Avoid these common MEMS failure mechanisms


Demand for micro electro-mechanical systems (MEMS) technology is on the rise. To service that demand with reliable products, both developers and users of MEMS devices need to know about likely failure mechanisms and how to avoid them. Stiction, electrostatic discharge (ESD), micro-contamination, and mechanical shock are key reliability failure mechanisms to understand.

An important driver for the demand of MEMS is, and will continue to be, the Internet of Things (IoT). MEMS and sensors are being used increasingly in healthcare, consumer electronics, low power applications, security, asset tracking, automotive technologies, and smart homes, to name a few, with MEMS marketing and industry analysts predicting tens of billions of shipments within the next decade. With so many interacting MEMS and sensors in the field, up-time is important and reliability is critical.

The first step in ensuring MEMS reliability is to avoid common pitfalls during the design and process development phase to assure a stronger and more reliable part-upon-marketplace introduction. And the time to market for MEMS is fast. Upon product launch, the part must meet all its datasheet specifications as well as storage, shipping, and operational environment reliability tolerances. One of the first things to be prepared to deal with is stiction.

Stiction

The term stiction comes from "static friction" and it has been a factor for years in a wide variety of technologies, including suspension linkages for cars, polished glass, hard disk drives, and precision gage blocks. It occurs when two objects are initially brought into contact (Figure 1). In a MEMS device, objects that could come in contact include elements such as actuators, proof masses, and sensing fingers. Such contact may occur as part of the device's normal operation, or may unintentionally occur as the result of an external force such as a mechanical shock. Either way, however, once contact has occurred the device needs a reliable way to ensure that it can separate the surfaces again in order to keep functioning properly.
The primary forces that come into play upon bringing two surfaces very close together are electrostatic attraction and surface work of adhesion. The force of electrostatic attraction is proportional to $1/d^2$, and surface work of adhesion is proportional to $1/d^3$. Surface work of adhesion in MEMS is primarily due to van der Waals and hydrogen bond forces.

The two surfaces must be very close to be drawn into contact for stiction. The electrostatic force attraction distance is a function of the potential difference between the surfaces, and is typically in the micron range. Once the two surfaces are in single digit Ångstrom range, van der Waals and hydrogen bonding forces come into play. Although the latter forces are classically defined as weak interactions, they are additive and become significant in stiction.
Figure 2. Surfaces are in contact (lateral stiction)

Release from stiction is only possible if the release forces, also called restoring forces, exceed the forces that allow the surfaces to stay in contact: $F_{\text{release}} > F_{\text{contact}}$. Release forces in a MEMS device include the mechanical properties of the MEMS design (spring constant) and, when packaged in a gas or fluid, squeeze film damping.

To ensure that a device can overcome stiction as needed, the design needs to properly address all these forces. Increasing a structure's stiffness (spring contact) will increase $F_{\text{release}}$, for instance, but there are serious trade-offs. Stiffness affects the pull-in voltage needed to move an element.

Another approach to ensuring that stiction can be overcome would be the reduction of surface work of adhesion. Such reduction traditionally been performed with both design and manufacturing methods to reduce $F_{\text{contact}}$. A popular design method for reducing $F_{\text{contact}}$ involves reducing surface area of contact through the inclusion of stoppers or bumpers. Manufacturing methods include reducing surface area through surface roughening techniques, also called ‘nano-texturing’. In Figures 3a and 3b, diagrams represent surface texture through, for example, oxidation of polysilicon. Lower surface area of contact is the goal.

Figure 3a: Representation of smooth surface  
Figure 3b: Rougher surface due to oxidation

Another popular and long-used manufacturing method for reducing contact forces involves the use of anti-stiction coatings that reduce the surface work of adhesion. Early coatings such as OTS (octadecyltrichlorosilane) reduced work of adhesion to a polysilicon surface by 3 to 4 orders of magnitude. Due to growth in MEMS designs and applications, new surface coatings are always in development.

**Electrostatic Discharge**

Along with the mechanical problems of stiction, MEMS are susceptible to electrical problems, such as ESD (electrostatic discharge). The generation of static charge and its transfer between two objects (discharge) will frequently occur in normal use and ESD generation is so well-known to cause havoc in semiconductor devices that entire careers have been spent in designing ESD protect circuits.

ESD can also cause failure for some MEMS. If your MEMS device is electrostatically actuated, for instance, then ESD is a likely failure mechanism for your part. ESD could cause the actuator to move beyond its intended range, possibly resulting in contact and stiction. You should test your part to the proper standards both to quantify the effect and to determine if the device will fail in the field.

Electromechanical failure due to ESD can be reduced by eliminating the electric potential differences between the MEMS element and any potential landing location. Again, this is a design decision and landing features can be designed with ESD effects in mind. Yet in severe cases where design cannot prevent the failure, protect circuitry is recommended for MEMS ESD prevention.
For high resonant-frequency devices, the structure is so stiff that ESD related motion is less likely. The timescale of the ESD pulses are on the order of nanoseconds, too short to result in significant motion. In these cases, the movement in the MEMS is primarily that of resonance and damping.

