FATIGUE DAMAGE ACCUMULATION AND MITIGATION IN SILICON STRUCTURAL FILMS

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ABSTRACT

Although a wide variety of structural films have been developed over the past decade, silicon continues to maintain its position as the dominant material in microelectromechanical systems (MEMS). However, the limited damage tolerance of silicon leaves it particularly vulnerable to failure due to crack initiation and subcritical crack growth. Although it is well established that silicon thin films are susceptible to fatigue failure, the mechanistic origins are a topic of continuing investigation and debate. Recent investigations have attributed fatigue of heavily doped silicon films to the initiation and growth of cracks within a surface oxide layer that thickens due to the cyclic stresses. This "reaction-layer fatigue" mechanism suggests that control of the surface layer structure and service environment should be effective means of mitigating fatigue damage accumulation in silicon films. In this work we will examine our current understanding of the experimental support for and fracture mechanics analyses of the reaction-layer fatigue mechanism. Specifically, a series of controlled environment and surface morphology experiments have been performed using micromachined fatigue characterization structures and miniature tensile and fracture mechanics specimens. The fracture surfaces, microstructure, and surface morphology of the specimens have been analyzed with electron microscopy and surface analysis techniques. The relevant finite element analyses of the driving force for crack advance and failure criteria for reaction-layer fatigue of silicon films will be discussed in the context of these experimental results.

1 INTRODUCTION

The fatigue performance of microelectromechanical systems (MEMS) is a consideration for aggressive service environments and vibrational operation modes (e.g. a resonator). The room temperature susceptibility of silicon thin films used in MEMS has been well established via extensive stress-life (*S*/*N*) fatigue studies of polycrystalline silicon [1-7] and single-crystal silicon thin films[8, 9]. These studies have established that micron-scale silicon films can fail due to fatigue in ambient air at room temperature. However, how fatigue damage accumulates in these films has been a topic of vigorous debate. In this presentation we will examine our current understanding of the of the reaction-layer fatigue mechanism for silicon fatigue. A series of controlled environment and surface morphology experiments have been performed using micromachined fatigue characterization structures and miniature tensile and fracture mechanics specimens to investigate the underlying mechanisms of silicon film degradation. Analyses of the failed specimens, stress-life fatigue data, and numerical models of the damage accumulation process will be reviewed.

2 STRESS-LIFE FATIGUE OF SILICON FILMS

Over the past ten years, investigators have generated extensive stress-life (*S*/*N*) fatigue data for silicon thin films at room temperature (Fig. 1) [10-14]. In general, silicon films subjected to fully-reversed stress amplitudes less than one half of the fracture strength will fail after $\sim 10^{11}$ cycles [14, 15]. Critical crack sizes in these tests are typically 10's of nanometers in length and are found in components and films that are microns to tens of microns in size.

