

SIDEWALL ROUGHNESS EFFECTS ON SILICON-ON-INSULATOR (SOI) MEMS FRACTURE STRENGTH

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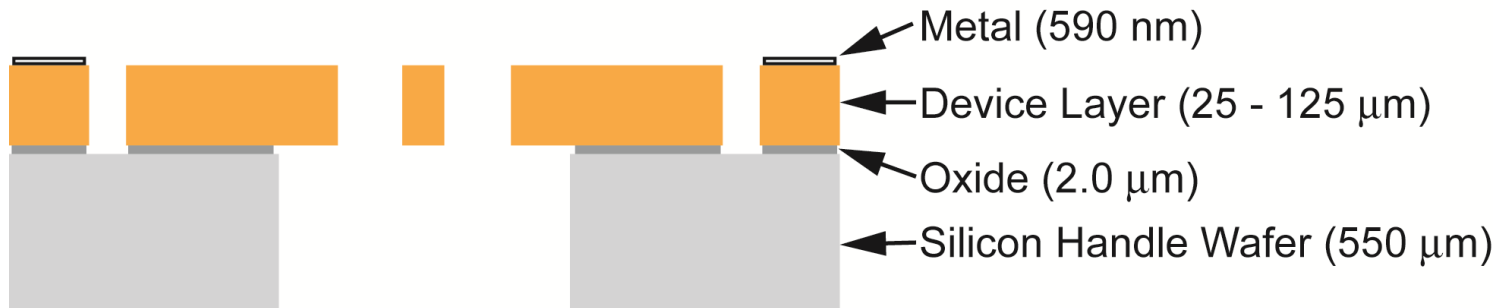
Outline

- SOI processing and sidewall features
- Strength testing and results
- Analysis of critical flaws and strength distributions

Details of the SOI Process

-used to fabricate the structures for this investigation

Schematic Cross-Section of fabricated SOI structures



- Handle wafer p-doped Silicon (Ultrasil Corp.)
- Device layer $\langle 100 \rangle$ orientation
- Test sample ligaments aligned with a $\langle 110 \rangle$ direction

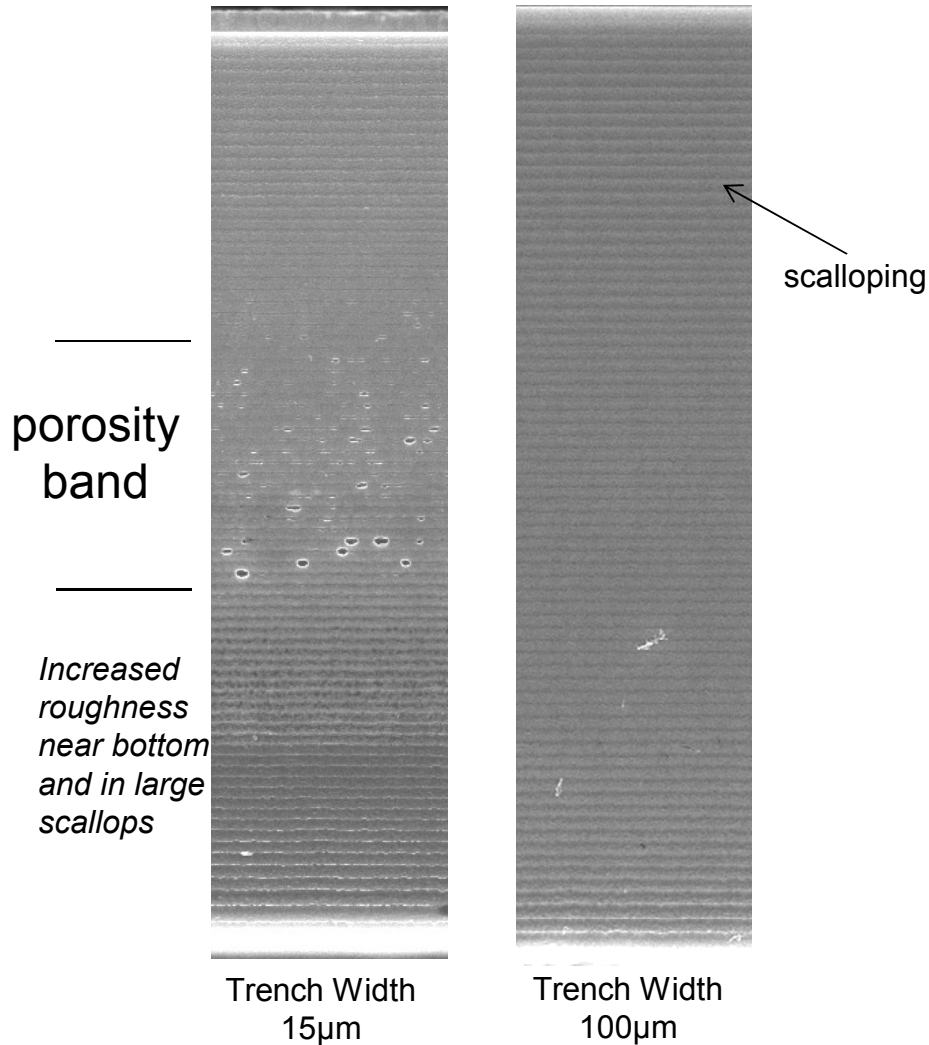
DRIE process – alternating etching and passivation process steps which creates fairly vertical sidewalls.

