

# Micro IMU Utilizing Folded Cube Approach

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**Abstract** – One of the main challenges of developing a chip-level IMU is combining multiple high-performance sensors on a single die capable of detecting motion along independent directions with minimal cross-axis sensitivity. To address this challenge, a folded-chip approach is being explored utilizing a 3D SOI backbone suitable for high-aspect ratio sensor fabrication. Assembly is done on the wafer level and the panels are silicon-to-silicon welded, forming a compact rigid 6-axis system of sensors. Accelerometers and gyroscopes are fabricated in parallel with the folded structure on the same substrate, and are electrically and mechanically interfaced through flexible integrated thin-film polyimide hinges and interlocking silicon latches. Due to the advantages of high aspect ratio SOI based sensor fabrication, high-performance single axis sensors with low cross-axis sensitivity can be employed. The investigated folded-chip approach can be used to create an entire IMU including with integrated inertial sensors, clock, IC, and power source.

## I. INTRODUCTION

There is an ever increasing desire to measure inertial motion for many different purposes. Being able to track the motion of an object or piece of equipment has significant impact on many industries including defense, aerospace, mining, exploration, navigation, and even personal entertainment [1]. However, current inertial measurement devices are several cubic inches in volume, limiting the scope of applications. In recent years the need for miniaturizing an inertial measurement unit (IMU) has increased dramatically and many methods have been explored. In this paper, a novel folded MEMS approach for creating a micro IMU is explored, and challenges are discussed.

Compact IMUs currently available generally consist of off-the-shelf sensors that are assembled onto printed circuit boards (PCB's) with the signal processing electronics. To provide independent orientation of each sensor, the PCB's are assembled into a 3D structure on the order of 2-3 in<sup>3</sup> in volume [2,3]. The main advantages to this approach are the use of single-axis sensors for all axes of detection, and relative maturity of the current technology. However, further miniaturization is challenging if not impossible, and a significant amount of assembly of separate components is required.

Alternative approaches have been recently explored to create all sensors on a single chip. One technique is to fabricate all the sensors onto one large die [4]. Overall volume of this type of device is very small, however the footprint is large because the die contains six individual sensors. This type of design additionally suffers from having to create in-plane and out-of-plane active vibrating sensors on a single substrate. In general, these types of devices are created using different technologies, such as surface micromachining and bulk micromachining for out-of-plane and in-plane devices,

respectively. Therefore a compromise in performance must be made to make parallel fabrication possible.

Another approach for a micro IMU is to use chip-stacking technology [5], including each sensor on an individual die in the stack. The footprint of this device is equal to that of a single die, and all necessary sensors are included. Signal detection electronics can also be provided in the stack by creating a separate die with IC components. Challenges involved with this technique include thermal management throughout the stack [6], as well as electrical cross talk caused by the dense concentration of electrical signals being transmitted within the stack.

## II. FOLDED MEMS APPROACH

A new technique of fabricating 3D MEMS structures on a wafer level has been developed to combine the advantages of the current approaches. High aspect ratio single-axis sensors are created on a single substrate using a parallel fabrication process for all devices [7]. Bulk micromachining is done to create three in-plane accelerometers and three z-axis gyroscopes using a developed process optimized for single-axis sensors. In parallel, a foldable structure is fabricated on the same substrate and is assembled into a 3D structure providing spatial orientation required for inertial measurement along independent axes. The folded structure consists of an SOI substrate containing a sensor on each sidewall, flexible hinges, and electrical interconnects. Once assembled, the entire package utilizes less than 1 cm<sup>3</sup> of volume with a footprint less than 1 cm<sup>2</sup>. A concept of a folded IMU integrated with a timing device is shown in Figure 1. A clock is necessary for integration of acceleration and rate of rotation to determine position and orientation. Rather than using an external oscillator, a clock can be included to create a self-contained IMU.

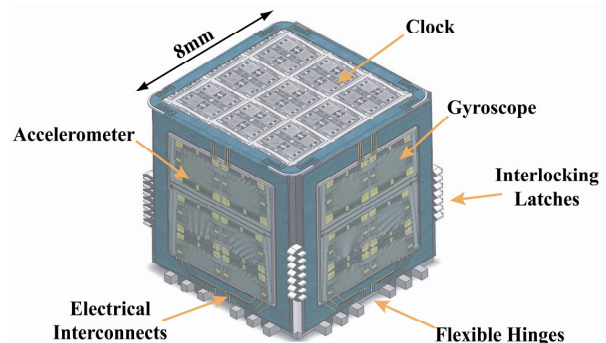


Figure 1. Concept of folded IMU cube integrated with a clock

Several fundamental challenges are involved with development of an IMU using the described approach. Initially, developing a novel fabrication process suitable for making a folded IMU is considered. Separately, processes have been proven successful including DRIE etching, polyimide patterning for flexible hinges, metal deposition to create electrical interconnects, and SOI device fabrication. When all are combined, however, process incompatibilities must be addressed.

