

# Micromechanical Testing of Thin Films

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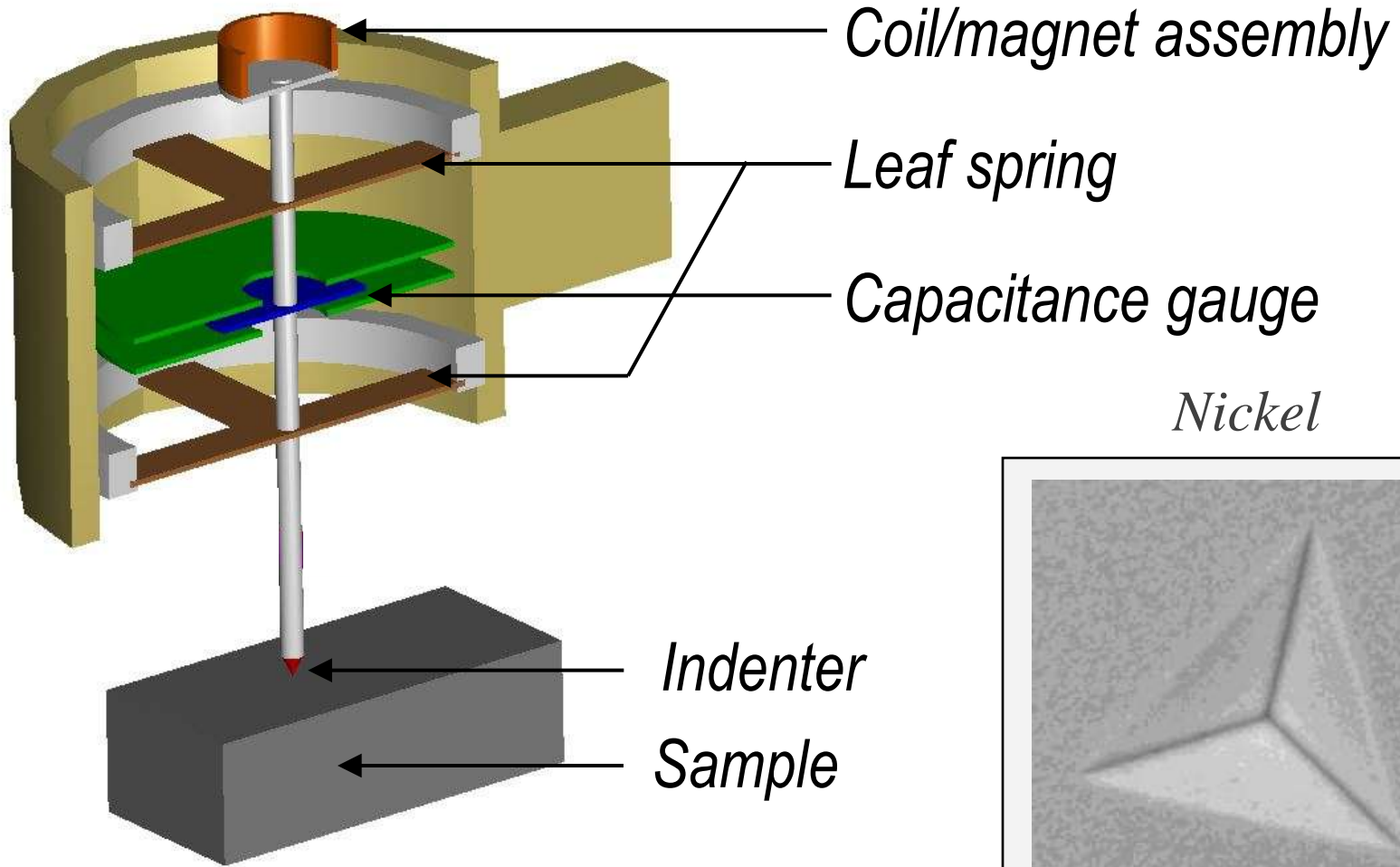
# Nano Indenter<sup>®</sup> G200

- Precise mechanical testing in the micro to “sub-nano” range of loads and displacements

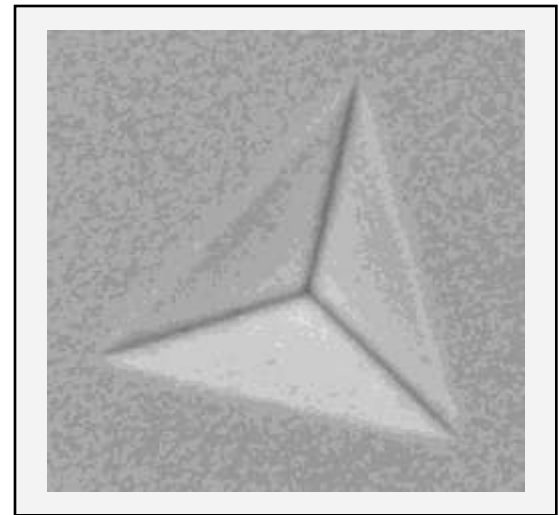


# Testing instrumentation: Nano Indenter<sup>®</sup>

## XP

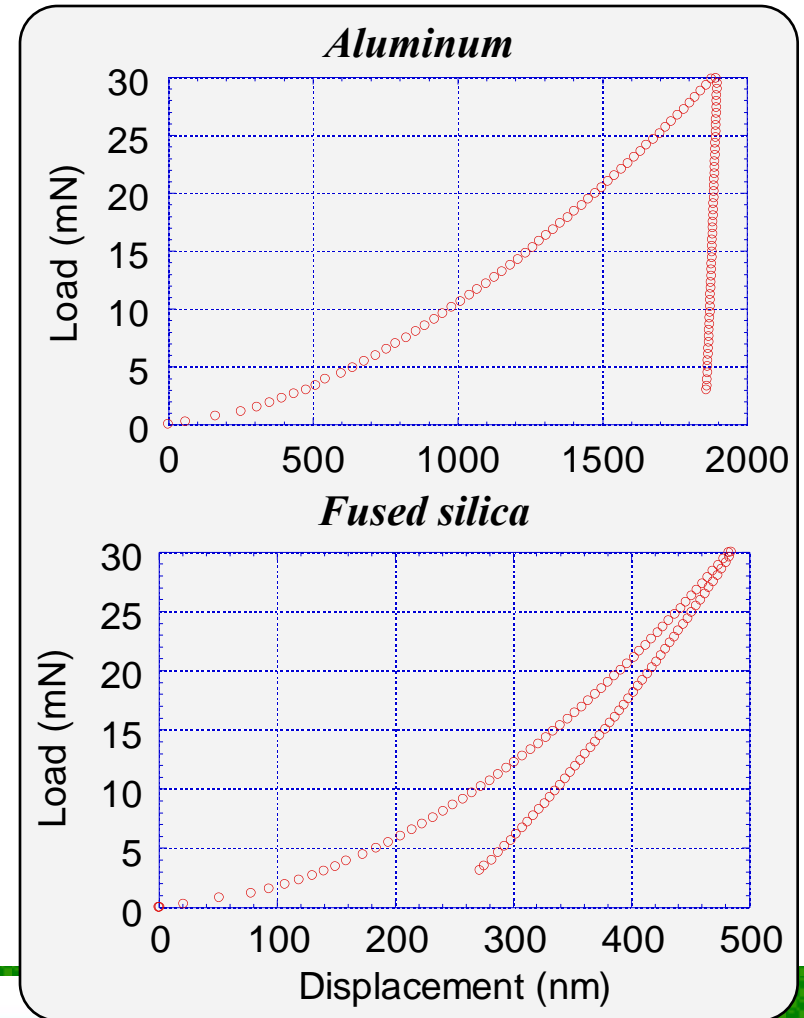


*Nickel*

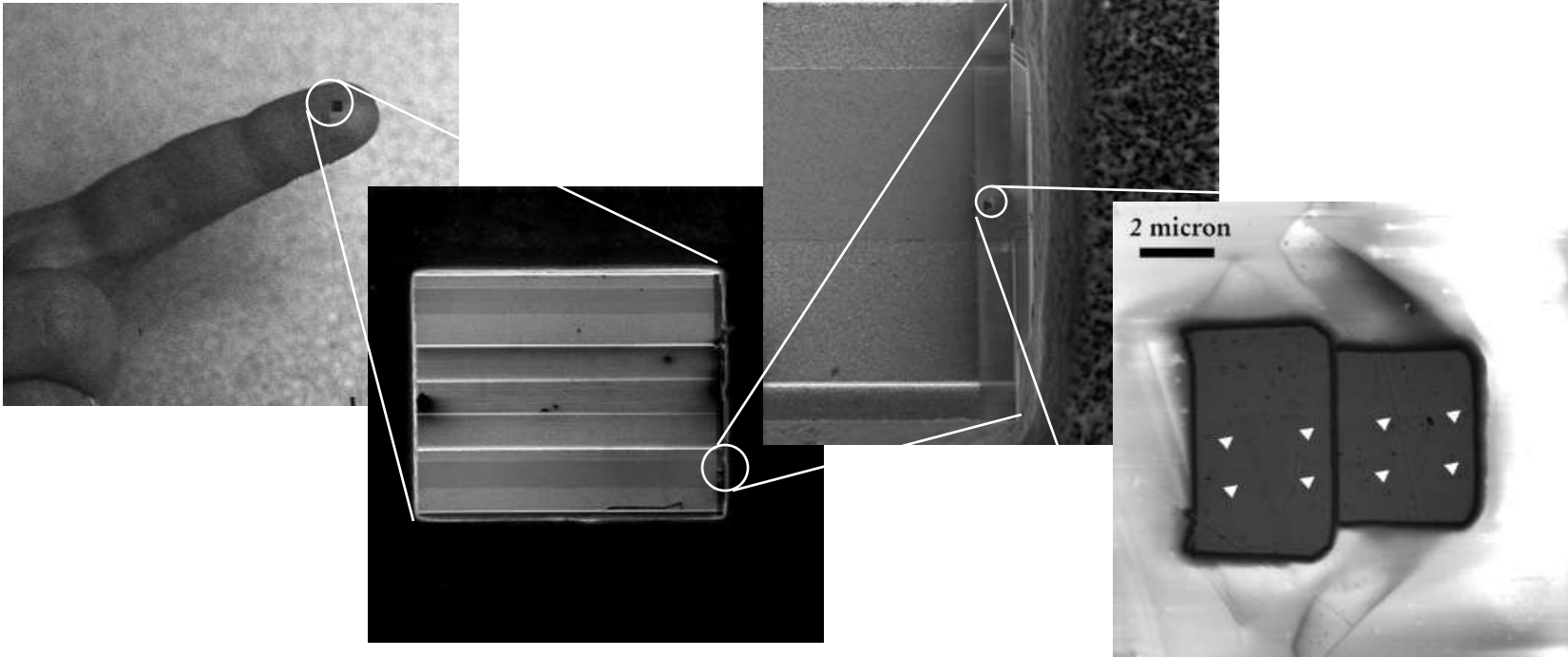


# Load-displacement behavior

- Aluminum, typical of soft metallic behavior, shows very little displacement recovery upon unloading
- Fused silica, typical of ceramic behavior, shows large elastic recovery upon unloading