More Processing Details:

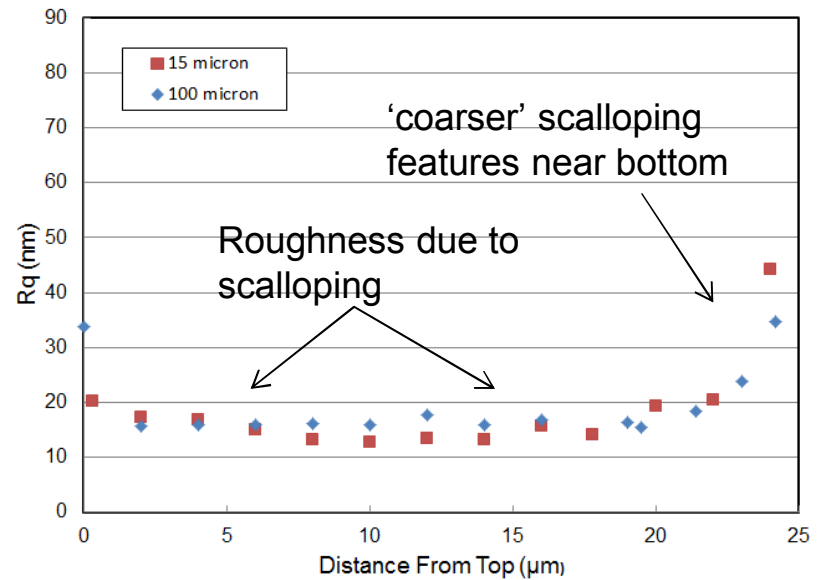
Buchheit, T.E. and Phinney, L.M. "Sidewall Roughness Effects on SOI MEMS Fracture Strength", to be submitted JMEMS 7/2014

