Mat. Res. Soc. Symp. Proc. Vol. 821 © 2004 Materials Research Society P2.5.1

UTILIZING ON-CHIP TESTING AND ELECTRON MICROSCOPY TO STUDY FATIGUE AND WEAR IN POLYSILICON STRUCTURAL FILMS

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Abstract

Wear and fatigue are important factors in determining the reliability of microelectromechanical systems (MEMS). While the reliability of MEMS has received extensive attention, the physical mechanisms responsible for these failure modes have yet to be conclusively determined. In our work, we use a combination of on-chip testing methodologies and electron microscopy observations to investigate these mechanisms. Our previous studies have shown that fatigue in polysilicon structural thin films is a result of a 'reaction-layer' process, whereby high stresses induce a room-temperature mechanical thickening of the native oxide at the root of a notched cantilever beam, which subsequently undergoes moisture-assisted cracking. Devices from a more recent fabrication run are fatigued in ambient air to show that the post-release oxide layer thicknesses that were observed in our earlier experiments were not an artifact of that particular batch of polysilicon. New *in vacuo* data show that these silicon films do not display fatigue behavior when the post release oxide is prevented from growing, because of the absence of oxygen. Additionally, we are using polysilicon MEMS side-wall friction test specimens to study active mechanisms in sliding wear at the microscale. In particular, we have developed *in vacuo* and *in situ* experiments in the scanning electron microscope, with the objective of eventually determining the mechanisms causing both wear development and debris generation.

Introduction

Recent advances in micromachining have increased the demand for more reliable microscale structures. Although silicon is an excellent construction material at the microscale and is most widely used in these structural thin film applications, it is very brittle. Consequently, reliability is often the limiting factor as far as commercial applications are concerned. Since the surface to volume ratio of these structural films is very large, classical models for failure modes cannot always be applied. At these size scales, surface effects may become dominant in determining the mechanical properties of the material. The main reliability issues for microelectromechanical systems (MEMS) are stiction, fatigue and wear. Stiction occurs when freestanding parts stick to the substrate or to each other when releasing the device (release stiction), or while operating, due to particular surface contact conditions (in-use stiction) [1]. Fatigue is important in cases where parts get strained a large number of times below their fracture stress, whereas wear occurs at contacting moving surfaces. While the reliability of MEMS has received extensive attention, the physical mechanisms responsible for these failure modes have yet to be conclusively determined [2-7]. The goal of this research is to find the mechanisms responsible for wear and fatigue in polysilicon structural thin films. In this work, on-chip testing methods are combined with electron microscopy. Specifically, fatigue specimens were cycled and observed using high-voltage transmission electron microscopy (HVTEM). For the wear studies, an *in situ* scanning electron microscope (SEM) method was developed to permit the collection of wear debris while the films are wearing.

