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High-G Testing of MEMS Mechanical Non-Volatile Memory and Silicon Re-Entry Switch

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Abstract

Two different Sandia MEMS devices have been tested in a high-g environment to determine their performance and survivability. The first test was performed using a drop-table to produce a peak acceleration load of 1792 g's over a period of 1.5 ms. For the second test the MEMS devices were assembled in a gun-fired penetrator and shot into a cement target at the Army Waterways Experiment Station in Vicksburg Mississippi. This test resulted in a peak acceleration of 7191 g's for a duration of 5.5 ms. The MEMS devices were instrumented using the MEMS Diagnostic Extraction System (MDES), which is capable of driving the devices and recording the device output data during the high-g event, providing in-flight data to assess the device performance. A total of six devices were monitored during the experiments, four mechanical non-volatile memory devices (MNVM) and two Silicon Re-entry Switches (SiRES). All six devices functioned properly before, during, and after each high-g test without a single failure. This is the first known test under flight conditions of an active, powered MEMS device at Sandia.

Acknowledgment

The authors would like first like to thank Tony Mittas and Ben Welch for their work on the MDES system. Without them and the MDES project this test would not have been possible. We would also like to thank Tom Martinez, Ed Henry and the gun team at WES for their expertise in executing the gun test. Finally, thanks to Randy Lockhart for his help in designing and fabricating the device housing used in the test.

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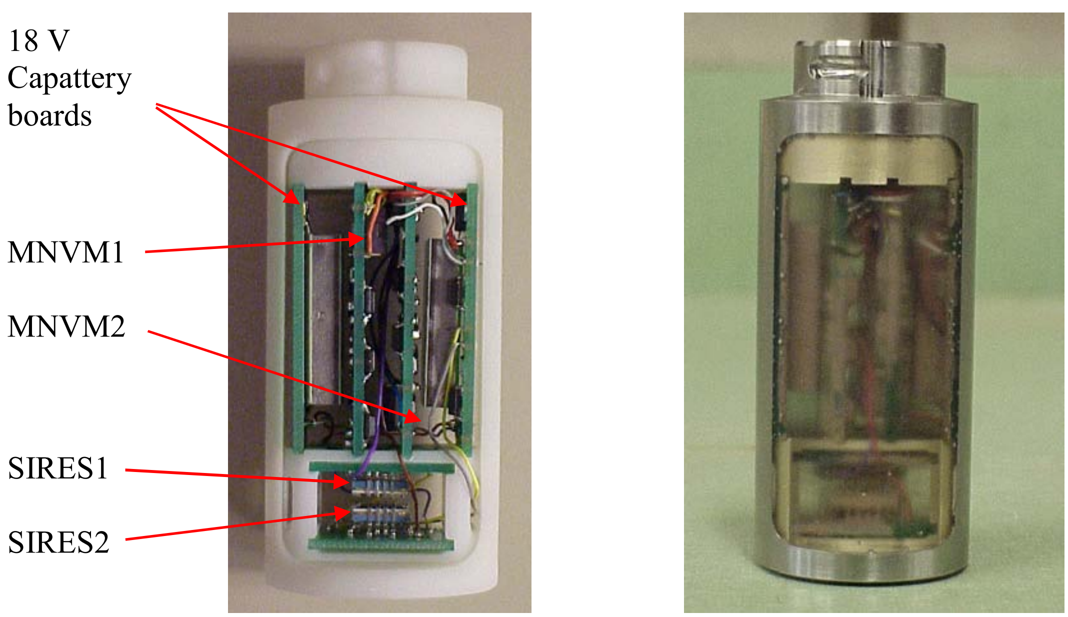
1. Introduction

Microelectromechanical Systems (MEMS) technologies are being studied to determine their robustness to high-g shock and vibration environments. They are expected to perform well due to their relatively low mass. High-g tests have been conducted in the past on various Sandia MEMS components; however, they have all been performed on passive un-powered devices [1-5]. In these past experiments, device functionality was verified before and after shock testing but data had not been available on performance during the acceleration environment.

This report summarizes the results of two high-g tests performed on two different Sandia MEMS devices. In each experiment, the MEMS devices under test were operating during the acceleration event, and performance data was logged using a newly developed diagnostic extraction system allowing for analysis of device operation during the acceleration load. The first shock test was performed using a drop-table to generate a peak acceleration load of 1792 g's over a duration of approximately 1.5 milliseconds. In the second test the device was assembled in a gun-fired penetrator and shot into a cement target producing a peak deceleration of 7191 g's for a duration of 5.5 milliseconds.

