MEMS Structural Reliability and DRIE: How Are They Related?

AMFitzgerald-Tegal Collaboration

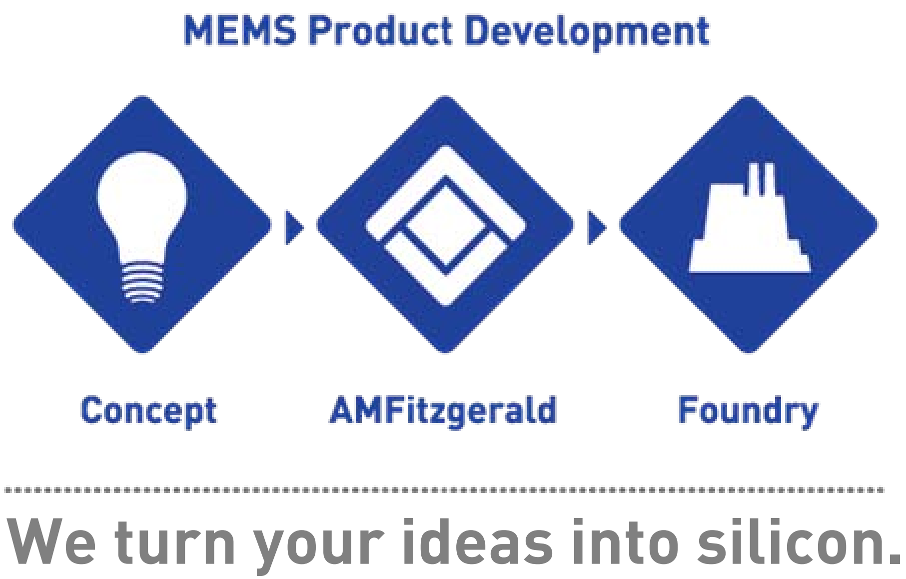
Alissa M. Fitzgerald, Ph.D. | July 27, 2010

AMFITZGERALD
& ASSOCIATES

Overview

- About AMFitzgerald and Tegal
- Motivation for this study
  - Deep reactive ion etch (DRIE)
  - Brittle material properties
- Fracture strength of three DRIE recipes
- Practical application of strength data

Mission


MEMS Product Development
Concept
AMFitzgerald
Foundry
We turn your ideas into silicon.

Fully integrated services: concept to foundry

Technology Strategy	Design Simulation	Prototyping	Testing	Foundry Selection

- **Complete design and project management**
- **Feasibility and cost analysis**
- **Design optimization using simulation**
- **Process development on 100 mm or 150 mm wafers**
  - Prototype fabrication with own staff engineers at UC Berkeley's Microlab
- **Test system development**
- **Packaging, system integration**
- **Technology transfer to foundries for production**

AMFITZGERALD & ASSOCIATES

Tegal ICP Product Range... From R&D to mass production

Contact Paul Werbaneth: (707) 765-5608
pwerbane@tegal.com

Production Volume: Low / Medium / High

Tegal 110
- Manual Single Wfr

Tegal 200
- Single Cassette

Tegal 3200
- Cluster Platform: 1 to 3 PM
- Single Vacuum cassette

Tegal 4200
- Cluster Platform : 1 to 4 PM
- 2 Vacuum cassettes

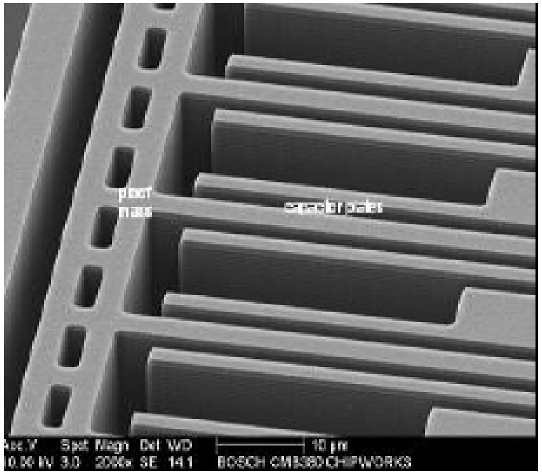
100 % Process Compatibility

Motivation for this study

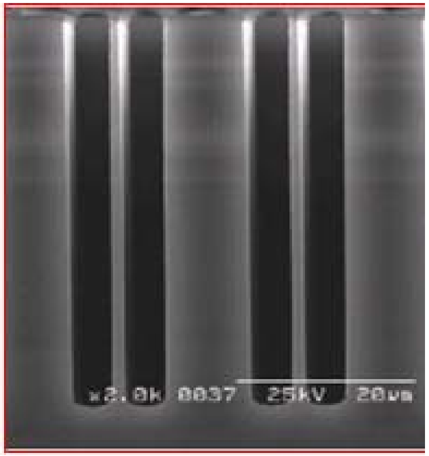
- **Many MEMS devices are fabricated by DRIE**
- **Trench sidewall roughness is a function of DRIE recipe**
- **Smoother surfaces typically exhibit higher fracture strengths**
- **How does fracture strength vary with DRIE recipe (sidewall scallop size)?**

Deep Reactive Ion Etch (DRIE) and MEMS

- **Fundamental etch process for fabricating vertical sidewalls, high-aspect ratio structures**
  - **MEMS**
    - **Gyroscopes**
    - **Accelerometers**
    - **Microphones**
    - **Etc.**
  - **3D structures**
    - **Through silicon vias (TSV)**
    - **Electrical isolation trenches**



