Critical Issues for Interconnects: Mechanical Strength and Adhesion based on Nanoindentation

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Outline

I. Why nano-Indentation ?

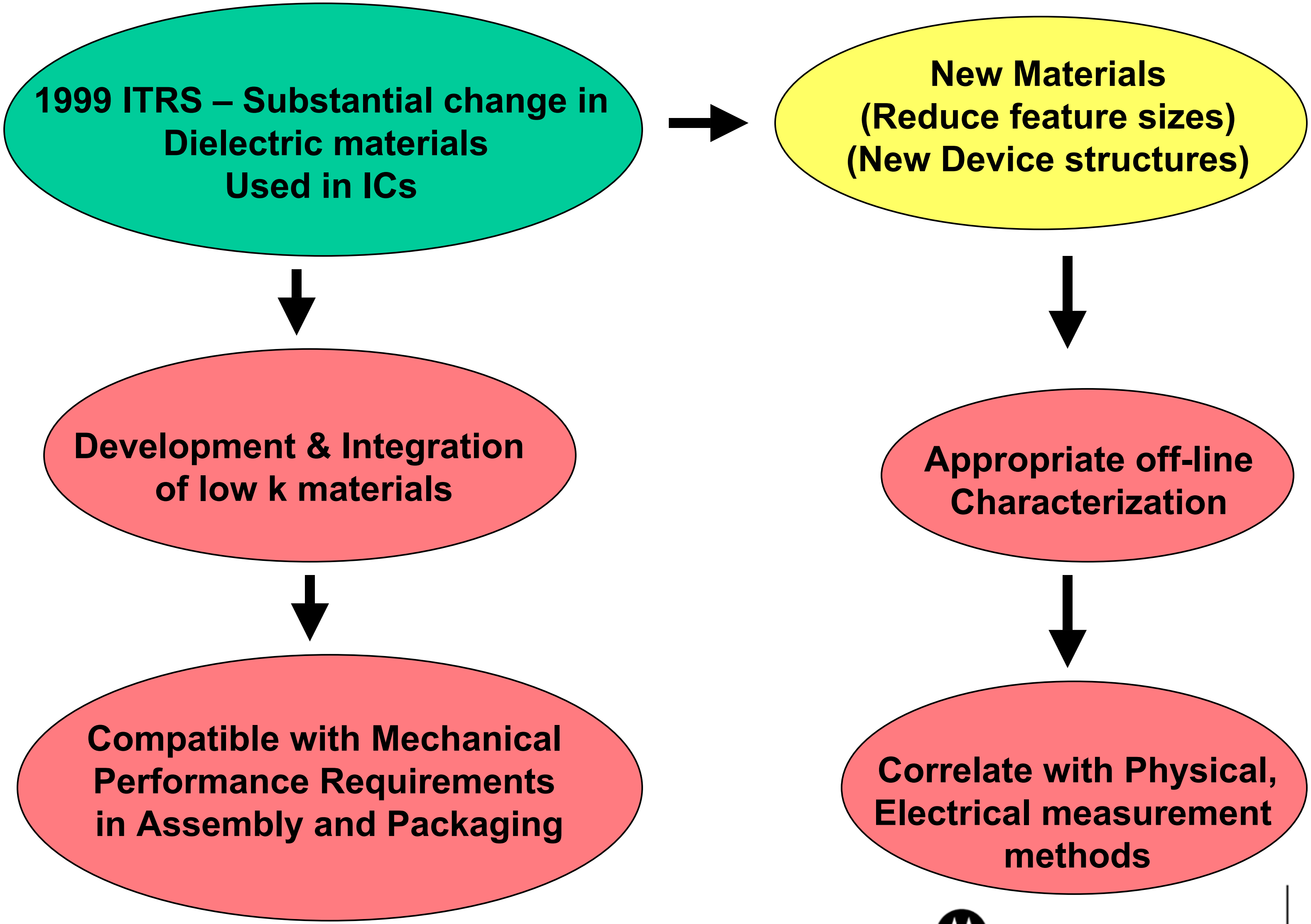
II. Overview of OSG Structure and Properties

III. NanoIndentation Metrology of Low-k Materials
   A. Utility of Hardness and Modulus
   B. Mechanical Properties Give Insight to Porosity
      -Percolation Theory

IV. Adhesion and Fracture Toughness Measurements
   A. Description of Methodology and Limitations
   B. NanoIndentation induced fracture calculations

V. Conclusions

Why Nano-Indentation ?



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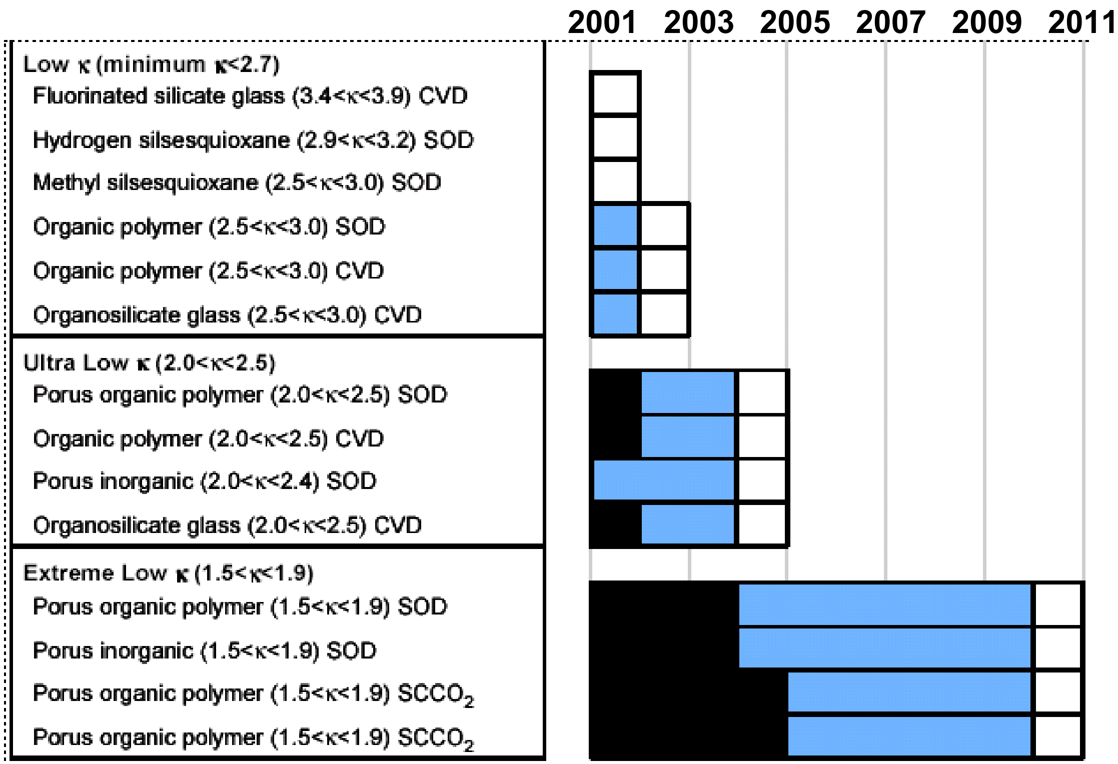
Development & Integration of low k materials

