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MEMS reliability from a failure mechanisms perspective

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Abstract

Over the last few years, considerable effort has gone into the study of the failure mechanisms and reliability of microelectromechanical systems (MEMS). Although still very incomplete, our knowledge of the reliability issues relevant to MEMS is growing. This paper provides an overview of MEMS failure mechanisms that are commonly encountered. It focuses on the reliability issues of micro-scale devices, but, for some issues, the field of their macroscopic counterparts is also briefly touched. The paper discusses generic structures used in MEMS, stiction, creep, fatigue, brittle fatigue in silicon, wear, dielectric charging, breakdown, contamination and packaging.

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1. Introduction

Reliability of micro-electromechanical systems (MEMS) is a very young and fast-changing field. In this paper, we will give an overview of the current status of the available relevant literature. The discussion is not exhaustive; the objective is to provide an overview of the important issues in MEMS reliability, some background, and to discuss a number of papers on each subject that are particularly interesting. Here, we only deal with the most common failure modes and their mechanisms.

We start with a short overview of commonly used generic elements in MEMS devices, and a list of failure modes that are often encountered. Then we separately discuss stiction, creep and fatigue, brittle fatigue in silicon, friction and wear, dielectric charging and breakdown, and contamination and packaging.

2. MEMS failure mechanisms

MEMS devices come in a wide variety of applications, but the amount of different structural parts used in them is rather limited. Most MEMS are designed with some basic parts, which re-occur throughout the field: cantilever beams (single side clamped, double side clamped), membranes (either closed at the sides to another structural member, or as a free floating plate), springs (often doubling as cantilever beams), hinges, etc. (Fig. 1). Of course, these elements often suffer from the same degradation or failure mechanisms, regardless of their application. In Table 1, an overview is given of the most common generic elements found in MEMS devices, most of them taken from the JPL/NASA MEMS reliability report [1].

Combined with the material of which these elements are made and the environmental stressing conditions they are subjected to, we can say some things about the expected degradation modes or failures, if at all occurring. A list of common degradation/failure mechanisms of MEMS is given in Table 2.

The material properties of structural parts are not all well known, especially not in thin film technology, where properties often differ from the macroscopic bulk behavior. The research in thin film material properties is carried out worldwide, and to have easy access to most

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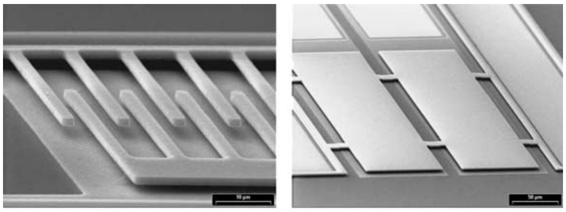

Free standing beams in a comb drive (MUMPs process, courtesy of IMEC)

Floating membranes (MUMPs process, courtesy of IMEC)

Alls sides clamped pressure sensor membranes (courtesy of xfab)

Membrane that is pulled out of the plane functioning as a positionable mirror (courtesy of Sandia)

Fig. 1. Examples of generic structural parts in MEMS.

of the findings of this research, a database on the internet has been set up at the MEMS Clearinghouse web-site of the University of Southern California. [1] For degradation of structural part materials we are not so lucky; not much research has been carried out yet. But from a basic distinction between metals and brittle materials, like silicon or ceramics, we can already find that some failure modes do apply more to one group of materials than to another. Creep and fatigue are more important concerns in metal MEMS than in brittle silicon MEMS, and more so when the melting point of the structural metal is relatively low, like in aluminum devices, as we will see later.

In silicon, a fatigue-like phenomenon has been observed, but it occurs only at very high stress intensity levels, at which it is hardly a good idea to use brittle materials anyway. On the other hand, sudden fracture due to a short "overload" condition below the yield strength is likely to destroy brittle materials (containing small flaws), but not tough materials like metals, although the ultimate fracture strength of a metal MEMS structure may well be lower than that of its brittle counterpart. Likewise, charging and leakage of dielectrics will only apply to a certain class of materials. Stiction can cause failures in almost all MEMS devices with a small gap between structural parts (e.g. in surface micromachining).

