Leveraging Simulation in MEMS Development

Coventor Workshop | Woburn, MA

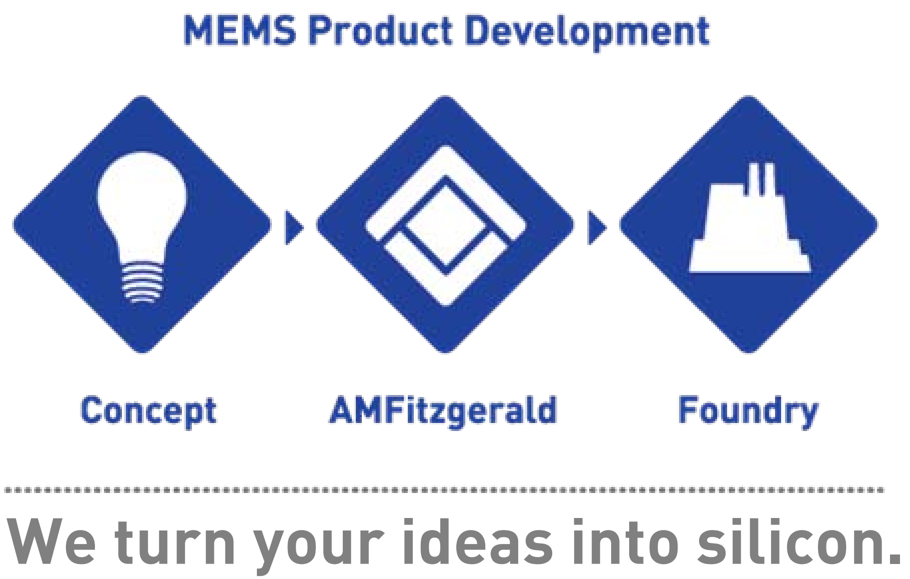
Alissa M. Fitzgerald, Ph.D. | October 28, 2010

AMFITZGERALD
& ASSOCIATES

Overview

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

Mission

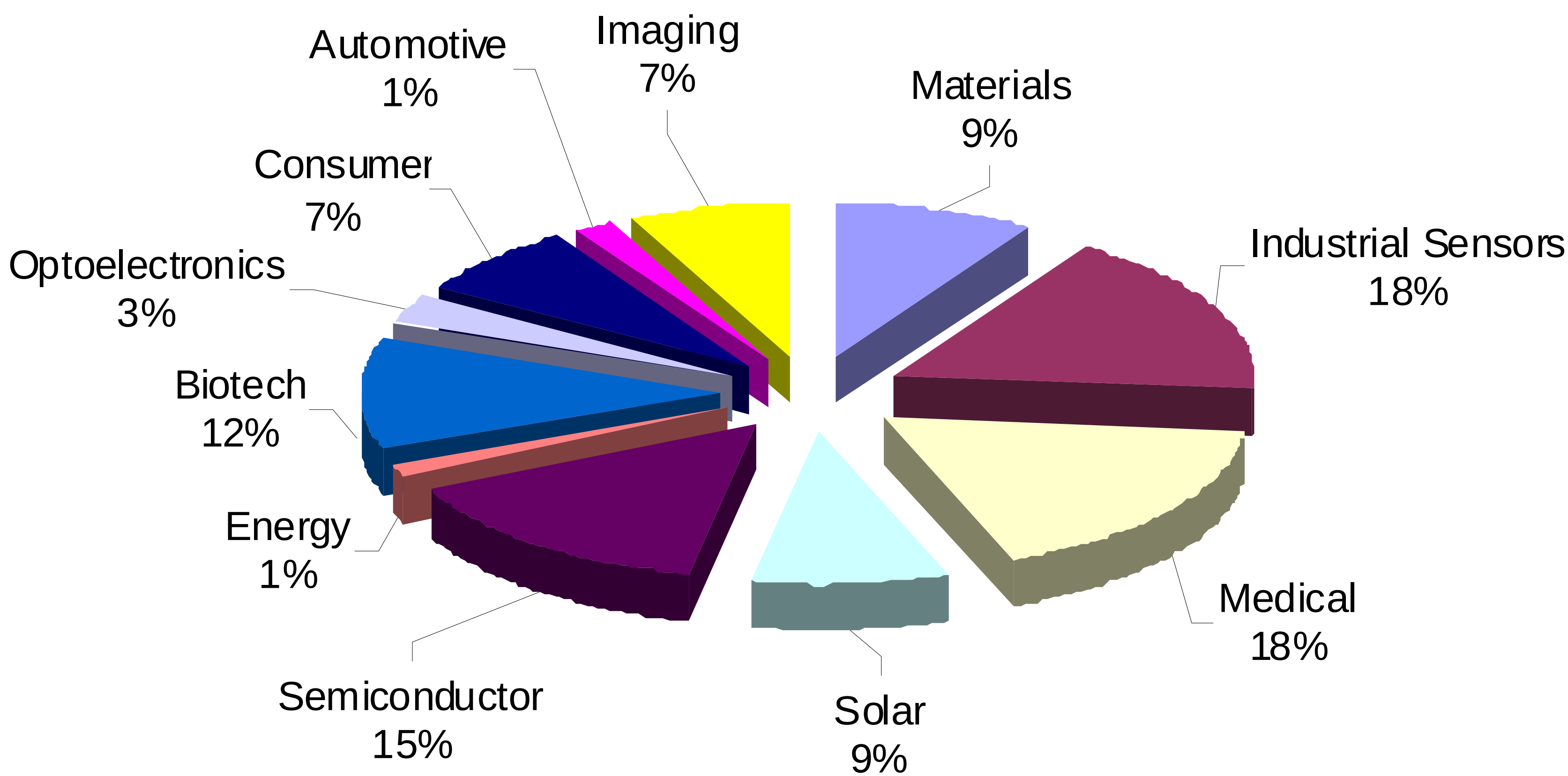

MEMS Product Development
Concept
AMFitzgerald
Foundry
We turn your ideas into silicon.

