the folded structure. Once folded, the sidewalls of the 3-D structure are fused together using silicon laser welding or integrated resistive heating. Structural rigidity and alignment stability of the reinforced folded IMU have been shown in [9].

An integral part of the process is the technology of Thru-Wafer Interconnects for Double-Sided (TWIDS) realization of sensors on Silicon-on-Insulator (SOI) wafers. In folded TIMU, thru-wafer interconnects provide a path for electrical signals from sensors on the device side of the wafer to Application-Specific Integrated Circuit (ASIC) components on the back side of the wafer. Thru-wafer interconnects enable efficient utilization of the TIMU inner volume, which can be equipped with signal processing electronics.

Fabrication Process

Manufacturing process for double-sided folded TIMU requires 6 fabrication masks, [10]. The process starts with Deep Reactive-Ion Etching (DRIE) of blind via holes through the 500 μm handle substrate of the SOI wafer, Fig.4(a). This is followed by removal of 5 μm buried oxide layer inside the via holes to permit electrical contact with the 100 μm device layer. Different etching techniques might be used to remove the oxide, such as wet etching with HF or dry etching with Reactive-Ion Etching (RIE) . The via holes are then filled with copper using sonic-assisted seedless electroplating method. This approach does not require any additional conductive seed layer deposition, but utilizes a highly doped silicon device layer as a seed for electroplating, Fig. 4(b). This technique

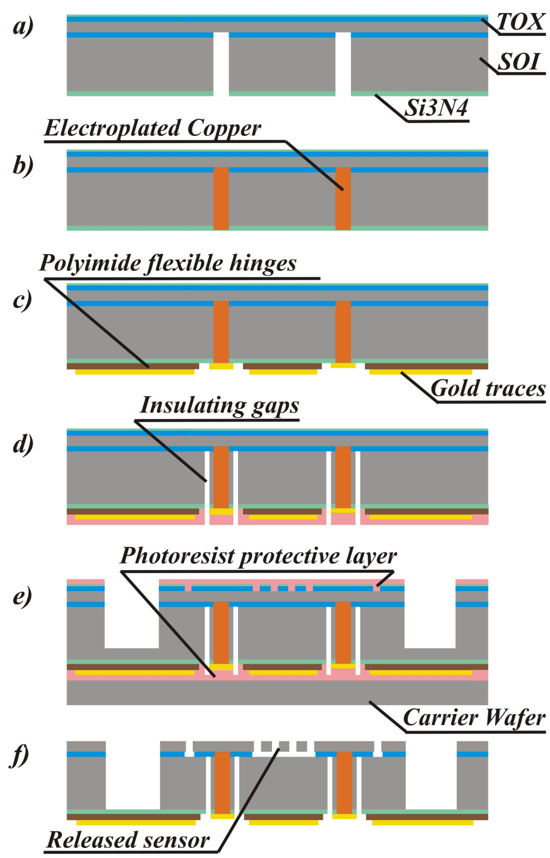

Fig. 4. 6-Mask wafer-level fabrication process for double-sided TIMU with thru-wafer interconnects.

assures high aspect-ratio void-free features and allows for high density array of ultra-low resistance thru-wafer interconnects, [11].

Following the fabrication of TWIDS, the wafers are lapped to prepare for the next lithography step. Photo-definable polyimide is deposited by spin-coating the substrate and a pattern is photo-lithographically defined, Fig. 4(c). After curing at 375 °C, the polyimide layer thickness is typically around 20 μm. Polyimide acts as a structural material for flexible hinges and as an insulation material for metal interconnects. Metal traces are created on top of the polyimide layer, using a metal lift-off process, then 35 μm donut-shape insulating gaps are etched around the copper filled vias, Fig. 4(d).