Table 1
Generic MEMS elements

- Structural beams
    - ○ rigid
    - ○ flexible
    - ○ one side clamped
    - ○ two sides clamped
- Structural thin membranes
    - ○ rigid
    - ○ flexible
    - ○ with holes
- Flat layers (usually adhered to substrate)
    - ○ conductive
    - ○ insulating
- Hinges
    - ○ substrate hinge
    - ○ scissors hinge
- Cavities
    - ○ sealed
    - ○ open
- Gears
    - ○ teeth
    - ○ hubs
- Tunneling tips
- Reflective layers

Table 2
Common MEMS failure mechanisms

- Fracture
    - ○ overload fracture
    - ○ fatigue fracture
- Creep
    - ○ applied stress
    - ○ intrinsic stress
    - ○ thermal stress
- Stiction
    - ○ capillary forces
    - ○ van der Waals molecular forces
    - ○ electrostatic forces
    - ○ solid bridging
- Electromigration
- Wear
    - ○ adhesive
    - ○ abrasive
    - ○ corrosive
- Degradation of dielectrics
    - ○ leakage
    - ○ charging
    - ○ breakdown
- Delamination
- Contamination
- Pitting of contacting surfaces
- Electrostatic discharge (ESD)

In conclusion, we have for every observed failure under stated environmental conditions one or more generic structural parts failing, made of one or more

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[1] http://www.memsnet.org/material.

structural materials. In the following parts, we discuss their failure mechanisms in more detail.

3. Stiction

One of the most important and almost unavoidable problems in MEMS is stiction (Fig. 2). MEMS structures are so small, that surface forces can dominate all others, and cause microscopic structures to stick together when their surfaces come into contact. The most important surface forces in MEMS are the capillary force, the molecular van der Waals force, and the electrostatic force.

The first to report comprehensively on the stiction phenomenon were Bowden and Tabor in 1950, with macroscopic structures [2]. With the advent of MEMS, these forces became an important design parameter, but quantitatively they were largely unknown.

The capillary forces acting during the drying process after the release etch were modeled by Mastrangelo and Hsu [3,4]. Failures in this stage of the production may give rise to dead on arrival (DOA) failures. From a reliability point of view, in-use stiction problems are of more interest. Measurements concerning the adhesion energy between surfaces (surface interaction energy) were initiated by Mastrangelo and Hsu as well [5]. They used single side clamped cantilever beams sticking to the substrate over a certain length at the tip to calculate the adhesive forces between the lower surface of the beams and the substrate (Fig. 3). The higher the surface interaction energy (and hence the stiction forces), the larger the length over which the beams appear stuck. Yee et al. [6] made later modifications to the model to include residual stress (gradients) in the free-standing thin film beams. De Boer also did modeling work on this problem [7]. Maboudian and Howe [8], Legtenberg et al. [9] and Tas et al. [10] reviewed the in-use stiction problems, mostly from an experimental point of view.

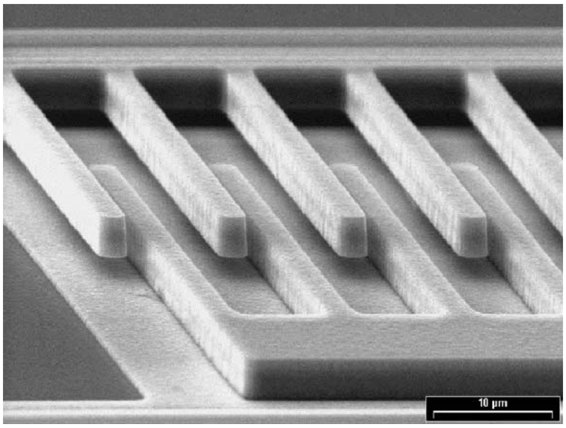

Fig. 2. Scanning electron microscope (SEM) picture of a stiction failure of a comb drive (MUMPs process, courtesy of IMEC).

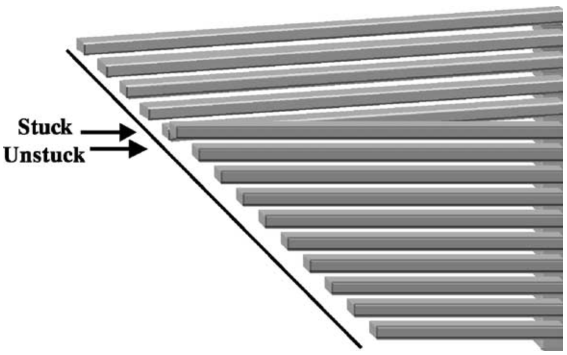

Fig. 3. Cantilever beams stuck at the free end: the length at which the transition from adhered to non-adhered takes places is a measure for the surface interaction energy.

