# Modeling of thin-film stress in MEMS devices

*OzenCon 2024*

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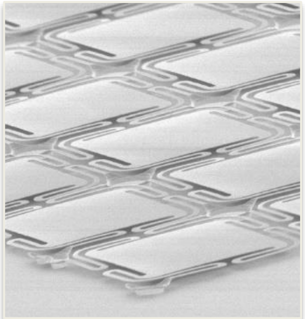
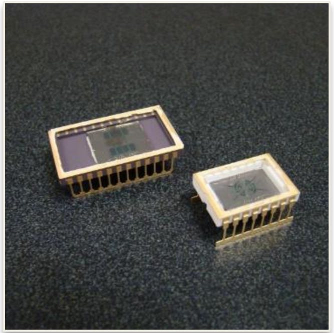
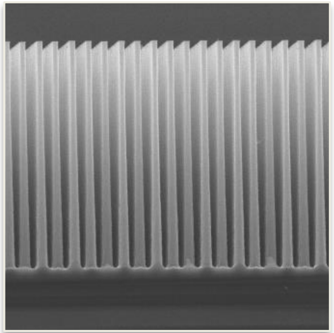
# AMFitzgerald: Your partner in specialty MEMS and microtechnology development



AMFitzgerald develops innovative
MEMS and sensor solutions
for specialty applications

We collaborate with our customers
to create high value products
enabled by customized microtechnology





With integrity, expertise, and attention to detail,
we deliver what has never been done before

# AMFitzgerald is a global business in MEMS product development

Headquarters in Burlingame, CA
5 minutes from SFO airport

Our Class 100 cleanroom for 200 mm wafer-level test and measurement. Clients may install project-specific equipment.

- **Company profile**
  - **Founded 2003, privately held**
  - **California Bay Area, near Silicon Valley**
    - **Burlingame: Headquarters and Class 100 cleanroom for metrology**
    - **UC Berkeley: 15,000 sq. ft. (Class 100 and 1000) rented MEMS fab access**
    - **UC Davis: 10,000 sq. ft. ISO 5 (Class 100) rented MEMS fab access**
  - **Over 400 projects completed to date, from startups to public multi-national enterprises**

AMFitzgerald client locations





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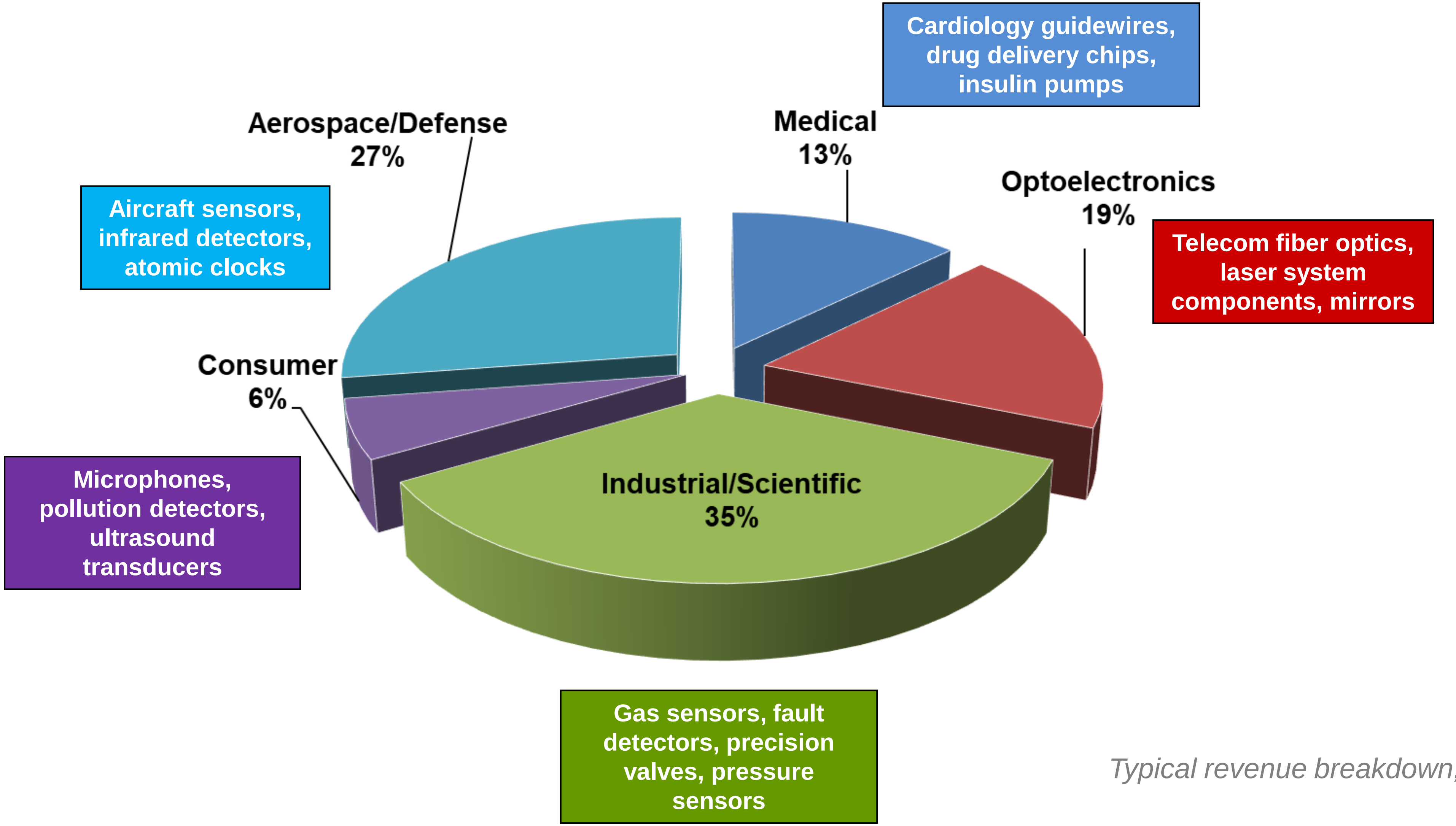
# We design custom MEMS for products in high value markets




