Reliability and Fatigue Testing of MEMS

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Abstract

Microelectromechanical structures (MEMS) utilize brittle materials such as polycrystalline silicon (polysilicon) under potentially severe mechanical and environmental loading conditions. These structures may be subjected to high frequency, cyclic loading conditions, accumulating large numbers of cycles in relatively short periods of time. Failure Analysis Associates has developed a technique for characterization of fatigue crack initiation and growth in MEMS materials. Preliminary results show that fatigue cracks can initiate and grow in polysilicon MEMS devices, and that water vapor is important in sub-critical crack advance. This research provides a basis for characterizing long-term durability and stability of micron-scale structures.

1. Introduction

State-of-the-art inertial guidance systems, airbag deployment sensors, and active control surfaces for aircraft integrate a variety of often brittle materials such as polycrystalline silicon (polysilicon) and nitride films under potentially severe mechanical and environmental loading conditions. These structures may be subjected to cyclic loading conditions with of kilo and megahertz frequencies, accumulating large numbers of cycles in relatively short periods of time. The application of thin films of materials such as polysilicon in safety-critical devices and structures represents a significant challenge for conventional bulk materials characterization and design approaches.

Macro-scale fatigue crack initiation and growth characterization techniques (Dowling 1996; Saxena and Muhlstein 1996) have developed largely due to the needs of the aerospace industry. The fracture and fatigue behavior of a variety of bulk ordered intermetallics and ceramics have been evaluated for potential aerospace and biomedical applications.(Evans 1980; Ewart and Suresh 1986; Dauskardt, Yu et al. 1987; Rao, Kim et al. 1995) These and related studies have established the importance of subcritical crack growth in brittle materials and design methodologies to mitigate the risks associated with placing such materials in service. Thin film polycrystalline silicon is one of the most common materials used in microelectromechanical systems (MEMS) to date. Consequently, the mechanical properties of this brittle material are critical to reliability and performance of MEMS devices.

Basic mechanical properties of thin films such as Young's modulus (E), Poisson's ratio (υ), and tensile strength are not completely characterized, and the applicability of standard test techniques and specimen geometries remain undetermined. Current studies have remained limited to "microtensile" testing (Sharpe, Vaidyanathan et al. 1996; Sharpe, Yuan et al. 1996; Sharpe, Yuan et al. 1997) and a variety of novel test structures.(Johansson and Schweitz 1988; Hong, Weihs et al. 1989) A similar lack of understanding is found in failure modes traditionally associated with long-term durability such as static and cyclic fatigue as well as time-dependent properties such as creep. With the exception a few investigators (Bhaduri and Wang 1983; Chen and Leipold 1986; Connally and Brown 1992; Connally and Brown 1992; Brown, Arsdell et al. June 16-19, 1997), subcritical crack growth in many MEMS materials remains unexplored and is a crucial issue which must be addressed. The anecdotal evidence from investigators who have resonated microdevices without noticing changes in performance must not be considered proof of long term stability.

This investigation sought to develop a specimen geometry and test structure for characterization of fatigue crack initiation in thin films and to use this geometry to explore fatigue crack initiation in polycrystalline silicon. Furthermore, the geometry developed during the course of this investigation was intended to be a standard technique which is both robust and amenable to a variety of materials and processing platforms.

2. Materials and Experimental Procedures

Fatigue crack initiation studies are typically conducted per the recommendations of ASTM E 466. This standard addresses appropriate specimen design and techniques for bulk metallic materials. In fatigue crack initiation testing, specimens are usually subjected to uniaxial, cyclic loads until the accumulation of a preselected plastic strain (i.e. 1%) or until complete separation of the specimen occurs. The mean and amplitude of the loading may be varied to probe various aspects of the material behavior and to reflect actual service conditions. The time to failure, or "life" of the specimen is then represented as a function of the range of applied cyclic stress or strain. Provided the specimen has been properly designed, this data may be used to estimate component life and to minimize the risk of fatigue failures.

