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Micromachined Contact Fuses for Earth Penetrator Applications

LDRD Final Report

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Micromachined Contact Fuses for Earth Penetrator Applications

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ABSTRACT

MEMS is an enabling technology that may provide low-cost devices capable of sensing motion in a reliable and accurate manner. This paper describes preliminary work in MEMS contact fuse development at Sandia National Laboratories. This work leverages a process for integrating both the micromechanical structures and microelectronics circuitry of a MEMS devices on the same chip. The design and test results of an integrated MEMS high-g accelerometer will be detailed. This design could be readily modified to create a high-g switching device suitable for a contact fuse. A potential design for a low-g acceleration measurement device (suitable for such fusing operations as path length measurement device of both whole path length or safe separation distance) for artillery rounds and earth penetrator devices will also be discussed in this document (where $1\text{ g} \approx 9.81\text{ m/s}^2$).

2.0 INTRODUCTION

The acceleration environment experienced by the sensors and electronics in an earth-penetrator weapon is extreme, with average accelerations in the 20,000-g range and peak transient accelerations up to several hundred thousand g's. Earth penetrators often contact earth, concrete, rocks, or other hard materials while traveling at thousands of feet per second. Sensors must be able to survive both penetrator launch as well as contact and penetration while distinguishing between each. Commercially available accelerometers used in shock testing of earth-penetrator weapons components are both expensive (\$1800 each) and prone to failure.

Commercially available accelerometers tend to fail due to lack of damping and breaking packaging leads. The only reported silicon-based high-g accelerometers are bulk-micromachined¹. Preliminary failure analysis of these commercial sensors indicated that failure modes included both undamped high-frequency resonances of the sensor itself and catastrophic failure of the packaging.

Designs for suspended high-g and low-g plate mass sensors were developed and will be described in this paper. The high-g sensor design was developed to directly measure acceleration and shock during earth-penetrator operation. The low-g sensor design was developed to begin coupling multiple fuse functions into a single, integrated device in order to reduce size, power, and cost while increasing reliability and performance. Both high-g acceleration measurement and weapon distance measurement are crucial to artillery round and penetrator weapon fusing.

High-g acceleration measurement is used to determine target contact, target composition (density and/or hardness), and launch velocity. In some cases, weapon fusing is based on contacting a physical structure (weapon hits the ground or other target). In other cases the weapon fusing is based on discriminating between multiple layers of different materials (like sand, gravel, concrete, steel, air, etc.) while it is passing through each. Additionally, fusing may be based in part on the weapon traveling a minimum distance from the launcher. Integration of high-g launch acceleration to obtain exit velocity can be accomplished using a high-g acceleration measurement device.

Low-g acceleration measurements are necessary to accurately measure velocity and distance traveled of weapons traveling through air or water. For instance, the exit velocity of a weapon fired from an artillery gun might be determined using a high-g accelerometer. Velocity and distance information relevant to weapon fuse operation might then be determined using the low-g accelerometer. Velocity and distance information is relevant to weapon fusing to ascertain such important parameters as safe separation distance, weapon position and orientation, safe fusing velocity and direction, impact velocity, and target proximity.

2.1 Fuse Component Customer Requirements Study

Discussions with Victor Rimkus (2522) and Mark Grohman (2522) resulted in a series of development guidelines that were used as a customer requirements study. A summary of the development guidelines are included in the Appendix.

It appears that all four types of fusing relevant to artillery shell and penetrator weapons (time, proximity, contact, and penetrating delay) can be addressed with MEMS devices coupled with microelectronics circuitry. It is impossible to accurately predict the performance of such devices without actually fabricating and testing appropriate devices. The high-g and low-g acceleration measurement devices were targeted in this research because they apply in many of the fusing applications identified and can be used to fulfill multiple purposes. A detailed discussion of the design of these two components and some test results from a preliminary fabrication of a high-g component will be discussed in subsequent sections of this report.

Measurement of both rotation rate and rotation number of a spinning weapon could be accomplished by mounting a low-g accelerometer on the weapon housing. A purely mechanical device (pendulum-spring) has been designed for counting weapon rotation revolutions. This device employs a pendulum element with a period matching the rotation rate of the weapon. Successive rotations of the weapon are mechanically "counted" as incremental deflections of a spiral spring. The spiral spring tension is proportional to the number of weapon rotations. The design of a 26 Hz (26 rps) device is shown in Figure 1 below.