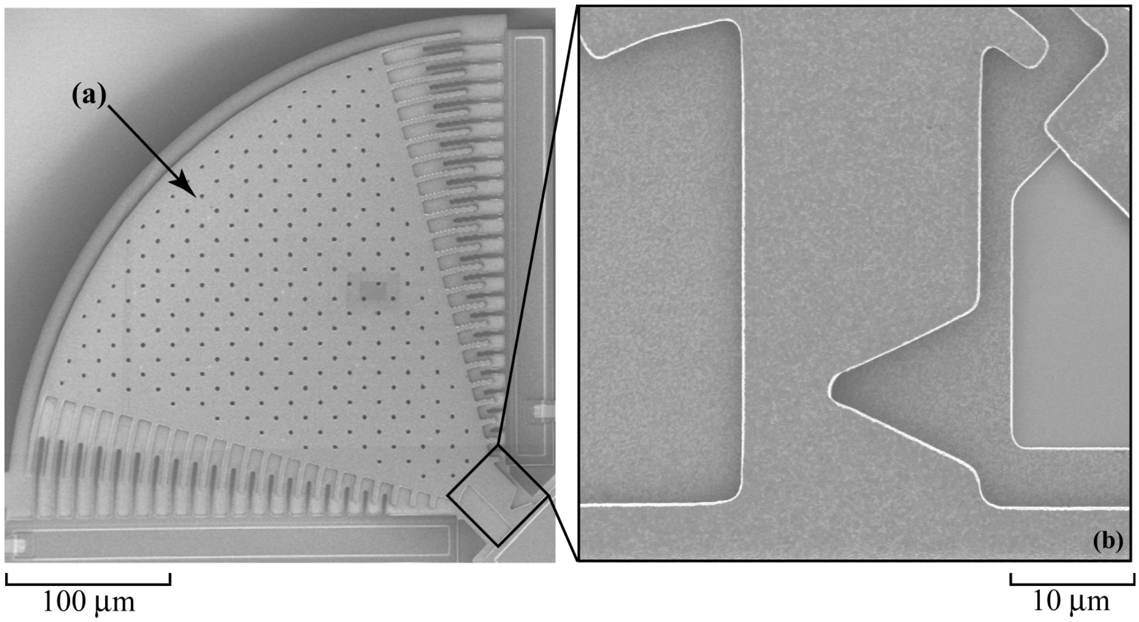

Figure 1: Scanning electron micrographs of the polysilicon MEMS fatigue life characterization resonator fabricated at the MEMSCAP MUMPs foundry (formerly CRONOS) [8]. a) Triangular proof mass with interdigited comb drive actuator and capacitive displacement sensor; b) notched cantilever beam connecting the resonator mass and anchor.

Fatigue

Our previous work [9-12] has shown that micron-scale silicon structural films, unlike bulk silicon, display high cycle fatigue behavior at room temperature. Fatigue resonator devices, actuated by an interdigited comb drive (Figure 1a) at ~40Khz and a load ratio (R) of -1 at ~25°C with 30-50% relative humidity (RH), have been used to measure the fatigue behavior of a notched cantilever beam (Figure 1b). The devices are actuated by one of the comb drives, while using the other one to monitor displacements using capacitive sensing electronics. With this system, displacements can be kept constant during the entire test. With known dimensions, finite element calculations are used to calculate the stresses at the notch root. To summarize our previous results, a “metal-like” stress versus number of cycles to failure (*S/N*) curve was obtained for 2 µm thick polysilison. Additionally, HVTEM of fatigued and fractured fatigue test devices revealed a thickening of the post-release oxide layer at the notch root for fatigued samples, in contrast to (manually) fractured specimens which showed no such thickening. This led us to propose a ‘reaction layer’ fatigue mechanism consisting of three steps: (i) the initial post-release oxide layer grows while mechanically stressed during cycling, (ii) moisture-assisted cracking of the oxide layer results in stable crack growth, and (iii) provided the oxide layer is thick enough, at some point the critical crack size for the entire structure is reached and the structure fails catastrophically.

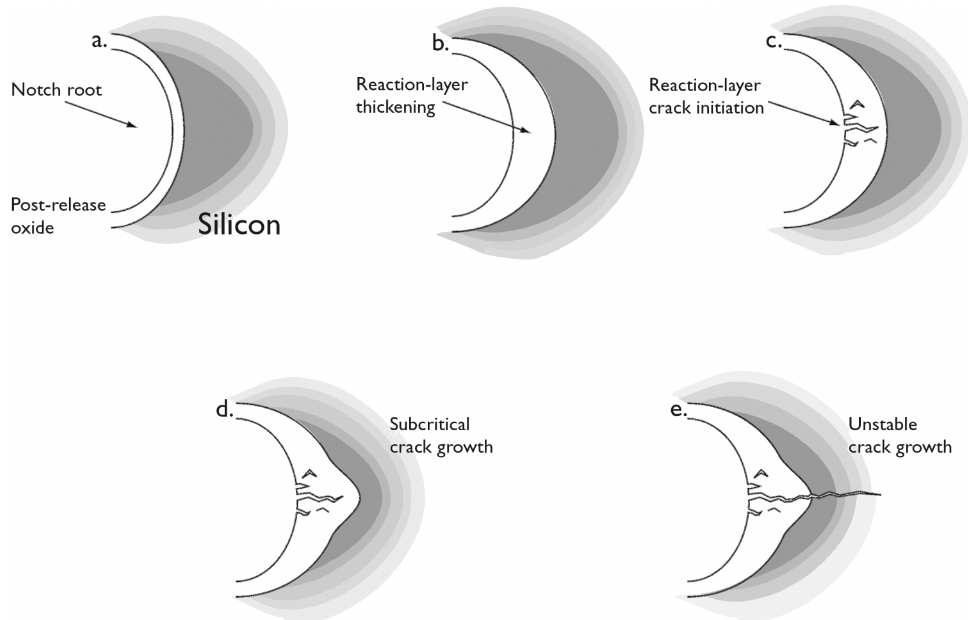

Figure 2: Schematic of the reaction-layer fatigue mechanism at the notch of the polycrystalline silicon cantilever beam (a). (b): Localized oxide thickening at the notch root. (c): Environmentally assisted crack initiation in the native oxide at the notch root. (d): Additional thickening and cracking of reaction layer. (e): Unstable crack growth in the silicon film.

