METHOD FOR FABRICATION OF A MULTIPLE RANGE ACCELEROMETER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application No. 63/333,360, filed on April 21, 2022, the entire contents of which are incorporated herein by reference.

TECHNICAL FIELD

The general technical field relates to Microelectromechanical Systems (MEMS) fabrication.

BACKGROUND

Micro-electro-mechanical systems (MEMS) are an increasingly important enabling technology. MEMS inertial sensors are used to sense changes in the state of motion of an object, including changes in position, velocity, acceleration or orientation, and encompass devices such as accelerometers, resonators, gyroscopes, vibrometers and inclinometers. Broadly described, MEMS devices are integrated circuits (ICs) containing tiny mechanical, optical, magnetic, electrical, chemical, biological, or other, transducers or actuators. MEMS devices can be manufactured using high-volume silicon wafer fabrication techniques developed over the past fifty years for the microelectronics industry. Their resulting small size and low cost make them attractive for use in an increasing number of applications in a broad variety of industries including consumer, automotive, medical, aerospace, defense, green energy, industrial, and other markets.

SUMMARY

As the sensitivity of inertial sensors can impact performance, a MEMS inertial sensor device having a plurality inertial sensor elements with different operating ranges can be fabricated to more accurately sense movement of an object undergoing a large range of accelerations. Preferred examples can include a plurality of accelerometers in which a first accelerometer measures a lower range of acceleration and a second accelerometer measures a higher range of acceleration. It is further advantageous to fabricate the plurality of MEMS sensors using a single fabrication process and preferably in a single chip package thereby providing alignment of the devices in a smaller area and weight and that operate at reduced power.

Preferred embodiments can be fabricated using a plurality of silicon-on-insulator (SOI) wafers that can be processed and fusion bonded together to provide a hermetically sealed chip

package. There can preferably be two, three or four accelerometers fabricated on a single wafer, for example. Further embodiments can include different types of inertial sensors such as gyroscopes or can further include non-inertial sensors such as pressure sensors, time of flight (ToF) sensors and magnetometers. The sensor data can be processed and employed for navigation and/or platform and image stabilization, for example, using processing circuitry that can be included in the chip package in preferred embodiments. A processor can be programmed with sensor data fusion software to process the sensor data for specific applications. This type of sensor fusion is extensively used to obtain assured position, navigation and timing (A-PNT) in particular when a combination of sensors serves to extend the ability of a system to maintain precise navigation without the aid of GPS for extended periods of time (i.e. "dead reckoning"). In this example, the inertial sensors also help to support, aid and improve the performance of the other sensors that are part of the sensor fusion mix most of which are image sensors (including cameras, LIDAR, radar, and sonar). Another example includes the monitoring of all of the accelerometer outputs and using the output of the low range (high sensitivity) accelerometer unless it exceeds a preset threshold value. At this point the output of the high range accelerometer can be selected. In parallel, an impulse monitor (high-pass accelerometer operating at resonance) can be monitored. When the impulse monitor output signal amplitude rises above the average acceleration of the active filtered accelerometer, it is recorded as an impulse force that can be included in the dynamic calculation of velocity and position. Some specialized applications such as health and usage monitoring systems (HUMS), aka "Condition Monitoring" for various types of equipment exposed to high shock environments and autonomous vehicles require lower noise over higher frequency ranges and bandwidths beyond 10KHz, high accuracy and very low size, weight, power (SWaP) requirements. Sensor fusion aims to reduce the complexities of various sensor data by improving the signal -to-noise ratio, decreasing uncertainty and increasing reliability, resolution and accuracy for longer periods of time. A fusion of sensors are used to compensate for other sensors' weaknesses to improve reliability especially in cases where data must be processed "on the fly" such as the case in dead reckoning situations involved in navigation. When computing resources are finite, artificial intelligence and machine learning can also support the determination of the best sensor data fusion strategy based on real-time operating conditions. This is particularly the case when implementing sensor fusion applications not only related to navigation but also in stand-alone Industry 4.0, Internet of Things (IoT), Internet of Moving Things (IoMT), machine vision and image processing applications.

