A 3-BIT DIGITALLY OPERATED MEMS ROTATIONAL ACCELEROMETER

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ABSTRACT

This work presents an electrostatically tunable MEMS rotational acceleration switch and its operation as a 3-bit digital rotational accelerometer. The concept of operating electrostatically tunable acceleration switches as digital MEMS accelerometers, as previously demonstrated, has been applied to rotational acceleration switches in this work leading to an ultra-low power potential alternative to MEMS gyroscopes for lower resolution applications like gaming. The sensor consists of a circular proof mass surrounded by a number of electrostatic actuators. Following a simple algorithm to sequentially turn different actuators ON or OFF, a binary search can be performed by a digital controller to find the rotational acceleration. A 3-bit prototype was successfully fabricated and operated with a resolution of 49 rad/s^2 (limited by the available test setup) and full scale acceleration of 392 rad/s^2.

INTRODUCTION

Inertial sensors have a broad range of industrial applications (e.g. automotive, oil and gas, and consumer electronics) [1,2]. The automotive industry applies inertial sensors in driving assistance systems which improves steering [3] and helps with stability and control. With the incorporation of magnetic sensors, they are also used to improve the ability of GPS navigation systems in cars and mobile devices. MEMS based inertial sensors offering much of what is desirable for high volume applications, while providing adequate sensitivity, have become very successful commercial products and are widely used in modern integrated systems.

In the evolving market of portable mobile devices, besides MEMS accelerometers, MEMS based vibratory gyroscopes are also being applied in a growing number of such applications due to the progressing miniaturization of footprints and reduced costs [4]. Such portable devices are normally battery powered and require frequent charging or replacement of the battery due to power loss. Commercially available MEMS gyroscopes like the A3G4250D from STMicroelectronics and the ADXRS290 from Analog Devices require 15-30mW of power for their operation. Most of the large power consumption of such sensors is attributed to the analog control, error correction, and readout circuitry needed for reading, processing, and analog to digital conversion of the sensor output [5,6]. Therefore, significant power savings can be achieved by elimination of the analog front-end.

The concept of operating electrostatically tunable acceleration switches as digital MEMS inertial sensors has been previously demonstrated [7]. Such devices only require bias voltages for operation (zero static power consumption) enabling significant power reduction by eliminating the need for an analog-front-end. This would also enable smaller sized batteries, thus further shrinking the overall system, facilitating smaller implantable units and enhancing comfort and compliance for small wearable units. Multi-bit linear accelerometers based on the above-mentioned concept have been previously shown [8,9]. A similar approach has been applied to rotational acceleration switches in this work leading to an ultra-low power potential alternative to MEMS gyroscopes for lower resolution applications like indoor navigation and gaming controllers.

OPERATING PRINCIPLE

A dynamically tunable acceleration switch capable of performing a binary search with the help of a digital processor has been employed to realize a fully digitized rotational accelerometer. Acceleration switches are simple devices with an output that can be high (ON) or low (OFF) depending on the pre-determined acceleration threshold of the device and the acceleration the device is subjected to [10]. An acceleration switch is comprised of a suspended mass anchored to a substrate with flexible tethers. If the device is subjected to an acceleration higher than its threshold value, the suspended mass will come in contact with an electrode closing a circuit and signaling that the acceleration threshold has been reached. Hence, such devices require close to no power for operation and their output can be directly fed to a digital processor without any further processing. However, an acceleration switch cannot provide quantitative information about the magnitude of the applied acceleration and can only indicate whether the applied acceleration is higher or lower than the set threshold. In other words, an acceleration switch can be referred to as a single bit digital accelerometer. Similar to the multi-bit linear accelerometers, devices shown in this work are acceleration switches that can perform quantitative rotational acceleration measurements with the help of a digital controller.

Device Structure

Figure 1 shows a simplified schematic view of a single axis 3-bit rotational accelerometer operating based on the principle of an acceleration switch with digitally tunable threshold. The structure consists of a number of electrostatic parallel plate electrodes that can apply an assistive force to the circular proof-mass, thus changing its acceleration threshold over a wide range.