*Typical revenue breakdown, by market*

# MEMS are useful in many applications

**10-20 MEMS**
**Microphones**
**Radio frequency filters**
**Motion sensors**
**Pressure sensor**

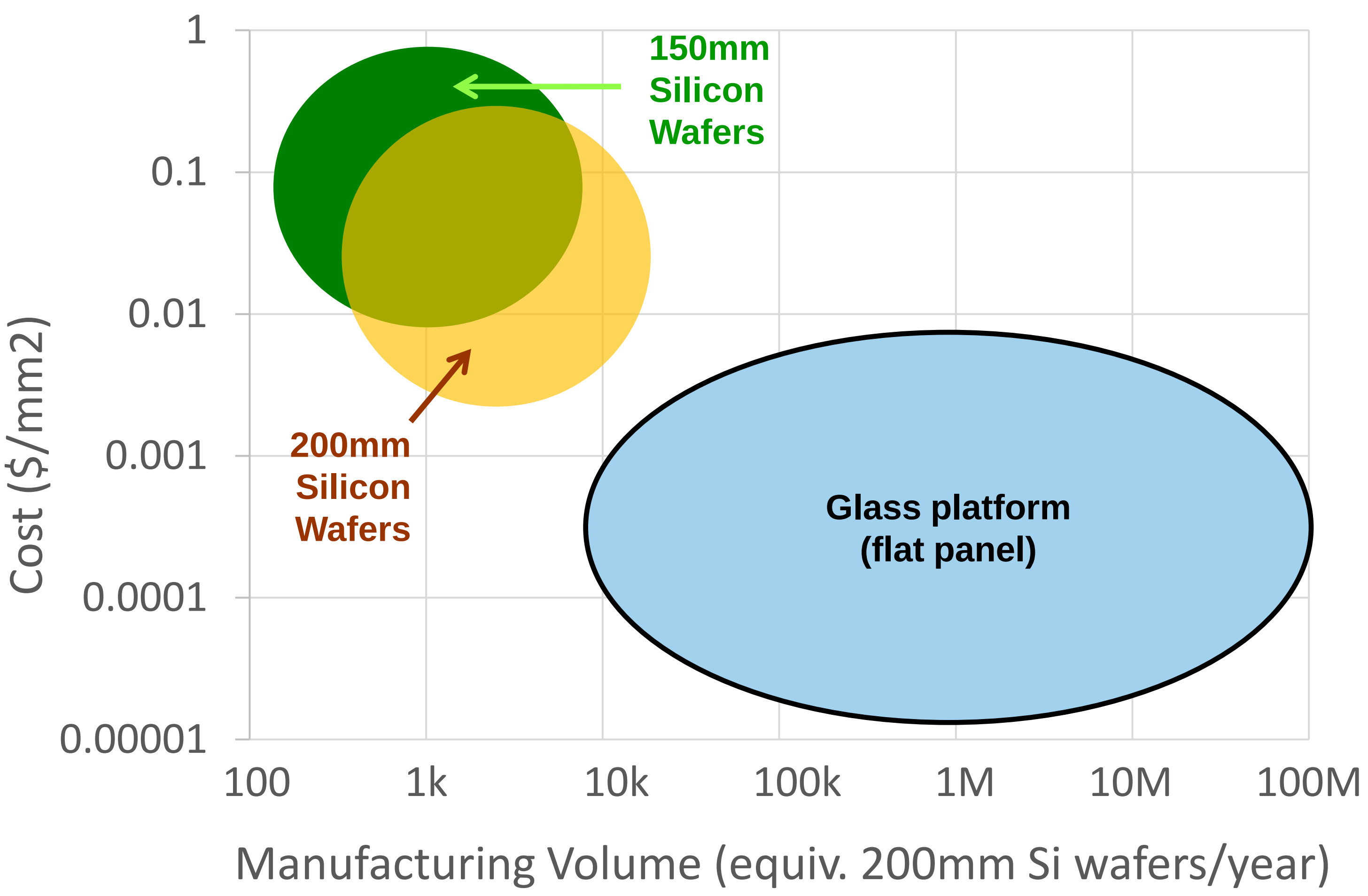
**1-2 MEMS**
**Motion sensor**
**Pressure sensor**