Top-side processing involves etching of sensor features and thru-wafer etching, which is necessary for separation of panels for subsequent folding in a 3-D shape. The process starts with creating a SiO_2 hard mask. The thru-wafer etch is then performed by, first, covering the sensors with a layer of photoresist, then DRIE etching a 100 μm device layer, removing buried oxide, and DRIE etching a 400 μm handle wafer, Fig. 2(e). At this point the thru-wafer etch is not complete and another 100 μm of the handle wafer needs to be removed. This is done by stripping off the photoresist protective layer to open the sensors features and continuing etching, using the previously defined SiO_2 hard mask. During this step the sensors and the last 100 μm of the handle wafer

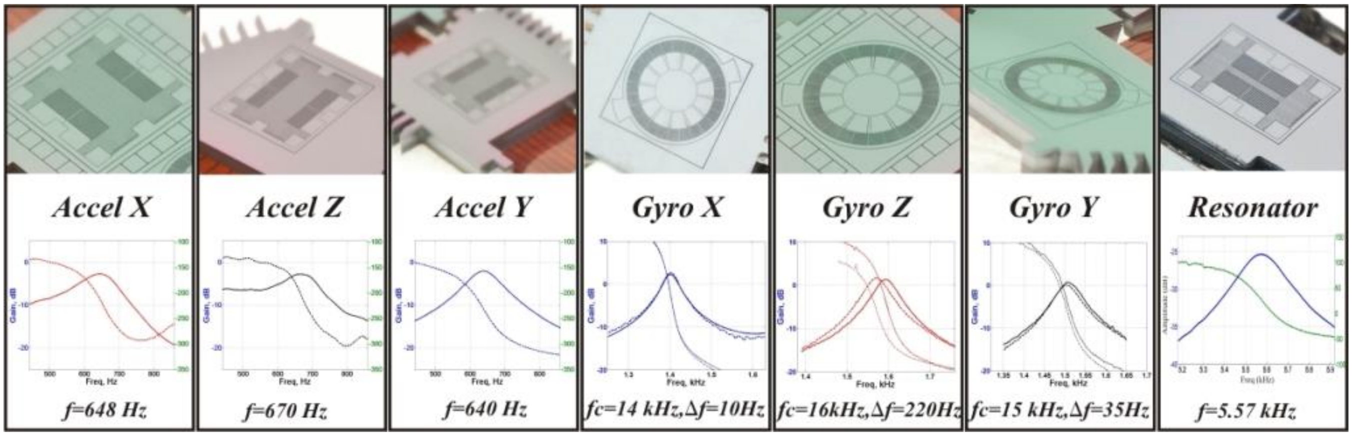

Fig. 5. Frequency sweeps of 3 accelerometers, 3 gyroscopes, and a resonator implemented on the same TIMU device. Gyroscopes Q-factor of 27, and accelerometers Q-factor of 5 (in air). Frequencies are separated to minimize mechanical cross-talk between sensors.

are etched in parallel, Fig. 2(f). The sensors are then released, using vapor HF.

After fabrication process is complete, the TIMU devices are folded into a 3-D configuration, using flexible hinges. The sidewalls are fused together to maintain the original alignment of sensors.

Experimental Results

The fabricated TIMU is comprised of three single-axis toroidal ring-gyroscopes, three accelerometers, and a resonator, Fig. 6. When folded, the TIMU occupies a volume of <50 mm^3, Fig. 7.

The SOI accelerometers implemented on the TIMU sidewalls are comprised of the suspended proof-masses. Two pairs of differential electrodes with parallel plates are used for sensing the capacitance change under the applied acceleration. The SOI toroidal ring gyroscopes consist of an outer anchor that surrounds the device, a distributed ring structure, and an inner electrode assembly [15]. The suspension system consists of sixteen 10 μm thick concentric rings, connected to each other using spokes between the rings. Vibration energy is concentrated at the innermost ring. The distributed support structure decouples the vibrational motion from the substrate. This decoupling mitigates anchor losses to the substrate. The device is designed to operate in n = 3 wineglass modes. The inner electrode assembly is comprised of 12 radial electrodes used as a forcer and as a pick-off for each mode.