2. Test Devices

Two different MEMS devices were tested simultaneously during the shock tests, the mechanical non-volatile memory and Silicon Re-entry Switch. Each device was packaged



(a) **(b)**

Figure 2-1: (a) Photo of the plastic prototype unit with parts labeled. (b) Photo of the final steel test unit after potting.

and mounted on a printed circuit board with associated drive and output electronics. These circuit boards were then mounted inside a stainless steel test housing that was designed to fit within the allocated volume of the penetrator experiment, and to make electrical interface with the MEMS Data Extraction System (MDES). A picture of the assembled test housing is shown in Figure 2-1. After assembly and wiring of the boards in the test unit, the free volume was potted with an epoxy that provided component stability during the high-g tests.

The connection to the MDES battery is not expected to survive the launch and impact environment, so the test unit was designed to operate under its own power for several seconds after launch. So, in addition to the four test boards (MNVM1, MNVM2, SiRES1 and SiRES2), there are also two capattery boards, connected in series. Each capattery board contains a 22 milli-Farad capacitor, and is charged to 18 V by the MDES system battery before the launch event.

2.1. Mechanical Non-Volatile Memory

The mechanical non-volatile memory device (MNVM) is a surface-micromachined SUMMiT V design. It is a latching DC micro-relay where the open or closed state of the relay is used to store a single bit of data. As the relay is toggled, it makes or breaks a pair of metallized contacts that provide an electrical output to monitor the switch position. Power is required to switch the state of the relay, but once set in the open or closed position it will remain there indefinitely without power.

The MNVM switch is based on a compliant bistable mechanism design [6,7], with thermal actuators used to toggle the device between open and closed states [8,9]. An image of the device is shown in Figure 2-2, with the CAD layout superimposed on the photo to better illustrate the function of the device. The mechanism and actuators are not visible because they are protected by the uppermost polysilicon layer in the SUMMiT V^{TM} process. This upper layer is used as a shadow-mask for the post-release metal evaporation step that creates the switch's metal contact surfaces.

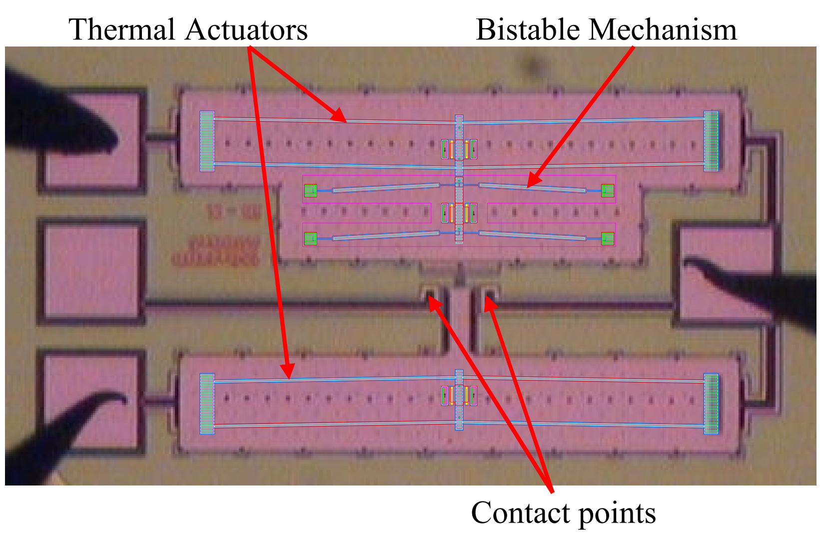


Figure 2-2: Labeled photo of MNVM device with over-laid CAD drawing.

A printed circuit board was designed to generate the necessary drive signals for the MNVM device, and to provide an analog output to the MDES unit (shown as MNVM1 and MNVM2 in Figure 2-1). A schematic of the MNVM layout on this board, along with the generated input signals is shown in Figure 2-3 (a). The "open" and "close" thermal actuators require an input square pulse with an amplitude of 7.2 V, and a pulse width of at least 750 microseconds. To improve contact lifetime and performance, the device is operated in a cold-switching mode where power to the contacts is turned off for each switch event. After every switch toggle, power to the contact is turned on momentarily to determine the switch position. The input signals generated by the NVM circuit board as inputs to the device package are shown in Figure 2-3 (b).

