Tools and Techniques for Failure Analysis and Qualification of MEMS

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Abstract

Many of the tools and techniques used to evaluate and characterize ICs can be applied to MEMS technology. In this paper we discuss various tools and techniques used to provide structural, chemical, and electrical analysis and how these data aid in qualifying MEMS technologies.

1. Introduction

MEMS are a unique set of electronic devices where much of the valuable information can be found by assessing the functionality of the device. To better understand a MEMS device, knowledge and insight into how the device operates and what function it serves in the whole system is critical. Analysis of MEMS falls in one of three categories. These categories are:

- Structural/mechanical
- Chemical/materials
- Electrical

Proper analysis using structural, chemical, and electrical characterization tools will aid in determining how the device operates, what its primary function is (electrical), what materials systems are used to fabricate and/or coat the structure (chemical), and how to assess the physical geometries and how the MEMS device operates (structural) in the system. A variety of analytical tools and techniques adapted to MEMS FA will be shown illustrating how they can be used to assess these devices. The same tools and techniques used to diagnose and characterize ICs can be used to assess the functionality and materials properties of MEMS. Many of these tools and techniques have been described in previous reports that focus on IC analysis. Since MEMS are constantly changing, (i.e. developments in device design, fabrication and application), the toolsets discussed in previous reports may be used in a different manner to assess MEMS.

2. Structural Analysis

To properly assess the functionality of MEMS, the device must be powered and operated. Visual characterization and inspection using tools and techniques such as optical, electron beam, and ion beam microscopy help assess how a device functions, the root cause of failure, and qualify a device for operation.

Conventional analytical techniques that are based on optical beams, electron beams, or ion beams have proven to be most useful in discerning the root cause of failure and qualifying a device for application.

2.1 Optical Microscopy

As a preliminary measure for evaluating MEMS devices, bright field optical microscopy serves as an easy, cost-effective method for quickly determining the functionality and integrity of a device. Optical microscopy can provide an initial view of the device in regards to component design and geometry.

Other optical analysis methods such as dark field and Nomarski-DIC can give a general overview of how MEMS components are oriented (tilted, flat, etc). Optical microscopy in conjunction with electrical probing can yield information about device functionality and how the device interacts with other components on the die or in the system. This process is straightforward assuming the MEMS component or levels of the MEMS component are unobstructed. Other methods can be used to structurally analyze MEMS covered by other features or components (such as a capping layer or packaged die). Electrical probing can be conducted on the bond pads, or special fixtures can be made to work with packaged MEMS components to be powered and operated. These allow for dynamic analysis of the device, which helps in repeating a failure mechanism in the laboratory as well as surveying the device for qualification. An example of a failed microengine (microgear with orthogonally positioned electrostatic actuators) is shown in Fig. 1. Note the large quantity of worn material along the surface of the gear and the surface of the ground plane directly underneath the structural material as well as a broken pin joint used to rotate the gear.
Observation into the motion of MEMS is indispensable in evaluating their operation, measuring their resonance frequencies, and their interaction with other components. Many different systems designed to analyze in plane (2-D) and out of plane (3-D) motion are available. Such systems include: optical 3-D imaging methods based on laser interferometry, Mirau interferometry, speckle, micro-Moire, scanning laser Doppler velocimetry [1], high-speed photomicrography, and the newest method of 3-D imaging (DEEPVIEW) [2]. A comprehensive overview, showing results on ink-jet printheads, microturbine, microrelays and micropumps, is given in [1].

2.2 Interferometry

Interferometry is a technique that uses a monochromatic, coherent light source (typically a laser) projected onto a sample. A Michelson interferometer uses a 547 nm green light interference filter to analyze polysilicon MEMS structures. Green light is weakly transmitted through polysilicon, eliminating secondary fringes caused by transmitted light reflecting from the device. Interferometry is a particularly powerful tool used to measure mechanical properties (residual stress, curvature, and Young’s modulus) [3]. This tool can also be used to detect tilt or deflection of a sample. An algorithm used to convert linescan intensity (fringes) data along a device’s length into out-of-plane deflection versus position data will detail how high a component is deflected (within nm resolution) and at what angle the component is. This particular aspect is important if the degree of tilt a MEMS component is crucial to the successful operation of the device.

As shown in Fig. 2, an interferogram of micromirrors reveals local minima and maxima used to measure the deflection of the gold-coated polysilicon micromirror used in this experiment. Note some mirrors are tiled at higher angles than others. The variable tilt angles may be attributed to material prohibiting the mirrors from achieving full-tilt. For interferometry to give reliable results, the RMS roughness of the surface should be less than the expected amount of deflection.

