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FRACTURES AND FAILURE ANALYSIS IN MEMS

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Abstract: **Design and reliable operation of Microelectromechanical systems (MEMS) depends on the material parameters that influence the failure and fracture properties of brittle and metallic thin films. Failure in brittle materials is quantified by the onset of castarophic fracture, while in metal, the onset of inelastic deformation is considered as failure as it increases the material compliance. This dissertation research developed new experimental method to address three aspects on failure response of these two categories of materials: (a) the role of microstructure and intrinsic stress gradient in the opening mode fracture of material which includes sharp pre-cracks in amorphous in poly crystalline brittle thin films, (b) the critical conditions for mixed mode I/II pre-cracks and their comparison with linear elastic fracture mechanism (LEFM) criteria for crack initiation in homogeneous materials, and (c) the strain rate sensitivity of textured monocrystalline Au and Pt films with grain sizes of 38 nm and 25 respectively. One of the technical objectives of this research was to develop- experimental and tools that could become standards in MEMS and thin film experimental mechanism. In this regards, a new method was introduced to conduct mode I and mixed mode I/II fracture studies with micro scale thin film specimens containing sharp edge pre-cracks. The mode I experiments permitted the direct application of LEFM. On the other hand, the newly introduced mixed mode I/II experiments in thin film were conducted by establishing a new protocol that employs non-standard oblique edge pre-cracks and a numerical analysis based in the stress intensity factors.**

Keywords: **Mems- micro electro mechanical devices, castrophic fractures, failure responses, linear elastic fracture mechanism (LEFM), farctures analyses of thin flims.**

NOMENCLATURE

- Ø linear elastic fracture mechanism (LEFM),
- Ø bill of material (BOM)
- Ø Digital Micromirror Devices (DMD)
- Ø Focused Ion Beam (FIB)
- Ø low-pressure chemical vapor deposition (LPCVD)
- Ø poly methyl meth acrylate (PMMA)

I. INTRODUCTION

Microelectromechanical Systems (MEMS) are miniature devices comprising of integrated mechanical such as(levers, springs, deformable membranes, vibrating structures, etc.) and electrical (resistors, capacitors, inductors, etc.) components designed to work in concert to sense and report on the physical properties of their immediate or local environment, or when signaled to do so, to perform some kind of controlled physical interaction or actuation with their immediate or local environment. Some well-known examples of MEMS-enabled functionality in everyday life are airbag the accelerometers found in automobile which are deployment in automobiles; motion and orientation detection in smartphones; and blood pressure measurement in IV lines and catheters.

II. EVOLUTION OF MEMS

1. Why Is MEMS Important

MEMS is an innovative technology that, in one embodiment, generates continued, sustained improvements in, for example, the functionality of small microphones, small cameras, and small electrical signal filters for wireless communication. In its other, disruptive, embodiment, MEMS technology creates entirely new kinds of products, such as inexpensive, multi-axis inertial motion sensors useful for smartphone-based navigation, and Digital Micromirror Devices (DMD), arrays of MEMS micromirrors used for high speed, efficient, and reliable spatial light modulation in industrial, medical, telecom, security, and other applications.

2. History of MEMS

Harvey C. Nathanson (born October22, 1936) is an American electrical engineer who invented the first MEMS (micro-electro-mechanical systems) device of the type now found in consumer products ranging from cellular phones to digital projectors.

MEMS devices, which are made using integrated circuit fabrication techniques, are composed of small moving mechanical elements that generally range from 1 to 100 micrometres (0.001 to 0.1 mm) in size. Typical MEMS devices include the accelerometers found in automobile airbags and video game controllers, and piezoelectric mechanisms used in inkjet printers.

Nathanson conceived the first MEMS device in 1965 to serve as a tuner for microelectronic radios. It was developed with Robert A. Wickstrom and William E. Newell atWestinghouse Research Labs in Pittsburgh, PA., and patented as a Microelectric Frequency Selective Apparatus.

A refined version of the device was subsequently patented as the Resonant Gate Transistor.

In his work developing similar devices, Nathanson pioneered a method of batch fabrication in which layers of insulators and metal on silicon wafers are shaped and undercut through the use of masks and sacrificial layers, a process that would later become a mainstay of MEMS manufacturing.