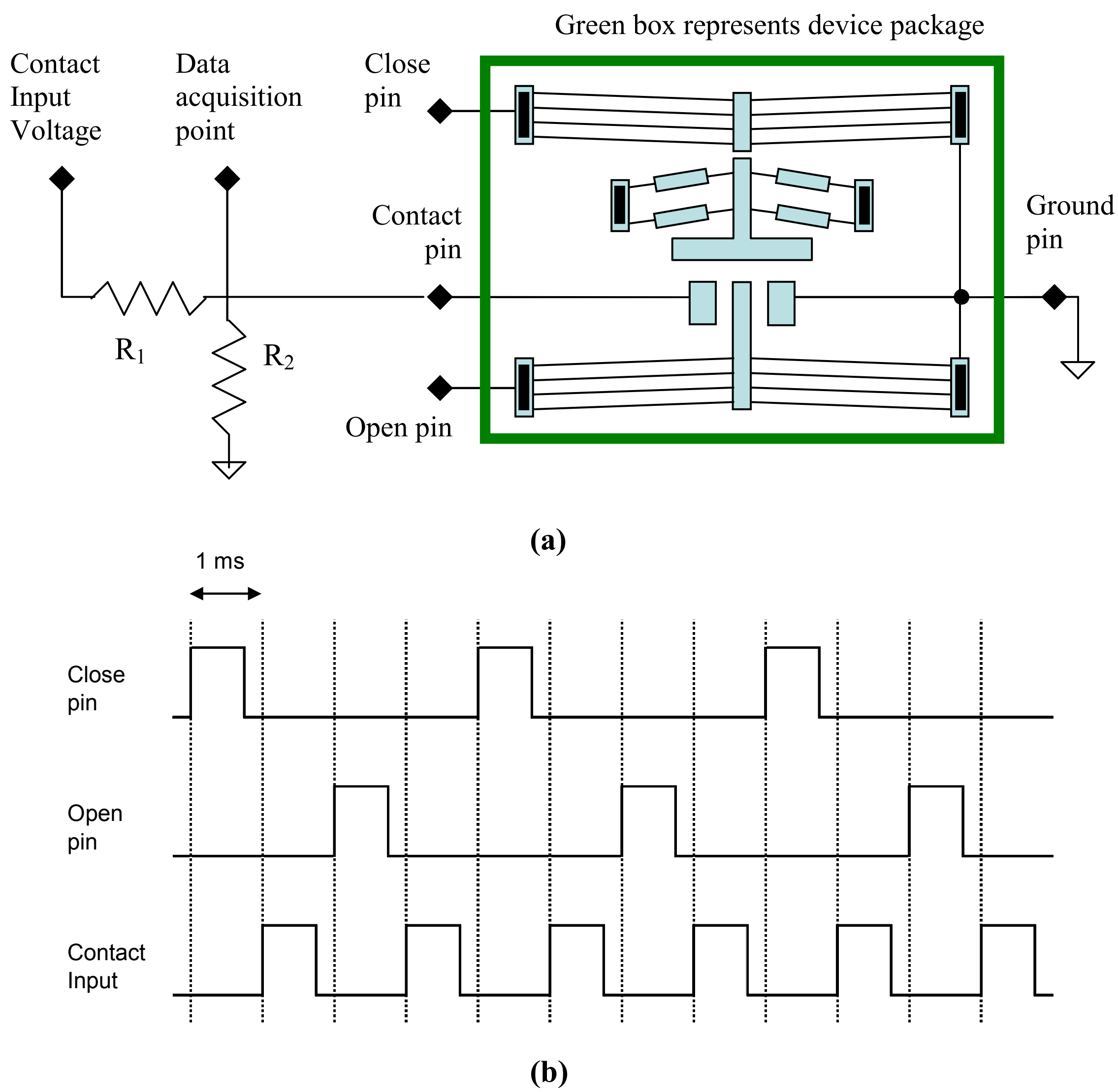


Figure 2-3: (a) Schematic showing MNVM device and electrical connections to the package and data acquisition system. (b) Timing of input signals to MNVM device.

The drive circuitry uses an adjustable voltage regulator to reduce the system voltage to 8.0 volts, which provides voltage not only to the circuit logic but also to the drain of an N-channel FET. Taking into consideration the gate to source voltage drop of 0.8 volts, the output voltage to the device is on the order of 7.2 volts as required by the thermal actuators. For simplicity in the board design, this same voltage is used for the contact input. However, the MDES data recorder requires a maximum of 5.0 volts on the analog and digital inputs. The resistors, R_1 and R_2, shown in Figure 2-3 (a) are used as a voltage divider and maintain a 4.9 volt level to the MDES recorder when the switch is in the open state. When closed, the contact resistance across the switch is much less than the value of R_1, causing the voltage at the data acquisition point to drop to less than 1.0 volt. The expected input to the MDES system for the MNVM device is shown in Figure 2-4. This figure shows the alternating high and low voltage amplitudes recorded from the switch as it is toggled between the open and closed state respectively. The region of zero voltage between each individual square pulse corresponds to the time when the contact voltage is turned off and the switch is being toggled between states. The devices are switched at approximately 250 Hz, or 2.0 milliseconds between each switch event.

