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Modeling of fatigue in polysilicon MEMS structures

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This paper presents an empirical approach to the modeling of fatigue in silicon MEMS structures. The approach is based on the regression analysis of stress-life data obtained from prior fatigue experiments on polysilicon and single crystal silicon. The possible directions for future modeling efforts are identified at the end of the paper, following a discussion on the implications of the current model fatigue life prediction. © *2003 Kluwer Academic Publishers*

1. Introduction

Polycrystalline silicon (polysilicon) is used extensively in a wide range micro-electro-mechanical systems where cyclic loading may induce sub-critical damage at loads that are significantly below those required for failure in one loading cycle [1–3]. These include applications in accelerometers and micro-switches [1, 2], where repetitive cyclic load may lead eventually to fatigue failure, especially in the presence of aqueous environments [4–15].

However, prior experiments have shown that bulk silicon does not undergo either static or cyclic fatigue processes [16, 17]. This is due largely to its inability to undergo plastic deformation by slip [18]. Hence, since normal fatigue generally requires the occurrence of partially reversible slip/deformation, bulk silicon does not undergo cyclic fatigue. Similarly, bulk silicon does not appear to be susceptible to environmentally-assisted static fatigue [18] due to crack-tip transport and chemisorption/reaction of chemical species such as water vapor.

Nevertheless, there have been a number of studies that have demonstrated the occurrence of fatigue failure in polysilicon deformed under cyclic loading in lab air with relative humidities between 40 and 80% [4–15]. These studies are reviewed in Section 2 of this paper before presenting empirical multiparameter models for the analysis of the measured stress-life data in Section 3.

2. Review of prior work

There have been a number of studies of fatigue in silicon MEMS structures [4–15]. The measurements of fatigue are reviewed in two papers by Sharpe [9, 11]. Two complementary emerging views on the mechanisms of fatigue are also presented in recent papers by Muhlstein *et al.* [15] and Shrotriya *et al.* [14]. These are summarized in this section along with the results of the stress-life measurements.

2.1. Measurements of stress-life behavior

The easy studies of fatigue in Si MEMS structures [4–11] have focused largely on the measurement of stress-life behavior. Following the initial studies of cantilevered structures by Brown and Connaly [4, 5], Brown *et al.* [6] developed inter-digitating comb-drive structures (Fig. 1) for the study of stress-life behavior. Following careful calibration schemes and finite element analyses, they presented stress-life data (Fig. 2) for notched specimens (Fig. 1). The studies by Brown *et al.* [6] showed that the total fatigue life was dominated by the crack "nucleation" stage. Furthermore, structures that were tested below 77% of failure amplitude stresses did not fail before the tests were stopped. The authors suggested a possible mechanism of native oxide fatigue.

Subsequent work by Van Arsdell *et al.* [7] has explored the influence of water vapor (relative humidity) on the fatigue behavior of polysilicon. Using changes in resonance frequency associated presumably with

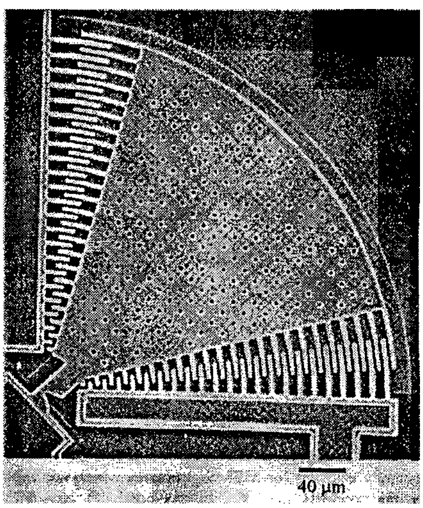

Figure 1 Comb-drive test structure of Van Arsdell *et al.* [7].