In 1973 he patented the use of millions of microscopically small moving mirrors to create a video display of the type now found in digital projectors.

In 2000 Nathanson was awarded the Millennium Medal by the Institute of Electrical and Electronics Engineers for "outstanding contributions to the Society and to the field of electron devices."

A graduate of Carnegie Mellon University, he holds more than 50 patents in the field of solid-state electronics.

3. What Is The Current Scenario Of MEMS

The potential benefits of doing so? Creating “The marvelous biological system.” “Miniaturizing the computer.” Deploying “a hundred tiny hands” for a world in which we are “Rearranging the atoms.” In one sense, MEMS industry.From those very early days and origins, MEMS has enjoyed classic hockey stick growth: i.e. a dramatic increases in sales revenue or unit shipment growth over time that started at a normal, linear pace from the 1960s through to the 1990s, hit an inflection point and took off in the 2000s, and sustained its considerable momentum into the 2010s, fueled by such MEMS-enabled killer apps as the Nintendo Wii, the Apple iPhone, Bosch airbag systems, Epson ink jet printheads, microphones from Knowles Electronics, and blood pressure sensors from Acuity, Merit Sensor, and others.

4. What Is the Future of MEMS

The future of MEMS is rich with commercial possibilities, including the trillions of MEMS sensors envisioned to be used as the eyes and ears of the Internet of Things (IoT); the future of MEMS also includes local MEMS-based environmental monitoring devices; deployments in the MEMS-enabled quantified self movement and in personalized medicine applications; MEMS-containing wearables; and MEMS-reliant drones and other small personal robots.

5. Why Do We Choose MEMS

The compelling reasons why thousands of OEMs have successfully chosen MEMS devices to sustaining innovation and disruptive innovation business models include these: MEMS-based solutions yield product cost advantages for a given functionality; Employing MEMS devices usually results in a reducing cost for a given product, MEMS components typically demonstrate less power consumed per a given function than do other, macro-based solutions. The fact that MEMS devices knowns for its product reliability.

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III. INTRODUCING MEMS IN FRACTURE AND FAILURE ANALYSIS

Experiment with thinner films can be instructive about the mechanisms of deformation. In surface micromachining, a silicon water acts as a supporting structure for the deposition, pattern forming, and removal of individual surface layer with the help of intermediate sacrificial layers. A typical surface micromachining process is presented below

Different processing methods and conditions used in MEMS fabrication result in different microstructure, internal and residual stresses, defects which affect significantly the overall mechanical behavior of the material.

1. Reliable Material which is implied for the fabrication

The material used in MEMS fabrication could be ceramics, metals or polymers. Brittle materials are used most commonly owing to their high stiffness and thermal stability as well as their resistance to environmental conditions. Brittle materials employed in MEMS components are single crystal silicon, polycrystalline, silicon, silicon nitride, silicon carbide and tetrahedral amorphous diamond like carbon (ta-C). Although brittle films possess stable mechanical properties required for most MEMS, their electrical and thermal conductivities are significantly inferior to metals even in their doped state. Additionally, metallic films produce large displacements at low power RF-MEMS. Metals such as gold, platinum nickel and aluminum are extensively used in MEMS. Polymeric materials, such as polyamide, SU-8 resist, etc.., are primarily used in conjunction with other brittle and metallic materials to provide flexible structures and channels in macro electronics and microfluidics but they lack self-actuation capabilities. This research focuses only on the mechanical behavior of brittle and metallic materials.

2. Objectives of Failures

Design of reliable thin film structures at the MEMS scale requires knowledge of the material constitutive and failure properties. Even though many complex systems have been built at the MEMS, scale there is still considerable lack of understanding and quantitative information about the material and structural response to mechanical loads. In addition to the operation failure (device station) and degradation in electro mechanical performance. Failures occur due to quasi-static overloads, mechanical wear, impact or dynamic loads and cyclic loading. Failure in polysillicon MEMS structure due to static overload.