The SUMMiT V™ die was packaged in a 16-pin narrow well dual in-line package. Each die contained two devices that were wire-bonded for test. One of these devices was cycled as described above, with the output of the switch recorded using an analog channel on the MDES unit. The other device was not actuated, but the contact output was continuously monitored on a digital MDES channel to determine if the switch toggled states on its own under the applied acceleration load. Two boards were included in the final test housing as shown in Figure 2-1, with the second board rotated 180 degrees from the first. With this configuration the switches on the MNVM1 board are oriented such that the bistable

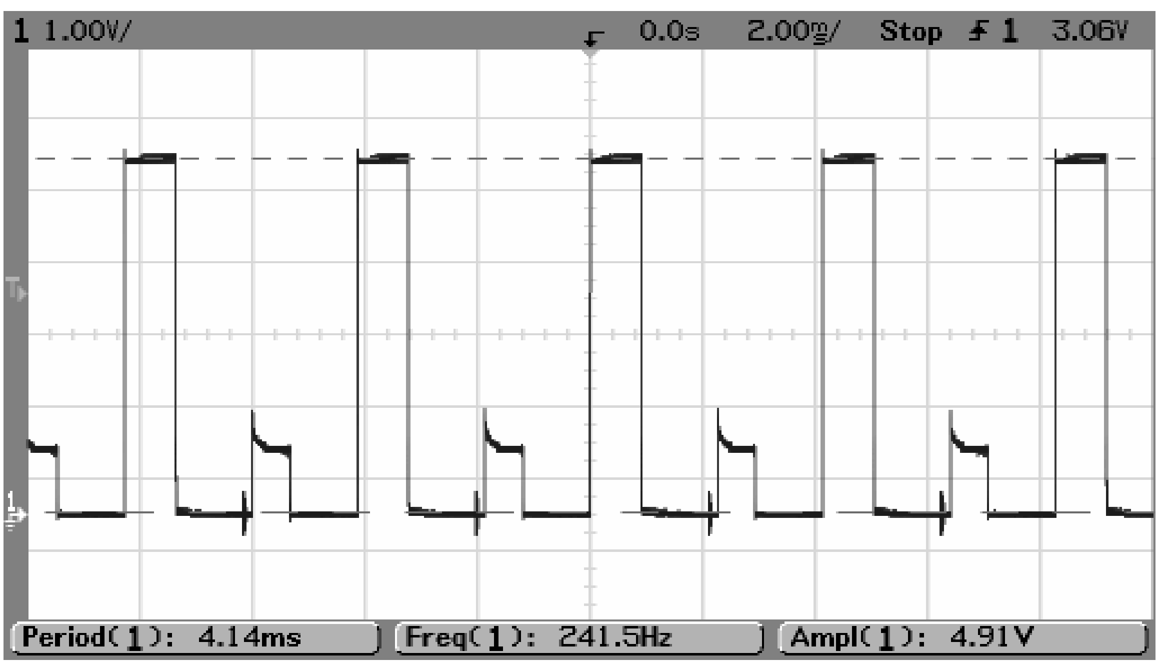


Figure 2-4: Output capture from the data acquisition point for working device.

mechanism would be pushed closed by the deceleration at impact, and the MNVM2 board is oriented such that the switches would be pushed open on impact.

2.2. Silicon Re-Entry Switch

The Silicon Re-Entry Switch (SiRES) is a bulk micromachined acceleration switch made using silicon-on-insulator technology. It uses a piece of the silicon substrate as a proof-mass, patterned using deep reactive-ion etching, suspended by a set of springs patterned out of the top silicon layer on the SOI wafer. When the proof-mass is deflected under an acceleration load it closes a metallized contact. The designed set-point for the devices used in this test is 12-15 g's.

When installed in the test housing, the SiRES1 board is oriented such that the switch will be pushed open on impact, with the SiRES2 board rotated 180 degrees such that it will be pushed into the closed position by the deceleration at impact. The switch state is monitored by measuring the voltage drop across a pull-up resistor at 4.5 volts. When open, the measurement will read 4.5 volts, and when closed it will be 0 volts with respect to ground. Both switch outputs are recorded using separate analog input channels on the MDES unit.