Figure 1: Pendulum-Spring Rotation Counter MEMS Design

CMOS exhibits dielectric breakdown at approximately 100 volts. Higher voltages are theoretically unattainable as the voltage difference would result in arcing between elements of differing voltage to take place. High current is also problematic, but promising designs of MEMS relays are ongoing. High currents result in excessive heating of the polycrystalline silicon structures as well as deformation and failure in some cases.

3.0 INTEGRATED SUSPENDED MASS HIGH-G ACCELEROMETER DESIGN

A suspended mass, high-g accelerometer was designed and fabricated in a variation of Sandia's

integrated surface-micromachined polysilicon / electronics manufacturing process². This sensor consists of a parallel-plate capacitor, with one plate stationary with respect to the sensor housing and the second plate suspended by flexible beams that deflect in proportion to the magnitude of the acceleration imposed upon the sensor housing. The sensor was designed to measure accelerations up to 50 kilo-g with a resolution of 50 G. Dominant design tradeoffs include balancing sufficient plate deflections sufficient to obtain acceptable signal-to-noise ratios from the capacitive sensors against stiff mass suspension elements necessary to obtain responsive sensor measurements (high bandwidth). Additional design tradeoffs include optimizing response by designing a critically damped system subject to processing constraints. This design takes advantage of Sandia's new integrated surface-micromachining/CMOS manufacturing process to incorporate the capacitive pick-off electronics on-chip. Additionally, multiple sensors were fabricated together on the same chip, so that multiple sensors could be tested with a single shock, and the sensors could be readily used in a redundant, fault-tolerant architecture.

The mechanical elements of the high-g accelerometer were fabricated using two layers of polycrystalline silicon with a separation of two microns. The upper layer contains the moving mechanical element of the sensor, and the bottom layer acts as both a structural and electrical ground. The sensor principle of operation is to measure capacitance changes between the two plates with CMOS electronics located adjacent to the mechanical elements (same substrate).

3.1 High-g accelerometer specifications

Nominal parallel-plate capacitance for the 50 kilo-g sensor is 100 fF at a 2 μm gap. This capacitance level is constrained by the necessity to interface with an existing CMOS microelectronics design. When no acceleration was applied to the sensor, its nominal capacitance requirement constrained both the gap spacing and plate overlap area. This translated into a plate overlap area of $\cong 22,500 \mu\text{m}^2$ ($\cong 150 \mu\text{m} \times 150 \mu\text{m}$ square area), where the no acceleration gap spacing was constrained by the 2 μm thick sacrificial oxide layer used in the fabrication process. The desired gap spacing during acceleration of 50 kilo-g is 1 μm . The resonant frequency of the sensor suspension is constrained to be greater than 100 kHz to accommodate sampling frequencies and the induced vibration caused by the sampling voltage electrostatic attractive force. To obtain adequate response, a target range of 0.4 to 0.6 for the damping ratio is also desired. This range was principally dictated by fabrication considerations, specifically the requirement for sufficient spacing of etch-release holes. In this case, there is very little design flexibility to control damping.

3.2 High-g accelerometer mechanical design

The first prototype suspended mass sensor consists of fourteen beam elements (seven on each side) that act as springs to cantilever a $22,600 \mu\text{m}^2$ plate mass (top layer of polycrystalline silicon) over a bottom electrode (bottom layer of polycrystalline silicon). A top view of the sensor and reference capacitor is shown in Figure 2. The sensor consists of two plate masses, one of which serves as a reference capacitor during acceleration measurements. The sensor element on the right is suspended by 14 beams, each 7 $\mu\text{m} \times 90 \mu\text{m}$ in size. Each beam acts as a spring allowing the square plate mass in the center of the sensor to move up or down. The reference capacitor, on the left, is a parallel plate capacitor identical in

geometry to the sensor parallel plate capacitor with the exception of spring elements. Spring elements in the reference capacitor are designed to be very stiff, so that at the acceleration levels relevant to sensor operation, the spring elements permit negligible deflection of the plate mass. The reference capacitance and sensor capacitance are compared electronically to measure acceleration.

Each suspended mass is perforated by 324, $2\mu\text{m} \times 2\mu\text{m}$ etch-release holes. The number and spacing of the etch-release holes (necessary for proper fabrication of the sensor element) results in a damping ratio at 50 kilo-g of acceleration of ≈ 0.4 . The calculated natural frequency of the sensor is ≈ 127 kHz with a damped natural frequency of ≈ 118 kHz. Cross-axis sensitivity should be minimal and the fracture factor of safety of the device was calculated to be almost three. Results of testing the suspended mass prototype sensor are included in section 3.4 of this paper.

