Challenges of Designing and Processing Extreme Low-G Micro Electrical-Mechanical System (MEMS) Accelerometers

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ABSTRACT

There is an increasing demand to build highly sensitive, low-G, microscale acceleration sensors with the ability to sense accelerations in the nano-G (10^{-8} m/s^2) regime. To achieve such sensitivities, these sensors require compliant mechanical springs attached to large masses. The high sensitivities and the difficulty in integrating robust mechanical stops into these designs make these parts inherently weak, lacking the robustness to survive even the low level accelerations encountered in standard handling, from release processing, where supporting interlayers present during fabrication are etched away, through packaging. Thus, the process of transforming a MEMS-based acceleration sensor from an unreleased state to a protected functional state poses significant challenges. We summarize prior experiences with packaging such devices and report on recent work in packaging and protecting a highly sensitive acceleration sensor that optically senses displacement through the use of sub-wavelength nanogratings. We find that successful implementation of such sensors requires starting with a clean and robust MEMS design, performing careful and controlled release processing, and designing and executing a robust handling and packaging solution that keeps a fragile MEMS device protected at all times.

Keywords: MEMS, nano-G, accelerometer, sub-wavelength grating, MEMS packaging, MEMS release

1. INTRODUCTION

To provide high sensitivity, direct-sensing MEMS accelerometers make use of relatively large masses suspended by relatively compliant springs. When fabricated in silicon, these elements are quite fragile. Under inertial or capillary forces, these elements may be subjected to large stresses that can cause catastrophic failure if they are not properly protected. Additionally, because these mass-spring systems are often underdamped, these elements may routinely contact brittle mechanical stops that can cause chipping and eventual failure of the device under dynamic inertial loading. Thus a key aspect in the realization of a successful direct-sensing MEMS device is adequate protection for its critical components during processing and in use.

We report our experiences with fabricating an in-plane MEMS-based nano-G sensor. This sensor has silicon springs that are very compliant in the x-direction but are very stiff in the y- and z-directions, and are robust in the x- and y-directions but fragile in the z-direction. The sensor also makes use of fragile nanogratings that require close clearances without contact in the z-direction, and are subject to damage by handling. Because of the fragility of these elements, there are numerous challenges with building, testing, and ultimately using this device.

2. PRIOR WORK: ACCELERATION SWITCH

We previously packaged a silicon acceleration switch having similar protection issues. A schematic of the previous device is shown in Fig. 1. In this device, a sense mass was suspended using 3-micron thick curved silicon cantilever springs. When subjected to a vertical upward acceleration of the device, the sense mass moves down relative to the device and, by means of a metallized area on the bottom of the sense mass, completes an electrical path between the two contacts located in the package, which also function as the lower mechanical stop. An upper mechanical stop is fabricated by adding metal to the inside of the lid. Cut-outs in the sense mass enabled the sense mass to move upward from its neutral position without colliding with the fragile springs. A study of the reliability of the silicon flexural elements under cyclic loading to about 500 MPa indicated that the flexural elements exhibited no degradation in performance after 4200 hours of cycling in 5000 ppmv humidity air at 29° C.[1]

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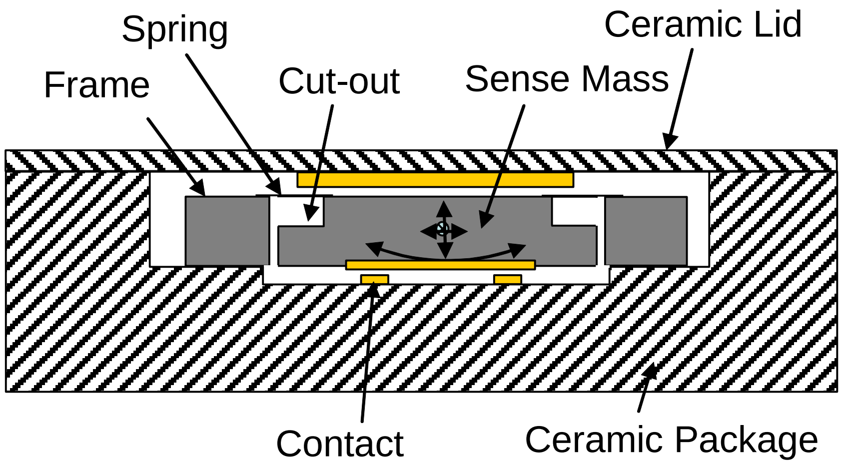

Fig. 1. Lower and upper hard stops permit the closing of a switch and prevent damage to the springs, respectively.

In contrast to the nano-G sensor that is the focus of the current work, the main challenge for this device was protecting it from large lateral accelerations. Ideally, the springs would be stiff enough and strong enough to prevent the sense mass from moving laterally under any acceleration or shock under which the device was expected to survive, eliminating the need for lateral stops. However, because the springs were very thin, they tended to buckle, and possibly break, during large lateral accelerations. To help protect the springs and the rest of the device, lateral mechanical stops were built into the silicon device in the form of tabs permitting only a small 25 µm clearance between the sense mass and the sidewall in what would ordinarily be a 100 µm wide cut in the 400 µm thick device formed by a process known as deep reactive ion etching (DRIE).

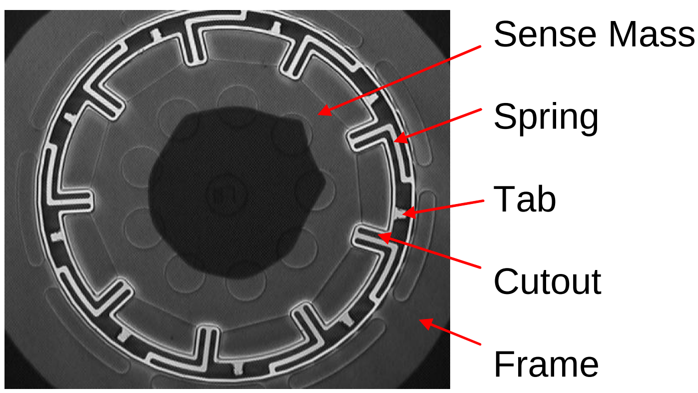

Fig. 2. A plan view of the acceleration switch shows sense mass, springs and tabs.

The next consideration was whether the mechanical stops added to protect the springs would be able to survive all loading scenarios under which the switch must survive without damage. Because the tabs are brittle, the impact energy at the contacting surfaces of the mechanical stops during an abrupt lateral acceleration can cause failure. This energy is the kinetic energy of the moving element relative to the stop that constrains it. From Newtonian mechanics and ignoring the restraints by the spring under large accelerations, the distance, *d*, traveled by a body initially at rest over a period of time, *t*, and under an applied acceleration, *a*, is

$$d = \frac{1}{2} a t^2 \tag{1}$$

Solving for time at which a distance *d* is traveled, we obtain

$$t = \sqrt{\frac{2d}{a}} \tag{2}$$

The velocity of the body, v, as a function of time is given by

$$v = at \tag{3}$$

Substituting for the time at which the body travels a distance d, the velocity at that time is

$$\begin{aligned} v &= a\sqrt{\frac{2d}{a}} \\ &= \sqrt{2ad} \end{aligned} \tag{4}$$

The kinetic energy, E, of a body with a mass, m, is

$$E = \frac{1}{2}mv^2 \tag{5}$$

Substituting in the velocity of the body after it has traveled a distance d, the kinetic energy at that point is

$$\begin{aligned} E &= \frac{1}{2}m(at)^2 \\ &= \frac{1}{2}ma^2\left(\frac{2d}{a}\right) \\ &= mad \end{aligned} \tag{6}$$

Thus we find that the kinetic energy at contact from a single lateral acceleration is directly proportional to the mass of the body, the acceleration, and the clearance between the body in its neutral state and the mechanical stop. Smaller gaps help control the energy that could damage the stops from large lateral acceleration.

