Failure Analysis of Worn Surface Micromachined Microengines

Jeremy A. Walraven, Thomas J. Headley, Ann N. Campbell,
and Danelle M. Tanner

Sandia National Laboratories, P.O. Box 5800, MS 1081, Albuquerque, NM 87185-1081, USA
email: jawalra@sandia.gov

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AUG 24 1999

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ABSTRACT

Failure analysis (FA) tools have been applied to analyze failing polysilicon microengines. These devices were stressed to failure under accelerated conditions in both oxidizing and non-oxidizing environments. The dominant failure mechanism of these microengines was identified as wear of rubbing surfaces. This often results in either seized microengines or microengines with broken pin joints.

Analysis of these failed polysilicon devices found that wear debris was produced in both oxidizing and non-oxidizing environments. By varying the relative percent humidity (%RH), we observed an increase in the amount of wear debris with decreasing humidity. Plan view imaging using scanning electron microscopy revealed build-up of wear debris on the surface of microengines. Focused ion beam (FIB) cross sections revealed the location and build-up of wear debris within the microengine. Seized regions were also observed in the pin joint area using FIB processing. By using transmission electron microscopy in conjunction with energy dispersive x-ray spectroscopy (EDX) and electron energy loss spectroscopy (EELS), we were able to identify wear debris produced in low (1.8% RH), medium and high (39% RH) humidities.

Key Words: wear debris, Scanning Electron Microscopy, Transmission Electron Microscopy, Focused Ion Beam, Energy Dispersive X-ray Spectroscopy, Electron Energy Loss Spectroscopy, MEMS

INTRODUCTION

MicroElectroMechanical Systems (MEMS) that sense, act and think are rapidly becoming an integral part in today's technology. Current estimates of the global market for MEMS are \$6 - \$8 billion (1999) with expectations of \$20 billion by the year 2002.¹ Texas Instrument's Digital Mirror Device² which is an array of micromachined mirrors, Analog Device's accelerometers which comprise most of the automotive airbag deployment systems³, and Hewlett Packard's inkjet print head⁴ found in all of their inkjet printers are only a few examples of industries who have capitalized

on the application of MEMS technology in commercial products. MEMS devices may also play critical roles in the biological and medical arenas as well as the electrical and nuclear industries. To assess the reliability of these and various other MEMS technologies, experiments yielding knowledge and insight into their failure modes are paramount. A four-step process for analyzing MEMS devices may consist of: 1) verifying the part has failed, 2) locating the failure site, 3) determining the failure mechanism or root cause of failure, and 4) acting on the results.

Many types of MEMS devices are currently employed for a variety of functions. To properly categorize these devices and those currently under development, a general taxonomy of MEMS devices has been developed. This consists of four classes of devices:

Class 1 devices have no moving parts. This class of devices consists of accelerometers, pressure sensors, ink jet print heads, strain gauges, etc.

Class 2 devices incorporate moving parts without rubbing or impact on their surfaces. These include gyros, comb drives, resonators, and filters.

Class 3 structures contain moving parts with impacting surfaces. These consist of relays and valve pumps.

Class 4 devices contain moving parts with impacting and rubbing surfaces. This class of MEMS consists of shutters, scanners, locks, discriminators and optical switches.⁵ MEMS technologies developed at Sandia National Laboratories, with polysilicon processing technology fall into this category and must function in a wide variety of environments.

The information provided in this paper will discuss the various FA techniques and tools used to characterize the failure mechanisms of Sandia MEMS as well as the results obtained from these investigations.

BACKGROUND

In applications where class 4 MEMS devices are operated in humid, oxidizing, and non-oxidizing environments, the dominant failure mechanism can be attributed to wear of rubbing surfaces. Gabriel⁶ et al. have estimated dynamic coefficients of friction for polysilicon and silicon ranging in value from 0.25 to 0.35. The effects of friction on MEMS increased power

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requirements of actuators and, more significantly, wear of rubbing surfaces.⁷ This effect has been shown by both Tanner⁸ et al. and Patton⁹ et al. to be very detrimental to MEMS devices tested in various humid environments. To illustrate the effects of wear as a function of humidity, Tanner et al.⁸ operated MEMS devices in environments ranging from 1.8% - 39% RH. These microengines were stressed at a frequency of 1720 Hz, which is slightly higher than the resonant frequency of the device. After the micro-engine was operated for a number of cycles, the device was tested at 1 Hz for reliability assessment. During this assessment, if a device is unable to complete one revolution in a 10 second interval, it fails. This process is then repeated, doubling the number of cycles and evaluating the microengines until they have failed. The accumulative number of cycles at failure is recorded.