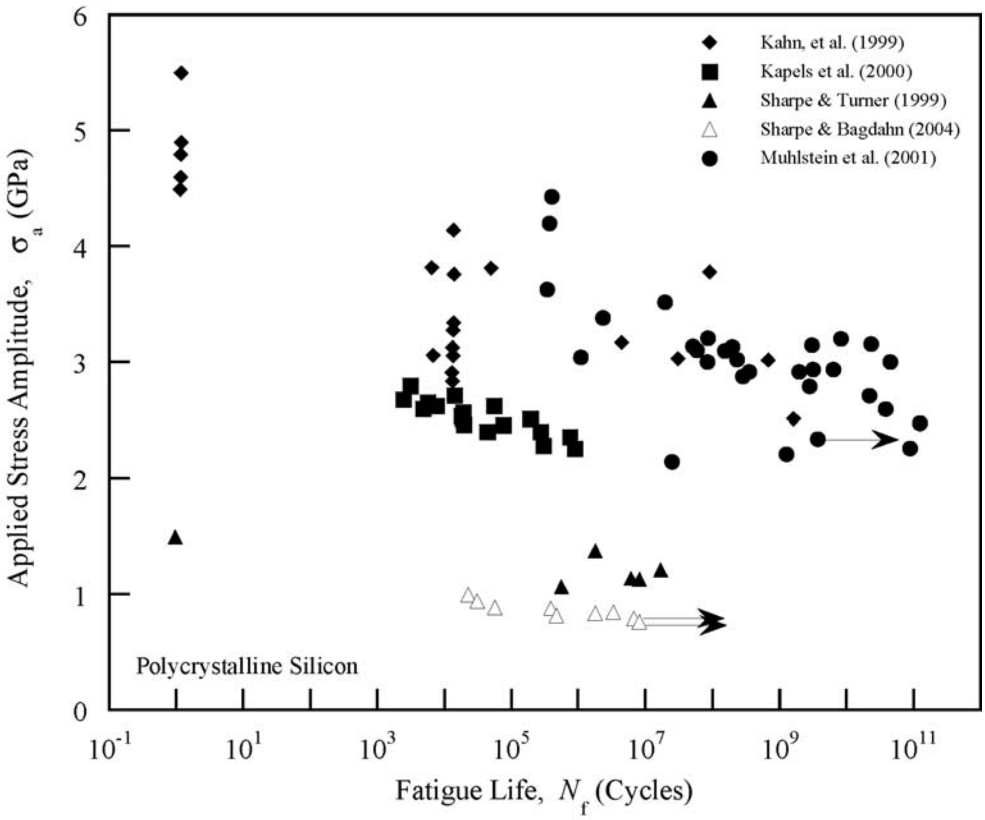

Fig. 1 Stress-life fatigue behavior of polycrystalline silicon thin films at room temperature.

In studies conducted by the author, the stress-life (*S/N*) fatigue behavior of “as released” and coated silicon films were determined using a ~300-µm square, surface micromachined fatigue characterization structure, as described in ref. [5] (Fig. 2). Briefly, the notched cantilever beam specimen (~40-µm long, 19.5-µm wide, with a 13-µm deep, ~1 µm root radius notch) is attached to a large, perforated plate-shaped mass and is electrostatically forced to resonate. On opposite sides of the resonant mass are interdigitated "fingers" commonly known as "comb drives"; one side is for electrostatic actuation, the other provides capacitive sensing of motion. The specimen is attached to an electrical ground, and a sinusoidal voltage (with no direct-current (DC) offset) at the natural frequency is applied to one comb drive, thereby inducing a resonant response in the plane of the figure. These conditions generate fully reversed, constant amplitude, sinusoidal stresses at the notch, i.e., a load ratio (ratio of minimum to maximum load) of $R = -1$, that are controlled to better than 1% precision with a resolution of ~5%. Specimens were cycled to failure at resonance (~40 kHz) in ambient air (~25ºC, 30-50% relative humidity) at stress amplitudes ranging from ~2 to 4 GPa using the control scheme detailed in ref. [5]. The change in resonant frequency during fatigue loading conditions has been correlated with fatigue damage accumulation in the structural silicon.

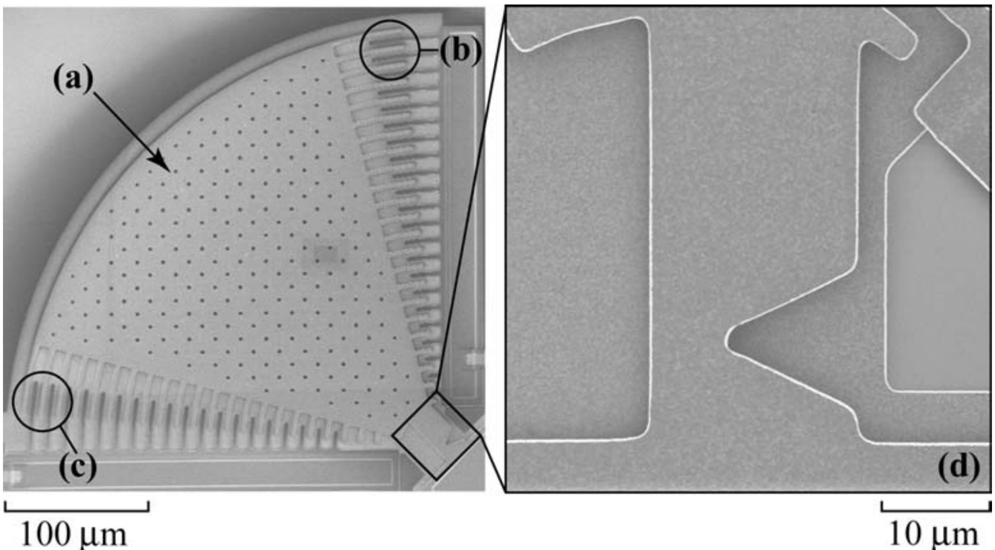

Fig. 2. Scanning electron micrograph of the fatigue life characterization structure and notched cantilever beam specimen used in this investigation. The (a) mass, (b) comb drive actuator, (c) capacitive displacement sensor, and (d) notched cantilever beam specimen (inset) are shown.