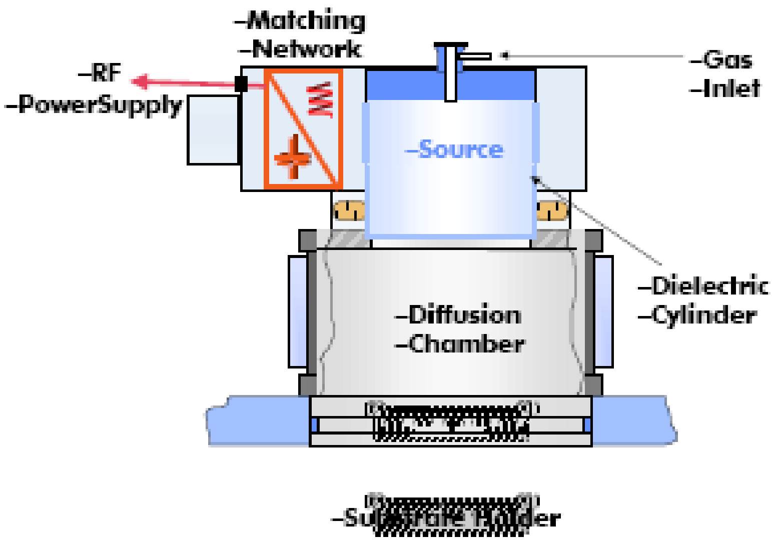
Source: Chipworks
Bosch SMB380 3-axis accelerometer