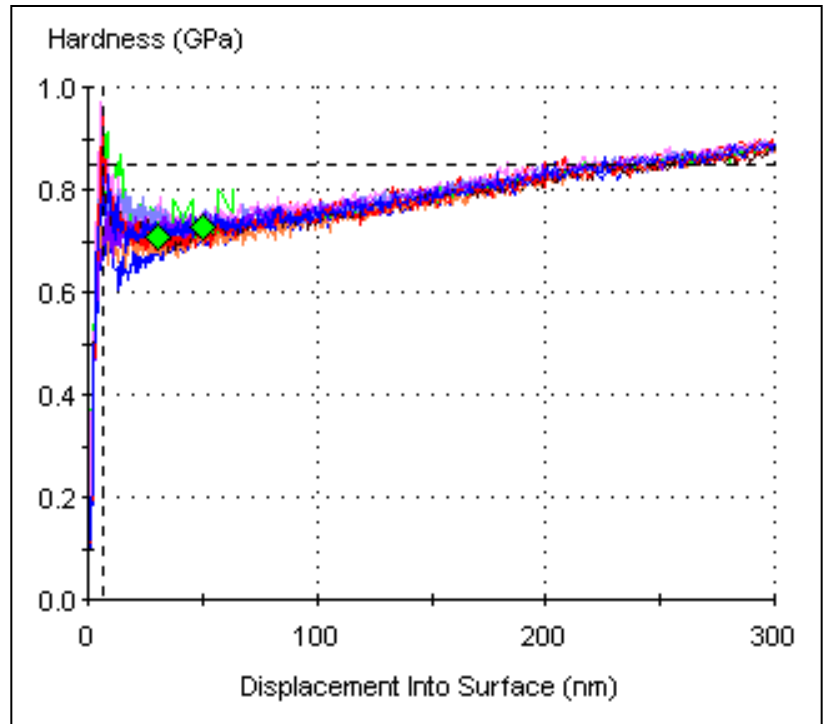
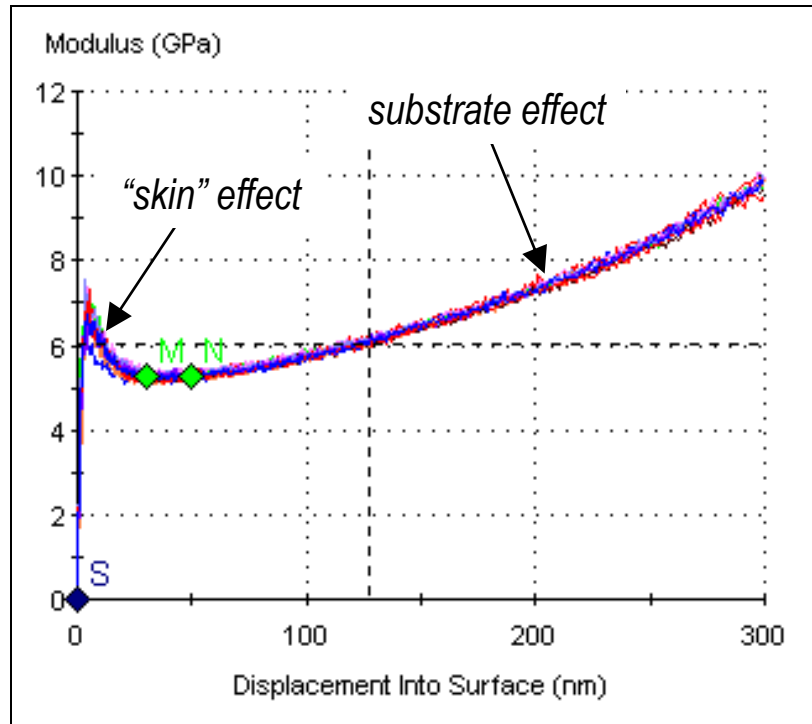


# Read Heads



# The problem...

*Indentation results for 1- $\mu\text{m}$  low-dielectric-constant (low-k) film on silicon*



*All data are affected, to some extent, by either "skin" or substrate. So what is the modulus of this film? Problem is not too bad for 1-micron films, and hardness is less sensitive than modulus. But our microelectronics customers tell us they really want to test 200nm films!*

# The goal

*The goal of this work is to develop an empirical model that:*

- Is appropriate for a realistic range of low-k materials*
- Correctly models the influence of the silicon substrate*
- Requires no a-priori knowledge of film properties beyond thickness*
- Can be incorporated into Testworks*
- Is relatively independent of diamond tip radius*

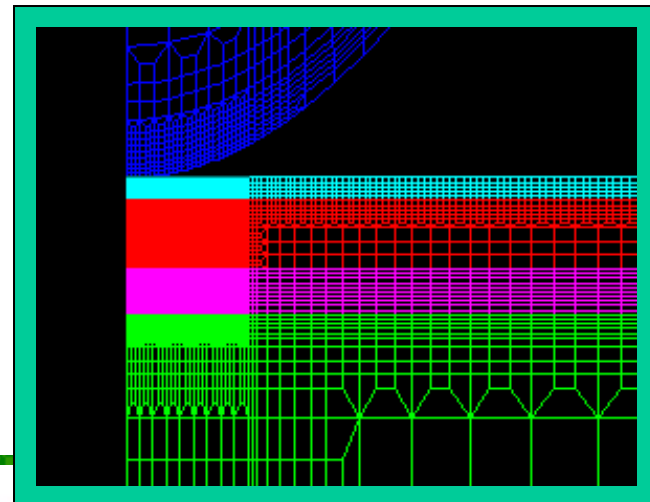
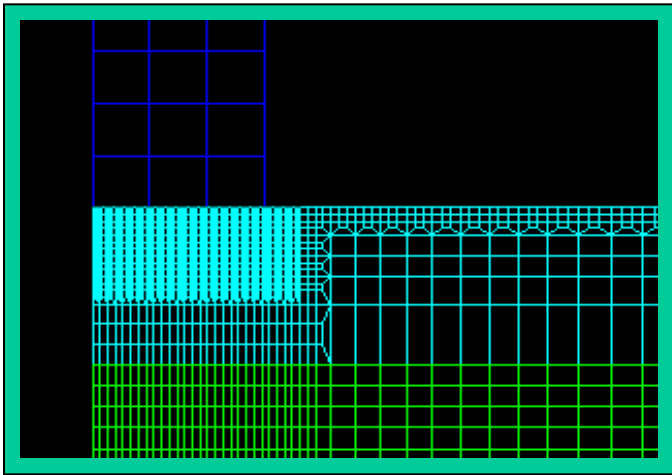
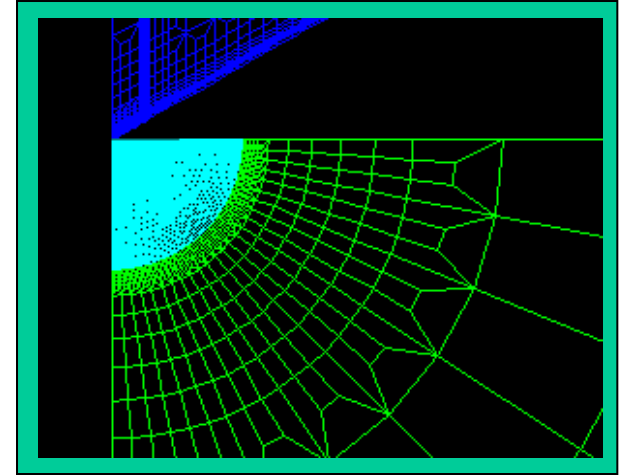
# Developing the model

*There is much to be learned from the process of developing the model.*

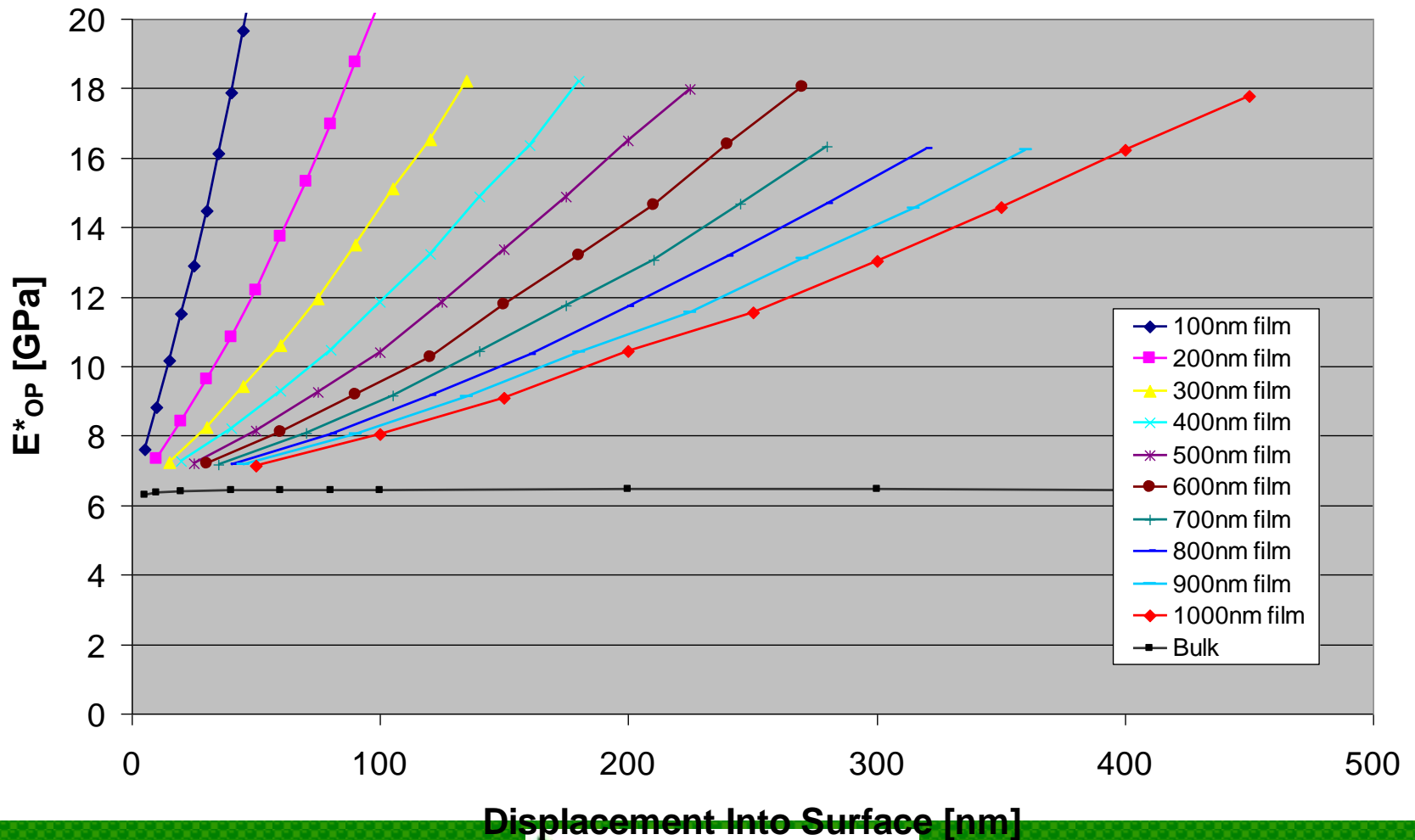
- 1. Survey experimental results. Select properties that bound the range of interest in terms of  $E$  and  $H$ .*
- 2. Perform preliminary simulations to get  $\sigma_y = f(E, H)$ . Select properties that bound the range of interest in terms of  $E$  and  $\sigma_y$ .*
- 3. Perform simulations for “boundary” samples.*
- 4. Calculate errors in modulus and hardness, relative to expected properties for bulk materials.*
- 5. Plot error as a function of parameters that are **relevant, knowable, and dimensionless**. Derive model for error by curve fitting.*
- 6. Test model with more simulations (on materials inside boundaries)*
- 7. Test the model experimentally*