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 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**

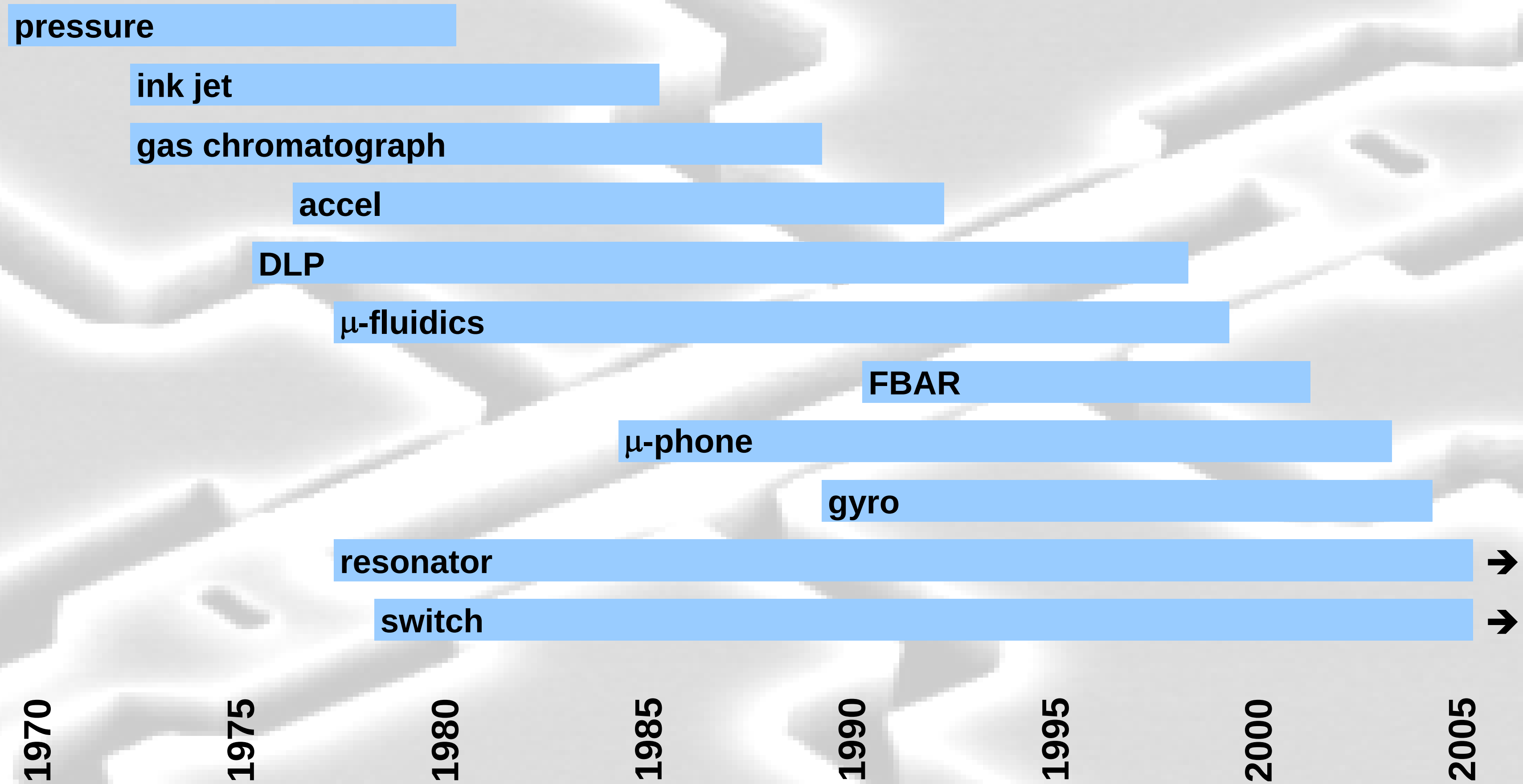
Over 70 clients served

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?

