ULTRA-LOW POWER SELF-COMPUTING BINARY OUTPUT DIGITAL MEMS ACCELEROMETER

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ABSTRACT

This work presents the concept and preliminary results for electromechanical self-computing binary output digital accelerometers. Such devices require only bias voltages and no readout or control electronics for operation (zero static power for operation). The device comprises of a number of acceleration switches (equal to the number of the bits of resolution) which are coupled to each other via electrostatic actuators. As a result of an applied acceleration and interactions of switches and actuators with each other, a digitized binary acceleration output is generated. In this work, a 2-bit accelerometer operating in the 0-1g range is successfully demonstrated.

INTRODUCTION

MEMS accelerometers and inertial measurement units (IMU) are utilized in numerous consumer electronics, industrial, biomedical, and automotive applications because of their small size, reliability, low cost and low power consumption. Examples of such include wearable medical sensors, sports watches [1], smart phones, navigation systems, vehicle crash detectors and acoustic and seismic sensors [2]. MEMS based accelerometers, gyroscopes, and magnetometers have thus become very successful commercial products.

MEMS accelerometers with various sensing mechanisms have been demonstrated by researchers. Some of the most popular detection mechanisms used in MEMS accelerometers include piezoresistive [3], piezoelectric [4], capacitive [5], and electron tunneling readout [6]. Most commercially successful MEMS accelerometers work based on capacitive detection, which involves measuring the change in the capacitance between stationary electrodes fixed to the substrate and movable electrodes on a suspended mass. The suspended mass, also called the proof mass, has to be relatively large (typically in the millimeter range) to have adequate accelerometer sensitivity for most consumer applications.

In the state of the art wireless electronics, power consumption is one of the most essential limiting factors. Frequent charging or replacement of the battery due to power loss is simply not feasible. With aggressive power reduction in digital electronics in recent years, MEMS sensors remain one of the most power hungry components in integrated systems. For example, Lee et al have demonstrated a wireless sensor network (WSN) for monitoring the health and performance of motors which includes MEMS sensors, two signal processors, and the communication modules. The total nominal power consumption of the WSN is as high as 35mW, out of which close to 62% (21.6mW) is the power required for operation of the MEMS sensors, with the wireless link and signal processing unit being responsible for only close to a third of the total power consumption [7]. In most cases the large power consumption of MEMS sensors is attributed to the analog front end needed for reading, processing, and analog to digital conversion of the sensor output, which is typically responsible for most to all the power consumption of the whole sensor [8].

Therefore, by eliminating the analog front end responsible for a substantial amount of the power consumption, significant power savings (in some cases close to zero static power consumption) can be achieved. This can be accomplished by designing digitally operated MEMS sensors directly interfaced with digital micro-controllers [9]. In an effort to further reduce the power consumption of MEMS inertial sensors and eliminate the need for any control/readout electronics, this work presents the concept and preliminary and implementation of a fully digital coupled switch MEMS accelerometer providing a 2-bit binary digital output without the need for analog to digital conversion.

PRINCIPLE OF OPERATION

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]. Most acceleration switches are 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 can only indicate whether the applied acceleration is higher or lower than the set threshold and cannot provide quantitative information about how much acceleration is applied to the device at each time. In fact, an acceleration switch can be considered a single bit digital accelerometer. The approach demonstrated in this work is to utilize an array of such acceleration switches electromechanically coupled to one another to turn them into self-computing digital accelerometers providing a binary output.

Figure 1 shows a highly simplified schematic of a 3-bit coupled switch accelerometer comprised of three acceleration switches. Each acceleration switch corresponds to one of the bits of the binary output and consists of a mass-spring combination and a stationary output electrode. The switches are to be designed so that the acceleration threshold of each switch is 2X larger or smaller than the next corresponding switch. The highest