3. MEMS Diagnostic Extraction System

To demonstrate the performance of MEMS devices under penetration and other high-g environments, the device must be instrumented and data recorded during the flight. The MEMS Diagnostic Extraction System (MDES) was developed under LDRD funding to meet this need and provide a flexible platform that would allow MEMS devices to be powered and monitored on flight tests of opportunity, without interfering with the tests' primary purpose. The MDES unit is capable of generating needed input stimulus for the device under test as well as logging data from the device for post-test examination. A three-axis accelerometer is included in the system to provide information on the acceleration environment seen by the device. More information on the MDES system can be found in the final LDRD SAND report that will be published at the end of 2005 [10].

Figure 3-1: Photo showing the MDES unit (larger cylinder on the left) next to the MNVM/SiRES test unit (smaller unit on the right).

A picture of the MDES unit, adjacent to the MNVM/Sires test unit, is shown in Figure 3-1. While the MDES unit is capable of generating both analog and digital outputs to the device under test, this capability is not utilized in this work due to the independent nature of the MNVM/SiRES test unit's circuitry which provided the required drive signals. An 18 volt DC input power and ground were provided by MDES to the test unit. The electrical connection between the MDES unit and the test unit is provided by a 19-pin Nanonics connector.

The data recorder on the MDES unit captures voltage data at a rate of approximately 78.15 kHz. Three analog channels are reserved for the three-axis accelerometer data, two are used for the active MNVM devices, and two for the SiRES output. Two additional digital channels are used to record the state of the two passive MNVM devices to determine if they change states due to the acceleration load while un-powered.

4. Drop Table Test

The first test that was performed utilized a drop table to generate 1792 g's over a 1.5 millisecond duration. The MDES and test units were assembled in a cylindrical aluminum housing with bolt holes that allow the housing to be directly mounted onto the shock table as shown in Figure 4-1. The test set up requires a wire tether to remain attached to the test block to provide power to the unit.

Plots of the captured data from the test are shown in Figure 4-2. The two digital channels monitoring the un-powered MNVM devices are not shown; however, they were both recorded at a constant high value indicating that the devices did not change state due to the acceleration load.

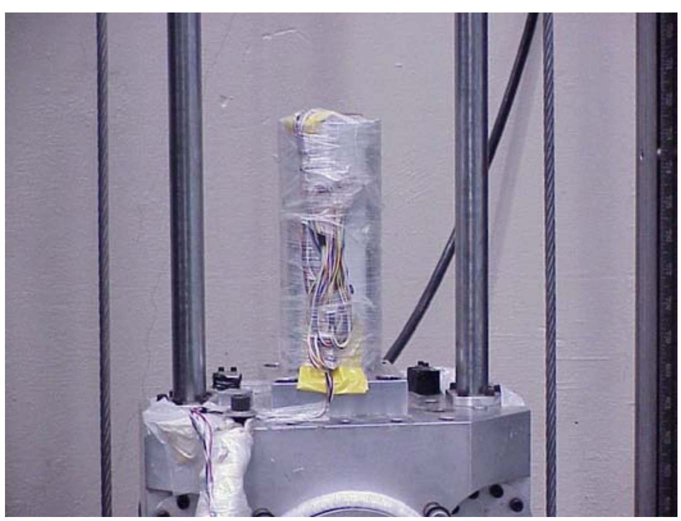


Figure 4-1: Photo of the aluminum housing mounted on the drop table.