Dielectric Potential Solutions

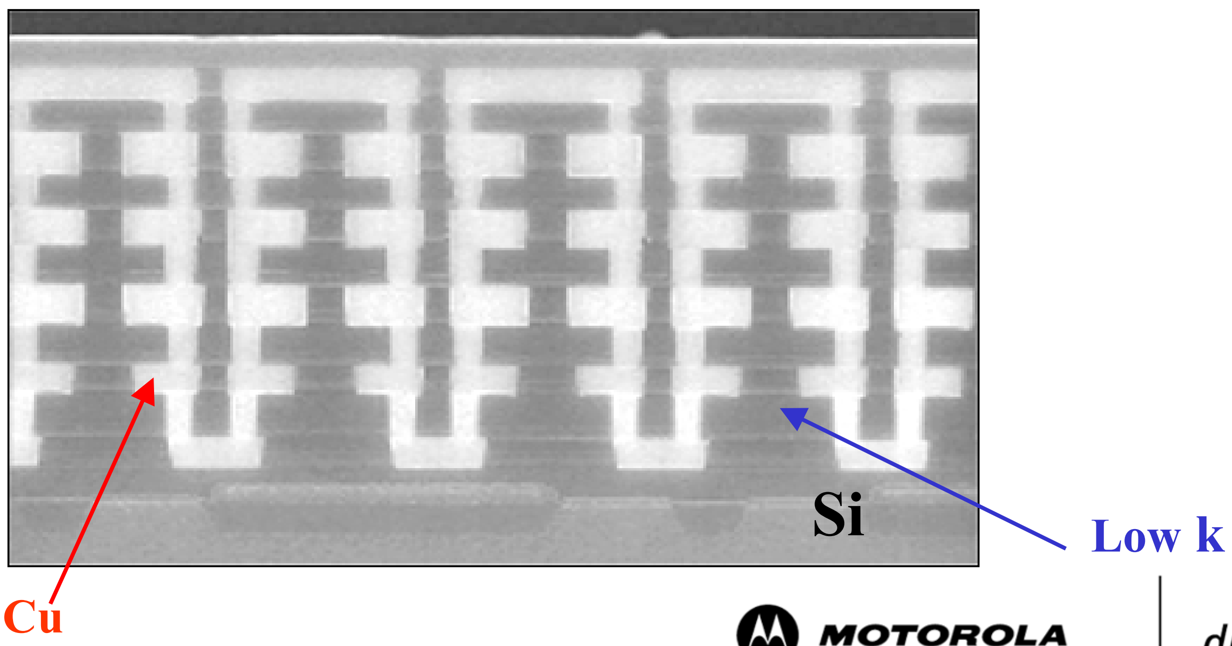


Metrology Challenges

1. Mechanical Strength
   - Modulus
   - Hardness
   - Fracture
2. Interfacial Adhesion
3. Pore size distribution

Organo-silicate Glass (OSG) Low-k Integration at Motorola

- **Dielectric properties of fully dense silica (k~4.1) can be extended by**
  - **reducing the density**
  - **increasing the porosity,**
  - **utilizing the dielectric constant of free space (k=1) and organic inclusions.**
- **Electrical properties provide a smooth transition from traditional silica to next generation IC's**
- **Mechanical reliability properties require extensive study in thin film form. Often these films cannot be grown to thicknesses greater than 3µm.**
- **Nanoindentation offers unique capabilities in classifying these types of materials.**



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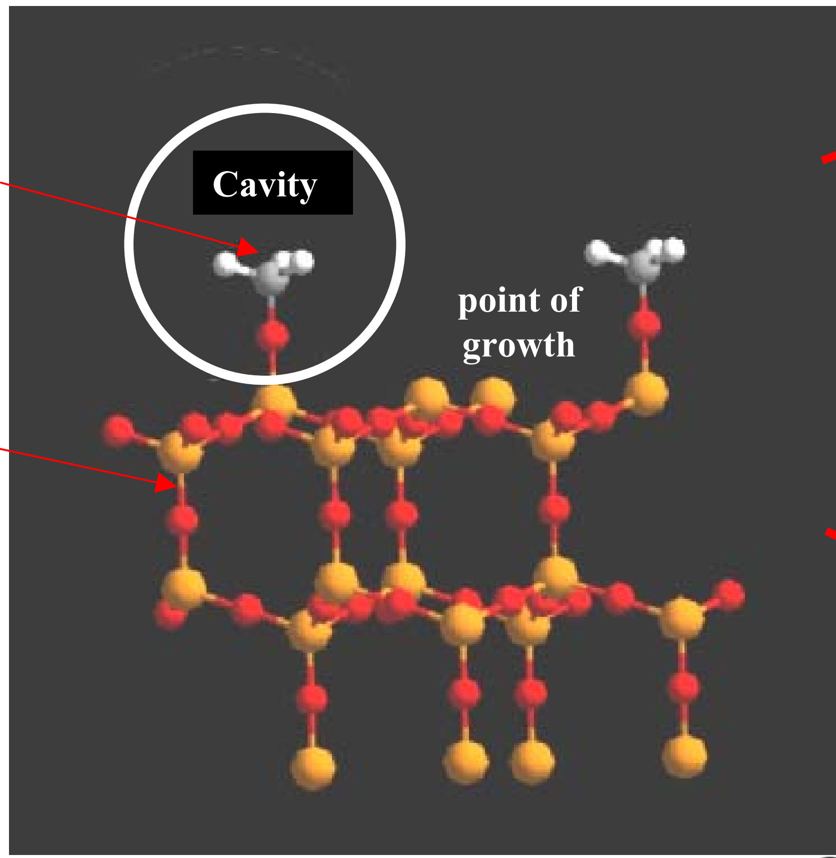
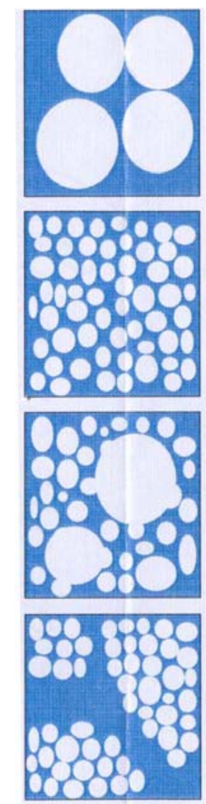
OSG Pore Distribution

