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REAL-TIME IN SITU ELECTRONIC MONITORING OF DYNAMIC CONTACT BEHAVIOR OF MEMS HIGH-G SWITCHES

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ABSTRACT

This paper presents for the first time real-time contact monitoring of packaged high-g switches under acceleration loads up to 50,000 g. Such loads are typical in impact and pyroshock phenomena such as multistage rocket launches and earth penetrating weapons. Contact monitoring is performed using a fully electronic methodology utilizing an ultra low-power (<60 µW) CMOS interface that is directly integrated to the MEMS chip and accurately senses the capacitance change around the contact region at a sampling rate greater than 500 kHz. Experimental and modeling results agree to within 5% for the switch closing time under high-g condition, confirming the validity of the measurement technique.

INTRODUCTION

Dynamic contact behavior of MEMS devices under high-g conditions (20,000 - 60,000 g) is of particular practical value in impact and pyroschock phenomena such as earth penetrating weapons and multistage rocket launches. Although optical techniques can provide real-time height and and velocity information [1], these methods are difficult to implement due to the nature of the measurement environment and application space [2]. Similarly, contact behavior is also difficult to predict due to the presence of rarified gas conditions particularly right before contact. The authors have previously demonstrated an ESBGK-based damping model for predicting the response time of such devices [3]. We now present a real time CMOS-based monitoring system for directly measuring the near-contact behavior of g-switches, from which the response times can also be accurately measured. This CMOS based monitoring system has been successfully demonstrated for measuring the contact behavior of RF MEMS switches under a pull-in voltage [4] and senses capacitance changes at sampling rates greater than 500 kHz. The semi digital nature of the circuit enables us to further develop a digital readout circuit for detecting the sensed acceleration level as shown in Figure 1.

HIGH-G SWITCH

Previously developed high-g MEMS switches consisting of single crystal silicon (SCS) cantilevers with resistive contacts were utilized to implement this monitoring strategy. The switches were fabricated on silicon-on-insulator (SOI) wafers having device and handle resistivities of 0.01-0.02 Ω-cm using the process developed in Raghunathan et al. [2]. Figure 2 shows a typical cantilever fabricated using this process having a length of 634.87 µm, a width of 68.66 µm and thickness of 20.03 µm and a contact gap of 1.95 µm. All measurements are determined with an Olympus LEXT OLS-3100 confocal microscope [5]. This particular cantilever was designed to contact the substrate with a 50 µN force when subjected to a load of at least 20,400 g. A CMOS monitoring circuit is connected to the switch and is used to measure the capacitance change between the beam and contact point.

CAPACITIVE READOUT CIRCUIT

The CMOS readout circuit functions as a semi-digital capacitance to pulse-width modulated (PWM) signal readout interface [6]. The sensor interface chip is designed and fabricated using TSMC 0.13-µm CMOS technology, utilizes 67 transistors, occupies an area of 105 µm × 105 µm. This is then packaged using MLF20 and soldered onto a printed circuit board (PCB) for evaluation. Figure 3 shows a picture of a three channel capacitance measurement setup and a simplified schematic of the measurement setup.

Using the properties of an RC controlled pulse generator, the readout circuit produces a pulse width modulated output whose width is linearly proportional to the RC time constant. The sensing resistor (Rsen) is fixed to a known value and the capacitance change from when the switch closes is determined from the pulse width. As a result of this and the usage of CMOS logic, the circuit is inherently linear when compared to it’s analog counterparts [7].

In this circuit, low power self tuning comparators compare the input voltage to a reference value set to half the supply voltage (VDD). These self tuning comparators are insensitive to process and temperature variations and hence...
prevent performance degradation in a harsh environment such as the one described in this work [6]. As long as the voltage across the capacitor \( V_c \) exceeds the reference value during the ON state of the clock cycle, the output of the interface circuit is high. The voltage across the capacitor can be determined as shown in Equation 1

\[
V_c = V_{DD}e^{-t/R_{on}C}
\] (1)

The time \( T \) required for \( V_c \) to reach \( V_{DD/2} \) is then given by [7]

\[
T = R_{on}C\ln(2)
\] (2)

Thus it can be seen that there is a linear dependence between the change in pulse width and the capacitance change caused by the closing of the switch. The maximum capacitance that can be determined using this circuit is limited by the ON time \( T_{HIGH} \) of the clock signal and the OFF time \( T_{LOW} \) of the clock. This is represented in Equations 3 and 4 [6].

\[
C_{MAX} = \frac{T_{HIGH}}{R_{on}C\ln(2)}
\] (3)

or

\[
C_{MAX} = \frac{T_{LOW}}{5(R_{on}/R_{on})}
\] (4)

Where \( R_{on} \) is the transistor’s on resistance and the factor 5 in Equation 4 is due to the assumption that it requires 5 time constants for the transistor to be completely discharged. The minimum detectable capacitance is determined by the total jitter \( \langle \sigma_j \rangle \) at the output and is given by Equation 5 [6].

\[
C_{res} = \frac{\langle \sigma_j \rangle^2}{R_{on}C\ln(2)}
\] (5)

However in this experiment, the measured capacitances are much greater than the thresholds for minimum detectable capacitances. Jitter can be reduced by employing a crystal oscillator for generating the clock signal. A function generator was sufficient for the needs of this experiment. Power consumption in this circuit is measured to be 60 \( \mu \)W with a reference resistance of 2.7 M\( \Omega \) and reference capacitance of 1 pF at an operating frequency of 32.768 kHz [7]. The proposed interface also achieves 13-aF to 10.7-nF capacitive measurement range at these specs [6,7].