With the recognition that MEMS surfaces are always rough (measurements of De Boer et al. [11]), and that this roughness is a major influence in the stiction phenomenon, more quantitative modeling of the effect of surfaces roughness on stiction was performed, resulting in the van Spengen stiction model [12,13]. In this model, the statistical distribution of the distance of the two rough surfaces with respect to each other is used to calculate the surface interaction (stiction) energy (Fig. 4). Because the capillary and van der Waals interaction energies for flat surfaces are already known for a long time [8], and the distribution function gives the "amount" of surface at a certain distance, the surface interaction energy can be calculated with

$$E_i = \int_0^\infty \frac{c_i}{z^{n_i}} h(z)\,\mathrm{d}z, \tag{1}$$

in which E_i is the surface interaction energy due to mechanism i (e.g. capillary force), c_i/z_i is the dependency of the amplitude of the surface interaction energy on the distance z, and $h(z)$ is the distribution of the distance between the rough surfaces. When all contributions of the different forces are added together, the total adhesion

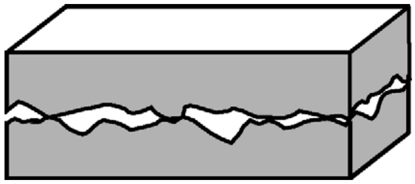

Fig. 4. The distance between two rough surfaces in contact is not a single number, but a distance distribution giving rise to the $h(z)$ function.

energy is obtained, which is a measure of the energy required to separate the surfaces.

Fluoro- or hydrocarbon coatings are used on MEMS surfaces to lower the surface interaction energy and prevent stiction. These coatings provide a hydrophobic surface on which water cannot condense. Therefore, the most important stiction force capillary condensation will not occur. Coatings used are based on plasma deposition [14,15], vapor phase deposition [16] and liquid phase self-assembled monolayer (SAM) deposition [17–19]. The reproducibility and reliability of these coatings is still an important issue [20,21]. Another concern is that most of them are not able to stand the high temperature steps required in packaging MEMS.

The way the possibility of stiction influences the reliability of silicon MEMS acceleration sensors were described statistically by Hartzell et al. [22] and Bart et al. [23].

4. Creep and fatigue

Creep and fatigue are important issues for the reliability of metal MEMS. The only large publicly available source of information on the degradation of metals in MEMS is the research done by Texas Instruments (TI) on the Digital Micro-mirror Device (DMD). They found that thin film surface micromachined structures made of aluminum (Al) are much less susceptible to metal fatigue than their macroscopic counterparts. However, creep (the slow movement of atoms under mechanical stress) is much more severe in metal microstructures than expected from macroscopically known behavior [24]. It is expected that this kind of creep will ultimately limit the lifetime of all bending structural parts made of low melting point metals under significant mechanical stress.

The creep effect in Al thin films (TI call it "memory effect" [25]) was so large that they had to find other materials for the structural beams of their mirrors to obtain a reliable device (Fig. 5). To stay compatible with the Al-etch processing that was already in use and well characterized, they developed a number of Al compounds having fewer primary slip systems than aluminum and a much higher melting point (a high melting point metal often has low creep). These Al compounds, which etch in an Al etch process, were patented in 1996 [26]. The ones they found to be particularly useful were Al_3Ti, AlTi, AlN, and a mixture of AlN and Al_3Ti.

Macroscopically, creep is a well-known phenomenon. When a load is applied to a material, its strain response ε consists of a rapid elongation related to the Young's modulus and a time dependant term due to creep. The general observation is that, macroscopically, creep is virtually non-existent, as long as the temperature is kept below 0.3 times the melting temperature of the material in Kelvin (T_m) and the mechanical stress in the material is not extreme. The creep rate then behaves logarithmically (Fig. 6).

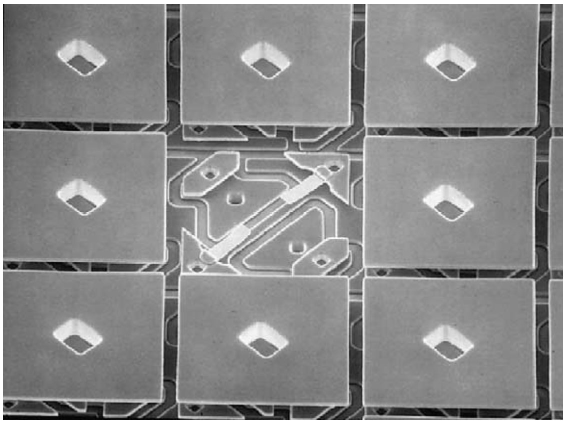

Fig. 5. SEM picture of the Digital Micro-mirror Device (DMD); the two beams that are stressed during operation are clearly visible in the middle (courtesy of Texas Instruments).

At 0.4 T_m creep is worth a serious investigation and at 0.5 T_m creep often rapidly results in fracture or in an otherwise defective structure. While we cannot apply the macroscopic laws in the microdomain (as was shown by the case of the DMD), we expect the creep behavior of the materials still to follow the basic rule that a higher T_m is likely to result in a higher creep resistance at or near room temperature.

Most metals and alloys are degraded by material fatigue when subjected to a large repetitive mechanical stress. Their behavior is often graphically represented in an S-curve (also called S/N-curve or Wöhler-curve). In such a curve, the applied mechanical stress is given as a function of the number of cycles to failure.