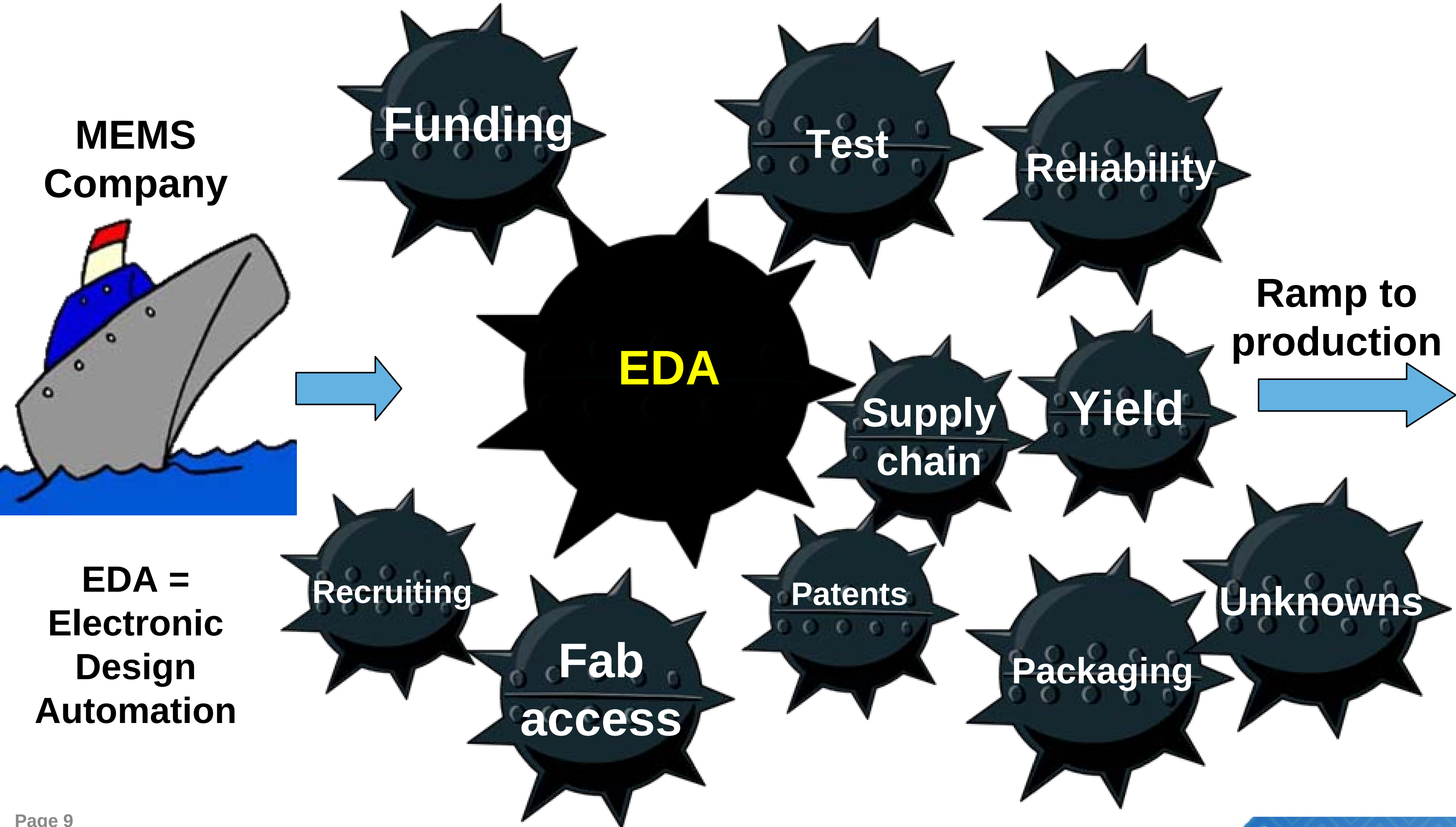
MEMS R&D Cycles



Source: Kurt Petersen, 2005

The perilous MEMS development journey (early stage)

Millions of dollars, years and many casualties



EDA = Electronic Design Automation

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

Semiconductor EDA

Reference designs, IP blocks	Verified physics models	Foundry-specific design rules	Process simulation	Design simulation	Rule checking, Verification

New Design — **18 months, 95+% yield** → Product

MEMS Industry EDA

Reference designs, IP blocks	Verified physics models	Foundry-specific design rules	Process simulation	Design simulation	Rule checking, Verification

New Design — **5+ years, ?% yield** → Product

GOOD	FAIR	POOR

MEMS industry must work to close these gaps

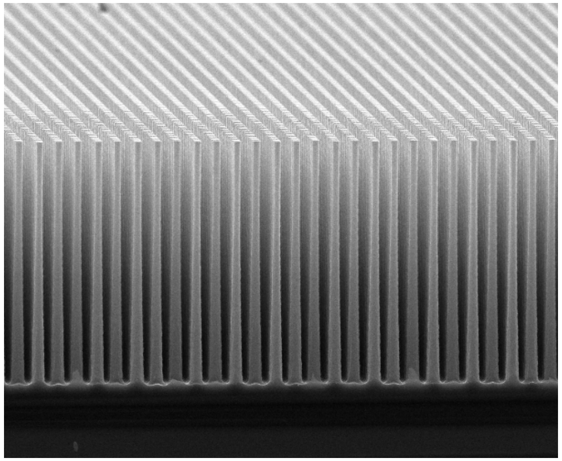
Reference designs, IP blocks	Only established MEMS companies have these (proprietary) – a major advantage
Verified physics models	Stiction, electrostatic charging, fracture, time-dependent material behavior
Foundry-specific design rules	Rules to prevent unfeasible or marginal designs
Process simulation	Understanding how process affects mechanical performance

Foundry-specific design rules

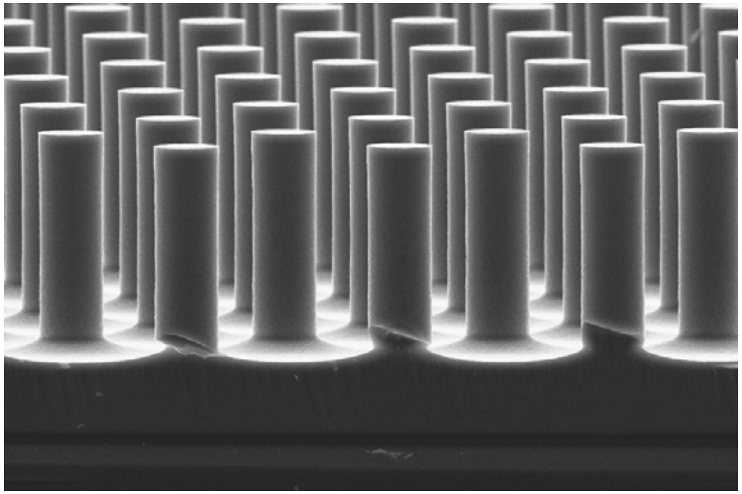
Rules to prevent unfeasible designs

- **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



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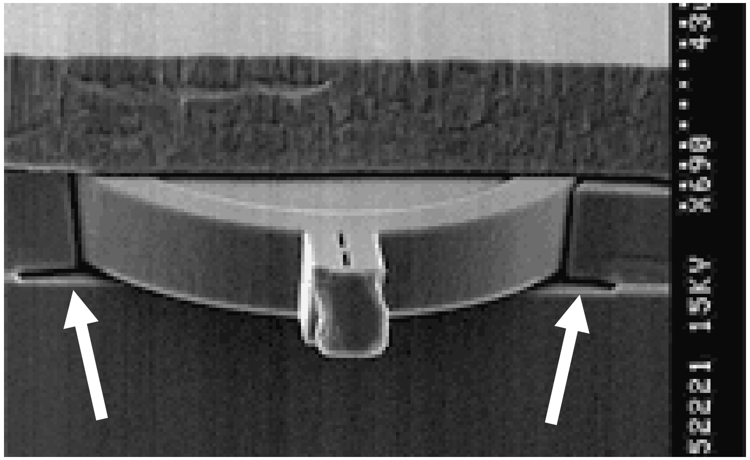
Process simulation