# Virtual Indenter™ Features

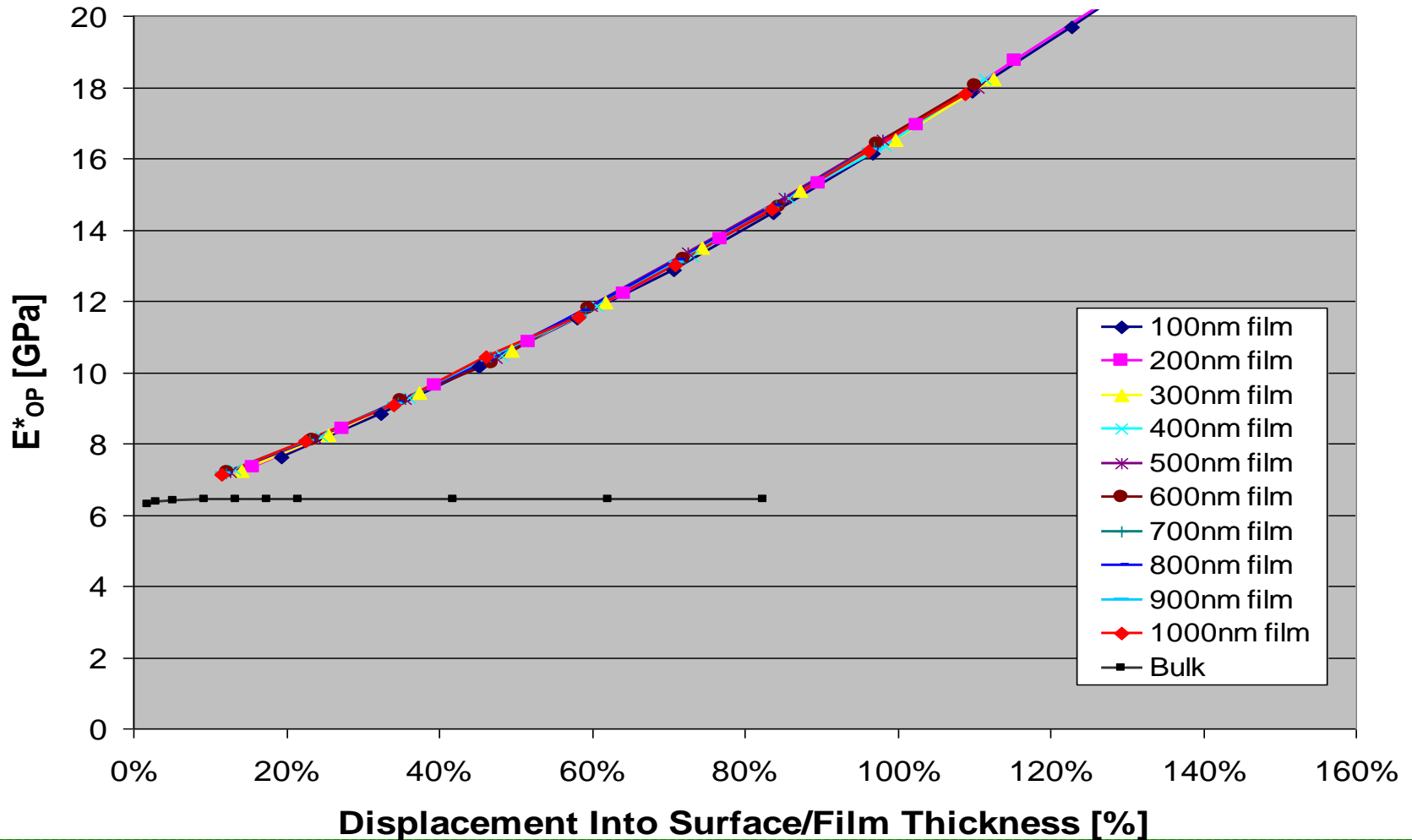
- Real area functions, spheres, flat punches
- Bulk materials
- Up to three stacked films
- Particle/fiber/disk in a matrix
- Range parameters easily
- A variety of constitutive models
- Automated Excel output