**> 100 MEMS**
**Safety, engine and emissions control systems:**
**Pressure sensors**
**Motion sensors**
**Microphones**
**Gas sensors**
**Autonomous Vehicles: LiDAR, infrared sensors**

## High volume commercial uses of MEMS

- **Yole projects year-to-year growth of MEMS market to be 6-7% year-to-year till 2030**
- **<u>Growing demand for MEMS devices urges the development of cost-effective, high volume manufacturing solutions</u>**

# Cost vs. Volume By MEMS Manufacturing Technology




Glass platform is seen as a cost-effective solution for high volume manufacturing

# MEMS on glass limitations

- **MEMS on glass requirements:**
  - **Mechanical layers may be a-Si or SiO, SiN**
  - **Release layers may be a-Si, Al, Mo, SiO, Cr**
  - **Device layer thicknesses typically less than 5um**
  - **Critical dimensions greater than 2um for contact lithography**

- **Which MEMS devices are suitable for glass platform?**
  - ✓ **Pressure sensors**
  - ✓ **Resonators**
  - ✓ **Temperature sensors**
  - ✓ **Microfluidic devices**
  - ✓ **Biosensors**
  - ✓ **Optical MEMS**
  - x **High-Q resonators or gyroscopes**
  - x **High profile structures such as comb drive actuators (<<1:1 aspect ratios)**

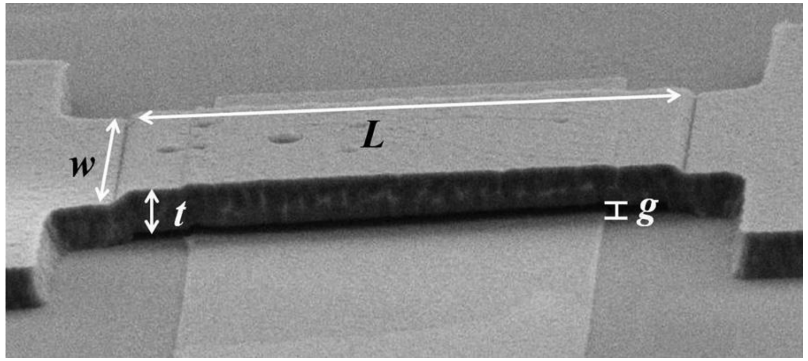
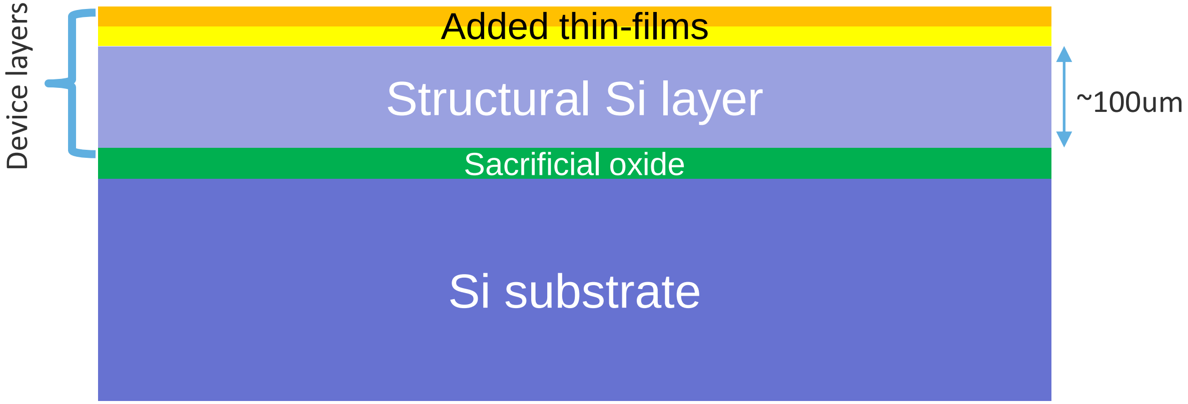



Image of 2um thick amorphous silicon resonator on glass substrate (Mouro, Chu and Conde, 2016)

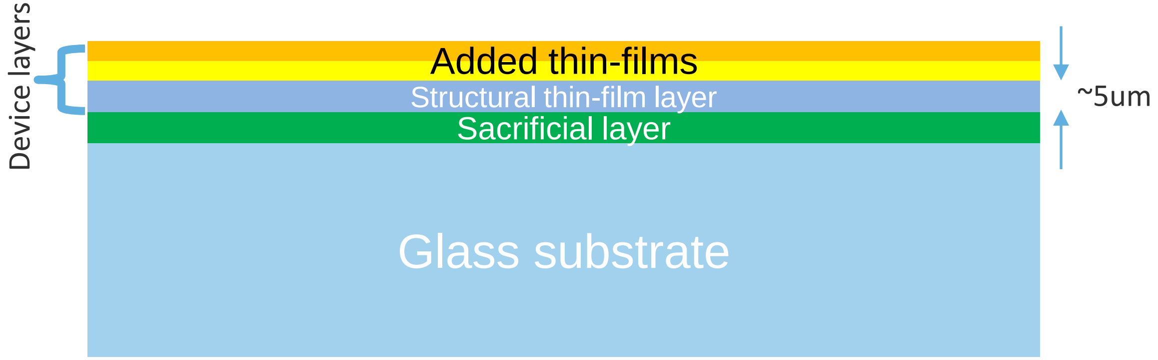
# Design space of MEMS on Si vs MEMS on glass