Fig. 1. a) worn material on the gear surface, b) broken pin joint, c) focus on the ground plane exposing wear debris, d) focus on the gear revealing more wear debris.

Fig. 2. An interferogram of ten mirrors found in a micromirror array. Note the difference in fringe count and spacing along many of the mirrors. Fringe count indicates out-of-plane deflection.

2.3 Scanning Electron Microscopy
SEM is a very useful tool for characterizing and diagnosing mechanical, electrical, and chemical properties of MEMS components. The large depth of focus, high depth of field, wide range of magnifications, and minimal sample preparation make this a technique of choice for MEMS inspection and analysis. Characterization of device geometries can be analyzed with fine detail and structure. SEMs equipped with electrical feed through capabilities allow actuation of a device during examination. One drawback to using the SEM for MEMS analysis is the inability to see under multiple layers of mechanical structures and inadvertent motion of devices that use electrostatic actuation signals. Having the ability to tilt and rotate samples to large angles improves the ability to analyze MEMS components and assess their functionality. Devices with large areas and tight tolerances are very difficult to analyze and require other techniques to resolve lower levels obscured from view.

Aside from structural analysis, SEM imaging is also useful for determining the electrical continuity of MEMS under static (unbiased) and operating (biased) conditions. Static analysis can be performed for conventional structural characterization as well as electrical analysis. Electrical analysis under static conditions can be used to determine if a device is electrically shorted or floating. Dynamic analysis with appropriate electrical stimulus can be used to assess the functionality of MEMS components. By applying the proper electrical signals to the device, Voltage Contrast [4] or Resistive Contrast Imaging [5] techniques can be used to obtain electrical information from the device, where they are powered, and what function the powered components have. To determine electrical continuity, proper electrical connections and equipment are needed to operate the device. No special sample preparation is required to perform electrical analysis in the SEM. The only components required are electrical connections and feed throughs as well as the equipment needed to operate the device.

Other tools and techniques can be used in conjunction w/ SEM to provide localized chemical analysis (x-ray microanalysis) and will be discussed in the chemical characterization section of this paper.

Overall, SEM is a non-destructive imaging technique. The electron beam can induce motion on MEMS driven by electrostatic forces. However, MEMS devices can be operated after examination. Some carbon may be deposited on the imaged surface (raster burn) locally changing the surface properties. SEM can be destructive on IMEMS technology. IMEMS are susceptible to damage through the CMOS circuitry. Typical SEM damage to IC components (transistors, memories, etc.) can occur in IMEMS technology. Special care is taken to image at low energies so that damage is minimized along the CMOS regions. Examples of SEM analysis on MEMS in static and dynamic states are shown in Figs. 3 and 4.

2.4 Focused Ion Beam

Focused Ion Beam (FIB) systems are extremely valuable tools used to analyze design layouts diagnose failure mechanisms, and modify and/or repair structures in MEMS [6-8]. FIB systems use a focused beam of Ga\(^+\) ions (typically 25 – 50 keV) for precise material removal (by physical sputtering). The FIB provides the best method for producing clean cross sections of the area of interest in MEMS structures. Cross sections can be made of both large and small structures with submicron accuracy. This is particularly important when information about lower level structures (or substructures) is required without damaging the entire device. The only region affected by the FIB process is the...
region where the ion beam is exposed, and in regions in close proximity where sputtered material can potentially be redeposited.

In MEMS, cross sections of mechanical components can be made without disturbing other regions of the device. In FIB processing, strategic regions can be preferentially removed to allow inspection of lower level structures. Conventional cross-sectional analysis (potting, polishing, etc.) of released MEMS is extremely difficult to achieve without inducing failure and compromising the device. Fig. 5 shows a FIB cross section of a microgear revealing the lower levels of the hub and pin joint (connection between two orthogonal positioned actuators). These preferential FIB cuts can be performed along strategic regions of the device reducing the damage around other MEMS components while examining all layers and structures in the region of interest.