Sidewall Features in 25 μm Device Layers

SEM image

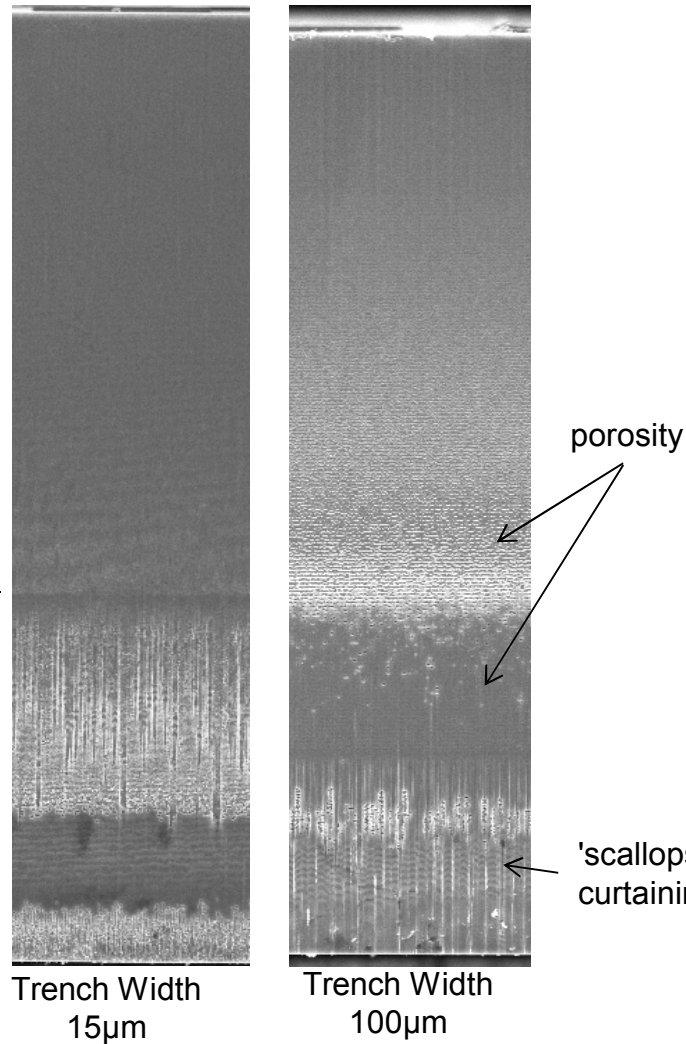


Result from AFM scan

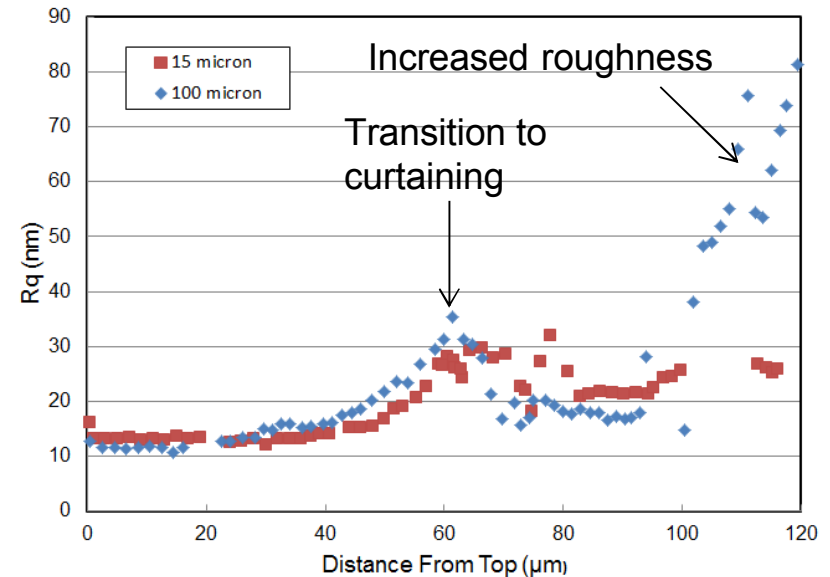


Sidewall Features in 125 μm Device Layers

SEM image

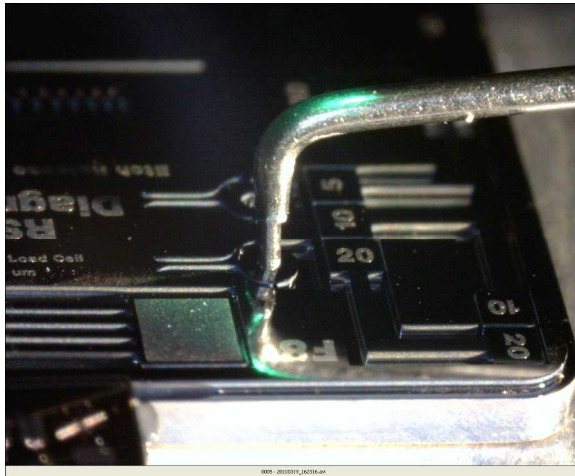


Result from AFM scan

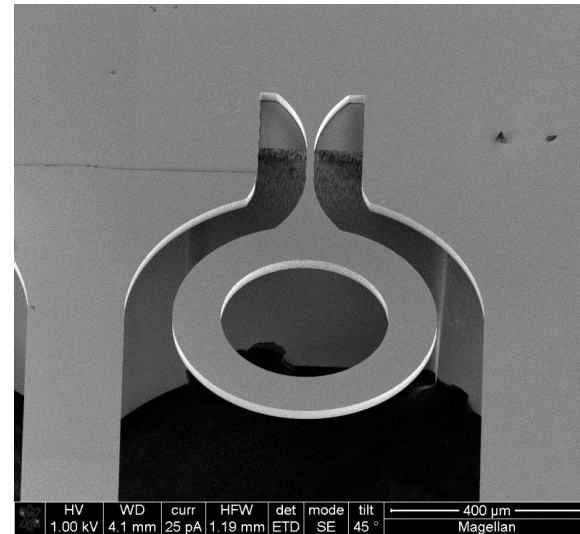
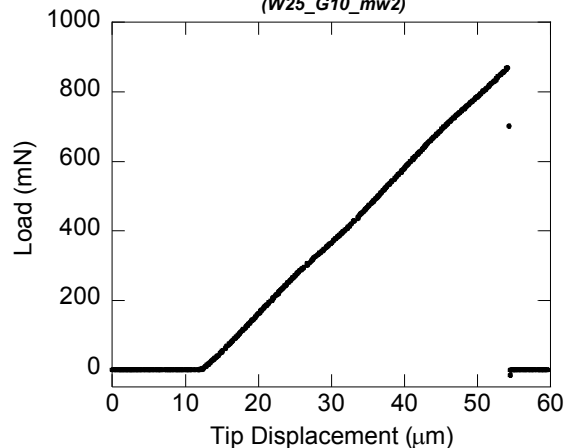


- Not a significant difference due to adjacent trench width except near bottom of 125 μm device layer

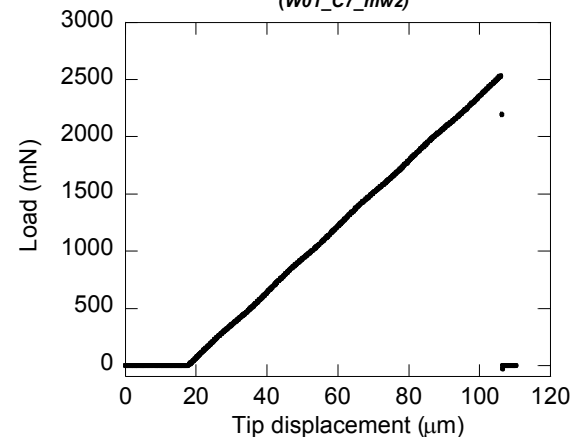
Typical Load-Displacement (Strength) Measurements



Load vs. Displacement
(W25_G10_mw2)



Load vs. Displacement
(W01_C7_mw2)



- No alignment feature and much higher loads to failure than previous similar test structures/studies

Sandia SMM ~20 mN (Boyce et al. 2007), MUMPS SOI ~ 250 mN (Miller et al. 2007)

Pull-Tab Test Geometry and Experiments Sandia National Laboratories

25 μm device layer

Specimen Designation	Length (μm)	Trench Width (μm)	Aspect Ratio	No. of Tests
short-narrow (W25-sn)	100	15 ↓	1.667 ↓	9
medium-narrow (W25-mn)	500			9
long-narrow (W25-ln)	3000			3
short-wide (W25-sw)	100	100 ↓	4 ↓	9
medium-wide (W25-mw)	500			6
long-wide (W25-lw)	3000			6

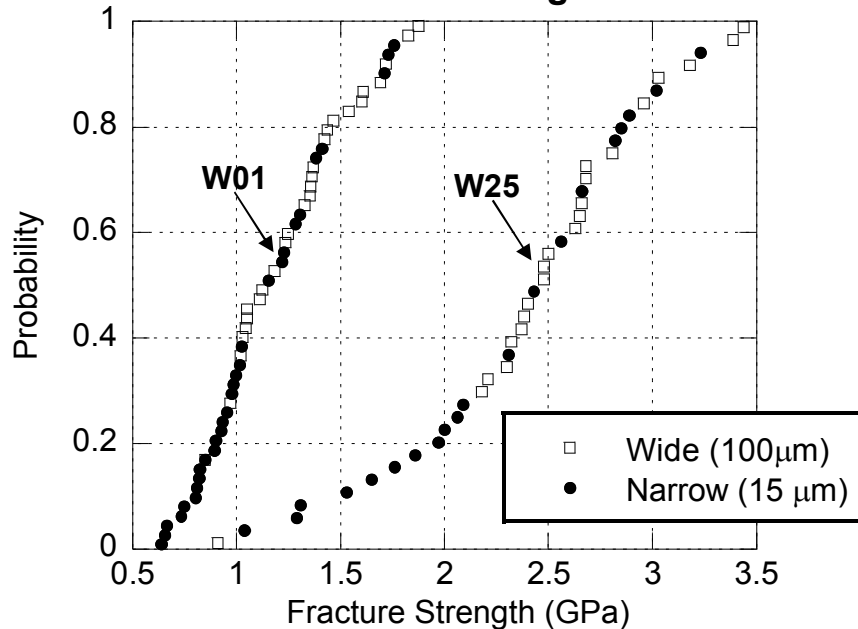
125 μm device layer

Specimen Designation	Length (μm)	Trench Width (μm)	Aspect Ratio	No. of Tests <i>W01/W02</i>
short-narrow (W01-sn)	100	15 ↓	8.333 ↓	5
medium-narrow (W01-mn)	500			11
long-narrow (W01-ln)	3000			14
short-wide (W01/W02)-sw	100	100 ↓	1.25 ↓	11/8
medium-wide (W01/W02)-mw	500			6/8
long-wide (W01/W02)-lw	3000			9/8