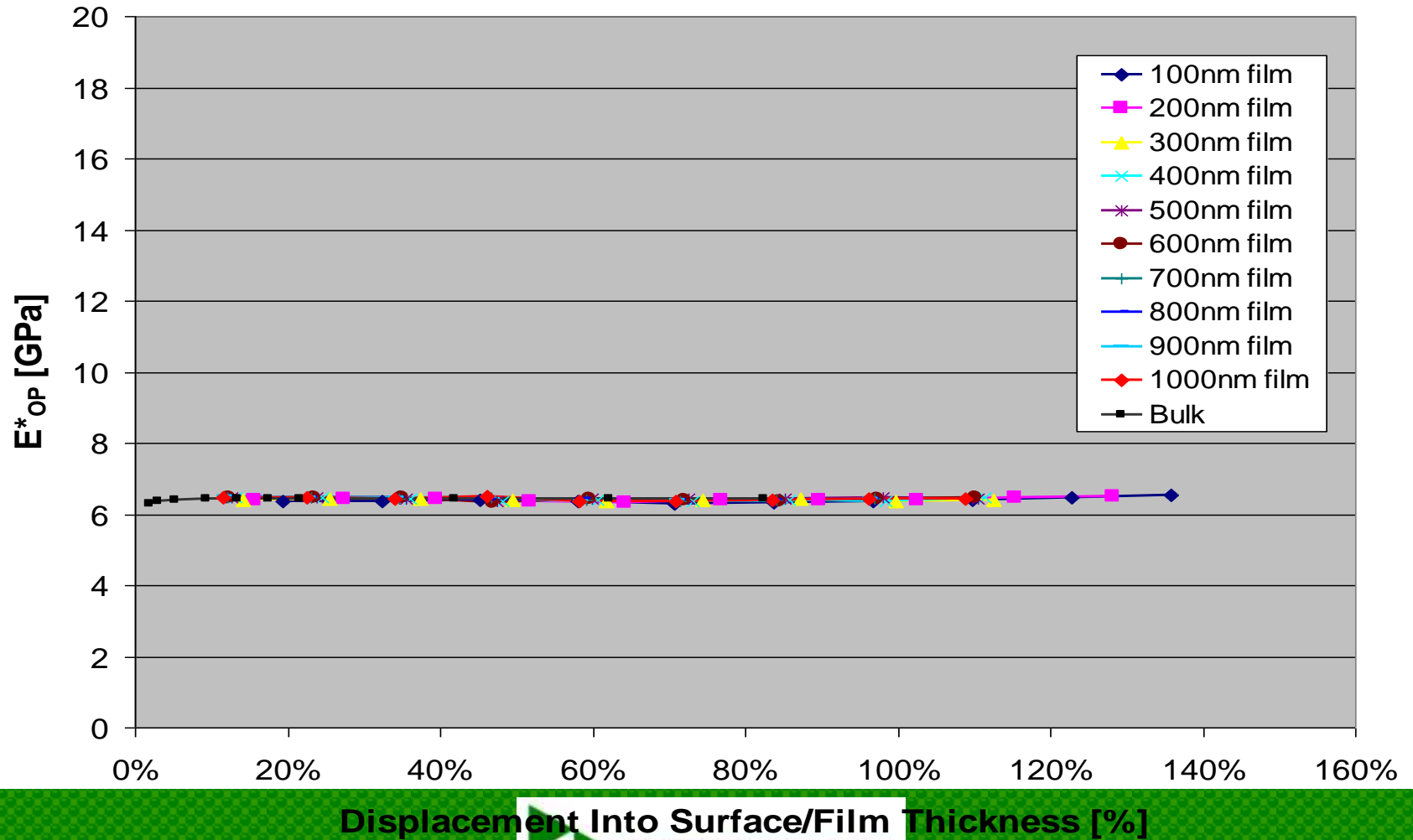
# Uncorrected modulus from simulation



# Uncorrected modulus vs. normalized contact radius



# Corrected modulus vs. normalized contact radius

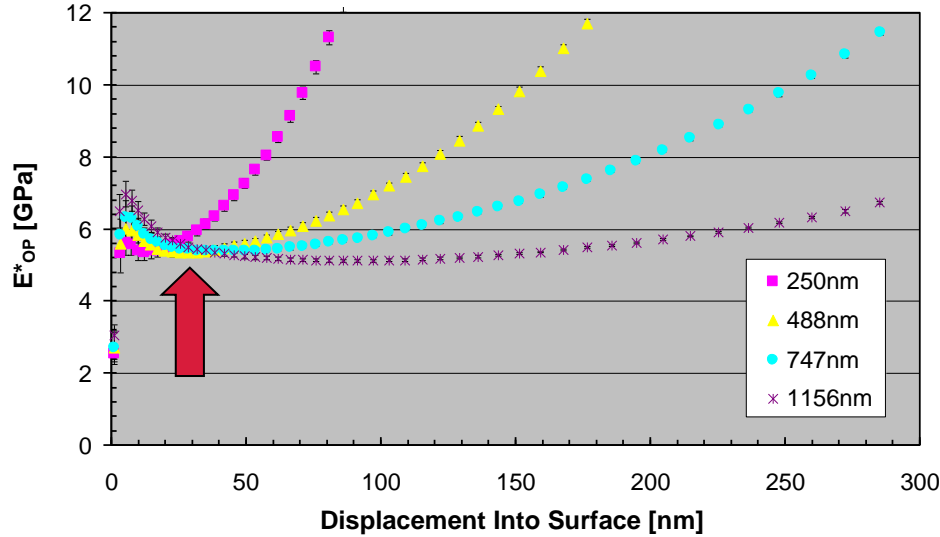


# Applying the model to experimental data

*Wafers supplied by SEMATECH:*

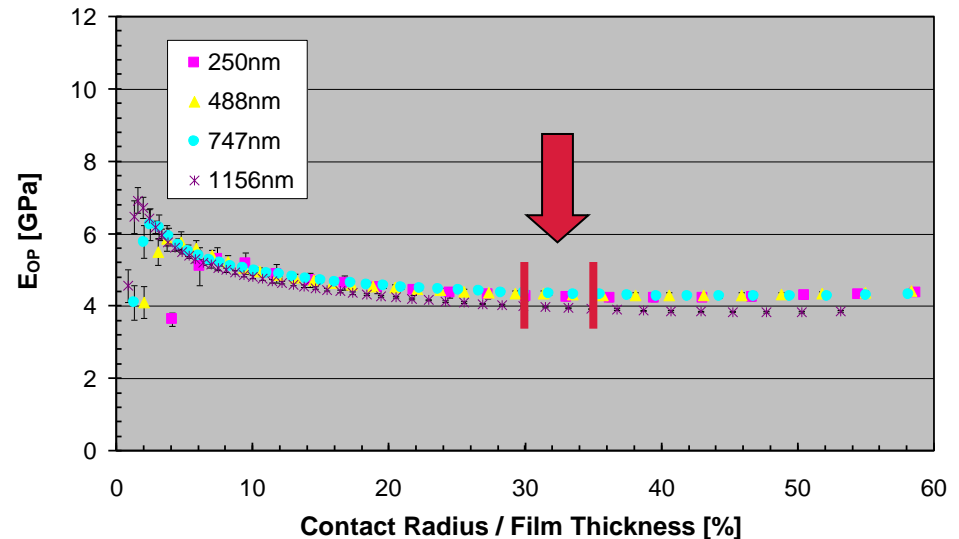
- *4 wafers of nominally the same film, different thicknesses*
- *250nm, 488nm, 747nm, 1156nm*
- *$k \sim 2.3$*
- *Technology targeted for use beyond 45nm node*
- *Deposited using “porogen” and then UV cured to cause residual pores. Cure times varied with thickness. UV cannot penetrate past 750nm.*

# Calculating modulus old way and new way



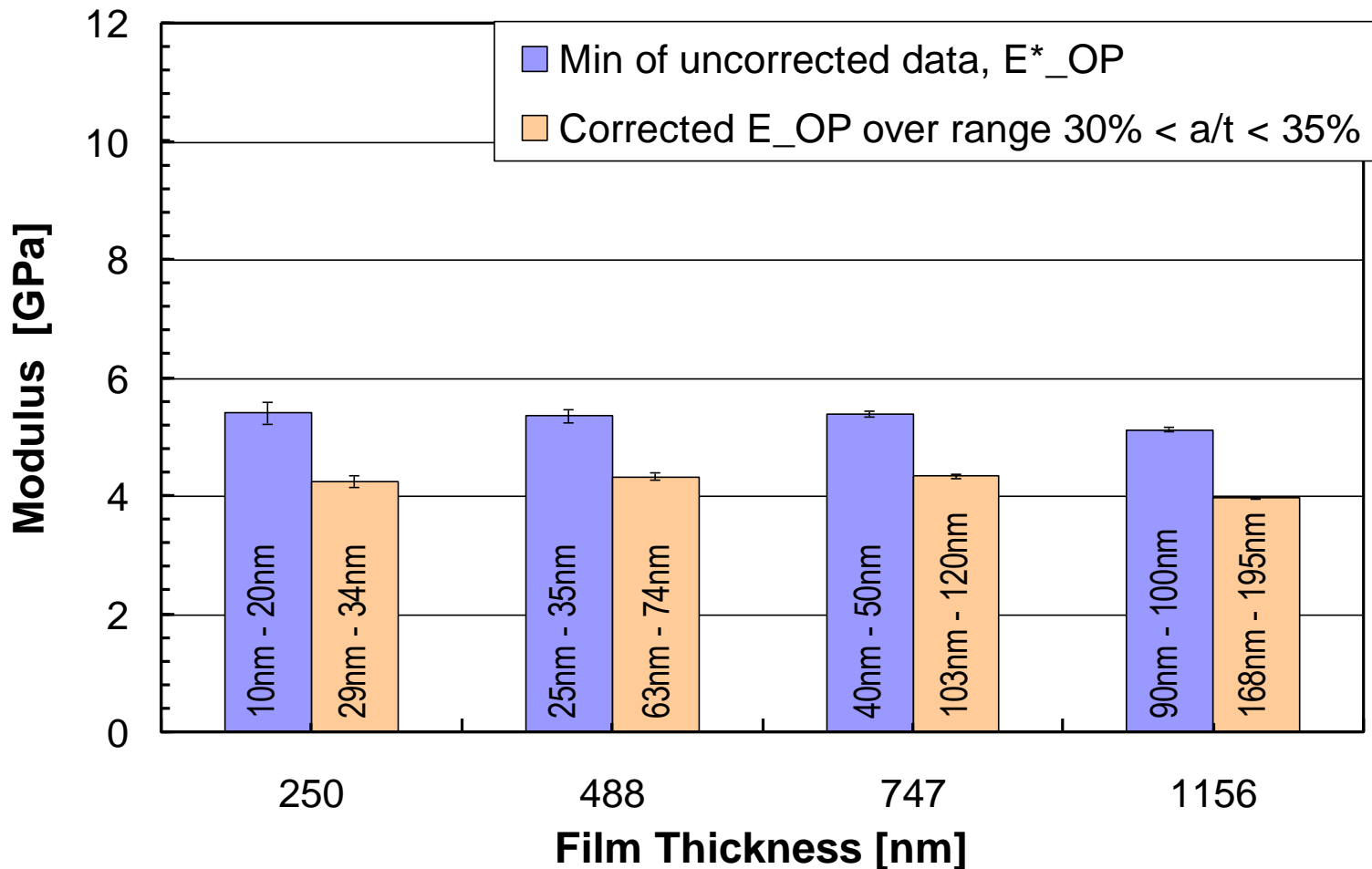
*Old way: take minimum*

*New way: take data for  $30\% < a/t < 35\%$*

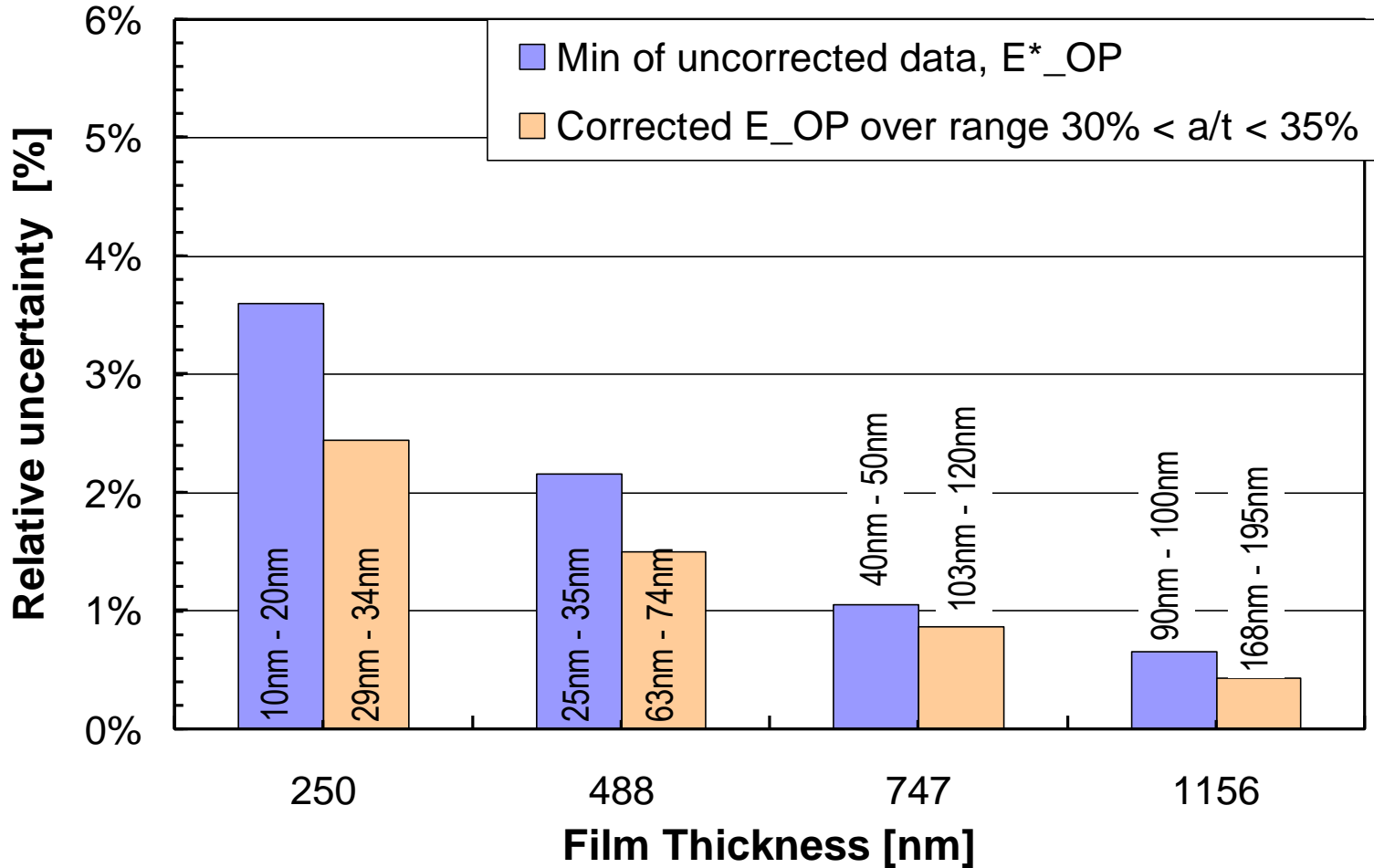


# Calculating modulus old way and new way

*Moduli calculated by old way are too high by 30%, because data at minima are significantly affected by substrate.*



