EFFECTS OF VARYING MEAN STRESS AND STRESS AMPLITUDE ON THE FATIGUE OF POLYSILICON

R. Ballarini, H. Kahn and A.H. Heuer
Case Western Reserve University
Cleveland, OH 44106 USA

ABSTRACT

Polysilicon deposited by low-pressure chemical vapor deposition (LPCVD) is a brittle material at room temperature. However, dynamic fatigue – delayed fracture under applied cyclic stresses – has been reported for micrometer-scale polysilicon specimens [1-5]. Fatigue in polysilicon has been observed for fully reversed (tension/compression) stress cycling [1,2] and for tension/zero stress cycling [2,3]. For both cases, the lifetime under high-cycle fatigue depends only on the number of cycles, not on the total time or the frequency of the test, for testing frequencies ranging from 1 Hz through 40 kHz [4]. This implies that dynamic fatigue is mechanical in origin, and is not caused by time-dependent environmental effects such as stress corrosion, oxidation, or other chemical reactions.

We recently demonstrated that low-cycle fatigue strengths are strongly influenced by the ratio of compressive to tensile stresses in the loading cycle, but not by the ambient (air or vacuum) [1]. That study had involved application of a (tensile or compressive) mean stress to a fatigue specimen, and then slowly increasing the amplitude of the cyclic load until fatigue fracture occurred. Therefore, fatigue fracture was obtained at a specific combination of applied mean stress, σ_m, and fatigue stress amplitude, σ_a, where

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}, \quad \text{and} \quad \sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}.$$

This talk presents the results of fatigue tests on polysilicon specimens with independently varied σ_m and σ_a [6]. Single edge-notched fatigue specimens with micrometer-sized dimensions were micromachined and subjected to cyclic loading using an integrated electrostatic actuator. The effects of fatigue were determined by comparing the monotonic bend strength measured after cyclic loading to the monotonic bend strength of specimens that received no cycling. Both strengthening and weakening were observed, depending on the levels of mean stress and fatigue stress amplitude during the cyclic loading. Monotonic loading with similar stress levels prior to bend strength measurements had no effect on measured bend strength. Possible physical mechanisms responsible for this complex fatigue behavior are discussed.

The figures on the next pages summarize the experimental setup and results.

[1] H. Kahn, R. Ballarini, J.J. Bellante, and A.H. Heuer, Science, **298**, 1215 (2002).
[2] H. Kahn, R. Ballarini, R.L. Mullen, and A.H. Heuer, Proc. R. Soc. Lond. A, **455**, 3807 (1999).
[3] C.L. Muhlstein, E.A. Stach, and R.O. Ritchie, Acta Mater., **50**, 3579 (2002).
[4] J. Bagdahn and W.N. Sharpe, Jr., Sensors and Actuators A, **103**, 9 (2003).
[5] H. Kapels, R. Aigner, and J. Binder, IEEE Trans. Elec. Dev., **47**, 1522 (2000).
[6] H. Kahn, R. Ballarini and A.H. Heuer, MRS Symp. Proc., in press.

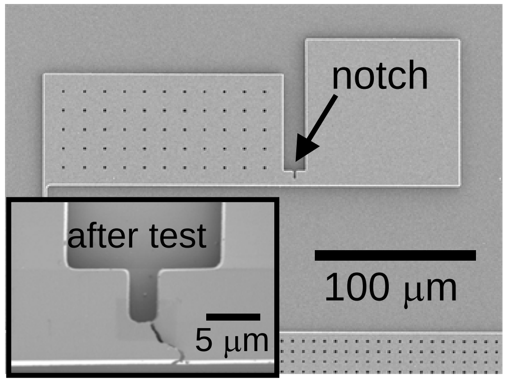

Figure 1. Scanning electron micrograph of the micromachined single edge-notched polysilicon fracture mechanics specimen. The site of stress concentration is the notch root. The inset shows the notch area after testing. Crack propagation is catastrophic after crack initiation.