In this paper, we report on fatigue data acquired from devices from a different run at the Multi User MEMS Process (MUMPs) foundry, as well as new *in vacuo* observations. This allows us to check the reproducibility of our previous findings and to characterize the changes in fatigue behavior and development of reaction layers in a relatively oxygen-free environment. Figure 3 shows a *S/N* curve from previously obtained fatigue data [9,10] in ambient air from devices from MUMPs run 18 (best fit line). These data are compared to the current data from MUMPs fabrication run 50, acquired in both ambient air (~25°C, 30-40% RH) and vacuum (~2.0 x 10^{-7} mbar). No samples failed *in vacuo*; correspondingly, the data points plotted are run-outs (i.e., the number of cycles when the tests were stopped). From these results, two important deductions can be made: the fatigue tests performed with specimens from a different fabrication run display identical fatigue behavior to previous tests. Next to that, the attempts to fatigue polysilicon in vacuum showed that the devices did not fail at stresses up to the fracture strength, even after cycling up to a high number of cycles. HVTEM of fatigued and fractured devices in ambient air and in vacuum reveals a thickening of the oxide layer for the specimen fatigued in ambient air of up to 100-150 nm. However, this local thickening at the notch root is not visible for the fractured specimens in ambient air and in the specimens that were loaded monotonically. For the latter specimens the post release oxide layer (~30 nm) is not thick enough to accommodate the critical crack size for the structure (~50 nm) [11]. In order to see the oxide in the notch root, the samples that did not fatigue in vacuum were either fractured manually or by applying large displacements electrostatically. Thereafter, they were lifted from the chip onto a TEM clamshell grid. Both the newly acquired fatigue data as well as the TEM micrographs of the oxide layers point towards the ‘reaction layer’ fatigue mechanism being the governing mechanism for fatigue failure in polycrystalline silicon thin films.

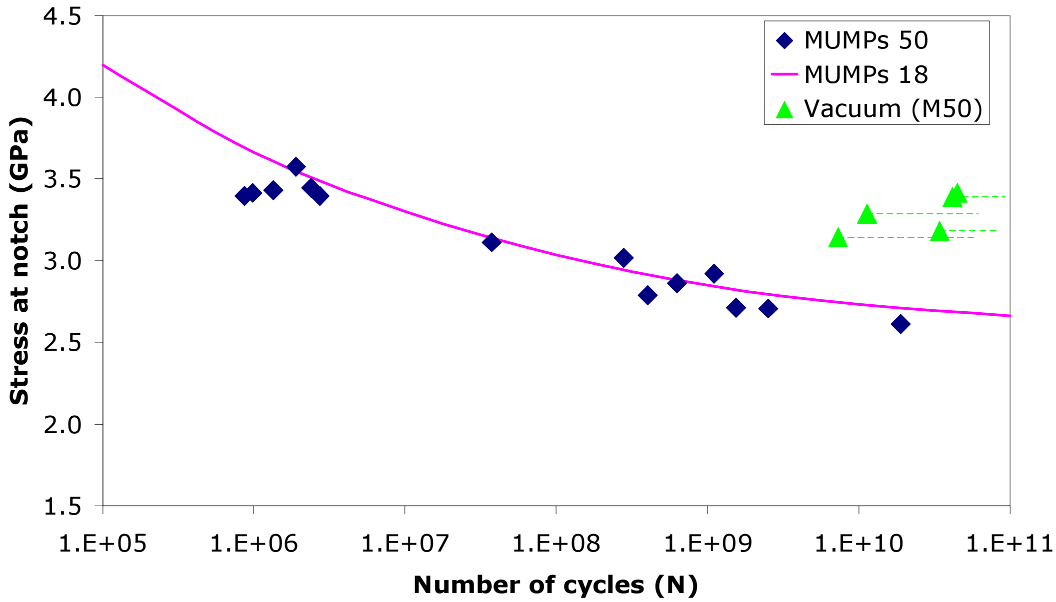

Figure 3: Polysilicon *S/N* curve. Fitted line for previous data from MUMPs run #18 in ambient air [9,10] compared with current fatigue data from MUMPs run 50 in ambient air and vacuum (~2.0 x 10^{-7} mbar). As no fatigue failures are seen *in vacuo*, data points are run-outs.

