Failure Analysis of Tungsten Coated Polysilicon Micromachined Microengines

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ABSTRACT

Failure analysis (FA) tools have been applied to analyze tungsten coated polysilicon microengines. These devices were stressed under accelerated conditions at ambient temperatures and pressure. Preliminary results illustrating the failure modes of microengines operated under variable humidity and ultra-high drive frequency will also be shown.

Analysis of tungsten coated microengines revealed the absence of wear debris in microengines operated under ambient conditions. Plan view imaging of these microengines using scanning electron microscopy (SEM) revealed no accumulation of wear debris on the surface of the gears or ground plane on microengines operated under standard laboratory conditions. Friction bearing surfaces were exposed and analyzed using the focused ion beam (FIB). These cross sections revealed no accumulation of debris along friction bearing surfaces. By using transmission electron microscopy (TEM) in conjunction with electron energy loss spectroscopy (EELS), we were able to identify the thickness, elemental analysis, and crystallographic properties of tungsten coated MEMS devices. Atomic force microscopy was also utilized to analyze the surface roughness of friction bearing surfaces.


INTRODUCTION

MicroElectroMechanical Systems (MEMS) that sense, act and think are rapidly becoming an integral part of 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]. New MEMS systems are being developed to solve problems throughout industry. These include accelerometers for airbag deployment systems [2], inkjet printheads to increase printing resolution [3], mirrors to reflect fine beams of light [4], and as switches to place devices in either the off or on state [5]. For the optical networking industry, metal films are deposited on reflective MEMS surfaces to improve their reflective properties. Although these devices do not have rubbing or impacting surfaces, the metal film is used to improve the overall functionality of the device by improving its reflective properties. In devices with rubbing and impacting surfaces, films and coatings can be used to improve device functionality and reliability.

MEMS devices with rubbing and impacting surfaces are susceptible to wear. Gabriel et al. has estimated dynamic coefficients of friction for polysilicon and silicon ranging in value from 0.25 to 0.35 [6]. One effect friction will have on MEMS is an increase in the amount of power required to operate the device [7]. This effect has been shown by both Tanner et al. and Patton et al. to be very detrimental to polysilicon MEMS devices tested under different humidities [9, 10].

Various coatings have been applied to polysilicon microengines to improve resistance to wear. Anti-stiction coatings or self-assembled monolayers (SAMS coatings) and PECVD Teflon have been used to reduce stiction and wear by diminishing the coefficient of friction [8]. Results indicate these coatings do not provide adequate wear resistance in either dry or humid environments [9]. These coated microengines often failed by either seizing of the gear or fracture of the pin joint. In either instance, wear was found to play a crucial role in the failure of polysilicon devices. Illustrated in Fig. 1 is an optical micrograph of the Sandia polysilicon microengine accompanied with SEM micrographs of the gear and comb drive actuators respectively. The gear region is of specific interest because the pin joint and hub are areas that are most susceptible to wear. A major driving force for improving the reliability of MEMS devices is to reduce the friction and hence wear along rubbing surfaces.

One novel method developed to reduce wear in MEMS devices involves selective deposition of tungsten by chemical vapor deposition [11]. Tungsten is deposited on exposed polysilicon surfaces creating a thin wear resistant film. By reducing or eliminating wear as the dominant failure mode, the lifetime and
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reliability of microengines will improve significantly. The information provided in this paper will provide a brief background on the deposition chemistry of selective tungsten. This paper will also discuss the failure modes found in microengines stressed using an ultra-high drive frequency and low humidity (2% RH).

EXPERIMENTAL METHOD

Tungsten was deposited along exposed polysilicon surfaces of the Sandia microengine (illustrated in figure 1). The chemical reactions for selective tungsten deposition using chemical vapor deposition are:

\[
2WF_6 + 3Si \rightarrow 2W + 3SiF_6
\] (1)

\[
WF_6 + 3Si \rightarrow W + 3SiF_2
\] (2)

This process is extremely selective since the reaction does not occur on silicon dioxide or silicon nitride. The deposition temperature also determines which reaction dominates [11]. This deposition process is also self-limiting since each tungsten atom deposited must interact with an exposed silicon atom, consuming silicon to deposit tungsten.

Tungsten coated microengines were operated under three different conditions. The first experiment was performed under ambient laboratory conditions (24% RH) at a drive frequency of 1720 Hz, (103,000 RPM). The time to failures was accelerated through the use of a large tangential force to rotate the gear. Second, microengines were operated in low humidity (2% RH) using the same drive frequency of 1720 Hz. Third, microengines were operated under ambient laboratory conditions but with an ultra-high drive frequency of 8300 Hz (500,000 RPM). When microengines failed during accelerated lifetime testing, the accumulated number of cycles at failure was recorded.