Process affects mechanical performance

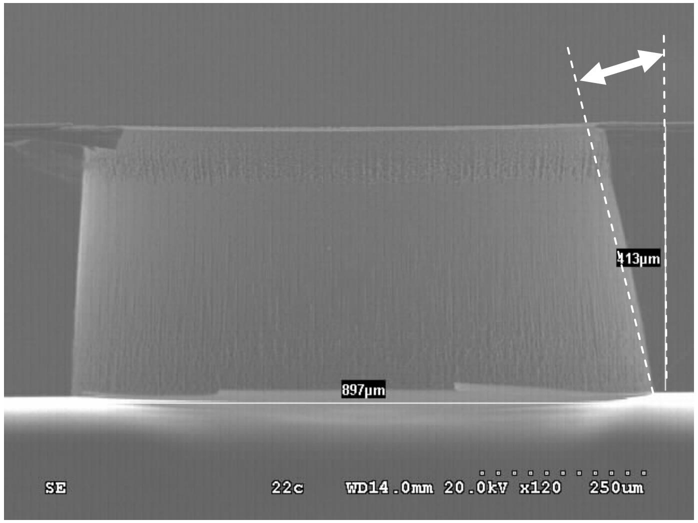
- **Lateral undercutting (boundary conditions)**
  - **Resonant structures greatly affected**
- **Thermal budget (film stresses)**
- **DRIE etch sidewall (geometry)**
  - **Critical to inertial sensor performance**

Undercut during sacrificial release



Chipworks, SiTime

DRIE sidewall taper in large open area



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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

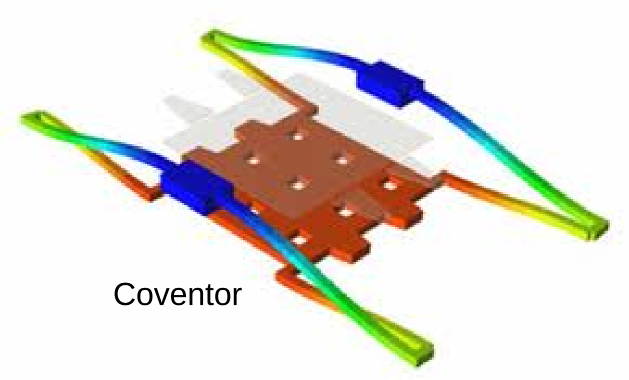
With some effort, you could find your way with a compass

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

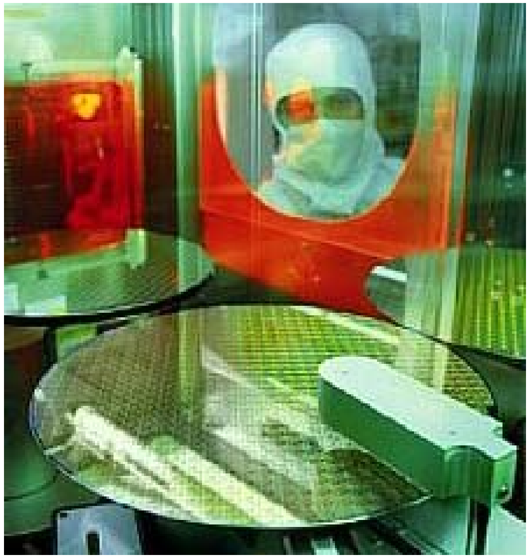
MEMS development often gets lost in the wilderness

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

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



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

	Man-hours	Cost	Time, weeks
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 <u>much</u> better than nothing

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

Leveraging simulation – practical tips

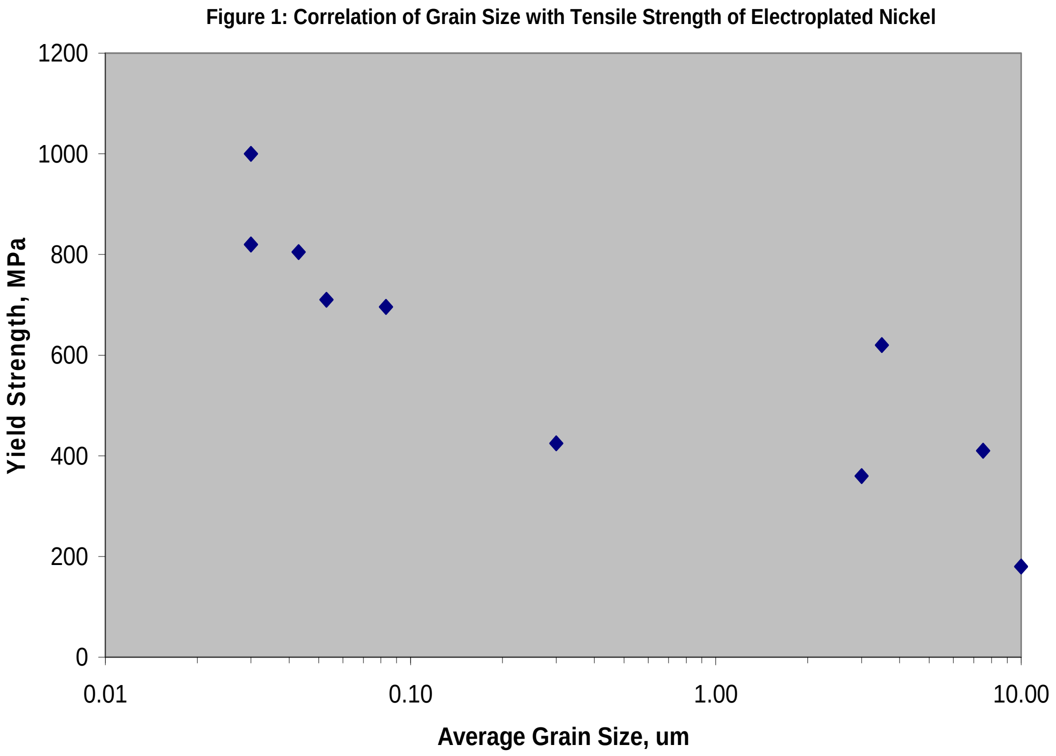
Typical challenges in simulation of MEMS