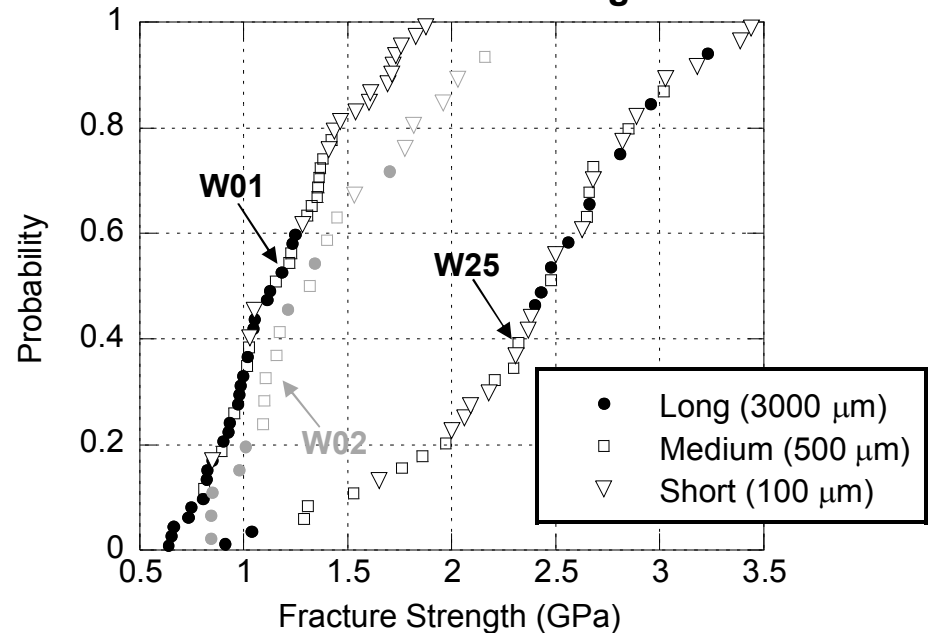
- Two device layer thicknesses across three wafers (W25, W01, W02)
- 3 lengths spanning 2 orders of magnitude
- Two adjacent trench widths (may play a role in sidewall roughness)

Cumulative Distribution of Strength Results across Three Wafers (**W01, W02**- 125 μm and **W25** – 25 μm)

Cumulative Distribution of Fracture Strengths



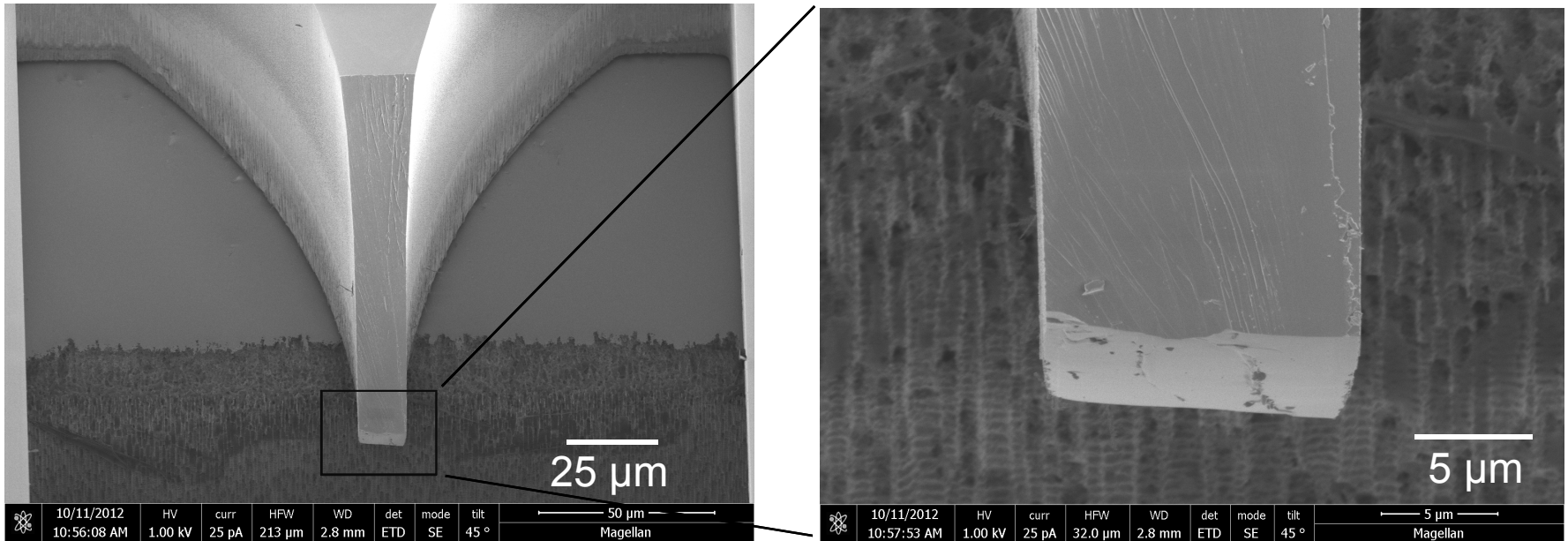
Cumulative Distribution of Fracture Strengths



- W25 results exhibited significantly higher and broader distribution of fracture strengths when compared with W01, W02 results
- **W01, W02** distributions are similar (suggests limited wafer to wafer variation)
- Narrow trench width seemed to lower strength distribution
- Length dependence in **W01** (125 μm) wafer results