3. Limitations While Fabricating

The motivation for this research stems from the lack of standardized experimental tools and methods to quantify about the effects of microstructure and intrinsic material deformation process (dislocation and grain boundary plasticity) on the mechanical behavior of brittle and metallic films used for MEMS. The custom nature of current micro fabrication requires the establishment of robust and accurate experimental methods for micro scale experimentation and testing. Changes in the fabrication parameters result in microstructural changes and those in turn cause different mechanical behavior. Therefore, bulk material properties cannot be applied to MEMS design. Furthermore, many of the materials fabricated for MEMS application do not exist or are not possible to fabricate in bulk form because they are fabricated layer-by-layer deposition rather than bulk processing. From an experimental standpoint, macro scale mechanical testing methods cannot be directly applied or scaled down to MEMS scale due to the small size of the specimens. Therefore, it is evident that major improvements and new work are required in this area of experimental capabilities and knowledge about MEMS materials. The methods presented here could be extended to any material system and potentially under variable temperatures with minor modifications to the experimental apparatus.

IV. STATE OF THE ART IN FAILURE AND FRACTURE OF THIN FILMS FOR MEMS

In this section, we discuss about the failure and fracture of thin films by making a distinction between brittle and metallic materials on the basis of failure initiation. Brittle materials are considered elastic and therefore their deformation and failure defer considerably from metals, which consist of elastic, and inelastic (non-recoverable deformation) response.As a result which results in cracks and failure.

V. FRACTURE EXPERIMENTS WITH BRITTLE FILMS

Designs of MEMS using brittle materials is conducted based on their tensile strength as failure is due to atomic bond breaking. In polycrystalline materials, fracture occurs because of crack initiation at a major defect inside a grain, or at the grain boundary, especially when their latter is also identified with a surface groove. Brittle material do not undergo plastic deformation and their fracture is sudden with catastrophic crack propagation.

This process leads to conservative design of device geometries, which also limits the performance of complex devices, common failure critical components in MEMS are slender structures, such as tether and suspension beams that that have cross section on the order of 2mm and are often designed to carry stresses of 1Gpa. The tensile strength of these components assumes a stochastic character, both because of the statistical flow distribution, and the local cleavage anisotropy. The simple application of Weibull probability density function to describe and potentially predict the probability of failure is limited to specific device geometries and flaw populations (related to surface area and volume under stress). Though the Weibull analysis of MEMS components failure has been extended to non-uniform geometries property and statistical analysis cannot efficiently take into account the effect of microstructure, i.e., inhomogeneity and individual grain anisotropy, because of the large scale calculations that are required. Thus, predictions are limits to homogenous materials and structures in which there is statistical homogeneity of flaws and grain orientations.

In this regard fractures studies using sharp cracks of controlled orientation and length eliminate the stochastic contribution of random flaws and focus on the statistical distribution of local toughness. Such information derived from boundary force measurements, although mediated by the effect of material inhomogeneity in transferring stresses to a crack tip, still provide a measure for the fracture toughness distribution measurements do not provide a unique value for the intrinsic property of a material, it becomes pretend to measure the effective fracture toughness in brittle polycrystals and employ it as a failure criterion. Given that the flaw size and orientation is completely determined by the presence of a dominant pre-crack, the applied far-field stress can be described in terms of Weibull statistics. This can be also understood by the simple argument that even if fabrication processes are significantly improved to remove surface and sidewall roughness, the measured strength will still have a unique value for fracture toughness and theoretical strength in the absence of surface and internal flaws.

Several techniques have been developed to obtain the material critical stress intensity factor, K_{IC}, from MEMS scale specimens with thickness smaller than 10µm. Fan et al estimated the fracture toughness of LPCVD silicon nitride by using tensile residual stresses to load micro-bridges containing notches with finite radius of curvature. Using a similar approachs we,obtained estimates for polycrystalline silicon fracture toughness using MEMS test specimens with notches varying in radius from 1µm to tens of nanometers fabricated by a Focused Ion Beam (FIB). A similar procedure for notch preparation was employed in blunt crack to compute an estimate of the value of fracture toughness for various materials. The fore mentioned methods employed notches that resulted in a finite stress concentration and provide only an approximation for the fracture toughness. For polysilicon,The experiments showed that previously measured fractured toughness values from notches which has high estimates. Because of similar reasons, measurements performed by higher force of (6.2MPa)