- **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**

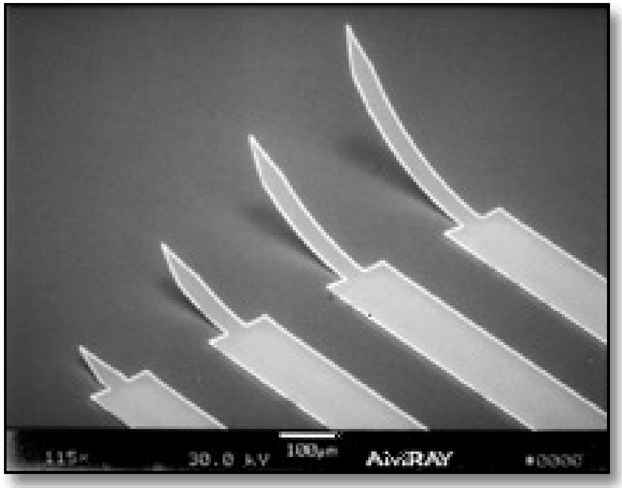
Problem: Materials properties of thin films

- **Recipe dependent**
- **Tool to tool variation**

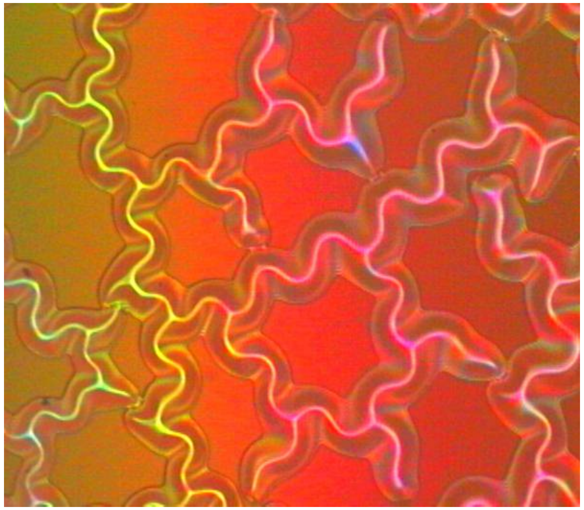


Problem: Residual stress in thin films

- **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**