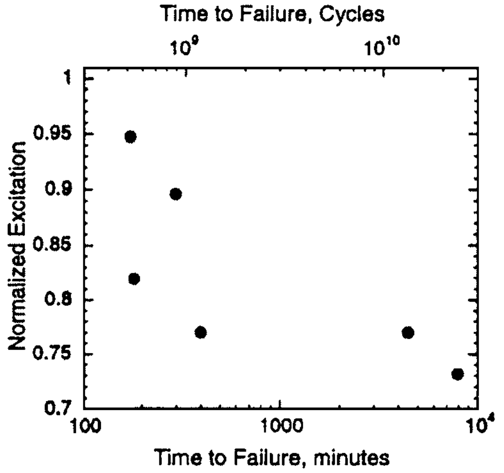

Figure 2 Stress-life plot of Brown *et al.* [7].

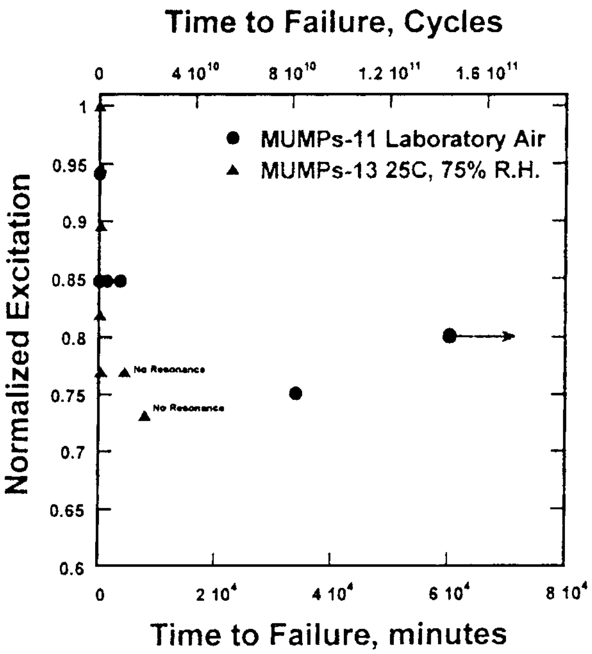

Figure 3 Effect of relative humidity on polysilicon fatigue.

sub-critical crack growth, they show that the fatigue behavior of polysilicon is strongly affected by changes in environment (Fig. 3). However, the mechanistic reasons for the measured changes in compliance (presumably due to crack growth) are yet to be established. These were presumed by Van Arsdell *et al.* [7] to be due to stress corrosion cracking in the topical silica layer that forms on unpassivated silicon surfaces during normal exposure to water vapor or air [2].

Kahn *et al.* [8] have also conducted detailed studies of fatigue on polysilicon test structures with inter-digitating comb drives. They use 1456 pairs of electrostatic comb actuators to generate enough force on the specimen during resonance at a cyclic frequency of ~20 KHz. Their specimen geometry is similar to that of Brown *et al.* [6]. However, it has a greater thickness, $t = 5.2\ \mu$m, compared to the test structure of Brown *et al.* [6], which has a thickness of ~2 μm. The results of the tests on B doped Si structures are presented in Fig. 4. As in the tests by Brown *et al.* [6, 7],

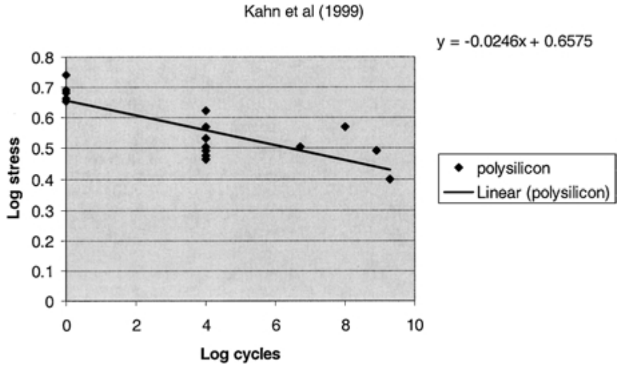

Figure 4 Stress life results of Kahn *et al.* [8].

the stresses were computed using finite element methods after obtaining displacement calibrations [8]. The results of Kahn *et al.* [8] show the usual form of the stress-life curve, for maximum tensile stresses greater than ~2.5 GPa.