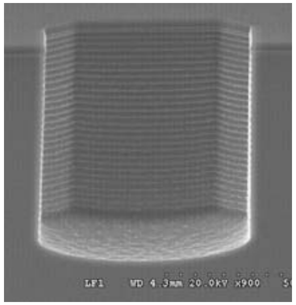


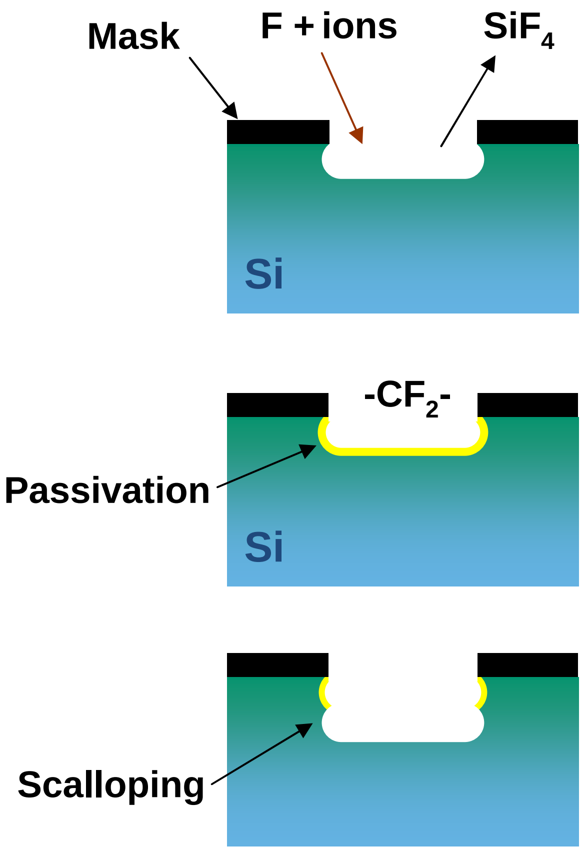
Tegal DRIE for TSV application

The Bosch DRIE Process

A cyclic process alternating between etch and passivation







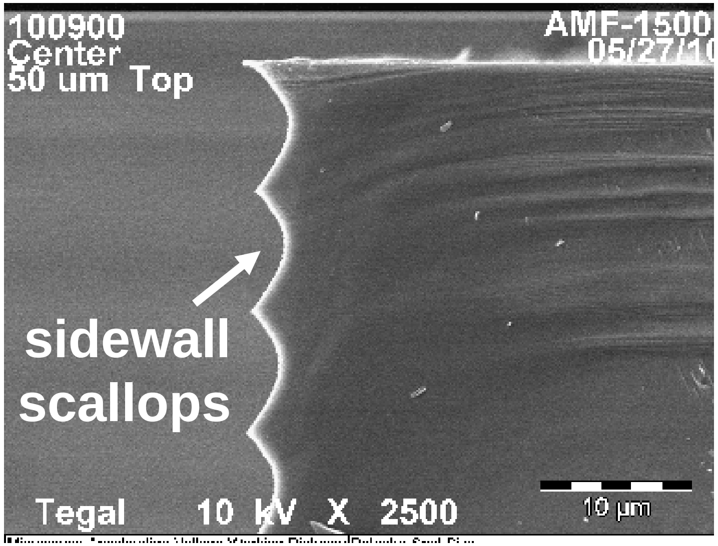
SF_6 Plasma

C_4F_8 Plasma

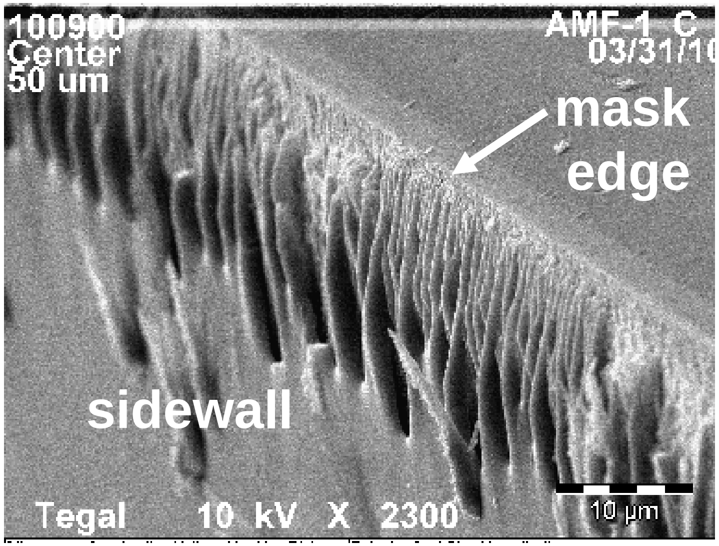
SF_6 Plasma

Two types of DRIE surface features

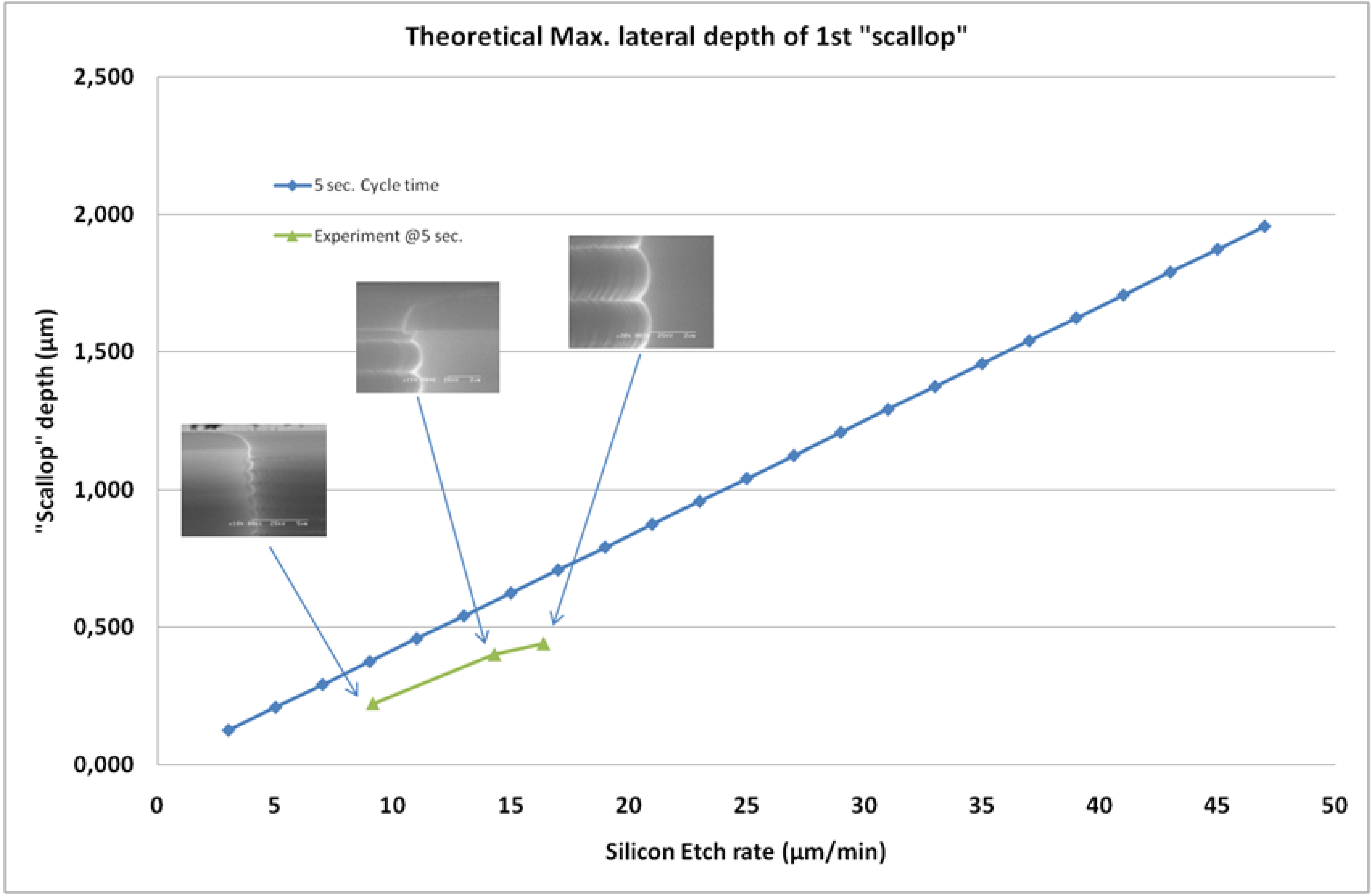
- **The cyclic nature of the Bosch process forms an undulating etched sidewall**



- **Mask edge roughness transferred during silicon etch, forming vertical ridges**
  - **a.k.a “micro-masking”**

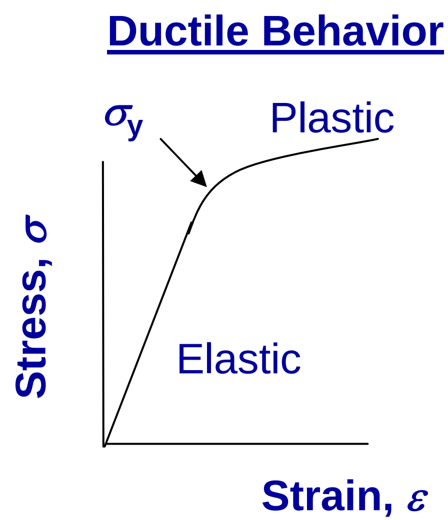


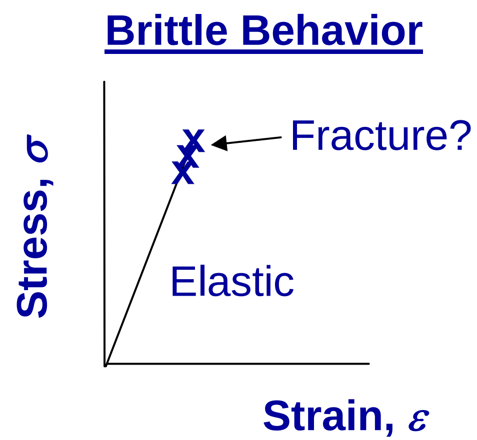
Scallop depth vs. etch rate (for ~ 25% open area)