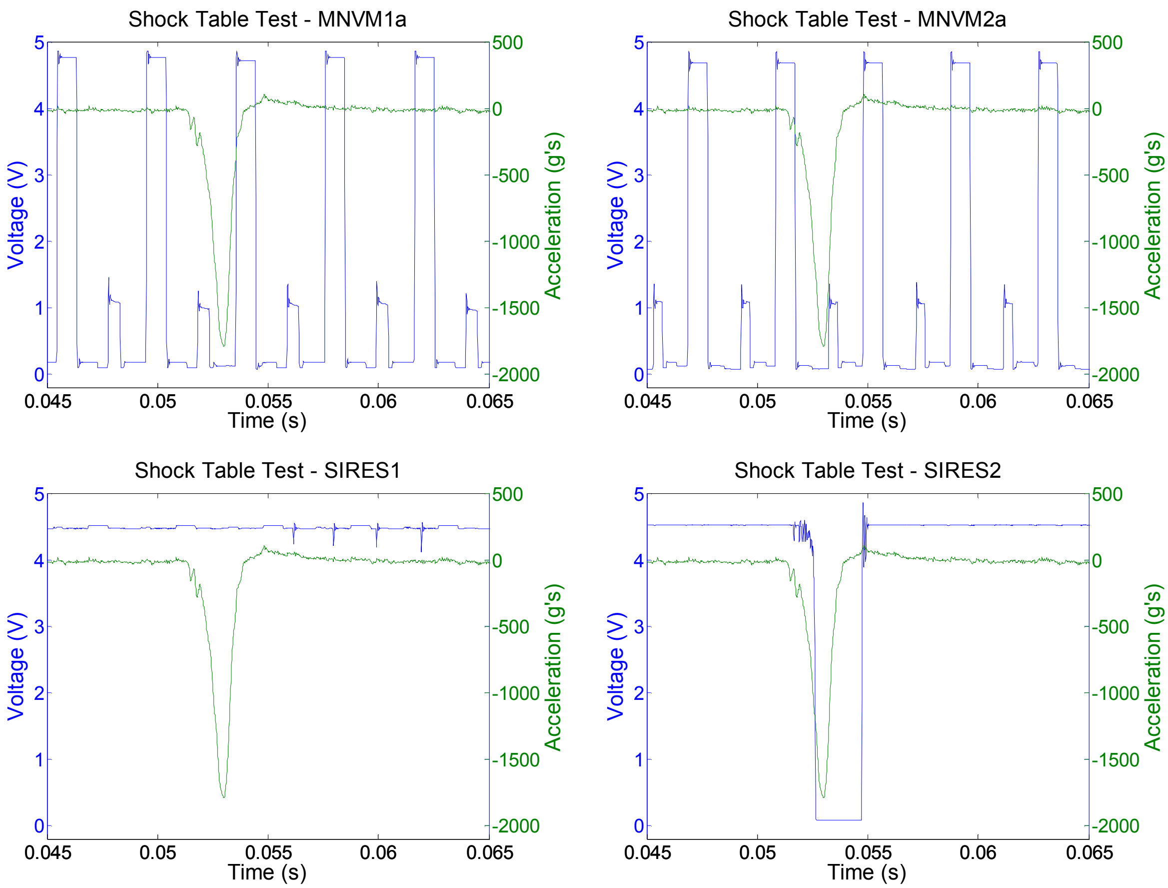


Figure 4-2: Data from drop table test.

As can be seen in the data plots, there is some cross-talk coupled between the analog channels. This is evident when comparing the SiRES data plots, where a small square-wave appears superimposed on the SiRES1 data plot that is not present in the SiRES2 data. Similarly, a small amplitude square wave signal is superimposed on both of the MNVM data plots. However, the amplitude of this cross-talk induced by the MNVM channels is small and may be considered negligible when interpreting the test results.

The MNVM1 device is oriented such that the switch is pushed closed by the impact deceleration. The deceleration pulse occurred while the device was switching from closed to open, resulting in a worst-case loading condition. The MNVM2 device is rotated 180 degrees in the housing with respect to the MNVM1 device, and it also experienced worst case loading while switching from open to closed. Both MNVM devices functioned through the acceleration pulse without any errors in their behavior.

Based on the orientation and design of the SiRES test units in the housing (see Section 2.2), they also functioned properly. SiRES1 remaining open during the test and SiRES2 closed on impact and then re-opened.

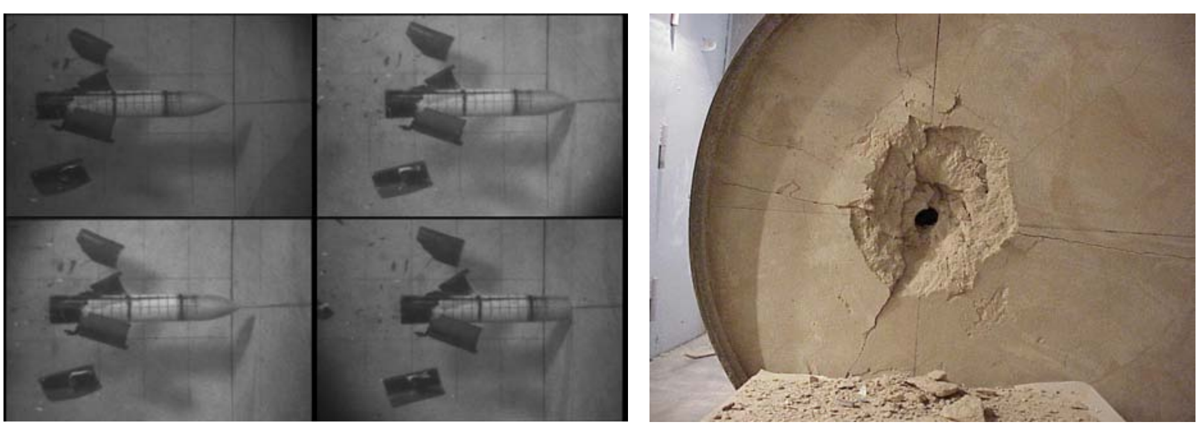
(a) (b)

Figure 5-1: The gun (a) that was used to fire the penetrator into the cement target (b).