- Pore is created by the introduction of CHx group that retards Si-O bonding network.
- Small pore size (1nm) therefore is largely occupied by the dangling methyl group



Various Pore Population Distributions?



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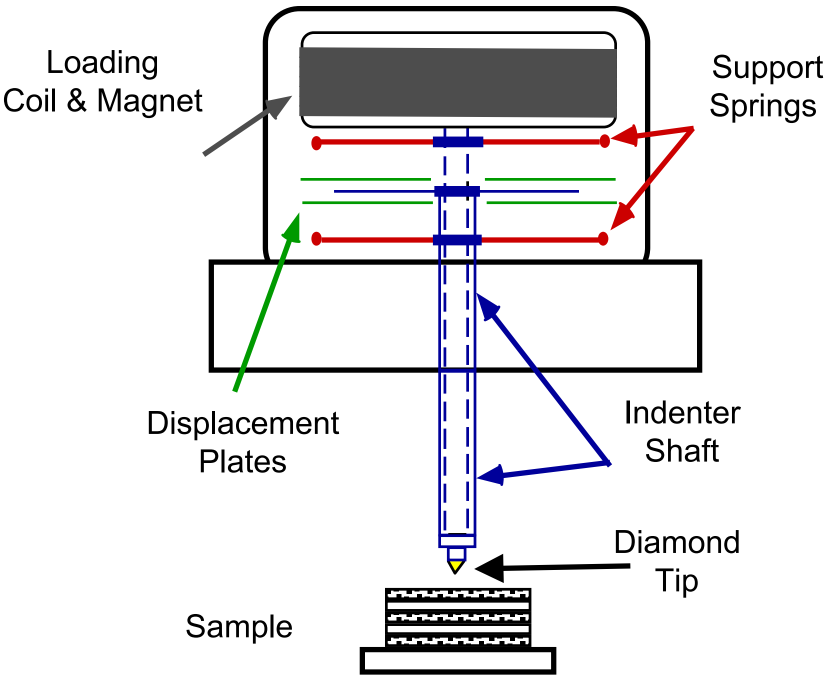
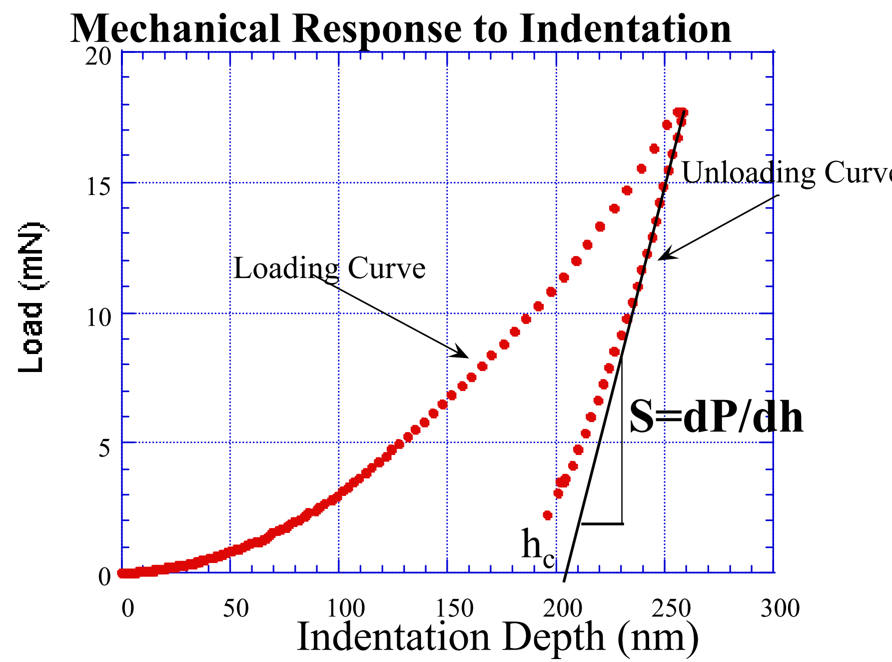
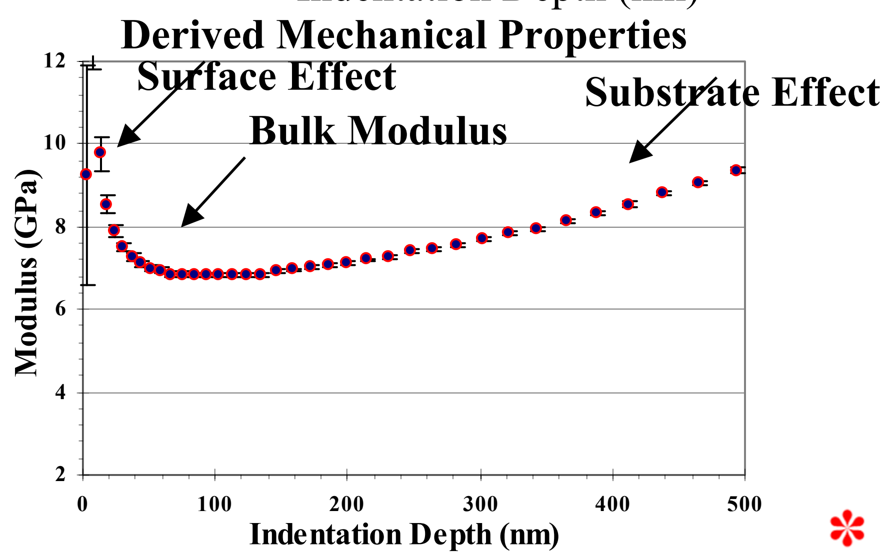
Mechanical Property Measurements