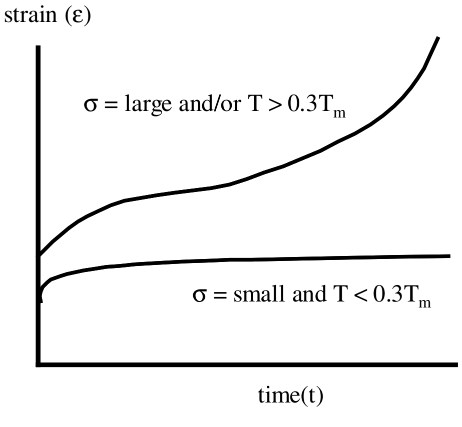

Fig. 6. Creep in metals as a function of melting point.

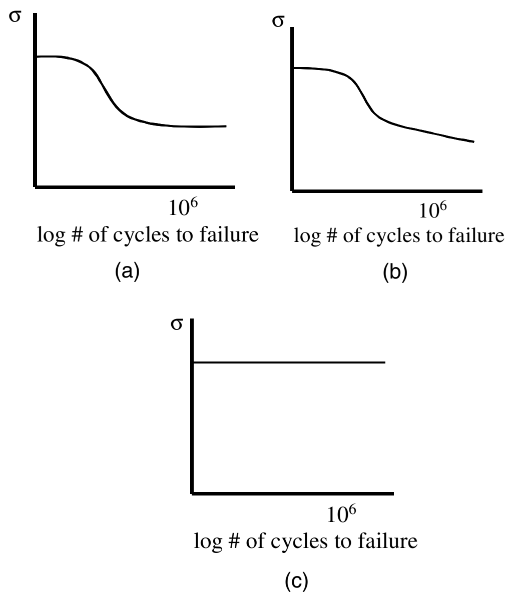

Fig. 7. S-curve with (a) and without (b) threshold. (c) S-curve for ceramic.

Two curves are commonly encountered macroscopically, depicted in Fig. 7a and b. The curve of Fig. 7a applies to most steels. We see that for high maximum stress amplitudes the number of cycles to failure is low. For lower applied mechanical stress, the life is extended to a larger number of cycles, until we reach a plateau. If care is taken that the maximum stress anywhere in the structure is always below this value, the structure will never fail due to fatigue. Other metals, including aluminum, and, to a lesser extent, its alloys, do not have such a fatigue limit (Fig. 7b). Even after as much as 10^{10} cycles the curve is still decreasing, albeit slowly, as shown in.

Brittle materials like ceramics and silicon (Fig. 7c) do not have a significant cyclic fatigue effect (although a "static fatigue" effect may be present in ceramics containing small flaws). Poly- and possibly mono-crystalline silicon seem to suffer from a stress corrosion cracking (SCC) mechanism in which small cracks under tensile stress propagate due to hydrolysis of the native oxide layer in a not completely water-free environment. We will discuss this effect in the next paragraph.

The fatigue properties of thin layers are entirely different from those of bulk materials. The most important general observation for metal thin films, is that they exhibit much less fatigue than do their macroscopic counterparts [24]. Macroscopic fatigue models are based on a movement of dislocations to the surface of the material forming fatigue cracks after enough damage has been accumulated. Thin films do not have so many grain boundaries and defects inside the material, as they are more or less only one or a few grains thick, so that not enough damage will be accumulated to form fatigue cracks. Therefore, not enough damage will accumulate at the surface of thin films for fatigue cracks to appear [24]. However, *low-cycle* fatigue in aluminum thin films was reported [27,28], so its possible occurrence at high cyclic stresses should be taken into account. The absence of *high-cycle* fatigue, however, means that the S-curve of thin-film aluminum resembles qualitatively that of bulk steel (Fig. 7a) instead of that of bulk aluminum (Fig. 7b). In the following paragraph we discuss a fatigue-like phenomenon in (poly-)silicon.

5. Brittle fatigue

It has been known for a long time that glass is prone to slow fracture in a humid environment at stress levels considerably lower than its yield strength. The effect is a manifestation of SCC. It occurs due to the stress-assisted hydrolysis of silicon dioxide. The crack propagation speed can be so slow that it shows up as a detrimental effect only after a considerable time.

In MEMS, for structural members that have to resist large stresses, silicon is often used. Silicon by itself does not exhibit SCC due to humidity [29]. However, in air, it is always covered by a thin native oxide layer, and concern was raised that this layer might be susceptible to SCC. Connally, Brown and van Arsdell [29–33] were the first to investigate the SCC behavior of silicon MEMS using resonant specimens, and found indications that SCC in silicon does occur.