The bulky circular proof mass (~54.3 μg) moves back and forth in a rotatory manner as a result of the applied rotational acceleration. The proof mass/anchor is connected to electrical ground (GND). Once the applied acceleration exceeds the set threshold, the tip located on the proof mass comes in contact with the stationary output

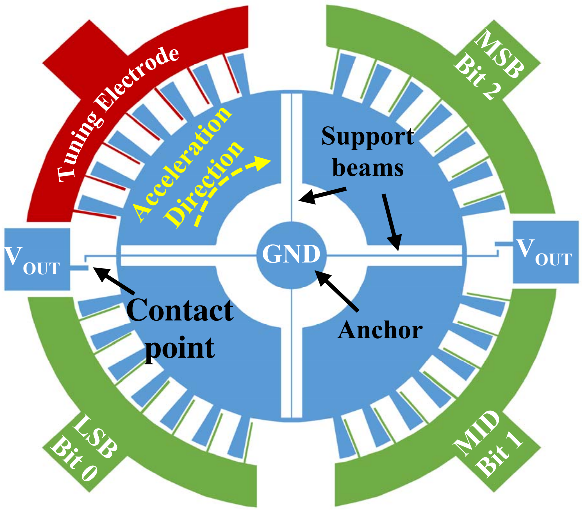

Figure 1: Simplified schematic of the 3-bit digitally operated rotational accelerometer.

electrode which is biased with a bias voltage through a large resistor (V_{OUT}). Upon making the contact, the output electrode voltage will go to zero, which can be easily detected. Four sets of electrostatic electrodes surround the proof mass. Three out of the four electrostatic set of actuators (MSB, MID and LSB) act as the bit electrodes, i.e. the three-bit output of the binary output rotational accelerometer along with the fourth electrode acting as the tuning electrode. Application of a bias voltage to any of the electrostatic electrodes creates an assistive force which pulls the proof mass towards the metallic tip consequently lowering the acceleration threshold. In this manner, having an arrangement of multiple electrostatic actuators with appropriate strengths based on the electrode finger size/number or by controlling the bias voltage applied to them around the proof mass and selectively turning the bit electrodes ON or OFF, a binary search can be performed to find the value of the applied acceleration. The mass of the proof mass and the stiffness of the tethers is to be chosen in a way that when the device is subjected to full scale acceleration and all bit electrode voltages are set to zero with the tuning electrode voltage turned ON, the displacement is equal to the gap size between the metallic tip and the proof mass.

To perform an acceleration measurement, the three bit electrodes are to be turned ON or OFF in a sequential manner via an interfaced digital controller. Turning an electrode ON means application of a pre-determined fixed voltage to the electrode by the digital controller. The actuator associated with the most significant bit (MSB), which is Bit 2 in this case (Figure 1), requires twice the amount of force as compared to the next most significant bit (Bit1). Due to the same number of electrodes and electrode sizes designed for each of the bits, such a mechanism of forces needs to be achieved by changing the bias voltages given to each of the bits. In other words, Bit 2 provides an actuation force which is exactly twice that of Bit 1 (MID) when turned ON (voltage bias given to bit 2 is $\sqrt{2}$ times more than bit 1 as Force $\propto V^2$). Similarly, the amount of force provided goes down by a factor of two from each more significant bit to the next less significant bit and the least significant bit (Bit 0) provides the least force (and thus requires the smallest bias voltage). The bias voltages for all the electrodes are to be chosen so that upon application of the ON voltage to the MSB actuator and the tuning electrode, a force equal to 50% of the full scale acceleration force is applied to the proof mass. For each combination of activated actuators, depending on whether the proof mass contacts the output electrode, it can be determined whether the applied acceleration is larger or smaller than the acceleration threshold for that combination. To minimize the number of required trials until the closest binary output to the applied acceleration is determined, activation of different electrodes should follow a binary search as described below.

