A 5-BIT DIGITALLY OPERATED MEMS ACCELEROMETER

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ABSTRACT

This work presents an electrostatically tunable MEMS acceleration switch and its operation as a 5-bit digital accelerometer. The concept of operating tunable acceleration switches as digital MEMS accelerometers and a 2-bit prototype have been previously demonstrated [1]. 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 work demonstrates increased resolution (higher number of output bits) for such devices by successful fabrication and operation of digital accelerometers with up to 5-bits of resolution. The sensor consists of an acceleration switch (proof mass with an output contact electrode) surrounded by sets of electrostatic actuators each corresponding to one bit of the digital binary output (Fig. 1). Performing a binary search and activating different actuators in proper order (e.g. by a digital controller), the applied acceleration can be determined [1]. The tested 5-bit prototype shows good agreement between the applied acceleration and sensor output with resolution limited by the number of bits, i.e. 1/32 of the full-scale acceleration (159 mg and 62.5 mg for full-scale acceleration of 5.1g and 2g, respectively).

INTRODUCTION

Compact, low cost, and low power accelerometers are required for numerous industrial, biomedical, geological and automotive applications that include smartphones [2], early detection of Alzheimer disease [3], Detection of Driving Events [4]. MEMS based accelerometers 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. Over the past few decades, different types of accelerometers based on various operation principles have been demonstrated. Some of the most popular detection mechanisms used in MEMS accelerometers includes piezoresistive [5], piezoelectric [6], capacitive [7], and electron tunneling readout [8]. 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) so as to have a highly sensitive accelerometer. In today's modern wireless world, power consumption is one of the most essential limiting factors which directly affects the life or suitability of a sensor system. In most cases, 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 [9]. 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 [10]. Therefore, significant power savings (in some cases close to zero static power consumption) can be achieved by elimination of the analog front-end. This calls for a paradigm shift in MEMS sensor design moving from analog sensors towards sensors with direct digital operation/output. For example, Kobayashi et al have demonstrated a piezoelectric accelerometer connected to an array of CMOS converters with satellite capacitors. The on-state and off-state of CMOS inverters correspond to logic '0' and '1'. The number of on-state CMOS inverters responses to increasing the acceleration applied to the piezoelectric accelerometer [11]. In an effort to dramatically reduce the power consumption of MEMS inertial sensors, we have demonstrated a fully digital 5-bit MEMS accelerometer by digitally operating a tunable MEMS acceleration switch.

OPERATING PRINCIPLE

Background

Acceleration switches are simple devices with an output that can be high (ON) or low (OFF) depending on the predetermined acceleration threshold of the device and the acceleration the device is subjected to [12]. 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 moment. In other words, an acceleration switch can be referred to as a single bit digital accelerometer. The approach demonstrated in this work is to add digital control ability via electrostatic tuning to acceleration switches and turn them into multi-bit digital accelerometers. Therefore, devices shown in this work are acceleration switches that can perform quantitative acceleration measurements with the help of a digital controller.

Device Structure

Figure 1 shows the schematic view of the 5-bit accelerometer prototype operating based on the principle of an acceleration switch with digitally tunable threshold. The structure consists of sets of electrostatic actuators mounted around a large proof mass. Each bit of resolution in the sensor response is associated with an electrostatic actuator acting on the proof mass. Once activated, each actuator applies an electrostatic force to the proof mass lowering its switching threshold (by pulling the proof mass towards the output contact electrode). Each actuator applies twice as much force to the proof mass compared to the actuator associated with the next less significant bit. For each combination of activated actuators, depending on whether the proof mass contacts the output electrode or not, it can be determined whether the applied acceleration is

Figure 1: Simplified schematic of the 5-bit digitally operated accelerometer

larger or smaller than the acceleration threshold for that combination. The proof mass moves back and forth in the horizontal direction as a result of the applied acceleration. The proof mass connected to ground (GND) has a metallic tip that comes in contact with a stationary contact electrode when the applied acceleration exceeds the threshold. The stationary output contact electrode is biased with a bias voltage (V_{out}) through a large resistor, hence setting the output electrode voltage to zero. Application of an assistive force which pulls the metallic tip of proof mass towards the output contact electrode will lower the acceleration threshold and vice versa. In this manner, having an arrangement of multiple electrostatic actuators with appropriate strengths (electrode finger size and number) around the proof mass and selectively turning them ON or OFF, a binary search can be performed to find the value of the applied acceleration [1]. 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 electrode voltages are set to zero, the displacement is equal to the gap size between the metallic tip and the proof mass, i.e.:

$$K \cdot g = m \cdot a_{max} \quad (1)$$

where K is the stiffness of the tethers, g is the gap size between the metallic tip of proof mass and the contact output electrode, m is the mass of the proof mass and a_{max} is the full-scale acceleration.