Further embodiments include an inertial sensor chip package in which a processing circuit can be mounted on a circuit board or fabricated in a system-on-ship configuration that includes a system controller a clock included in the MEMS chip or located with the processing circuit to control timing operations within the chip package. Such embodiments can further include a neural processing unit the perform iterative computational analysis of sensor data and can also be configured to perform sensor fusion operations.

In an aspect according to the present disclosure, there is provided an inertial sensor device. The inertial sensor device comprises a first proof mass formed in a device layer of a silicon-on-insulator (SOI) MEMS wafer having the device layer over an insulating layer and a handle layer, the first proof mass positioned relative to first sensing electrodes to measure first inertial sensor signals. The inertial sensor device further comprises a second proof mass formed in the device layer of the SOI MEMS wafer, the second proof mass positioned relative to second sensing electrodes to measure second inertial sensor signals, the first inertial sensor signals and the second inertial sensor signals measuring a change in position of the inertial sensor device wherein the inertial sensor device is mounted within a single chip package. The inertial sensor device further comprises a processing circuit that receives the first inertial sensor signals and the second inertial sensor signals, the processing circuit being mounted within the single chip package and including a neural signal processor performing an iterative computational process to generate corrected attitude position data.

In a further aspect according to the present disclosure, there is provided a method of inertial sensing with an inertial sensor device. The method comprises sensing a motion of a first proof mass formed in a device layer of a silicon-on-insulator (SOI) MEMS wafer having the device layer over an insulating layer and a handle layer, the first proof mass positioned relative to first sensing electrodes to measure first inertial sensor signals. The method further comprises sensing a motion of a second proof mass formed in the device layer of the SOI MEMS wafer, the second proof mass positioned relative to second sensing electrodes to measure second inertial sensor signals, the first inertial sensor signals and the second inertial sensor signals measuring a change in position of the inertial sensor device. The inertial sensor device is mounted within a single chip package. The method further comprises detecting an image with an imaging sensor coupled to the inertial sensor device that generates image data. The method further comprises processing signals with a processing circuit that receives the image data, the first inertial sensor signals and the second inertial sensor signals. The

processing circuit is mounted within the single chip package and includes a signal processor performing an iterative computational process to generate corrected position data.

BRIEF DESCRIPTION OF THE DRAWINGS

It is noted that the appended drawings illustrate only exemplary embodiments of the invention and are, therefore, not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

Figure 1 is an isometric top view of a 3DS multi-range accelerometer with two accelerometers covering up to two acceleration ranges.

Figure 2 is an isometric view of the two-range accelerometer with the top cap removed to show the proof masses and support springs.

Figure 3 is a cross-section drawing of the two-range accelerometer of Figure 2 taken along the line A-B-C through the support springs of the two proof masses.

Figure 4 is an isometric view of the two-range accelerometer with the handle layer of the top cap removed to show the electrode arrangement.

Figure 5 is an alternative embodiment of the multi-range accelerometer with four accelerometers covering up to four acceleration ranges.

Figure 6 is the cross-section of Figure 3 showing the two proof masses responding to an acceleration in the negative z direction larger than the mechanical range of one of the accelerometers.

Figure 7 is one embodiment of the four-accelerometer of Figure 5 illustrating various modes of operation.

Figure 8A is a schematic, partially exploded perspective view of an integrated MEMS system, according to an embodiment. **Figure 8B** is a schematic, exploded perspective view of the integrated MEMS system of **Figure 8A**.

Figure 9A is a schematic, cross-sectional view of an integrated MEMS system, according to another embodiment.

Figure 9B is a schematic, cross-sectional view of an integrated circuit wafer.

Figure 9C is a schematic, cross-sectional view of a MEMS wafer stack.

CLAIMS

1. An inertial sensor device comprising:

a first proof mass formed in a device layer of a silicon-on-insulator (SOI) MEMS wafer having the device layer over an insulating layer and a handle layer, the first proof mass positioned relative to first sensing electrodes to measure first inertial sensor signals;

a second proof mass formed in the device layer of the SOI MEMS wafer, the second proof mass positioned relative to second sensing electrodes to measure second inertial sensor signals, the first inertial sensor signals and the second inertial sensor signals measuring a change in position of the inertial sensor device wherein the inertial sensor device is mounted within a single chip package; and

a processing circuit that receives the first inertial sensor signals and the second inertial sensor signals, the processing circuit being mounted within the single chip package and including a signal processor performing an iterative computational process to generate corrected position data.