Binary Search for Acceleration Measurement

Figure 2 shows a sample flow-chart for performing the binary search in a 2-bit accelerometer. The binary search to find the acceleration in each measurement cycle begins by activating the MSB electrode. If the switch closes when the MSB electrode is turned ON, i.e. the proof mass and the metallic tip come in contact due to the bias voltage given to the MSB alone, the acceleration is larger than or equal to 50% of the full-scale acceleration. In this case, the first digit (MSB) in the digital acceleration output is “1”. The MSB electrode is then turned OFF and the electrode associated with the next bit (LSB for a 2-bit accelerometer) is activated. Similarly, if this electrode alone is enough to keep the switch closed, the acceleration is above or equal to 75% of the full-scale acceleration and the second digit (LSB), will be “1” as well (2-bit binary output acceleration of 11). If there is no contact, the LSB would be “0” and the acceleration is somewhere in between 50% and 75% of full-scale (2-bit binary output acceleration of 10). In the case where the MSB does not initiate contact, the MSB value is “0” and it stays on while electrode associated with

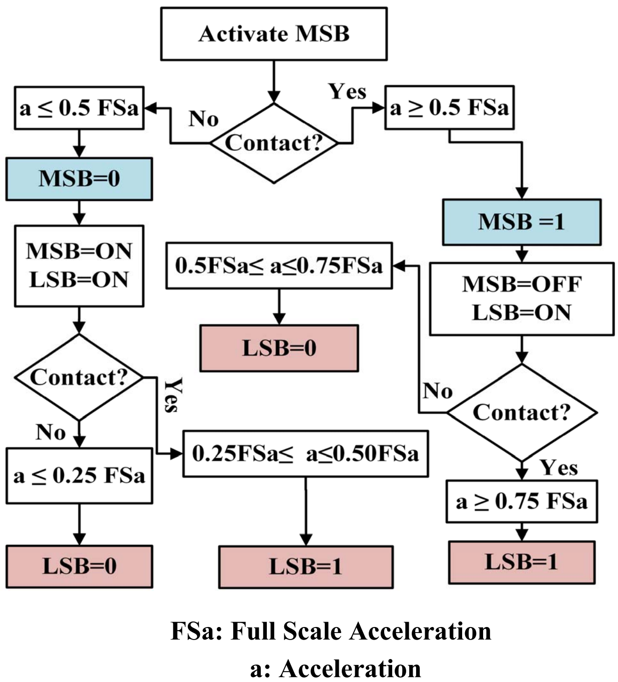

Figure 2. Flowchart showing algorithm for binary search in a 2-bit digital accelerometer.

the next bit is actuated. In this case, if contact occurs with the LSB active, acceleration is between 25% and 50% of full-scale (2-bit binary output acceleration of 01). If with both actuators ON contact still does not occur, then the binary output is 00 and the acceleration is below 25% of full-scale. It should be noted that the tuning electrode in this case is only responsible for setting the maximum acceleration threshold and remains ON at all times, while the digital interface controller follows the binary algorithm as shown in Figure 2. The same concept and operation procedure can be enhanced to higher number of bits to realize accelerometers with higher resolutions, e.g. 4-bit, 8 bit, etc. Therefore, the acceleration amplitude with a resolution of $1/2^n$ of full scale can be determined through n electromechanical operation steps.

FABRICATION

The rotational accelerometers were fabricated on an SOI substrate (35 μm thick device layer, 1μm thick buried oxide layer) using a two-mask micro-machining process as shown in Figure 3. The accelerometer silicon body was first defined in the SOI device layer via deep reactive ion etching (DRIE) all the way down to the buried oxide layer as shown in Figure 3(a). The backside was then patterned and etched to avoid any potential stiction issues for the large proof masses. Devices were then released by removing the buried oxide layer in hydrofluoric acid (HF) as shown in Figure 3(b). To create a high quality metal-metal contact between the proof mass and the output electrode tip, a 200nm thick layer of gold with slight sidewall coverage was sputtered on the fabricated fully silicon devices.