## Si platform




- SOI, C-SOI readily available
- Structural Si layer is typically ~ 100um
- Added thin-films ~ 1-2um
- Mechanical properties of device layers are dictated by Si structural layer

## Glass platform

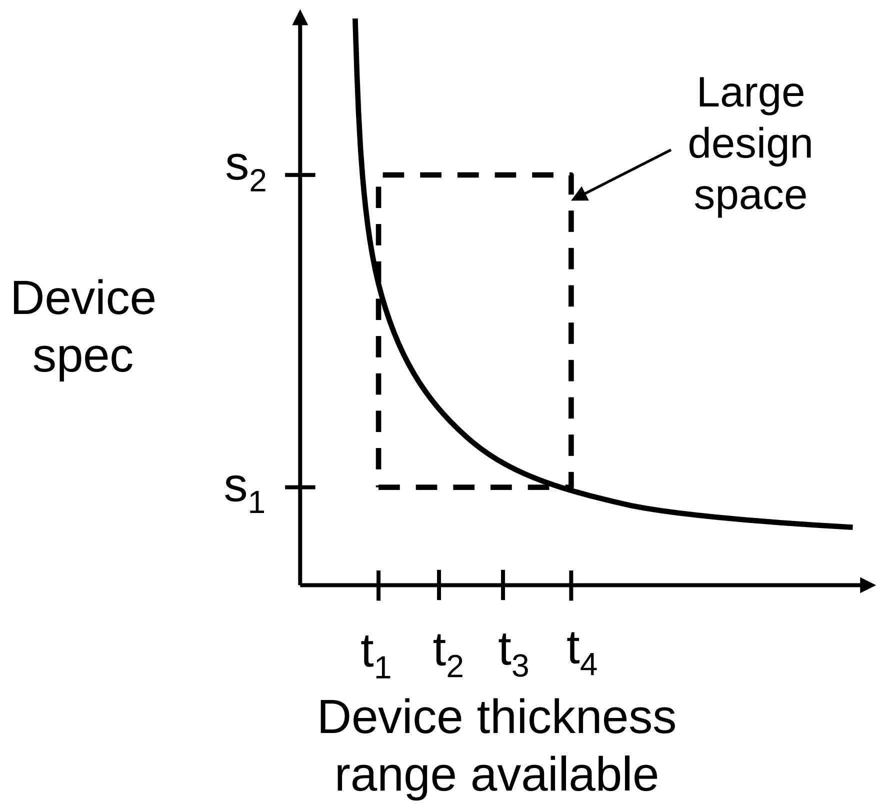



- Thin-film layers are deposited on top of glass substrate
- Structural thin-film layer is typically limited to ~ 5um
- Added thin-films ~ 1-2um
- Device layers form a thin-film laminate:
  - Complex mechanical properties
  - Vulnerability to thin-film stresses
  - Chemicals used for removal of sacrificial layer may change properties of thin films

