METHODS FOR PROTECTION OF SILICON SUSPENSIONS FROM HIGH SHOCK LOADING

S. Kumar, T. Hopf, W.T. Pike
Optical and Semiconductor Devices Group, Electrical and Electronic Engineering,
Imperial College, London, UK
skumar@imperial.ac.uk

Abstract — *There are many areas which require instruments to be operational after exposure to high levels of shock acceleration such as planetary missions, oil drilling, and military applications. MEMS devices are typically quite resilient to low shock due to their small mass and high resonant modes. Problems can arise, however, when devices with low resonant frequencies and large ranges of motion are placed under high shock loading. This work presents various methods and experimental results on surviving high shock loading for 10 Hz silicon suspensions with 100's of µm of lateral travel, for use in a microseismometer. Electrostatic clamping and mechanical latching are both analyzed for their effectiveness in shock protection. A method involving a sublimating substance used to encapsulate the suspensions completely during deployment is also presented, and furthermore shown to survive shocks in excess of 10,000g.*

Key Words: *Shock protection, MEMS, seismometer, space, penetrators, Moon, sublimating solid*

I INTRODUCTION

MEMS (Micro-electro-mechanical systems) devices like accelerometers, mechanical actuators, and gyroscopes typically contain a silicon suspension. These suspensions are often exposed to high shock loading during transportation and deployment, particularly when utilized in drilling, automotive applications, space deployments or military systems. High shock loading of suspensions can lead to failure due to fracture, delamination or stiction [1]. Additionally, for a suspension with a large range of travel and a low resonant frequency, the various components of the suspension colliding with each other can lead to spallation damage and thus to a broken or severely crippled device.

Low frequency suspensions with few 100's of µm of free travel are used in making miniature seismometers to monitor seismic events [2]. This particular study was undertaken to assess the feasibility of deploying seismometers on the Moon using penetrators, as part of the proposed UK Lunar mission MoonLITE [3]. Penetrators are utilized in planetary missions as an inexpensive alternative to landers and are characterized by a very high speed (200 – 700 m/s) impact landing onto the planet's surface, resulting in high shock loading on the order of 10,000g – 100,000g.

The key requirement of an instrument on board a penetrator is its ability to withstand high shock loading. Seismometers are typically very fragile devices due to the flexible suspensions used for low-frequency vibration sensing. Using a traditional seismometer on a penetrator mission is impractical due both to the large size and low shock (few g's) tolerance. Our group has developed a micromachined silicon seismometer [4] which can sustain a few 100g's of shock, and which has been modified in this study to demonstrate survivability at 10,000g shock levels.

II SILICON SUSPENSION

The microseismometer uses a micromachined silicon suspension as the sensing unit. This suspension is composed of a large proof mass attached to the external frame using thin silicon flextures (springs) as shown in Figure 1. Table 1 presents the various parameters for the suspension.

Table 1. Suspension dimensional parameters.

Parameter	Value
Proof mass weight	0.266 g
Die dimension	20 mm × 20 mm
Spring thickness	30 µm
Natural frequency	11 Hz

Failure of the suspension has a number of causes:

1. The stress in the suspension due to shock loading can exceed the fracture strength of the structure or fracture toughness of the material.

2. Various components of the suspension can collide with each other causing spallation damage.

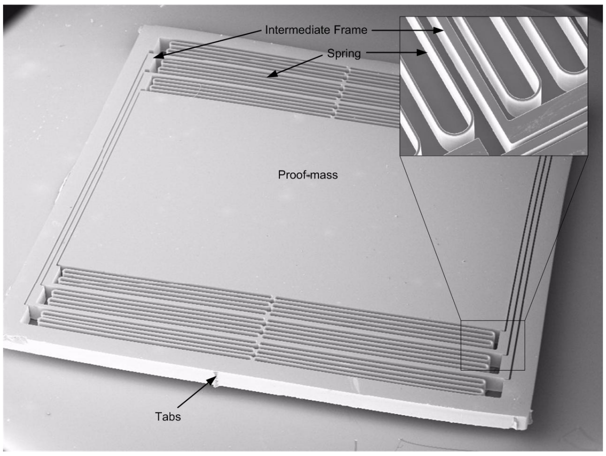
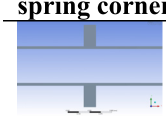
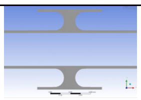
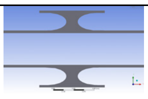
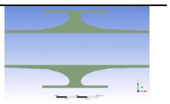


Figure 1. Micromachined silicon suspension used in the microseismometer.