Load Measurement

Current is applied through a coil in a magnetic field generating a force

Displacement Measurement

Movement of the Capacitor plate

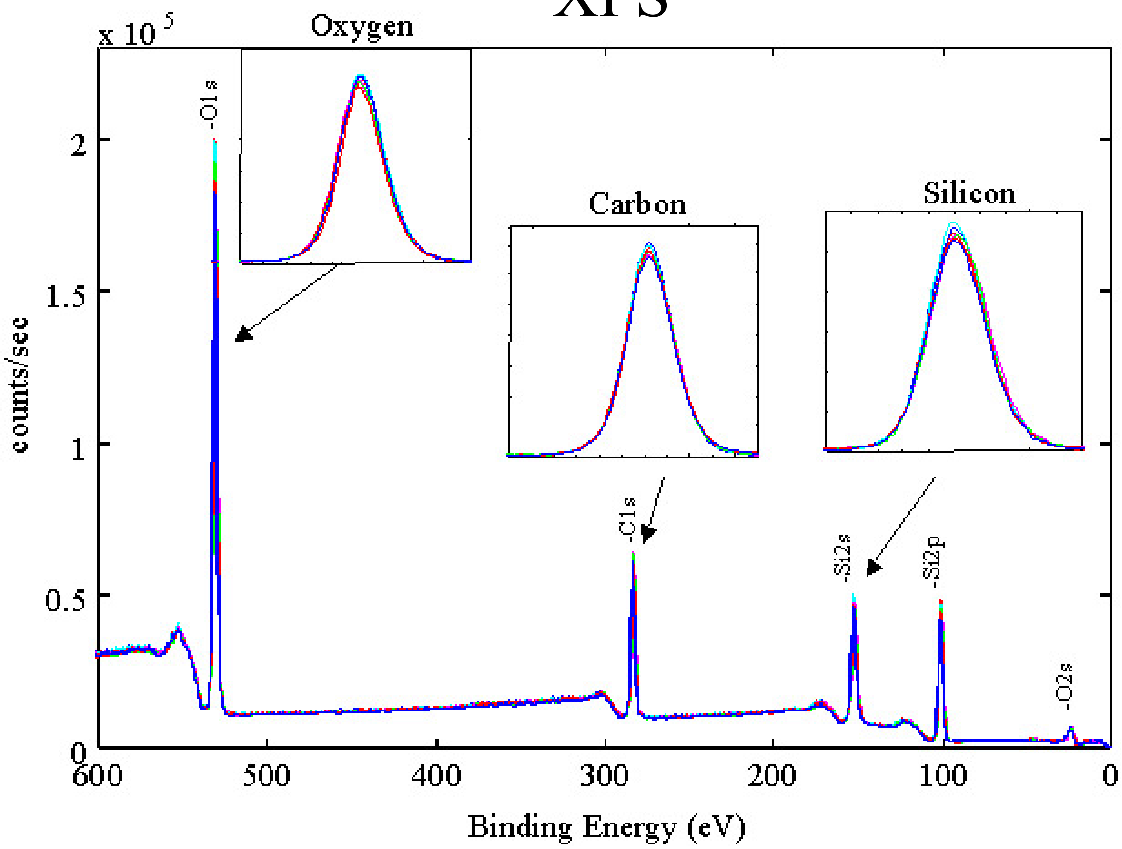
$$H = \frac{P}{A}$$

$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}}$$

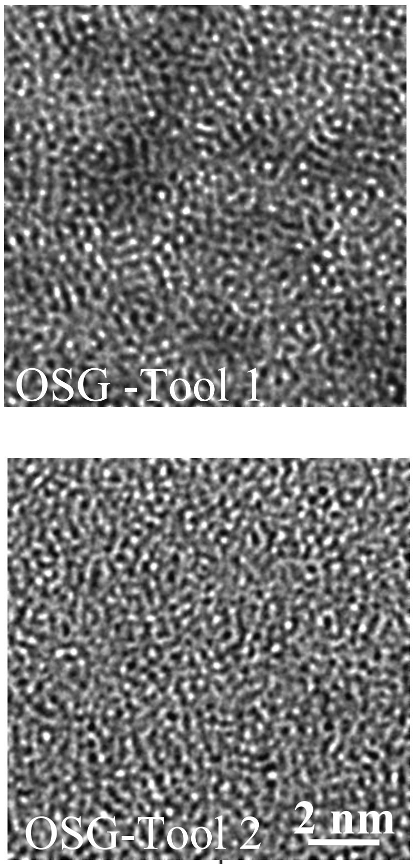
Low-K Film Metrology – New Tool Installation

- **X-Ray Photoelectron Spectroscopy shows that 7 OSG of varying process parameters are ostensibly chemically identical.**
- **TEM shows amorphous and possibly porous structure however no discernible discrepancies.**