Structural rigidity is another concern in creating a compact silicon structure for the purpose of inertial measurement. Small misalignments that occur during operation will adversely affect the performance of the IMU by causing bias errors. The structure must maintain strict orientation of the sensors with respect to one another, thus the rigidity must be maximized.

Cross talk, both electrical and mechanical, must also be considered. Electrical cross talk can occur because several interconnects are necessary for each sensor, in some cases for gyroscopes requiring up to a dozen independent signals. Interference between neighboring traces can induce false readings as well as reduce the signal to noise ratio, negatively affecting overall performance of the IMU. Mechanical cross talk is also a concern due to the close vicinity of each sensor to one another. Energy transfer to the substrate from one device could affect others, resulting in output errors.

Packaging of the folded IMU involves combining wirebonding of the sensors to the electrical interconnects and flip-chip attachment of the overall structure to a PCB. Current wirebonding techniques are not capable of bonding wires onto vertical sidewalls, therefore it is necessary to wirebond the sensors prior to assembly of the folded structure. However, the wirebonds could easily be damaged during assembly, making it difficult to find a compatible method of packaging the overall unit.

### III. FOLDED STRUCTURE DESIGN

Several design challenges are involved with developing a compact silicon structure with sensors and electrical interconnects, Figure 2. Each sidewall must be rigidly held in place after assembly to maintain alignment of the sensors. To meet this requirement, an interlocking latch design is used that provides rigidity and proper alignment of the folded structure. By using an interlocking design, a maximum number of latches can be fabricated on the edges of each sidewall, thus improving rigidity. To aid in assembly, the latches provide self-alignment of the sidewalls ensuring orthogonal configuration of the sensitive axes of the individual inertial sensors.

Design of the hinges requires consideration of several challenges. Significant flexibility is required for assembly, as well as durability, the capability of carrying electrical signals, and adhesion to the silicon and metal interconnects. Polyimide proves to be an appropriate material for this purpose due to its good electrical and mechanical properties, adhesion properties, and low surface roughness suitable for deposition of metal traces.

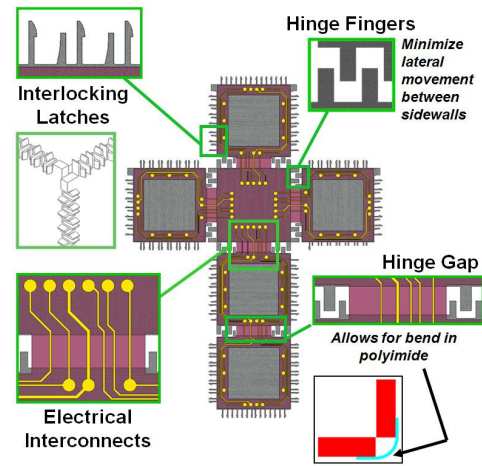


Figure 2. Folded IMU structure design

Hinge fingers are included at the base of each sidewall to reduce lateral movement of one sidewall with respect to another. Gap width at the hinges determines the bending radius and stress induced on the polyimide. The design shown in Figure 2 allows for a 500  $\mu\text{m}$  radius, allowing for low stress in the polyimide. For packaging purposes, electrical interconnects all terminate on the bottom of the cube capable of flip-chip bonding. The traces are designed to minimize impedance by optimizing the width, thickness, and distance between each trace.

In addition to cubic backbone structures, other folded shapes are also being explored. Pyramid structures have been designed, as shown in Figure 3, because inherently they are stronger structurally than cubes. Rigidity is therefore believed to be higher in a pyramid structure, which directly increases performance of the IMU.

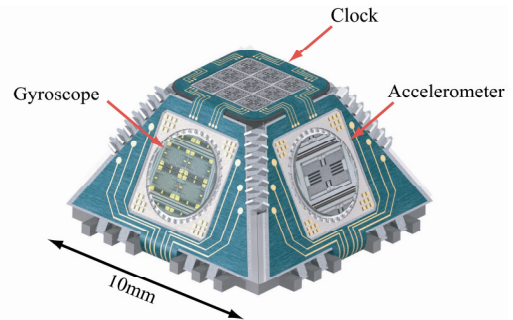


Figure 3. Concept of folded IMU pyramid with integrated clock

### IV. FABRICATION

A fabrication process based on SOI technology has been developed to create a folded IMU in both cube and pyramid shapes, Figure 4. First, a hard mask is created for the sensors by depositing and patterning silicon dioxide. Polyimide is then deposited to provide flexible hinges. The type of polyimide selected (HD-4110) can be patterned photolithographically, and provides a thickness of 20  $\mu\text{m}$  after curing. Metal traces are then defined on top of the polyimide to provide electrical interconnects to the sensors on each sidewall. Selective