Various tools and techniques have been used for tungsten coated MEMS failure analysis. Such techniques as scanning electron microscopy (SEM), transmission electron microscopy (TEM), focused ion beam (FIB), electron energy loss spectroscopy (EELS), and atomic force microscopy (AFM) have been used to characterize the tungsten film properties, and failure mechanisms found in microengines tested under accelerated conditions.

TUNGSTEN FILM ANALYSIS

Characterization of the tungsten film was conducted using transmission electron microscopy and electron energy loss spectroscopy. Transmission electron microscopy (TEM) is a powerful analytical tool capable of characterizing materials or devices at the micron, sub-micron, and even atomic scale. TEM has been used to characterize the debris morphology, crystal structure and chemical composition of wear debris produced along rubbing surfaces of worn polysilicon micromachines [8, 11]. In this instance, a Phillips CM30 300 keV TEM was used to analyze the properties of the tungsten thin film deposited on released MEMS devices.

The most difficult method of TEM sample preparation for analyzing MEMS devices involves producing cross sections on released movable devices. The aspect that makes sample preparation so difficult is immobilizing (or locking) the movable components of the device to a stationary object. This can be done by depositing a thin film on areas of the device to lock the movable components to either another portion of the device or to the substrate. Another method consists of embedding the device in an epoxy or glue. The problem with embedding a device in epoxy or glue is that there is the possibility of damaging the device. The epoxy should be extremely fluid so that it infiltrates the exposed and porous regions. When the epoxy hardens, the device can be polished down to electron transparency. When pouring and hardening the epoxy, the forces involved (capillary forces from the epoxy, expansion or contraction during curing) can cause the
structure to move or break, damaging the area of interest.

We have found that Gatan epoxy works very well in preparing a cross section of a released MEMS device without moving or breaking it. This sample preparation technique allowed us to analyze the material properties and interface between the tungsten thin film and polysilicon micromachine. Illustrated in Fig. 2 is a cross section through the hub and pin joint of a released tungsten coated micromachine. Figs. 3 and 4 are high magnification TEM micrographs showing the tungsten film on the polysilicon surface. Fig. 3 illustrates the tungsten film over two polysilicon grains. Here the film is uniform and free from defects over the polysilicon grains [12]. Fig. 4 is a high magnification image detailing the thickness of the tungsten film as well as the interface between the tungsten film and the polysilicon.

TEM examination of the tungsten film has revealed a thickness of \(-150 - 200\text{Å}\). Very small crystals are also present along the interface between the tungsten film and polysilicon crystals. These crystals have been shown acting as stress concentration sites where fracture of the polysilicon can occur [10].

In conjunction with TEM, electron energy loss spectroscopy (EELS) has been used to identify the possible contaminants present in the tungsten film. 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 was used to identify the presence of light elements within the tungsten film resulting from process modifications. These results indicate other elements are present within the tungsten film and at the tungsten film-polysilicon interface. Fig. 5 is an EELS elemental map representing the materials analyzed as possible contaminants. This analysis reveals the presence of nitrogen and oxygen. The nitrogen appears to be contained within the film, but the oxygen is
Fig. 5. Elemental maps of the tungsten film on polysilicon compared the bright field TEM image. Note the presence of nitrogen in the tungsten film (black arrow) and oxygen along the tungsten film polysilicon interface (white arrow).

This finding is counter-intuitive with how tungsten is selectively deposited on silicon surfaces. Here, tungsten is present directly on an oxidized surface, which (according to the deposition reaction) should not occur [10]. The presence of oxygen at the interface may be due to oxygen present in the CVD reactor during tungsten deposition. This can lead to competing reactions of deposition and oxidation.

**FAILURE ANALYSIS RESULTS**

*Stressed at 24% RH and 1720 Hz*

Scanning electron microscopy (SEM) is a useful tool for imaging defects and debris at high magnification. SEM analysis provides a larger depth of field, higher resolution, and higher magnification than optical microscopy. This enables features on both the substrate and gear surface to be in focus at the same time. An Amray 1850 field emission SEM was employed to characterize tungsten-coated polysilicon microengines.

SEM analysis of microengines operated under ambient laboratory humidity (24% RH) and standard accelerated lifetime testing (1720 Hz) did not reveal any signs of wear along rubbing surfaces. As illustrated
in Figs. 6a and b, plan-view inspection of these microengines did not reveal any wear debris along the top surfaces. These microengines were operated at (a) 379 million, and (b) over 1 billion cycles where testing was suspended, and the gear inspected for wear debris and other signs of failure.