TIMU devices were die-attached to an adapter board, packaged into a 181-pin, gold plated through-hole ceramic pin grid array (CPGA) package, and assembled with front-end electronics. Frequency domain characterization revealed the resonant frequencies of 3 accelerometers at 640, 648 and 670 Hz, Fig. 5. Gyroscopes characterization was performed in air and resulted in frequency splits of 10 Hz, 35 Hz and 220 Hz at center frequencies of 14 kHz, 15 kHz and 15.9 kHz, correspondingly, with a Q-factor of 27, Fig. 5. Frequencies of the devices are separated by design in order to minimize mechanical cross-talk between sensors.

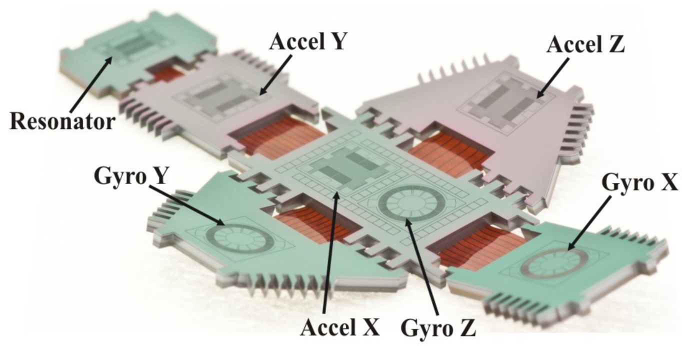

Fig. 6. Fabricated unfolded structure, featuring 3 ring gyroscopes, 3 accelerometers, and a resonator (a prototype of the reference clock).

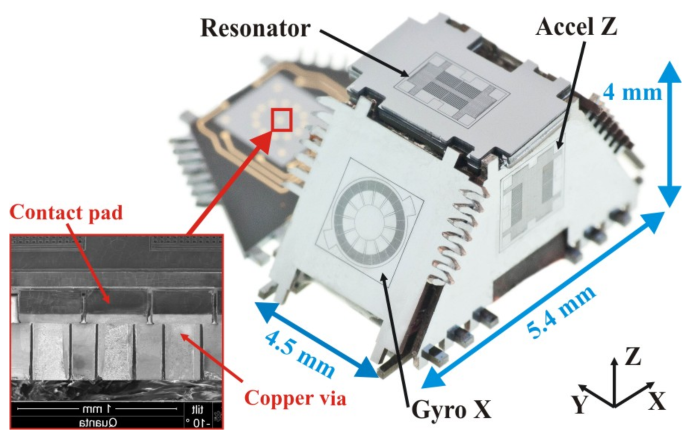

Fig. 7. Fabricated TIMU prototype, folded into a 3-D configuration. Insert: Copper electroplated thru-wafer interconnects.

Even though we demonstrated all 7 sensors operational, in this paper we focus on characterization of 3 accelerometers, implemented on the sidewalls of the same TIMU device. In order to derive the accelerometer's scale factor, the TIMU prototype and the signal processing electronics were mounted on the tilt table. The accelerometer response test was conducted

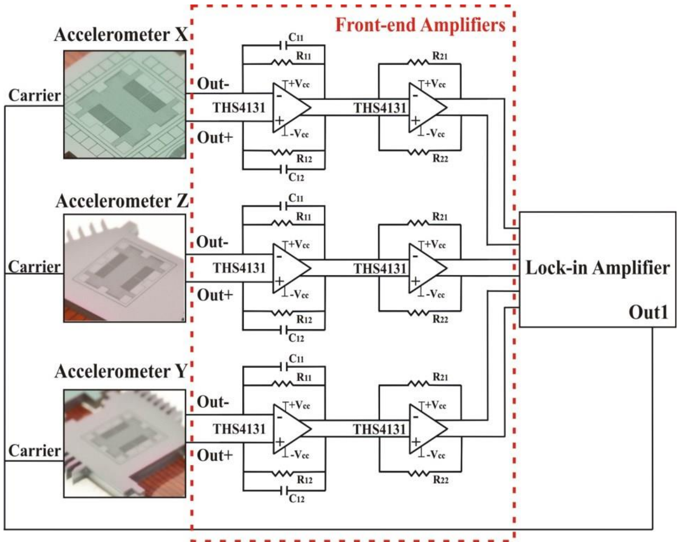

Fig. 8. Signal detection schematic utilized for characterization of accelerometers.

