

Leveraging Simulation in MEMS Development

Coventor Workshop | Woburn, MA

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AMFITZGERALD
& ASSOCIATES

Overview

- **About AMFitzgerald**
- **Why is MEMS development still so hard?**
- **Value of simulation**
- **Leveraging simulation – practical tips**
- **Closing remarks**

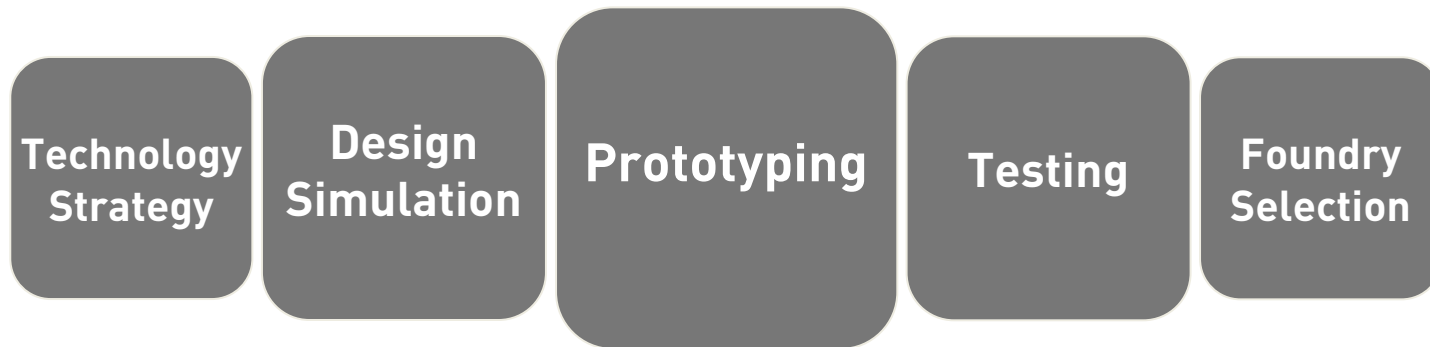
Mission

MEMS Product Development



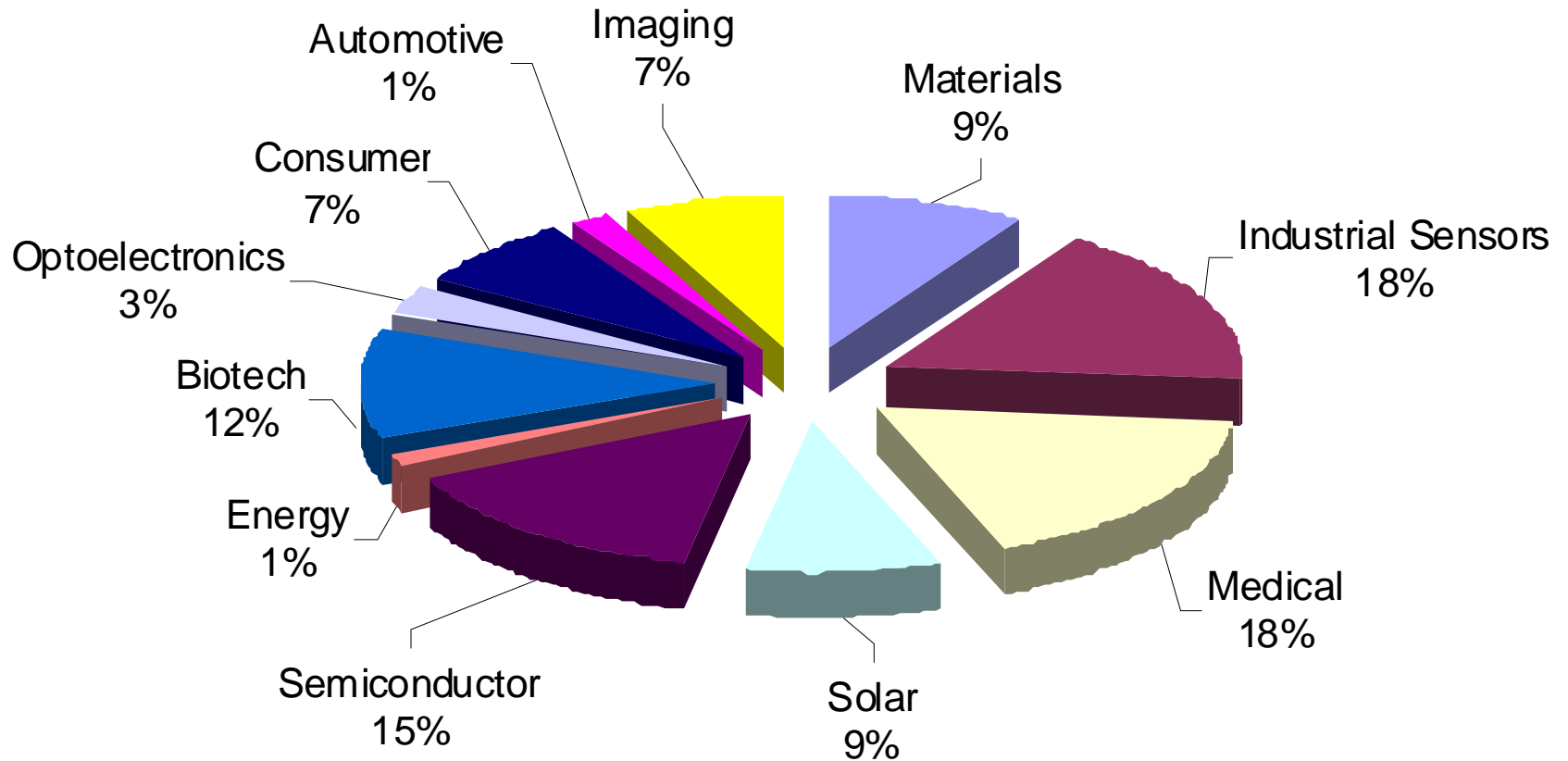
We turn your ideas into silicon.