Figure 4 shows SEM views of the digital accelerometer structure fabricated using the described fabrication sequence. Four identical electrostatic actuator finger sets (six 100μm × 10 μm × 35μm fingers on each set) surround the silicon proof mass (~1mm in diameter) in the device shown in Figure 4 allowing the operation of the device as a 3-bit accelerometer. Three of the four electrode finger sets are associated with the most significant bit (MSB), the middle bit (MID) and the least significant bit (LSB), while the remaining fourth electrode set (tuning electrode) could be used for tuning the device operating range. A 1.5 μm gap between the proof mass and the metallic tip was obtained after the mask-less sputtering the 200nm gold onto the device.

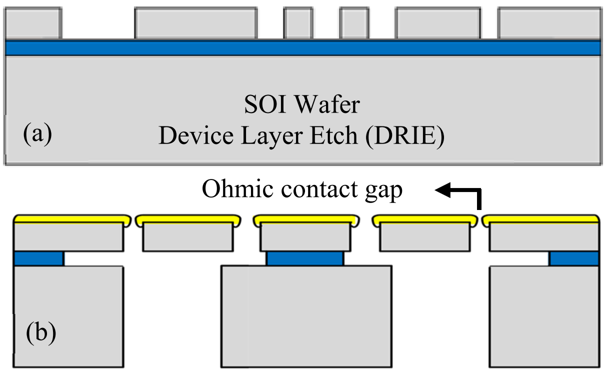

Figure 3: Schematic side view showing the microfabrication process flow:
(a) Device layer etch (DRIE)
(b)(i) Backside etch and HF release.
(ii) Gold deposition with sidewall coverage.

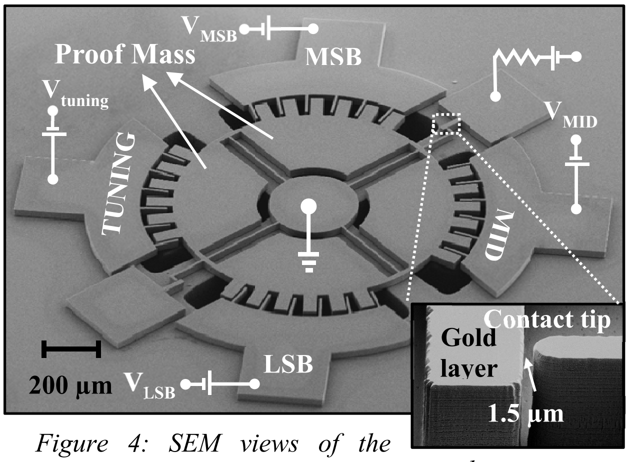

Figure 4: SEM views of the fabricated digital rotational accelerometer.

MEASUREMENT SETUP AND RESULTS

A DC motor capable of generating a maximum rotational acceleration of 392 rad/s^2 was utilized to apply different angular accelerations to the sensor. It was determined that a bias voltage of 57.4V is needed for the tuning actuator (while the other actuators are OFF) so that the proof mass comes in full contact with the output electrode when the device was subjected to maximum acceleration (full scale acceleration-FSa). This sets the 111 binary output of the accelerometer to 343rad/s^2 (0.875FSa), i.e. full scale acceleration of 392rad/s^2. Furthermore, it was determined that voltages of 26.00V, 18.40V and 13.04V are to be applied to the MSB, middle bit and the LSB actuators respectively to lower the threshold acceleration by 1/2, 1/4 and 1/8 of FSa, respectively. Also, it is evident from the values of the bias voltages that Bit 2 provides a force ~2X larger than the middle bit and ~4X larger than the least significant bit.

Device performance was validated by applying different accelerations and monitoring the output while manually turning different actuators ON/OFF. Measurable device sensitivity in this case was limited by the minimum acceleration that the motor could provide reliably (~98rad/s^2). For the device tested in this work, the control signals for altering the states of the three bit electrodes were applied manually instead of using a controller for its operation.