deposition is done with a lift-off process utilizing AZ nLoF 2035 photoresist, designed specifically for metal lift-off procedures. Once polyimide and metal processes are completed, the sensors are etched utilizing the oxide hard mask created in the first step. Etching is done using DRIE to a depth of 50  $\mu\text{m}$  to reach the buried oxide layer, finalizing front-side processing of the wafer.

To release the folded structures from the substrate, etching must be done from the backside through the entire wafer. Protection of the front-side features is provided by depositing a layer of photoresist, and then applying an additional layer of low-tack tape. Backside processing can then ensue without concern of damaging the front-side features. Etching through the entire thickness of an SOI wafer involves etching first the handle wafer (500  $\mu\text{m}$ ), then the buried oxide layer (5  $\mu\text{m}$ ), and finally the silicon device layer (50  $\mu\text{m}$ ). For the silicon handle and device layers, DRIE etching is done to provide near-vertical sidewalls.

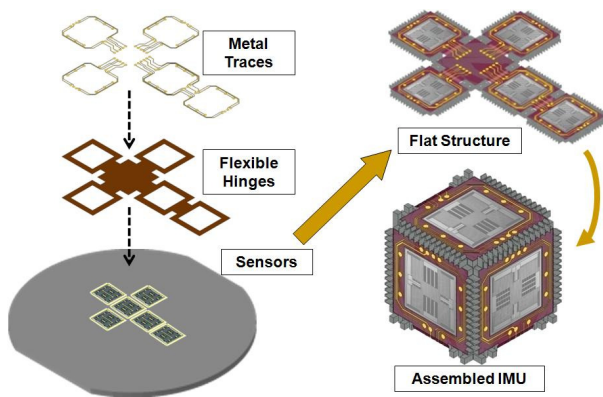


Figure 4. Overview of folded IMU fabrication process

To etch the buried oxide layer, either RIE or wet etching techniques can be used. Photoresist acts as a good mask for RIE etching, and is not attacked by buffered oxide etch (BOE), so both techniques are feasible. After through-wafer etching is complete and the structures have been released, the accelerometers and gyroscopes can be released by soaking in BOE to dissolve the buried oxide layer. Assembly and packaging can then be done to create folded IMU structures.

## V. PACKAGING

To successfully package the folded IMU, the sensors must first be wirebonded to the flexible interconnects followed by mounting the entire structure to a larger package or directly to a PCB. Wirebonding of the sensors using conventional techniques is challenging due to low rigidity of the polyimide substrate underneath the electrical interconnects. Therefore conductive epoxy is used as a substitute and has been successful.

Assembly of the folded structure is done thereafter, yielding a folded IMU structure. Electrical interconnects are designed to terminate at bond pads on the bottom of the structure to allow for flip-chip packaging. Bonding can either be done to a larger package, such as a can or DIP package, or directly onto a

PCB. To minimize overall package size, PCB mounting is preferred.

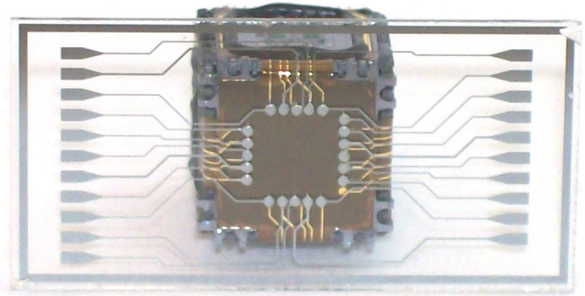


Figure 5. Photograph of an IMU cube mounted to an interconnect plate using flip-chip bonding (bottom view)

Initial PCB-mount testing has been done using a glass interconnect plate with bond pads that mate to the terminations on the bottom of the cube. Fabrication of the plate was done using a single-mask fabrication process to deposit gold onto a glass substrate. To mount the structure to the package, solder bumps were first created on the interconnect plate. Solder flux was then used to adhere the structure to the plate, and the solder was reflowed to make the connections. Figure 5 shows a bottom view of an IMU cube mounted to the interconnect plate where the bonds can be seen through the glass.