Stress concentrators are potential regions which are highly susceptible to fracture. FEA (Finite Element Analysis) of the suspension shows the maximum stress at the sharp corner where the spring is attached to the proof mass. Table 2 shows the effect of varying the amount of filleting at the spring corners in reducing stress at the corners.

Table 2. Effect of varying the amount of filleting of link-spring corner on stress.

			
Radius of curvature			
Sharp corner	**Circular** **110 µm**	**Elliptical** **230 µm, 110 µm**	**Elliptical** **500 µm, 170 µm**
Von Mises Stress (MPa)			
117.4	**113.2**	**105.6**	**102.1**

The suspension is made from single crystal silicon and the stresses induced in the springs after filleting are far below the fracture strength of silicon. The major cause of failure in high shock environments will therefore be spallation damage due to colliding structures. In light of this, we have investigated various methods which could potentially be used in order to ruggedize our structures against the 10,000g shock levels predicted for the MoonLITE mission.

III SHOCK MITIGATION TECHNIQUES

III.1 MECHANICAL LATCHING

Mechanical latching to restrain structures from motion is commonly used in MEMS devices like RF switches, optical networking components, and actuators [5]. The proof mass of the suspension has a large mass and needs to be restrained during high shock loading to avoid it from colliding with surrounding silicon structures and causing spallation damage.

The mechanical latch is typically actuated using thermal Joule heating, although electrostatically and electromagnetically actuated mechanical latches are also reported in literature. The advantage of thermal actuation is the large displacement achieved, but the power cost is high. The latch is based on a bistable mechanism with two positions – engaged and disengaged.

This mechanism works well for holding relatively larger structures and is low-power once the latch has been actuated, since it requires no power to hold the latch in engaged mode. The disadvantage is its unsuitability to hold down smaller and multiple structures on the device, like the intermediate frames and springs.

III.2 ELECTROSTATIC CLAMPING

By creating a potential difference between two flat plates, it is possible to generate a force between them which will constrain their relative vertical and lateral motion. The voltage required ($V_{pull\text{-}in}$) to pull-in the proof mass to a capping die separated by an airgap, *d,* is given by:

$$V_{pull-in} = \sqrt{\frac{kd^3}{\varepsilon A}}$$

where ε is the permittivity, k is the out-of-plane spring stiffness and A is the area of contact. The voltage that would be required for various gaps is shown in Figure 2.

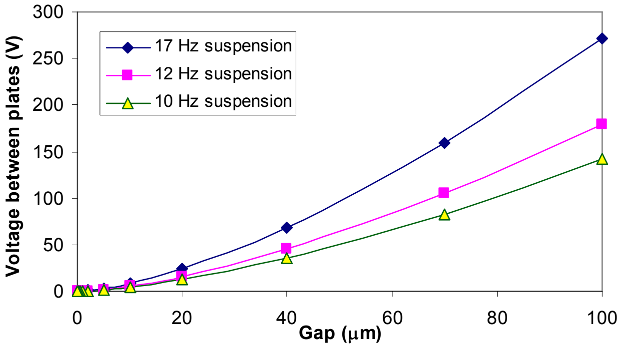


Figure 2. Pull-in voltage vs. gap between the suspension die and top capping die.