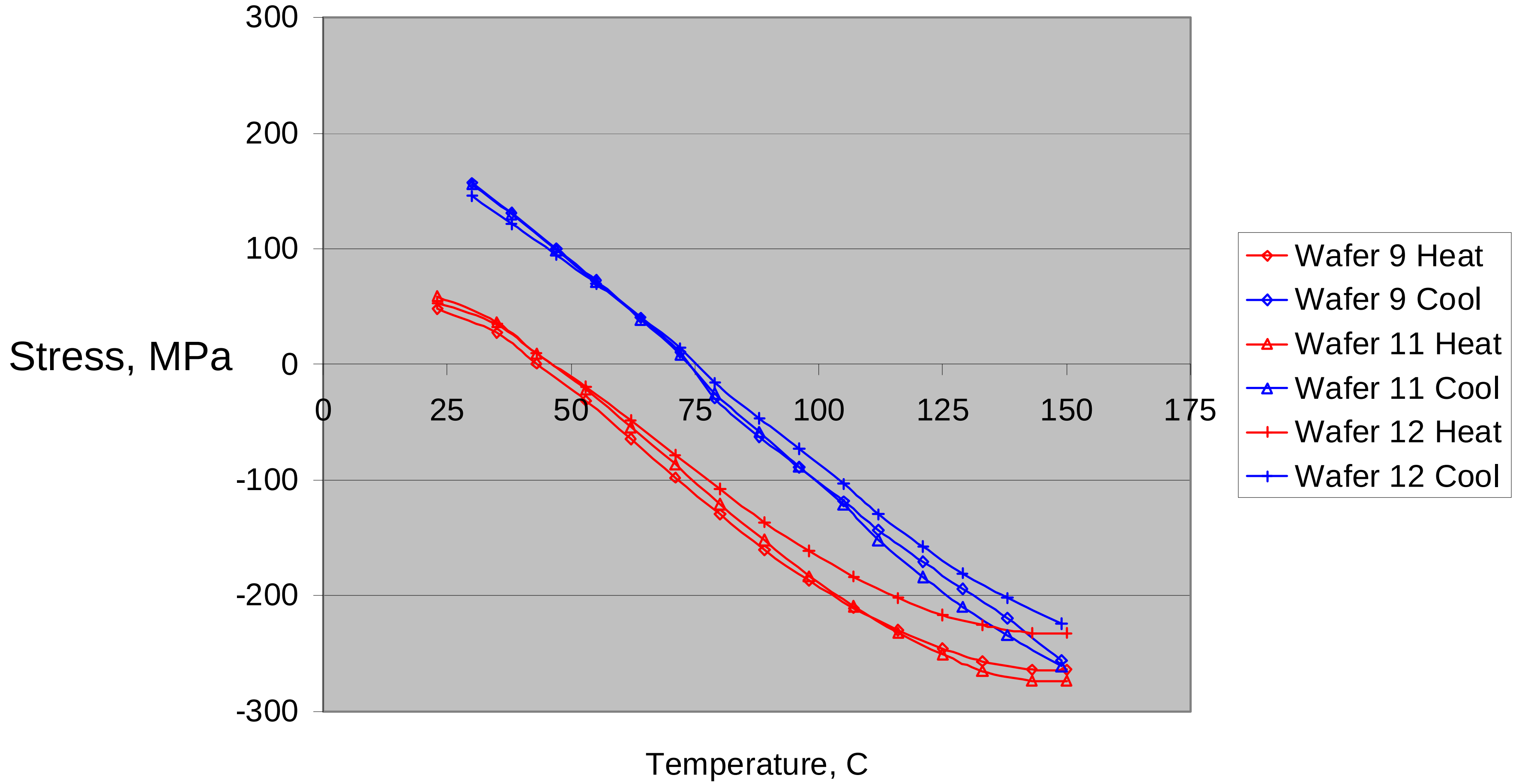
parc's StressedMetal AFM tips



Fraunhofer IOF

Problem: Thermal budget affects material properties

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



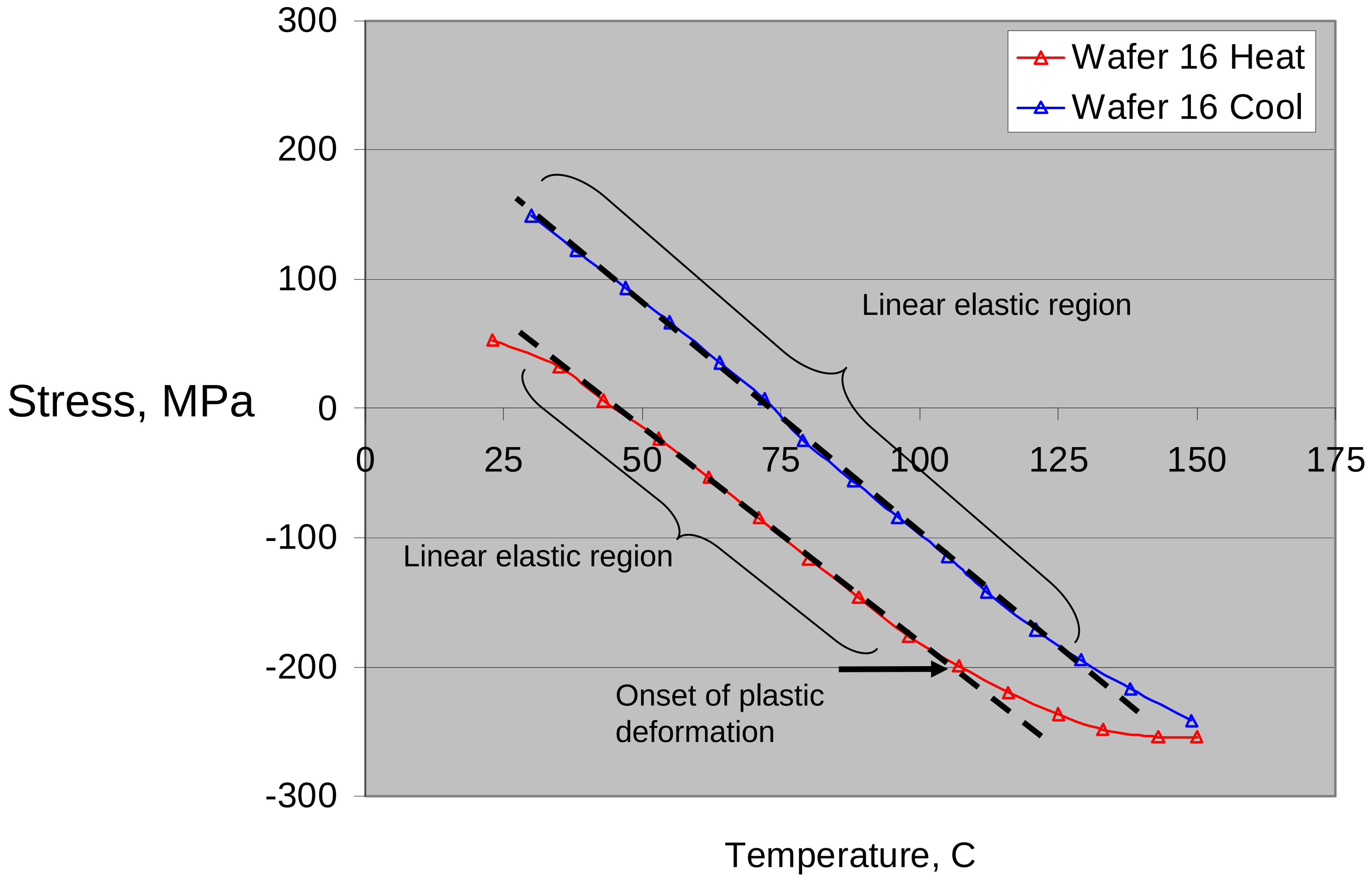
Solutions: Parameter sensitivity analysis