Fully integrated services: concept to foundry



- Complete design and project management
- Feasibility and cost analysis
- Design optimization using simulation
- Process development on 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

Our diverse customer base



MEMS design and prototyping expertise

Technologies we have developed:

- **Piezoresistive sensors**
- **Piezoelectric (AlN and ZnO) sensors**
- **Capacitive sensors**
- **Electrostatic actuators**
- **Micro-cantilevers**
- **Microfluidics**
- **Mold masters**
- **Gratings and lenses (x-ray, optical, acoustic)**
- **Solar cells**

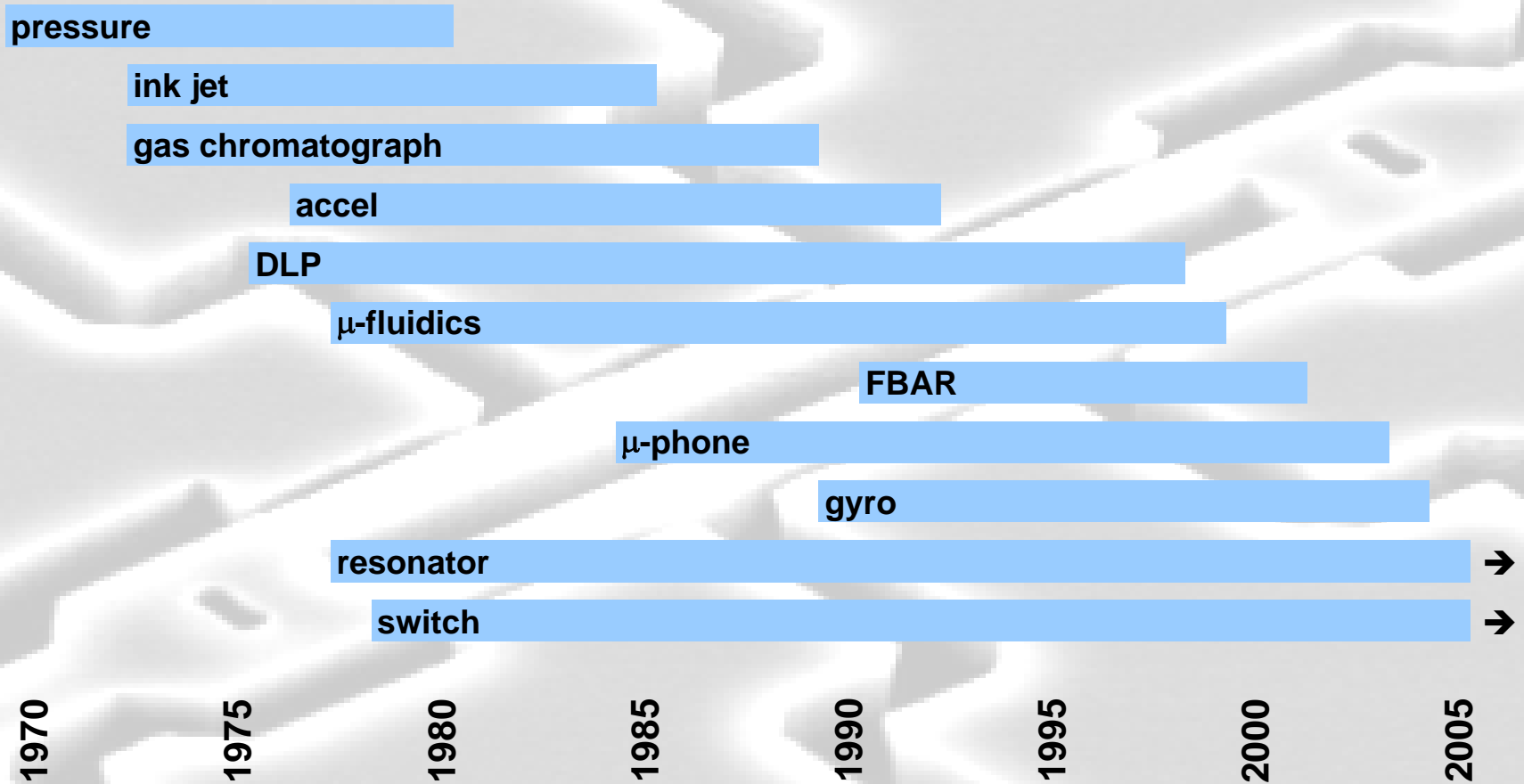
Over 70 clients served

Application areas:

- **Consumer electronics**
- **Medical implant**
- **Medical diagnostics**
- **Infrared imaging**
- **Industrial safety**
- **System health monitoring**
- **Ultrasound imaging**
- **Optical telecom**
- **Solid state lasers**
- **Chip cooling**
- **Cell culture**
- **Drug discovery**
- **Gas flow metering**
- **Advanced packaging**
- **Solar**

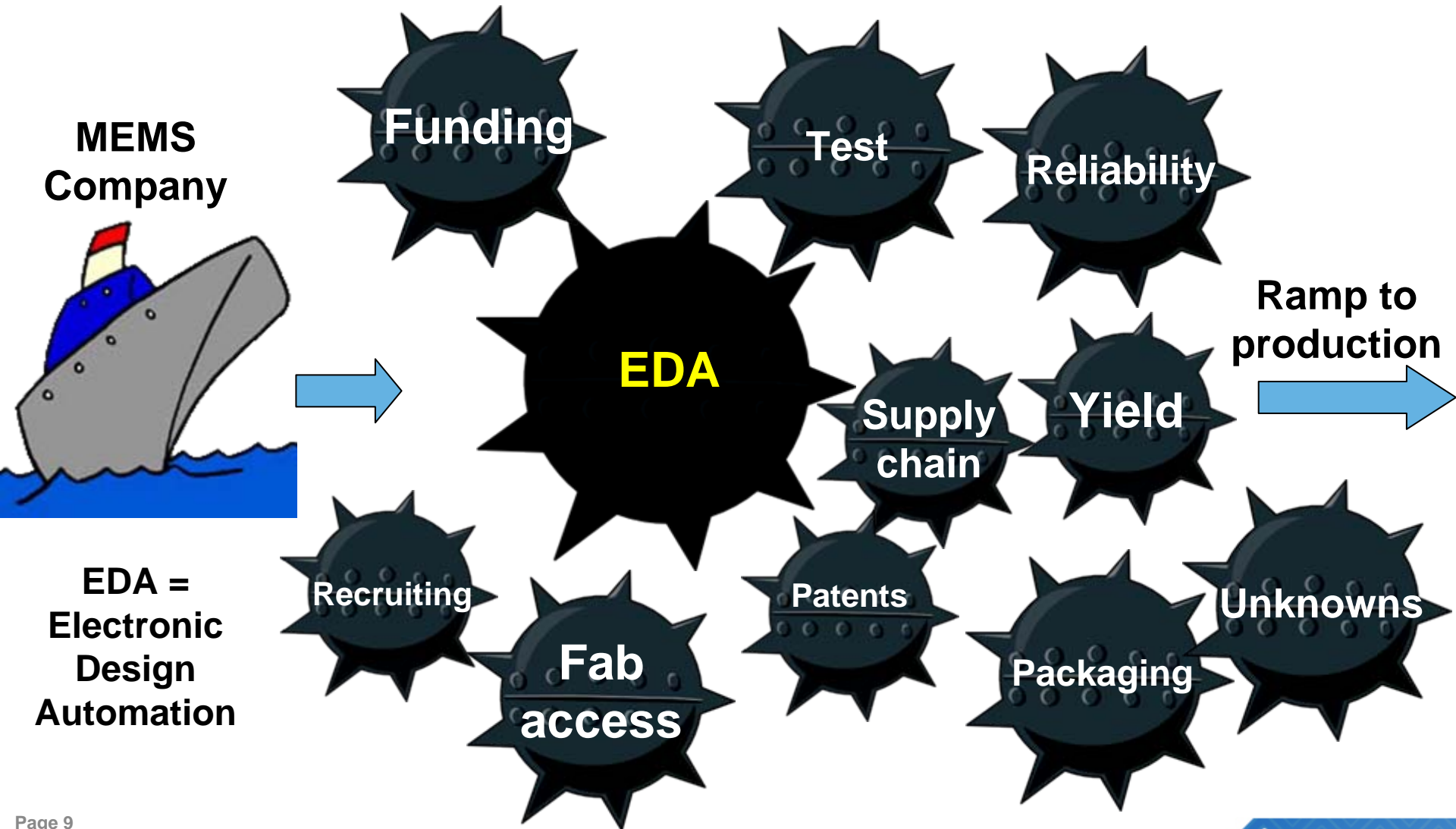
Why is MEMS development still so hard?