The report on fracture toughness measurements using sharp pre cracks was to combined on-chip micro devices with pre cracks generated by indentation as reported . Then the fracture specimens were loaded with an assembly of comb drives for electrostatic actuation. The applied load at failure was calculated by finite element analysis of the entire device. The advantage of their method was in the use of a sharp crack that represents a real and sharp material defect. However, the complicated specimen geometry and the FE analysis required to compute the boundary conditions and fracture toughness make this method rather impractical and of limited accuracy as there is no independent measurement of the applied force on the sample. Also, electrostatic actuation requires materials that are conductive, which limits the applicability of the method to a few materials. More recently fracture toughness measurements on ta-C were performed to use Nano indentation and a model assuming a cylindrical shape for the crack tip plastic zone. An estimate of the energy release rate was derived from the acoustic energy released during crack propagation. Given the aforementioned methods for fracture in brittle thin films, a simple and accurate method is still required for fracture toughness experiments at the micro scale. This is one of the issues on brittle fracture addressed in this work.

Additionally, all previous studies employed a single specimen thickness assuming no dependence on film thickness. In fact this is justifiable for brittle films. In macro scale fracture experiments where the toughness is calculated from boundary measurements, the crack tip process zone determines the minimum specimen thickness needed to consider the measured as the size independent material property. For brittle films used for MEMS such as effect is expected to be rather insignificant. However this films are different from bulk because they are fabricated by low-pressure chemical vapor deposition (LPCVD), ion implantation, and other gaseous process that result in variation through the thickness stress distribution (thermal & lattice mismatch stresses) and microstructure. Such local variations can then be responsible for an unexpected mechanical behavior, which may be identified as specimen "size effect". Consequently, intrinsic and interface stresses developed during material deposition and post deposition treatments , material texture or phase transformations can be sources for dependence of K_{IC}, on film thickness. For instance, researchers reports.

that the fracture toughness of polysilicon thin films varied with the annealing temperature due to microstructural changes. On the contrary, the average effective fracture toughness of LPCVD polysillicon is independent of the material microstructure and that the material (not the local grain orientation or crystal organization) in the vicinity of a crack tip controls the effective toughness. The last statement will be shown to be incorrect by the results of their dissertation research. Other than these isolated results , there are no other studies available than consider various thickness in free standing thin films.

VI. THE ROLE OF MICROSTRUCTURE IN FRACTURE INITIATION IN BRITTLE FILMS

The effect of microstructure on the fracture process has not been accounted for experimentally for polycrystalline MEMS. At the macro scale, failure has been shown to be affected by the local crack tip stress field and the near crack tip microstructure. Based on a grain size and distribution of relative grain orientations, crystal anisotropy (for a crack tip located inside the grain) is expected to affect the local and effective fracture toughness. Recent experiments on polysilicon by Cho and Chasiotis have shown that a minimum of 15*15 grading in MUMPS polysilicon (i.e. Polysilicon fabricated by the multi user MEMS process offered by MEMSCAP Cronos in North Carolina) are required to consider the material as isotropic and homogenous. These measurements, obtained in by the AFM/DIC method are of relevance to uniform stress fields only. It is therefore expected that the elastic K-field will also be perturbed by local elastic anisotropy. In effect, the local stress distribution near the crack tip can be different from that predicted for a homogenous material that can be anisotropic. Therefore, a statistical distribution of the effective fracture toughness values is inevitable. A method that provides accurate measurements for sharp crack initiation, coupled with precise knowledge of the crack tip location could shed light into such statistical variations.

The aforementioned considerations are further exacerbated by the fact that natural defects and cracks are randomly oriented and loaded by both normal and shear tractions. Besides local anisotropy anyways leads to mixed mode loading conditions in the vicinity of a crack tip. Therefore, mixed mode I/II loading is common for planar MEMS. So far, the mixed mode I/II stress intensity factors (SIFs), K_I and K_{II} (Actually the spectrum of their values with respect to the pre-cracks angle, or mode mixity) are not available. One of the objectives of this dissertation is to understand fracture initiation in polysilicon under mixed mode loading.