- **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**

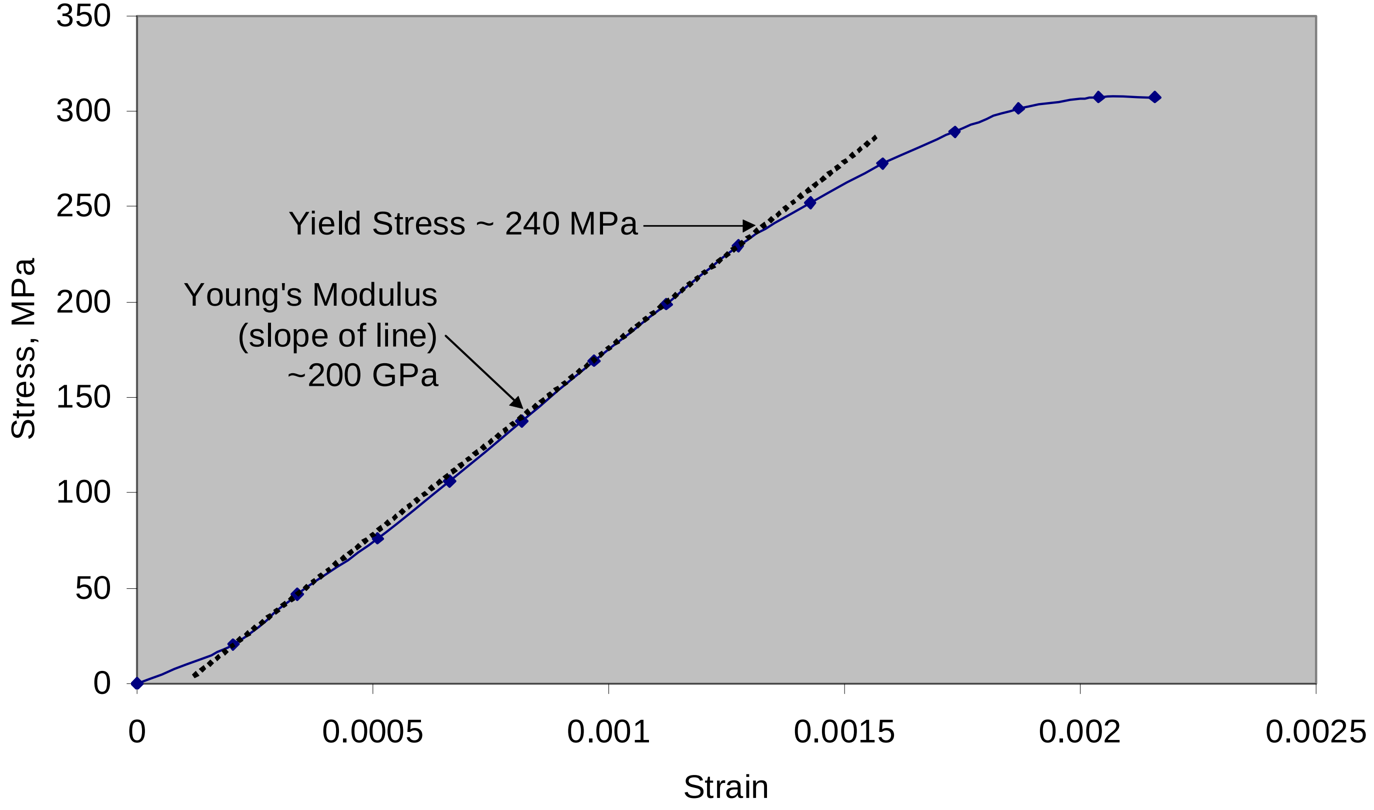
Solutions: Wafer-level measurements

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



Solutions: Wafer-level measurements

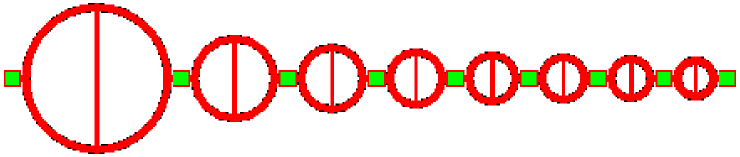
- **Modulus E, σ_{yield} can be estimated from wafer-level film stress data**



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

Solutions: Test Structures

- **Strive for simple test structures that can be made with a subset of the process flow**
  - **Cantilevers, Guckel rings, etc.**