MEMS R&D Cycles



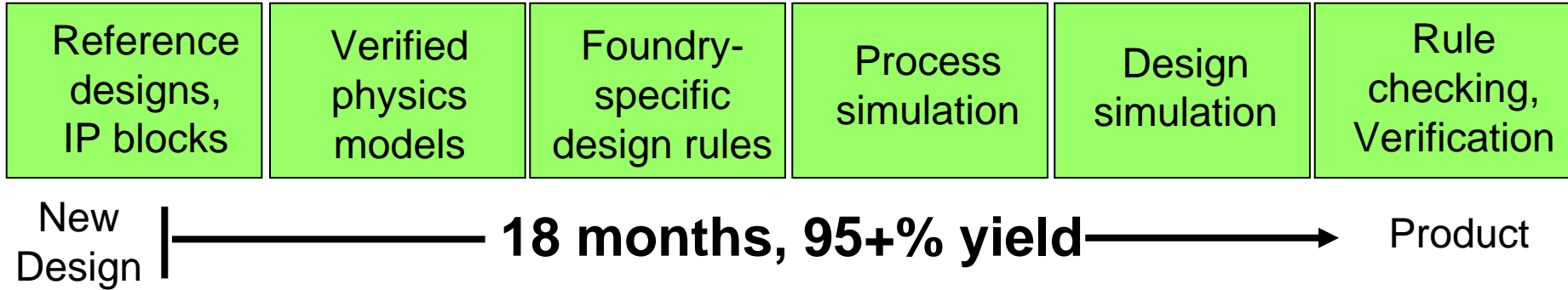
The perilous MEMS development journey (early stage)

Millions of dollars, years and many casualties

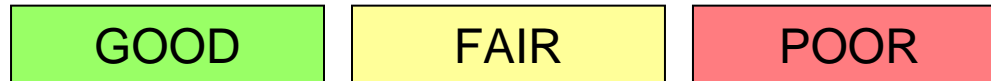
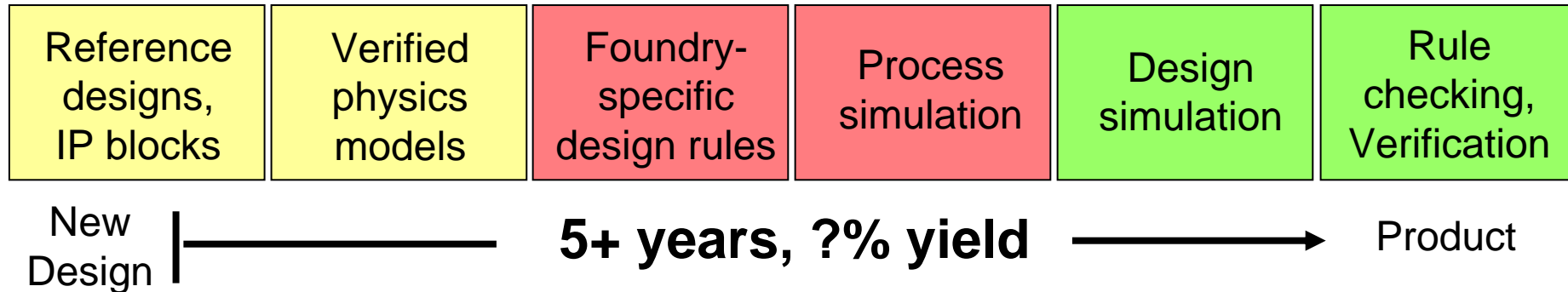


Lack of integrated EDA forces multiple design-fab-test cycles

Semiconductor EDA



MEMS Industry EDA



MEMS industry must work to close these gaps

Reference designs, IP blocks

Only established MEMS companies have these (proprietary) – a major advantage

Verified physics models

Stiction, electrostatic charging, fracture, time-dependent material behavior

Foundry-specific design rules

Rules to prevent unfeasible or marginal designs

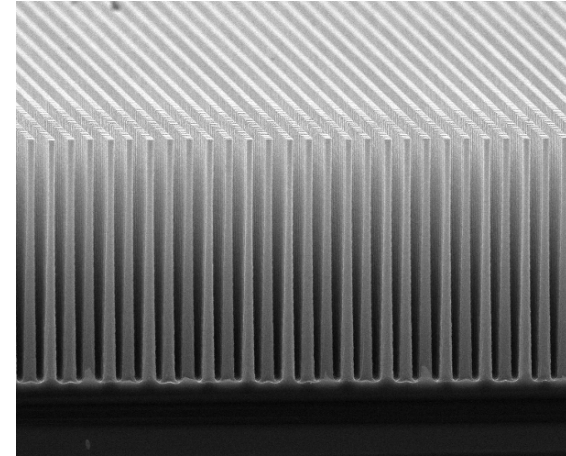
Process simulation

Understanding how process affects mechanical performance

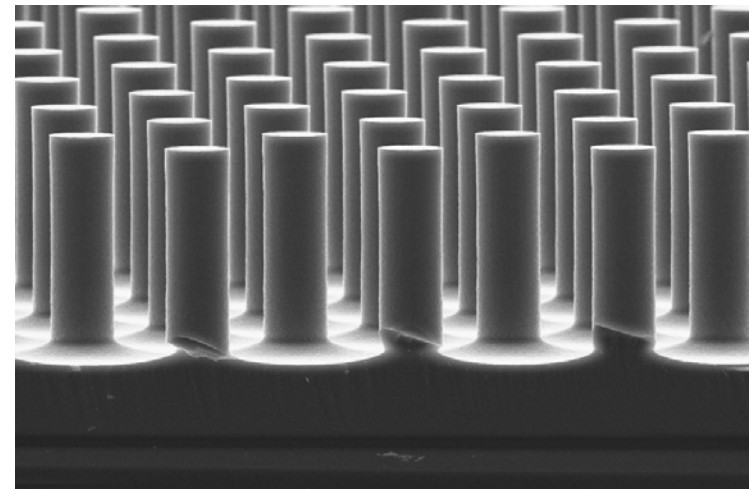
Rules to prevent unfeasible designs

- **MEMS PDKs needed – Process Design Kit**
 - What features can be robustly manufactured?
- **Examples of process/feature design rules:**
 - Feature size resolution
 - Step coverage geometry
 - Pattern load factor allowed (% of wafer being etched)
 - Process module sequencing
 - No litho after deep etch