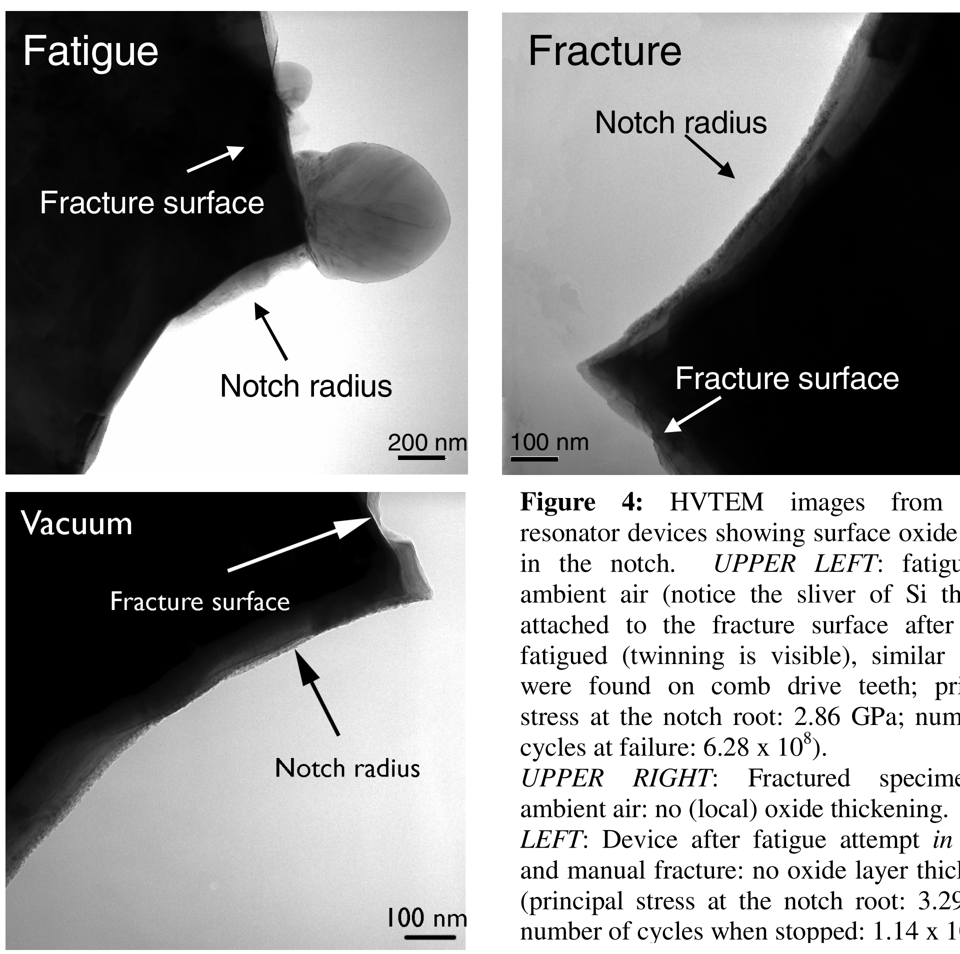

Figure 4: HVTEM images from failed resonator devices showing surface oxide layers in the notch. *UPPER LEFT*: fatigued in ambient air (notice the sliver of Si that got attached to the fracture surface after being fatigued (twinning is visible), similar slivers were found on comb drive teeth; principle stress at the notch root: 2.86 GPa; number of cycles at failure: 6.28 x 10^{8}).
UPPER RIGHT: Fractured specimen in ambient air: no (local) oxide thickening.
LEFT: Device after fatigue attempt *in vacuo* and manual fracture: no oxide layer thickening (principal stress at the notch root: 3.29 GPa, number of cycles when stopped: 1.14 x 10^{10}).

Wear

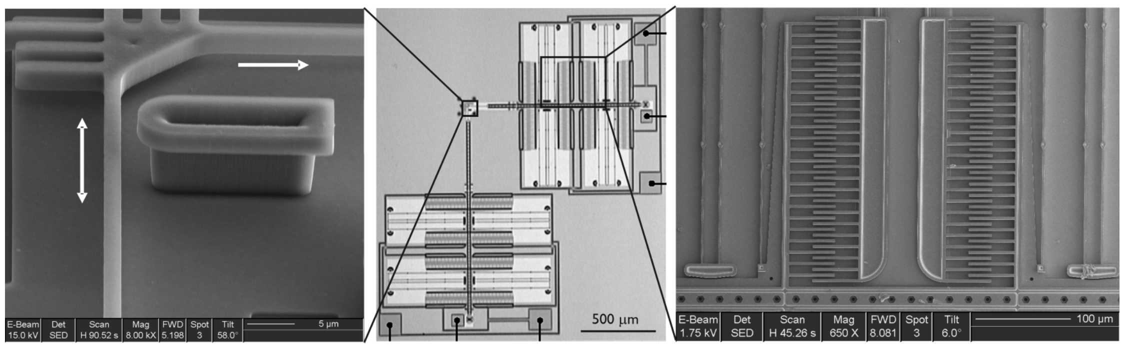

Figure 5: Polysilicon side wall friction test device fabricated at the Sandia SUMMIT process. The device produces two-axis motion provided by electrostatic actuation of interdigited comb drives used to pull a beam against a post to wear.