The fracture of silicon MEMS structures due to SCC in the surface covering SiO_2 is thought to happen in the following way [29,33]. A small crack in the SiO_2 surface layer can grow due to SCC if this layer is under tensile stress. Because the native SiO_2 layer has an intrinsic compressive stress, this can only happen if a large stress is applied, for example by actuation of a MEMS device. When the externally applied stress is so large that it forces the stress in the SiO_2 layer to become tensile, SCC may occur in the SiO_2, in which case crack growth will be observed. The stress is the highest in existing cracks at the surface (e.g. surface roughness). As the crack propagates, the silicon comes closer to the SiO_2/air interface, thereby facilitating the oxidation of the silicon deeper in the structure. The crack can grow further in the SiO_2, which itself now extends a little further in the structure. This process goes on, until the remaining part of the structure can no longer stand the concentrated stress, and fractures (Fig. 8).

This kind of crack growth in highly brittle solids is also sometimes called static fatigue, because a cyclically varying applied stress is not required for the crack growth to occur; the presence of a (sometimes non-varying) tensile stress is sufficient. Both statically and

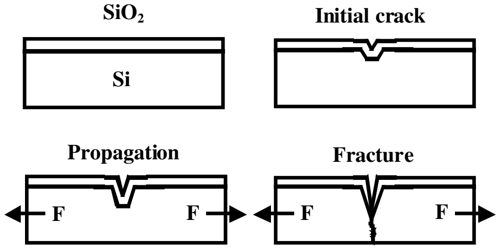

Fig. 8. SSC failure mechanism in silicon.

cyclically applied stresses may result in the previously described failure mechanism. The time to failure depends on the time the stress is applied, and, to first order, not on the frequency of the stressing cycle. Note that this effect can take place in both mono- and polycrystalline silicon, because it takes place in the native oxide layer only.

In the devices of Connally, Brown and van Arsdell [29–33] the crack growth was measured by monitoring the resonance frequency of the structures. Basically the device was a free-standing beam with a mass at the free end acting like a mass–spring system (Fig. 9). A crack in the beam will lower its stiffness and cause a decrease in the resonance frequency. A growing crack manifests itself by a lowering of the resonance frequency of the device. With analytical or finite element modeling it is possible to relate this resonance frequency to the length of the crack.

Muhlstein et al. [34] published a comprehensive experimental study on SCC failures in the same kind of devices. Contrary to the approach of van Arsdell and Brown [29], Muhlstein et al. [34] did not initiate a crack before the experiment started. This means that a real life situation was monitored in which both the initiation of a dominant crack and the propagation of this crack to failure contribute to the measured lifetime of the devices. In the van Arsdell and Brown [29] measurement only the crack *propagation* was measured. Muhlstein et al. [34] showed a definite trend between applied stress and fracture lifetime in the 26 devices they actuated to failure. Similar experiments on different structures were carried out by Kapels et al. [35] and Kahn et al. [36].

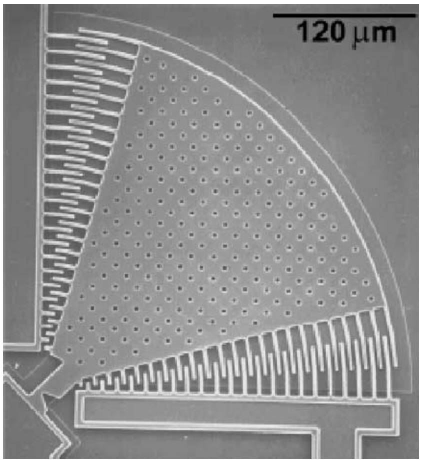

Fig. 9. Top view of the resonance specimen of both van Arsdell and Brown [29] and Muhlstein et al. [34] to measure brittle fatigue in silicon.

The lifetime data presented by Muhlstein et al. [34], Kapels et al. [35] and Kahn et al. [36] did not rely on the resonance frequency based crack length extraction of van Arsdell and Brown [29]. They presented the lifetime in number of cycles directly as a function of the applied stress, which does not involve a calculation of the stress intensity factor at the crack tip.

The explanation that the observed crack growth is caused by SCC is not supported by Sharpe and Bagdahn [37]. They showed that, when all the data available in the literature are plotted with the peak stress encountered in the silicon divided by the mean tensile strength of the material versus the number of cycles to failure in a single graph, a definite trend appears. Although these tests reported by different authors vary widely in actuation frequency, it is the number of cycles that count in this graph. This means that not the time the stress is applied is relevant but that the actuation frequency will govern the lifetime (Fig. 10). This contradicts the basic assumption of SCC, being a manifestation of static fatigue. The research continues.

6. Friction and wear

At Sandia National Laboratories, a lot of research is going on concerning wear and other degradation mechanisms of silicon microstructures having sliding surfaces. The people at Sandia have published a comprehensive report on their activities regarding MEMS reliability [38]. They developed a dedicated MEMS reliability test platform, SHiMMeR, one of the very few instruments dedicated to the testing of multiple MEMS at the same time for statistically significant reliability tests. It is used mainly to investigate wear in sliding/rotating MEMS.