2 um pillar, 20:1 aspect ratio



High load factor etch

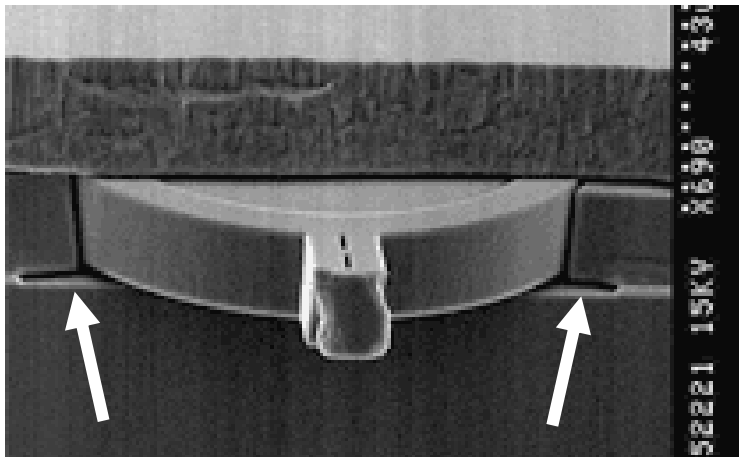


AMFitzgerald

Process affects mechanical performance

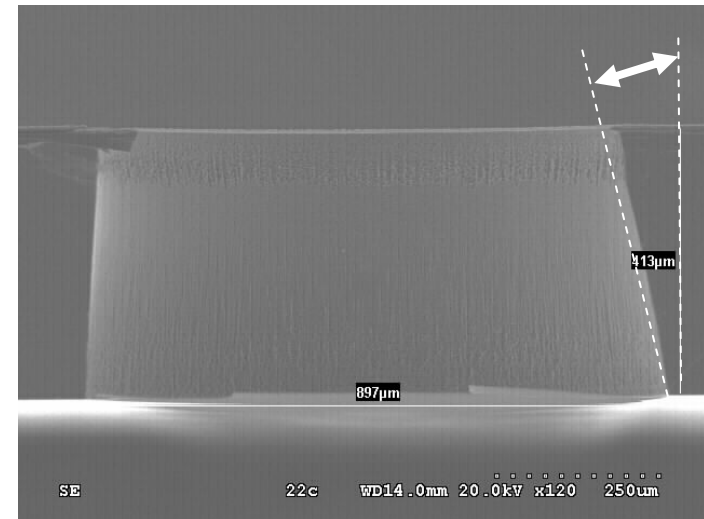
- **Lateral undercutting (boundary conditions)**
 - Resonant structures greatly affected
- **Thermal budget (film stresses)**
- **DRIE etch sidewall (geometry)**
 - Critical to inertial sensor performance

Undercut during sacrificial release



Chipworks, SiTime

DRIE sidewall taper in large open area



Tegal

Lack of integrated EDA hurts the entire industry

- **Time to market suffers badly**
 - Impaired ability to reach new markets
 - Opportunity cost
- **Under-utilization of simulation leads to wasted time and money in the fab**
 - More on this in a minute!
- **Escalating, unknowable development costs**
 - Soured investors, premature death of companies

The value of simulation

If you were lost in the wilderness...

If you had a GPS unit, it would be easy to get home



With some effort, you could find your way with a compass



But you wouldn't just start wandering around, would you?

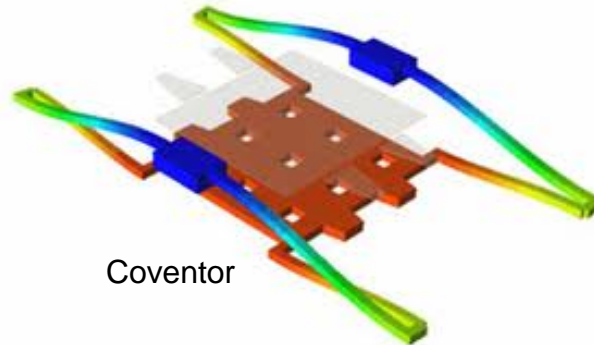


MEMS development often gets lost in the wilderness

We don't have a perfect EDA system to give us all the answers

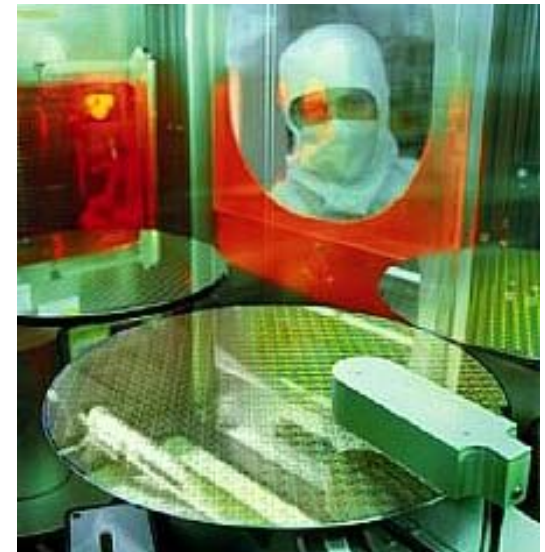


Simulation can't tell us everything, so why bother?



Coventor

We're fab guys - let's just build it and see what happens.



Top excuses for avoiding simulation

- 1. “The software is too expensive”**
- 2. “I don’t trust the results” (= I don’t understand how to use the software properly)**
- 3. “We don’t know our material properties”**
- 4. “We need to build prototypes anyway”**
- 5. “We can figure it out by doing lots of design variants” (Design of Experiments)**
- 6. “We tried, but we could never get the model to match reality”**

It's slow and expensive to "just build it"!

- **Bare minimum costs for a development batch of ten 150 mm wafers (recurring costs only)**

6 layer MEMS process

Burdened labor rate \$100/hr.

Fab cost per layer (mask+fab) \$15K, 1 week

	<u>Man-hours</u>	<u>Cost</u>	<u>Time, weeks</u>
Mask layout and checking	160	\$ 16,000	2
Fab cost		\$ 90,000	6
Test and measurement	80	\$ 8,000	1
Total		\$ 114,000	9

How many design-fab-test cycles can you afford?

The tools we have are much better than nothing

Take the time to learn how to use it properly. It could save your company.