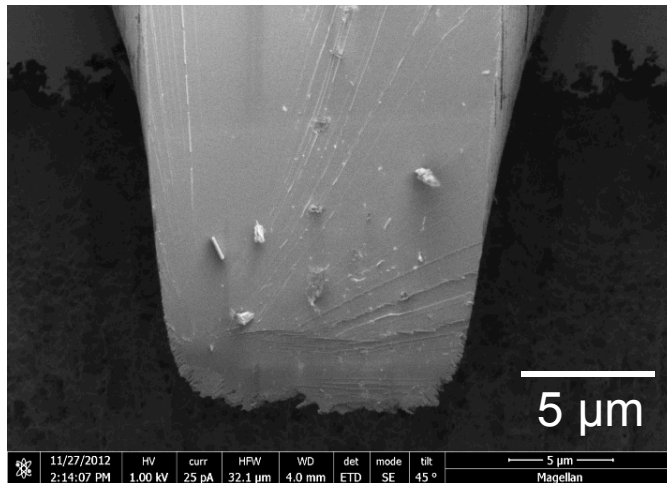
SEM Imaging Fracture Surfaces of Failed Specimens

A failed W01 (125 μm) ligament

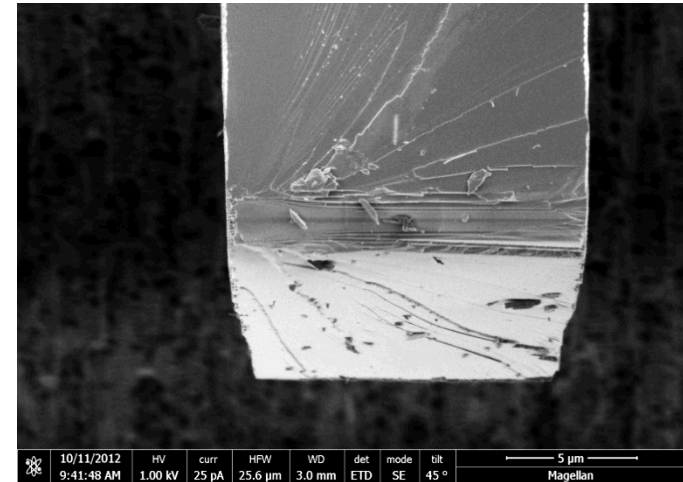


- FEI Magellan 400 high resolution scanning electron microscope
- Low voltage condition, Everhardt-Thornley detector

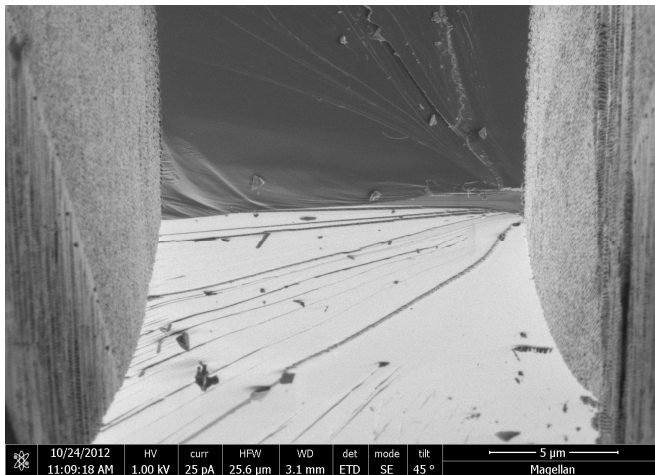
Typical Fracture Initiation Sites in W01 and W02 Ligaments



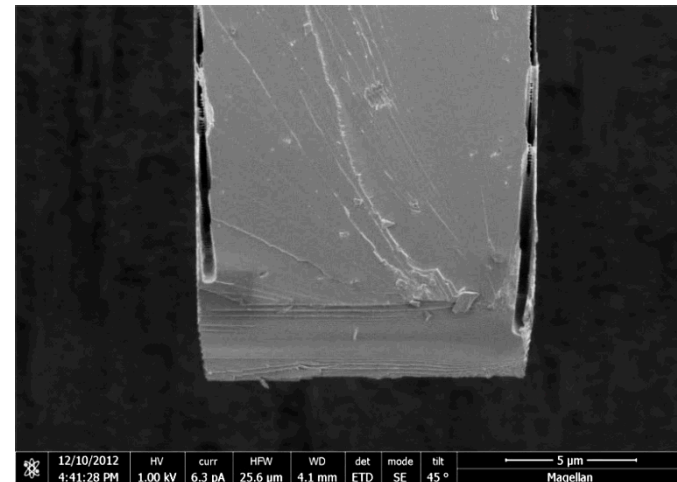
Roughened bottom



Sidewall scalloping features near bottom

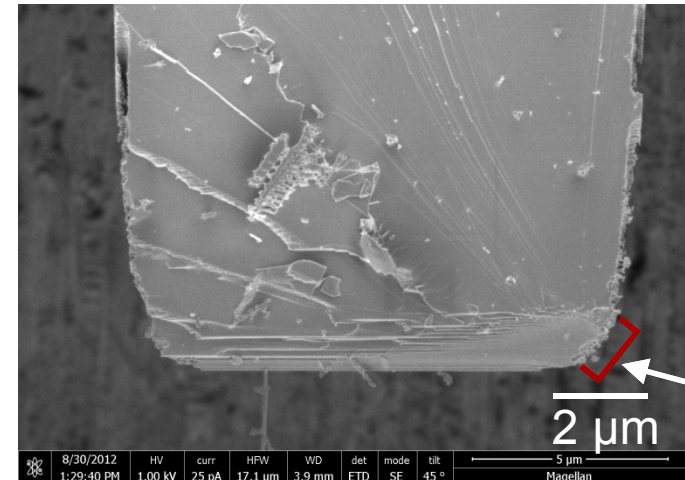
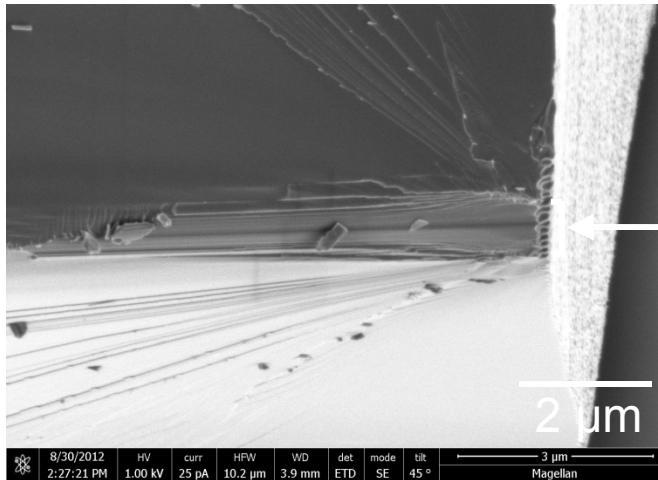