Papers dealing more specifically with a single topic of their research are, among others, a description of the characterization tools [39], an interferometric observation tool [40,41], test structures for fracture mechanics measurements [42] and some papers on stiction [43–45]. Their main strength however is in MEMS friction [46–48], wear experiments [49–57], and failure analysis [58].

A special micro-motor was developed by them, capable of providing a significant amount of force on the structure under investigation (Figs. 11, 12). The main

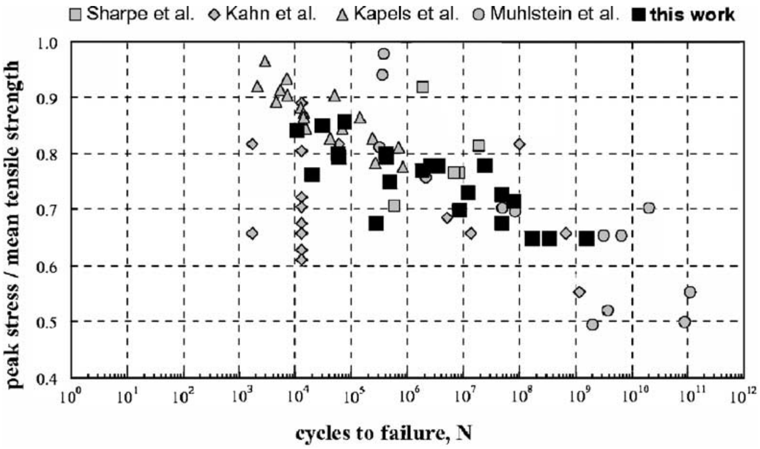

Fig. 10. Sharpe and Bagdahn [37] show that a definite trend appears if the applied stress is plotted as a function of the number of cycles to failure, contradicting the basic assumption of SCC.

wear mechanism in silicon MEMS was identified as adhesive wear (as opposed to, for example, abrasive and corrosive wear, taking place at higher contacting forces, or when a chemical reaction assists the wear process). In adhesive wear, contacting (rough) surfaces partly adhere to each other at their highest points (Fig. 13). These points are broken and stay attached to the other surface. In this way, material is transferred between the surfaces. When the asperities at the surface have grown to a certain size, they break off, leaving a partially worn surface and causing the accumulation of debris. An analytical model has been developed to predict the number of cycles to failure of the micro-motor as a function of actuation voltage and frequency.

Of course, others also studied friction and wear, as these issues pose severe limitations on the devices possible in MEMS technology [59–69]. The subject was

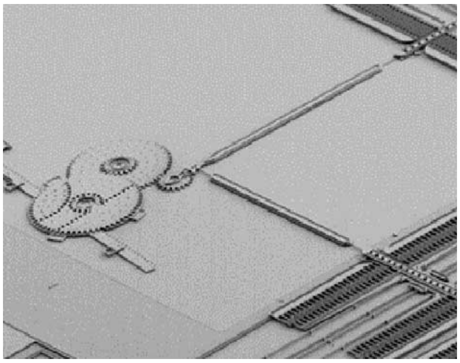

Fig. 11. The Sandia micro-motor test vehicle to investigate wear (courtesy of Sandia).

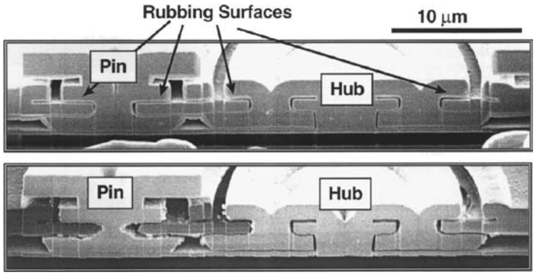

Fig. 12. Focused ion beam (FIB) cross-section of a worn micro-motor (courtesy of Sandia).

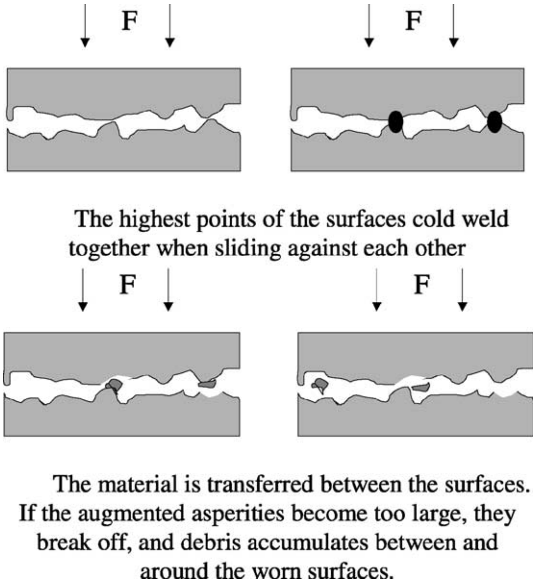

Fig. 13. Principle of adhesive wear.