5. Gun Test

The second test was performed at the Army Corps of Engineers Waterways Experiment Station in Vicksburg Mississippi. The test units (MDES and MNVM/SiRES) were assembled in a penetrator and fired out of a horizontal breech-loaded gun into a cement target. The gun and target are both shown in Figure 5-1. The penetrator shell when fully assembled weighed 13.692 kg, and was 3.0 inches in diameter and 22 inches long. It entered the target at a speed of 885 ft/sec, with a peak acceleration seen on launch of 1282 g's and the peak deceleration on impact of 7191 g's. The impact pulse duration was 5.5 milliseconds in duration. The penetrator was completely buried in the target with the final rest position of the back of the penetrator shell at a depth of 9 inches from the concrete surface as shown in Figure 5-2.

The data recorded by MDES for the devices under test is shown in Figure 5-3. For both MNVM devices, a second plot is shown with the scale adjusted to focus on the impact event.



(a) (b)

Figure 5-2: (a) High-speed camera images of penetrator leaving barrel and entering concrete target. Frame spacing of 200 microseconds. (b) Target after impact

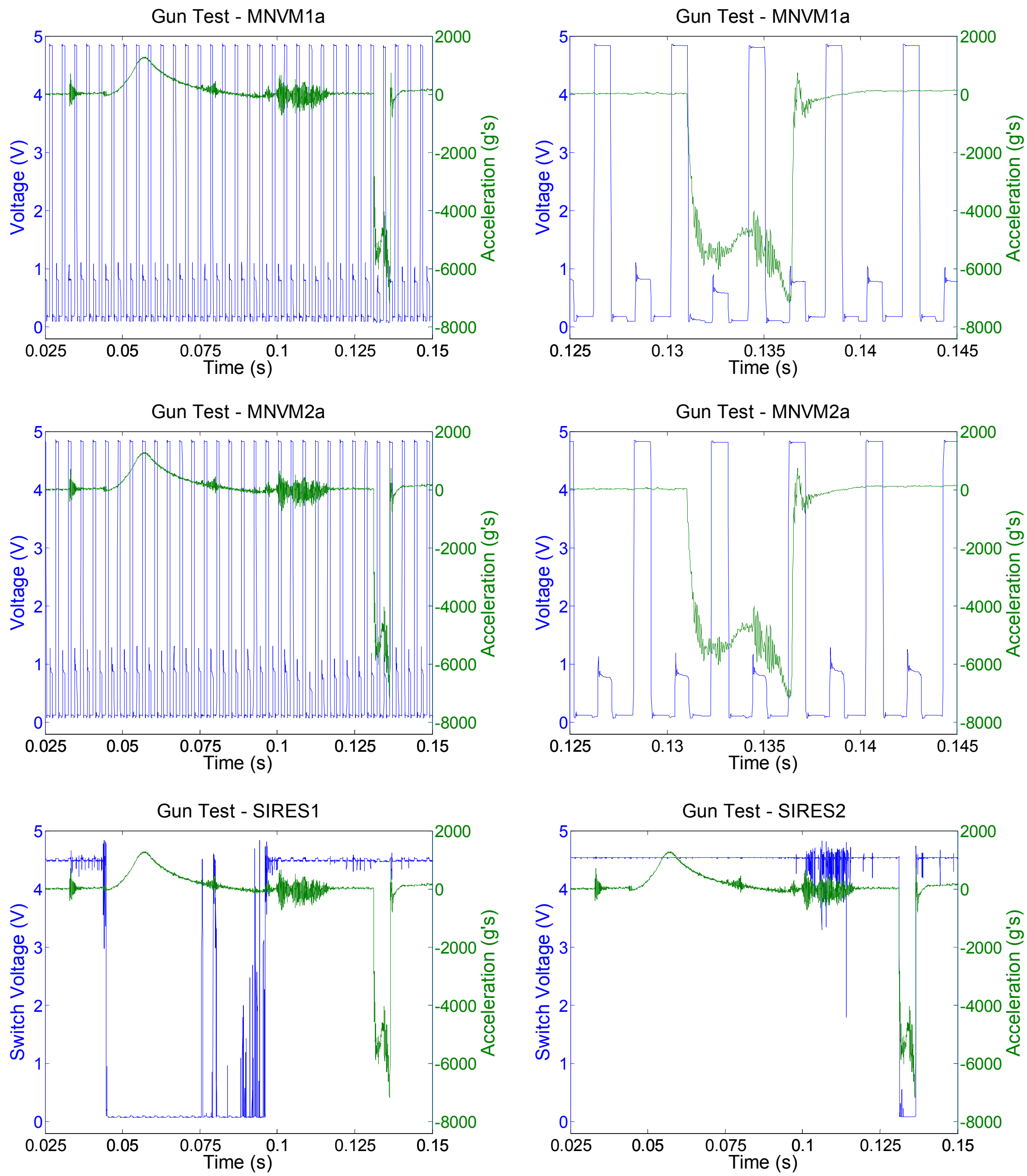


Figure 5-3: Data from gun test. MNVM1 and MNVM2 plots are also shown zoomed-in on the impact deceleration.