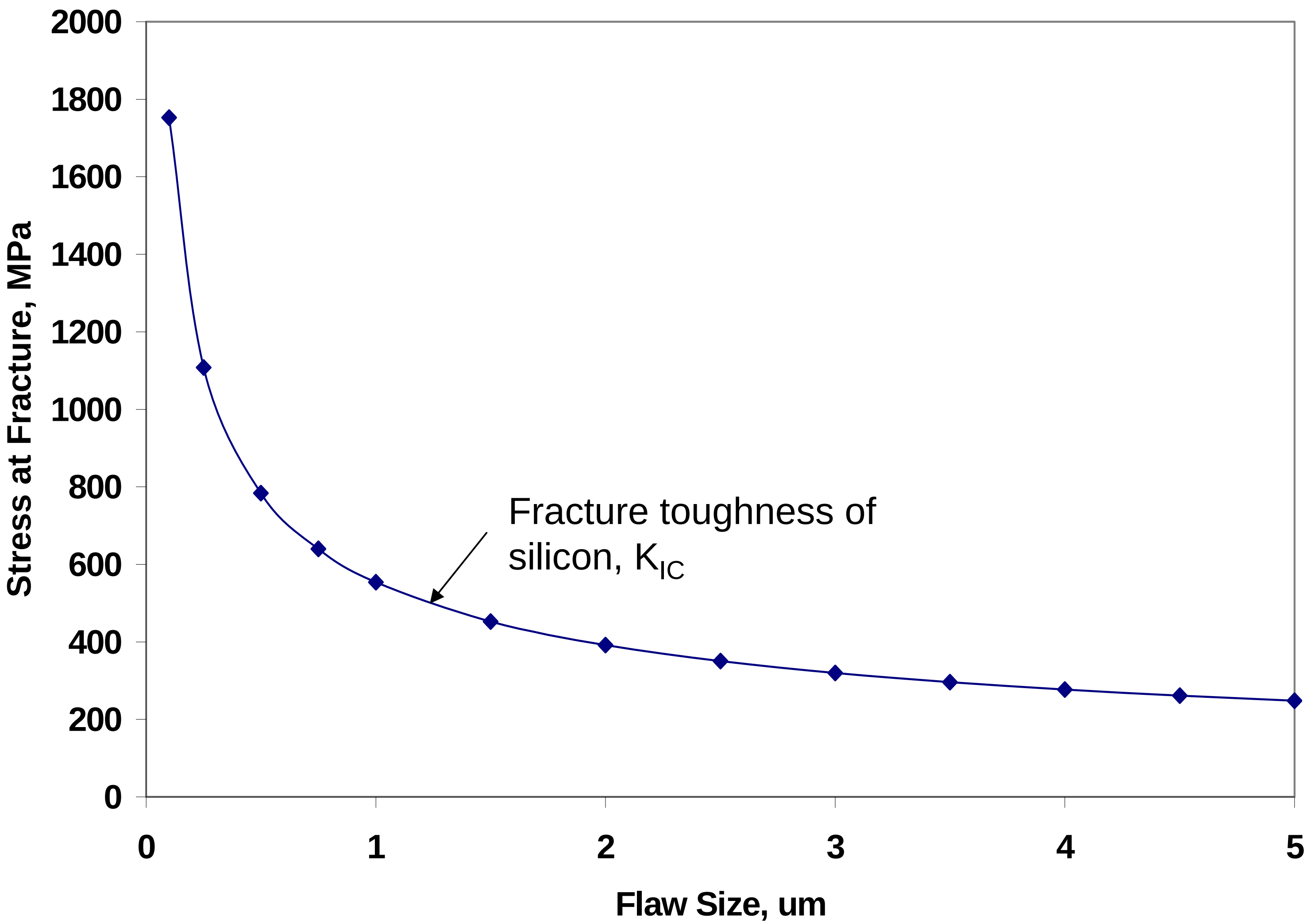
Brittle material behavior

- **Ductile materials (metals) fail at yield strength**
  - **Well-defined limit**
- **Brittle materials (silicon, glass) have a fracture toughness**
  - **Strength is a function of flaw distribution (size, location)**
  - **DRIE creates surface flaws!**
- **MEMS structural reliability depends on etched surface properties**