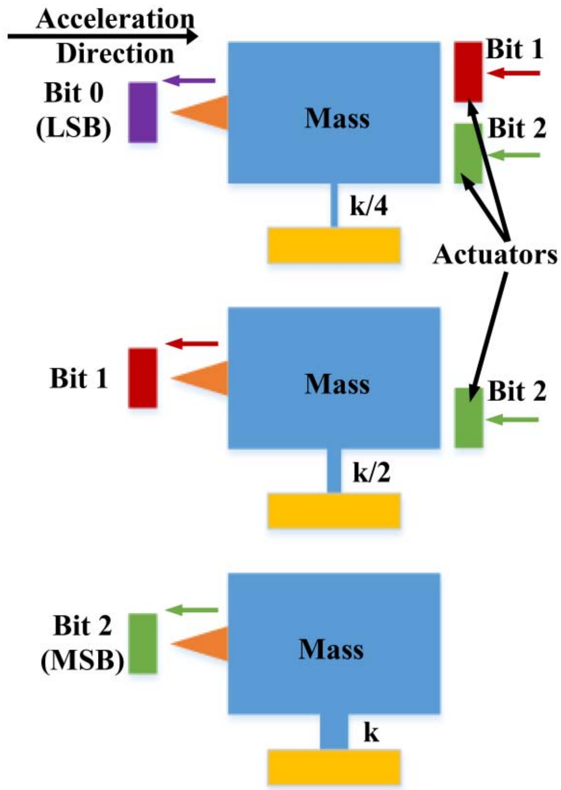

Figure 1: Simplified schematic of a 3-bit coupled switch accelerometer with digitized binary output.

and the lowest acceleration thresholds belong to the switches associated with the Most Significant Bit (MSB) and the Least Significant Bit (LSB) respectively. Each corresponding bit after the MSB has an acceleration threshold 2X smaller than the previous bit, i.e. in Figure 1, Bit 1 has an acceleration threshold 2X smaller than the MSB (Bit 2) switch and the LSB (Bit 0) switch has an acceleration threshold 4X smaller than the MSB switch. The output of every switch is electrically connected to and therefore controls an electrostatic actuator acting on every switch associated with bits with lower significance. For instance, in Figure 1, the MSB bit controls an actuator acting on Bit 1 switch and another actuator acting on the LSB switch, whereas Bit 1 only controls an actuator acting on the LSB switch. The tether spring constant and mass of the MSB switch are to be chosen so that the acceleration threshold of the MSB switch is half of the full scale acceleration (0.5FSa). If the applied acceleration in the direction shown in Figure 1 has an intensity higher than half of the full scale acceleration, the MSB switch will turn ON by making contact to its electrode on the left. As a result, the electrostatic actuator electrodes on the right hand side of switches for Bit 1 and Bit 0, which are electrically connected to the output of the MSB switch, will turn ON, pulling their masses away from the contact electrodes, hence increasing the threshold for those switches. In other words, when the MSB turns ON, the actuators acting on Bit 1 and the LSB switches turn ON, effectively subtracting half the full-scale acceleration force from the acceleration force acting on the lower bits by generating a counteracting force. If the remaining acceleration is larger than the threshold of the Bit 1 (4X smaller than full scale acceleration), Bit 1 also turns ON leading to subtraction of another 0.25FSa from the last switch. Depending on the intensity of the remaining acceleration, the LSB will now turn ON or OFF. In this way, the electromechanical system automatically computes a digitized binary output without involvement of any electronics. Basically, the device itself is just a passive switch requiring energy only for charging and discharging the actuators which would be given to it by the acceleration it is subjected to. Such devices can eliminate the need for the readout circuitry all together leading to stand-alone fully electromechanical accelerometers with digital binary output and close to zero power consumption.

SENSOR FABRICATION

Figure 2 shows the fabrication process used to fabricate the first generation of coupled switch accelerometers on a 15 µm thick device layer of an SOI substrate (1µm buried oxide layer) using a two-mask micromachining process. The accelerometer silicon body is first defined on the SOI device layer via deep reactive ion etching (DRIE) of silicon as shown in Figure 2a. Using a second mask, the silicon handle layer was patterned on the backside and etched all the way to avoid any potential stiction issues for the large proof masses. Devices were then released by removing the buried oxide layer in hydrofluoric acid (Figure 2b). The gaps created between the movable proof mass and the output electrodes were limited by photolithography. In order for the accelerometer to operate at low g accelerations, the gap needs to be

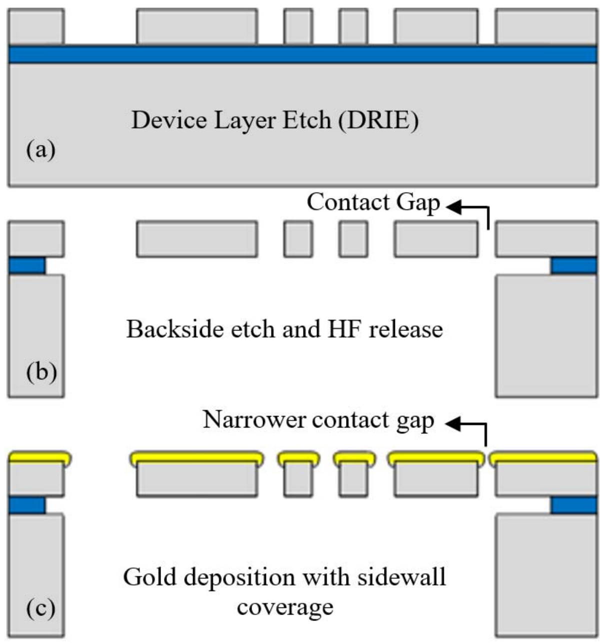

Figure 2: Schematic side view showing the microfabrication process flow.
(a) Pattern and Deep Reactive Ion Etching (DRIE) of the silicon device layer
(b) Backside pattern and etch to avoid stiction followed by removal of buried oxide layer
(c) Sputtering a thick layer of gold with slight sidewall coverage to narrow down the gaps.