Figure 2: Second prototype suspended mass sensor and reference capacitor top view

ANSYS AutoFEA 3-D finite element analysis software was used to analyze the expected deflection of this device at 50,000 g's of shock. The expected results are shown in Figure 3. The maximum deflection of the accelerometer at 50 kilo-g of acceleration was predicted to be 0.99 microns.

Figure 3: ANSYS AutoFEA 3-D Finite Element Analysis of High G Accelerometer Deflection at 50 kilo-g

Damping was determined by simultaneously applying three different models of squeeze film damping, each of which models some but not all of the applicable characteristics of the suspended mass prototype. Squeeze-film damping can be defined as the viscous loss of energy due to pumping a viscous fluid out from or into the volume between two moving surfaces.

The first model³ is applicable to squeeze-film damping between two parallel disks without perforations that are separated by several microns. In this model, viscous damping occurs due to the movement of fluid around the outside edges of the plates. The damping resistance, R_{film} , is characterized by the following equation:

$$R_{\text{film}} = 3\mu S^2 / 2\pi\delta^3 \quad (\text{N-s/m}) \quad (1)$$

where μ is the fluid viscosity (18×10^{-6} kg/m-s for air at 20 °C), S the plate area overlap, and δ the average plate spacing.

The second model³ is applicable to squeeze-film damping when one plate is perforated. In this model, viscous damping occurs due to the flow of fluid through the perforations. The damping resistance, R_{perf} , is characterized by the following equation:

$$R_{\text{perf}} = 12\mu S^2 / N\pi\delta^3 G(A) \quad (\text{N-s/m}) \quad (2)$$

where A is the fraction of open area in the plate, and N is the total number of holes in the perforated plate. The function $G(A)$ is described in equation (3).

$$G(A) = [A/2 - A^2/8 - (\ln A)/4 - 3/8] \quad (3)$$

The third model³ is applicable to squeeze-film damping at high frequencies (> 10 kHz). This viscous resistance is called radiation resistance and is characterized by the following equation:

$$R_{\text{rad}} = \rho c (A\omega/c)^2 \quad (\text{N-s/m}) \quad (4)$$

where ρ and c are the density and speed of sound of the viscous fluid, and ω is the motion frequency. Each of the three models was applied to the design of the suspended mass accelerometer by modeling each of their respective damping contributions and combining them as parallel elements.

3.3. High-g Accelerometer Electrical design

The CMOS circuit for the high-g accelerometer consists of a unity gain buffer followed by a gain stage and output driver. The purpose of the circuit is to measure the change in capacitance of the sensor capacitor relative to the fixed reference capacitor. The sensor capacitor and the reference capacitor are connected in series and an AC signal (100 kHz, ± 5 V P-P) is applied across the pair. If the two capacitors are not equal, an output signal appears at the common node of the pair. This signal is proportional to the acceleration and is sensed by the CMOS circuit.

Since the sensor capacitors are small, the input capacitance of the circuit is also very small. The first stage consists of an n-channel source follower by an input capacitance of $\cong 40$ fF. Noise limits the

sensitivity of the circuit, so the circuit was designed to have an input noise of less than $2\mu\text{V}/\text{Hz}^{1/2}$. The second stage is a combination gain stage and output driver. The gain is $\cong 100$ and the output driver is designed to be compatible with the off-chip loads.

Integrating the CMOS electronics on the same substrate as the micromachines enables the microelectronics to measure extremely small capacitance changes (on the order of fractions of atto Farads). This enables the sensor to be operated over a high dynamic range and still measure relatively small changes in acceleration. Additionally, parasitic noise is reduced while bandwidth is increased in the integrated electronics configuration.

3.4 High-g Accelerometer Test Results

Preliminary test results for the first suspended mass accelerometer prototype demonstrated reasonable correlation between acceleration levels and sensor output at g levels under 15 kilo-g (6 kilo-g, 10 kilo-g, and 14 kilo-g). At higher g levels (above 16 kilo-g), sensor output was saturated and so could not be correlated to acceleration level.

The suspended mass accelerometer output signals also appeared to contain carrier signal components, shock signal artifacts, and unidirectional output bias. A filtered sample test trace is included in Figure 4. A number of electronic as well as mechanical issues that likely contributed to the sensors' operation were identified and addressed. These issues included residual stress in the suspended mass suspension, resonant overtravel, output bias, underdamped mass motion, output amplifier saturation, excessive design gain, and incomplete comparator signal cancellation.