Initial analyses indicated that the tabs would survive collisions when the device was subjected to the maximum expected load. However, after failures were noted, further analyses indicated that the mechanical stops did not sufficiently inhibit rotational motion of the sense mass during abrupt lateral accelerations, causing the contact area at the stops to be reduced to the microscopically sharp edges of the tab while also permitting sliding to occur at the contact, as shown in Fig. 3. As a result, the tabs failed, as shown in Fig. 4. Thus, the lesson learned was to keep the gaps small, not only to reduce the impact energy at mechanical stops, but to reduce rotations of movable elements that can result in sliding contacts at sharp edges.

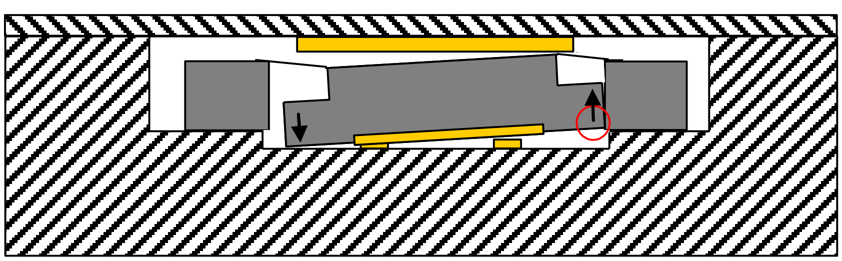

Fig. 3. Lack of sufficiently tight constraints can result in rotation causing sliding contacts at sharp edges.

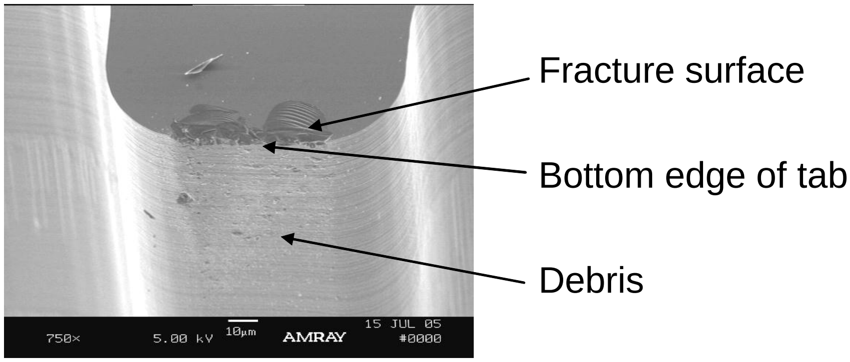

Fig. 4. Mechanical damage including debris and outright fracture resulted from a sliding grazing angle contact of the sharp bottom edge of a tab with the frame.

3. CURRENT DEVICE: NANO-G SENSOR

3.1 Overview

Like the previous device, the current device is primarily a bulk micromachined silicon acceleration sensor. Unlike the previous device, however, the intended motion of the sense mass is in the plane of the silicon die, and the springs are defined by the same DRIE process that defines the sense mass and the gimbal elements of the sensor. Also in contrast to the device described in the previous section, this device measures acceleration not by contact of the sense mass to electrical contacts, but by the relative displacement of two sub-wavelength diffraction gratings separated by 2 μm in the z-direction. The presence of the gratings makes the protection of the device more challenging because displacement of the sense mass by more than 2 μm can cause the gratings to contact and potentially snag on each other, causing them to break.

A schematic of the device is shown in Fig. 5, which shows the long slender sense mass springs that are very compliant in the y-direction. The width of the springs is nominally 20 μm and their thickness is nominally 400 μm, so the springs are nominally $\left(\frac{400}{20}\right)^3\left(\frac{20}{400}\right) = 400$ times stiffer in the z-direction than in the y-direction. Finite element analysis predicts the first mode in the y-direction at 114 Hz, the first mode in the z-direction at 1428 Hz, and the first mode in the x-direction at 1271 Hz. The actual y-direction frequency is about 44 Hz, and we believe that the discrepancy is due to having overetched springs whose actual cross sections are smaller than nominal. Note that mechanical stops are essentially built into the design in the y-direction because the springs can survive the movement of the sense mass until it makes a large-area contact with the gimbal and the springs are strong enough to forgo the need for mechanical stops in the x-direction. The motion of greatest concern occurs in the z-direction, where a 2 μm upward out-of-plane deflection can cause the gratings to make contact and a 5 - 10 μm upward out-of-plane deflection can cause the gratings to deform enough to immediately break. FEA modeling has shown that the out of plane deflection of the sense mass under a 1 g field is about 125 nm, so it is possible that the devices can be carefully handled in gravity without breaking. However, it is extremely difficult to handle a low-mass body without subjecting it to accelerations far in excess of 1 g. For this reason, the devices must be at least partially protected before they are even picked up for the first time.

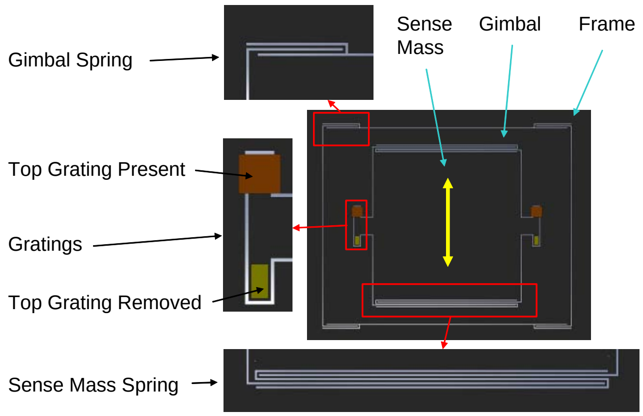

Fig. 5. A plan view of the nano-G sensor shows important elements (see highlighted images). The compliant direction is indicated by the double-ended arrow in the sense mass. The locations of the gratings are indicated with a nominal 2 µm gap between the top and bottom gratings. The top gratings are removed on the lower side of the die to show the lower gratings which are normally hidden by the top gratings.

3.2 Protection during processing

The nano-G sensor is fabricated using two silicon micromachining techniques. The gratings are fabricated using surface micromachining using the Sandia SUMMiT-V process where silicon mechanical elements are defined using a sequence of silicon and silicon dioxide layers that are deposited, patterned, and planarized. After this process, the gratings remain safely buried in a silicon dioxide layer. The wafer is then flipped and DRIE is performed from the backside to define the springs, the sense masses, the gimbals and the frames for the devices. The whole wafer is then mounted to UV-releasable dicing tape and saw diced. The devices are then wax mounted to a handle wafer and are then subjected to an HF etch batch to release the gratings from the protective SiO_2 layer. The wax is then removed using OptiClear™ solvent. The devices are then dried using supercritical drying to prevent surface tension of the evaporating liquid from breaking the gratings during drying[2].

Once the gratings have been released, the sense mass is free to move and the device becomes extremely fragile. The devices are released and dried on the silicon handle wafer to ensure that all parts remain coplanar during this processing. We found that it is not possible to safely handle the devices without support, and attempts to lift the devices from the handle wafer resulted in damage to them. We believe that the damage is caused by attraction between the sense mass and the handle wafer and / or air pressure holding the sense mass down as the device was lifted from its frame, deflecting the springs downward relative to the frame. Eventually, the sense mass is freed of this attraction and overshoots the neutral z-position, causing the gratings to contact each other and break. In order to prevent this from occurring, the devices are not lifted from the handle wafer, but are transferred to a separate wafer segment of equal thickness by setting both the handle wafer and the wafer segment on a flat surface, abutting the wafer segment to the handle wafer at the handle wafer flat, and then sliding the devices to separate wafer segments for individual handling. The parts are then transported to the packaging area for packaging / protection.