To perform an acceleration measurement, the tuning 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 4 in this case (Figure 1), has twice the number of identical parallel plate actuator fingers compared to the next most significant bit (Bit 3). In other words, Bit 4 provides an actuation force which is exactly twice that of Bit 3 when turned on. Similarly, the number of actuator fingers goes down by a factor of two from the most significant bit to the next less significant bit and the least significant bit (Bit 0) has the minimum number of actuator fingers. The number of electrodes, electrostatic actuator gap size, and electrode areas are to be chosen so that upon application of the ON voltage to the MSB actuator a force equal to 50% of the full-scale acceleration force is applied to the proof mass.

Also, the device is tunable for different full-scale accelerations by decreasing the contact gap between the contact tip of proof mass and the output contact electrode. To reduce the contact gap, a pre-determined tuning voltage could be applied to the electrostatic actuators on one side of the device. Electrostatic actuators on the opposite end were then given a separate actuating voltage (ON voltage) to define the different thresholds of acceleration for each specific bit of resolution.

FABRICATION

Monocrystalline silicon with a relatively thick coating of gold was used as the structural material for the accelerometers. Figure 2 shows the fabrication process used to fabricate the devices on an SOI substrate (50 μm thick device layer, 2 μm thick buried oxide layer) using a two-mask micromachining process. First, a very thin layer (100 nm) of chromium has been patterned on the SOI device layer as a hard mask (Figure 3(a)). Backside was then patterned and etched to avoid any potential stiction issues for the large proof masses. Then the buried oxide layer has been removed in hydrofluoric acid (HF) (Figure 3(b)). The accelerometer silicon skeleton was then defined in the SOI device layer via deep reactive ion etching (DRIE) all the way down to release the device (Figure

Figure 2: Schematic side view showing the microfabrication process flow: (a) Patterned Cr used as hard mask, (b) Backside etch (DRIE) and oxide etch in HF. (c) Device layer etch (DRIE) (d) Gold deposition with sidewall coverage.

Figure 3: SEM views of the fabricated five-bit digital accelerometer along with the zoomed-in views of the output contact tip and support beam

3(c)). To further narrow down the gap between the tip of proof mass and the output electrode, a thick layer of gold with slight sidewall coverage was sputtered on the fabricated fully silicon devices. The sputtered gold on the sidewalls also provides a high-quality metal-metal electrical contact between the tip of proof mass and the output electrode (Figure 3(d)). Thickness of the deposited gold on the sidewalls was thoroughly monitored to adjust the gap size between the contact tip and the proof mass. Figure 3(a) and (b) show SEM views of the digital accelerometer structure fabricated using the described fabrication sequence. Regular lithography and plasma etch constraints restrict the gap size between the proof mass and the metallic tip $\sim 3 \mu\text{m}$. By depositing a layer of gold with side wall coverage, gap sizes as small as $2.5 \mu\text{m}$ were achieved (Figure 3(c)).

Ten identical electrostatic actuator finger sets are included in the device shown in Figure 3(a) allowing operation of the device as a 5-bit accelerometer with 32 of the electrodes associated with the Most Significant Bit, 16 electrodes for the Bit 3, 8 electrodes for Bit 2, 4 electrodes for Bit 1 and 2 electrodes for the Least Significant Bit.

MEASUREMENT SETUP AND RESULTS

The tested 5-bit prototype (Figure 3) has a $1\text{mm} \times 1.9\text{mm}$ proof mass ($225 \mu\text{g}$), four support beams with overall stiffness of 5N/m , and contact gap of $2.5 \mu\text{m}$ leading to full-scale acceleration of 5.1g (binary output of 11111). This relatively big full-scale acceleration would require sophisticated high-g test and characterization equipment that were not available.

The MEMS chip was placed on a printed circuit board and thus tested for acceleration only less than 1g which could be easily applied by tilting the board at various angles with respect the horizon. It was determined that actuation voltage of 12.4V is to be applied to the actuators associated with MSB, Bit-3, Bit-2, Bit-1 and Bit-0 (LSB) actuators to lower the threshold acceleration by $1/2$, $1/4$, $1/8$, $1/16$ and $1/32$ of full-scale acceleration, respectively.

