Improving Mechanical Reliability of Si Nanobeams with Self Assembled Monolayers

CNF Project # I154-03
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Abstract:
The fracture durability of silicon nano-beams in air was improved considerably by methyl surface termination. 210-nm thick, doubly clamped beams with functionalized surfaces were tested after exposure to air over a period of 23 days. Experiments showed that the native oxide growth reduced the strength of the beams with H terminated surfaces from 16.2 GPa to 11.2 GPa. Coating the sample surfaces with methyl monolayers prevented oxidation and maintained the strength throughout the test period under same environmental conditions.

Summary:
Due to their small sizes and use of materials with very low defect densities, materials used in the nanoscale have the potential to sustain very high stresses. For microelectromechanical system (MEMS) applications, as important as the high initial strength, is the prevention of aging of the structure throughout its service life. Si devices operating in air are expected to have very high durability under mechanical loading as Si is not susceptible to stress corrosion cracking. However, the native oxide layer (amorphous SiO₂) may enhance fracture initiation and cause catastrophic failure [1]. How does air exposure influence the fracture reliability of single crystal Si under static loading? And how can the service life of Si structures in air be improved? Our study shows that effective protection of the surfaces is essential for the maintenance of the mechanical strength of nanostructures.

To characterize the effects of air exposure on the fracture reliability of nanostructures, 210-nm-thick, 500-nm-wide, 12-µm-long doubly clamped suspended beams with H and CH₃ terminated surfaces were fabricated from Si (111) wafers using previously described procedures [2,3]. After their fabrication, samples with different surface terminations were exposed to office air and tested at the 3rd, 13th and 23rd days with an AFM [4].

The Weibull strength, σ₀, of the H-terminated beams decreased steadily from 16.2 GPa to 11.2 GPa with increasing air exposure time, whereas the strength of the CH₃ terminated samples remained at 18 GPa over the test period of 23 days.

It is known that H-terminated surfaces show only a temporary protection against oxidation. An approximate 7-day air exposure results in an oxide thickness of 1.5 nm for H-terminated Si (111) [5]. The native SiO₂ has a lower fracture resistance and is prone to undergo moisture assisted cracking under applied stress. With increasing oxide thickness, the load that is necessary to initiate the crack, and hence the observed fracture strength, decreases. It should also be noted that the native oxide, unlike thermally grown oxide, does not necessarily have uniform properties. Its thickness and quality change randomly on the surface. We hypothesize that the inhomogeneous oxidation of the surface results in randomly distributed, local residual stresses, which, together with the increase in surface roughness may enhance fracture initiation, hence reducing the strength of the tested beams.

Our results show that methyl surface coating effectively protected the surfaces for up to 23 days by preventing oxidation and allowed fracture strengths to be maintained.

References:
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Surface protection plays a crucial role in maintaining the mechanical reliability of Si nanobeams.

Figure 1, top left: Weibull fracture probability plot of beams with H terminated surfaces. Inset: a) A test beam before and b) after the experiment.

Figure 2, bottom left: Weibull fracture probability plot of beams with CH\textsubscript{3} terminated surfaces.

Figure 3, above: Change in Weibull fracture strength of beams with H and CH\textsubscript{3} terminated surfaces with increasing air exposure.

Figure 1, top left: Weibull fracture probability plot of beams with H terminated surfaces. Inset: a) A test beam before and b) after the experiment.

Figure 2, bottom left: Weibull fracture probability plot of beams with CH\textsubscript{3} terminated surfaces.

Figure 3, above: Change in Weibull fracture strength of beams with H and CH\textsubscript{3} terminated surfaces with increasing air exposure.