The tests by Kapel *et al.*, [12] were conducted on polysilicon specimens 5 microns long, 0.7 microns wide and 4 microns thick. The actuating mechanism used was a thermal mechanism, and the loading frequency was kept at 1 Hz. As such, the life to the specimen is about 1 million cycles, and few orders of magnitude smaller than the other tests. The results of these tests are presented in Fig. 5.

Sharpe *et al.* [9–11] have also conducted fatigue tests on polysilicon MEMS structures. Similar to Kapel *et al.* [12], and unlike most of the above researchers (who use electrostatic comb-drive structures), they have used tensile specimens with uniform stress states to study fatigue behavior of polysilicon. They use a specimen similar to that developed by Tsuchiya *et al.* [19] to measure stress-life behavior. The specimens are glued to SiC fibers that are actuated with a piezoelectric system or a loud speaker (Fig. 6). The piezoelectric actuator has a maximum cyclic frequency of ~100 Hz, while the loudspeaker has a frequency response of ~1 KHz.

Sharpe and Bagdahn [12] present a review of their work, and prior work by other researchers. The results of Sharpe and Bagdahn [12] are presented in Fig. 7. These show the usual dependence of stress on fatigue life. However, the results also exhibit some scatter, and the measured fatigue lives are generally much lower than those reported by Brown *et al.* [4–7] and Kahn *et al.* [8] (~10^6 cycles).

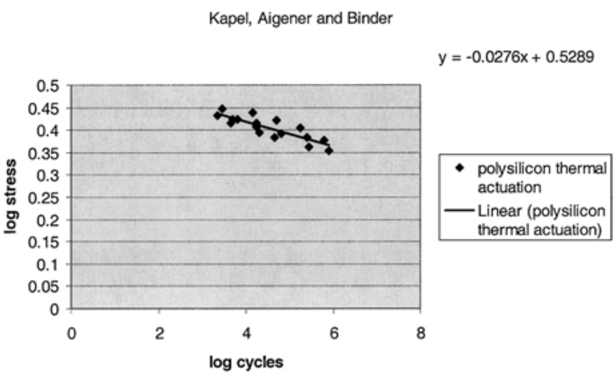

Figure 5 Stress-life results of Kapel *et al.* [12].

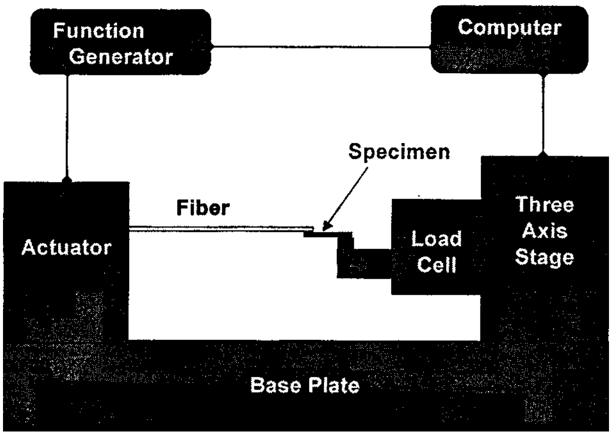

Figure 6 Schematic of the fatigue testing system of Sharpe *et al.* [9–11].

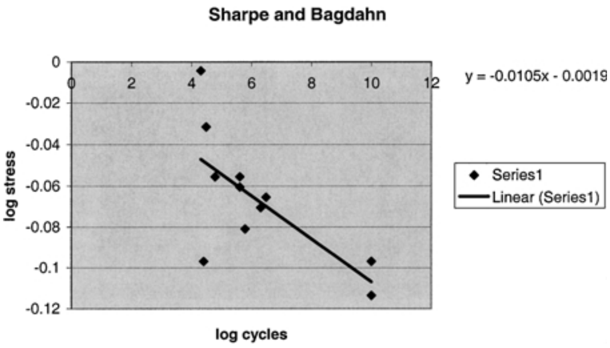

Figure 7 Stress-life behavior reported by Sharpe and Bagdahn [11].