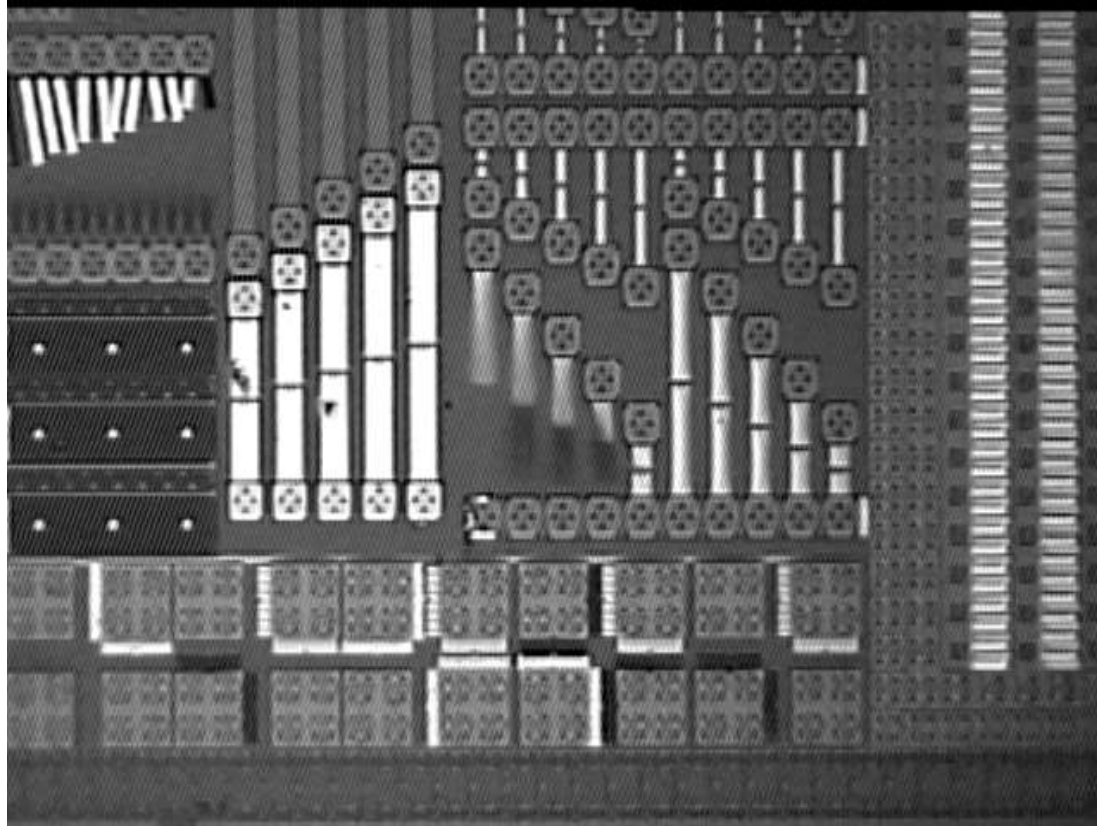
# Using new model also reduces uncertainty



# Conclusions

- *A model has been developed to compensate for the influence of the substrate on the indentation properties of thin low-k films.*
- *Model has been incorporated into a Testworks test method.*
- *Model significantly reduces both error and uncertainty, especially for very thin films.*
- *We continue to test the model on more low-k films.*

# Uniaxial Testing of Free Standing Films



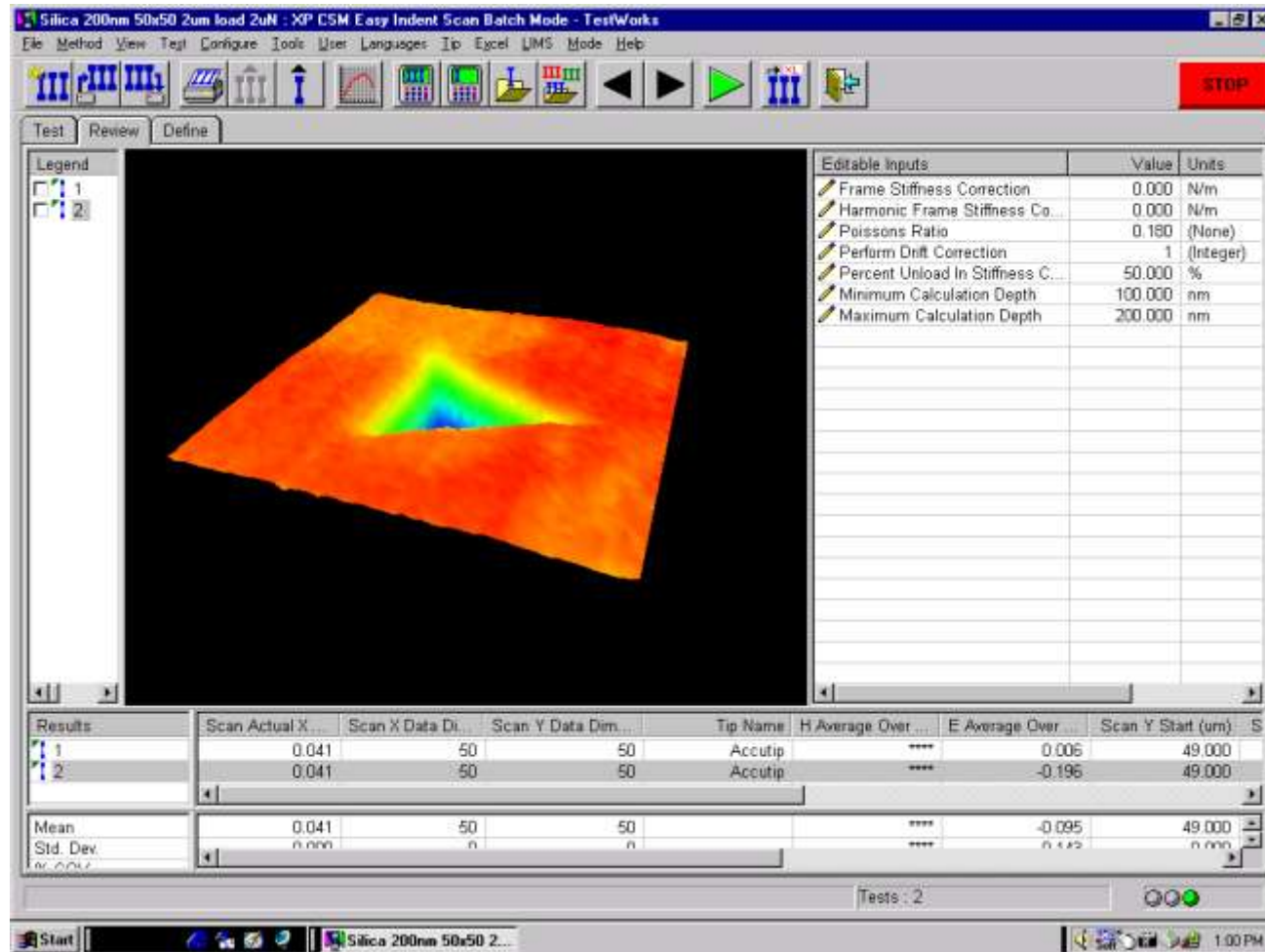
Warren C. Oliver and Erik G. Herbert, MTS Corporation  
Johnathan Doan, Reflectivity

# Nanovision Stage

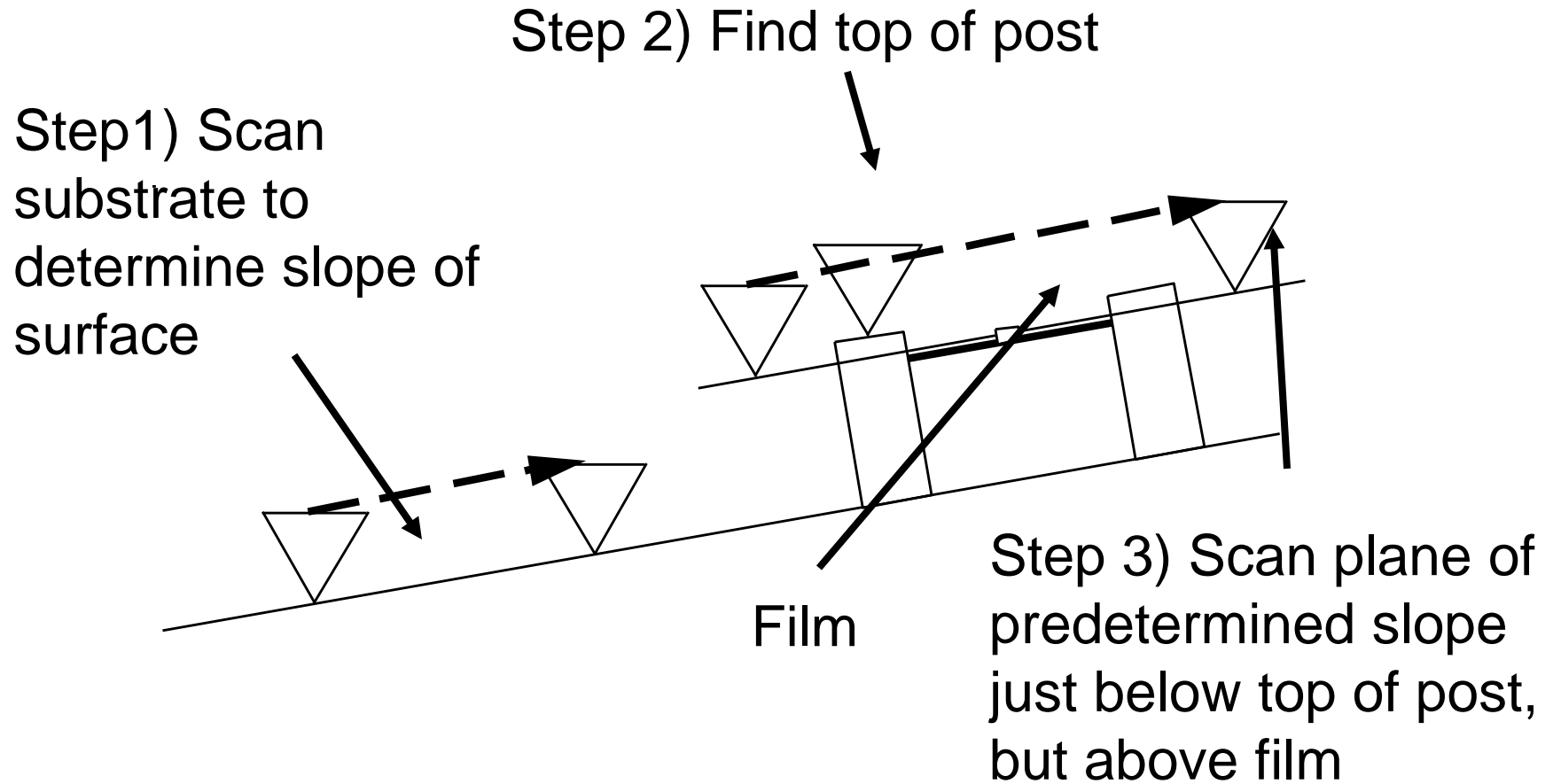
Travel: 100  $\mu\text{m}$  x 100  $\mu\text{m}$   
Resolution/Noise: 2 nm  
Flatness of travel: 1-2 nm  
Accuracy: 0.01 %  
Settling Time: 2 ms-  
Capacitive feedback  
control