2. The device of claim 1 wherein the first proof mass comprises a first accelerometer that is aligned with the second proof mass comprising a second accelerometer, the first accelerometer measuring a first range of acceleration and the second accelerometer measuring a second range of acceleration.

3. The device of claim 2 further comprising a third accelerometer formed in the device layer.

4. The device of claim 2 wherein the first accelerometer and the second accelerometer are coplanar.

5. The device of claim 1 wherein at least one proof mass comprises a gyroscope proof mass formed in the device layer and having three axes of motion, the proof mass suspended by springs within a cavity.

6. The device of claim 2 wherein the first accelerometer proof mass comprises a device layer, an insulating layer and a handle layer, the proof mass being movably mounted in a cavity with one or more springs.

7. The device of claim 1 wherein the processing circuit further comprises a low pass filter and a high pass filter and a lock-in amplifier to detect a frequency of motion above a resonant frequency of at least one proof mass.

8. The device of claim 1 wherein the signal processor is connected to receive digitized sensor signals for processing of inertial sensor data.

9. The device of claim 1 wherein the device further comprises an inertial measurement unit (IMU).

10. The device of claim 1 further comprising a first cap SOI wafer that is fusion bonded to the SOI MEMS wafer to form an hermetically sealed cavity, the first cap SOI wafer having one or more electrodes that in a cap device layer that perform at least one of sensing and driving a motion of at least one proof mass, and wherein the SOI MEMS wafer is bonded to a conductive single crystal silicon second cap wafer.

11. The device of claim 9 wherein the IMU further comprises a position sensor such as a GPS or GNSS sensor.

12. The device of any one of claims 1-11 wherein the inertial sensor including the MEMS SOI wafer is stacked vertically with the processing circuit comprising an integrated circuit in the single chip package.

13. The device of any one of claims 1-11 wherein the processing circuit comprises an analog to digital converter and a power management circuit.

14. The device of any one of claims 1-11 wherein the processing circuit comprises a memory and/or a shared memory and wherein the processing circuit further comprises a system controller connected to a data processor that comprises a neural processor.

15. The device of any one of claims 1-11 further comprising a connection to an autonomous vehicle such as an aerial drone or a ground vehicle.

16. The device of any one of claims 1-11 wherein the processing circuit is connected to a further sensor including a camera, or a pressure sensor, or a temperature sensor, or a magnetometer, or a LiDAR, or a radar, or a sonar, or combinations thereof.

17. The device of any one of claims 1-11 wherein at least one proof mass moves in a single plane through the MEMS SOI wafer and optionally wherein at least one proof mass moves out of a plane extending through the MEMS SOI wafer.

18. A method of inertial sensing with an inertial sensor device comprising:

sensing a motion of a first proof mass formed in a device layer of a silicon-on-insulator (SOI) MEMS wafer having the device layer over an insulating layer and a handle layer, the first proof mass positioned relative to first sensing electrodes to measure first inertial sensor signals;

sensing a motion of a second proof mass formed in the device layer of the SOI MEMS wafer, the second proof mass positioned relative to second sensing electrodes to measure second inertial sensor signals, the first inertial sensor signals and the second inertial sensor signals measuring a change in position of the inertial sensor device wherein the inertial sensor device is mounted within a single chip package;

detecting an image with an imaging sensor coupled to the inertial sensor device that generates image data; and

processing signals with a processing circuit that receives the image data, the first inertial sensor signals and the second inertial sensor signals, the processing circuit being mounted within the single chip package and including a signal processor performing an iterative computational process to generate corrected position data.

19. The method of claim 18 wherein the first proof mass comprises a first accelerometer that is aligned with the second proof mass comprising a second accelerometer or a gyroscope wherein the device further comprises an inertial measurement unit (IMU) and wherein sensing electrodes and drive electrodes are formed in an SOI device layer of a cap wafer that encloses at least one proof mass in a cavity.

20. The method of any one of claims 18-19 further comprising controlling an autonomous vehicle wherein a system controller is connected to the autonomous vehicle and performing closed loop control of an operation of the autonomous vehicle, the

autonomous vehicle comprising an aerial drone or a ground vehicle having a position sensor such as a GPS or GNSS sensor.