Leveraging simulation – practical tips



Typical challenges in simulation of MEMS

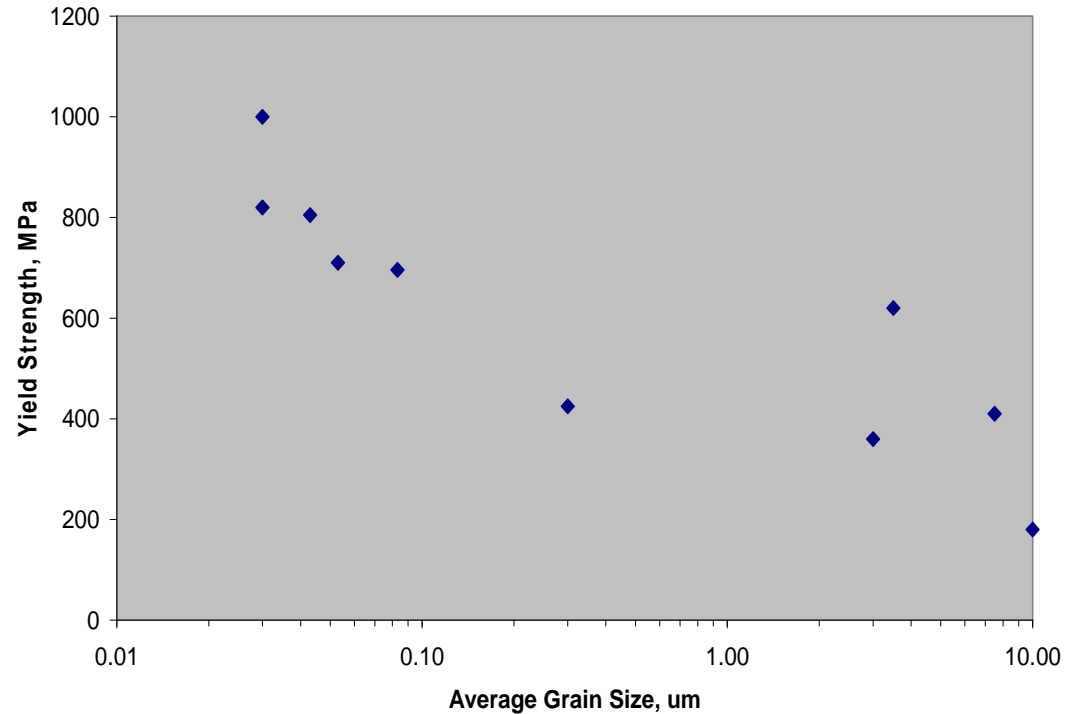
- **Materials properties uncertainty**
 - Thin film properties
 - Non-linear behavior
- **Boundary conditions**
- **Load limits for brittle structures**

- **You can work around these – with some effort – and reap the benefits of simulation**

Problem: Materials properties of thin films

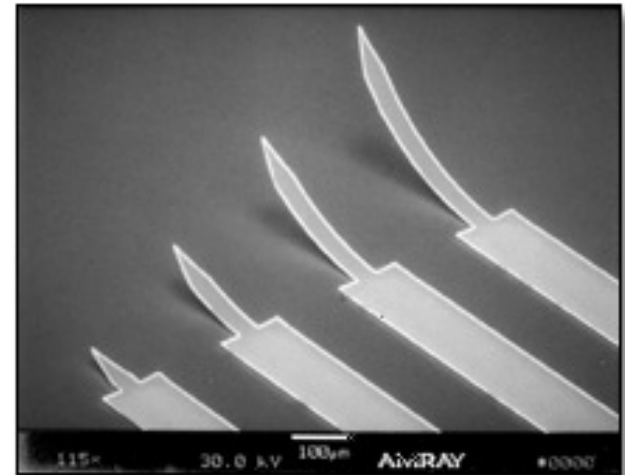
- Recipe dependent
- Tool to tool variation

Figure 1: Correlation of Grain Size with Tensile Strength of Electroplated Nickel

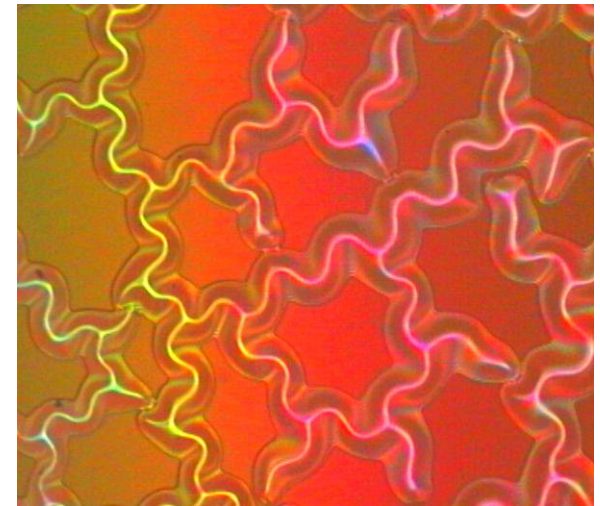


Problem: Residual stress in thin films

- **Stress due to CTE mismatch and/or intrinsic to material**
 - Metals typically tensile
 - Oxides always compressive
 - *Stress can change with thermal budget*
- **Released structures are affected: beams, membranes**
 - Bowing, buckling
 - Cracking
 - Frequency shifts