X-ray imaging was done to analyze the quality of the bonds, shown in Figure 6. It can be seen from the image that all connections were made successfully, and no short circuiting occurred. Resistance measurements confirmed this result after packaging was complete. Many voids exist in the solder bonds; however this can be alleviated by modifying the reflow process. Overall, flip-chip packaging is proven to be a feasible method for mounting the IMU cube and pyramid to a PCB or other type of package.

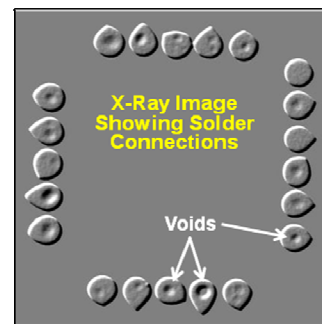


Figure 6. X-ray imaging of flip-chip bonding results

## VI. STRUCTURAL RIGIDITY

A major concern with any IMU is rigidity of the enveloping structure. After initial calibration, misalignments from impact or high acceleration loads will cause errors in the signal. Generally this is addressed by using threaded fasteners or heavy-duty solder joints to mount the individual PCB's or sensor units. For the folded IMU cube, however, these techniques are not convenient. Therefore other methods are explored.



To lock the sidewalls in place after assembly, interlocking latches are provided along the edges of each sidewall. This type of design allows for a maximum number of latches to provide rigidity and aid in aligning the sidewalls during assembly. To initially test structural rigidity, vibration testing has been conducted on samples using a vertical shaker unit. Harmonic oscillations were induced from 50 Hz – 3.5 kHz, resulting in no damage to the structure. While this shows that it is feasible for the interlocking latches to provide stability, results were obtained under light-duty dynamic testing. More stringent testing will be required for many applications, for example shock and high acceleration loads. For this reason, it is desired to bond the sidewalls together to enhance structural rigidity. However, material used for bonding will inevitably have different thermal properties than that of silicon. Under large temperature variations, this could induce stress to the structure, resulting in misalignment of sensors or damage to the structural integrity.

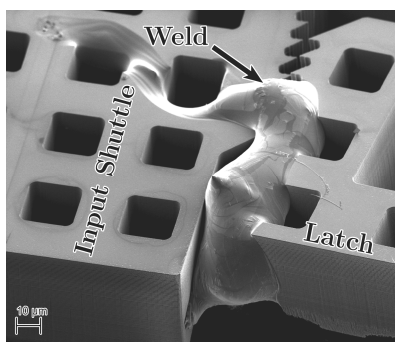


Figure 7. Silicon welding demonstrated on 50 µm device, courtesy of Adam Schofield

Silicon welding is being explored to provide a method for providing maximum rigidity by creating permanent silicon joints along the sidewall edges. Advantages of this approach are the lack of variation in thermal properties due to different materials, as well as overall rigidity of the folded structure. On a macro scale, two general methods are generally used for welding: resistive and laser welding. Resistive welding is the most common technique, using a DC current applied through the weld joint to melt the substrate and provide a permanent connection. Similarly, laser welding heats the welding joint locally to melt the substrate. Results of resistive welding of silicon have been successful on a 50 µm device [8], as shown in Figure 7. To apply this technique to the folded structure, a similar process must be developed for welding of bulk silicon. Both resistive and laser welding methods will be explored.

## VII. VACUUM PACKAGING

MEMS gyroscopes and accelerometers typically require different levels of vacuum for optimal performance. High vacuum is required for gyroscopes to minimize damping thus improving gain of the vibratory sense-mode, and low vacuum or ambient pressure is necessary for accelerometers to provide damping, thus increasing bandwidth. To accomplish this, wafer-level packaging can be done using glass lids with getters deposited in the center, as shown in Figure 8. Lids are applied prior to assembly of the structure, using different eutectic

compositions for each vacuum level needed. High vacuum devices are to be packaged first by using a eutectic solder preform with a melting temperature higher than that of the remaining vacuum sealing processes. This ensures that vacuum packaging of the first devices will not be adversely affected from reflowing solder preforms for successive devices. This order of packaging also reduces the amount of leakage that could occur from packaging low vacuum devices first and then exposing them to high vacuum during reflow.