Near surface pore features

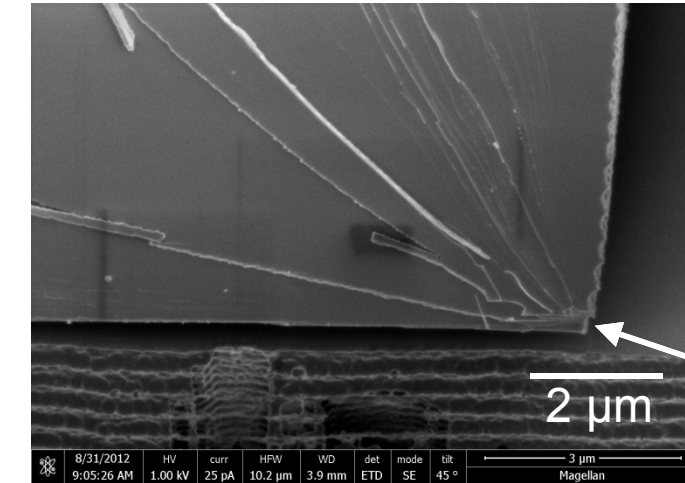
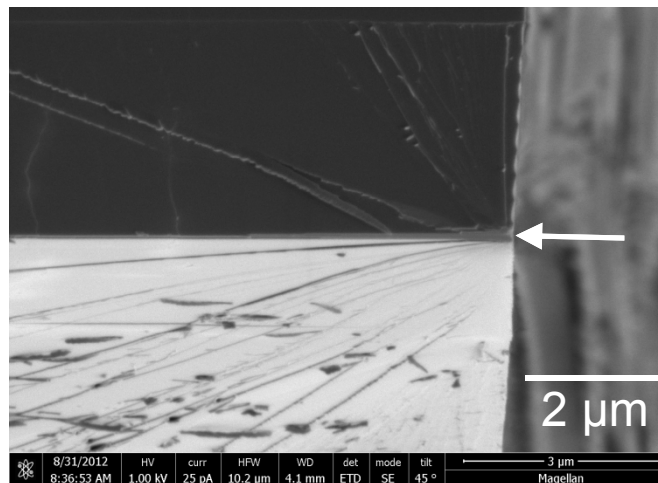


W02 curtaining/digging feature

Typical Fracture Initiation Sites in W25 Ligaments

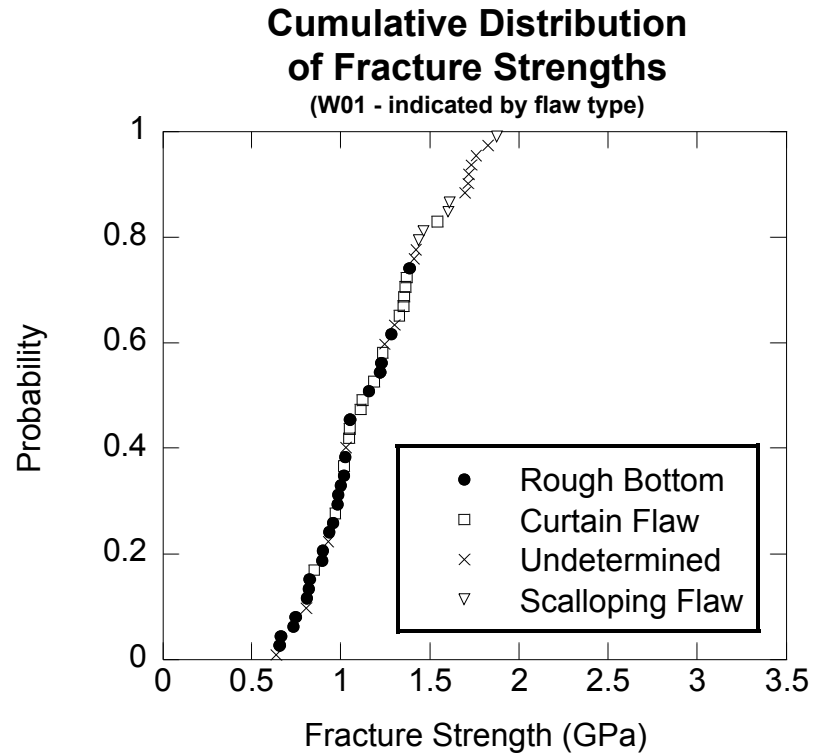
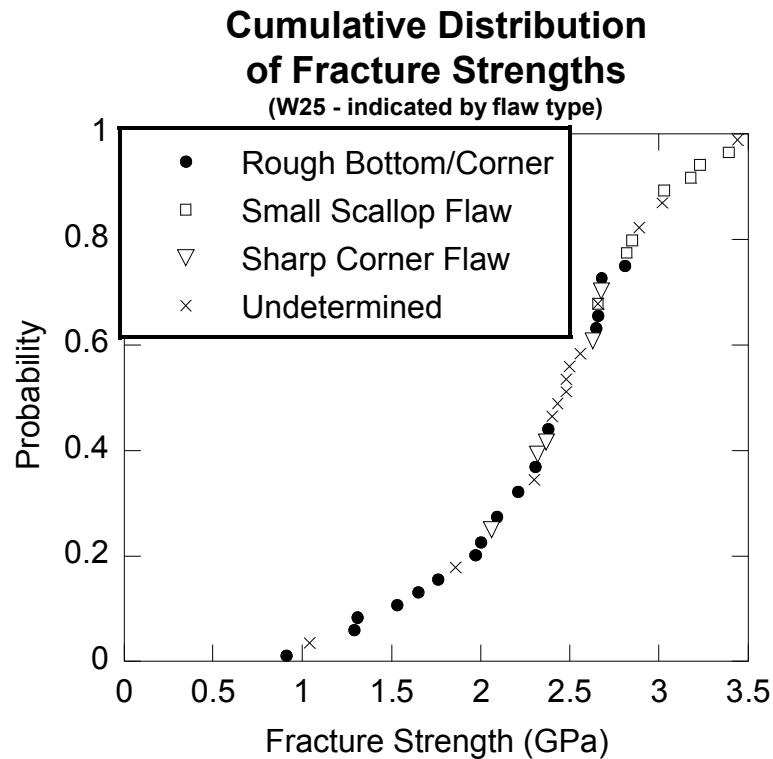