XPS



TEM



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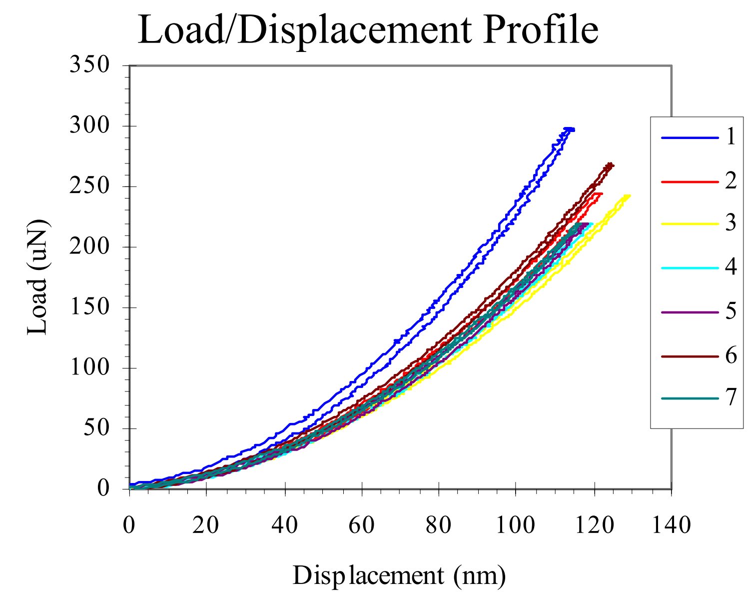
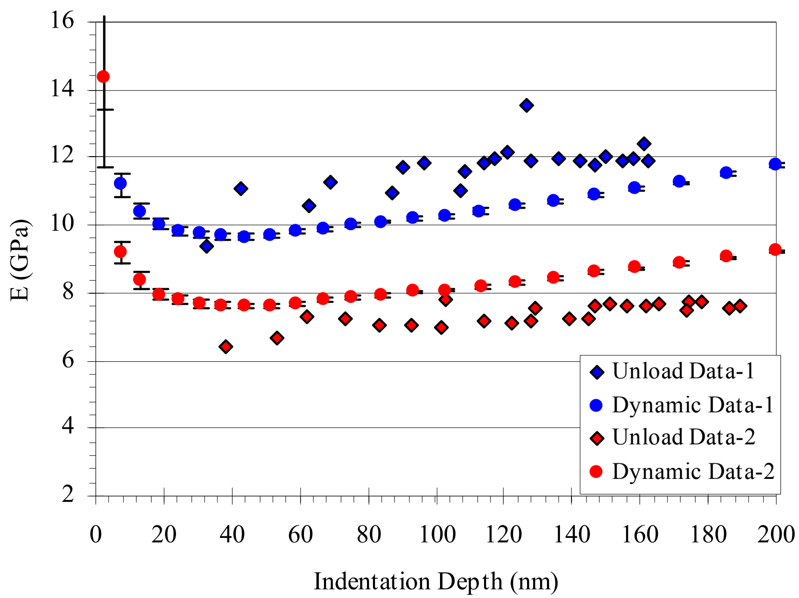
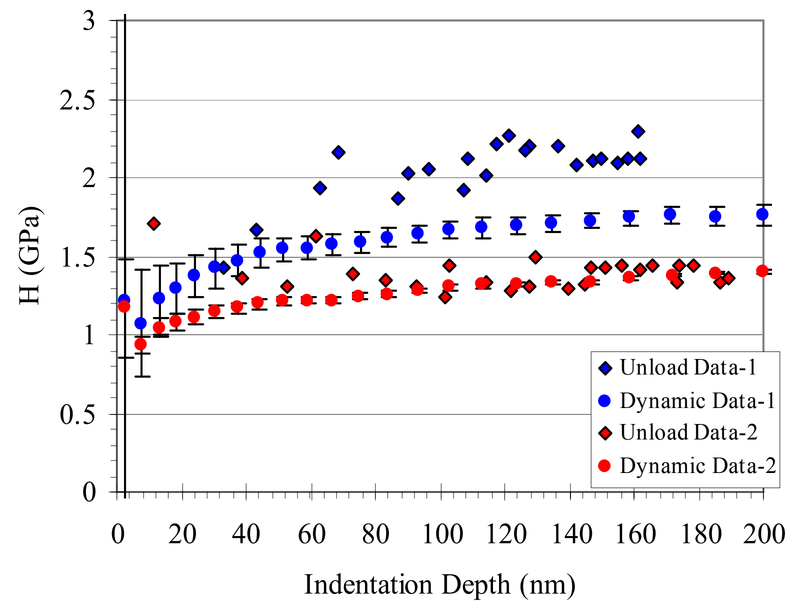
NanoIndentation results of OSG series



- Significant mechanical properties difference observed among the two tools
- Load/displacement profile shows entirely elastic contact to depths of 120nm





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Does Percolation Theory Hold Up on the Nanoscale?

Percolation Theory

$$\frac{E^*}{E_0} = \left(1 - \frac{p^*}{p_c}\right)^f$$

FILM 1	Open Pore Porosity (%)	Closed Pore Porosity (%)
Modulus Data Calc	59.7	76.8
Hardness Data Calc	58.9	70.2