Other functional aspects of the FIB system make it an extremely valuable tool for MEMS analysis. Most FIB systems can preferentially etch, and deposit material with submicron accuracy. FIB systems have been used to perform circuit modifications by deposition of a silicon oxide insulator and tungsten or platinum metallization. The same types of circuit modifications can be made in MEMS technology to repair specific regions of the device or to lock down and make a structure immobile. The metal deposition capability allowed metal to be deposited between the two regions and make the device functional. The same process can be used to make a region non-functional, to electrically or mechanically isolate discrete features of the device. Newer FIB systems have been developed with both ion and electron beam columns. The addition of electron beam is used to image the cross sectioned region, eliminating the effects of ion beam induced damage during imaging. Other systems come equipped with probers or plucking systems to electrically stimulate or remove lamella from the device.

Another advantage of FIB analysis of MEMS is electrical feed-through capabilities for dynamic testing, modification, and analysis. Packaged devices can be inserted into an electrical fixture in the FIB. Electrical stimulation to the device during FIB analysis aids in analyzing different mechanical components by physically coupling and de-coupling them.

FIB processing offers many advantages for MEMS analysis; preferential cross sectioning, material deposition, device repair and modification, electrical stimulus, etc. One disadvantage of using FIB processing for MEMS is the permanent affects of FIB processing on the sample. Special care must be taken to ensure
sputtered material is not redeposited into critical functional areas of the device. FIB analysis is also a serial process. Considerable time and effort may be required for analysis of one sample. All other information should be attempted before applying this destructive technique.

2.5 Transmission Electron Microscopy

Transmission electron microscopy (TEM) can be used to characterize the morphology, crystal structure, and chemical composition (in conjunction with X-ray microanalysis) of MEMS structures. This technique will resolve grain structure, grain orientation, and grain size of materials used to fabricate a MEMS device. Thin films deposited on MEMS can also be analyzed for dimensional analysis and materials structure. The high-energy electron beam penetrating through the sample can be used to produce electron beam diffraction patterns. Electron beam diffraction aids in determining the crystalline structure of the sample in very localized areas. TEM is particularly powerful for MEMS analysis because of its high magnification and diffraction capabilities, but is under utilized because of sample preparation difficulties associated with a released device. However, other structural analysis tools such as the FIB greatly aid the TEM sample preparation process.

TEM samples can be prepared in either plan-view or cross-section. Either sample preparation method is difficult due to device motion during preparation. TEM plan-view specimens can be prepared using a replica-stripping technique. A thin section of poly-acetate film softened with a drop of acetone can be placed on the device then stripped to remove the MEMS component(s). The parts are then coated with a thin carbon film and transferred to a TEM specimen grid. The remaining polyacetate film is dissolved with acetone, allowing the MEMS components to rest on the carbon film supported by the TEM specimen grid. Cross section TEM specimens can be prepared using Gatan G-1 epoxy to impregnate the device, or using the focused ion beam and thinning from both directions. When using the epoxy impregnation method, a glass slide is typically glued to the surface to provide accurate measurements for cross-sectioning the region of interest. This method is time consuming and is destructive to the die. Cross sections can be prepared using a FIB. This technique is relatively straightforward; the region of interest is thinned down from the front and back to ~ 100 nm. The sample is removed using either a probe in the FIB to extract the sample and place it on a TEM grid, or by using a glass probe outside the FIB to remove the sample and place it on a TEM grid. A TEM cross section of a released microgear is shown in Fig. 6. Note the crystal structure of the gear, and the crystal structure of the thin film.

Information obtained using this technique will identify the materials structure. This may provide insight into how the device was fabricated as well as special coatings used to improve or enhance functionality. Information on surface coatings, bulk material, chemical makeup/composition, etc. can be obtained. This technique would be employed when materials properties aid in determining the function of the device. An example of electron beam diffraction is shown in Fig. 7. Here, a reference polysilicon MEMS structure (b) is compared to material found adhered to the edges of a tested polysilicon MEMS device (a). The initial speckled
ring pattern is typical of polycrystalline material. The diffraction pattern of the adhered material has a “halo-like” structure indicative of amorphous (non-crystalline) material. TEM is a destructive technique that requires considerable expertise, multiple samples, and access to a TEM. The device would no longer be able to function after TEM characterization. Techniques used in conjunction with TEM include x-ray and electron beam microanalysis (Energy Dispersive X-ray Spectroscopy ‘EDS’, and Electron Energy Loss Spectroscopy ‘EELS’), and electron beam diffraction. Microanalysis techniques will be discussed in the chemical characterization section.

Overall, TEM analysis of a MEMS component will offer insight into the materials properties and constituents used to fabricate and/or coat the device.