Figure 1. Optical image of a Sandia microengine with an expanded view of both the gear (left) and comb drive actuator (right) regions. The white arrow indicates the direction of microengine rotation.

These microengines often failed by either gear seizure or pin joint breakage. In either instance, wear was found to play a crucial role in the failure of the device. Illustrated in figure 1 is an optical micrograph

of the Sandia microengine accompanied with SEM micrographs of the gear and comb drive actuator.

Various failure analysis tools and techniques used in integrated circuit analysis can be applied directly to MEMS FA. Such techniques as optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), focused ion beam (FIB), energy dispersive x-ray spectroscopy (EDX), and electron energy loss spectroscopy (EELS) have been used to characterize the failure mechanisms and analyze the worn regions of these microengines. Diffraction analysis techniques have helped characterize the crystallographic nature of wear debris caused by wear of rubbing surfaces.

FAILURE ANALYSIS TECHNIQUES & RESULTS

OPTICAL MICROSCOPY

As a preliminary measure for evaluating MEMS devices, optical microscopy serves as an easy, cost-effective method for quickly determining the integrity of a device. Optical microscopy can provide an initial view of defects such as fracture, chipped parts, abnormal displacement, and debris. No specimen preparation is required to image these samples. Insight into the failure mechanism can be achieved in minutes. A microengine that failed due to a broken pin joint can be discerned from a microengine that failed by gear seizure. These two failure modes are illustrated in figures 2a and b. In figure 2a, the seized microengine reveals wear debris around the pin joint and hub. Figure 2b reveals a broken pin joint and like figure 2a, wear debris is scattered across the entire gear. By imaging through a series of focal planes, the location of wear debris is observed on the gear surface as well as the substrate. Figures 2c & 2d represent the same microengine with focal planes on the ground plane and gear surface respectively.

These images suggest the dominant mode of failure is wear of rubbing surfaces. This mode of failure occurs in microengines operated in oxidizing and non-oxidizing environments. In oxidizing environments, the amount of wear debris varies as a function of % RH^{8,9}. The microengine illustrated in figure 2c seized after 2,000,000 cycles. This may be the result of accumulation of wear debris along the rubbing surfaces of the microengine. Although wear debris can be observed, its morphology and structure are too small to be resolved using optical microscopy. A tool with higher magnification is needed to discern the debris morphology.

Figures 2a, b, c and d. Optical images of failed microengines tested in dry nitrogen. Figures a and b show a seized microengine and broken pin joint respectively. Figures c & d focus on the ground plane and gear revealing debris on both surfaces as indicated by the arrows.

SCANNING ELECTRON MICROSCOPY

Scanning electron microscopy (SEM) is a useful tool for imaging defects and debris at high magnification. Using voltage contrast imaging, a microengine's electrical continuity in both static and operating conditions can be assessed. SEM analysis provides a larger depth of focus and higher

magnification than optical microscopy. This enables debris on both the substrate and gear surface to be in focus at the same time. A field emission SEM was employed to locate debris produced in devices tested in humid and non-oxidizing environments. As illustrated in figures 3a & b, two microengines were tested in 1.8% and 30% RH. These microengines failed at approximately the same number of cycles (600,000 and 608,000 respectively). The microengine operated in a dry environment (1.8% RH) produced the most amount of wear debris.

Figures 3a and b. SEM images of microengines stressed at 1.8% (3a) and 30% (3b) RH at 25°C. Note the accumulation of wear debris on the surface of 3a compared to 3b.