While keeping the devices on a wafer during handling protects the devices by keeping the sense mass coplanar with the frame, another danger lurks during transportation. Because both the bottom of the devices and the wafer segment are polished silicon and are therefore extremely smooth, it appears that vibrations during careful hand transport are sufficient to enable to cushion of thin air to sometimes form under the devices, allowing them to glide over and off of the wafer segments where they are damaged. This problem was solved by building barricade over which the devices could not glide – we found that tape was sufficient to do the job, as shown in Fig. 6. Leaving the die on full wafers sized to fit in the wafer carriers could have also prevented the possibility of the die gliding off the wafers during transport, but such wafers were typically too large to fit in the pick-and-place machine and would have required additional handling at packaging.

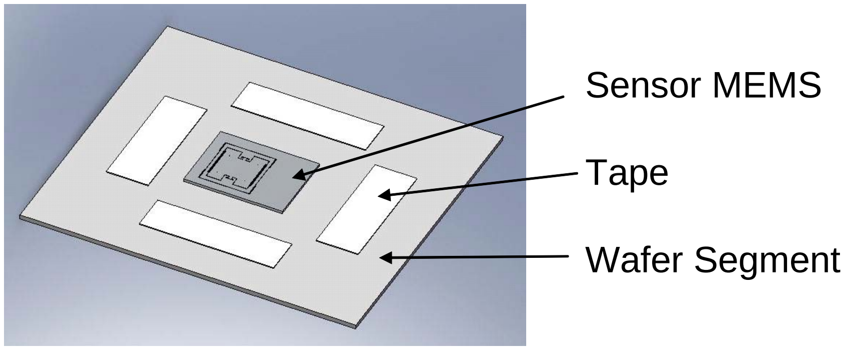

Fig. 6. The nano-G sensor devices remain on a flat wafer segment from the time of released until packaging. Tape placed around the edges of the wafer segment act as barricades to keep the device from gliding over the edge during hand transport. Though thin, the barricades never failed to do their job.

The "packages" that we used to protect the device were planar materials between which the device was sandwiched, the details of which we will discuss later. In order to safely package the device we had to put the top side of the package on before we could move the device from the wafer segment. Once the top side of the package is installed, the sense mass can no-longer overshoot the neutral position by an amount sufficient to damage the gratings, and it is relatively safe to remove the device from the wafer segment and turn it over so that the bottom side of the package can be installed. Once both sides are installed, the device is robust enough to be handled and tested.

3.3 Package design

The challenge of the device packaging was to come up with a design and a process that could adequately protect the device without interfering with its operation. We use the term packaging loosely here. The package that we have thus far developed is sufficient for protecting the device through testing, but not sufficient for protecting the device in a more hostile environment. The extent of our package is two appropriate flat substrates bonded to the device sandwiched between them.

We initially considered using alumina substrates for package. Alumina substrates are fairly flat, rigid, reasonably tough, and easy to precisely machine using a CO_2 laser we have at our disposal. We also thought that its greater roughness as compared to polished silicon would tend to prevent adhesion and stiction should the sense mass come in contact with the substrate. Fig. 7 shows an early attempt at a package using an alumina substrate. The package is essentially has the geometry of a window frame with a bar across the middle of the window which acts as a mechanical stop for the sense mass. The substrate was adhered to the device using Hardman® Double/Bubble® Extra Fast Setting Epoxy, which typically sets in 3-5 minutes and contains no fillers. One of our initial concerns was that the epoxy applied on the corners of the frame would be wicked throughout the small gap between the substrate and the device, eventually bridging the gaps between the frame and the gimbal, and the gimbal and the sense mass, bonding these features to each other and to the substrate, and rendering the device inoperable. The goal of this design was to maximize the distance of the path that the epoxy would have to follow to be able to bridge these gaps. The main problem with this design is that the alumina that we used is not guaranteed flat enough to constrain the sense mass to less than 5 μm upward vertical motion at the gratings without getting it so close that it could touch the sense mass. Another problem is that the span across the sense mass is long – since flatness is measured in units of length / length, a long span translates to a larger absolute deviation from flat for the same material flatness. Finally, the bar is fairly narrow as compared to the size of the sense mass and the gimbal, allowing these elements to rock slightly and allowing for more vertical motion at the gratings than at the stop. We found that the package did not adequately protect the device without interfering with its motion.

Fig. 7. The first package version used an alumina substrate and incorporated a bar across the sense mass to constrain vertical motions while attempting to allow lateral motions.

In the next iteration, we still used alumina substrates, but we modified the design to limit the span of the mechanical stops so as to reduce their absolute amount of deviation from flat, and place them further towards the corners of the gimbal and sense mass to better limit the rotation of these elements. We also made the stops smaller to reduce the amount of potential attraction between the surfaces of the sense mass and the stops. Fig. 8 shows the second iteration of the package design. In this particular instance, the device was accidentally rotated relative to the package. Note that one stop was left out to prevent contact between the stop and an extra grating on the device. Again, because the alumina was not flat enough, the package could not adequately protect the device without interfering with its motion. Interferometer measurements confirmed that there was a 20 μm deviation in the flatness of the machined substrate as shown in Fig. 9.

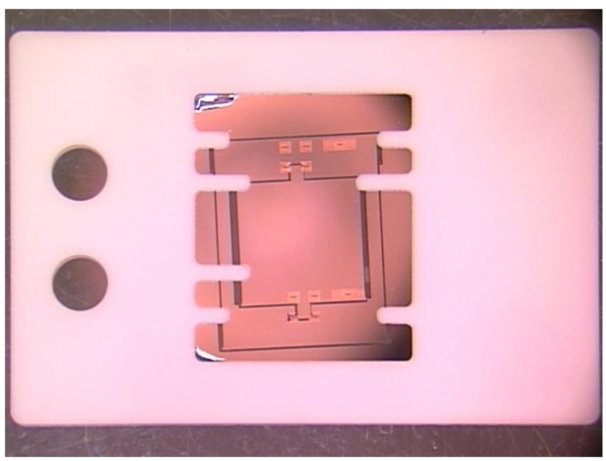

Fig. 8. The second version of the package still used an alumina substrate, but employed widely spaced fingers to better constrain the sense mass while reducing the overly large area of contact.

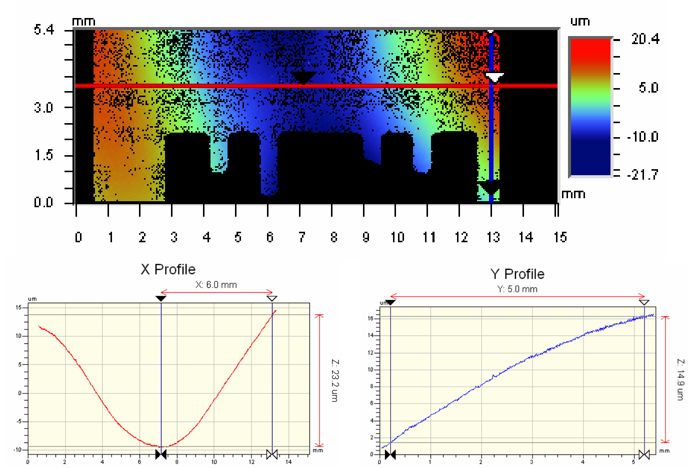

Fig. 9. Interferometry on the second version of the package indicated a 23 µm deviation in the flatness of the machined substrate.

The missing ingredient to a successful package was a sufficiently flat substrate. Again, because we had a CO_2 laser at our disposal, we still wanted a substrate material that could be machined by this laser, and fused silica wafers are such a material. The flatness of fused silica wafers approaches that of silicon wafers and fused silica can be machined by a CO_2 laser due to its reasonable absorption in the long IR (10.6 µm) and its low coefficient of thermal expansion that minimizes thermal stresses and cracking. An added benefit of a fused silica package is that it is transparent so that the state of the springs and the extent of the epoxy wicking after packaging can be determined. Fig. 10 shows the bare substrate after machining.