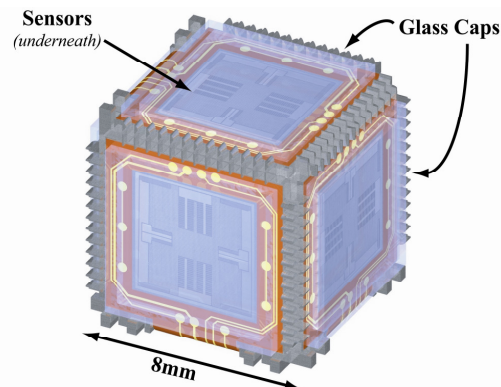


Figure 8. Concept of IMU Cube with vacuum packaged sensors

Prior in-house developments have proven to be successful for ceramic packages [9]. Lids are fabricated on a wafer-level with gold for adhesion to a solder preform and getters in the center of the lid to maintain long-term vacuum, Figure 9. The lids are then applied to the package at the desired vacuum level and sealed by reflowing the solder preform. With modifications to this procedure, lids can be created and utilized for wafer-level vacuum packaging of the IMU cube sensors, and provide the different pressures required by accelerometers and gyroscopes [10].

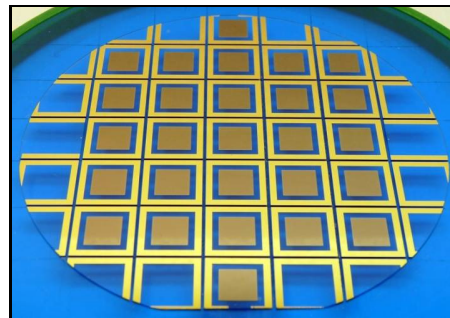


Figure 9. Glass lids for vacuum packaging fabricated on a wafer level [9]

## VIII. ACCELEROMETERS AND GYROSCOPES

Due to the modularity of the folded IMU design, many different sensor designs can be used. The SOI device fabrication process utilizes a 50 µm device layer with a 10:1 aspect ratio for etch trenches. Various designs of accelerometers and gyroscopes can be implemented to adhere to requirements for different applications. One type of accelerometer is shown in Figure 10 with its corresponding response curve.

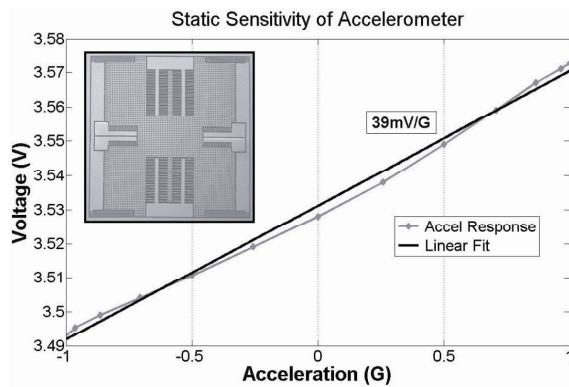


Figure 10. Example of one possible accelerometer and response curve [1]

An example of a gyroscope integrated into the IMU cube is shown in Figure 11. The device shown is robust to environmental variation in temperature over a broad range. A similar tuning fork design can also be used to minimize energy transfer to the substrate, effectively reducing mechanical coupling to other sensors on sidewalls. The design is also scalable, allowing for integration into IMUs of various size for many applications. Other gyroscopes have been designed and tested using the same fabrication techniques, such as high-Q devices, that can also be integrated into the IMU structures.

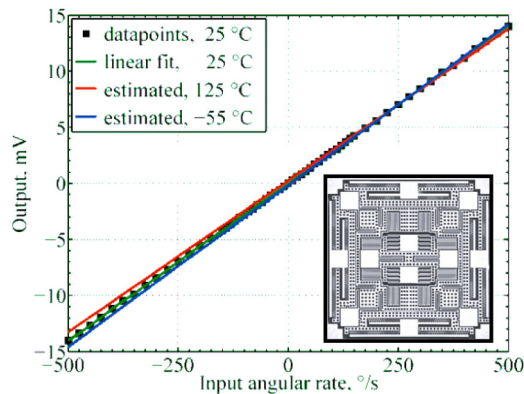


Figure 11. Example of an integrated gyroscope [11]

## IX. CONCLUSION

A new approach for a chip-level IMU has been explored utilizing fabrication of SOI sensors in parallel with a folding

silicon backbone. Many challenges have been addressed, including mechanical and electrical design, structural rigidity, vacuum packaging, and sensor modularity. Design aspects of the folded structure include inertial sensors, flexible hinges with fingers to prevent lateral motion, interlocking latches that provide rigidity and alignment, and electrical interconnects.

For maximum rigidity and robustness to thermal variation, an approach for silicon welding was shown to be a feasible process for silicon structures. Wafer-level vacuum packaging was explored and can be applied to the folded IMU by modifying the fabrication process of glass lids and the folded structure. Additionally, it is shown that a wide variety of accelerometers and gyroscopes can be integrated into the cube for different application requirements. Overall, a new paradigm for bringing MEMS from 2D to 3D using wafer-level folded structures to create a chip-level IMU is feasible with technology currently available.

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