Plan view inspection of microengines tested in low humidity indicated wear debris was produced and accumulated at the hub and pin joint regions. Debris also accumulated on the surface of the gears, linkage arms, and substrate. Larger pieces of debris were typically found on the substrate and top surface of the gear. By increasing the % RH, the amount of wear debris appears to decrease. At 30% RH, debris is located primarily around the hub and pin joint regions. Figures 3a and b are characteristic of microengines operated in these environments. Higher magnification can be used to gain insight into the morphological

properties of debris found in the hub and pin joint regions.

SEM imaging revealed that changes in the testing environment affect the morphology of the wear debris. As illustrated in figures 4a & b, the wear debris morphology appears "particulate" when the microengine is operated in a dry environment (1.8% RH) and "stringy" or "fibrous" when operated in a humid (39% RH) environment, showing a strong dependence of morphology with humidity. While in some instances the morphology of the wear debris can be characterized using an SEM, the debris can be more completely characterized using transmission electron microscopy (TEM) if the debris is electron transparent.

Figures 4a and b. SEM micrographs of debris morphology for 1.8% RH (4a) and 30% RH (4b) samples.

To reduce the effects of oxidation on the polysilicon microengine surfaces, MEMS devices were operated in vacuum. To conduct these experiments, a fixture capable of running up to eight microengines was mounted inside the SEM chamber. Using a computer equipped with the Sandia Super μ driver software¹⁰, we were able to apply the appropriate power and drive signals to the microengines. The SEM chamber vacuum pump was on overnight (14 hrs.) prior to testing. This pump down time yielded a pressure of $\sim 10^{-6}$ torr (with a partial pressure of oxygen at $\sim 10^{-9}$ torr, well below the threshold for oxidation).

As illustrated in figure 5, a microengine operated to failure in vacuum shows debris accumulating along the hub and pin joint regions. Consistent with results from low humidity testing, the morphology appears to be spherical and particulate. However, it appears that the amount of debris formed is considerably less than that found in 1.8% RH. This result indicates that oxygen has a pronounced affect on the wear properties of a microengines.

Figures 5a and b. SEM micrographs of a microengine operated in vacuum over 2,000,000 cycles. Note the lack of debris compared to the 1.8% RH sample and its morphology.

In experiments with microengines in humid environments, the rubbing surfaces are believed to be SiO_x on SiO_x . In the case of a microengine operated in vacuum, the rubbing surfaces initially begin as oxidized polysilicon on oxidized polysilicon. If the oxide is worn away, the rubbing surfaces may be polysilicon on polysilicon. This will result in a significant change in wear characteristics. As illustrated in figure 5b, the debris morphology is similar to that found in microengines tested at low humidity (figure 4a, 1.8% RH). Further analysis of this wear debris will determine if the chemical constituents are silicon and oxygen as well as the presence of any polycrystalline silicon. One theory proposed by Gardos¹¹ focuses on the passivation of silicon (or lack thereof) during testing in vacuum.

Another environment used to evaluate MEMS devices was dry nitrogen. Dry nitrogen was selected for its accessibility and relative inertness to silicon. A General Eastern humidity monitor (Model HYGRO M4) using chilled mirror technology can measure a minimal dewpoint at -40°C equivalent to 0.4% RH @ 25°C . These microengines show significant wear occurring around the pin joint and hub regions. A large amount of wear debris is found on the surface of the gear and the substrate. Figure 6 shows debris accumulating on the surface of the gear as well as the ground plane. This experiment will be discussed further in the FIB section.

Figure 6. Debris accumulated along the substrate and surface of the gear of a microengine operated to failure in dry nitrogen.

SEM analysis of a microengine with a broken pin joint has revealed uneven wear along the pin joint. By over-stressing the microengines (by running them at 1720 Hz), the frictional forces between the pin joint connecting the gear to the linkage arm change severely.¹² These forces directly impact the friction-bearing surfaces throughout the microengine which may cause the gear to fail by seizure or breakage of the pin joint. Previous results¹² have shown that these microengines exhibited linear clamping. By optimizing the drive signals, thus creating a fluent circular motion of the pin joint and gear, the wear along the pin joint and hub regions can be reduced substantially.