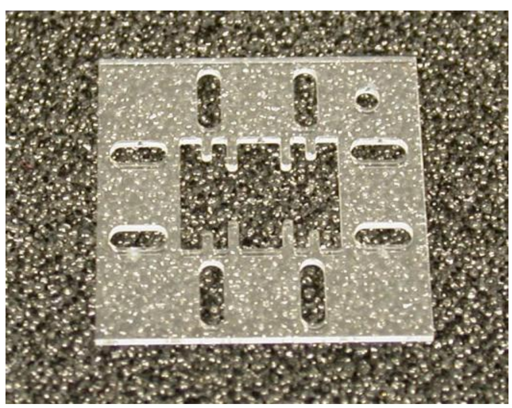

Fig. 10. This is a picture of a fused silica substrate.

3.4 Packaging process

The devices were packaged using a Finetech Pico pick-and-place machine. This is a completely manual machine that allows one to place die and other flat objects onto substrates with 5 µm accuracy relative to visual fiducials on the substrates using a split-image prism optic system. We placed the wafer segment holding the device on the stage of the machine, then we mixed the epoxy and dispensed using a fine-tip probe to put a small dot on each corner of the die. We placed the top side of the package using approximately 50 N (5 kgf) of force. The applied force when placing the top die can be quite high because the small amount of sag of the sense mass with the gratings facing up will hold it off from the mechanical stops even if we compress the bond line to zero. When using small amounts of a two-part epoxy, the increased variability in the mixing ratio and the suppression of an exothermic temperature rise can cause curing to be delayed. To ensure that the epoxy was fully cured before moving the part, we heated the assembly to 50°C for 5 minutes with the placement force applied.

After the top side of the package was attached, we flipped the device over and attached the bottom side of the device using the same epoxy. In this case, we desire a thicker bond line, so we only applied approximately 20 N (2 kgf) of force for 5 min at room temperature, then we removed the force and completed the cure at 50°C for 5 minutes.

Fig. 11 shows a plan view of the completed packaged device. This particular variant has a larger sense mass and the outermost stops which constrain only the gimbal on some variants but effectively constrain both the gimbal and the sense mass on this variant.

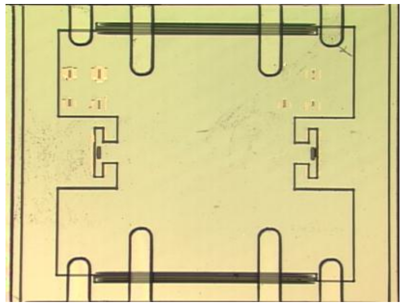

Fig. 11. This is a plan view showing nano-G sensor protected by stops machined out of attached fused silica die. Note that the gratings are removed on this device, revealing the through holes under the gratings.

3.5 Testing

After packaging, the devices were robust enough to be tested for functionality using the test setup shown in Fig. 12. When tested, the devices exhibited a noise floor of 17 nG/√Hz directly measured using the grating.

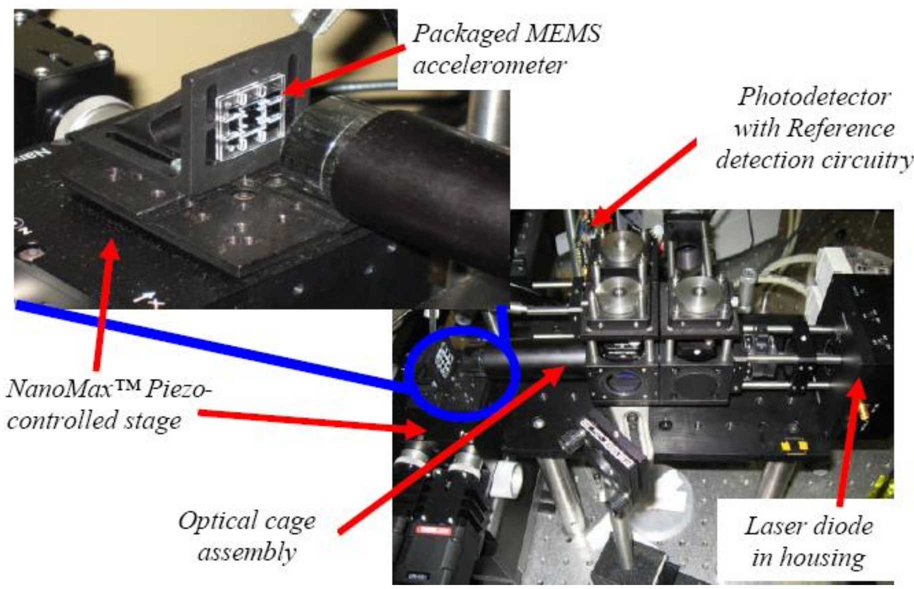

Fig. 12. This is the experimental setup for optical testing of nanograting accelerometers showing packaged device, optical setup, 5 nm resolution piezo-actuation stage and photodetector with reference detection electronics.

4. FUTURE WORK

The packaging here was performed to obtain a testable device to demonstrate a sensor concept. In order to make a more producible device, the device itself must be designed to allow for packaging while it is still well protected. We have considered packaging the device prior to oxide release. This would require using protective substrates that are at least relatively inert in HF, which fused silica is not, and finding a bond composition that can withstand HF.

Additionally, to make the device manufacturable, better control of the stand-off distance between the sense mass in its neutral position and the stops on the package needs to be engineered into the package design rather than relying on an epoxy bond line thickness. We have considered various etching and deposition processes that could create features on the surface of the protective substrates that could better define this stand-off distance. A silicon substrate that is etched where it would be in contact with the sense mass or has a deposited layer where it would be in contact with the stationary portions of the device, for example, would provide both the standoff desired and be inert to HF.

Finally, in order to obtain a usable device, a package must be devised to protect the MEMS device from a chemical environment, must house all the ancillary electronics, and must be able to withstand large temperature excursions. We could either have two layers of packaging – one for device mechanical protection and one for integrating the system and providing protection from the external environment, or one integrated packaging solution that does both. While the former is more realizable in the short term, the latter in principle can save space and processing steps.

ACKNOWLEDGEMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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January 22, 2008

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for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

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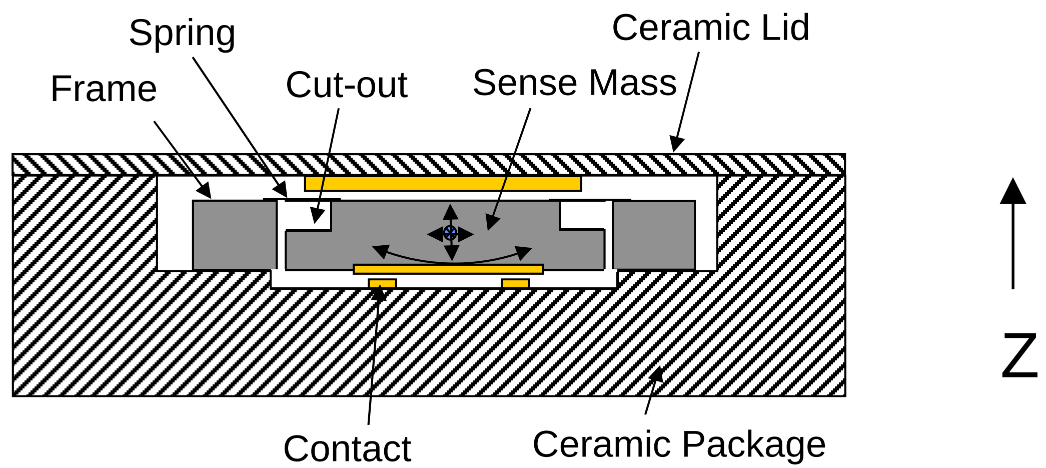
Outline

- Why are direct-sensing MEMS accelerometers a challenge to process and protect?
- Case Study 1: Direct sensing acceleration switch
  - Design
  - Failures
  - Lessons learned
- Case Study 2: Nano-G sensor
  - Design
  - Processing challenges
  - Package design and design iterations
  - Testing
- Conclusions

Why Are Direct Sensing MEMS Accelerometers a Challenge to Process?