reviewed in 1999 by Rymuza [70,71]. The problem with friction and wear in MEMS, is that the lubrication techniques being used in macroscopic systems are not applicable to microsystems. Common lubricants have so much viscosity, that the low actuation forces possible in MEMS are hardly able to counteract the resulting friction. The capillary condensation due to the ambient relative humidity often already provides accurate lubrication, but this depends on the environmental conditions and packaging. Coating with hard materials and lubrication by incorporating carbon in the wearing structure itself seems to be advantageous [71]. For the moment, it seems that wear in sliding surfaces is so large that a designer of any MEMS structure which is to survive more than a couple of million cycles should probably best avoid rubbing surfaces altogether.

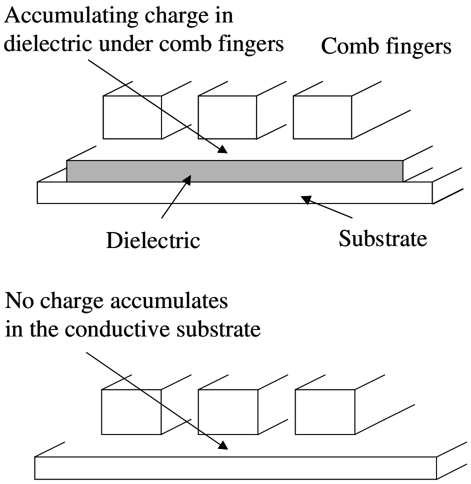

Fig. 14. Accelerometers without a dielectric suffer less from ionizing radiation.

7. Dielectric charging and breakdown

A known problem with MEMS containing dielectric layers is the charging that may occur in the dielectric layer. Sensors are known to drift over time due to charge accumulating at the surface [72]. Parasitic charge accumulating in MEMS may alter actuation voltages and change the device mechanical behavior.

The most obvious source of dielectric charging is ionizing (nuclear) radiation, which can be a major problem for the application of MEMS in space. The effect of nuclear radiation on the dielectrics of MEMS has been tested on accelerometers [73,74]. The conclusion of this research is that MEMS containing functional dielectrics may survive a small dose of nuclear radiation, but that large doses will inevitably result in malfunction of the device. Accelerometers without dielectrics are much more resistant to nuclear radiation as shown in an example in Fig. 14. Shown is part of a comb structure of an accelerometer. The beam in the middle will move in plane when subjected to an acceleration because it is connected to a large moving free mass. The distance between the beams will then change, and is measured capacitively. This capacitance change is a measure for the acceleration. If the dielectric under a comb drive is charged by the ionizing radiation and causes a change in position of the comb fingers due to electrostatic attraction/repulsion, the sensor output will drift. If no dielectric is present under the comb drive, no charging can occur, and the output of the sensor does not drift.

A more widespread problem with dielectrics is charging due to the high field strengths required for actuation of electrostatically actuated MEMS. This is especially a problem in capacitive RF MEMS devices [75–79]. A typical dielectric of 200 nm with an actuation voltage of 40 V across it, will feel a field strength of 2×10^8 V/m. With field strengths this high, conduction is not governed anymore by Ohm's law, but by non-linear conduction effects due to charge injection and conduction via traps, like Schottky- and Poole–Frenkel type conduction [80].

The Schottky effect causes a current to flow due to thermionic emission over a field lowered barrier (due to the charge image force), and *Poole–Frenkel conduction* is caused by traps in the dielectric. In general, most dielectric films give a high field current density versus voltage relationship of the form

$$J = J_0 \exp\left[\frac{q\beta\sqrt{E}}{kT}\right], \tag{2}$$

where J_0 is a constant, T is the absolute temperature, q is the charge of an electron, E is the field across the dielectric, and k is Boltzmann's constant. The coefficient β is the field lowering coefficient. This relation describes a leakage current through the dielectric, which, at high levels, may cause degradation effects and ultimately breakdown. The charge injection may also be visible as a temporarily effect, because the "mean trapping time" of a charge carrier may be significant compared to the time of an actuation cycle, or even permanent, causing stiction of the moving part of a MEMS device.

Although no modeling of this effect is known from the MEMS literature, charging effects are also observed in the (much thinner) high-k dielectrics studied for transistor gates. This has resulted in the model presented by Zafar et al. [81]. The trapped charge density $n(t)$ can be written as

$$n(t) = qN_0\left[1 - \int_0^\infty \frac{\rho(\tau)}{N_0}\exp(-t/\tau)\,\mathrm{d}\tau\right] \tag{3}$$

In this equation $\rho(\tau)$ is the distribution of the capture time constant τ, q is the elementary charge, N_0 is the total trap density, and t the charging time.