narrowed down further than what is possible by regular photolithography (1.5µm). To further narrow down the gap, a thick layer of gold with slight sidewall coverage was sputtered on the fabricated silicon structures (Figure 2c). The sputtered gold on the sidewalls also provides a high quality metal-metal electrical contact between the proof mass and the output electrode. Thickness of the deposited gold on the sidewalls was thoroughly monitored to adjust the gap size between the contact tip and the proof mass in the deep submicron range without the need for nanolithography or any sophisticated processing. Figure 3 shows SEM views of the 2-bit coupled switch accelerometer fabricated using the described fabrication sequence. By depositing a thick layer of gold with side wall coverage, the 1.5µm gap constrained by photolithography and the plasma etch was reduced to 400nm (Figure 3c).

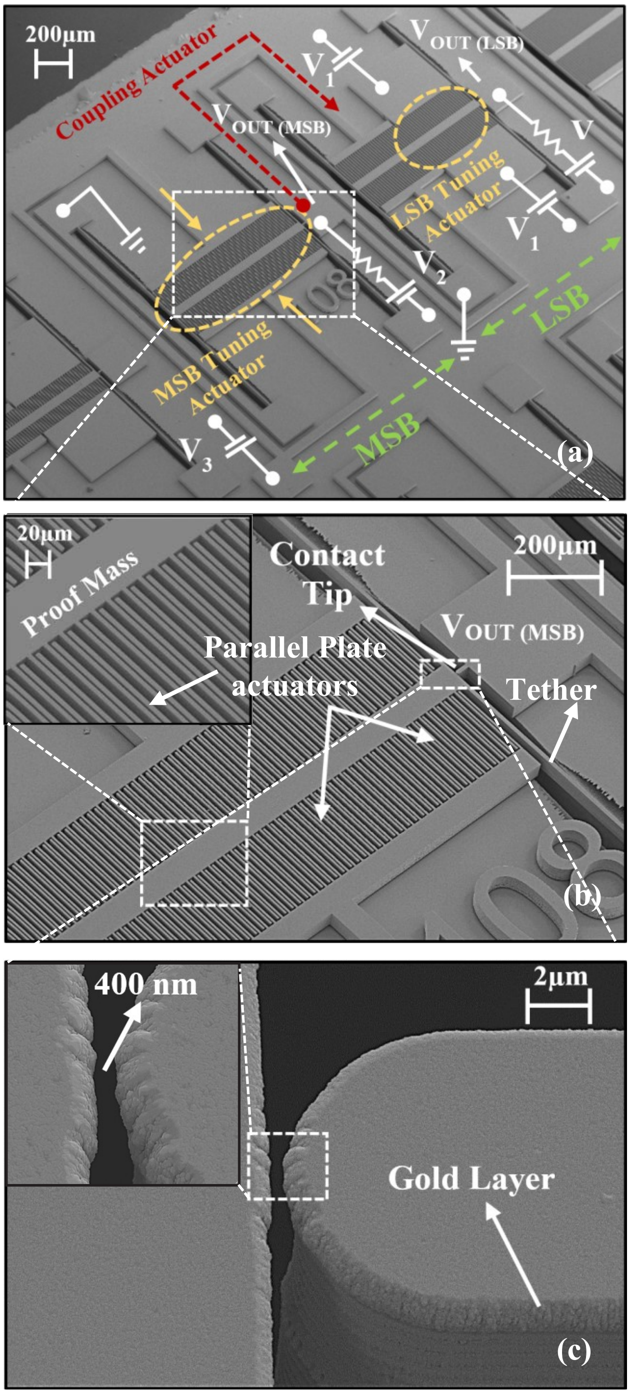

Figure 3: SEM views of the two-bit digital accelerometer along with the zoomed-in views of the contact gap.

The device consists of two acceleration switches coupled to one another providing a 2-bit resolution binary digital output. In addition to the array of coupling parallel plate actuators connected to the output of the MSB switch that acts on the LSB switch, another array of similar parallel plate actuators have been embedded in each of the MSB and LSB switches for tuning purposes. Applying voltages to the tuning actuators can further bring the proof mass closer to the output electrode to reach the desirable acceleration threshold for each switch (V_1 and V_3 for the LSB and the MSB respectively).