by tilting the stage 90 deg around the X and Y axes, providing ±1 g of acceleration amplitude. The carrier demodulation with a Zurich Instruments lock-in amplifier was used to measure the output current, Fig. 8. A low-noise fully input/output differential amplifier (Texas Instrument Op. Amp. THS4131) was used in a transimpedance configuration in order to convert current to voltage, as well as to increase the signal-to-noise ratio. The scale factors of 39.9, 46.2, and 34 mV/g were measured for X, Y, and Z accelerometers, correspondingly, Fig. 9. Experimental characterization of 3 accelerometers showed bias instability as low as 0.2 mg, and VWR of 0.057 $m/s^2/\sqrt{h}$, Fig. 10. Initial TIMU characterization proved the feasibility of the double-sided fabrication approach for compact folded TIMU, potentially capable to operate on the level of tactical performance.

Conclusion

Wafer-level process for fabrication of miniature <50 mm^3 TIMU has been presented in this paper. The approach is based on folding high aspect-ratio single-axis sensors on wafer-level, which permits a significant reduction in TIMU size without compromising in sensor performance. In addition, wafer level integration with electronic components is possible if a technology of Thru-Wafer Interconnects for Double-Sided (TWIDS) MEMS fabrication process is used.

The TIMU prototype that contains three gyroscopes, three accelerometers, and a resonator have been successfully fabricated and all seven operational sensors have been demonstrated. Characterization of accelerometers revealed VRW of 0.057 $m/s^2/\sqrt{h}$ and in-run bias instability of <0.2 mg.

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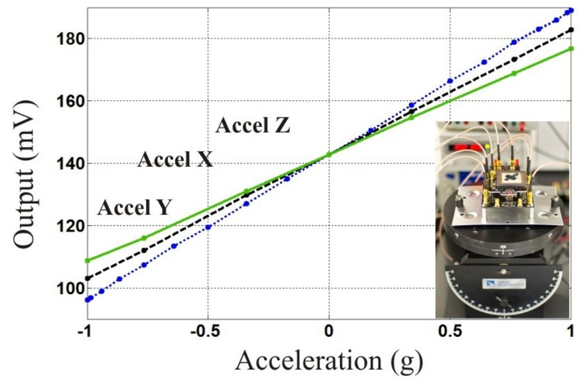

Fig. 9. Scale factors of 3 accelerometers from the same TIMU prototype.

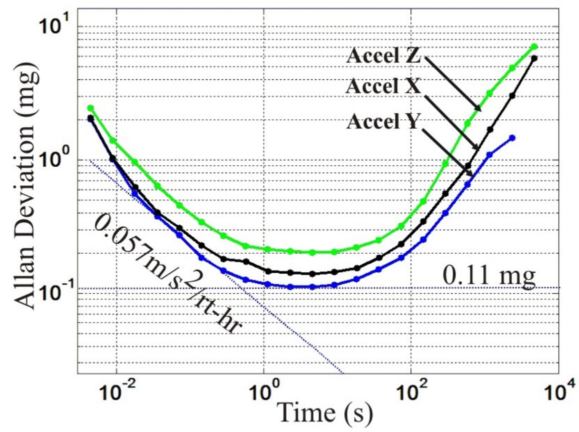

Fig. 10. Allan deviation of 3 accelerometers from the same TIMU prototype, showing bias instability of <0.2 mg.

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