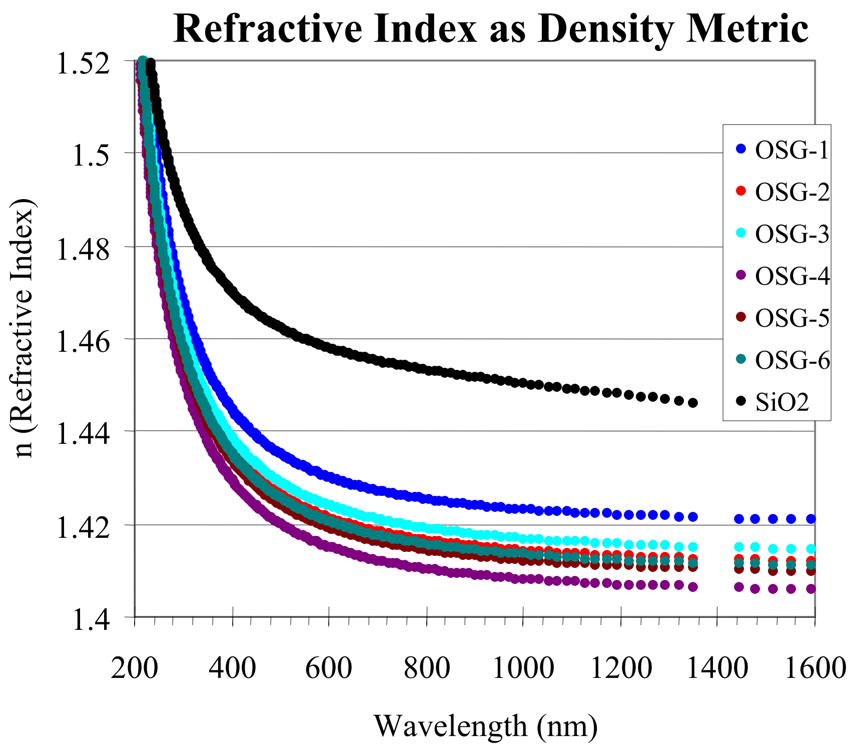
Gibson and Ashby Predictions

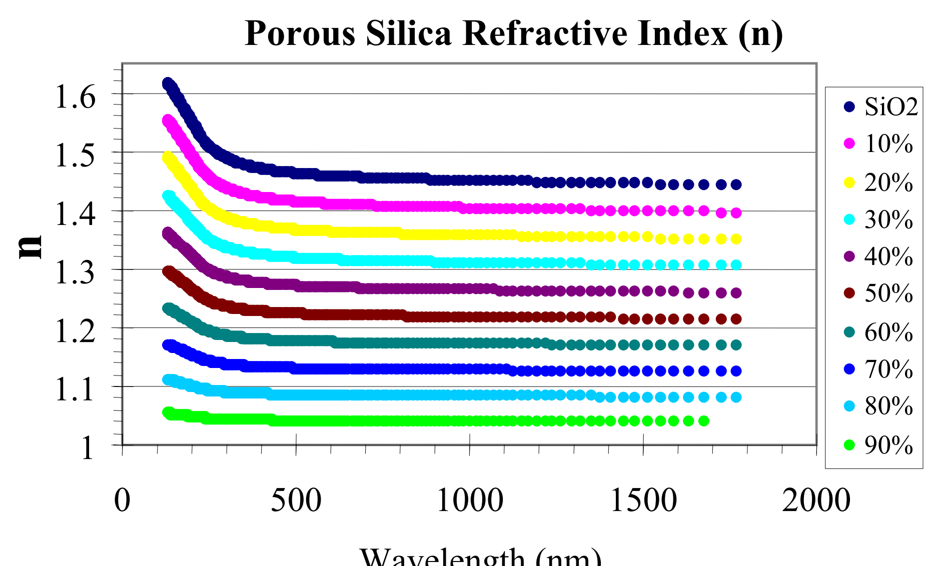
	Open Cell Pores	Closed Cell Pores
Modulus	$\frac{E^*}{E_0} = \left(\frac{\rho^*}{\rho_0}\right)^2$	$\frac{E^*}{E_0} = \phi^2\left(\frac{\rho^*}{\rho_0}\right)^2 + (1-\phi)\left(\frac{\rho^*}{\rho_0}\right)$
Hardness	$\frac{H^*}{H_0} = .23\left(\frac{\rho^*}{\rho_0}\right)^{3/2}\left(1+\left(\frac{\rho^*}{\rho_0}\right)^{1/2}\right)$	$\frac{H^*}{H_0} = .3\left(\phi\frac{\rho^*}{\rho_0}\right)^{3/2} + .4(1-\phi)\left(\frac{\rho^*}{\rho_0}\right)$
Fracture Toughness	$\frac{K_{Ic}^*}{K_{Ic0}} = .65\left(\frac{\rho^*}{\rho_0}\right)^{3/2}$	$\frac{K_{Ic}^*}{K_{Ic0}} = \left(\frac{\rho^*}{\rho_0}\right)^{3/2}$

E. O. Shaffer II, K. E. Howard, M. E. Mills, P. H. Townshend, *Mat Res. Soc. Symp. Proc.*, Vol. **612**, (2000)

L. Gibson and M. Ashby, Cellular Solids, 2nd Ed. (1997).

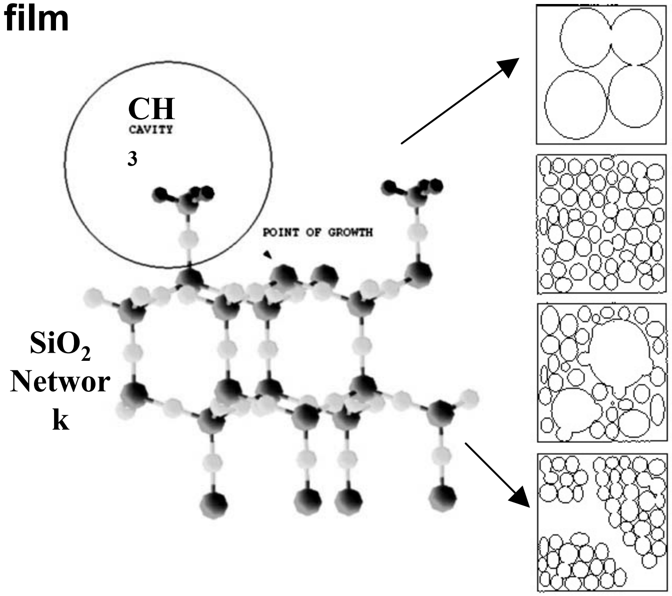
Spectroscopic Ellipsometry Shows Difference in Density