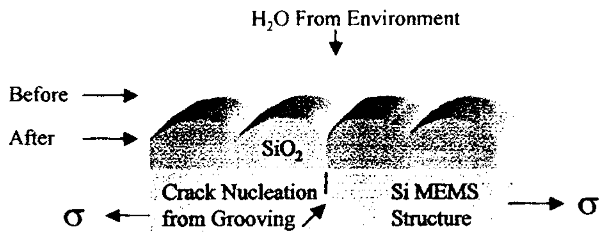

Figure 8 Schematic of possible fatigue crack nucleation mechanism in Si MEMS structures.

More recently, careful experiments have been conducted to study the physics of crack nucleation and propagation in silicon MEMS structures [13, 14]. Two complementary viewpoints have emerged form work by Muhlstein *et al.* [13] and Shrotriya *et al.* [14].

The studies by Shrotriya *et al.* [14] have shown that the surface topography does evolve (surface roughening occurs) during the cyclic loading of comb-drive polysilicon MEMS structures developed by Brown and co-workers [4–7] (Figs 1 and 8). This has been confirmed in prior studies by Shrotriya *et al.* [14] using in-situ atomic force microscopy (AFM) techniques. However, the possible transition from evolving surface roughness (on the SiO_2 layers that form on the surface of polysilicon during normal exposure to lab air) to a fatigue micro-crack (Fig. 8) is yet to be demonstrated.

In a complementary study on the same type of structures developed by Brown and co-workers [6, 7], Muhlstein *et al.* [13] have shown that the SiO_2 layer on the polysilicon can develop microcracks during cyclic fatigue loading. They, therefore, attribute the subsequent propagation of such cracks to stress corrosion cracking phenomena that have been shown to occur in silica glass in prior work by Wiederhorn [17] (Fig. 9). Further work is clearly needed to establish the relative contributions from surface roughening and sub-critical crack growth to the overall fatigue life. This remains a challenge for future experimental studies of fatigue in silicon MEMS structures.

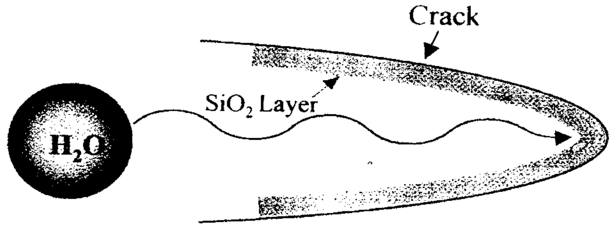

Figure 9 Schematic of crack growth by stress corrosion cracking.

Nevertheless, it is still possible to explore empirical approaches [6–12] and perturbation analysis approaches [14] to the prediction of fatigue in such structures. Such methods could provide some useful engineering estimates until more robust mechanism-based models emerge from ongoing work. Empirical stress-life and multiparameter approaches will be presented in Section 3 before discussing non-linear perturbation models for the prediction of surface roughening in Section 4.

3. Stress-life and multiparameter approaches

The empirical approach to fatigue relies on the use of stress-life or strain-life curves for the prediction of fatigue life [16]. Depending on the number of cycles to failure, the problems are often characterized as low-cycle fatigue (LCF) are high-cycle fatigue (HCF) problems. However, the distinction between LCF and HCF can be somewhat arbitrary, depending on the number of cycles that is chosen to represent the transition between LCF and HCF. In any case, for cyclic deformation in the elastic regime, Basquin's law [20] has been shown to provide a good fit to experimental data. Similarly, for elastic-plastic deformation, the Coffin-Manson law [21, 22] is used widely in the estimation of fatigue life.