- They sense by measuring the movement of a sense mass, not by feedback to prevent movement
- They combine
  - Relatively massive sense mass
  - Relatively compliant springs
  - Range of motion sufficient for measurement
- This combination results in the potential for underdamped massive elements to exert large stresses on fragile elements and collide with each other under inertial loading

Case Study 1: Acceleration Switch



Side View

- **Main Features**
  - **Senses acceleration in the z-direction**
  - **Closes electrical switch when target acceleration is reached**
  - **Large mass is needed to close switch with sufficient force to make good electrical contact under target acceleration**
  - **Thin springs can buckle under large lateral loading**

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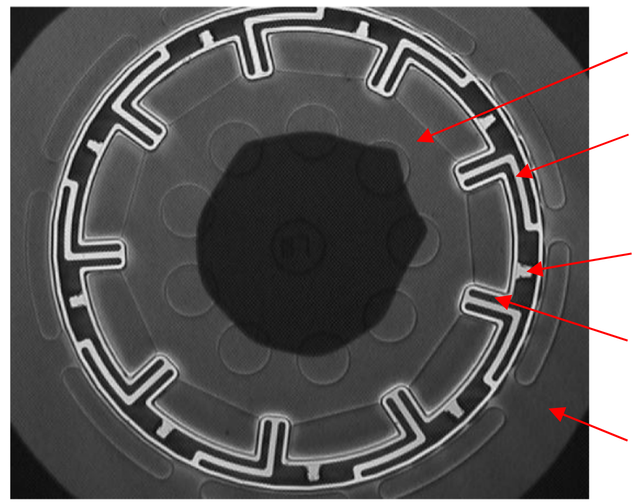
Features to Protect Compliant Springs

- **Cutouts in sense mass to move upward from neutral position without hitting springs**
- **Tabs on edges of sense mass limit lateral motion of sense mass**
- **Package lid limits upward motion of sense mass**
- **Electrical contacts limit downward motion of sense mass**



Plan View

$d = \frac{1}{2}at^2$

Limiting Motion Limits Impact Energy

- **Consider the collision of a massive element of mass m with its mechanical stop having a nominal gap of d under a large acceleration a which overwhelms the restraint by the springs**
- **Using simple Newtonian mechanics ($E = \frac{1}{2}mv^2$, $v = at$, and $d = \frac{1}{2}at^2$) we obtain the impact energy E of the the sense mass with its stops to be** $E = mad$
- **For brittle elements that may fail due to impact with each other, the more the motion of the sense mass is constrained, the lower the impact energy, and the more robust the device**

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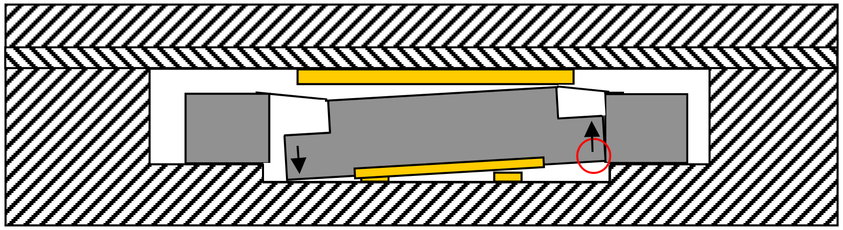
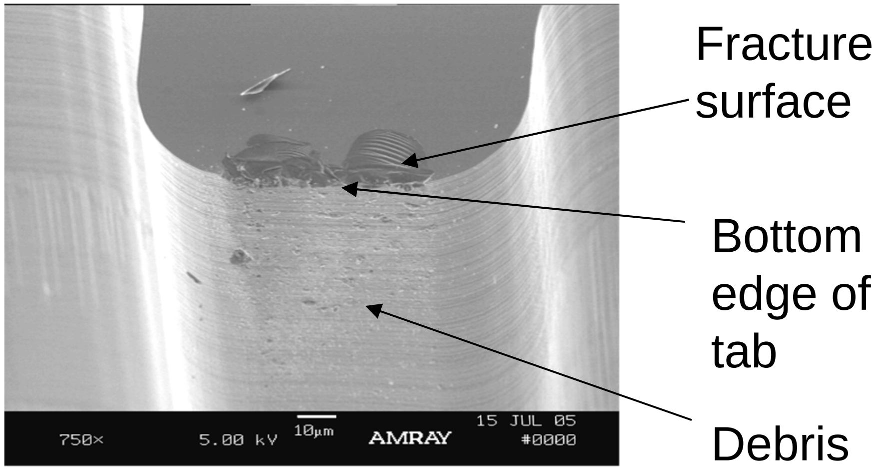
Stops Must Constrain All Motions

- **Tabs limit lateral motion but rotation is still a problem**
- **Grazing angle sliding contact at tab edges resulted in large local stresses**
- **Edges of tabs chipped out causing failure of the device**





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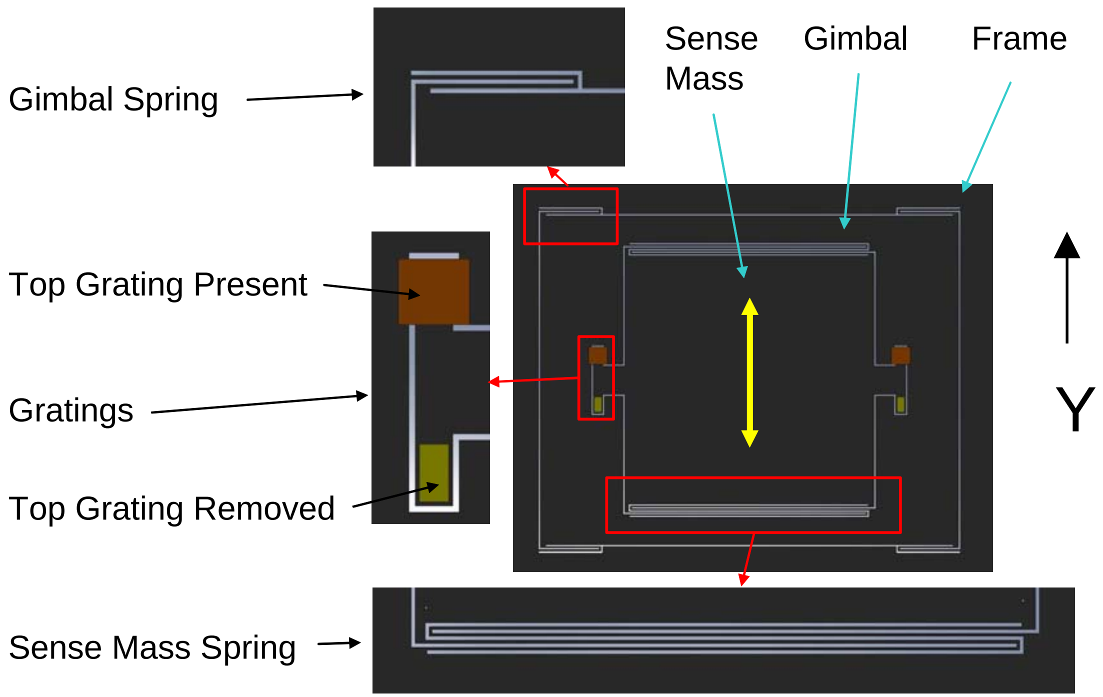
Case Study 2: Nano-G Sensor

- Main Features
  - Senses acceleration in the y- direction
  - Uses relative motion of closely spaced nanogratings to detect motion
  - Protection of nanogratings is most difficult aspect of protecting