MEASUREMENT SETUP AND RESULTS

For the specific device tested in this work, different magnitudes of tuning voltages were required due to the similar stiffness of tethers used for both the MSB and the LSB switches. Consequently, the tuning volt ages were set so as to have a full-scale acceleration of 1g so that the device could be tested by holding the device at different angles, utilizing the Earth's gravity. Table 1 summarizes device dimensions and electrical parameters used in measurements. For the device in question, with the proof masses grounded, the actuation voltages V_1, V_2 and V_3 are to be determined such that the MSB switch makes contact at 0.5g, while the LSB switch make contact at 0.25g when MSB switch is OFF, and at 0.75g when MSB switch is ON. In contrast to the schematic demonstration in Figure 1, the force from the array of coupling parallel plate actuators connected to the output of the MSB switch does not oppose the acceleration force applied to the device but in fact helps it. In other words, the array of parallel plates of the

Table 1: Device Dimensions and electrical parameters

Parameter	Value
Stiffness of each tether	4.5 N/m^2
Proof mass on each bit	3.055e-9 Kg
Number of electrodes on the MSB	112
Number of electrodes controlled by the MSB on the LSB	56
Number of electrodes on the LSB	56
Length of each parallel plate actuator electrode	200µm
Width of each parallel plate actuator	5µm
Device Layer thickness	15µm
Capacitive gap between parallel plate actuators	3µm
Electrode Proof-mass gap on each bit	400nm
Output electrode voltage for LSB-V	5 V
LSB Tuning Voltage-V_1	49 V
Coupling Actuator voltage/Output electrode voltage for MSB-V_2	2.8 V
MSB Tuning Voltage-V_3	10.8 V

Table 2: Measurement results of the accelerometer along with expected values

Acceleration (Theoretical)(g)	Acceleration (Measured) (g)	MSB	LSB
g<0.25	g<0.23	0	0
0.25≤g<0.5	0.23≤g<0.5	0	1
0.5≤g<0.75	0.5≤g<0.77	1	0
g≥0.75	g≥0.77	1	1

coupling actuator helps the LSB in making contact when the MSB is OFF. To determine the required bias voltages, the device is first subjected to an acceleration of 0.75g. With V_2 and V_3 set to zero, V_1 should be just large enough for the LSB switch to make contact right at 0.75g. Leaving V_1 ON, the device is then subjected to 0.5g and V_3 is determined so that the MSB switch makes contact right at 0.5g. To determine V_2, an acceleration of 0.25g was applied and V_2 was set to a value just large enough so that the LSB switch makes contact right at 0.25g. The contact made by the movable masses to the stationary electrodes is determined by reading the current at the output of the MSB and the LSB stationary electrode ($V_{OUT(MSB)}$ and $V_{OUT(LSB)}$).

Once the voltages have been determined, device performance was validated by rotating the device from 0g (0 degree with respect to the horizon) to 1g (90 degree with respect to the horizon) range. The MEMS device in Figure 3 was wirebonded to a printed circuit board and was subjected to different accelerations ranging between 0 and 1g by tilting the board to various angles while maintaining the tuning and coupling actuator voltages and monitoring the output of the MSB and LSB switches for each acceleration. Upon reaching 0.25g, contact was observed at the LSB switch turning the digital output from 00 to 01. Tilting the device further, upon reaching 0.5g, the contact was observed at the MSB switch, effectively negating the effect of the coupling actuator voltage V_2, thus turning off the LSB (Digital output 10). Upon application of 0.77g, contact was observed at both the LSB and the MSB switch indicating a digital output of 11.

The results are summarized in Table 2 showing that the device can distinguish between accelerations in the ranges of 0-0.23g, 0.23g-0.5g, 0.5g-0.77g and >0.77g which are very close to the theoretically expected ranges. By changing the values of the tuning actuation voltages, the accelerometer can be tuned to measure any desired range of acceleration.

CONCLUSION

The concept of utilizing electrostatically coupled acceleration switches as ultra-low power digital MEMS accelerometer was demonstrated. A coupled switch accelerometer consisting of two electrostatically tunable acceleration switches was fabricated using a 2-mask fabrication process and successfully tested as a binary output 2-bit digital accelerometer. The same device principle can be utilized to implement higher resolution (higher number of bits) binary output digital accelerometers. Elimination of the need for an analog front-end and signal conditioners can lead to significant power savings and leap forward towards ultra-low power MEMS inertial sensors.

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