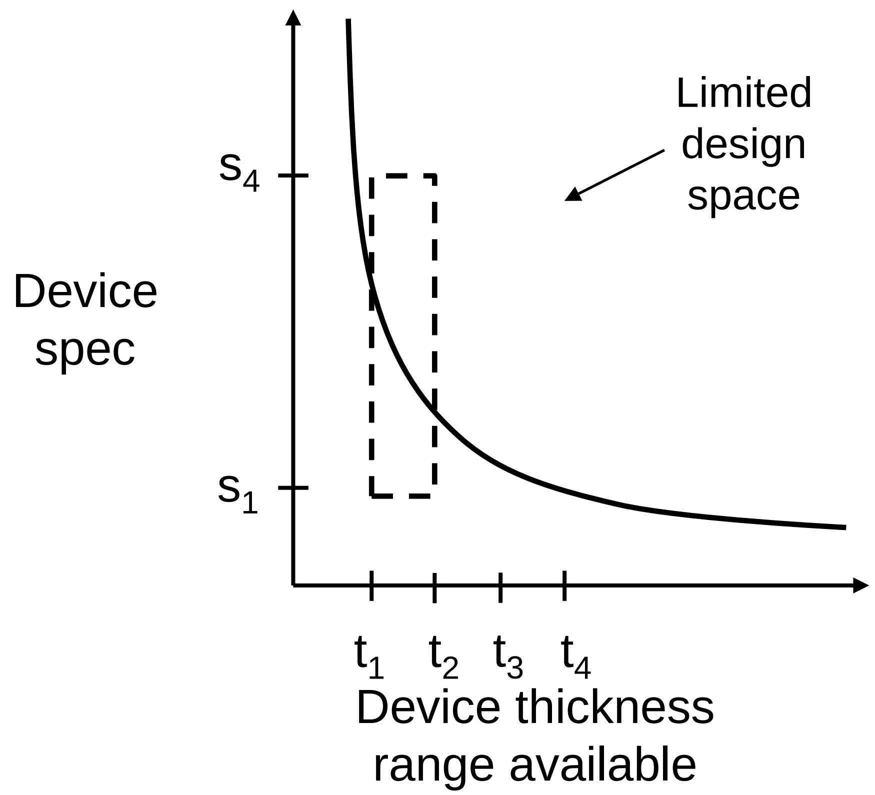
Layers thicknesses are not to scale

# Design space of MEMS on Si vs MEMS on glass

## Si platform




## Glass platform




- **Design of MEMS on glass is much more challenging due to very limited design space compared to Si platform**

Adapted from Figure Fig. 10.1 *MEMS Product Development*

# MEMS development is a long journey that surprises people

STRONG | FAIR | WEAK

## Digital ASIC

New Design: Verified models of device physics | Foundry process design rules | Process simulation | Design simulation | Rule checking, verification | Tapeout, fab

**1.5 year, 95+% yield** → Product

## MEMS on Si platform

New Design: Verified device physics | Foundry process design rules | Process simulation | Design simulation | Rule checking, verification

New Process: Feasibility batch, evaluation, mask revision | Prototype batches | Pilot qualification

**5+ years, ?% yield** → Product

Timelines not to scale

Adapted from Figure 1.1 *MEMS Product Development*

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| --- |
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New Design

- Verified device physics
- Foundry process design rules
- Process simulation
- Design simulation
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New Process

- Feasibility batch, evaluation, mask revision
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- Pilot qualification

5+ years, ?% yield → Product

Timelines not to scale

Adapted from Figure 1.1 *MEMS Product Development*





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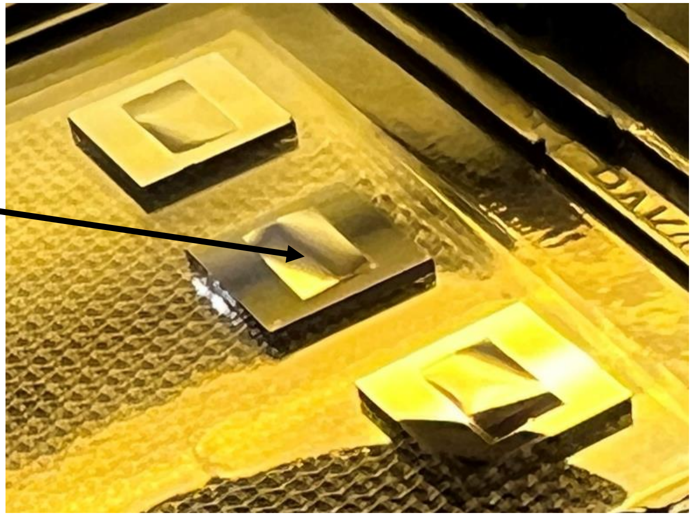
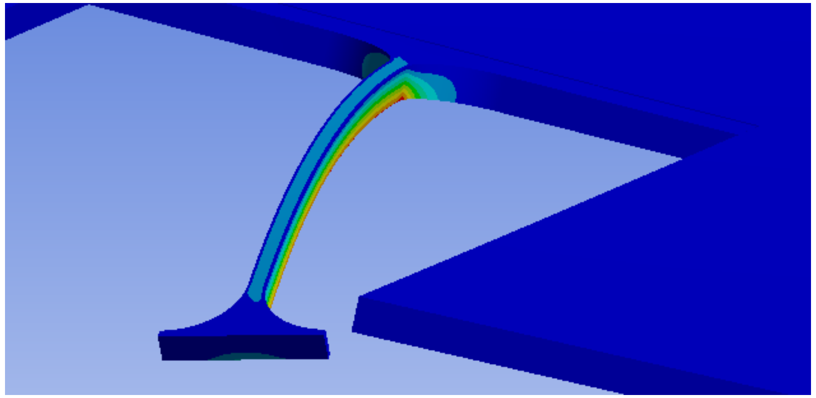
# Released test a-Si membranes attached to narrow flexures