3 REACTION-LAYER FATIGUE

Researchers have attributed the mechanistic origins of the fatigue susceptibility of silicon films to two classes of mechanisms. Kahn et al. [2] have used experiments conducted on notched cantilever beams at large negative load ratios to suggest that fatigue of silicon occurs due to microcracking mechanisms observed in fatigue of bulk brittle materials. In contrast, Muhlstein et al. attribute the fatigue of silicon thin films to sequential, stress-assisted oxidation and environmentally-assisted cracking of the reaction layer which forms upon exposure to oxygen atmospheres through a process termed *reaction-layer fatigue*[7, 16]. This mechanism is supported by high-voltage transmission electron microscopy (HVTEM) images of fatigue-damaged polysilicon thin films that show thickened, cracked oxides at the notch root. In situ monitoring of the change in natural frequency of the fatigue characterization structure during testing was found to be consistent with quantified (using finite element modeling) damage evolution in the form of oxide thickening and subcritical crack growth within the oxide. Recent studies by Allameh et al. [17] and Shrotriya et al. [18] further suggest that under cyclic loading conditions the surface oxide layer on the silicon thickens and have highlighted the importance of the bimaterial configuration in the mechanistic understanding of how fatigue damage accumulates. Preliminary research by Bagdahn and Sharpe [19] further confirms the susceptibility of some silicon films to environmentally-assisted cracking and the presence of thickened oxide layers subjected to monotonic and cyclic stresses. The presence of the amorphous silica-silicon bimaterial system must be carefully modeled to understand how damage accumulates in silicon films.

Recent models developed by the author and his collaborators have further clarified how fatigue failures occur in silicon structural films. A series of 2-dimensional, plane strain finite element models were used to investigate the driving force for crack advance and the critical conditions for failure during reaction-layer fatigue of silicon films [20]. The finite element models