To study active mechanisms in sliding wear we have used polysilicon MEMS side-wall friction test specimen fabricated at the Sandia National Labs SUMMIT process (Figure 5) [13]. *In vacuo* and *in situ* experiments in the scanning electron microscope (SEM) were conceived, with the objective of determining the mechanisms causing both wear development and debris. Wire feed-troughs and special stages built for a dual beam focused ion beam (DB-FIB) system and a field emission scanning electron microscope (FESEM) allowed the side-wall friction devices to be run *in situ*. Imaging actuated devices is a trade-off between the amount of detail that can be resolved (resolution) and the stability of the images. The alternating charges on the comb drives, induced by voltages from ±80 V, influence the electrons coming off the sample. A high kV beam provides the most stable image, but it has less surface detail visible (Figure 6b). A low

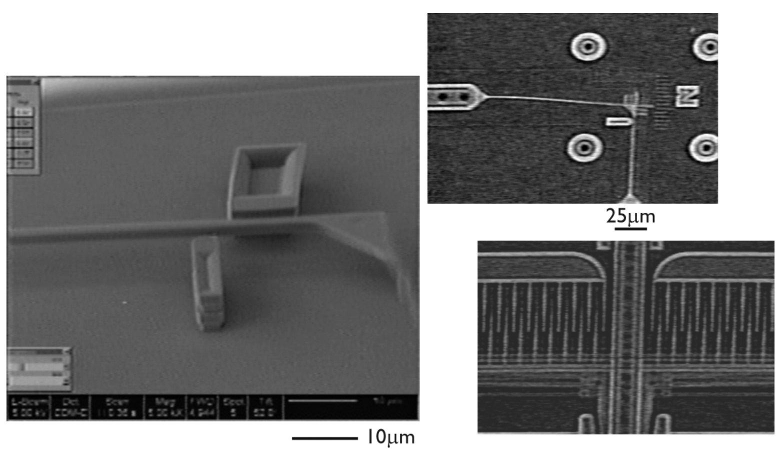

Figure 6: Screenshots from *in situ* SEM wear experiments (a: *LEFT*) synchronized driving frequency and image acquisition at lower beam acceleration (5 kV) (b: *RIGHT*) wear (*TOP*) and comb drive (*BOTTOM*) at higher beam current (20 kV).

kV beam results in a heavily vibrating image but with more detail. To optimize the information that we could obtain, the devices were run at the frequency of the electron detector (around 3Hz; depending on the magnification). This results in a stable synchronized image that can reveal the development of wear debris with time (An example of the type of video acquired can be seen in Figure 6a). Current research including FIB lift-off sample preparation techniques to make TEM samples of worn beams are used to complement these results and promises a fruitful way of learning more about the mechanism(s) that cause wear on the micro-scale.

Conclusions

Fatigue and wear in silicon structural films were investigated. To illustrate the reproducibility of earlier acquired fatigue data and to verify the relevance of the used material [9,10], devices from MUMPs run 50 were actuated in ambient air. When compared with earlier data on MUMPs run 18, identical fatigue behavior was observed and HVTEM images revealed the same post-release oxide layer thickening after fatiguing as in earlier tests. Most importantly, for fatigue studies at stresses very close to the fracture strength and at a large number of cycles, no fatigue failures at all were observed in vacuum (~2.0 x 10^{-7} mbar). In addition, the local oxide layer thickening at the notch root was absent in the vacuum tests. These new results serve as additional evidence to support the validity of the 'reaction layer' fatigue model.

An *in situ* SEM method of collecting wear data was developed. Synchronizing the device's actuation with the SEM detector refresh rate results in a stable image that shows a high amount of detail. Preliminary results were obtained and in combination with FIB TEM lift off sample preparation techniques this will serve as a powerful tool to obtain more detailed knowledge about the mechanisms that cause wear in polysilicon at these length scales.

Acknowledgements

The authors would like to thank Bob Ashurst for sharing his experience of operating the wear devices. This work was supported by the Laboratory Directed Research and Development Program of Lawrence Berkeley National Laboratory under the Department of Energy Contract No. DE-AC03-76SF00098.

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