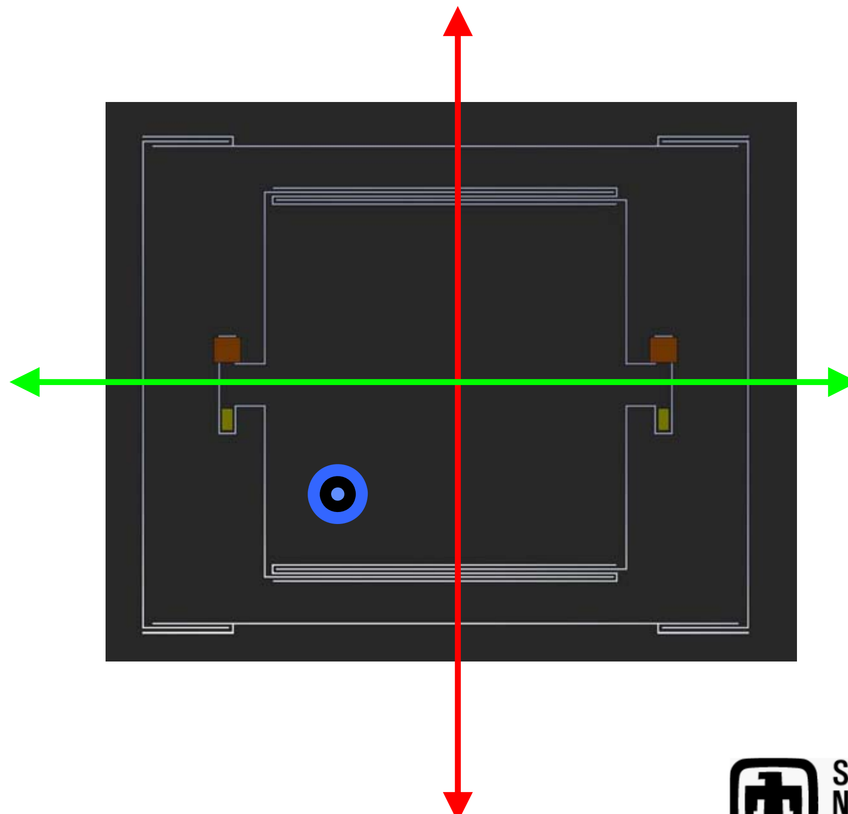


Plan View

Features to Protect Device

- **Device is inherently protected in the x- and y- directions**
- **Concern is in the z-direction**

Built-in stops in y-direction
f = 114 Hz (design)
f = 44 Hz (actual)

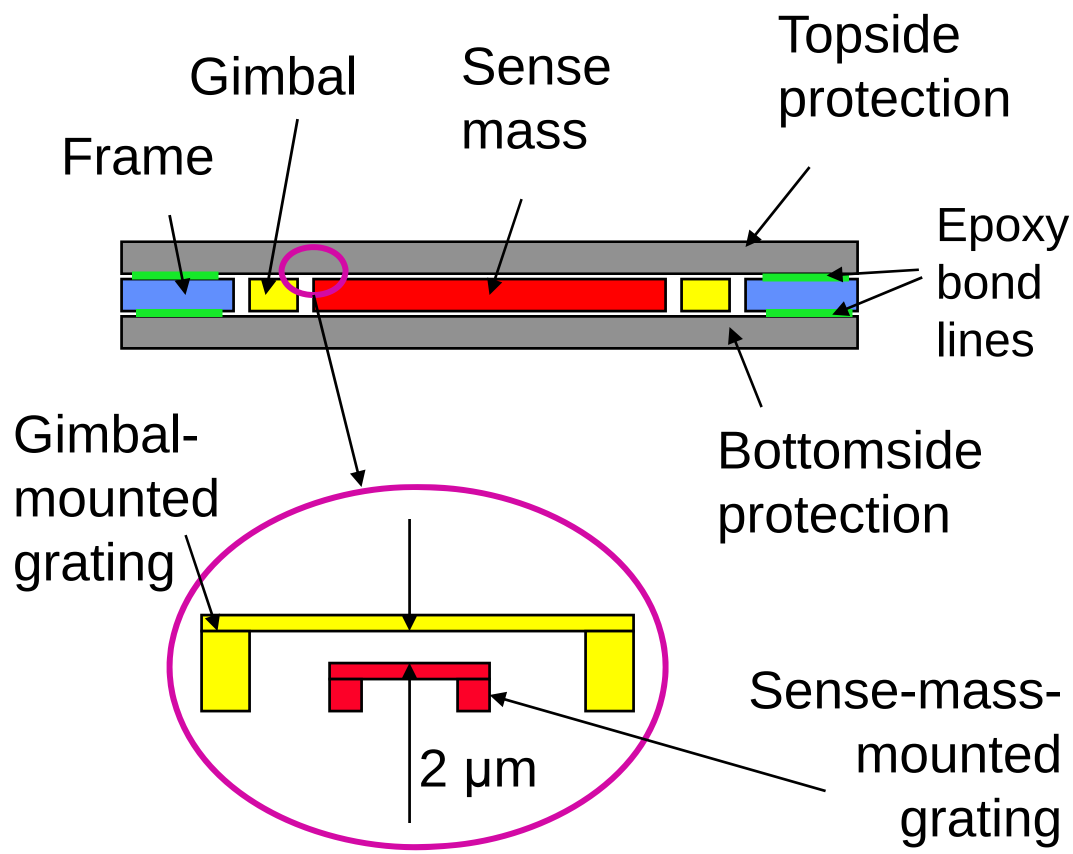


Strong and stiff in x-direction
f = 12710 Hz

Stiff, not strong in z-direction
f = 1428 Hz

Z Direction Protection in Testable Device

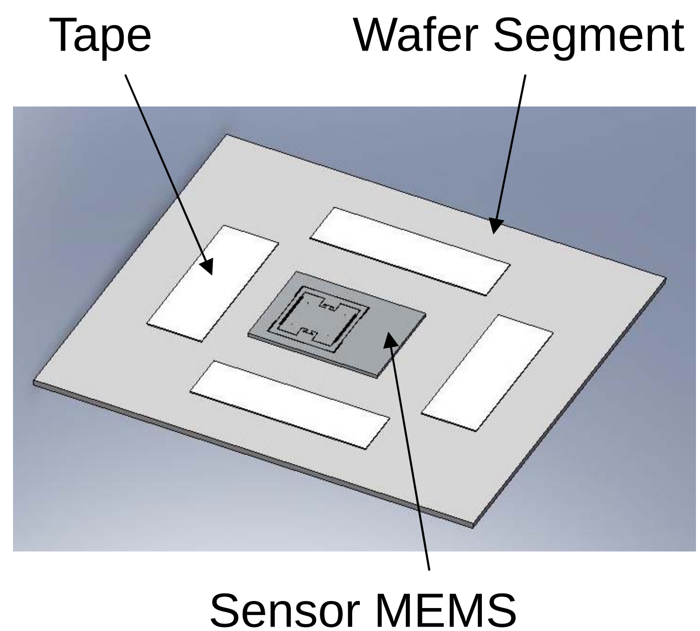
- **Clearance between gratings is 2 μm**
- **Stops must be added on top and bottom to limit vertical displacement to about 2 μm**
- **Sense mass droops 125 nm under 1-g acceleration, so want larger bottom bond line than top bond line**
- **Challenge is in protecting device until stops applied and getting tightly controlled stop clearance to limit displacement while normally avoiding contact**