An ESD event can yield a combination of electrical and mechanical failures in MEMS devices. Joule heating effects, for instance, can cause melting of MEMS structures such as a MEMS comb finger. It can end up ‘welded’ to the ground plane as the result of ESD. (The welding mechanism in this case can appear like a stiction event.) Of course ESD damage can also be purely electrical, such as an insulator breakdown or metal lead fusing and melting.

Methods for elimination of ESD in MEMS are similar to those for semiconductor devices. ESD protective handling procedures and packing materials, for instance, can be critical to protecting an ESD-sensitive MEMS device. Design changes a developer might consider to reduce sensitivity to ESD in MEMS include wider spacing between leads and wider leads to carry higher current densities.

Testing for ESD failure is a case where industry standards for semiconductors can be applied to MEMS devices. HBM (human body model), MM (machine model), and CDM (charged device model) are the typical standard tests (see Table 1). The human body model simulates when a person touches a device. The machine model has a faster pulse and a more severe discharge from a charged machine. The charged device model is common in semiconductors. Recently, many standard organizations have obsoleted the Machine Model standards. JEP172A explains the discontinuation yet it is recommended to test MEMS to this model and use scientific methods to determine applicability of results to the MEMS and use environment.

<table>
<thead>
<tr>
<th>ESD Model</th>
<th>AEC-Q101 Standard</th>
<th>JEDEC Standard</th>
<th>ESDA Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(previously JESD22A-114F)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(target JEP144A.01)</td>
<td></td>
</tr>
<tr>
<td>(Decommissioned)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDM</td>
<td>AEC-Q101-005</td>
<td>JESD22-C101F</td>
<td>ANSI/ESDA/JEDEC JS-002-2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(target JEP157)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Three ESD Models and associated specifications

(See page 2 for more MEMS failure causes: Micro-contamination and Shock)

More MEMS Failure Causes: Micro-contamination and Shock

Micro-Contamination

In the manufacture of MEMS devices, micro-contamination is another potential failure source. Micro-contamination can be split into two categories: molecular and particulate. Molecular contamination is gaseous in phase. This contamination is in the form of a molecular cluster that has not reached the critical cluster size to grow into the condensed form of a particle. Such molecular contamination can deleteriously affect the MEMS surface.
For example, MEMS designers can eliminate stiction mechanisms by reducing the surface work of adhesion with anti-stiction coatings by orders of magnitude (recall the force balance equation). But if outgassing chemical species from, for example, organic die attach materials are able to adsorb to an anti-stiction surface and inhibit its effectiveness, the force balance equation can be reversed. For instance, PDMS (polydimethylsiloxane) is commonly found in adhesives. Upon outgassing and re-deposition to the MEMS surface, the surface work of adhesion increases to the range of polysilicon.
The semiconductor world has studied and treated AMC (airborne molecular contamination) with activated carbon filtration, and filtration methods from semiconductor manufacturing facilities can
be used in MEMS fabrication. Elimination of the source is preferred, however. If stiction is of concern in the MEMS design, knowledge of what airborne molecular contamination can inhibit and deleteriously change your MEMS surface is key to the elimination and/or proper filtration of the AMC source.

Particles are another form of micro-contamination that can cause failures. In moving MEMS, particles can mechanically obstruct the structure from proper movement, though some MEMS, such as thermal accelerometers, will not experience mechanical obstruction due to particles. Yet in other cases, particles that are conductive in nature can create shorts if they are in a critical location.

The potential for failure due to particle micro-contamination may not always be apparent during manufacturing test. Particles greater than one micron move primarily with gravity and electric field. Thus, a particle in a MEMS package can create no problem initially, but can move into a critical area under the right conditions and create failure in the field.

Particulate contamination is the reason MEMS manufacturing and packaging are performed in cleanroom environments. But cleanrooms are never completely free of particles, so particle shedding materials and particle generating operations must be identified and eliminated if particle contamination is present. In order to elementally identify the particle source and eliminate it, we recommend that developers employ x-ray mapping of the particle using energy dispersive x-ray analysis (EDS) in a scanning electron microscope to separate the particle from background elements.

Manufacturing operations that typically create particles but are not a problem in integrated circuits, such as wafer dicing, require specialized treatment in MEMS fabrication. A common technique is to cap MEMS structures, for instance, so that packaging cleanrooms, typically with more particles per unit air volume than wafer cleanrooms, do not have to be retrofitted into costly uber-clean spaces to eliminate particulate contamination.