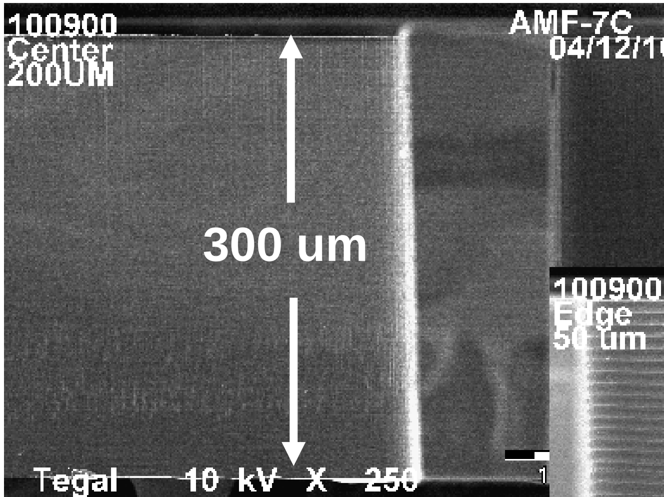




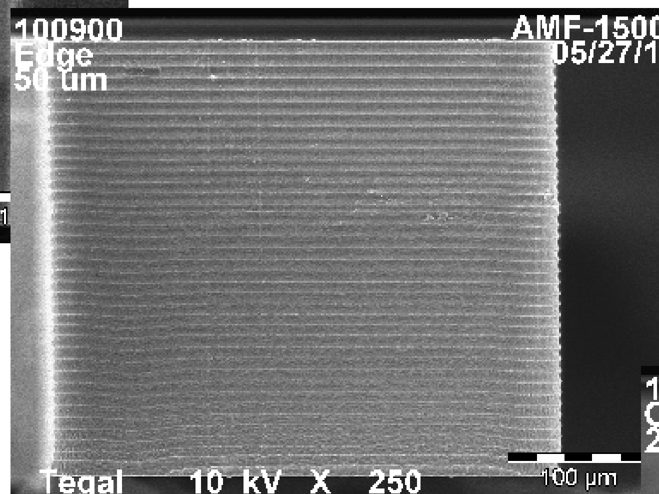
Theoretical stress-flaw size relationship for silicon



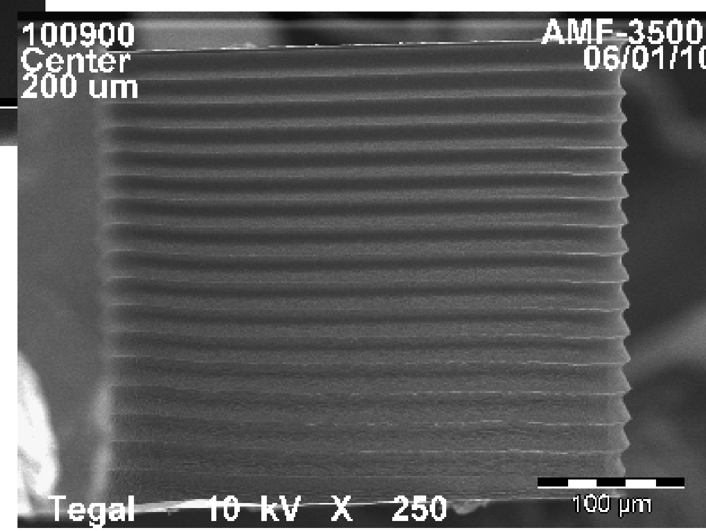
Measure the fracture strength of three different etch recipes



Scallop depth = 150 nm

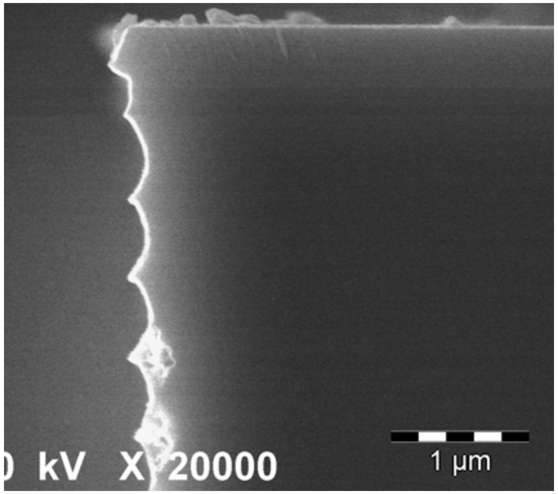


1500 nm



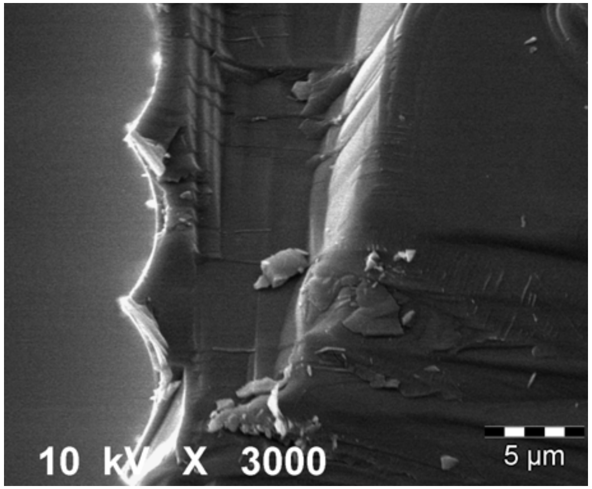
3500 nm

Three different etch recipes: close-up view



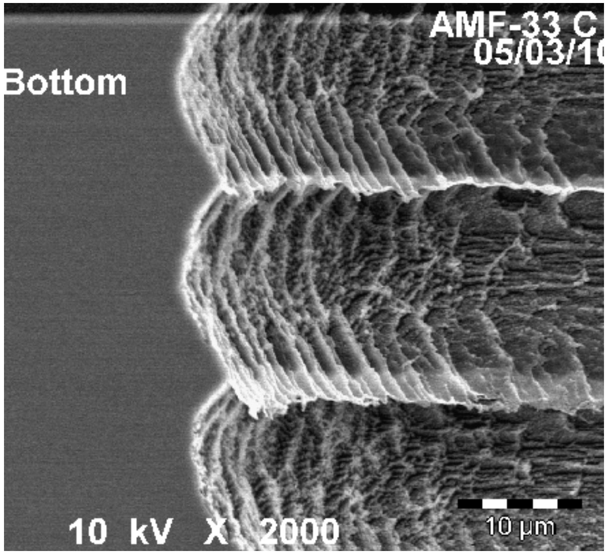
Shallower scallops, but more apexes

150 nm



1500 nm

Which flaws are most significant?