Series of scallop features near and at bottom corner



Single features at mid-section or bottom corner

Fracture Strength Distributions Designated by Flaw Type



Estimation of Weibull parameters

W01 Estimation of Weibull Parameters				
Specimen Designation	Gage Length (μm)	No. of Tests	m <i>unbiased</i>	σ_{char} (GPa) <i>unbiased</i>
W01-lw+ln	3000	24	5.705	1.003
W01-mw+mn	500	15	7.299	1.260
W01-sw+sn	100	16	7.564	1.639

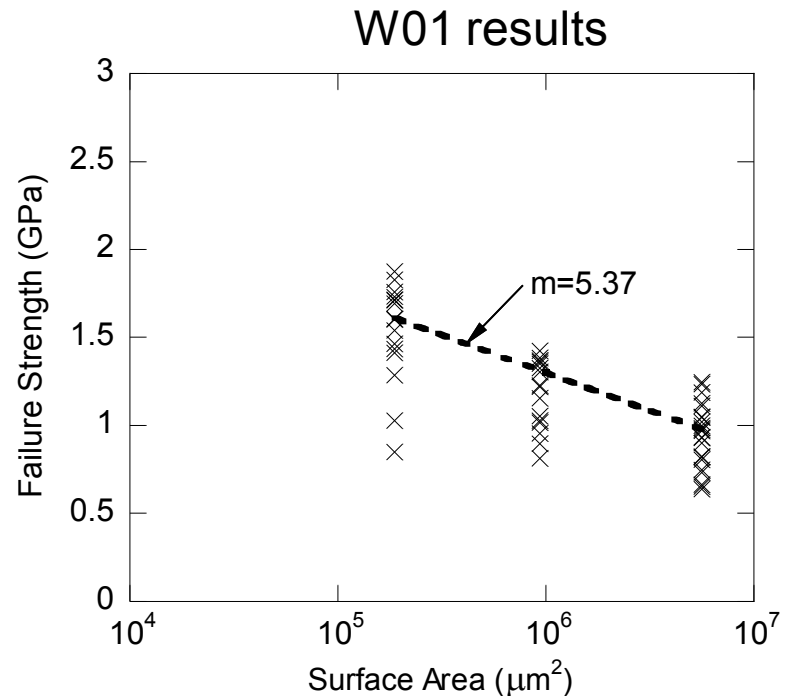
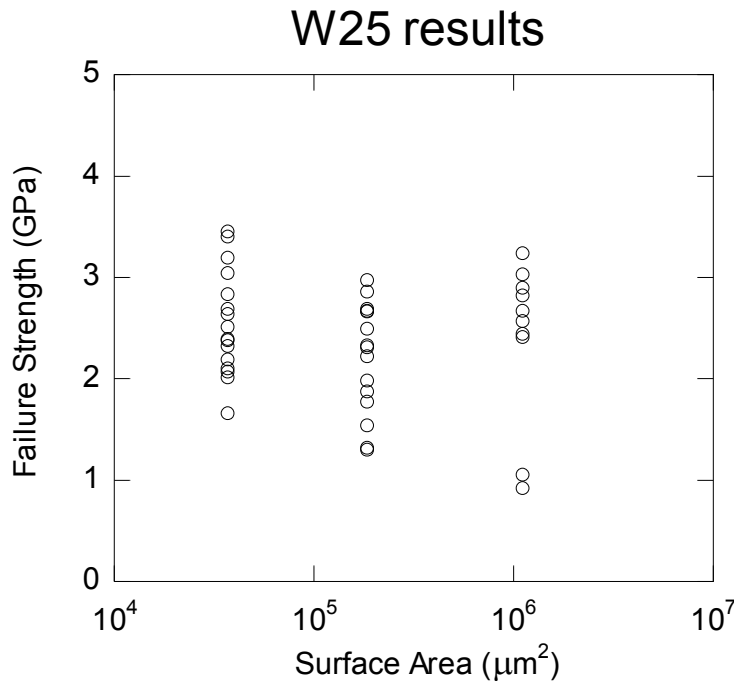
W25 Estimation of Weibull Parameters				
Specimen Designation	Gage Length (μm)	No. of Tests	m <i>unbiased</i>	σ_{char} (GPa) <i>unbiased</i>
W25-lw+ln	3000	10	3.545	2.565
W25-mw+mn	500	15	3.699	2.469
W25-sw+sn	100	17	5.246	2.753
W25-(lw+mw+sw)	-	21	5.431	2.823
W25-(ln+mn+sn)	-	21	3.879	2.385
W25-all	-	42	4.461	2.627

- Broad distribution of strengths, especially in W25 results
- Captures difference in strength between W01 and W25 results
- Adjacent trench width does not seem to influence the distributions.
- Characteristic strength does not scale with surface area in W25 samples.