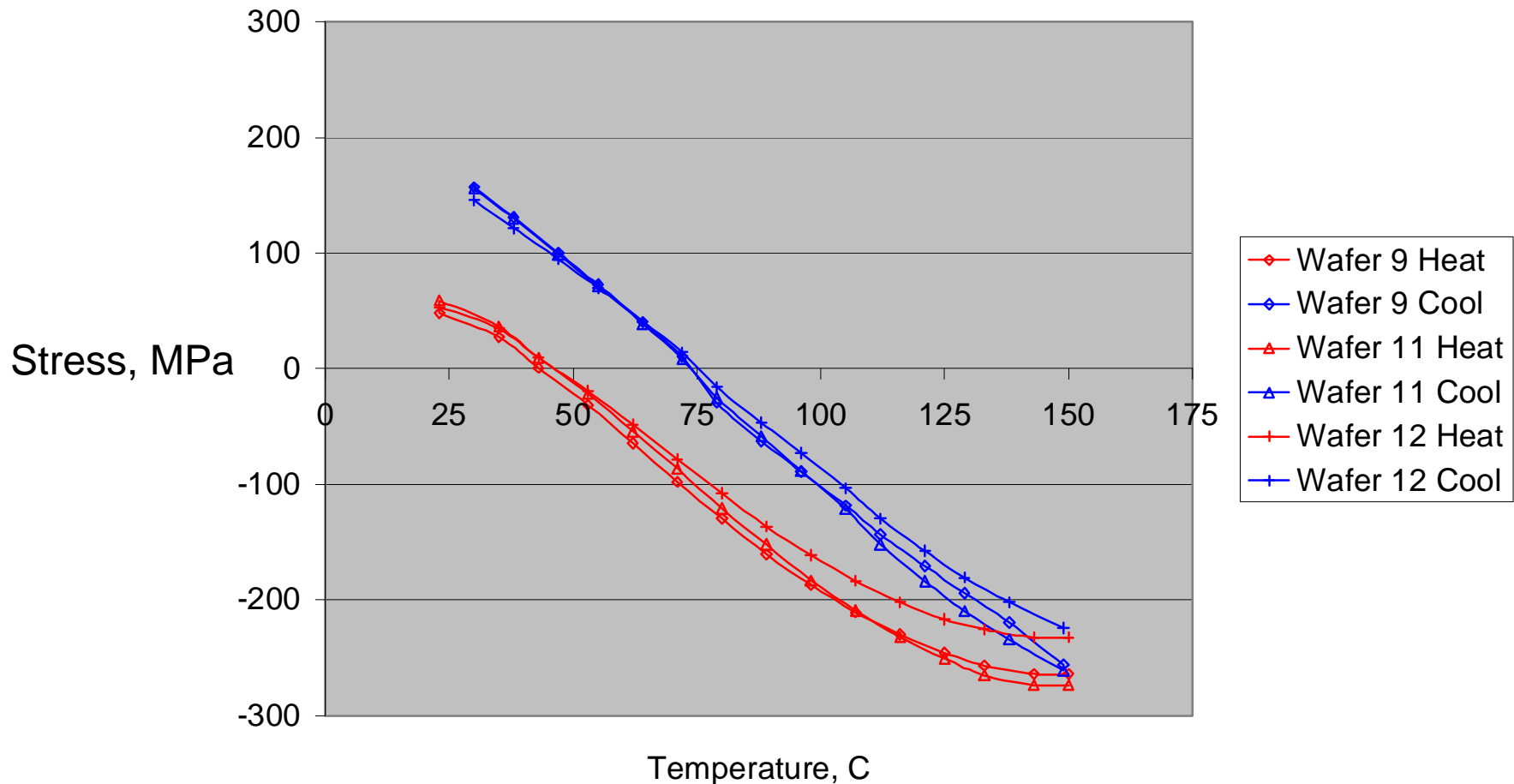
parc's StressedMetal AFM tips



Fraunhofer IOF

Problem: Thermal budget affects material properties

- Thermal cycle caused 100MPa change in residual stress due to plastic deformation in metal film



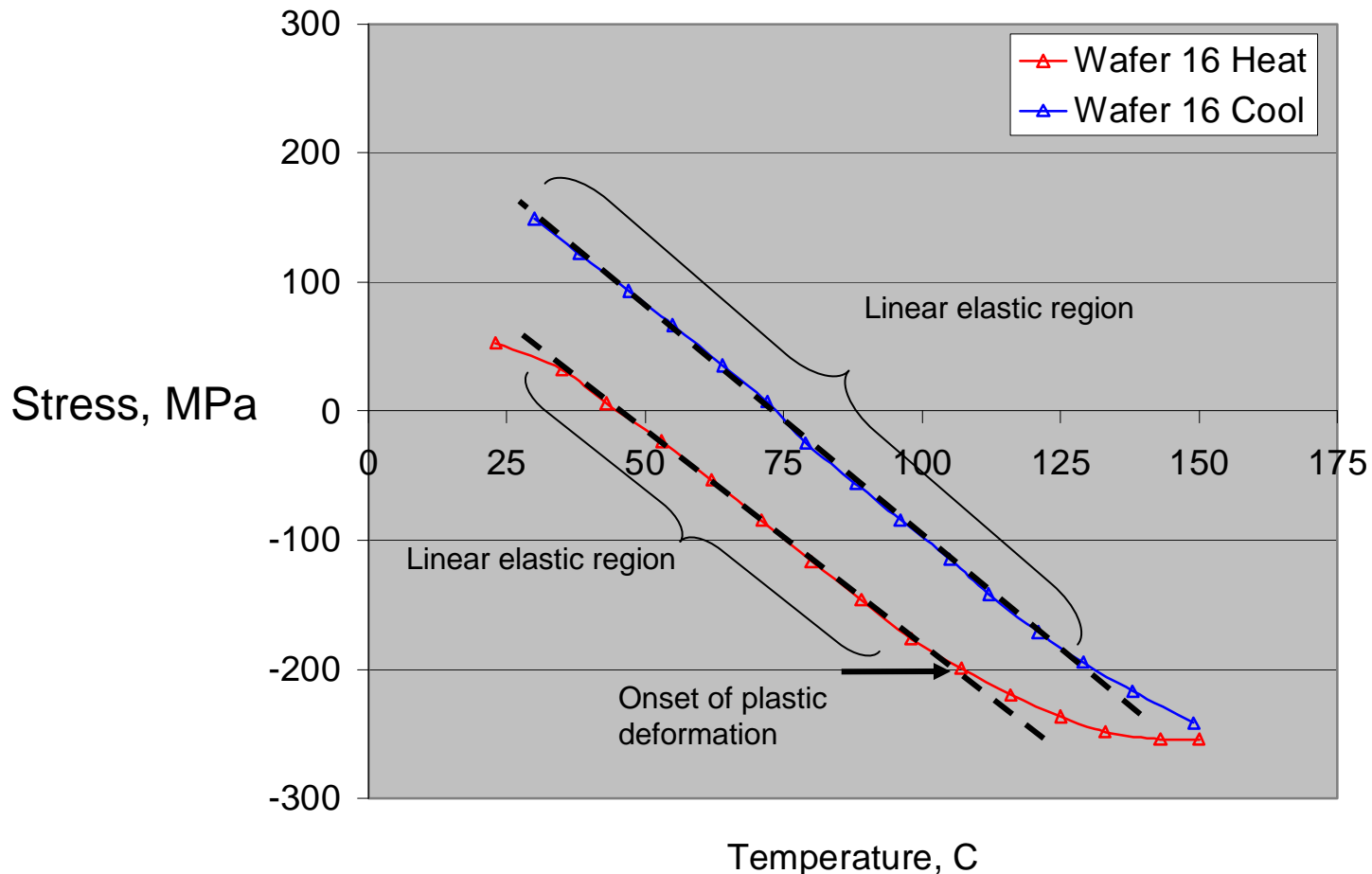
Solutions: Parameter sensitivity analysis

- **Conduct Design of Experiments in the computer, not the fab! Many permutations can be quickly evaluated.**
 - Start with textbook material property values
 - Hold modulus (E) constant, vary geometry
 - Hold geometry constant, vary E, etc.
 - Try to reduce sensitivity to material properties through smart design choices

- **If your design is sensitive to material properties, you will need measurements to improve simulation accuracy**
 - Wafer-level
 - Test structures