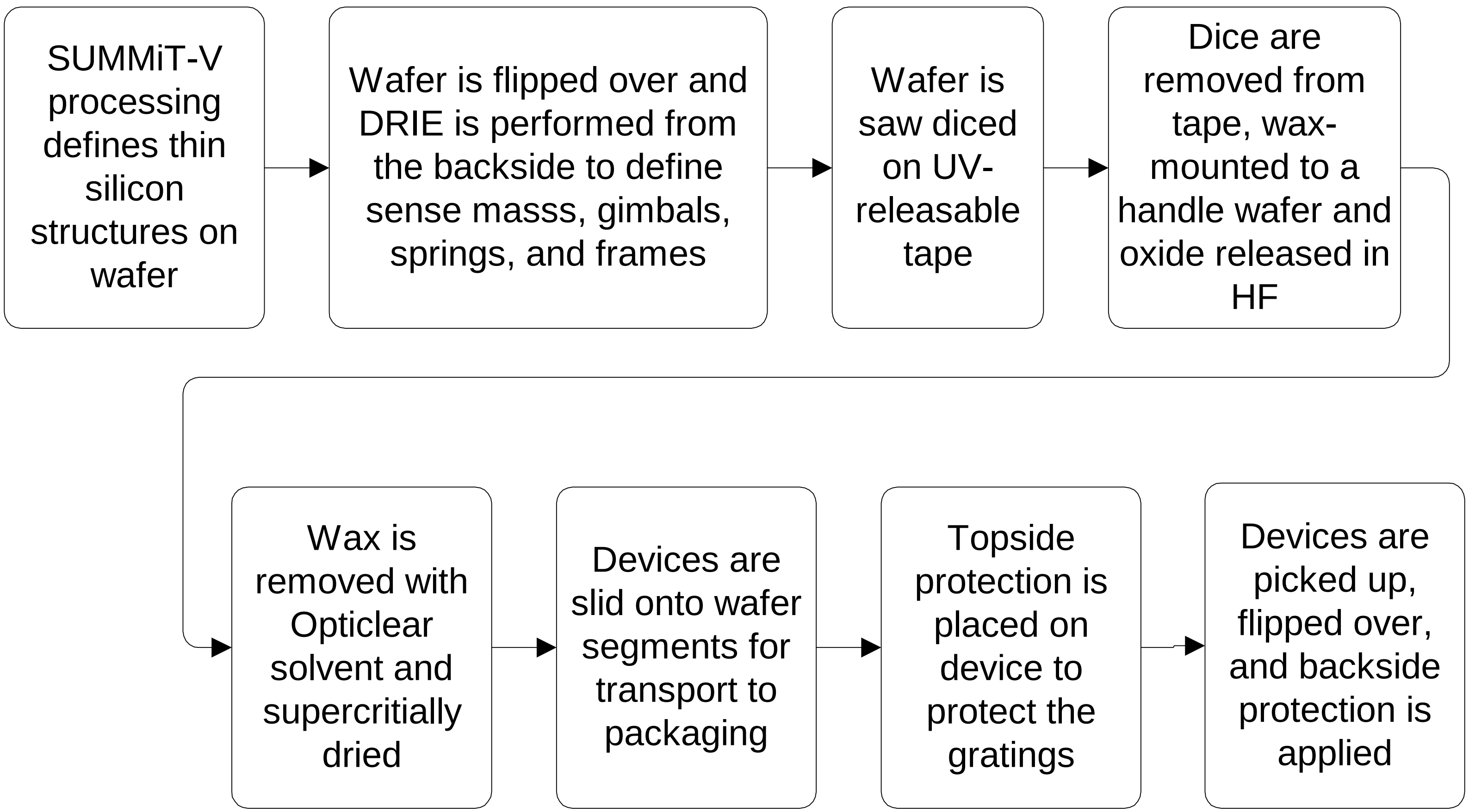
Upward sense mass motion leads to broken grating

Protection of Device During Processing

- **Due to the oscillatory response of the sense mass, deflection of the sense mass downward results in an upward overshoot once freed**
- **Removal of the unprotected device from a flat surface can therefore cause the gratings to be damaged**
- **We prevented damage by never lifting the device from the surface it was released upon until the grating was protected**



Process Flow For Sensor Processing



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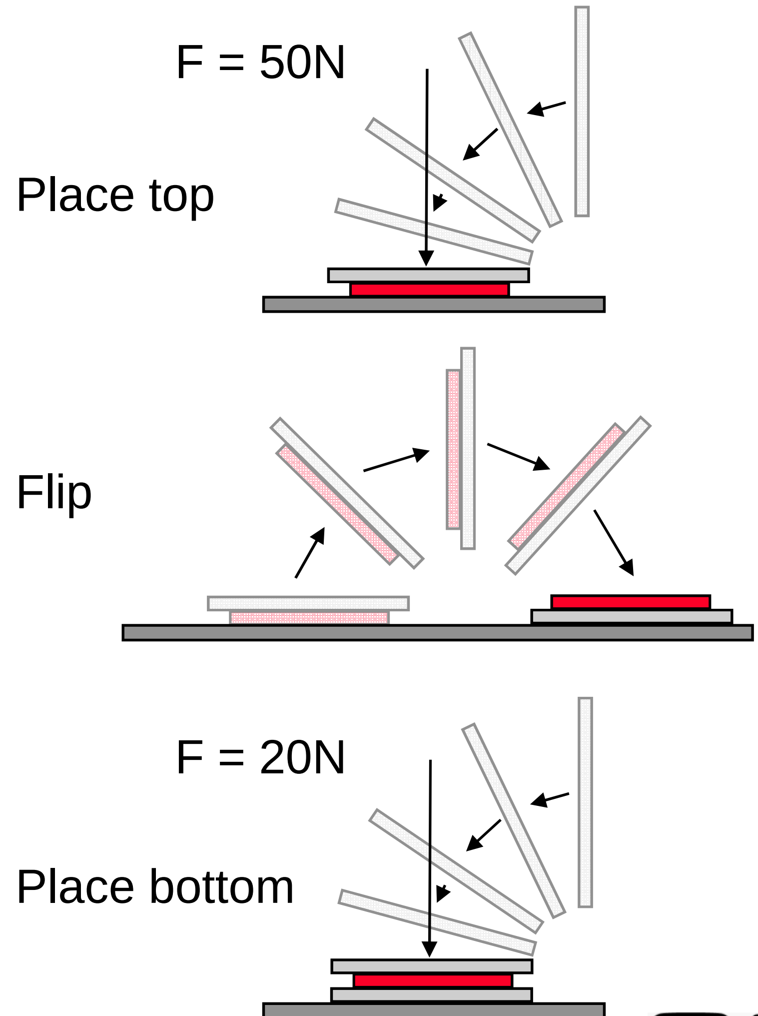
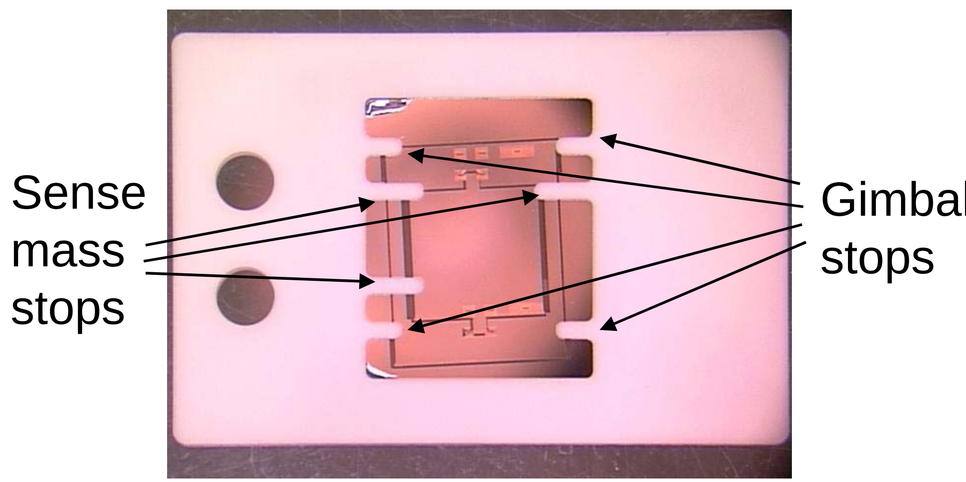
Assembly