Fatigue specimens must be designed to fail in the gauge section under well-defined loading conditions. Furthermore, material anisotropy, residual stresses, and processing limitations must also be considered. Finally, the actual service conditions of the engineering components must be considered to ensure the fatigue life data ma be used for remaining life predictions and engineering design. The extreme difference in scale between MEMS and conventional structural components is a significant barrier to material property characterization. Testing geometries must be MEMS-scale due to size effects related to the sensitivity of brittle materials to flaws. In addition, the geometry must minimize the effects of residual stress, be conveniently loaded, and carefully monitored. Consequently, the materials and processing constraints common to MEMS play an important role in the development of the specimens used in this study.

2.1. MATERIAL

Thin film polysilicon has been shown to display limited ductility (Sharpe, Vaidyanathan et al. 1996; Sharpe, Yuan et al. 1996; William N. Sharpe, Yuan et al. 1996; Sharpe, Yuan et al. 1997) and fracture toughness (Rybicki 1988) at room temperature. Due to the brittle nature of polysilicon, it is crucial that specimens reflect the loading conditions and scale expected in service, particularly because etching or release processes may cause variations in surface roughness that in turn affect strength and fatigue resistance.

The polycrystalline silicon tested in this study was manufactured at MCNC during runs 11 and 13 of the multi-user MEMS process (MUMPs). The nominally 2 μm thick polysilicon was deposited by low pressure chemical vapor deposition (LPCVD) in a three-layer polysilicon surface micromachining process. The specimen was fabricated from the POLY1 layer of the MUMPS process. Microstructural characterization studies of MUMPs polysilicon suggest that MUMPs polysilicon consists of approximately 0.5 μm diameter columnar grains which extend through the thickness of the film.(Koester 1997)

2.2. SPECIMEN GEOMETRY AND PREPARATION

The specimen geometry used for this investigation is the in-plane, resonant cantilever structure pictured in Figure 1. The specimen is fixed at the base of a short beam that is in turn attached to a large plate that serves as the resonant mass. Opposite sides of the plate include comb drive structures. One side is for electrostatic actuation; the other side provides capacitive sensing of motion. Applying an alternating voltage to the actuation comb drive at the appropriate frequency induces a resonant response in the plane of the figure.

A stress concentration is introduced in the beam through the mask set, as shown in Figure 1. The radius of the stress concentration and the remaining beam ligament were selected to ensure that the specimen could be broken immediately at resonance. The longer-term fatigue response can then be measured by exciting the specimen at some fraction of the short time breaking amplitude. It should be emphasized that the stress concentration presented here is used to investigate predominantly crack initiation. This geometry has been widely distributed and used on a wide variety of platforms including multiple polycrystalline silicon, single crystal silicon, and aluminum fabrication lines. Another similar device using a deliberately introduced crack is used to evaluate crack propagation.(Arsdell 1997) For many MEMS, the most relevant issue is initiation and not growth because once a crack has initiated it rapidly propagates to failure.

The 30 μm wide, 250 μm long cantilever resonant structure was nominally 2 μm thick. The specimen resonates in the plane of the figure, generating fully reversed (maximum load/minimum load = R = -1) loading conditions at the notch. The root radius and remaining ligament of the beam were selected to ensure that failures occurred within the gauge section, and that a representative volume of material was tested at the maximum stress amplitude. The cantilever beam geometry provided well-characterized boundary conditions not possible with multiply-supported structures. The on-chip device also ensured proper specimen alignment, well characterized loading conditions, and that data was representative of MEMS-scale structures.

The sacrificial oxide from the micromachining process was removed from the fatigue specimens using standard hydrofluoric acid release procedures. Devices were placed in 49% HF for 2.5 minutes followed by rinsing for several minutes in deionized water. The structures were then rinsed in alcohol and dried for 10 minutes in air at 110°C. Specimens were then die and wire bonded in ceramic dual inline packages (DIPs) to facilitate testing.