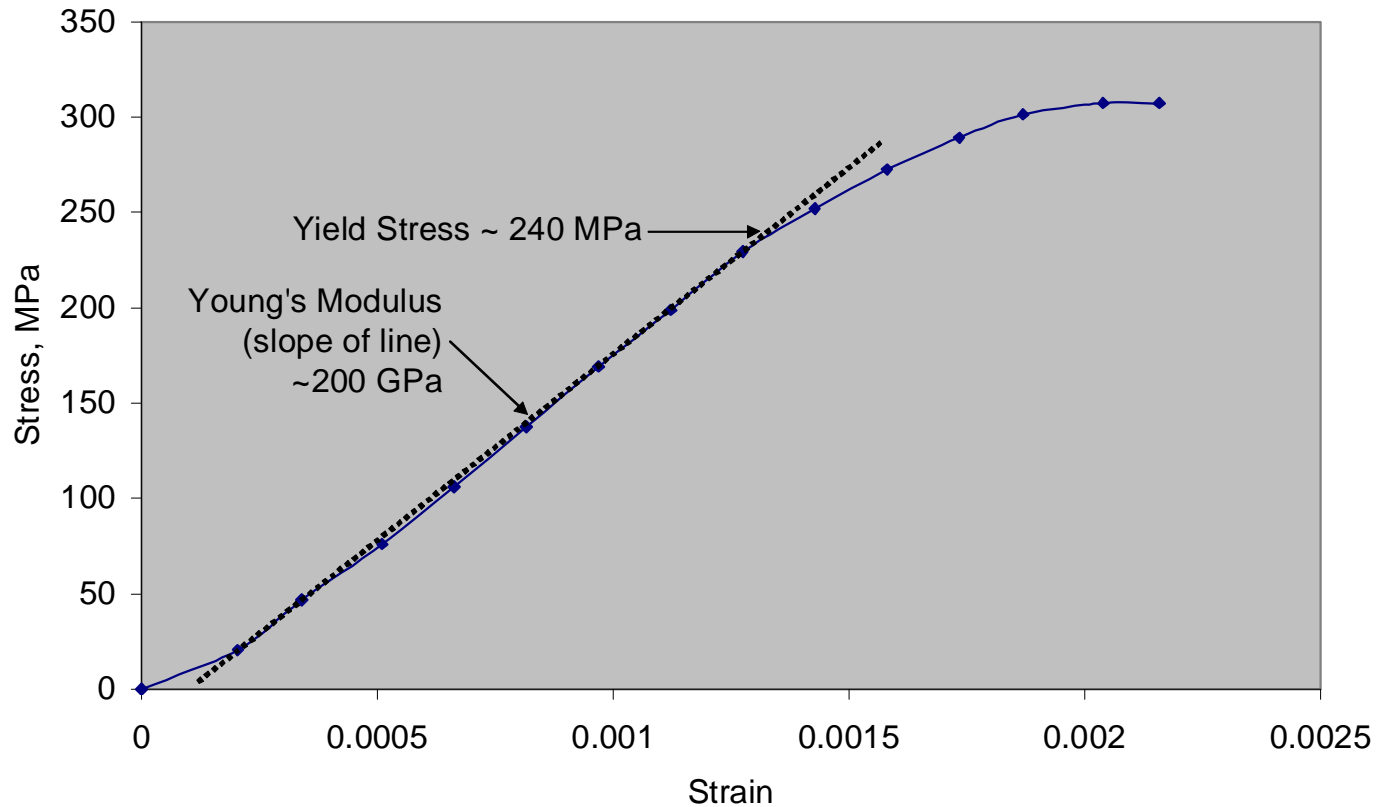
Solutions: Wafer-level measurements

- KLA-Tencor Flexus scans on whole wafers with blanket films can provide a lot of useful data



Solutions: Wafer-level measurements

- Modulus E , σ_{yield} can be estimated from wafer-level film stress data

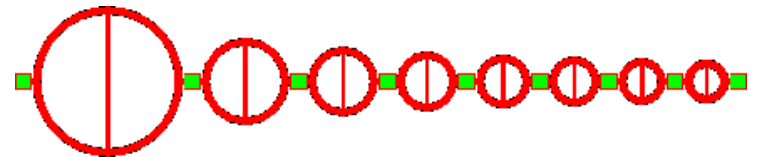


$$\varepsilon = \alpha \Delta T$$

Solutions: Test Structures

- **Strive for simple test structures that can be made with a subset of the process flow**

- Cantilevers, Guckel rings, etc.



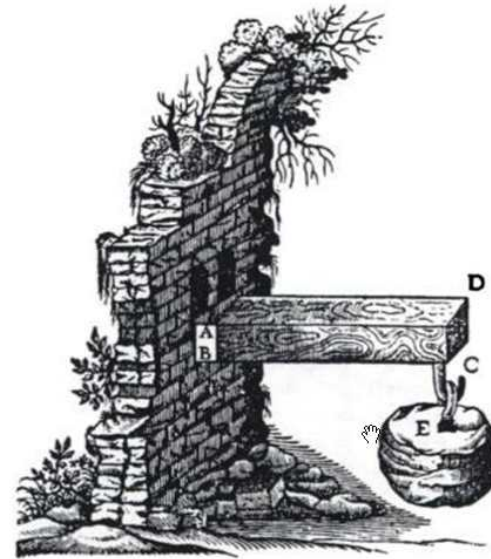
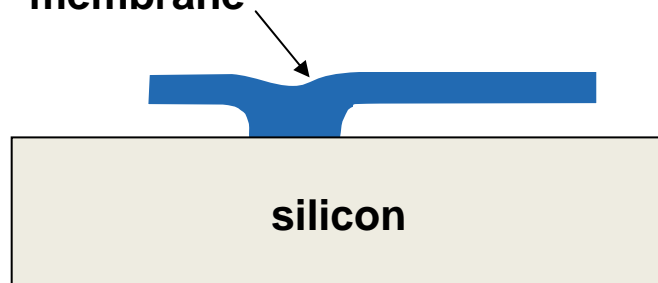
Visual indicator of stress

- **Resources for test structures and techniques:**
 - NIST: <http://www.eeel.nist.gov/812/test-structures/MEMSCalculator.htm>
 - MUMPS: <http://www.memscapinc.com/cug/mc6.html#3.3.3>
- **NIST and ASTM standards for thin film testing:**
 - E 2244, 2245, 2246: Measurements of Thin, Reflecting Films Using an Optical Interferometer

Problem: Accurate model boundary conditions

- “Fixed” condition usually too stiff compared to reality
- Thin film structures do not have true “built-in” conditions

Polysilicon cantilever or membrane

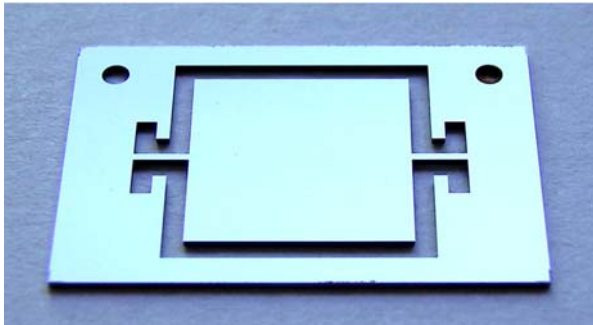


Fixed condition: Galileo's model of the built-in cantilever

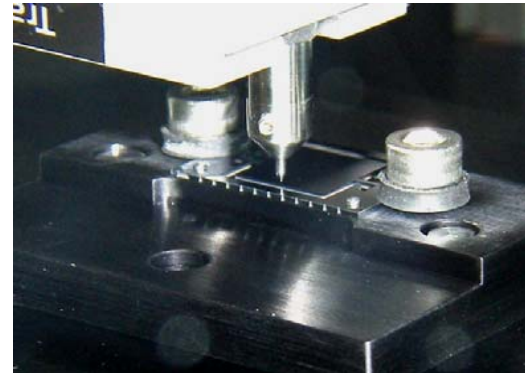
J.W. Wittwer, L.L. Howell, “Mitigating the Effects of Local Flexibility at the Built-In Ends of Cantilever Beams”, *Journal of Applied Mechanics*, Volume 71, Issue 5, pp. 748-751 (2004)