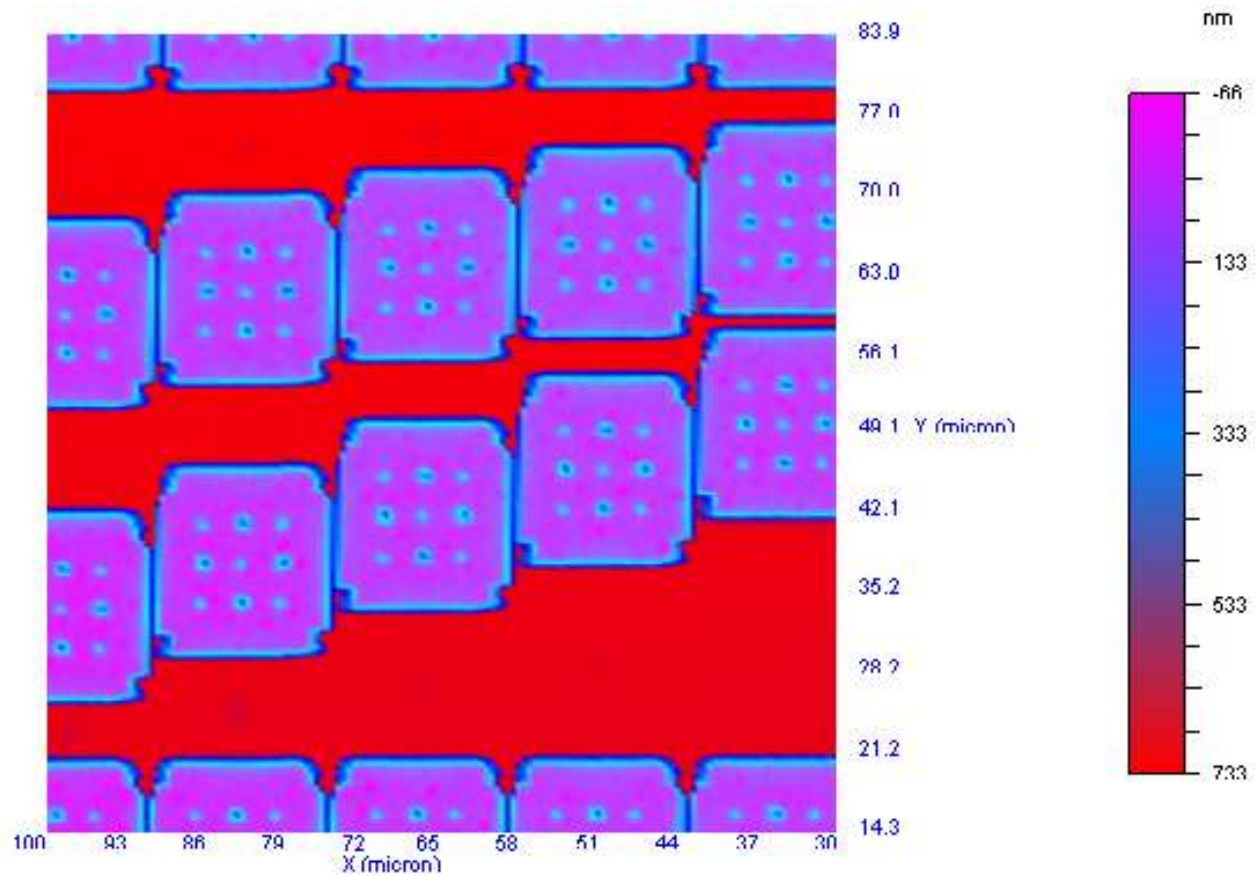
# Automated Indent and Scan



# Scan Procedure

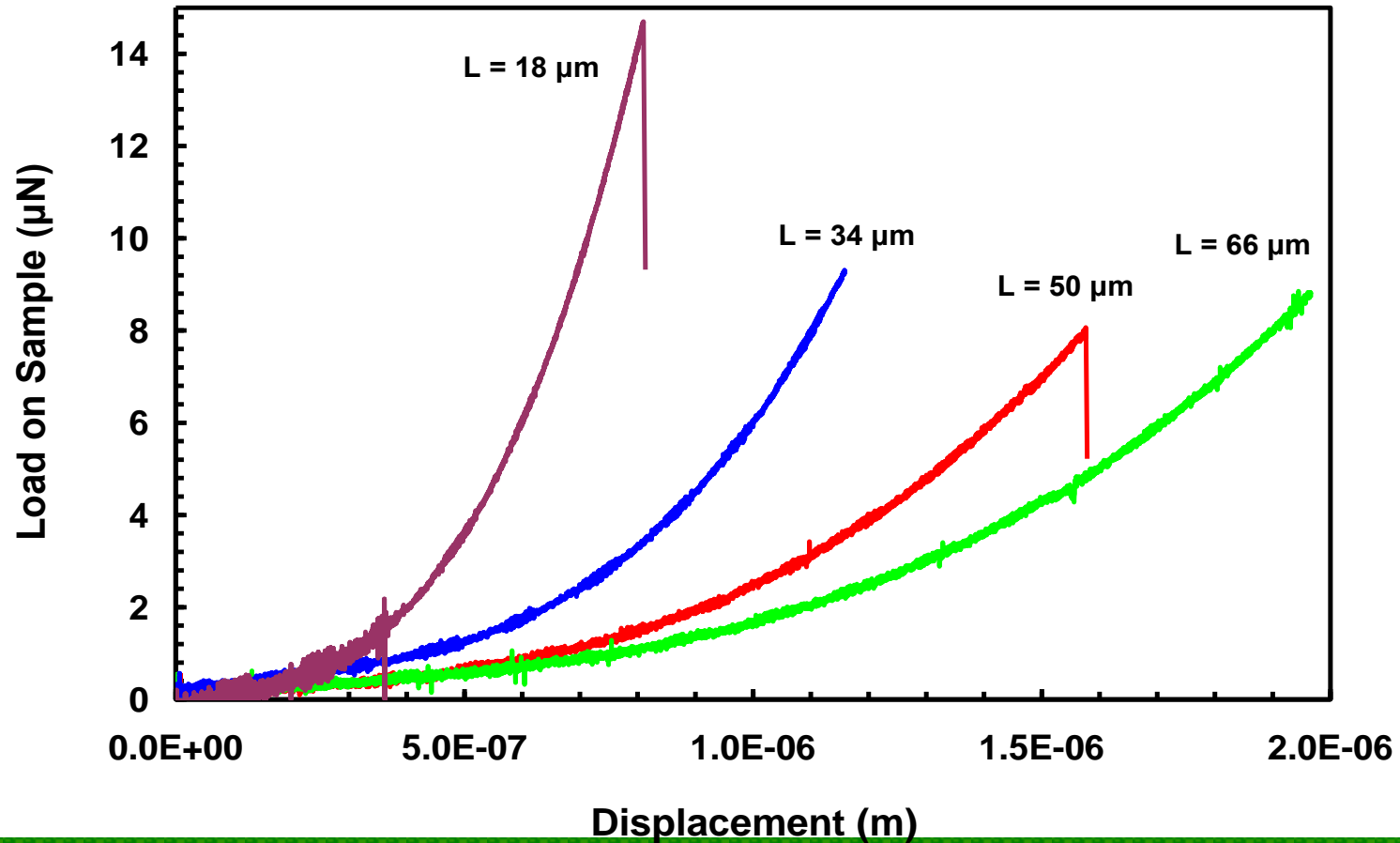


# Leveled Targeting Scan

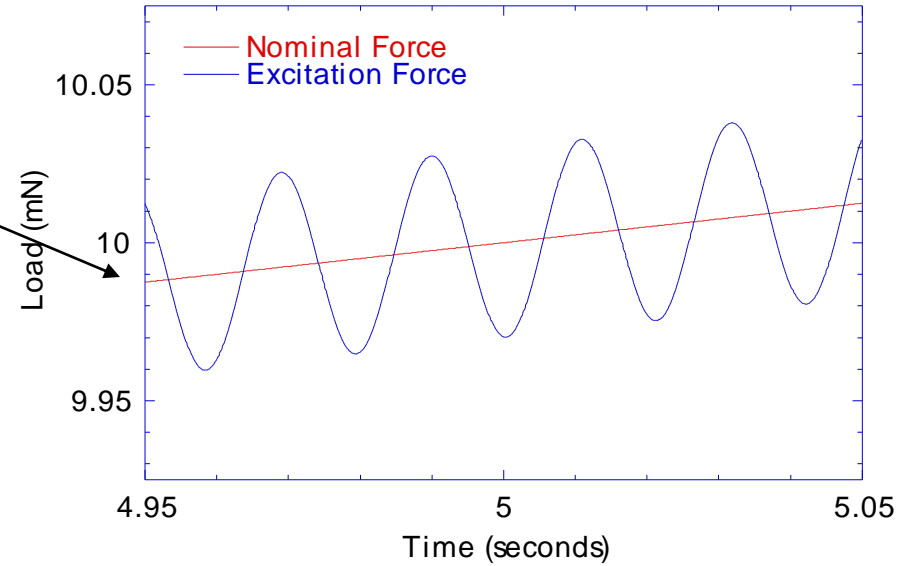
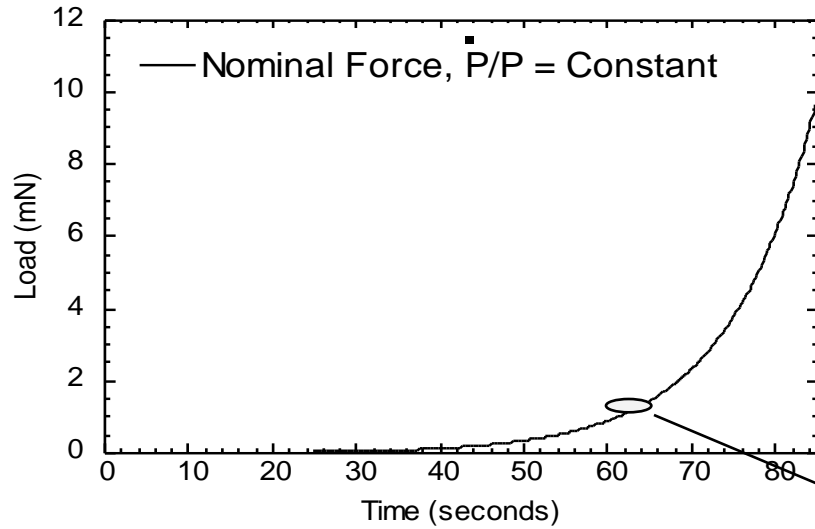