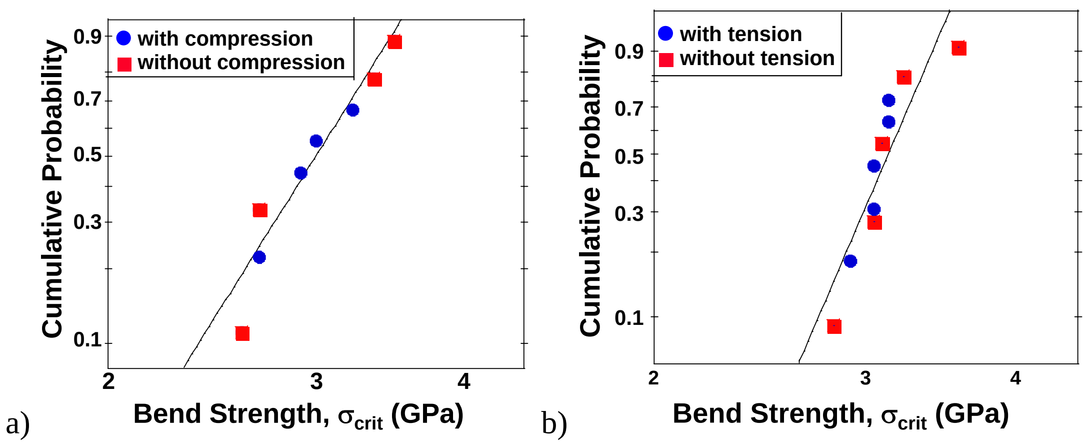

Figure 2. Weibull probability plots for monotonic bend strength tests. The data from standard bend strength tests (squares) are plotted along with data from samples that endured a constant hold stress before monotonic bend strength testing (circles) In a), the samples represented by circles were held for a few seconds at –4.5 GPa; in b) the samples represented by circles were held at 2.7 GPa for 10 minutes. In each plot, a single Weibull distribution describes all the data, indicating that the constant hold stresses did not affect the bend strength. The average bend strength and Weibull modulus are 3.0 GPa and 8, respectively, for a) and 3.1 and 14, respectively, for b). The difference in Weibull modulus is not considered significant, given the limited data sets.

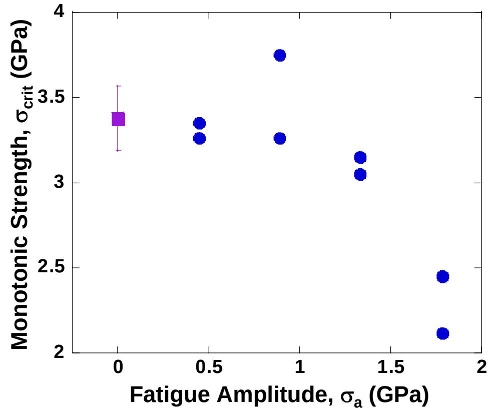

Figure 3. Results from cyclic loading tests of undoped polysilicon. For all tests, the mean stress, σ_m, was -2.2 GPa. The monotonic bend strength is shown as the solid square.

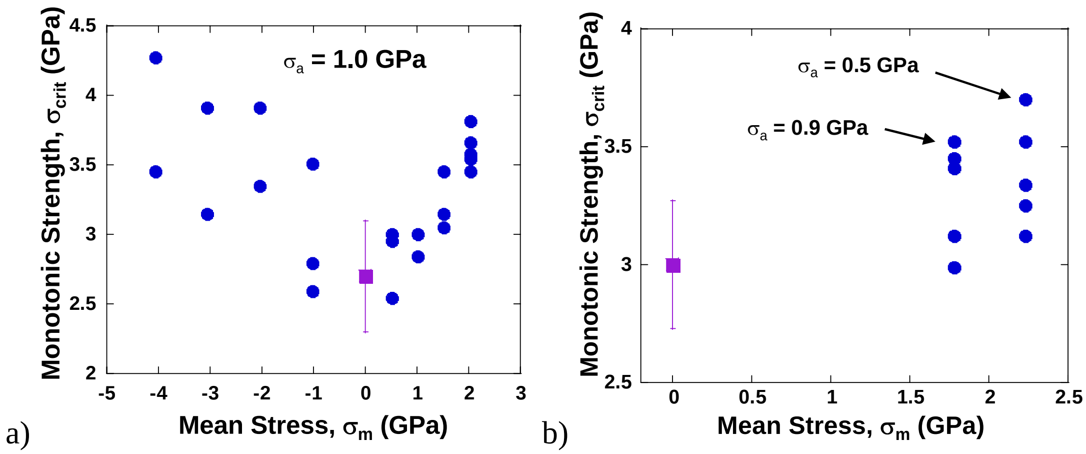

Figure 4. Results from cyclic loading tests. a) shows data for undoped polysilicon, and b) shows data for B-doped polysilicon. In a), the stress amplitude, σ_a, was 1.0 GPa for all tests. In b), the stress amplitude, σ_a, was 0.9 GPa for the tests with a mean stress, σ_m, of 1.8 GPa, and the stress amplitude, σ_a, was 0.5 GPa for the tests with a mean stress, σ_m, of 2.2 GPa. In each plot, the monotonic bend strength is shown as the solid square.

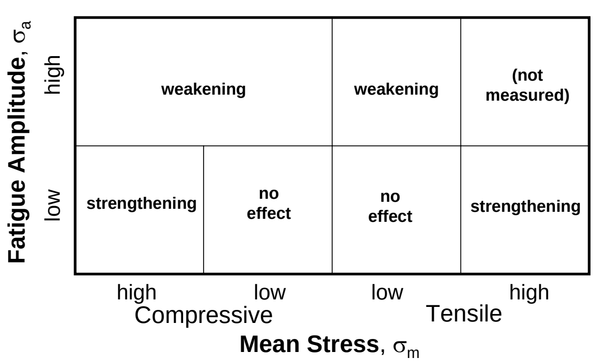

Figure 5. The qualitative effects of stress amplitude, σ_a, and mean stress, σ_m, on strength, σ_{crit}.