Released 5um thick a-Si membranes warped from film stress



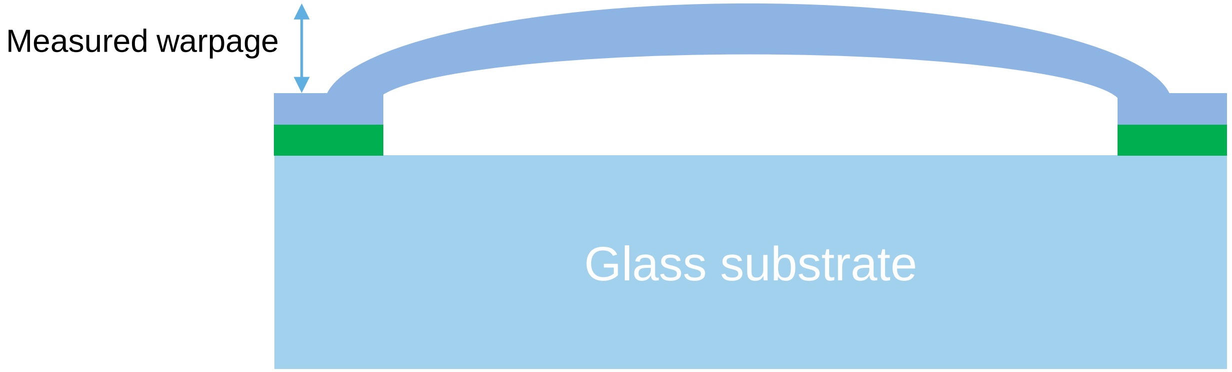


Stress is concentrated
in narrow flexures causing their breakage

- In our modeled and prototyped structures, flexure elements support a released membrane
- Even low stress in thin-films (<70 MPa) can cause pronounced warpage of released structural a-Si layer
- Stress data collected from substrate test samples did not match observed stress behavior in the released structures
  - Cannot design using data from conventional substrate-level bow measurements
- Stress in a-Si is varies with thickness
  - Thickness is not a good design variable
- The narrow flexure elements that support the released membrane become stress concentrators due to their form factor
  - Are very likely to break even due to low thin-film stress

# ANSYS is used estimate stress in released membranes

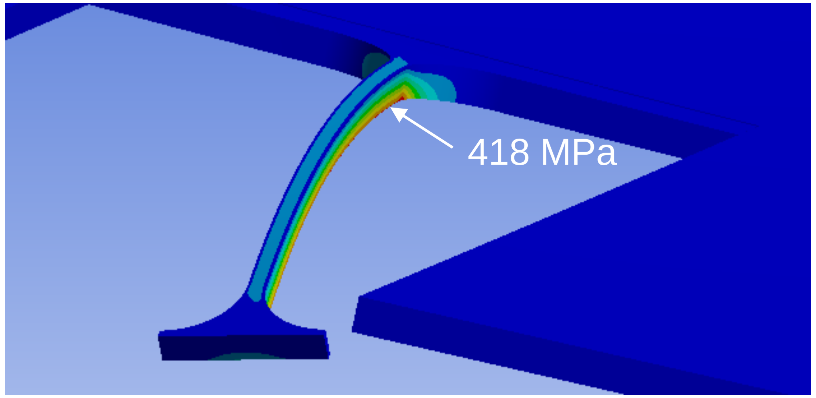
- **Inspected released membranes**
- **Estimated the warpage using laser microscope on series of devices**
- **Calculated approximate elongation of membranes due to warpage from film stress**
- **Perform ANSYS simulation to estimate the stress inside elongated membranes**
- **Good agreement with test measurements**




Cross-section of a released test membranes with thin-film stress

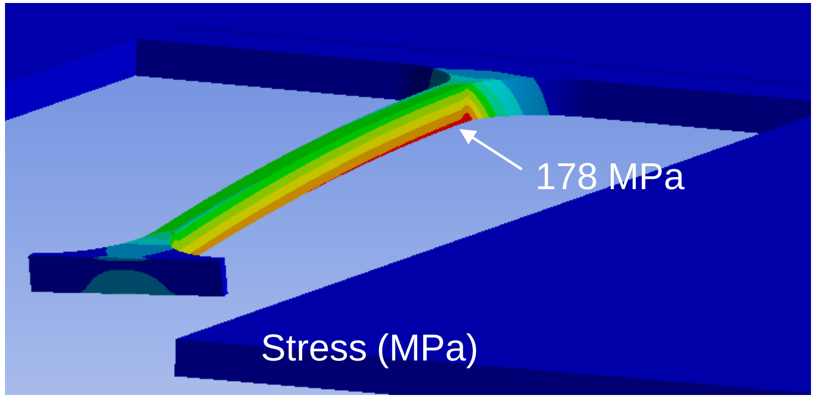
# Stress balancing within the membrane

- **During the intermediate steps we have collected stress measurements in individual films:**
  - **a-Si (after release) - 70 MPa, Compressive**
  - **Metal 1 – 150 MPa, Tensile**
  - **Metal 2 – 240 MPa, Compressive**
- **We used the collected stress information and using ANSYS we have design composite laminate stack with balanced stress**
- **Good agreement with test prototypes measurement**