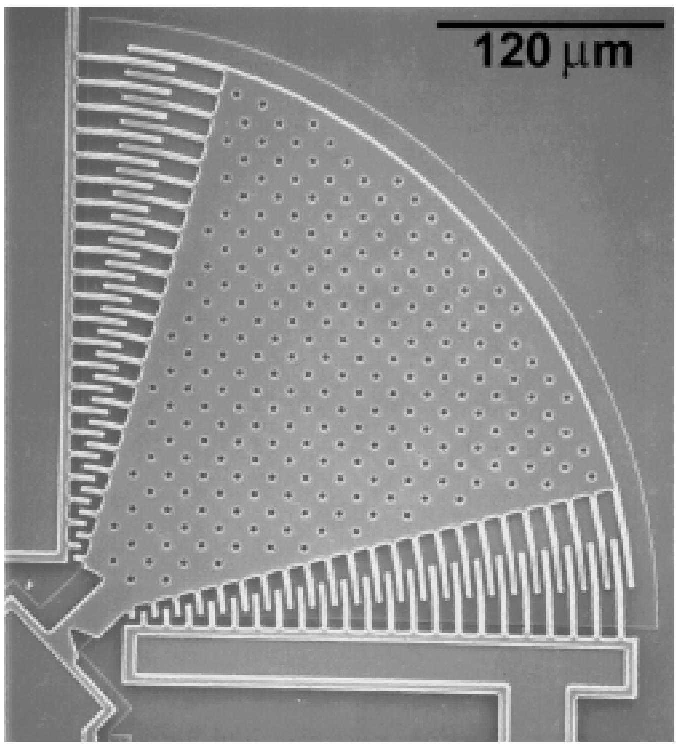

Figure 1. Fatigue crack initiation specimen.

2.3. TESTING METHODOLOGY

The device is driven at resonance using the following control scheme. The first mode resonant response of the specimen is determined by sweeping a range of frequencies around the expected response and monitoring the amplitude of response. The peak amplitude is selected by fitting a second order polynomial to the peak and extracting the maximum. The specimen is excited at the peak frequency at a defined excitation voltage for a period of time. The frequency response is then again evaluated by sweeping around the excitation frequency. Over time this permits measuring any change in resonant frequency and consequently any change in the mechanical response of the specimen.

Tests were conducted under controlled environmental conditions (27±0.1°C, 75 ± 1% relative humidity) and laboratory air until complete separation occurred at the notch. Specimens were allowed to resonate for 1 to 5 minutes followed by recharacterization of the resonant frequency. The notched beams were loaded with a sinusoidal wave form from 70 to 80 V_{rms} ± 1% at one half the resonant frequency (approximately 40 kHz). These conditions generated fully reversed (minimum load/maximum load = R = -1), constant amplitude loads at the notch. As stated earlier, changes in resonant frequency were monitored by sweeping the drive frequency ± 50 Hz and recording the amplitude response. The peak response from a given sweep was fit with a second order polynomial, and the maximum response was used as the drive frequency for the next test interval. Changes in resonant frequency may be correlated with accumulation of damage in the material or with changes in the dynamic response of the device due to accumulation of oxides, debris, and moisture. Furthermore, changes in the environment such as temperature and relative humidity may also effect the material and the dynamics of the device. The resonant frequency of the devices used in this study will decrease approximately 1 Hz per nanometer of crack growth.

3. Results and Discussion

The notched cantilever resonant specimens used in this study provided insight to the strength and fatigue crack initiation behavior of polysilicon thin films. Although the material exhibited high strength, the initiation of fatigue cracks is instrumental in the durability and stability of MEMS devices.

Figures 2 and 3 summarize the results of this fatigue crack initiation study. Seven constant load amplitude, fully reversed tests were conducted at 27 ± 0.1°C and 75 ± 1% relative humidity. Two devices stopped resonating, but did not fail at the notch. Six tests were conducted in laboratory air at ambient conditions on MUMPs-11 polycrystalline silicon. Load levels are normalized by the excitation level which resulted in immediate failure of the specimen.