The vertical forces generated during the shock loading can be balanced by the electrostatic force between the two plates, while the lateral force exerted on the proof mass is balanced by the frictional force between the two plates. To calculate the frictional force in the lateral direction an Si–SiO_2 interface is assumed, with a static coefficient of friction of 0.31. The necessary plate voltage for lateral clamping is then given by:

$$V = \sqrt{\frac{2\delta^2 \mu m g}{\varepsilon A}}$$

where μ is the static coefficient of friction for the interface and δ is the thickness of the SiO_2 layer.

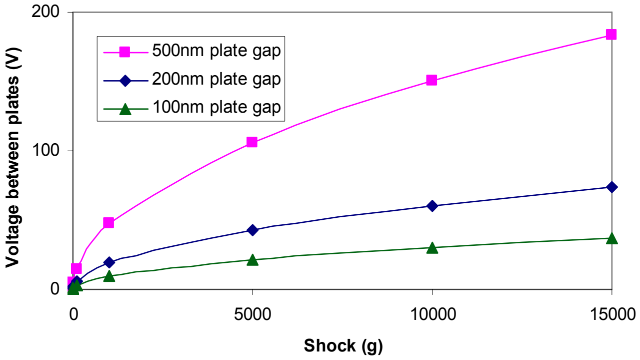


Figure 3. Voltage vs. lateral shock levels for clamping down the suspension proof mass.

Figure 3 shows the voltage required to clamp the proof mass at various lateral shock loadings. The advantage of an electrostatic approach is the lower power requirements for actuation and clampdown. The disadvantage is its unsuitability for clamping down the springs due to their lower surface area, high actuation voltage and the need to power the clamping mechanism throughout the shock envelope.

III.3 SUBLIMANT ENCAPSULATION

One key concern with all of the methods discussed until now has been the unsuitability of the mechanism for either clamping or damping the spring elements. The springs are thin silicon flextures, which will undergo large motion at a relatively low acceleration. When these flextures come into collision with the frame or proof mass they will often sustain physical damage, in certain cases enough to completely disable the suspension.

By completely embedding the suspension in a wax-like material which solidifies around the proof mass and springs and thereby restrains them from motion, it should be possible to prevent any damage to these structures even in high shock environments. This encapsulating material would then be entirely removed via sublimation in order to return the suspension back to its original condition. The release of this material could be mediated by a seal that would act to contain the sublimant both during launch and transit, but which would nevertheless be weak enough to be broken during the high shock phase associated with the penetrator impact.

Some potentially suitable substances that could be utilized for this purpose include naphthalene, paradichlorobenzene, biphenyl, or camphor. These are all classified as sublimating solids, since they all have relatively high vapor pressures at STP. The rate of sublimation for these chemicals will be dependent both upon their vapor pressure as well as on the external pressure to which they are exposed [6]. Thus, the presence of these substances in either a high-temperature or low-pressure environment (i.e. the Moon) would act to rapidly enhance their rate of sublimation.

IV TEST SETUP

IV.1 SHAKER TABLE

The suspension is enclosed between two glass capping dies and then clamped to the test bed of a Ling Dynamic Shaker at AOPP, University of Oxford. The vibrator has a maximum force rating of 8 kN, the vibration profile used is US DoD MIL-STD-810F Transportation and Ariane Acceptance profiles.

IV.2 PENETRATOR TESTS

Three trials were conducted by the UK MoonLITE consortium at Qinetiq facility in Pendine, Wales. The impact velocity was ~310 m/s, impact angle between 8°–10° creating a ‘tail slap’ with a high in-plane acceleration. The on-axis peak acceleration was 20,000g at the front of the penetrator and around 10,000g at the rear of the penetrator. The lateral peak accelerations were measured at the rear of the penetrator and were 16,000g and 6,500g along the vertical and horizontal axes respectively. The compartment containing the suspensions was approximately in the middle of the penetrator.

V RESULTS AND DISCUSSION

The packaged suspensions were able to sustain 75g in-plane and 35g out-of-plane shock loading on the shaker table. The two classes of failures can be classified as fracture and surface spallation. Fracture affected the suspension at the spring linkages as shown in Figure 4. Spallation damage was common at the corners of the intermediate frames and proof mass as shown in Figure 5.