Without stress balancing

2.3 times reduction of stress concentration




With stress balancing



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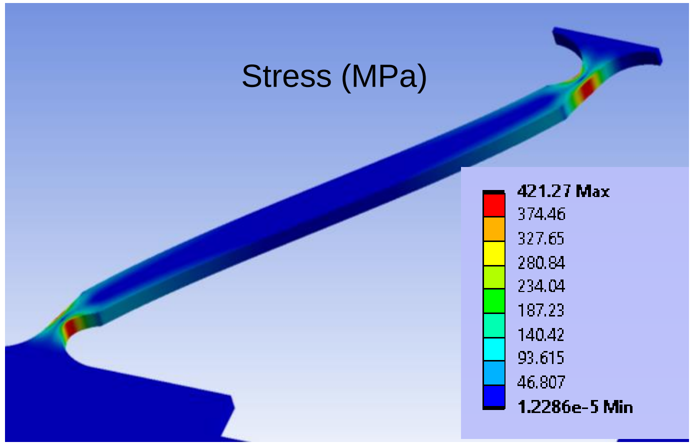
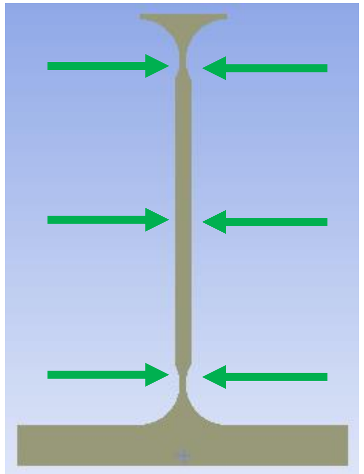
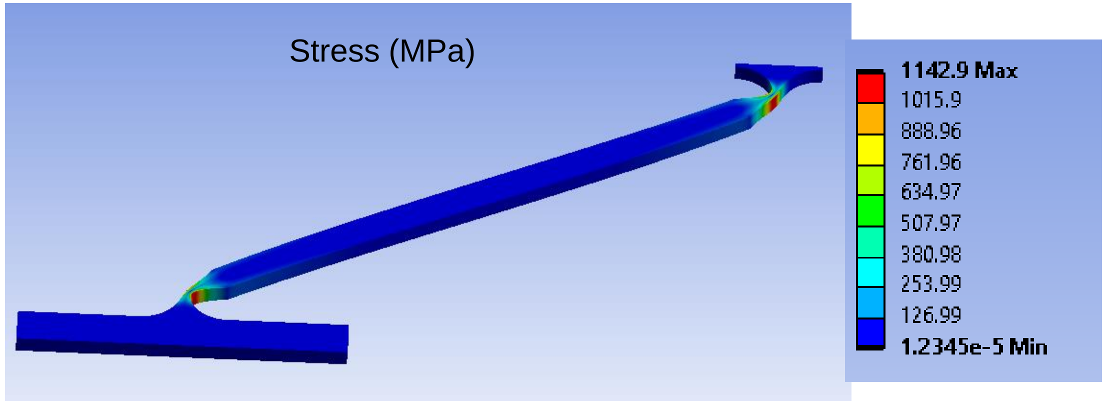
# Analysis of process linewidth control on flexures