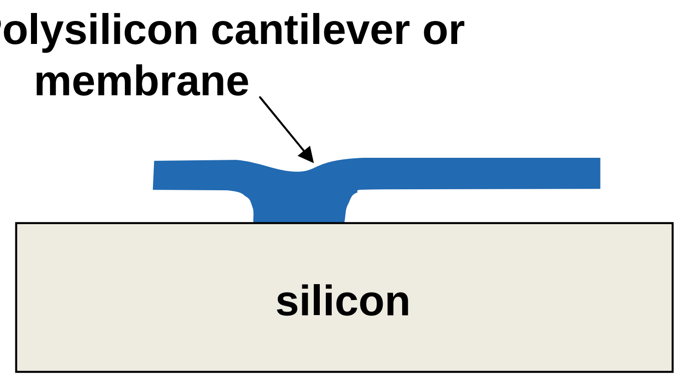
Visual indicator of stress

- **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**

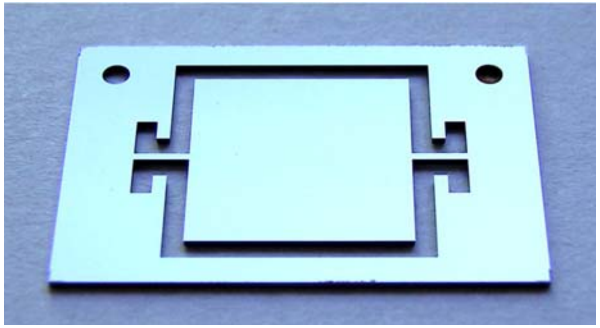


Fixed condition: Galileo’s model of the built-in cantilever

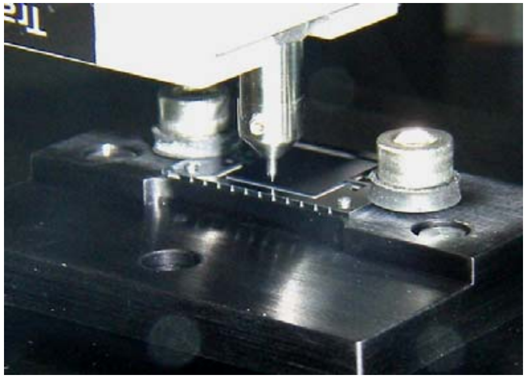
J.W. Wittwer, L.L. Howell, “Mitigating the Effects of Local Flexibility at the Built-In Ends of Cantilever Beams”, Journal of Applied Mechanics, Volume 71, Issue 5, pp. 748-751 (2004)

Solution: Measure stiffness to correct model

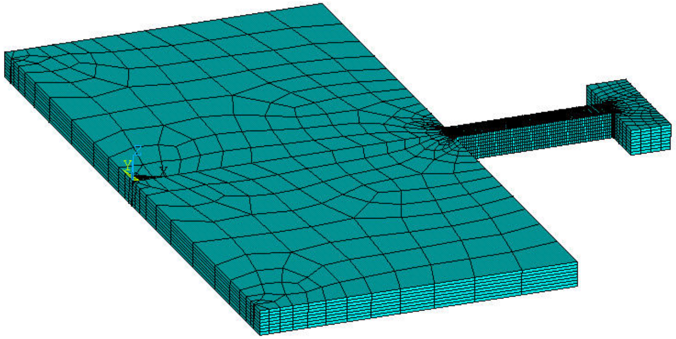
Simple micro-mirror



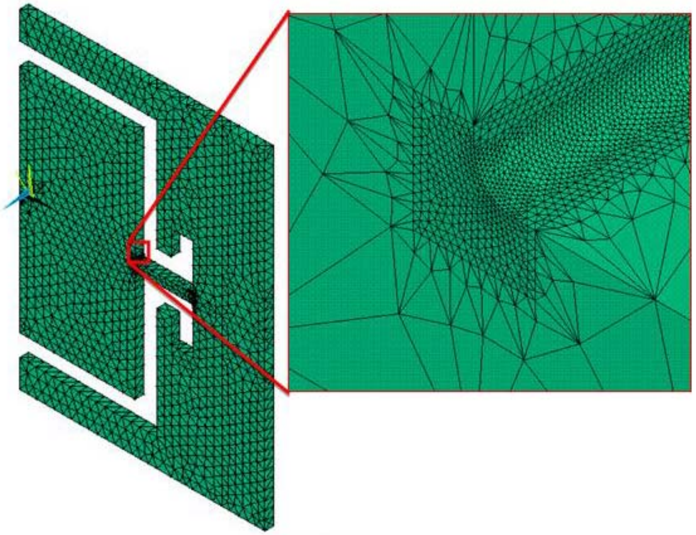
Force vs. displacement measurements proved original model too stiff!



Original FE half-model



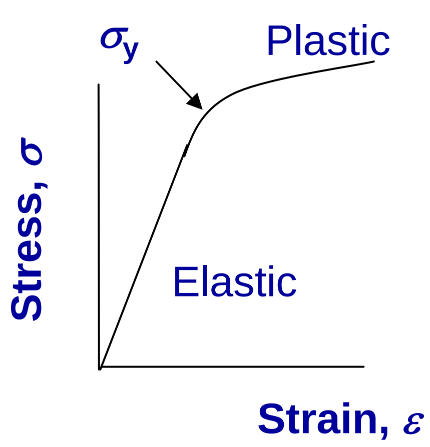
Improved half-model



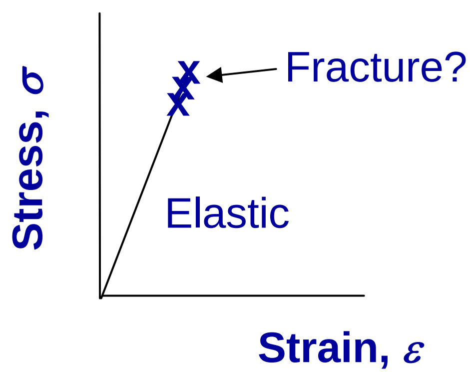
Problem: Predicting load limit of a brittle structure

- **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**

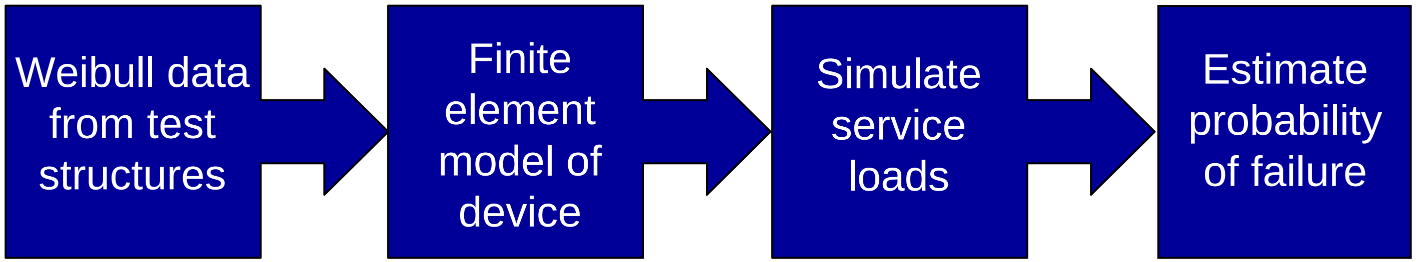
Ductile Behavior



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 <u>any</u> 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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