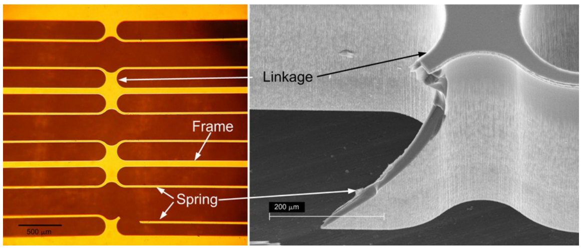


Figure 4. Fracture of the spring at the linkage.

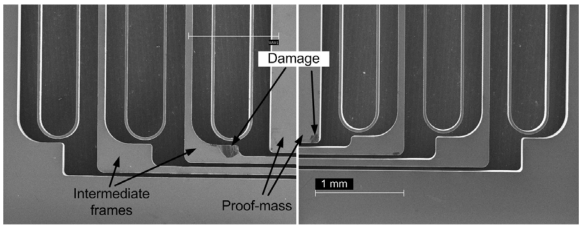


Figure 5. Frame and proof mass damage due to collision at the corners.

In the current penetrator tests there was no facility to include a battery for the electrostatic clamping. To simulate a scenario where the proof mass will be completely immobilized we created a test sample with single springs of varying thicknesses surrounded by an external frame. These springs were enclosed between two glass capping dies such that they had all degrees of freedom.

Three such samples were included perpendicular to each other in each run, to assess the effect of both in-plane and out-of-plane shock. All of the spring units survived in all the runs. This demonstrates that given a completely immobile proof mass, one spring suspensions will survive very high shock loading. A set of suspensions without any shock mitigation strategy were also included, and as expected they failed due to spring fracture and suffered severe spallation damages.

Other suspensions were encapsulated within camphor, naphthalene and paradichlorobenzene (PDB) in a metal box. The sublimants were melted and poured into the boxes containing the suspensions. After the penetrator tests, these boxes were exposed to a 10^{-3} Torr vacuum, resulting in successful sublimation. All the suspensions enclosed in camphor had failed due to fracture, most likely generated during the solidification process. 9 out of 12 suspensions that were encapsulated in naphthalene survived, as did 11 out of 12 suspensions that were encapsulated in PDB. In both cases the sublimation was clean, resulting in suspensions with quality factors similar to those measured before the tests.

VI CONCLUSION

We have explored various methods to mitigate high shock loading in low-frequency large range-of-motion silicon suspensions. The suspensions were then exposed to shock loadings as high as 16,000g using a penetrator. The springs themselves were found to be very resilient to high shock levels and there was no failure during the shock testing.

Tests were also carried out using solid sublimants to immobilize the suspensions. PDB and naphthalene encapsulated suspensions survived the peak shock acceleration of 10,000g out-of-plane, and 16,000g in the lateral direction, with this method likely to enable survival of the suspensions even at much higher shock levels.

REFERENCES

[1] V. T. Srikar and S. D. Senturia, "The reliability of microelectromechanical systems (MEMS) in shock environments," *J. Microelectromech. S.*, vol 11, pp 206-214, 2002.

[2] W. T. Pike, I. M. Standley, and A. Trnkoczy, "Micro-machined accelerometer." US Patent 6776042, 2004.

[3] G. Collinson and T. U. P. Consortium, "Planetary Penetrators: The Vanguard for the future exploration of the Solar System," *JBIS*, vol 61, 2008.

[4] W. T. Pike and S. Kumar, "Improved Design of Micromachined Lateral Suspensions using Intermediate Frames," *J. Micromech. Microeng.*, vol 17, pp 1680-1694, 2007.

[5] R. R. A. Syms et al., "Scalable electrothermal MEMS actuator for optical fibre alignment," *J. Micromech. Microeng.*, vol 14, pp 1633-1639, 2004.

[6] M. Tesconi et al., "A method for the rapid estimation of sublimation rates of organic compounds at standard temperature and pressure," *J. Pharm. Sci.*, vol. 86, pp. 1299-1302, 1997.