Figure 4: Filtered acceleration vs. time trace for suspended plate accelerometer shock test at 10 kilo-g

4.0 REVISED HIGH-G ACCELEROMETER DESIGN (3rd Prototype)

Two different revised mechanical designs were developed and are currently being fabricated using the Sandia integrated process. The first revised mechanical design is shown in Figure 5. In this design, the suspension system was modified to incorporate greater compliance in both the vertical and horizontal directions. The additional vertical compliance was added to enable increased movement of the plate mass in the sensing direction. The additional horizontal compliance was added to relieve any residual stress that might remain in the structural polycrystalline silicon after processing. The bent beams provide stress relief in the horizontal plane. Both the mechanical design and CMOS circuit design used in the first suspended mass prototype were enhanced to resolve performance reduction factors identified in the previous section. The revised mechanical element was designed to be compatible with the improved CMOS circuitry.

Figure 5: Bent beam mechanical design for high-g accelerometer (3rd prototype)

4.1 Finite element analysis of the high-g accelerometer bent beam design (3rd prototype)

Finite element analysis software was used to verify the design of the bent beam high-g accelerometer. The finite element software that was used is called ANSYS/AutoFEA[®] 3D, and is compatible with AutoCAD[®] generated geometry. Results of this analysis software predicted somewhat different deflection and resonant frequency values than those obtained through manual analysis. The software predicted that the structure would resonate at 151 kHz as compared to manual analysis resulted in a prediction of 101 kHz (Table 1). The finite element software predicted maximum deflection at 50 KG of 0.64 microns compared to 0.95 microns using manual analysis techniques (Figure 6). Additionally, finite element software predicted a maximum principal stress level of 93.2 MPa at 50 kilo-g compared to 74 MPa using manual analysis techniques (Table 1).

• Vibration Frequencies:	• Maximum Deflection
– Mode 1: 151 kHz	(@ 50 k-g's):
– Mode 2: 240 kHz	– 0.64 microns
– Mode 3: 470 kHz	• Maximum Stress
– Mode 4: 498 kHz	(@ 50 k-g's):
– Mode 5: 747 kHz	– 93.2 MPa
– Mode 6: 876 kHz	

Table 1: Finite element predictions of frequency modes, maximum deflection and stress of third prototype high-g accelerometer

Figure 6: Deflection of revised high-g sensor design at 50 kilo-g

5.0 LOW-G ACCELEROMETER

Both high-g and low-g acceleration sensing are important elements for fuse applications. High-g accelerometers are necessary for measuring shock levels and discriminating between impact and shock acceleration events. Low-g accelerometers are necessary for such functions as safe separation distance verification, navigation, and condition monitoring. A low-g accelerometer was also designed and will be fabricated using a new microelectronics integrated three-level polycrystalline silicon process recently developed at Sandia. The low-g accelerometer was designed to measure accelerations between ± 25 G's. Design of the mechanical suspension and microelectronics is similar to the high-g accelerometer design with appropriate scaling applied. Additionally, the low-g accelerometer mechanical structure was designed to be controlled using a force balancing control system. The spring suspension system as well as electrostatic electrodes is shown in Figure 7. Mechanical stops were also implemented at each corner and the center of the capacitive plate sensor to restrict lateral and vertical movement during high-g events.

Figure 7: Schematic of low-g accelerometer

5.1 Finite element analysis of the low-G accelerometer

Finite element analysis software was also used to verify the design of the low-g accelerometer. Results of this analysis software predicted maximum deflection at 10 G of 0.15 microns (for the open loop control case) and resonance at 4 kHz (Figure 8 and Table 2). Additionally, the design factor of safety exceeds 10 for the stress states calculated for a 10 G acceleration event.

Figure 8: Low-g accelerometer deflection at 10 G

• Vibration Frequencies:	• Maximum Deflection
– Mode 1: 3,898 Hz	(@ 10 g's):
– Mode 2: 7,008 Hz	– 0.15 microns
– Mode 3: 7,049 Hz	• Maximum Stress
– Mode 4: 13,281 Hz	(@ 10 g's):
– Mode 5: 13,573 Hz	– 925 KPa
– Mode 6: 19,592 Hz	

Table 2: Finite element analysis of low-g accelerometer

6.0 SUMMARY

The first prototype suspended mass high-g accelerometer design showed promising results up to 14 kilo-g, but was not suitable for higher acceleration levels. A second generation series of designs have been developed to improve and correct those factors that contributed to the unsatisfactory performance of the first prototype. These second generation prototypes include two different mechanical designs and three different electronic circuit designs. The second generation prototypes are currently being fabricated and should be ready for testing in the next few months. A low-g accelerometer design has been developed which is compatible with the new integrated microelectronics, three-level polycrystalline silicon process. The low-g accelerometer is suitable for use in a high-g environments as a fuse component.