As illustrated in figure 7a, the pin joint has rubbed against the gear causing significant wear along the y-axis. The preferential wear of the pin joint may be a result of abrupt changes in acceleration the gear experiences during each revolution. This may be a result of inadequately optimized drive signals, linear clamping of the actuators, manufacturing variation, or a combination thereof. This mode of failure can be detected in the optical microscope by tracing the location of the debris along the substrate. Figure 2c illustrates small particles of wear debris on the substrate. This debris is preferentially distributed along

the y-axis (actuator) of this microengine. Through design modifications and further optimization of drive signals, issues involved with linear clamping have been resolved.

Illustrated in figure 7b is a higher magnification of the fractured pin joint in the boxed region of figure 7a. Notice the significant wear along the bottom of the pin joint. This non-concentric wear indicates strong forces occur along that direction resulting in preferential wearing. This type of wearing process can cause the pin joint to fracture, seize (with the accumulation of wear debris), or rock about the worn region. In a rocking failure, the gear will move but not make a complete revolution at 1 Hz.

Figures 7a and b. Non-circular wearing of the pin joint connecting the gear to the linkage arm caused by overstressing the microengine.

FOCUSED ION BEAM

Focused ion beam (FIB) systems are extremely valuable tools in the failure and yield analysis of MEMS devices.^{13,14} FIB systems use a focused beam of Ga^+ ions (typically 25 – 50 keV) for precise material removal (by physical sputtering), material deposition (by ion beam assisted chemical vapor deposition), and for imaging (by detection of secondary electrons or ions generated during beam exposure). The FIB system

provides the best method for producing clean cross sections of the precise area of interest in MEMS structures; cross sections can be made of both large and small structures with submicron accuracy. Further, the FIB can also be used to free, and in some cases remove, portions of the device to enable the analysis of otherwise inaccessible areas.^{13,14}

Figure 8. MEMS device with an exposed cross-section of the gear produced from FIB machining.

We have used the FIB system extensively in the evaluation of the amount and location of wear debris formed during the operation of microengines. FIB cross sections have revealed debris located throughout the pin joint and hub regions of the microengine. Illustrated in figure 8 is a FIB cut through a gear tested at 1.8% RH. This image illustrates the debris on the surface of the gear as well as revealing a cross section of the pin joint and hub regions. Figures 9a, b, c, and d show four cross sections of microengines from various humidities.

The FIB also helps resolve the root cause of failure for various microengines. In instances where the microengine is seized up, it is important to determine the region most susceptible to sticking. Using the FIB, it became apparent that the majority of seized regions occurred at the pin joint. In this case, either worn material from the pin joint accumulated and caused the microengine to seize or the wearing away of material allowed a protruding part of the gear to get stuck in the pin joint. Another cause of seized microengines can be attributed to induced motion along the z-axis of the device causing the bottom of the pin joint to contact and seize to the substrate.

Figures 9a, b, c and d. MEMS gears tested in: 1.8% (9b), 24% (9c), and 39% RH (9d) environments (control (9a)). Note the accumulation of debris in as a function of humidity.

Figures 10a and b. Seized microengine with the pin joint sheared through (10a). A microengine with the seized region exposed (10b). Note the wear along the pin joint.

Figures 10a and b illustrate seized portions of the microengines occurring at the pin joint. The severe wear of the pin joint revealed by the FIB cross-section

indicates that worn material had been accumulated around the portion of the gear that contacts the pin joint. By accumulating debris along these regions, the as-fabricated geometry has changed from 90° sidewalls to rounder, sharper ends protruding into the pin joint, leading to excessive wear and damage. This mechanism may also be the root cause in the fracture of pin joints. Evidence has shown that microengines operated in low humidity fracture more frequently than those run at higher humidities.⁸

Using the FIB, we have found tracks of wear debris around the hub and outer perimeter of the pin joint as illustrated in figures 11a and b. Of primary interest was evidence that a pin joint is firmly adhered to the ground plane. This result indicates undesirable displacement has occurred along the z-axis resulting in the pin contacting the ground plane. This motion may have occurred when the hub and pin joint regions were significantly worn away resulting in wobbling along the z-axis during operation. The end result is friction welding of the pin to the substrate.

Figures 11a and b. Debris tracks along the outer perimeter of the pin joint and hub on the surface of the substrate.