3. Chemical Analysis

MEMS devices may have added materials processes to improve device performance and functionality. Thin film processes may be used to improve functionality by; protection from wear, chemicals, harsh environments, increased sensitivity to certain chemical species, increased surface conductivity and other properties. The deposition of these films may determine the overall functionality of a MEMS device. Tools and techniques used to analyze materials can be used to assess these films. However, for thin film technologies, tools and techniques that are very sensitive to surface properties are needed. This section will describe some of the tools and techniques used to analyze the chemical constituents of thin films, materials contamination, foreign material, and bulk materials used to fabricate a MEMS device.

3.1 X-ray Microanalysis (EDS and WDS)

X-ray microanalysis measures the energy and intensity distribution of X-ray signals generated by the electron beam striking the surface of the specimen. The elemental composition at a point, along a line, or in a defined area can be easily determined to a high degree of precision (0.1 – 0.5 wt.%) [4]. Typical systems are used in conjunction with secondary or backscattered electron imaging, transmission electron microscopy, and focused ion beam imaging.

Various x-ray microanalysis techniques include EDS (Energy Dispersive X-ray Spectroscopy), and WDS (Wavelength Dispersive X-ray Spectroscopy). X-ray microanalysis can provide information on chemical compositions of surface coatings, foreign material, and bulk materials used to fabricate MEMS devices. Although both techniques are used to resolve characteristic x-rays from the sample, WDS has more sensitivity and higher resolution on the x-ray lines. Using EDS, the typical resolution as defined by FWHM (Full Width Half Maximum) is approximately 140 ev for Fe Kα. Using WDS crystal spectroscopy, the typical resolution for Fe Kα is approximately 6 ev. This high resolution enables detection of close proximity X-ray lines that EDS may not be able to separate. The technique is slower than EDS but offers higher resolution. In some instances, multiple crystals are needed for materials analysis, and analysis times may be long.

EDS detectors consist of a solid state device that discriminates between x-ray energies. The EDS detector measures the number of emitted x-rays versus the energy.

Fig. 7. Electron beam diffraction patterns of a) an amorphous material deposited on polysilicon, and b) polycrystalline silicon.
of the emitted x-ray. Although more limited in resolution than WDS, EDS analysis is often faster than WDS. The information obtained via EDS or WDS can be displayed in either graphical form or as a compositional map. Both techniques can resolve heavy and light elements. Light elemental analysis is limited to Be or in many instances, C and N. X-ray microanalysis is a non-destructive technique. No special preparation is needed to perform the analysis. Preparation may be required to reveal specific regions within the device for analysis.

3.2 Auger Spectroscopy

Auger Electron Spectroscopy, is an electron beam technique used to perform qualitative and semi-quantitative compositional analysis the surface of materials. The Auger technique is particularly powerful for thin film analysis. A beam of energetic electrons, 3 to 25 keV, is used to eject a core level electron from atoms on the surface of the device. To release energy, those atoms may emit Auger electrons from their induced excited state. The energy of the Auger electron, specific to the atom from which it originated, is measured and the quantity of Auger electrons is proportional to the concentration of the atoms on the surface. Auger electron spectroscopy can measure two-dimensional maps of elements on a surface and elemental depth profiles when accompanied by ion sputtering. Initial Auger electron emission occurs within the first 3-30 Å (1 – 8 atomic layers) from the surface. The addition of an ion sputter etch system, common to most modern Auger Spectroscopy systems, allows the user to generate depth profiles for interface and dopant profile analysis.

For MEMS applications, Auger is extremely valuable in determining the composition of surface material, contamination, or thin films. Auger analysis has been used to determine what material is present along the surface of a landing feature on various MEMS components. In other areas, Auger was used to determine what lubricating films were used on a sample to reduce stiction and improve reliability and performance.

3.3 Secondary Ion Mass Spectroscopy (SIMS)

SIMS yields compositional analysis of the sample with sensitivities in the ppm to ppb (atomic concentration range). In most cases, the surface of the sample is sputtered away by energetic ions and the compositional analysis of the material at the surface is collected. For time-of-flight SIMS analysis, a pulsed ion beam (Cs or microfocused Ga) removes molecules from the very outermost surface of the sample. Material removal is done with sufficiently low intensity to insure that the molecular chains emitted from the surface are not broken into their elemental constituents. The particles removed from the surface (secondary ions) are accelerated into a tube and their mass is determined by measuring the exact time at which they reach the detector. The exact masses can be calculated with such accuracy that particles with the same nominal mass (e.g. Si and C2H4) are easily distinguished from one another. The sensitivity and accuracy of this technique make it the technique of choice for surface analysis. Depth profiling of thin films, doping levels, and foreign material are easily analyzed. This technique is much more surface sensitive than most other surface techniques, and will work on very thin anti-stiction coatings such as self-assembled monolayers (SAMS coatings) or a variety of wear resistant coatings such as tungsten metallization, or amorphous diamond. Although this technique physically removes material from the device, it may or may not impact the functionality (based on where the examination is conducted). The area under analysis may have a small pit bored into it but the device will still function mechanically.