Device performance was validated by applying different accelerations and monitoring the output while manually turning different actuators ON/OFF. To test the device with accelerations in the zero to 1g range, actuation voltage was applied to Bit-4 (MSB) and Bit-3 to keep these bits turned ON and hence, reduce the contact gap in a way that all the digital outputs would correspond to an acceleration less than 1g . By manually switching ON and OFF the actuation voltages to different combinations of the actuators of Bit-2, Bit-1 and Bit-0 all the possible binary outputs between 11010 to 11111 were selectively tested. Table 1 shows resulting sensor binary outputs for different applied accelerations showing the closest possible binary output in each case.

Furthermore, full-scale acceleration of the devices was tuned by utilizing one set of electrostatic electrodes (located on one side of the proof mass) as tuning electrodes. By applying a voltage of 12.5V to the tuning electrodes, the contact gap was effectively reduced from $2.5 \mu\text{m}$ to $1 \mu\text{m}$. This eventually tuned the full scale acceleration from 5.1g to 2g . The device could now be tested for a as a 5-bit accelerometer in the zero to 2g range. To the other set of electrostatic actuators, an actuating voltage of 10.5V was applied

Table 1: Measurement results of the five-bit 5.1g full-scale accelerometer for six selected applied accelerations (Bit values in the Table indicate the ON/OFF (1/0) status of the actuator of the respective bit when contact occurs). Input accelerations are produced from the earth gravity (g) by mounting the sensor chip with a certain tilt angle also shown in the table.

Actuators status					Sensor Mounting Angle (θ)	Input Acceleration $a = g \sin(\theta)$	Measured Acceleration (g)	Sensor Binary Output
MSB	Bit-3	Bit-2	Bit-1	LSB				
1	1	0	1	0	62	0.882	$.796 \leq g < .956$	(00101)
1	1	0	1	1	45	0.708	$.637 \leq g < .796$	(00100)
1	1	1	0	0	32	0.530	$.478 \leq g < .637$	(00011)
1	1	1	0	1	20	0.355	$.318 \leq g < .478$	(00010)
1	1	1	1	0	15	0.265	$.159 \leq g < .318$	(00001)
1	1	1	1	1	0	0	$g < .159$	(00000)

Table 2: Measurement results of the five-bit accelerometer tuned for 2.0g full-scale acceleration for eight selected applied acceleration (Bit values in the Table indicate the ON/OFF (1/0) status of the actuator of the respective bit when contact occurs). Input accelerations are produced from the earth gravity (g) by mounting the sensor chip with a certain tilt angle also shown in the table.

Actuators status					Sensor Mounting Angle (θ)	Input Acceleration $a = g \sin(\theta)$	Measured Acceleration (g)	Sensor Binary Output
MSB	Bit-3	Bit-2	Bit-1	LSB				
1	0	0	0	0	70	0.94	$.9375 \leq g < 1$	(01111)
1	0	0	0	1	62	0.882	$.875 \leq g < .9375$	(01110)
1	0	0	1	0	56	0.829	$.8125 \leq g < .875$	(01101)
1	0	0	1	1	31	0.515	$.5 \leq g < .5625$	(01100)
1	1	0	0	0	16	0.275	$.25 \leq g < .3125$	(00111)
1	1	1	0	0	8	0.139	$.125 \leq g < .1875$	(00011)
1	1	1	1	0	4	0.069	$.0625 \leq g < .125$	(00001)
1	1	1	1	1	0	0	$g < .0625$	(00000)

and the binary search was followed to obtain digital outputs for various accelerations as shown in Table 2.

CONCLUSION

It was demonstrated that the concept of contact-based acceleration switches can be enhanced to perform higher resolution quantitative acceleration measurements. A digitally operated MEMS accelerometer with a 5-bit of resolution was successfully demonstrated. A simple 2-mask fabrication process was used to fabricate the devices and the contact gap size was reduced by a simple mask less fabrication technique. Also, it has been demonstrated that the device can be tunable for different full-scale acceleration. The same device principle can be utilized to implement 7-bit, 8-bit or even higher resolution digital accelerometers. Elimination of the need for the analog front-end and analog signal conditioning can lead to significant power savings and a leap forward towards ultra-low power MEMS inertial sensors.

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