The surface forces described in the stiction section apply to small particle adhesion as well, making the removal of small particles difficult. Yet the common semiconductor practice of wet cleans are not realistic in MEMS manufacturing, because capillary stiction can occur upon drying. Critical CO2 cleaning has some limited success in MEMS fabrication but is not implemented widely. Design of the MEMS structure to be less sensitive to particles is the best way to avoid the problems of small particles, using wider spacings, larger distances from the ground plane, and capping structures if possible.
Failure Due to Mechanical Shock

Dropping a product that has MEMS inside, such as consumer cell phones and tablets, can result in thousands of g’s of acceleration in the form of a shock profile. The simulation of a cell phone drop in Figure 6, for instance, predicts a maximum g level of 5000 g’s for a cell phone that has a polymer protective case. Without the case the shock level would be higher. Wearables can also experience high shock levels. Who hasn’t broken their watch glass when it is on one’s arm? High shocks of wearables with installed MEMS should therefore be expected.

Failure modes due to mechanical shock include shattered MEMS, cracks in structures, packaging fractures, wafer breakage, die adhesion loss, and particle movement into critical locations. Proper design of the MEMS device is key to withstanding shock levels that may be experienced in the subsequent manufacturing environments, shipping, and user environment. Damping MEMS with stoppers, allowance of over-travel (for high shock resistance), and simulations of shock pulses are all important in the design phase. In manufacturing, choosing materials that can withstand the required shock levels and not be prone to crack initiation defect sites are areas to focus on. The final product containing the MEMS must also be designed knowing MEMS often need additional damping and protection from shock or drop events. With understanding, compactly packaged consumer electronics can pass high shock and drop testing.

Figure 6. Simulation results of a dropped cell phone.

The key to characterization of mechanical shock exposure and identifying where failure occurs, once parts are available, is performing experiments to evaluate sensitivity to shock levels of various
pulses and amplitudes. Experimentation can be performed with various testing set ups. Very high g testing can be achieved with a modified split Hopkinson pressure bar. A drop tower is used for moderate levels, and for lower g levels, pneumatic testers. Appropriate fixtures for MEMS and/or the consumer electronic part (with MEMS inside) with a reference accelerometer are important to proper monitoring and delivery of the shock profile.

**Tips for Systems Developers**

So what do these failure modes mean to the system developers who integrate MEMS in their products? Some, like stiction and contamination, are things the device manufacturer should have already addressed in their design and can discuss with system developers. Others, like ESD, need system designer attention. For instance, datasheets will typically have ESD ratings identified. Treating the MEMS device like an IC with the ratings is critical so to not to have yield issues in manufacturing and/or introduce weakened parts into the field. ESD mats, ground straps, ESD packaging in shipping, and system design are very similar to the IC industry - these methodologies are well known and should be replicated for an ESD sensitive MEMS device.

MEMS datasheets will also include temperature and relative humidity limits. System developers should think carefully before locating a MEMS device with a lower temperature limit near a heat-generating component in their design. Excess heat can reduce device lifetime via some thermally-driven failure mechanisms. Again, this situation can be simulated to determine how much heat would reach the MEMS device from an adjacent power dissipating device. As for humidity, devices with open packaging, such as MEMS microphones, could need to have their operation restricted to the relative humidity range of the datasheet. (Many MEMS microphones have solved the moisture problem but some other devices could still have sensitivity to humidity.)

The best bet for developers, then, is to always work with the MEMS manufacturer when designing a MEMS device into their system. The cost to redesign a system can be astronomical, and the timeframe for redesign could cause the project to miss the market window.

**Summary**

In closing, development and manufacturing of MEMS can successfully be performed with reliability in mind throughout the entire product development phase and into production. Upon product launch, reliability test data will both have proven the part reliable and identified the weak links in the design and manufacturing with time for completed cycles of learning. It is important to:

- Use learnings from previous MEMS products to accelerate the time to market by incorporating design and manufacturing fixes for applicable well-known failure mechanisms early in the program.
- Simulate these fixes with various design iterations to narrow down choices in a design for reliability.
- Focus on a fast and effective yield ramp, and elimination of the few surprise failure mechanisms that that were not even predicted can reduce the chaos and put the product into the market on time.
- Have system developers work with the MEMS manufacturers to determine important operational parameters and have the manufacturer suggest solutions to assure the MEMS device works reliably in the final system.

*Ms. Allyson Hartzell is a Managing Engineer at [Veryst Engineering](https://www.verystengineering.com) with more than three decades of*
professional experience in emerging technologies and a broad background in semiconductor and MEMS fabrication, yield enhancement, emerging technology manufacturing and reliability, packaging materials and processing, and cleanroom science—including particulate and molecular contamination. She is an internationally recognized expert in MEMS reliability, and has expertise in surface chemistry and analytical techniques for failure analysis. Prior to joining Veryst Engineering, Ms. Hartzell was Director of Engineering for Reliability, Failure Analysis, and Yield at Pixtronix, a wholly owned subsidiary of Qualcomm. She was a Senior Staff Scientist in Reliability and Yield at Analog Devices Micromachined Products Division, and has worked at IBM and Digital Equipment Corporation. Allyson has an M.S. in Applied Physics from Harvard University and a B.S. in Materials Engineering from Brown University.