The high-g accelerometer device could be redesigned for different sensitivity ranges by changing the geometry of the proof mass suspension springs. Future test results will be correlated to spring length, deflection measurement, and finite element analysis predictions to develop an algorithm for spring length design of high-g accelerometers. Modifying the high-g device to act as a switch could theoretically be accomplished by adding conventional MEMS "dimples" to the proof mass and modifying the spring geometry. Integrated low-g accelerometers could be used to both count the number of rotations and rotation rate of a spinning weapon. Additionally, a purely mechanical pendulum-spring device could be designed to count revolutions of a spinning weapon. MEMS relays could be designed to accommodate many of the switching and triggering functions, with certain voltage and current limitations.

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APPENDIX

SAFT ESAD Development Guidelines

November 19, 1996

The proposed Universal Artillery Standard is 155mm.

The 105mm gun will remain in the inventory and will use the same fuze as the 155mm.

The proposed Universal Mortar Standard is 120mm. (smooth bore)

The proposed Universal Tank Standard is 120mm. (smooth bore)

Our concern is to design an ESAD for a fuze which will be used on the 155mm and 105mm artillery rounds.

The present inventory has four types of fuzes. (time, proximity, contact, and penetrating delay)

The desire is to combine all of these fuzing options into a single universal fuze.

The universal fuze will have inductive fuze setting capability.

(the inductive fuze setting module will be separate from the ESAD).

(the time, proximity, contact, and penetrating delay will also be separate from the ESAD).

105mm round Muzzle velocity = 150 to 600 meters/second.

155mm round Muzzle velocity = 200 to 900 meters/second.

The standard barrel twist is 1 in 20 * caliber.

(155mm * 20 = 3.1 meters/revolution).

(105mm * 20 = 2.1 meters/revolution).

Safe separation considerations (the army does not believe these requirements are adequate)

No Arm before 400 * caliber	(155mm * 400 = 62 meters) '20 revolutions'	
fast round	(62/900 = 68.9 milliseconds)	290.3 rps
slow round	(62/200 = 310 milliseconds)	64.5 rps

	(105mm * 400 = 42 meters) '20 revolutions'	
fast round	(42/600 = 70.0 milliseconds)	285.7 rps
slow round	(42/150 = 280 milliseconds)	71.4 rps

All Arm by 800 * caliber	(155mm * 800 = 124 meters) '40 revolutions'
fast round	(124/900 = 137.8 milliseconds)
slow round	(124/200 = 620 milliseconds)

	(105mm * 800 = 84 meters) '40 revolutions'
fast round	(84/600 = 140 milliseconds)
slow round	(84/150 = 560 milliseconds)

A long artillery flight would be 200+ seconds. (The desire is to increase range as accuracy improves)

What should our SAFT ESAD contain?

Two Environment Sensors:

Setback activated battery. (If the output is sufficient this will power all fuze sub-systems).

Spin sensor or revolution counter.

Setback & spin time or revolution count will be used as the two independent environments.

Note: The present mechanical fuze inventory arms at 24 revolutions.

Oscillator:

Drive train generator for high voltage converter.

High Voltage Converter:

Three FET switches, transformer, HV diode, HV capacitor, Dual HV resistors, charge current sense circuit, HV switch and trigger circuitry.

Self Destruct Capability:

If the ESAD reaches full armed condition, it must detonate before it dies.

Explosive output:

PBXN-5 (copy current lead charge)

Desirable dual output: PBXN-5 & det cable or black powder initiation.

Packaging:

Our electronics must be packaged to withstand the MK399 penetrating fuze type environments.

My guess is that we can start generating the high voltage once setback and spin are detected. The energy stored on the capacitor should not ever be allowed to exceed the no fire threshold (500V?) before reaching the "No Arm before 400 * caliber" limit. Of course we must be above the all fire threshold no later than the "All Arm by 800 * caliber" limit. If the spin environment ceases before full arming the ESAD must automatically revert safe. Once fully armed, the built in self destruct logic must be enabled. If we do not receive a fire signal or the battery fails or the high voltage drops or the converter fails, etc. the ESAD must self destruct.