The bottom half of the gear also shows accumulation of debris around the hub and pin joint regions. Figures 12a and b illustrates significant wear along the hub and pin joint with the build up of debris at the pin joint. Initially, the gear failed by seizing up as opposed to fracture of the pin joint. However, while performing a FIB cut through the hub and pin joint, the microengine freed up and became mobile indicating the FIB cut freed up the seized portion of the polysilicon microengine.

Figures 12a and b. Debris located on the bottom gear surface (top) with debris accumulating along the worn pin joint. Note the lack of circular shape around the pin joint.

TRANSMISSION ELECTRON MICROSCOPY

Transmission electron microscopy (TEM) has been used to characterize the debris morphology, crystal structure and chemical composition. This technique was used to gain further insight into the debris morphology because of its high magnification and diffraction capabilities. Using a Philips CM30 300 keV transmission electron microscope, the debris morphology at low relative humidity has been identified as either spherical or rod-like structures. Spherical wear debris has been found to be as large as 250 nm in diameter. Rod-like debris was found to be up to 500 nm long with a diameter of 50 nm.

The morphology of the wear debris was determined by imaging the various particulate geometries while rotating them through angles of $\pm 25^\circ$ and $\pm 30^\circ$ in orthogonal x and y directions, respectively. By tilting the debris, no significant deviation from its initial geometry could be observed indicating that the morphology is homogeneous throughout a large degree of rotation.

TEM plan-view specimens were prepared using a replica-stripping technique. A thin section of polyacetate film softened with a drop of acetone was placed on the gear and then stripped to remove the gear and linkage arms from the microengine. The parts were then coated with a thin carbon film and transferred to a TEM specimen grid. The remaining polyacetate film

was dissolved with acetone, allowing the gear and associated debris to rest on the carbon film supported by the TEM specimen grid.

As illustrated in figures 13a and b, plan-view TEM reveals a large sliver of material removed from the hub region of a microengine tested in a 1.8% RH environment and displaced just beyond a gear tooth. The large sliver appears to be comprised of smaller spherical and rod-like debris. This debris accumulated along the sidewall of the hub region (as illustrated in the SEM and FIB images). Analysis of this sliver indicates the debris was torn off from within the hub region and thrown outside the gear during testing. Further chemical analysis of this debris using EDX and EELS indicates it is oxidized silicon. Diffraction analysis has shown that this debris is amorphous.

Figures 13a and b. Plan-view TEM images of a large sliver of wear debris (13a). Note the length of the sliver and the smaller particles comprising this debris (13b).

High-resolution electron microscopy did not reveal any boundaries or other features to indicate that the spherical or rod-like constituents are comprised of even smaller debris. One drawback to this technique is that at high magnifications, high-energy electron transmission can change the sample due to localized heating. In essence, if smaller pieces of debris made up

the spherical and rod-like structures, any boundaries in them may have been "fused" together during imaging.

Comparing wear debris produced during various humidities revealed a difference in debris morphology. At higher humidities, the debris appeared to be fibrous or stringy as illustrated in the SEM micrograph of figure 4b. Upon TEM examination of the wear debris, there were several regions where these fiber-like structures existed. As illustrated in figure 14, the wear debris from a 39% RH sample shows an area with fiber-like or filament-like debris. More detailed microscopy (not shown) in these regions indicated that the fiber-like debris is part of the sample and not an artifact resulting from sample preparation.

Figure 14. Wear debris produced at 39% RH. Note the stringy piece of debris.

Electron diffraction analysis was used to assess the crystalline properties of the debris. Diffraction patterns obtained from wear debris formed at low and high humidities revealed the debris is amorphous (non-crystalline) in both instances. As illustrated in figure 15, diffuse halos characteristic of amorphous material are observed in diffraction patterns taken from debris found in 1.8% and 39% RH (not shown). These results are compared with the diffraction pattern taken from a portion of the gear. Note the diffraction spots form sharp rings from the polycrystalline silicon gear.

Figure 15. Diffraction patterns illustrating the amorphous structure of wear debris (left) compared to a diffraction pattern of the polysilicon gear tooth (right).