Results of the above mentioned tests are tabulated in Table 1 showing that the device can distinguish between different accelerations in the desired range, which are very close to the theoretically expected ranges. Much better device sensitivity can be achieved by simply increasing the tuning actuator bias voltage (e.g. 70.5V for 8rad/s^2). By changing the value of V_{bias} and V_{ON}, the accelerometer full-scale value can be tuned to a wide range of accelerations. Also, it should be noted that the MSB, MID and LSB values in Table 1 indicate the required ON/OFF state for the two actuators to maintain contact over the associated acceleration range. The binary acceleration output of the sensor that is to be provided by the digital processor is the exact opposite of the MSB, MID, LSB actuator state.

Resonance Response

To estimate the settling time required for each measurement step, the mechanical resonance frequency of the device was also measured under vacuum. Two out of the four electrodes were utilized to act as the AC input and the AC output electrode while the anchor/proof mass is biased with a DC voltage (V_{dc}). The resonance frequency for the device tested in this work was measured to be 2.386kHz (with a quality factor of ~600 when operated in ~20mTorr of pressure). This is in agreement with its simulated frequency value as shown in Figure 5. This value of frequency corresponds to a ~1.6ms settling time, i.e. ~4.8ms for a 3-bit measurement, consequently allowing a maximum measurement frequency of ~200Hz.

Table 1. Measurement results of the accelerometer versus the expected values. (Bit values in the Table indicate the ON/OFF (1/0) status of the actuator of the respective bit when contact occurs, which are opposite to that of the sensor digital binary output)

(MSB, MID, LSB) (State)	Acceleration Measured (FSa)	Acceleration Theoretical (FSa)
0 0 0	a ≥ 0.901	a ≥ 0.875
0 0 1	0.901 ≥ a ≥ 0.765	0.875 ≥ a ≥ 0.75
0 1 0	0.765 ≥ a ≥ 0.629	0.75 ≥ a ≥ 0.625
0 1 1	0.629≥ a ≥ 0.502	0.625 ≥ a ≥ 0.5
1 0 0	0.502 ≥ a ≥ 0.361	0.5 ≥ a ≥ 0.375
1 0 1	0.361 ≥ a ≥ 0.205	0.375 ≥ a ≥ 0.25
1 1 0	0.205 ≥ a ≥ -	0.25 ≥ a ≥ 0.125
1 1 1	-	a ≤ 0.125

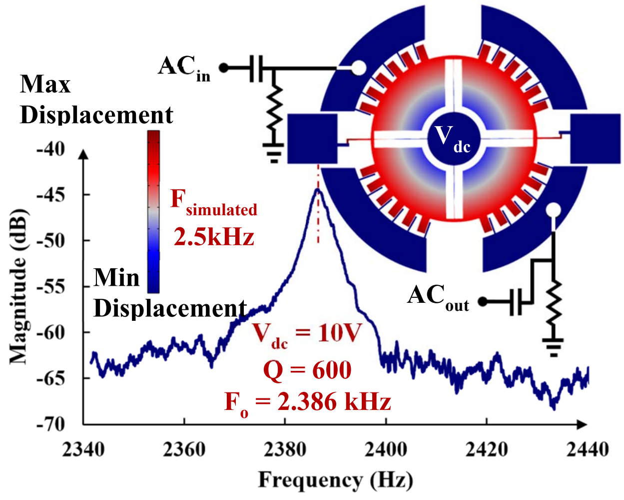

Figure 5: Measured sensor frequency response for polarization voltage of 10V along with finite element modal analysis of the structure showing the sensor's resonance mode shape.

CONCLUSION

The concept of multi-bit contact-based linear acceleration switches was successfully applied to rotational accelerometers which can be enhanced further to perform higher resolution quantitative acceleration measurements. A tunable digitally operated MEMS rotational accelerometer with a 3-bit resolution was successfully demonstrated. The same device principle can be utilized to implement 6-bit, 8-bit or even higher resolution digital accelerometers. Such an approach devising rotational acceleration switches can lead to an ultra-low power potential alternative to MEMS gyroscopes for low resolution applications.

ACKNOWLEDGEMENTS

This work was supported by the US National Science Foundation under ECSS award #1509063.

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