1 um of flexure width reduction

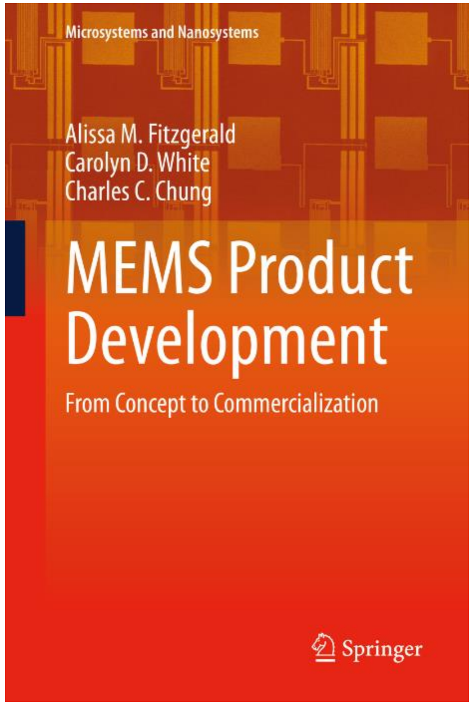


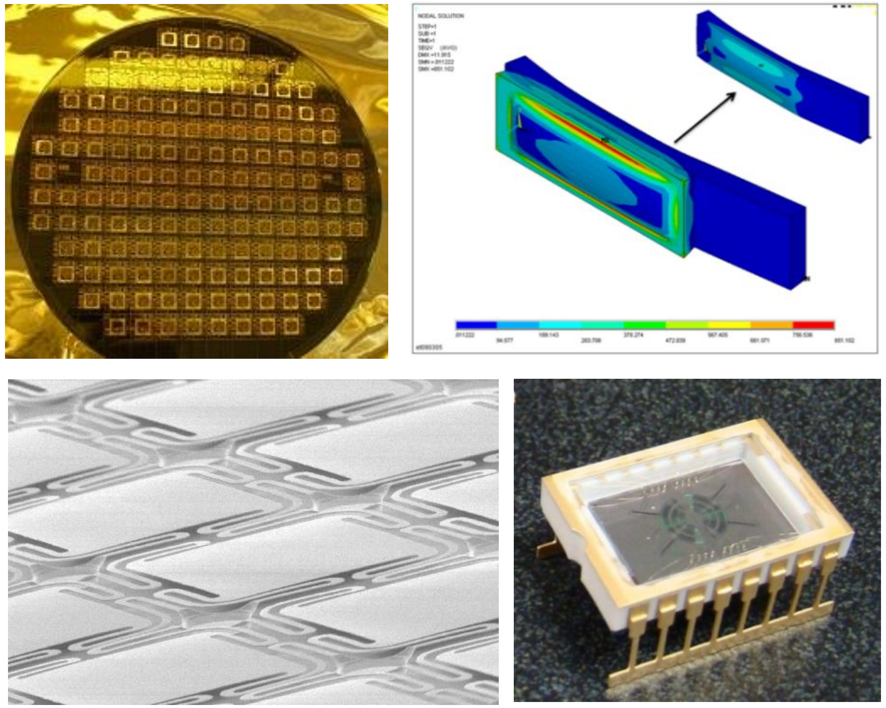

- **With the appropriate thin films stress inputs, the model can now be use to optimize critical feature dimensions**
- **Thinning the flexures by 1um results in 2.6 times increased stress in the stress concentration zones to achieve the desired stress under membrane deflection**

# Summary

- **Development and design of MEMS on glass is much more challenging than MEMS on Si due to thin-film stresses and process interplays of thinner, deposited structural layers**
- **Properties of thin films need to be carefully measured, sometimes extracting data from final structures and feeding data back to simulations vs. test substrate data collected prior to performing device simulations**
- **With accurate thin film material data, the model can better predict desired specifications**

# Questions?



*Designed and fabricated by AMFitzgerald*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# Extra slides

# We transform early prototypes into foundry-ready designs

*NASA Technology Readiness Level (TRL)*

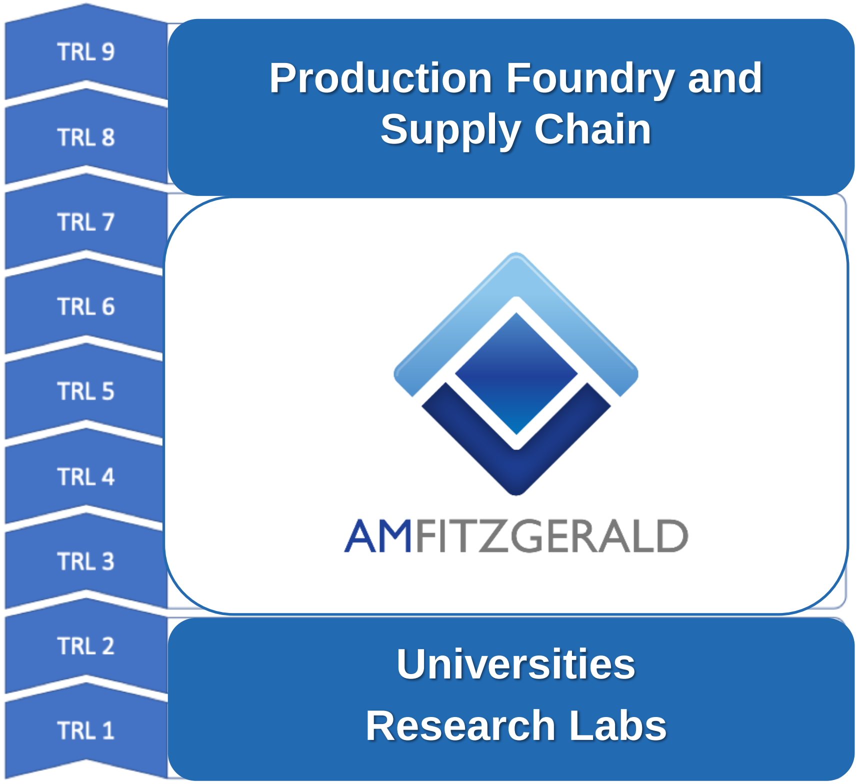
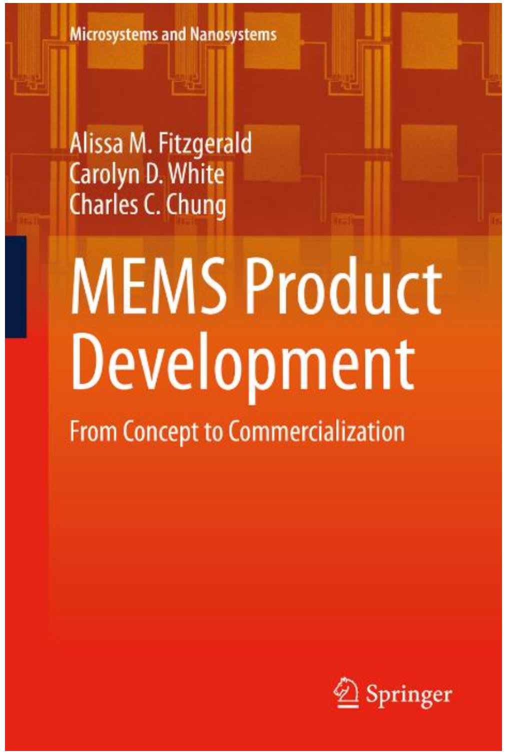



*Image source*

**AMFitzgerald's engineering work bridges the development gap (TRL 3-7)**




The topics we present today are covered more extensively in our book.



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