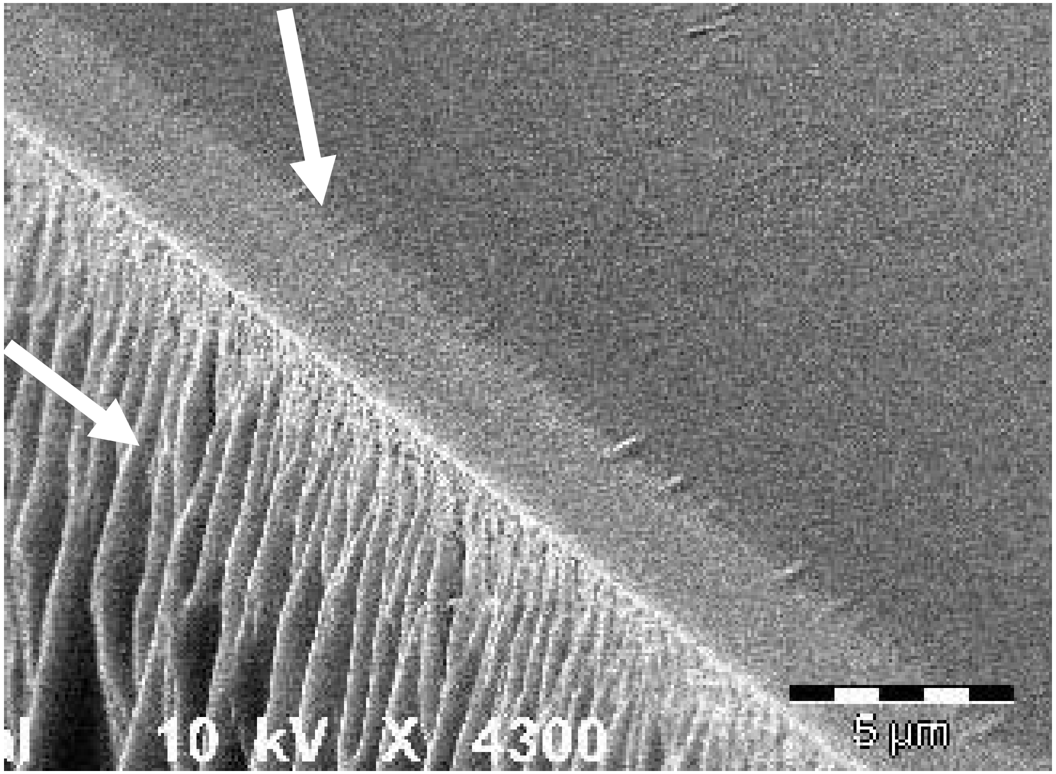


3500 nm

Fourth surface type: the result of poor resist prep

Resist eroded; hard mask revealed

Sidewall micro-masking

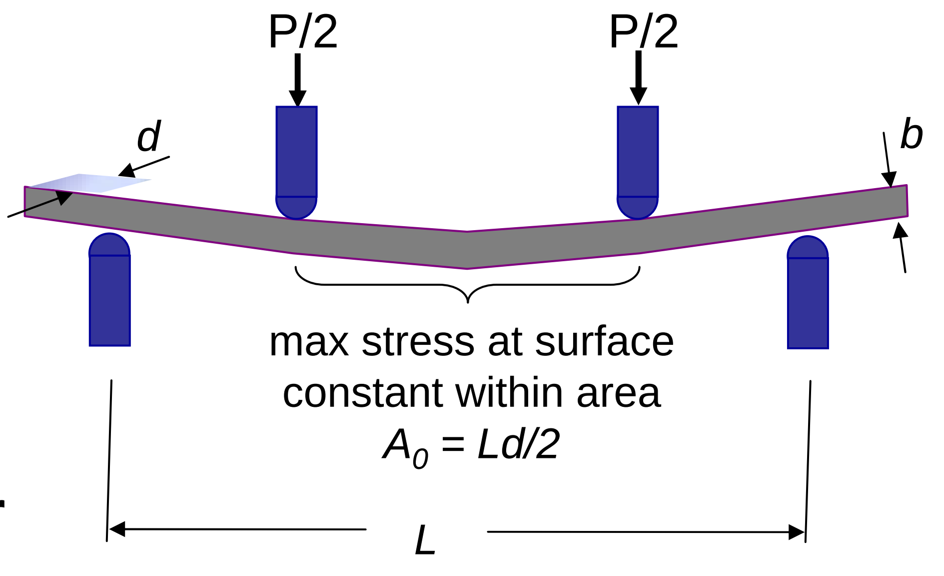


Corner Erosion

Measuring surface strength: four-point bend specimens

Simple but ideal test:

- **Uniform maximum stress develops on beam outer surface**
- **Strength calculated analytically from measured fracture load**
- **No need for inspection or modeling of each individual specimen**
  - **Cost-effective**
  - **Efficient**