Crosstalk is still visible on the MNVM and SiRES1 data traces, but the magnitude is small and may be considered negligible during the analysis. Again, both MNVM parts operated without error through the launch and impact sequence.

With an impact duration of 5.5 milliseconds the MNVM devices demonstrate robust operation through three switch events under load. The only change observed through the test is a reduction in the voltage measured on MNVM1 while in the closed state during the impact. This lower voltage corresponds to a reduction in contact resistance for this single switch event. Based on the orientation of this device, this result is consistent with an increase in contact force due to the acceleration load. As with the previous test, the data is not shown for the un-powered devices, but they did remain open as expected during the entire test.

Even though the SiRES devices are not designed or intended to operate under such high acceleration loads, they also perform well in this test. SiRES1 closes during launch and then re-opens during the impact event, while SiRES2 closes only during the impact. Some contact chatter is present on both devices during the penetrator flight through the gun barrel, which can be attributed to vibration levels in excess of the 12-15 g set point of the device.

6. Conclusions

High-g operational testing has been successfully performed on two different Sandia MEMS devices using both a drop-table and a gun-fired penetrator test. This is the first known test under flight conditions of a powered, active Sandia MEMS device. Maximum acceleration loads of up to 7191 g's were recorded, and both the mechanical non-volatile memory and Silicon Re-Entry Switch not only survived, but continued to operate correctly during these acceleration environments.

7. References

[1] Tanner, D., Helgesen, K., Walraven, J., Clement, J., Irwin, L., Brown, F., and Gregory, D., "MEMS reliability in shock, vibration, and temperature environments," SAND99-2488A, proposed for presentation at the International Reliability Physics Symposium, San Jose, CA, April 10-13, 2000.

[2] Tanner, D., Walraven, J., Helgesen, K., Irwin, L., Gregory, D., Stake, J. and Smith, N., "MEMS reliability in a vibration environment," SAND2000-0329C, proposed for presentation at the International Reliability Physics Symposium, San Jose, CA, April 10-13, 2000.

[3] Tanner, D., Walraven, J., Helgesen, K., Irwin, L., Brown, F., Smith, N. and Masters, N., "MEMS reliability in shock environments," SAND2000-0378C, proposed for presentation at the International Reliability Physics Symposium, San Jose, CA, April 10-13, 2000.

[4] Duesterhaus, M., Bateman, V. and Hoke, D., "Shock Testing of MEMS Devices," SAND2004-1356C, Proposed for presentation at the SEM X International Congress and Exposition on Experimental and Applied Mechanics, Costa Mesa, CA, June 7-10, 2004.

[5] Duesterhaus, M., Bateman, V. and Hoke, D., "Shock Testing of Surface Micromachined MEMS Devices," SAND2002-3889C, Proposed for presentation at the Workshop on Nana and Microsystems Technology and Metrology, Redstone Arsenal, AL, December 4-5, 2002.

[6] Wittwer, J. W., Baker, M.S. and Howell, L.L., "Robust Design of a Fully Compliant Bistable Micromechanism" Accepted to the ASME/IEEE Journal of Microelectromechanical Systems, July 2005.
[7] Jensen, B.D., Parkinson, M.B., Kurabayahsi, K., Howell, L.L. and Baker, M.S., "Design Optimization of a Fully-Compliant Bistable Micromechanism," Proceedings of 2001 ASME International Mechanical Engineering Congress and Exposition, New York, NY, November 11-16, 2001.
[8] Baker, M.S., Plass, R.A., Headley, T.J. and Walraven, J.A., "Final Report: Compliant Thermo-Mechanical MEMS Actuators LDRD #52553," SAND2004-6635, Printed December 2004.
[9] Wittwer, J.W., Baker, M.S. and Howell, L.L., "Force Characterization and Model Validation of a Thermal Microactuator," Submitted to Sensors and Actuators, July 2005.
[10] Mittas, A. et. al, "MEMS/Fuze Diagnostic Extraction in High-G Environments," LDRD Final SAND report to be published in 2005.

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