Fracture Strength Scales with Surface Area in W01 results but not in W25 results

For fracture initiating flaws spatially distributed on the surface of the test specimens:

$$\left(\frac{\sigma_1}{\sigma_2}\right) = \left(\frac{A_2}{A_1}\right)^{1/m}$$

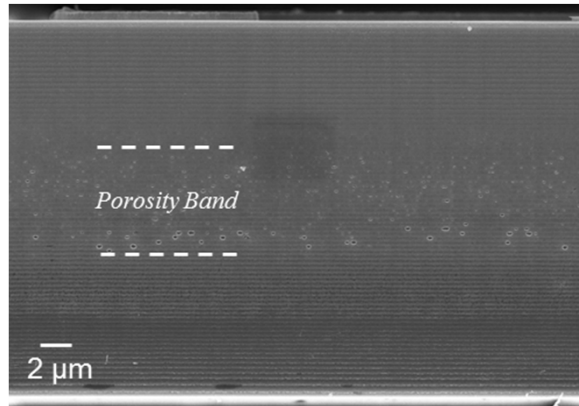


Conclusions

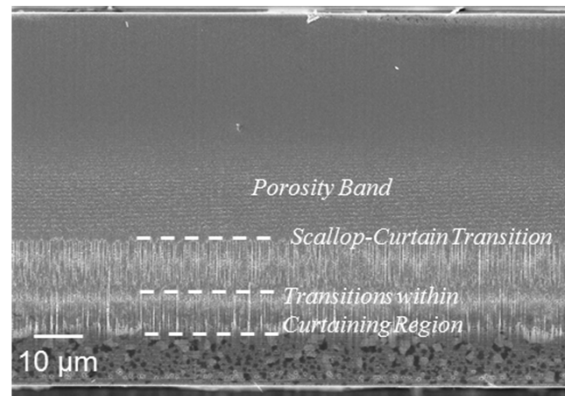
- Processing induced sidewall features and bottom features were significant and dictated the strength distributions generated from experiments on the pull-tab test structures.
- Fracture strengths ranged from 1.0– 3.5 GPa for the 25 μm thick samples and from 0.6 – 2.2 GPa for the 125 μm thick samples.
- Current processing methods may be sufficient for many MEMS designs/applications. (although broad distribution of strengths is a concern)
- Analysis of the fracture strengths suggested a spatially distributed flaw population along length of pull tab strength test structures in 125 μm specimen, but not along length of 25 μm test structures.

Processing Produced a Range of Sidewall Defects

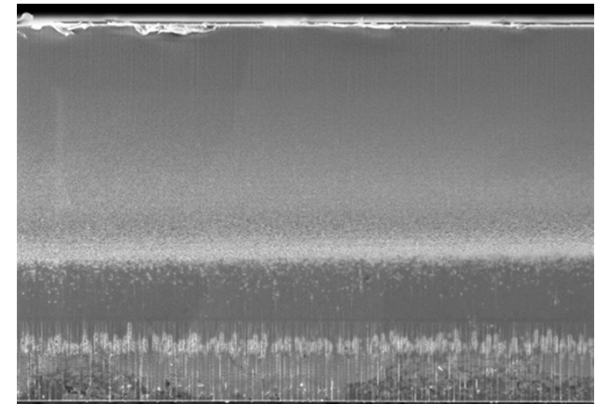
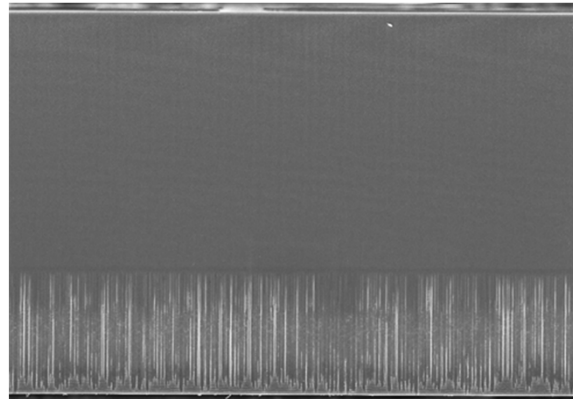
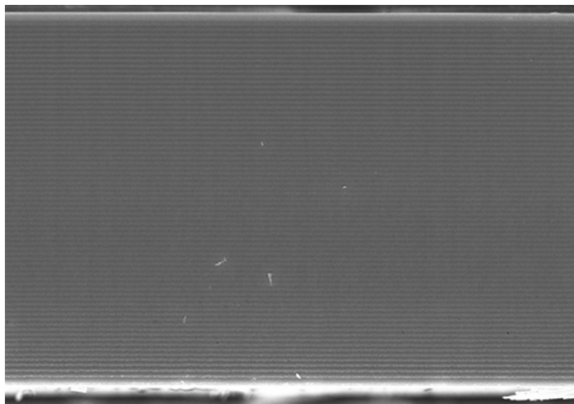
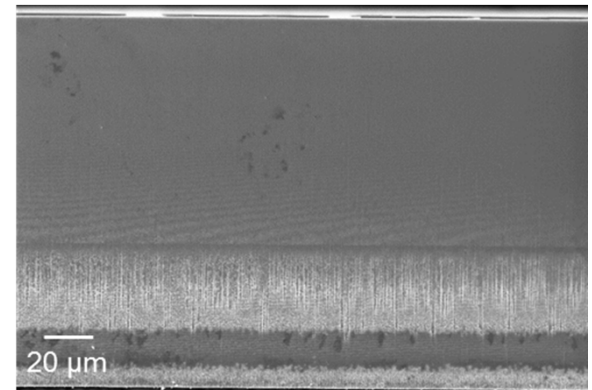
25 μm device layer



75 μm device layer



125 μm device layer



- Suspected a trend in sidewall morphology due to height and adjacent trench width (aspect ratio = device layer height/adjacent trench width)