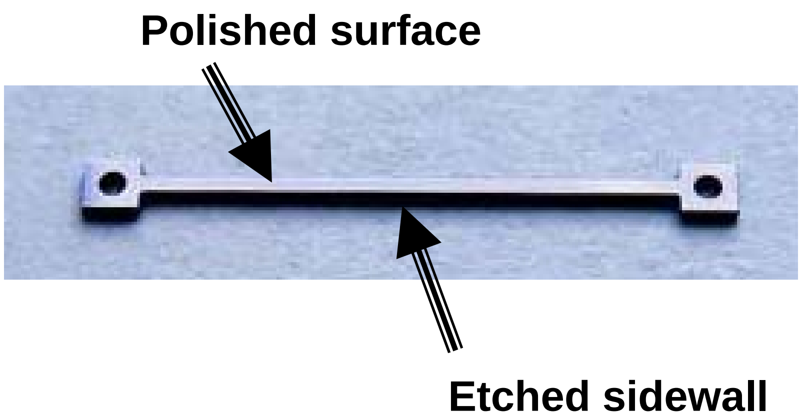
Follows ASTM D 6272-02

Test specimen fabrication

- **Test specimens etched using the different DRIE recipes**
  - **Through-wafer etch of a double-polished wafer**

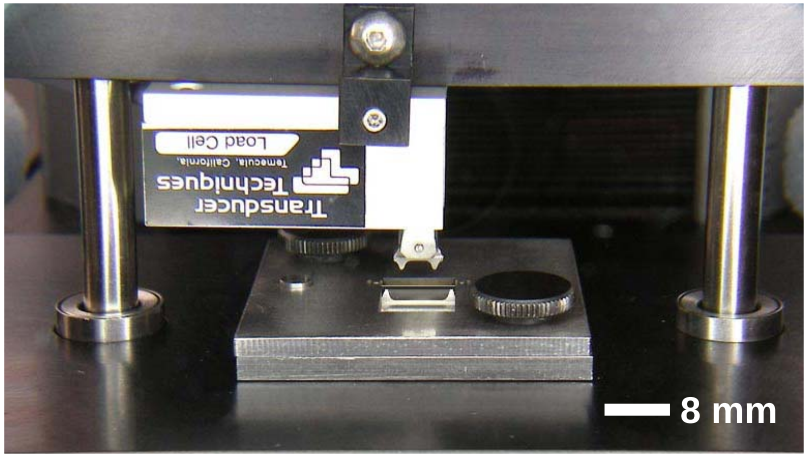
- **Design allows easy handling and testing in macro-scale apparatus**

DRIE-etched silicon test beams
L = 8 *mm*, b = 300 *µm*, d = 310 *µm*

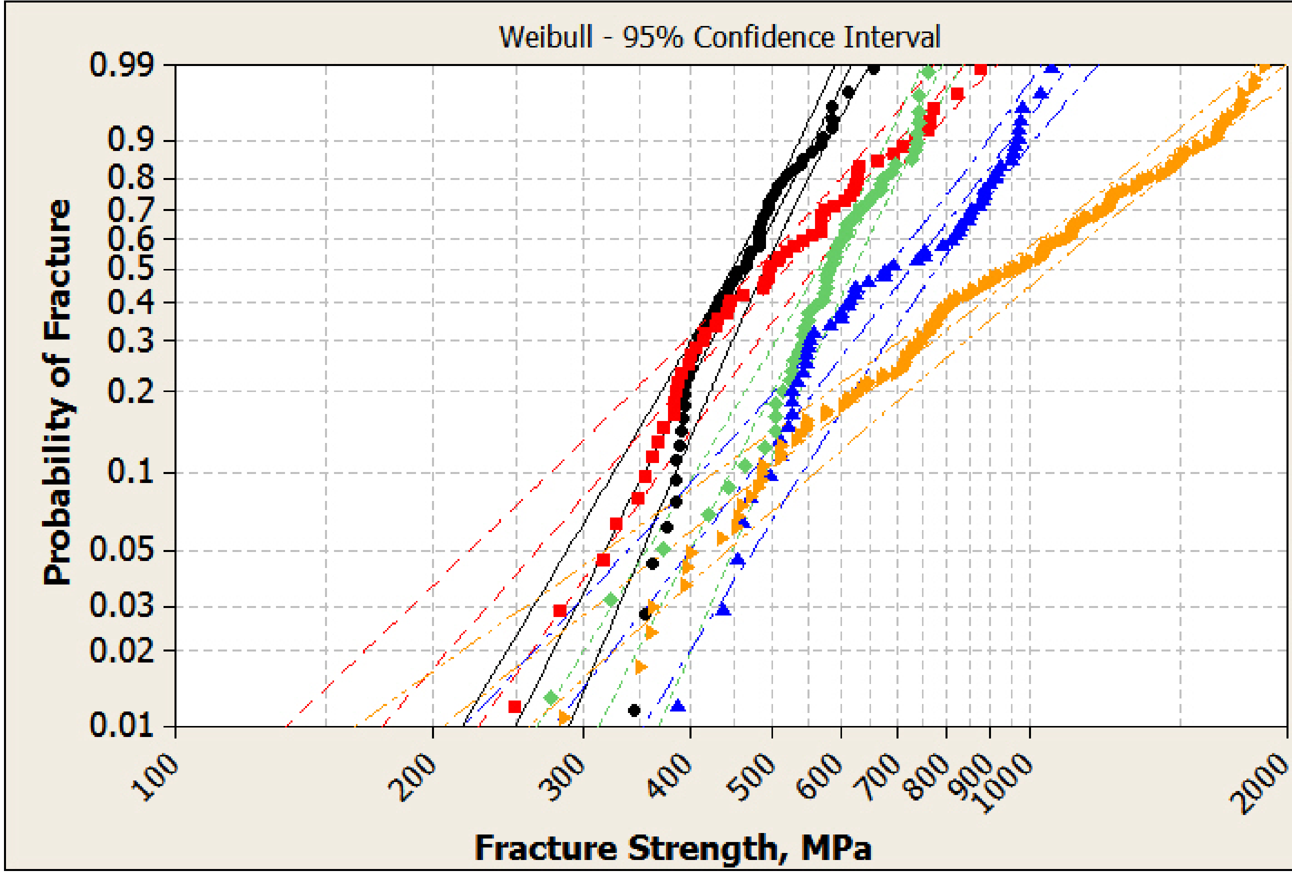


Test apparatus

- **Specially-designed test fixtures mounted to Instron 5542**
- **90º rotation of specimen allows selection of either polished or etched surface**
- **Measure load to fracture**