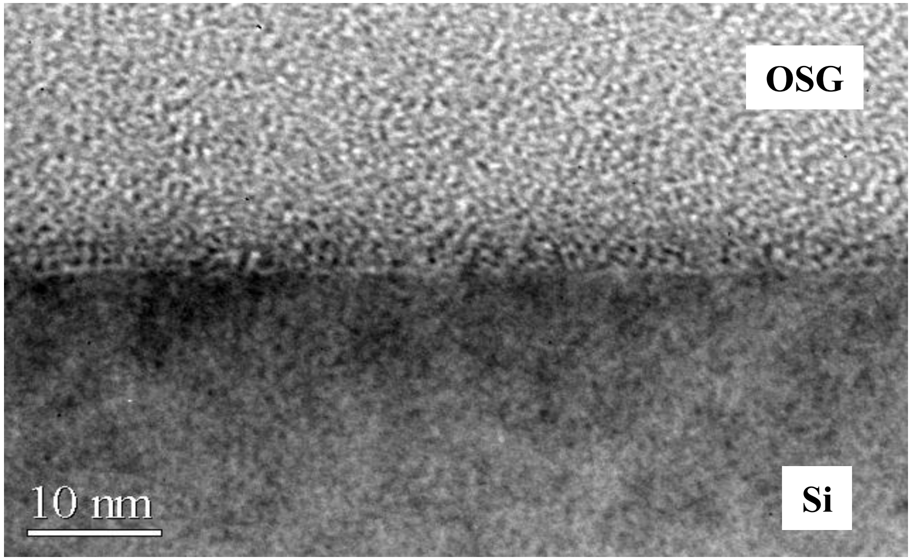


Evaluation of Porosity

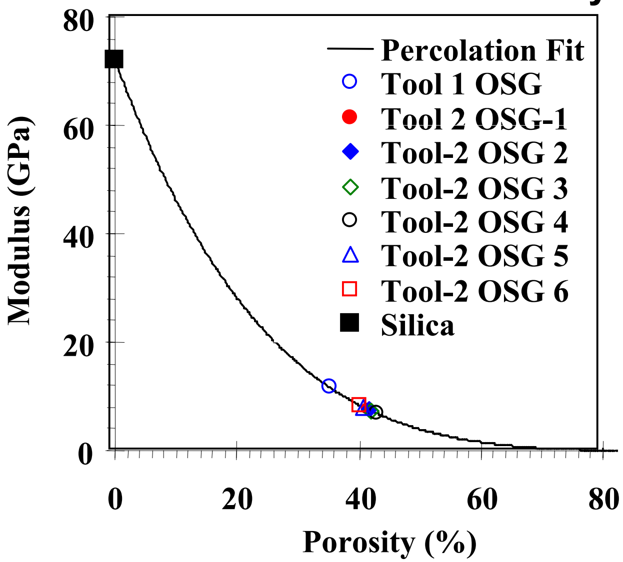
Porosity formation process in a low- k dielectric thin film



TEM cross section of a low- k dielectric film



Indirect measurement of Porosity through Modulus



	Modulus (GPa)	Percolation Porosity (%)
Tool 1 OSG	11.7	35.1
Tool 2 OSG-1	7.60	41.4
Tool 2 OSG-2	7.49	41.6
Tool 2 OSG-3	7.24	42.1
Tool 2 OSG-4	6.90	42.8
Tool 2 OSG-5	7.92	40.9
Tool 2 OSG-6	8.32	40.1
Silica	72.00	0.0

- Pores are created by methyl inclusion in a molecular scale.
- NI is able to determine the porus and dielectric nature of the films.

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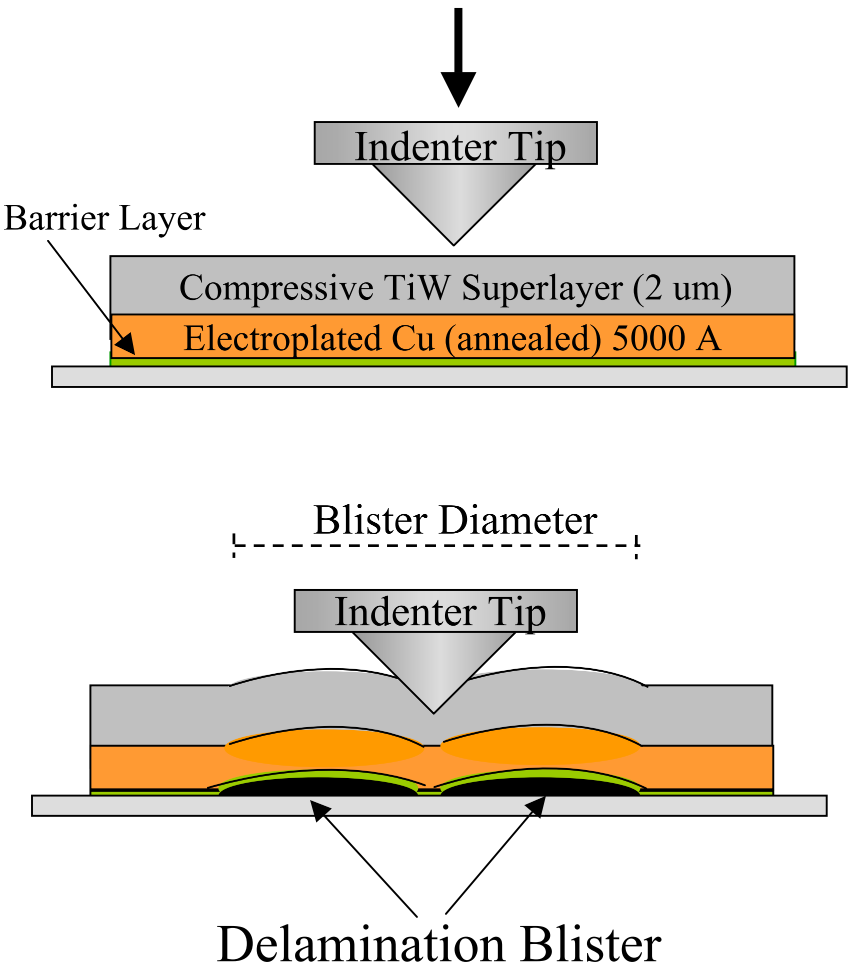
Adhesion Measurements



- Thin film delamination is induced by depositing a highly compressive superlayer capable of storing elastic energy
- Interfacial fracture is initiated by NanoIndentation at loads (25-700mN) and further driven by superlayer
- Delamination blister size is used to calculate Practical Work of Adhesion (J/m^2) (Smaller blister = Better adhesion)
- Material and residual stress properties of superlayer and underlying film must be known for calculation

NanoIndent Adhesion Test (Delamination blister)