In recent years, Soboyejo *et al.* [23] have shown that stress-life (S-N) curves can be fitted to empirical expressions of the form:

$$SN_{\mathrm{f}}^{\alpha} = \beta \tag{1}$$

where S is the applied stress parameter (stress amplitude or stress range), N_{f} is the number of cycles to failure, and constants α and β are constants, which may vary somewhat with microstructure and other key variables that affect the fatigue life.

The stress-life measurements presented in Section 2 have been fitted to Equation 1 using regression analysis. The results of the analysis are shown in Table I. These show clearly that Equation 1 provides a good fit to the measured data, reported previously in the literature [6–12].

TABLE I Summary of fatigue parameters

Source of data	α	Log β
Brown *et al.* [6]	−0.0425	0.3105
Kahn *et al.* [8]	−0.0246	0.6575
Sharpe and Bagdahn [11]	−0.0105	−0.0019
Kapel *et al.* [8]	−0.0276	0.5289

The values of the exponent, α, range from ~-0.0105 to ~ 0.0425. Typical values of α for conventional metallic materials are ~ 0.5 [21–23]. The S-N curves for the MEMS structures, therefore, exhibit relatively flat profiles, compared to those of conventional metallic materials. Similarly, the values of log β are somewhat different from typical values reported for conventional metallic materials, which have values of β of ~ 1. The values of log β in the study are between ~-0.0019 and 0.3105. These correspond to values of β between ~ 0.996 and 3.380. The current work, therefore, suggests that the empirical constants for Si MEMS structures are significantly different from those reported for conventional metallic materials. In any case, Equation 1 provides a simple expression for the estimation of fatigue life that can be applied to Si MEMS structures.

However, in most cases, the fatigue life of a MEMS structure is also dependent on specimen thickness, t, cyclic frequency, f, the relative humidity or partial pressure of water vapor, p, and the microstructure [4–15]. In such cases, a multiparameter approach is needed for the prediction of the combined effects of multiple variables. One simple form of the multiparameter expression is:

$$N_{\mathrm{f}} = \alpha_0 \sigma^{\alpha_1} t^{\alpha_2} \tag{2a}$$

or

$$\log N_{\mathrm{f}} = \log \alpha_0 + \alpha_1 \log \sigma + \alpha_2 \log t \tag{2b}$$

where α_0, α_1 and α_2 are constants, and the other variables have their usual meaning. Note that in this case,

TABLE II Summary of specimen dimensions

	Specimen dimensions		
Source of data	Width (μm)	Thickness (μm)	Area (μm^2)
Brown *et al.* [6]	12.5	2	25
Kahn *et al.* [8]	4.2	5.2	21.8
Sharpe *et al.* [11]	50	3.5	175
Kapel *et al.* [8]	0.7	4	2.8

log refers to the natural logarithm, ln. However, this need not be the case. In any case, using all the available measured data, which are presented in Fig. 10 and Table II, the constants α_0, α_1 and α_2 have been computed using multiple linear regression analyses. The resulting expression for the fatigue life is in Equation 3 in logarithmic form:

$$\ln N_{\mathrm{f}} = -1.11 - 25.6 \ln \sigma + 11.7 \ln t \tag{3}$$

where ln is the natural logarithm, σ is the applied stress in MPa and t is the thickness in μm. The correlation coefficient, r^2, of $= 0.79$ indicates only a moderate correlation. Additional testing and analyses, therefore, is needed to fully explore the extent to which Equation 3 can be used to estimate the fatigue lives of Si MEMS structures.