Solution: Measure stiffness to correct model

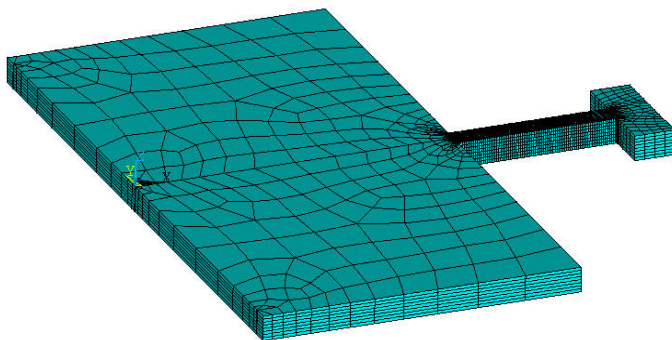
Simple micro-mirror



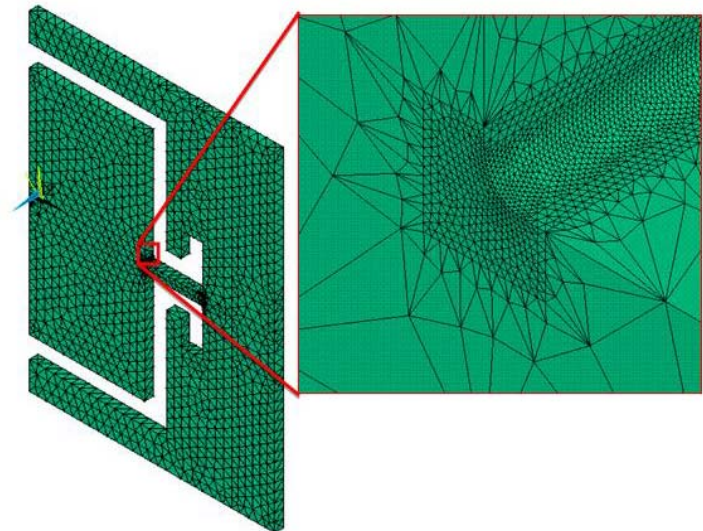
Force vs. displacement measurements proved original model too stiff!



Original FE half-model



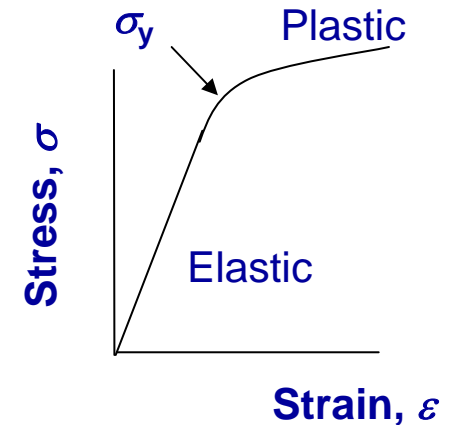
Improved half-model



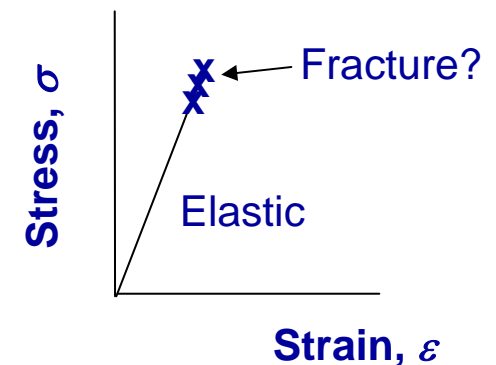
Problem: Predicting load limit of a brittle structure

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

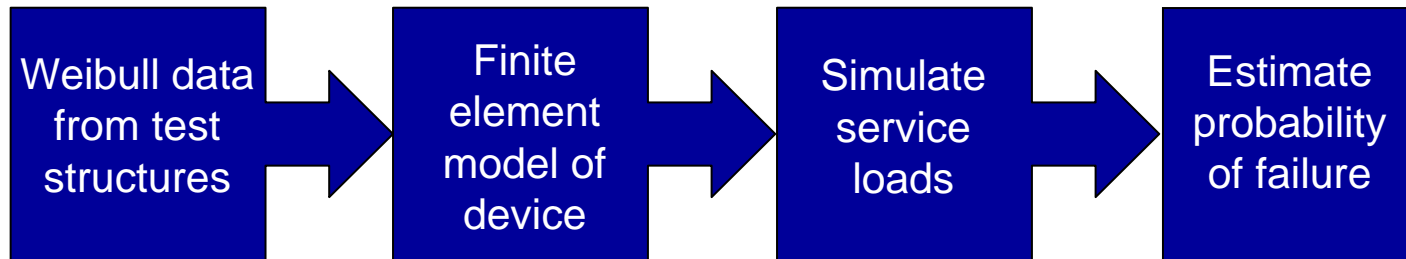
Ductile Behavior



Brittle Behavior



Solution: Integrate test data with simulation



- **Break test structures to determine fracture stress distribution of each machined surface**
 - Use Weibull statistics
 - Once process is characterized, use data to analyze any MEMS device made by that process
- **AMFitzgerald proprietary algorithm to predict fracture risk of a complex device *without having to build or break it***

Closing remarks

How to do more efficient MEMS development

- **Acquire a simulation tool AND an engineer skilled in modeling**
 - You'll save at least one fab round per year, they'll pay for themselves
- **Invest in developing accurate models for your technology, future products will benefit**
 - Simple tests can harvest important materials data
- **Practice good engineering discipline – fight the urge to “just build it”**
 - The fab is expensive, simulation is not!

How to help the MEMS industry mature

- **Give your EDA provider feedback on your simulation needs**
- **Motivate your foundry to provide characterized processes and materials property data**
- **Find ways to share data and insights without compromising confidentiality**
- **Participate in standards committees**

How we can help you with MEMS development

- **Expert design and simulation help**
- **Material properties data acquisition**
 - Test structure design
 - Measurement methods: wafer and die-level
 - Mechanical testing
 - Custom test apparatus
- **MEMS prototyping**
- **Foundry selection and transfer**



We use an Instron 5942 for mechanical testing



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