# Load Displacement Curves

## 8 $\mu\text{m}$ Wide, Doubly Clamped Bridges

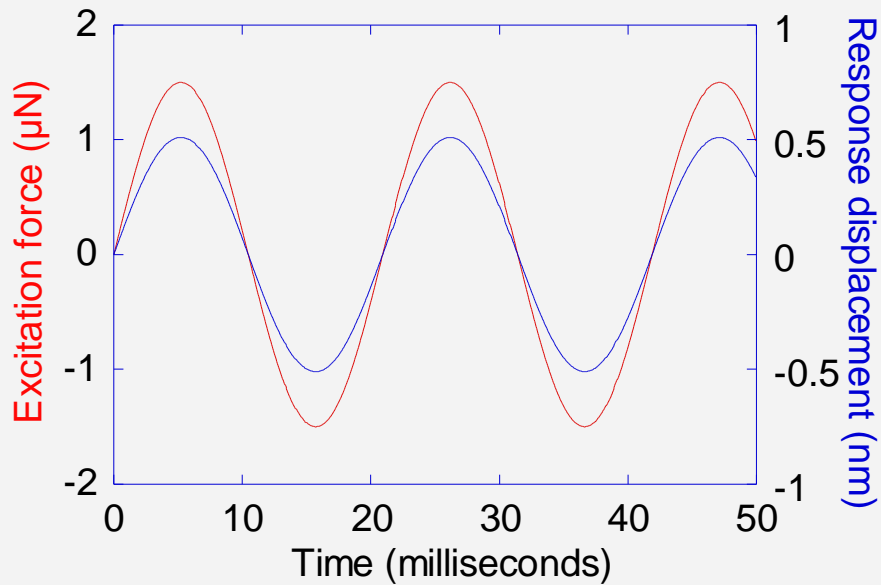


# Continuous Stiffness Measurement Technique (CSM)

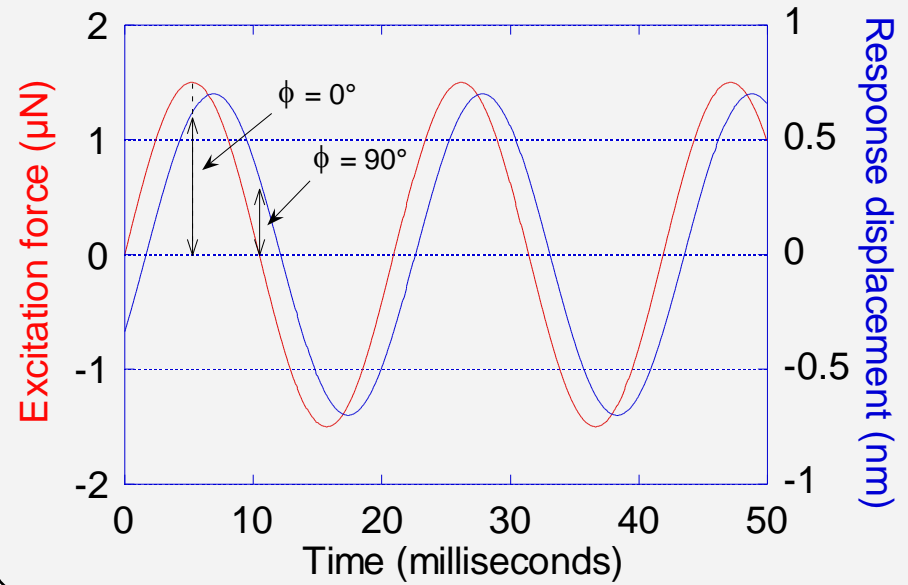


# CSM - Elastic & Viscoelastic

*Elastic*

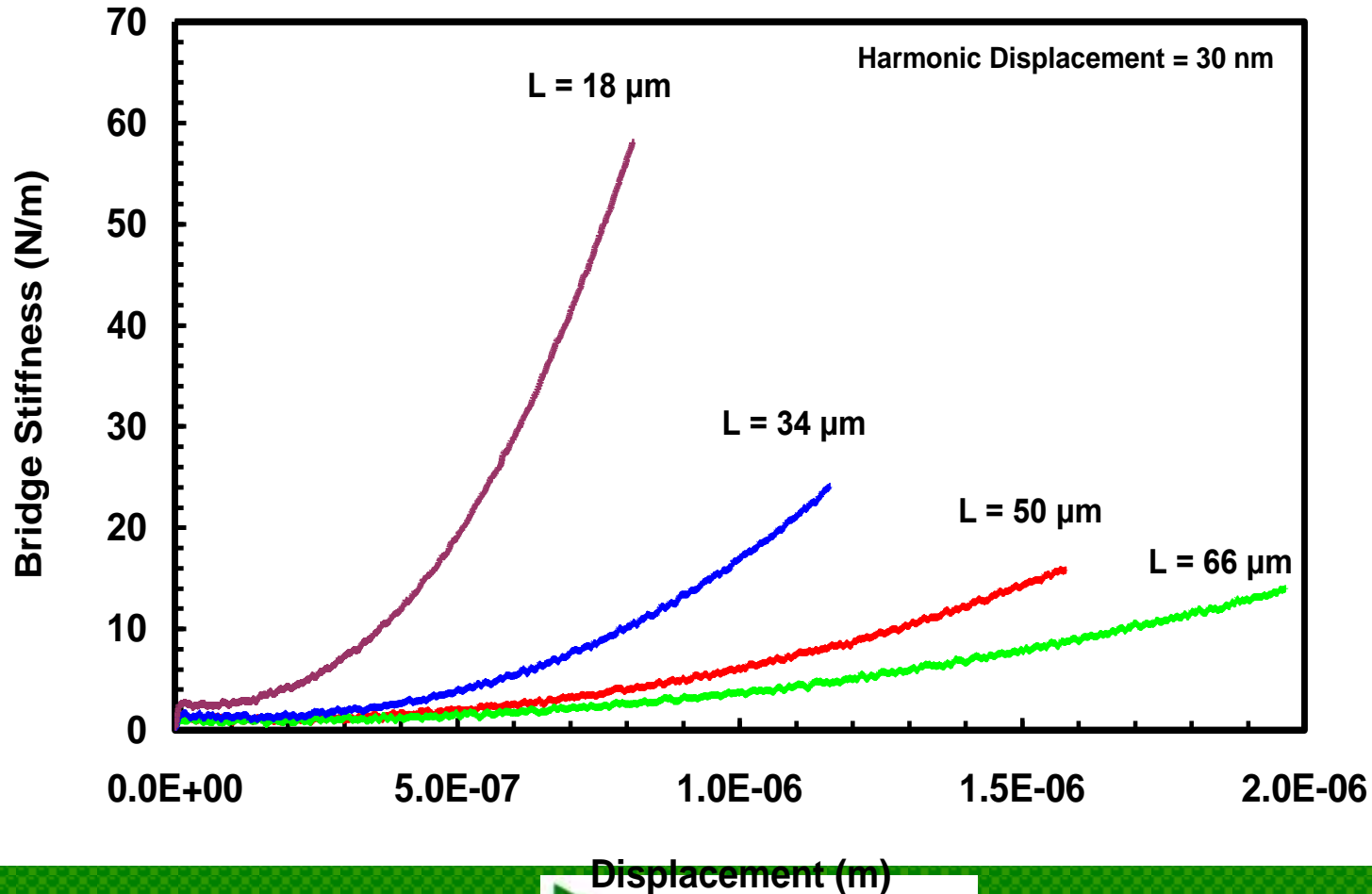


*Viscoelastic*

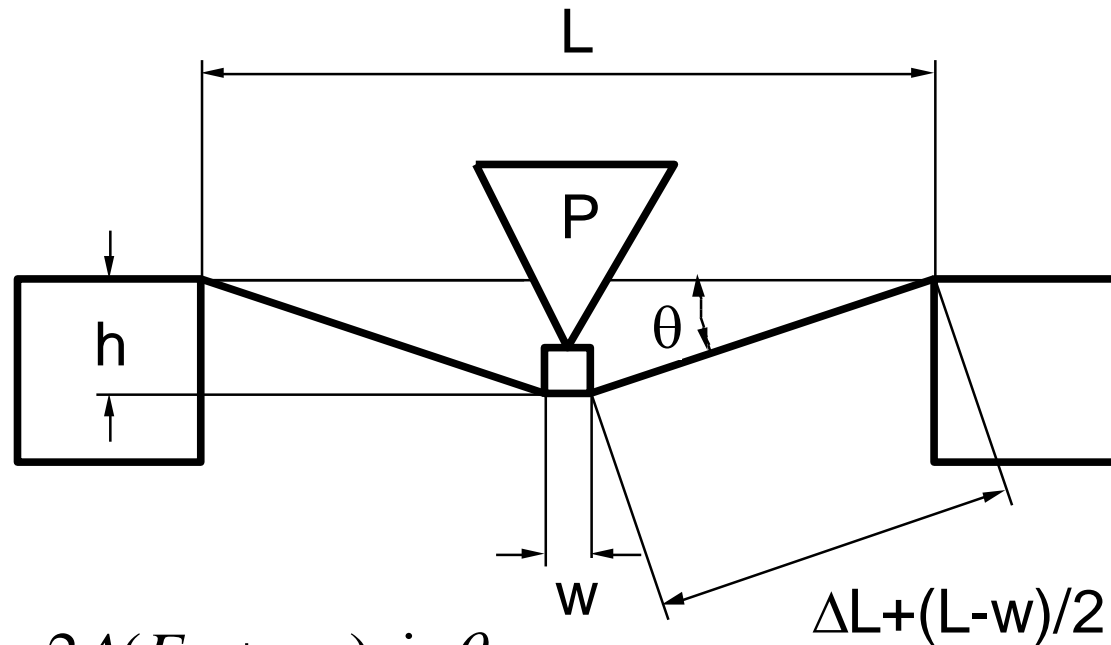


# Stiffness Displacement Curves

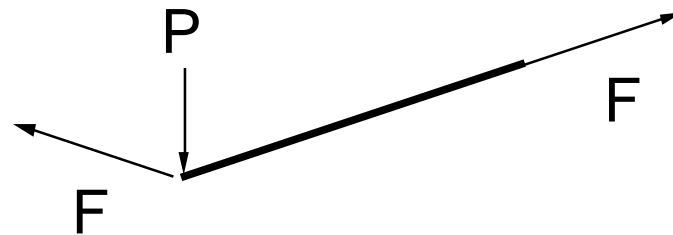
8  $\mu\text{m}$  Wide, Doubly Clamped Bridges



# Describing Bridge Tensile Specimens



$$P = 2F \sin \theta = 2A(E\varepsilon + \sigma_r) \sin \theta$$



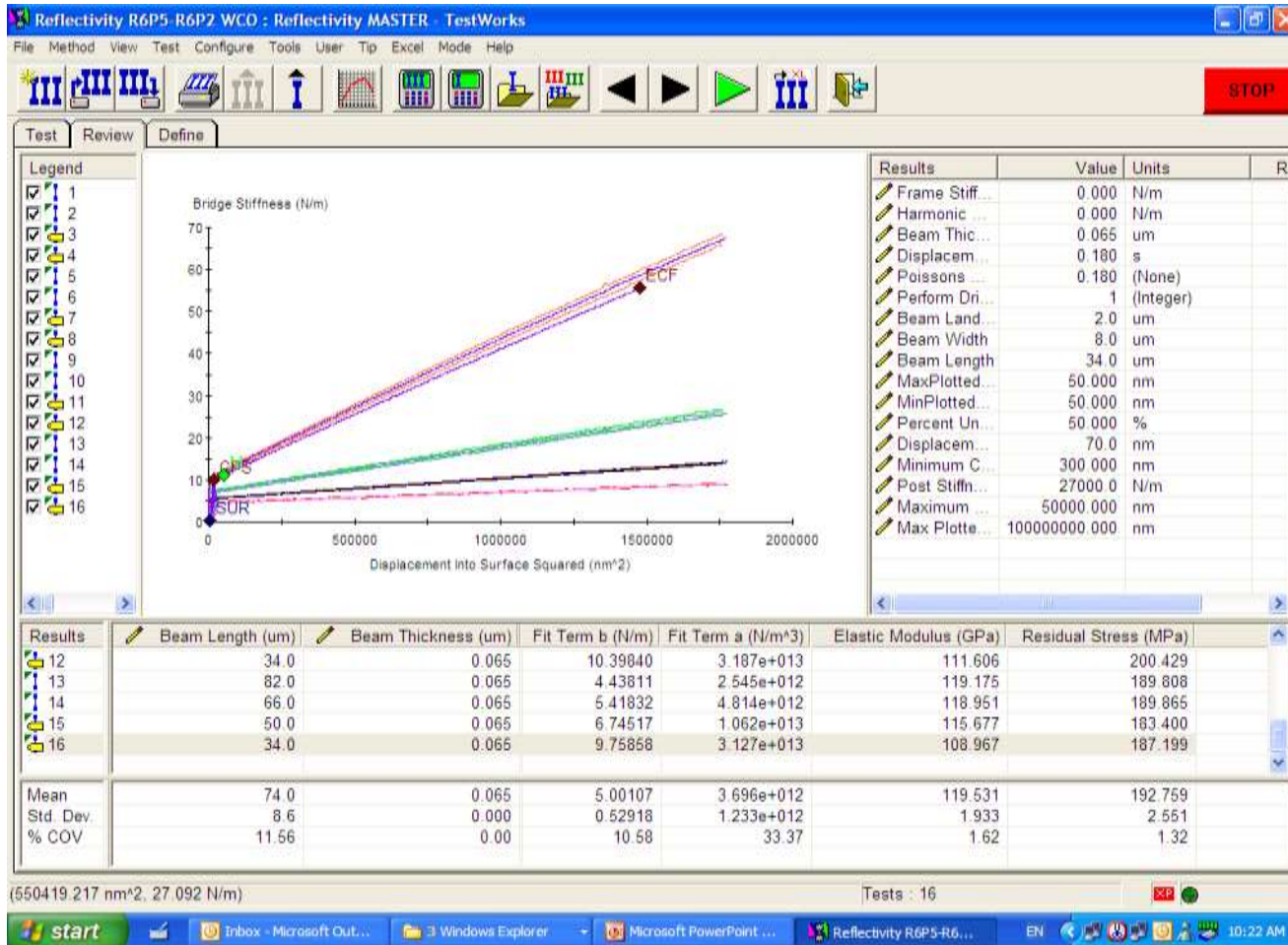
# The Stiffness Displacement Relationship:

$$P = \frac{4AEh}{(L-w)} + 2A \sin \left[ \tan^{-1} \left( \frac{2h}{(L-w)} \right) \right] (\sigma_r - E)$$