Results: Fracture strength distribution vs. DRIE recipe



m, Weibull modulus	sigma, char. strength	N
6.735	495.3	60
3.893	569.1	58
6.592	628.9	53
4.390	789.8	58
2.692	1133	156
	[MPa]	

Weibull analysis follows ASTM C 1239-07

AMFITZGERALD & ASSOCIATES

Observations

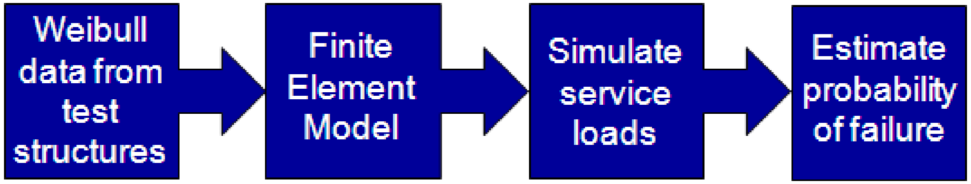
- **Polished surface ~ 2x stronger than etched surfaces**
- **40% difference in characteristic strength across three recipes**
- **Mask preparation influences surface strength**
  - **Resist recipe AND etch recipe are important**
- **Etch recipes have statistically distinct Weibull parameters**
  - **“Figures of Merit” for process control monitoring**

Application of Fracture Strength Data

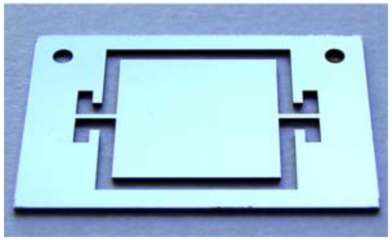
Applications for fracture strength data

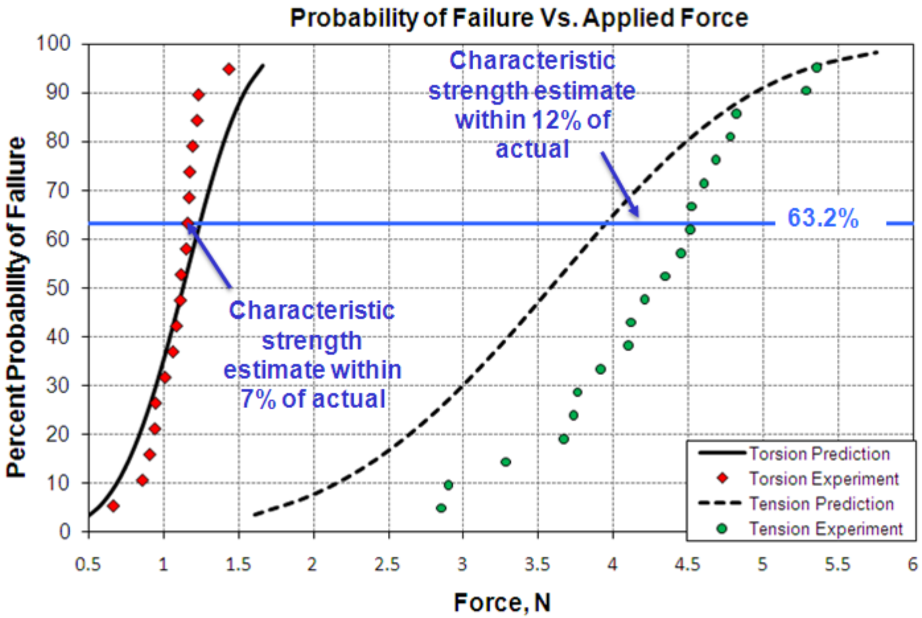
Foundry/Etch Tool Selection	• **Compare fracture strengths across recipes, etch tools, foundries** • **Make informed purchase decisions**
Cost Savings	• **Informed etch recipe selection to optimize wafer throughput without sacrificing reliability** • **Reduce development time** • **Improve yield**
Quality Control	• **Monitor etch process stability** • **Across-wafer uniformity** • **Diagnose in-process fracture failures** • **Improve mechanical reliability**
Design	• **Reliability simulation, fracture prediction** • **Performance improvements** • **Size reduction**

AMFitzgerald Fracture Prediction Methodology



- Identifies where and when a device is most likely to break
- Informed design
- Reduction of time to market: fewer design, fab, test cycles required
- Process IP stays secure: fabrication and fracture of test specimens is all that's needed





Summary

- **Fracture strength varied by 40% across recipes tested**
- **Mask preparation influences surface strength**
  - **Resist recipe AND etch recipe are important**
- **The methods used here have broad applicability to recipe/tool/foundry selection, quality control and design**
- **Contact Alissa Fitzgerald (amf@amfitzgerald.com)**
  - **Information on test services and fracture prediction**
  - **A copy of the slides**

Acknowledgments

- Brent Huigens, Dawn Hilken, Carolyn White
- Tegal: Geneviève Bèïque, Florent Modica, Paul Werbaneth
- Instron Corporation: Karl Malchar

AMFITZGERALD
& ASSOCIATES