ENERGY DISPERSIVE X-RAY SPECTROSCOPY

To identify the chemical constituents comprising the wear debris, both energy dispersive x-ray spectroscopy (EDX) and electron energy loss spectroscopy (EELS) were employed. EDX in conjunction with diffraction analysis indicated the presence of amorphous oxidized silicon along the worn surfaces. This indicates that the friction bearing surfaces are becoming oxidized during this experiment. As illustrated in figure 16, the chemical composition for wear debris formed at 1.8% (not shown) and 39% RH is oxidized silicon. This spectrum is shown with a spectrum from the gear tooth to illustrate an increase in the oxygen peak on the stress-tested samples. The carbon peak represented in both spectra is an artifact resulting from the sample preparation technique. We believe localized heating is occurring along the friction bearing surfaces resulting in the formation of silicon oxide. Contacting asperities along these friction-bearing surfaces may oxidize them during operation leading to wearing of oxidized surfaces. By operating microengines in vacuum the oxidizing environment is removed from the system.

Figure 16. X-ray spectrum comparing chemical compositions of wear debris at high humidity with an unworn region of the gear. Note the oxide peak in the high humidity spectrum.

ELECTRON ENERGY LOSS SPECTROSCOPY

Electron energy loss spectroscopy (EELS) analyzes the distribution of energy lost by beam electrons as they interact with atoms in the analyzed volume of the sample. The high energy loss region of the EELS spectrum will contain a series of energy-loss "edges" characteristic of the different atomic species present, superimposed on an exponentially decaying background.

EELS analysis of the debris formed at ~0.4% RH (nitrogen environment) indicates the debris is still oxidized silicon. In the presence of a non-oxidizing atmosphere, enough oxygen was present to provide passivation for the friction bearing surfaces of the microengine during operation. Figure 17 shows a portion of the EELS spectrum from this debris exhibiting a strong oxygen-K signal at 532 eV onset. Note the absence of any nitrogen signal, which would occur at 401 eV onset. The lower energy portion of this spectrum (not shown) contained a strong silicon signal ($L_{2,3}$ edge) at 99 eV onset. Electron diffraction analysis showed that this debris is also amorphous.

Figure 17. EELS spectrum of debris formed in a nitrogen rich environment. Note the absence of a nitrogen signal from the wear debris at 401 eV.

CONCLUSIONS

Using the various FA tools and techniques, we have shown that wear debris produced from friction-bearing surfaces in polysilicon MEMS devices consists predominantly of spherical, rod-like, or stringy debris. The morphology of the debris depends strongly upon the environment it is operated in (low humidity causes particulate or rod-like debris, high humidity causes stringy debris). When a microengine is operated in vacuum, the wear debris consists of spherical and rod-like morphologies, similar to microengines operated in low humidity environments. This indicates that the effect of pressure on debris morphology is negligible (at low pressures). Further analysis is required to identify the chemical constituents and crystallographic nature of wear debris produced in vacuum.

The chemical constituents of wear debris from low humidity, high humidity, and nitrogen atmospheres have been identified as oxygen and silicon. We believe this is a result of localized heating of friction bearing surfaces in the microengine during operation resulting in oxidation of these surfaces. Although the % RH was reduced below the measureable limit of our instrument, enough oxygen was present to oxidize the surfaces of the microengine resulting in oxidized wear debris. To

characterize these microengines after operation in nitrogen they had to be removed from the nitrogen container and imaged in ambient conditions. The experimental process allowed oxygen to infiltrate the microengines during their exposure to ambient conditions.

In oxidizing environments, we have also shown that the volume of wear debris increases with decreasing relative humidity. The addition of humidity to the operating environment of a microengine may act as a lubricant, reducing the amount of wear debris produced within the microengine.

ACKNOWLEDGEMENTS

The authors would like to thank Alex Pimentel for his FIB work, Michael Dugger for discussions of wear on silicon, and Richard Anderson and Jerry Soden for reviewing this paper. Sandia National Laboratories is a multiprogram laboratory operated by the Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000. For further information about MEMS technology at Sandia, please visit our website at: <http://www.mdl.sandia.gov/micromachine>.

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