These initial results show that fatigue is a critical issue for ensuring device reliability and stability. The typical decrease in device resonant frequency associated with accumulation of fatigue damage is shown in Figure 4.

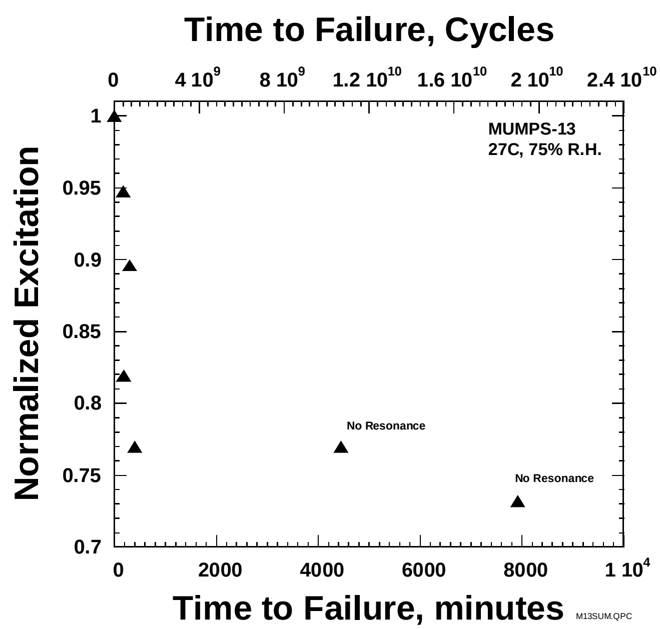

Figure 2. MUMPs-13 polycrystalline silicon fatigue initiation life at 27°C, 75% R.H.

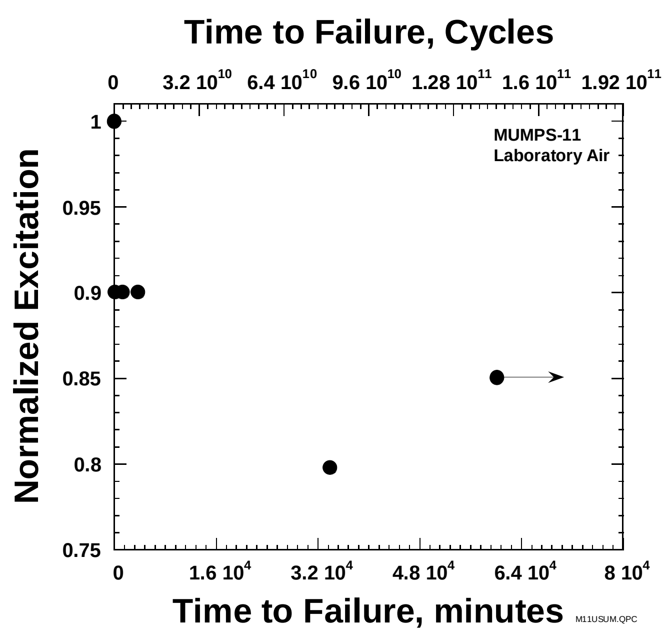

Figure 3. MUMPs-11 polycrystalline silicon fatigue initiation life in laboratory air.