Further investigation into the hub and pin joint regions did not reveal the presence of wear debris. These areas most susceptible to rubbing or impact did not reveal any signs of damage or degradation even in microengines operated for over 1 billion cycles. Previous results have shown that this version of the microengine linearly clamps resulting in additional forces on the pin joints [12, 13]. This additional force leads to wear debris formation and early failure (~105 cycles) in the majority of polysilicon microengines tested at 1720 Hz [14]. To fully analyze the wear resistance of tungsten coated MEMS devices, the underlying surfaces exposed to rubbing and impact need to be characterized.

Focused ion beam (FIB) systems are extremely valuable tools in the failure and yield analysis of MEMS devices [15, 16, 17]. 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 up sticking or seized microengines. In some instances, the FIB can be used to remove portions of the device to enable the analysis of otherwise inaccessible areas [17].
We have used the FIB system extensively in the evaluation of the amount and location of wear debris formed during the operation of microengines. [15, 17] FIB cross sections have revealed debris located throughout the pin joint and hub regions of polysilicon fabricated microengines [15]. The tungsten-coated gears illustrated in Figs. 6a and b were FIB cross-sectioned to examine the exposed but hidden surfaces along the hub and pin joint. FIB cross sectioning these regions did not reveal wear debris or wear tracks occurring in microengines stressed to (a) 2 million, (b) 379 million, and (c) over 1 billion cycles. The residual material present along the hubs and pin joints was identified as silicon. Redeposited silicon occurred as a result of higher ion beam doses used to penetrate the tungsten film. After penetrating the film, the Ga⁺ ions sputtered the polysilicon, which redeposited along the hub and pin joint areas. Modifications have been made to reduce the dose used to penetrate the tungsten film and reduce the redeposition of polysilicon. This should provide cleaner cross sections of tungsten coated MEMS devices.

Atomic force microscopy was used to analyze the rubbing surfaces along hub and pin joint regions of the microengines. As previously shown in Figs. 6 and 7, no wear was observed along the surface of the microengine, or on the rubbing surfaces revealed in cross section. AFM was used to examine the pin joint and hub regions on a microengine operated to 1 billion cycles without failure (Fig. 7). No wear tracks, wear debris, gouging, or signs of wear were observed. The surface roughness measured along the hub and pin joint regions matched the surface roughness measured on the top surface of the gear. This indicates either the surfaces were not in contact during operation, or the tungsten film prevented wear during operation.

Surface roughness measurements were also taken of a polysilicon microengine and compared to microengine deposited with tungsten. Results show the deposition of tungsten does not significantly impact the surface roughness of the microengine. Polysilicon microengines measured 7.8 nm of surface roughness, whereas tungsten coated microengines measured 9.1 nm of surface roughness, a ~17% difference. Even with a rougher surface, tungsten coated MEMS devices did not fail from wear of rubbing surfaces.

**Stressed at 2% RH and 1720 Hz**

Plan view SEM inspection of microengines operated at 2% RH reveal the presence of wear debris along the pin joint. As illustrated in figures 8a and b, by reducing the humidity to 2% RH, rubbing surfaces have begun to wear, producing debris along the pin joint region of a microengine operated to 2 million cycles. This microengine failed by seizing up at the pin joint. This was the result of accumulation of wear debris along the rubbing surfaces of the pin joint. Further analysis of the hub region did not reveal any wear debris or show any signs of wear.

Wear debris produced from tungsten coated microengines operated at 2% RH appear to have the same morphology as wear debris produced in polysilicon microengines operated in low % RH. The formation of wear debris and its morphology reveal a dependence of wear on surface micromachined microengines as a function of humidity as demonstrated in [9].
Stressed at 24% RH and 8300 Hz

Previous results have shown tungsten thin films are wear resistant at ambient laboratory conditions and 1720 Hz. By increasing the drive frequency from 1720 Hz (103,000 RPM) to 8300 Hz (500,000 RPM), microengines began to fail due to wear and fracture of the worn pin joint. This failure mode may be diagnosed as wear along rubbing surfaces, however, the pin joint motion of these microengines were much more erratic than those used at 1720 Hz. In addition to the clamping effect present at 1720 Hz, we have found that as the microengine drive frequency increases, the signals are not well matched to the dynamics of the rotating system [18]. This erratic motion can impact the sides of the pin joints and hub regions causing microengines to fail prematurely.

As illustrated in Figs. 9a and b, a microengine operated to 3,000,000 cycles failed by excessive wear and fracture of the pin joint. This is likely due to the characteristics associated with the 8300 Hz drive signal used to operate this microengine. This is evident in the preferential wear occurring along the pin joint area illustrated in Fig. 9b. Note the preferential wear along the top and bottom left and right corners.