**MODELING**

Computations were performed to determine the theoretical closing time of the g-switch for a given experimental acceleration profile and dimensions. The g-switch was modeled as a cantilever whose displacement is governed by the Euler-Bernoulli beam theory including the microscale gas damping and external acceleration. The equation that governs the dynamics of the beam is given by

\[
\rho bh^2 \frac{\partial^2 w}{\partial t^2} + \frac{Ebh^3}{12} \frac{\partial^4 w}{\partial x^4} + C_{damp}(x,t) \frac{\partial w}{\partial t} = f_{ext}(t)
\] (6)

where \( \rho \) is the density, \( E \) is the Young’s modulus, \( b \) is the width of the beam, \( h \) is the thickness and \( x \) is the distance along the length of the beam measured from the fixed end, \( w(x,t) \) is the displacement. The time-dependent external acceleration \( f_{ext} \) is prescribed based on experiments. The gas damping force coefficient \( C_{damp} \) plays an important role in determining the dynamics of the g-switches including the closing time. The dynamics are solved numerically using a semi-implicit finite difference formulation with a second-order central difference in space and a first-order backward difference in time.

In an earlier work [3], a near-contact damping model was developed for use in MEMS dynamics simulations. The model used in this work has been extended to various widths in the range 20 - 100 \( \mu \)m. The damping coefficient depends on the local gap \( g(x,t) = w_0 - w(x,t) \) and beam width \( b \). The initial gap \( w_0 \) is 2 \( \mu \)m in the current g-switch design. For large values of \( g/b > 0.015 \), \( C_{damp} \) is given by the modified Reynolds-equation model developed by Galis and Torczynski [8] (\( C_{GT} \)). For near-contact conditions, \( g/b < 0.015 \), the damping force coefficient was determined from Boltzmann-ESBGK simulations as

\[
C_{damp} = (111.62 - 10.15b)(g/b - 0.015) + C_{GT}(g/b = 0.015)
\] (7)

In order to account for 8 \( \mu \)m \( \times \) 8 \( \mu \)m release holes in g-switch beams, a smaller beam width value was used in the simulations. While predicting closing times numerically, contact was assumed to occur when the gap size is 50 nm.
EXPERIMENTAL TEST SETUP

The experimental setup involves the following key steps: 1) Packaging and electrical measurement setup and 2) Acceleration evaluation setup.

Packaging and electrical measurement setup

The fabricated die containing the high-g switches are packaged and wirebonded in a ceramic LCC package. This is then soldered onto a PCB with a coaxial output to reduce noise and minimize parasitic capacitances. This is encapsulated in a hollowed tungsten package as shown in Figure 4 [2] and connected to the PCB containing the capacitive sensor interface circuit with a $R_{sen}$ of 5 kΩ as in Figure 4. The interface circuitry is powered by a 1V DC supply and is connected to an external function generator for the clock input.

Acceleration evaluation setup

The acceleration evaluation is performed using a Hopkinson bar setup similar to the one described in Raghunathan et al. [2]. Hopkinson bar techniques have been shown to produce acceleration loads of 10,000 - 200,000 g with pulse durations of 150 - 550 µs and rise times as short as 50 µs [9, 10]. These techniques have been employed to evaluate the performance of piezoresistive accelerometers used in penetration experiments [10, 11]. Similar techniques were used in this study to evaluate the MEMS high-g switches.

Prior to a round of experiments, a commercial accelerometer (Endevco 7270A-200K) was used to verify the acceleration derived from the stress wave on the bar. Figure 4 shows the final picture of the experimental setup with the different sections of the setup.

RESULTS

The fabricated devices were tested with the experimental setup described above. Figure 5(a) shows an example of the raw pulse width modulated response for the cantilever mentioned in Figure 2 for a peak applied acceleration profile of 42,068 g. When the acceleration is below the threshold acceleration of the g-switch, the capacitance of the switch in the open state inclusive of the wires is maintained at 0.12 nF and this corresponds to 22% of the pulse width. When the acceleration first exceeds the threshold acceleration, the beams make a series of intermittent contacts with the substrate (contact bouncing), which is indicated by the transitions between high and low duty cycles as seen in Figure 5(c). This is then followed by the pulse width remaining at 80% when the beams finally settle into contact (Figure 5(d)).

Using Equations 2 and 3, the contact response is extracted and is plotted in Figure 6 as a change in capacitance. This extracted response shows the clear presence of bouncing when the beam first comes into contact.
peak acceleration profiles and are plotted in Figure 7. In all experiments, it can be observed that the closing times agree within 2 µs of each other, which confirms the validity of the measurements. The existing computational framework, however, does not capture contact bouncing due to the lack of a high-fidelity contact physics model that would include effects such as surface adhesion.

**DISCUSSION AND CONCLUSION**

The above results successfully demonstrate a real time in-situ monitoring of dynamic contact behavior of high-g MEMS switches using a low-power CMOS interface. The closing times measured by this method were found to agree within 5% of the modeling results confirming the validity of the measurement technique. Due to the limitations in the contact model employed in the dynamic simulations, contact bouncing is not captured. However, further refinement of the measurement technique to capture dynamic height information and development of suitable high fidelity contact physics model is still under investigation. This will further help to understand the dynamic behavior of these devices.

The low power, high sensitivity and the self tuning nature of this measurement technique makes it promising for use in harsh environments. The semi-digital nature of this technique also offers exciting possibilities for the development of digital acceleration readout circuit for high-g switches.

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