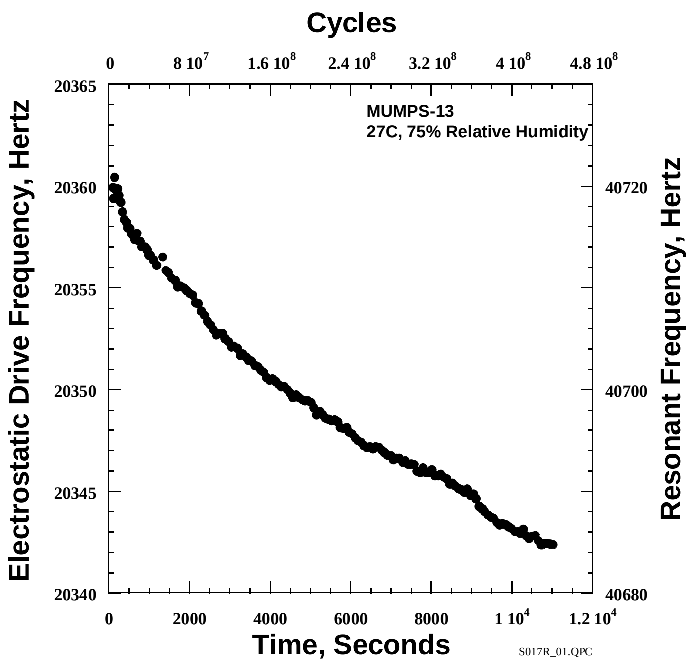

Figure 4. Change in resonant frequency of a MUMPs-11 polycrystalline silicon fatigue crack initiation specimen.

Testing of devices at progressively lower levels of excitation eventually leads to no short-term change in resonant frequency with time. This may represent a lower bound for initiation of fatigue damage in the material of interest. An upper bound strength and lower bound stable device response may be used to rapidly characterize the bounds for which fatigue damage is an important consideration. Changes in resonant frequency are intimately linked to the accumulation of damage in the polycrystalline silicon. Comparison of lives with uncontrolled laboratory air tests suggests that polycrystalline silicon device lives are shorter in moist air (Figure 5).

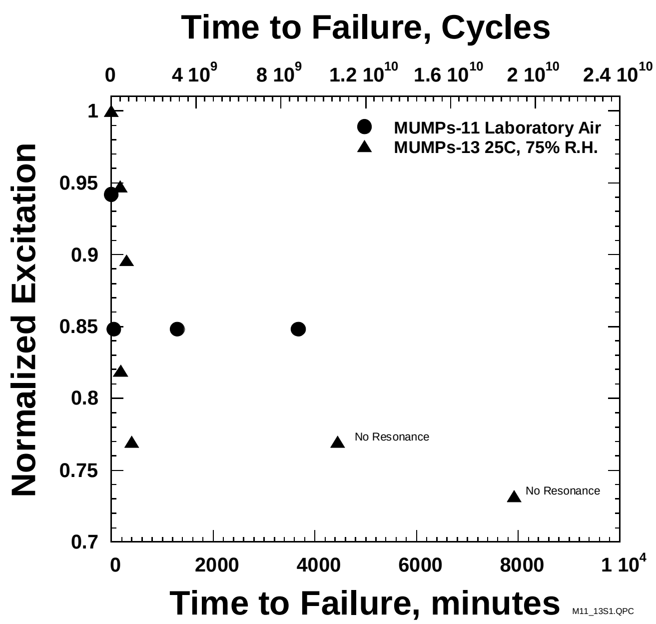

Figure 5. Effect of relative humidity on polycrystalline silicon fatigue crack initiation.

The dynamic response of the resonant fatigue structure is altered by changes in material and damping characteristics of the device. Consequently, it is important to monitor the frequency response of the device, not just the resonant frequency. Steady-state oxide layers are quickly formed on polycrystalline silicon exposed to laboratory air, and the effects of debris and moisture may be eliminated by providing clean, controlled testing environments.

4. Conclusions

This preliminary characterization of fatigue crack initiation in polycrystalline silicon provides information crucial to design of reliable, stable MEMS devices. Evidence of fatigue crack initiation under cyclic loading conditions in moist air. This study demonstrates the viability of MEMS-scale structures for fracture and fatigue characterization. This particular specimen geometry may be used for characterization of modulus, strength, fatigue crack initiation and growth, and fracture toughness. The geometry is applicable to conductive thin films amenable to standard IC photolithographic processing. This specimen and other micro and nano-scale test structures represent a unique platform for materials characterization and fundamental studies in both MEMS and traditional structural materials.

5. Acknowledgements

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