**Electrical Failure Mode**

A surprising failure mode occurred in microengines operated at 24% RH and 1720 Hz. During the operation of these microengines, some electrostatic actuators failed. These failures occurred on microengines stressed to 570 million and over 1 billion cycles. This failure mode was identified by the severe physical damage occurring along the fixed and movable comb fingers. Using optical microscopy and SEM to characterize the failed regions, we found severe damage along the comb fingers and ground plane. As illustrated in Figs. 10a, b, c and d, damage along the actuators consists of tungsten delaminating from the comb fingers, and molten polysilicon. The optical images illustrated in Figs. 10a and b show some discoloration along the base of the fixed comb fingers. Figs 10a and c represent an actuator that failed after 570 million cycles. The comb fingers on the top surface reveal delaminated tungsten, while the bottom comb fingers and ground plane reveal melted (deformed) polysilicon. Figs. 10b and d illustrate similar defects on a microengine operated over 1 billion cycles.

Speculation into the failure mechanisms for this failure mode include comb finger contact to the ground plane, lateral contact of a movable comb finger to a fixed comb finger, electrical discharge by arcing across conductive (tungsten) asperities, or an electrical “spike” from the testing apparatus. No electrostatic discharge (ESD) protection mechanisms were implemented during handling or experimentation.

Electrical failure by out-of-plane displacement of the moveable shuttle is unlikely. No wear tracks or debris were identified along the hubs, pin joints or guides. No conductive particles were found along the ground plane or between the comb fingers during the experiment. The initial damage site is difficult to pin point, however the electrical short likely occurred by contact to the ground plane or electrical discharge of conductive asperities. In either mechanism a significant amount of power is dissipated from a very small area, which will damage the comb fingers and/or ground plane. The apparatus used to test the lifetime of these tungsten coated microengines consisted of 4 Pragmatic 2414A 20 MHz arbitrary waveform generator and a 4-

Figs. 9a and b. SEM micrographs of a tungsten coated microengine operated at 8300 Hz (500,000 RPM). Note the fractured pin joint and accumulation of debris in that region.
channel high-voltage amplifier. This particular amplifier was not equipped with a current limiting output. A short circuit or electrical overstress event would allow a large current to pass through the device.

CONCLUSIONS

**Stressed at 24% RH and 1720 Hz**

Depositing tungsten on surfaces of polysilicon microengines has resulted in improved lifetime by reducing wear along rubbing surfaces (under ambient laboratory conditions). The tungsten film is shown to be uniform, conformal, and free of defects [19]. By reducing the formation of wear debris, an increase in the number of cycles to failure by 2 orders of magnitude is observed. Wear by rubbing surfaces is no longer the dominant failure mode in microengines operated under these conditions, but a new failure mode of electrical overstress has been identified.

**Stressed at 2% RH and 1720 Hz**

Results from tungsten coated microengines tested in 2% RH reveal wear debris along rubbing surfaces. Polysilicon microengines operated in low humidity also show more wear debris at lower %RH than microengines operated at ambient or high %RH [8]. In each case, the polysilicon microengine failed by excessive wear of rubbing surfaces, causing the gear to seize up or the pin joint to fracture. In tungsten coated microengines operated at low %RH, wear of rubbing surfaces appears to be a dominant failure mode. This indicates that tungsten coated microengines are dependant upon humidity to eliminate wear of rubbing surfaces as a failure mode.

**Stressed at 24% RH and 8300 Hz**

By increasing the drive frequency used in accelerated lifetime testing of microengines, we have found that failure occurs from wear of rubbing surfaces. We believe this occurs as a result of erratic behavior of the pin joint motion. Primary terms such as dampening, resonance, and geometry are accounted for in the model based drive signals. At higher frequencies, 2nd or 3rd degree terms (such as dynamic friction) which may not have been factors at 1720 Hz may prove to be of greater concern at higher frequencies. By not taking into account dynamic friction, the motion of the pin joint at 8300 Hz lead to impact or severe rubbing.

**Electrical Failure Mode**

Microengines operated under 24% RH and 1720 Hz have revealed a novel failure mode. Although the dominant failure mode (wear of rubbing surfaces) has been reduced, failure by electrical overstress appears to be the next obstacle in tungsten coated microengines.

**FUTURE WORK**

Further studies evaluating the reliability of tungsten coated microengines in humid and dry environments will be conducted. Optimization of drive signals for ultra-high accelerated testing will improve the speed and efficiency that microengines can be tested. Also, identification of the chemical constituents comprising the wear debris produced at low (and possibly high) %RH will reveal if the debris is only tungsten, tungsten and silicon, oxidized silicon, oxidized tungsten, or a tungsten and silicon hybrid (silicide). Also, further analysis of the electrical failure to isolate the root cause will help evaluate the reliability.
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REFERENCES