There are two ways to combat this charge build-up in dielectrics. Low field strengths in the dielectric and an as far as possible trap-free dielectric can alleviate these problems. Another approach is to make the dielectric so leaky that any charge present flows away immediately. This approach was patented in 1999 by Texas Instruments for Si_xN_y dielectrics [82]. The increase in leakage current has the disadvantage of making breakdown of the dielectric more probable.

8. Contamination and packaging

One of the most important reasons why many MEMS devices have not made their way to the market, apart from the reliability of the devices themselves, is the fact that many MEMS require non-standard packages. Because they interact with their environment in a certain way (sensors, actuators), the standard hermetic packages used for micro-electronic circuits are not appropriate for many MEMS devices.

Dedicated packages that provide adequate protection of the MEMS device, electronic contacts, and still retain the"window" to the outside world (whatever kind is required for the application), are more difficult to make than standard IC packages, and tend to be more expensive, because not so many of them are required as is the case in IC technology (Fig. 15). Contamination due to inappropriate packaging may interfere with the operation of moving MEMS structures. The effects of random contamination were modeled in a program called CARAMEL [83].

The effects of capillary stiction can be diminished by using a vacuum encapsulation or filling an encapsulation with an inert gas. This encapsulation usually takes the form of a zero-level package (a small package directly on the wafer/die, see Fig. 16). Gas filling seems feasible, but trace mounts of water still can play havoc. For a good vacuum, the use of molecular getters has been proposed [85], like is common practice in both radio and CRT (cathode ray) tubes. Usually, getters are sputtered reactive metals like Ti, Ba and Mg. By reacting with the water molecules in the package after it has been sealed, a virtually waterless environment is created and maintained. Common getters like reactive metals will also react with oxygen and nitrogen, so that only traces of noble gasses remain in the package. For MEMS zeolites can also be used, because they will achieve an environment with a specific moisture level, instead of a completely waterless environment [84]. A commercially available getter for MEMS is currently on the market, sold by Cookson Electronics. It is a selective, water binding layer, which can be put for example on the inside of the cap of the zero level package of a MEMS device [85].

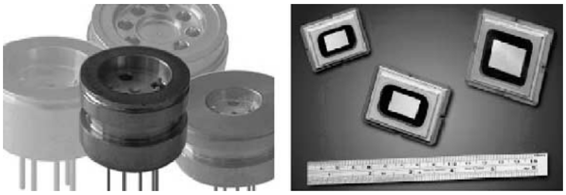

Fig. 15. Examples of "windows" in packages: a pressure sensor open air window (courtesy of Prolyx) and DMD packages with a window transparent to light (courtesy of Texas Instruments).

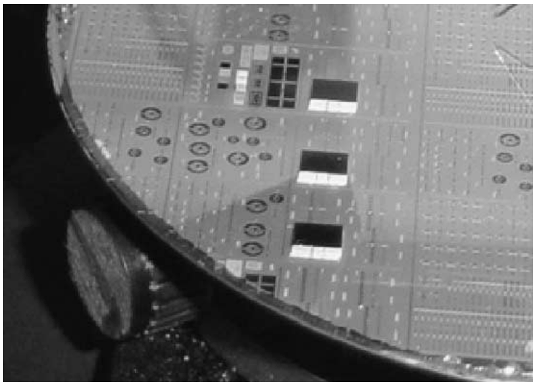

Fig. 16. Three silicon zero-level packages on a wafer before dicing (courtesy of IMEC).

The hermiticity of inexpensive zero-level packages is still under investigation. Because the cavities are so small, the standard MIL-spec fine- and gross-leak tests do not guarantee that zero-level packages are hermetic, because these procedures are not intended for the testing of such small cavities. It has been found that there exists a region of leakage rates that is not covered by any of the two methods, and research is ongoing to find other ways to measure the hermiticity of MEMS zero-level packages [86].

9. Comments on the current status of MEMS reliability research

As we have seen in the previous parts, most of the issues important for MEMS from a reliability point of view have been identified in the literature, at least those important for the current generation of MEMS. Our knowledge of the physics of degradation and failure mechanisms in the microdomain is still very limited.

There is currently hardly any dedicated equipment for MEMS reliability studies. A large research focus on the development of new, and the upgrading/changing of existing equipment is certainly highly desirable.

In conclusion, the research of MEMS reliability is a fascinating field of high importance for the successful application of MEMS technology. Far too little is known about MEMS reliability at this moment compared to the amount of devices already available as prototypes in laboratories all over the world and planned to become available in the near future. Many of these will only see a successful commercialization when the relevant reliability issues can be dealt with. The research of the failure modes and degradation mechanisms of MEMS devices—and the physics behind them—is therefore a challenging, but very rewarding task.

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