- **Protection was placed on device using a Finetech Fineplacer Pico**
- **Top side protection was placed with ~ 50 N force and epoxy cured at 50°C to make bond line as small as possible and hasten curing**
- **Part was flipped**
- **Bottom side protection was placed with ~20 N force**
- **Force was removed and epoxy cured at 50°C to give thicker bond line**



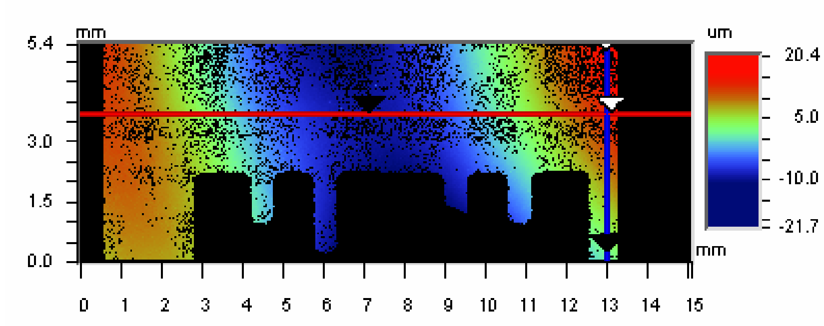
Design Iterations for Protection

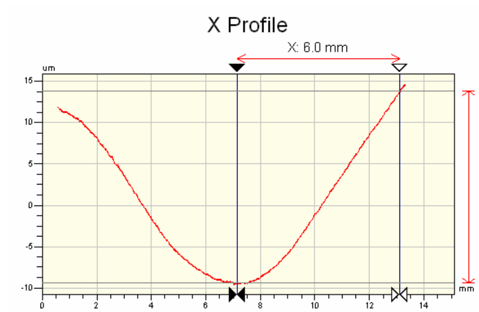
- **Design 1**
  - **Laser machined alumina substrate**
  - **Hardman Double / Bubble Extra Fast setting Epoxy**
  - **Assembled using Finetech Fineplacer Pico**
  - **Bar across center of sense mass**
  - **Very sensitive to flatness of bar**
  - **Narrow constraint didn't constrain sense mass from rocking**
  - **Didn't adequately protect sense mass without touching**
- **Design 2**
  - **Laser machined alumina substrate**
  - **Teeth provided constraint at corners of gimbal and sense mass**
  - **Less sensitive to flatness**
  - **Substrate was not flat enough**

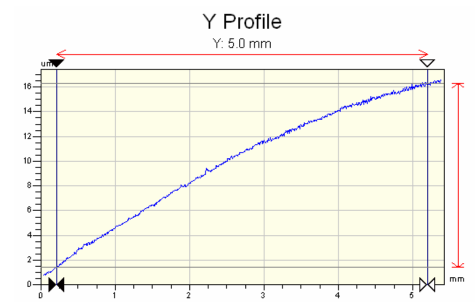


Need for Flatter Substrate

- **Problem with design was that it wasn't flat enough to hold to sense mass to 2 μm without touching**
- **Solution was to replace alumina substrate with fused quartz substrate**



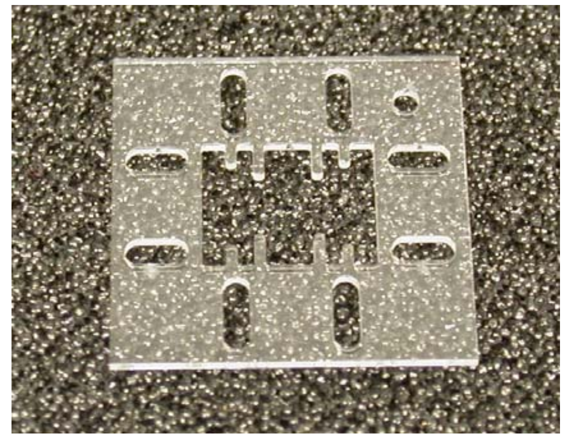


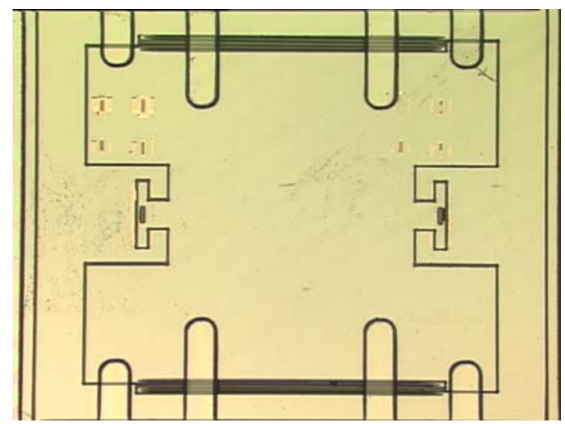


Alumina substrate deviated 20 μm from flat over area of device

Fused Quartz Substrate

- Design 3
  - Much flatter laser machined fused quartz substrate
  - Stops similar to design 2
  - Transparency allows for inspection of all elements
  - Succeeded in protecting die while allowing the sense mass to move freeely

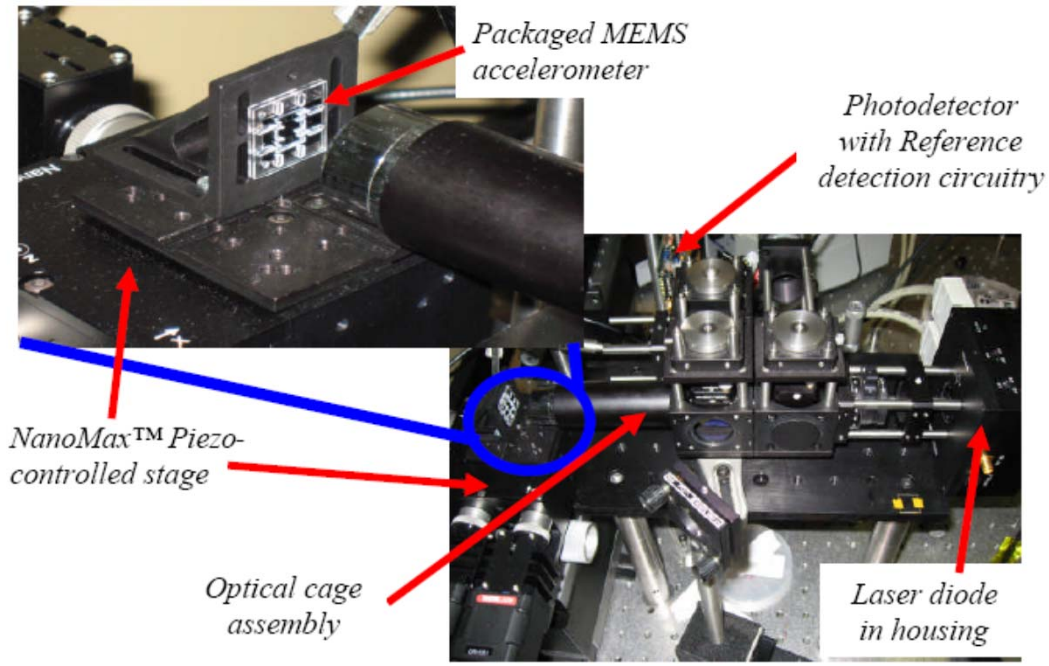




Large sense mass variant of device

Testing

- Devices exhibited a noise floor of 17 nG/√Hz directly measured using the grating
- To the best of our knowledge, these are the most sensitive accelerometers made to date



Conclusions

- Direct sensing accelerometers pose unique protection challenges
- Using appropriate mechanical stops and keeping gaps as small as possible while permitting the elements sufficient freedom of motion is key
- Utilized the flattest convenient materials and thin epoxy bond lines to protect a nano-G sensor
- Applying protection before oxide release would made handling easier and improve yields
- Better control of standoffs would be useful to ensure high functional yields
- Integrating device into a self contained system is a challenge that needs to be addressed.