Micro scale fracture experiments with MEMS scale specimens subjected to mixed mode conditions is significantly more challenging than purely mode I experiments. Most macro scale approaches are either very difficult or impossible to implement at the micro scale. At the macro scale edge cracked specimens have been employed to investigate mixed mode I/II fracture in brittle materials. Edge precracked specimen in asymmetric three and four point bending to measure the mixed mode SIFSs in alumina by controlling the asymmetry of applied bending loads. The mixed-mode SIFs were extracted by finite element analysis employing the interaction integral. The method of caustics to study the effect of mode mixed and crack length on the SIFs, K_I&K_{II}, in finite geometry poly methyl meth acrylate (PMMA) samples with oblique edge cracks. However in plane bending is not practical for free standing thin films that are never perfectly planar and have small bending stiffness and critical buckling load (in the absence of initial curvature). Therefore a different approach is needed at the research addressed the need for a mixed mode I/II fracture method and protocol for brittle films.which is illustrated below.

VII. STRESS INTENSITY FACTORS FOR VARIOUS MODES

Figure 1Two linearly independent cracking modes are used in fracture mechanics. These load types are categorized as Mode I, II, as shown in the figure.

Mode I, shown to the left, is an opening (tensile) mode where the crack surfaces move directly apart.

Mode II is a sliding (in-plane shear) mode where the crack surfaces slide over one another in a direction perpendicular to the leading edge of the crack.

Mode I is the most common load type encountered in engineering design.

Different subscripts are used to designate the stress intensity factor for the three different modes. The stress intensity factor for mode I is designated and applied to the crack opening mode. The mode II stress intensity factor, These factors are formally defined as

VIII. FRACTURE OF THIN FILMS WITH SHARP CRACKS

1. Develop and implement a protocol for conducting toughness experiments in micro scale brittle thin films with mathematically sharp pre-cracks and application of linear elastic fracture mechanics solutions.
2. Quantify the effect of grain anisotropy and polycrystalline inhomogeneity in thin film fracture by conducting fracture toughness experiments on polysilicon and amorphous ta-C films.
3. Investigate the influence of residual stress gradients on the effective fracture toughness of thin ta-C films as a function of film thickness.

IX. MIXED MODE I/II FRACTURE OF THIN FILMS WITH RELEVANCE TO MATERIAL MICROSTRUCTURE

1. Develop a protocol to conduct and conclude mixed mode I/II fracture experiments with sharp edge pre-cracks, coupled with finite element analysis, to measure the stress intensity factors K_I and $K_{II.}$

2. The result of mode I fracture experiments concluded that grain inhomogeneity in polycrystalline silicon was responsible for the larger scatter in effective fracture and toughness. Grain boundaries were found to be tougher by as much as 50% with respect to the smallest fracture toughness values in-grain crack tips, which was all most the as the smallest toughness values for single crystal silicon

3. Measure the mixed mode I/II fracture parameters of polycrystalline and amorphous (ta-C) films and compare them with theoretical predictions based on linearly elastic fracture mechanics. Identify the effect of polycrystalline inhomogeneity on the measured fractured parameters.

4. Useage is numerous many researchers proceeding their researches to modifiying its effects to achieve desired results and feasibility of the material.

X. CONCLUSION

There by We conclude and claim that, MEMS-based solutions yield product cost and competitive advantages for a given functionalityemploying MEMS devices usually results in a reduced BOM[bill of material] for a given product Parts which counts for MEMS-based products enables a more efficient supply chain The inherent compatibility of MEMS devices with CMOS electronics simplifies design cycles and speeds time-to-market MEMS components typically demonstrate less power consumed per a given function than do other, macro-based solutions The fact that MEMS device and product reliability is as good as any reliability can be – MEMS devices can be deliver to military / automotive / medical device-class reliability in rugged, real-world applications. It’s the biggest drawback that a larger unit or any bigger size devices has to placed if neglect MEMS in the fabrication In which MEMS resembles will incesases the commercial productivity and also retains the safety and conforts of mankind.

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