For not quite so small angles  $\sin \theta = \theta - \frac{\theta^3}{3!}$   $\tan^{-1} \theta = \theta - \frac{\theta^3}{3}$

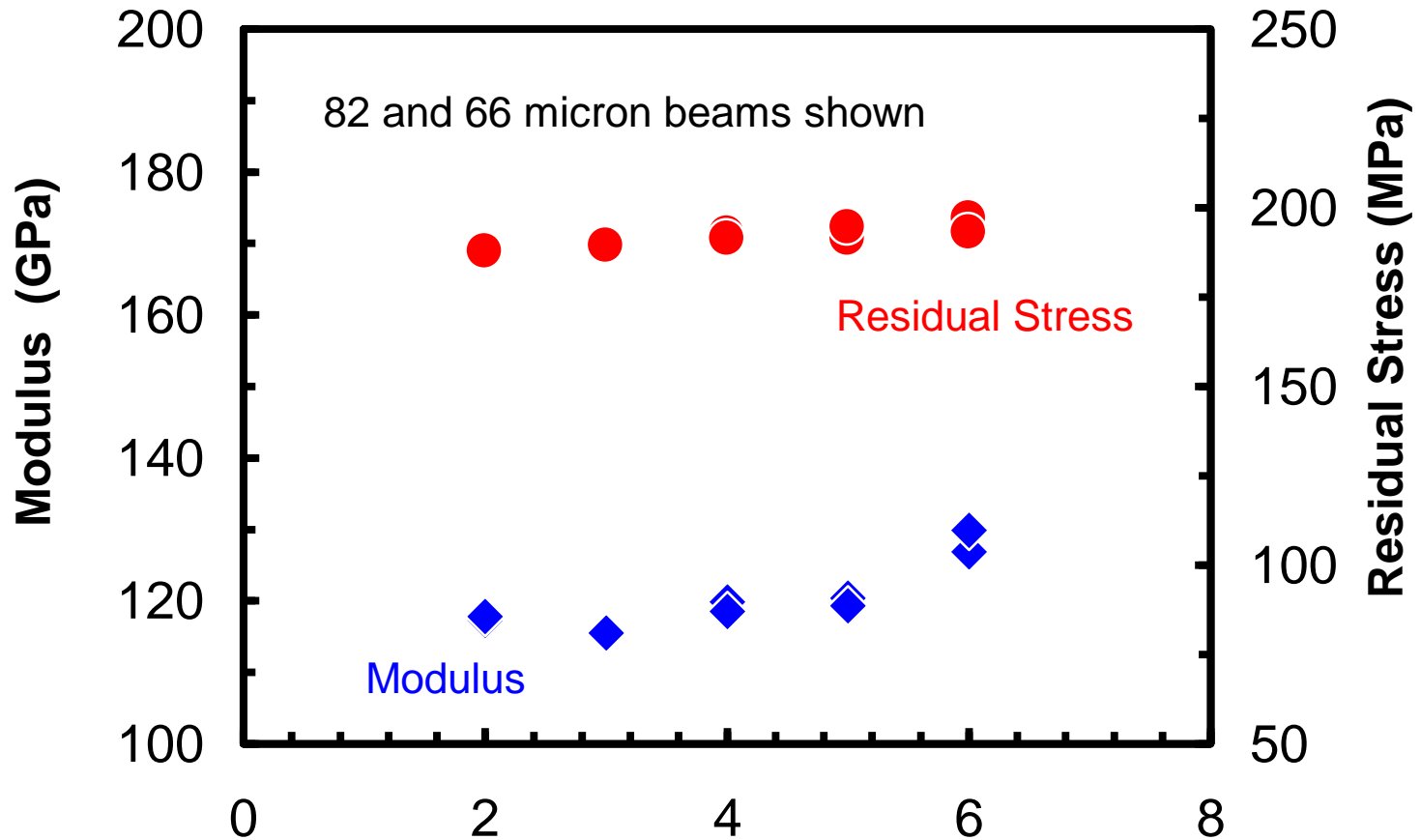
$$\frac{dP}{dh} = \frac{4A\sigma_r}{(L-w)} + \frac{24A(E - \sigma_r)h^2}{(L-w)^3}$$

# Testworks: A Complete Solution



# Now it gets Interesting

## Properties Versus Position on the Wafer



# TestWorks and the Nano Indenter G200

- Design of MEMS structural experiments was easily done with the flexibility and control offered by the TestWorks software
- TestWorks provides a user interface that facilitates the design of new (i.e. MEMS) and novel experiments without the need to have knowledge of C++ programming
- The Nano Indenter G200 system can provide this information quickly and reproducibly, offering manufacturers an attractive tool for product development

*Thank you!*