3.1. Implications

In the absence of physically-based fatigue life prediction models, the empirical single or multiparameter models provide useful approaches for the engineering estimation of fatigue life. They may also serve as useful tools in the analyses of the relative contributions from different variables to the overall fatigue life. In the current work, the relative values of α_1 and α_2 ($\alpha_1 = -25.6$ and $\alpha_2 = 11.7$) suggest that stress is the primary

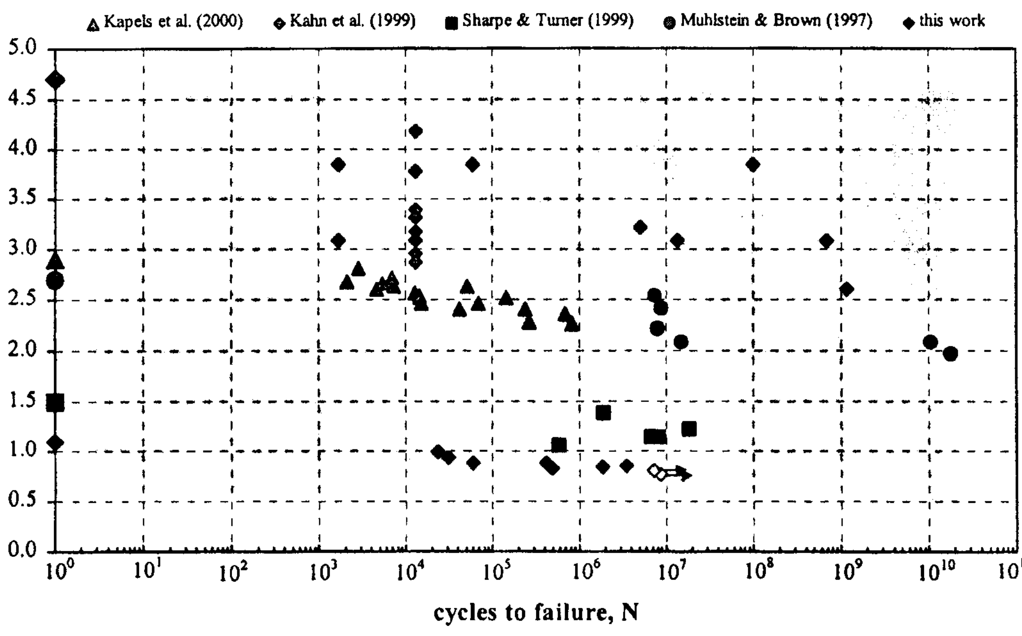

Figure 10 Summary of fatigue life data.

variable that controls fatigue life. However, thickness, t, also plays a significant role, with fatigue life increasing with increasing thickness.

Reasons for the observed dependence of fatigue life on thickness are yet to be fully established in ongoing basic studies of fatigue mechanisms in Si MEMS structures [13, 14]. Nevertheless, it is clear that the thicknesses of the Si structures could clearly be related to the underlying grain structures. The structural thicknesses could also affect the surface stresses or crack lengths that must be attained to reach the critical failure conditions required for final failure in Si structures. Further work is clearly needed to establish how structural thickness and stress affect the actual mechanisms of fatigue failure in Si MEMS structures.

3.2. Summary and concluding remarks

The stress-life behavior of polysilicon MEMS structures has been reviewed in this paper. Salient conclusions arising from this study is presented below.

1. Prior studies of the stress-life behavior of polysilicon indicate the usual dependence of fatigue life on stress amplitude. However, the fatigue life of polysilicon is also affected by structural thickness.
2. The stress-life behavior of polysilicon MEMS structures is well characterized by Coffin-Manson type expressions. However, the empirical constants are significantly different from those reported for conventional metallic materials.
3. A single multiparameter expression has been obtained for all the stress-life fatigue data reported so far for polysilicon MEMS structures. This gives the total fatigue life, N_f, as: $\log N_f = -1.11 - 25.6 \ln \sigma + 11.7 \ln t$. Alternatively, the total number of cycles to failure may be expressed as: $N_f = 3.034\, \sigma^{-25.6}\, t^{11.7}$
4. In the absence of physically-based MEMS life prediction models, the single and multiparameter expressions may be used to guide the fatigue design of polysilicon MEMS structures. They may also be used to estimate the relative contributions of different variables to the overall fatigue life. Further fatigue testing is needed to improve the predictive accuracy of the single and multiparameter models presented in this paper.

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