Although they are built using semiconductor equipment, micro-electromechanical systems (MEMS) devices in general have a completely different set of failure mechanisms and reliability concerns than integrated circuits (ICs). In order for MEMS engineers to produce commercially viable products, they must work around these issues in the design phase.

MEMS reliability focuses on mechanical failure modes rather than electrical ones. One major failure mechanism is stiction, or the tendency of two silicon surfaces to stick to each other. Another concern is wafer singulation. Wafer singulation procedures must keep contaminants away from MEMS structures and employ very specialized techniques. Packaging is a third concern and is one of the most difficult and expensive to address. Because MEMS devices contain exposed moving parts, they can be made nonfunctional by the presence of liquid, vapor, particles, or other contaminants. Only a few companies have successfully addressed these failure modes and supply reliable commercial MEMS devices in any significant volume.

Struggles with stiction
Stiction is recognized as a major potential failure mechanism in surface micromachined MEMS. Microstructures fabricated by surface micromachining feature large surface areas, small thickness, and gaps, along with dangling chemical bonds on the surfaces. As a result, large adhesion forces form between fabricated structures or between the structures and the substrate when they come in contact (see sidebar).

In wafer fabrication, stiction becomes an issue during the critical-release phase of the device (see figure). For devices released using wet-etches, the surface tension of evaporating droplets can pull two surfaces together, eventually bringing them into contact. Stiction manifests itself as a yield issue to the
A thin layer of spacers provide full-scale in any direction. Insulating magazine assume silicon surfaces will touch. Anti-stiction coatings will prevent surfaces from sticking and can be thought of as a passivation method for mechanical devices analogous to the use of oxynitride passivation in the IC world. A robust anti-stiction coating is one of the basic requirements in producing a high-reliability MEMS device.

MEMS devices require new types of reliability testing. At Analog Devices (Cambridge, MA), we use a series of mechanical tests to confirm resistance to mechanical shock, stiction, and other MEMS-specific failure modes. For example, drop testing is one of the best tools to confirm good mechanical design and stiction performance. Devices are typically dropped from heights of 1 ft to 3 ft onto hard surfaces in a variety of orientations.

die singulation and packaging

Singulation and handling of a MEMS die are very difficult. Unlike standard ICs, MEMS devices cannot be cleaned once they have been released. For this reason MEMS wafers must be singulated (cut up into individual die) and assembled using very specialized techniques. For example, during the singulation process, the MEMS die must be protected from particulates and contamination such as saw slurry, particles generated by laser scribing and from scribe and break. Dust landing on the wrong place can impede movement of a MEMS device or affect the electrostatic fields that govern its motion. Class 100 clean-room environments with localized Class 100 work areas are optimal for singulation.

Standard assembly tools are designed for fully passivated silicon die. Reducing the particles generated in these toolsets requires significant equipment modifications, but it is not economically feasible for a MEMS supplier to create a set of full custom tools. Particle reduction modifications must be done in a manner that allows the use of standard semiconductor equipment.

Packaging is sometimes an overlooked detail but, in fact, is one of the most difficult and expensive aspects of manufacturing MEMS devices. These devices contain exposed moving parts that can be made nonfunctional or unreliable by the presence of liquid, vapor, gases, particles, or other contaminants; hence, they need proper Packaging. Unfortunately, standard packages for MEMS devices do not exist, so suppliers are often forced to modify standard assembly equipment, assembly handling methods and tooling, and equipment environments to accommodate the intensive handling and particle control requirements for packaging microstructures.

Package cleanliness that is acceptable for standard ICs is unacceptable for MEMS devices, again because they are affected by particles and contamination that do not affect operation of an IC. To ensure MEMS reliability and performance, designers must evaluate the packaging environment to address issues such as out-gassing, particle contamination, assembly temperature, moisture levels, and chemical interactions with anti-stiction coatings. It is important to package the MEMS devices in a controlled, hermetic, particle-free environment. Every step, from die preparation to package seal, must be performed in a clean-room environment until the device is safely sealed in a clean, hermetic package. Clean-room techniques normally reserved for wafer fabrication must be extended to the probe, die-prep, and assembly environments.

causes of stiction

**capillary forces:** A thin layer of liquid between two surfaces can exert an adhesive force due to capillary action. The capillary force depends on the contact angle between the liquid and the solid surface and decreases as the angle increases. In surface micromachining, wet etching is often used for the release step, giving rise to large capillary forces that result in stiction.

**hydrogen bridging:** A native oxide layer forms rapidly on etched silicon surfaces that are exposed to room air or water. The oxide layer is 0.5- to 3-nm thick and has a high surface energy due to the presence of hydroxyl groups coming from adsorbed water vapor. When two such surfaces come in contact, hydrogen bonds may form between hydroxyl groups of the oxide layer.

**electrostatic forces:** Insulating layers on silicon surfaces are known to accumulate charges causing electrostatic attraction. Differences in work function of the adjacent layers can also cause charging that will result in electrostatic attraction.

**van der Waal’s forces:** van der Waal’s attraction comes from the electric interaction between instantaneous dipole moments of atoms. It is a very short-range force and cannot pull surfaces together but can contribute to holding surfaces together once they are in contact.

— S. B.
assembly areas. Thus, the packaging of the MEMS device is as challenging as the fabrication of the MEMS device itself. Customers who purchase a raw unpackaged die from a MEMS vendor and attempt to package the device themselves are probably underestimating the extent and complexity of the manufacturing process modifications necessary to meet quality and reliability requirements.

**Volume Production**
Manufacturing reliable MEMS devices is no easy task. Many manufacturers lack expertise in high-volume design and production. Compared to ICs, the devices are produced in low volume, which hampers yield enhancement and quality improvement. The only way to achieve quality control to single-digit parts-per-million (PPM) levels is to reach a stable and mature process through high-volume production. Only a handful of MEMS suppliers have achieved yields and process controls for MEMS devices that are as good or better than those achieved in the general, standard IC businesses.

Manufacturing requires the development of new MEMS-specific physical models based on millions of device hours of testing and evaluation. It can take a manufacturer five to 10 years to establish the volumes necessary to establish correlations between the physical attributes of their process and single-digit PPM failure modes. However, many of the failure mechanisms in MEMS devices are independent of the application. Only knowledge gained from high-volume applications can also be applied to lower-volume products.

Below is a list of questions to ask a supplier before purchasing a MEMS device or a system or component containing a MEMS device:

- How does the supplier control stiction?
- Has the supplier produced any production-qualified MEMS devices?
- What are the cumulative and monthly run rates the supplier produces today?
- What is the on-time delivery of their MEMS devices?
- What control systems are used to minimize delivery, quality, and reliability issues (ISO-9000, QS-9000, TL-9000, etc.)?
- What is the PPM failure rate for devices in the field, and what are the root causes?
- Do they have “drop test” or other mechanical-reliability data?

The combination of electronics and MEMS promises to greatly improve the quality, reliability, and performance of optical devices while bringing cost and size advantages. Because quality and reliability of optical components are important for applications such as telecom, designing wisely and selecting an experienced MEMS supplier are critical.

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