4. Electrical Analysis

Electrical analysis is usually performed at a probe station with appropriate electrical stimulus equipment. Electrical testing coupled with optical characterization allow dynamic analysis of the device in question. Depending on the platform and/or parts available (die or package) single or multiple devices can be tested in either series or parallel. Other tools and techniques have been developed to provide a stimulus and diagnose the response for failure analysis and defect localization.

4.1 Thermally-Induced Voltage Alteration (TIVA)

The application of thermally-induced voltage alteration to MEMS [9] presents some special opportunities for MEMS analysis. TIVA offers the capability of coupling structural analysis using infrared light with electrical stimulus to identify functional features. TIVA is particularly useful when MEMS components are covered with materials transparent to IR but opaque to conventional optical analysis. This technique has proven quite useful on silicon based MEMS technology. TIVA has been used to identify electrical failure modes not readily visible with electron or optical microscopy. IR analysis of a polysilicon device will reveal underlying layers not visible with optical microscopy. The addition of an electrical stimulus allows dynamic analysis of these underlying components without the removal of the obstructing components (which would alter device functionality).
To date, this technique has been utilized to identify electrically failed regions in MEMS structures where powered components have been shorted. MEMS are particularly suited to this technique since most devices are fabricated in an electrically open state. The environment surrounding the device acts as an insulator. Thermally isolated structures get hotter than devices with interconnects. The shorted regions act as thermocouples, which provide the signal for TIVA analysis. By monitoring the voltage (when held at constant current), changes in the voltage of the power supply are analyzed and correlated to a reflected light image. As shown in Fig. 10, a reflected light image of a shorted electrostatic comb drive is compared to a TIVA image of the same area. The resolved failure mechanism was a bottom level comb finger shorted to the substrate.

This technique is well suited to bulk and surface micromachined technologies that use silicon as the base material. An added benefit of TIVA analysis for MEMS is that most MEMS do not have active electrical junctions in the immediate region i.e., no Si diffusions. With these particular MEMS structures, there is no concern about photocurrent (electron-hole pair recombination) effects swamping out the TIVA signals. Therefore, shorter wavelength lasers can be used for TIVA analysis and offer improved spatial resolution and noise reduction. The improved spatial resolution can also be seen in the reflected light images used for comparison.

4.2 Resistive Contrast Imaging (RCI)

Resistive Contrast Imaging (RCI) can be employed to analyze a wide variety of MEMS technologies. This technique performed in the SEM generates a relative resistance map between two test points of an IC or MEMS device. If a resistance change occurs along a conductor linked to the test points, (such as an open conductor); the RCI image will display an abrupt contrast change at the open site [8]. As illustrated in Fig. 11a and b, the SEM and RCI images show an RF MEMS switch with the contact structure, bond pads, and actuation pads. By biasing across the two bond pads, the actuation pads should have a continuous contrast as the bond pads if it is electrically active. As shown in Fig 11b, the actuation pads should be at the same contrast level. The open actuator (right) shows no contrast. Further analysis revealed a break in the metal where it intersects the bond pad. One drawback to using this technique is the information obtained from the sample is from the material that interacts with the electron beam. Biased areas that do not interact with the beam will not be visible for RCI analysis.

5. Conclusions

Various tools and techniques are available for failure analysis and device qualification at the structural, chemical, and electrical analysis levels. Although many of the tools and techniques described in this paper were leveraged from the IC industry, several more tools and techniques are needed to identify application specific failure mechanisms. Non-destructive failure identification is crucial in many MEMS components. Current analysis and characterization techniques are destructive and require care to not compromise the failure mechanism. Multi-functional analytical tools able to operate several samples in parallel and extract structural, chemical, and electrical information at the same time will be required in the near future.

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7. References


Fig. 11. a) SEM image of an unbiased metal contact switch shows non-uniform contrast between the actuation pads. b) RCI image of an unbiased device reveals the left actuation pad has electrical continuity to the anchor is observed, while the right actuation pad is not electrically connected to the anchor.