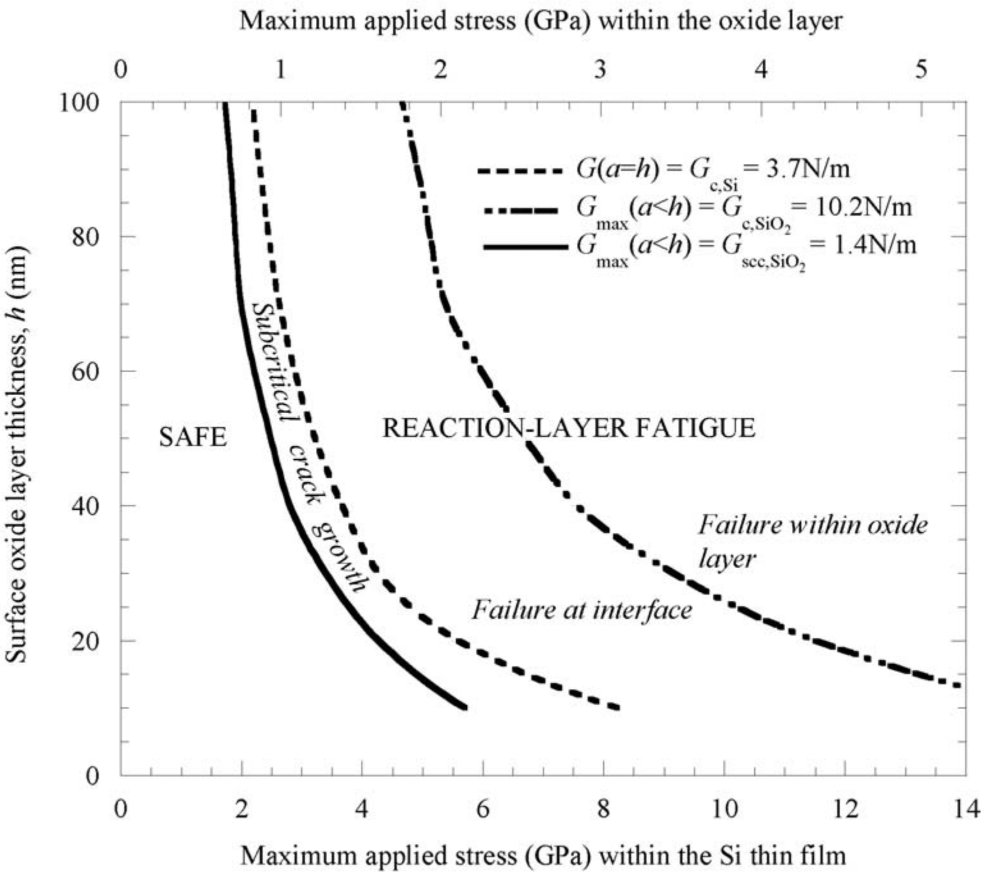

Fig. 3. Failure map for a 5μm silicon thin film, with oxide surface layer of thickness *h*.

developed in this study identify the driving force for advance of cracks from the earliest stages of initiation through to catastrophic failure. In contrast to previous analyses, which only considered failure due to cracks within the oxide layer, this work shows that a crack may initiate, grow subcritically within the oxide layer, and fail when only after the SiO_2–Si interface is reached. This additional failure mode significantly reduces the thickness of the oxide reaction layer that is required for the mechanism to lead to failure of silicon films. The model was used to create a failure map (Fig. 3) to identify the necessary geometry and loading conditions for reaction-layer fatigue of silicon films to occur.

4 MITIGATION OF SILICON FATIGUE

Provided that the appropriate manufacturing technique is available, surface treatments should provide a degree of protection against reaction-layer fatigue. In the case of silicon films, surface modifications that hinder the oxidation and stress corrosion of the native oxide should improve the fatigue resistance of material. Monolayer coatings such as 1-octadecene have been used by the author to suppress fatigue damage accumulation in silicon films [7, 21]. The change in specimen compliance clearly shows that the organic monolayer is affecting the damage accumulation process (Fig. 4).

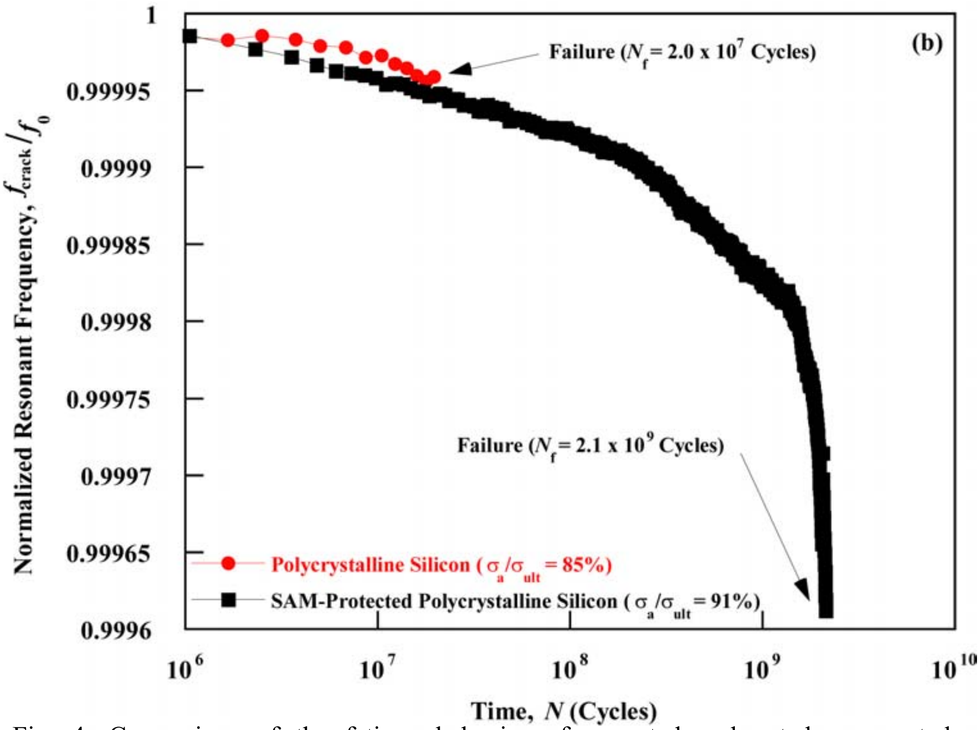

Fig. 4. Comparison of the fatigue behavior of uncoated and octadecene-coated, polycrystalline silicon thin films showing accumulated fatigue damage in terms of the change in natural frequency of the sample, f_{crack}, normalized by the natural frequency at the start of the test, f_0.

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