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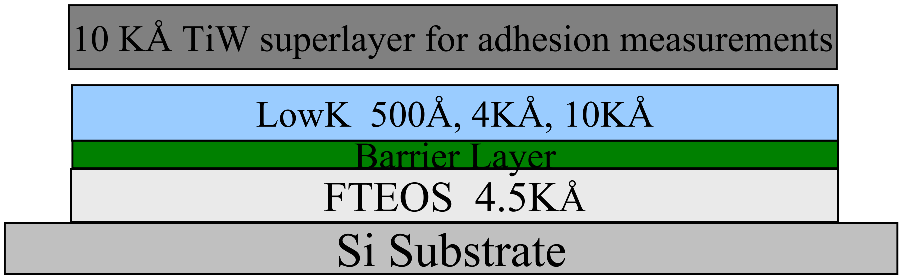
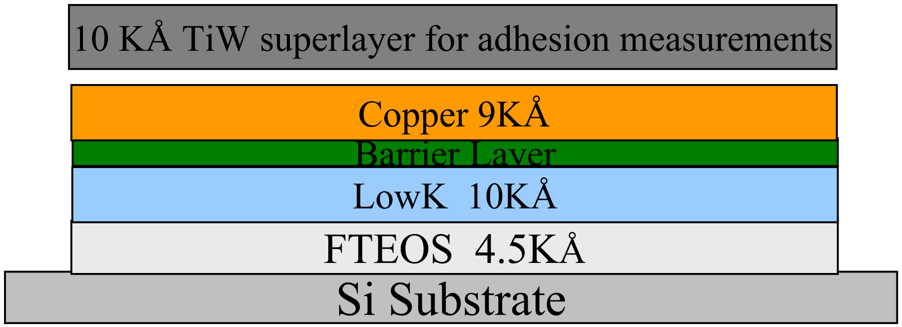
Low-k Test Structures

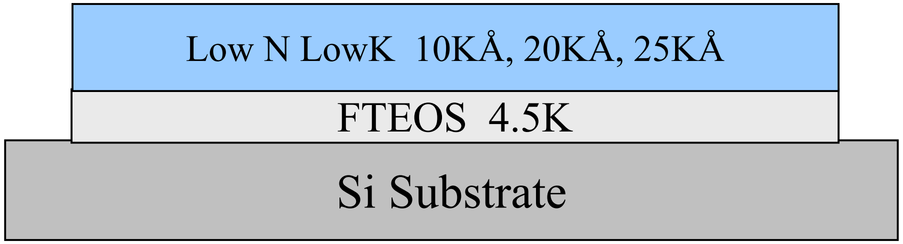
CVD Organic Glass Low-k

Adhesion





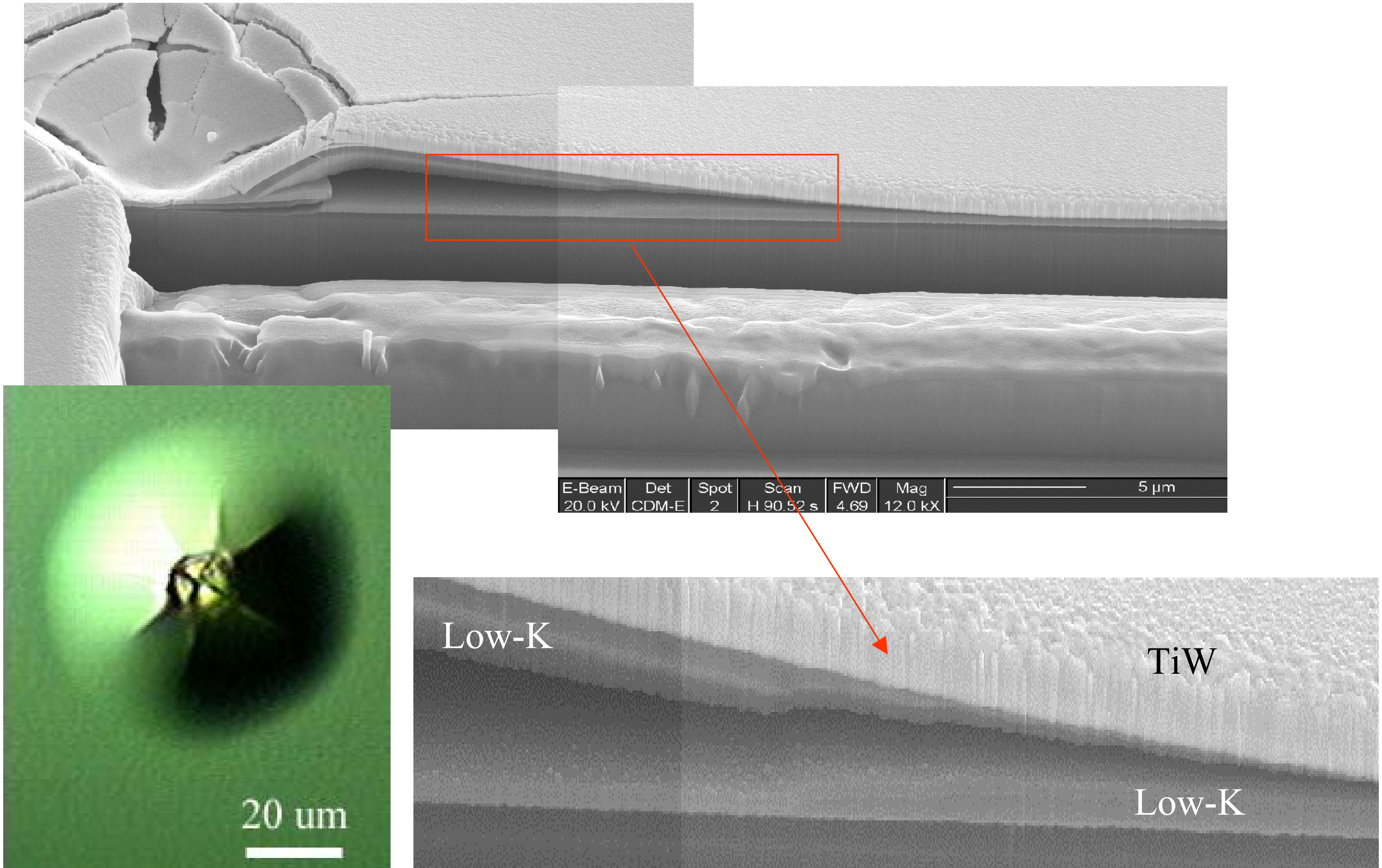
Fracture toughness



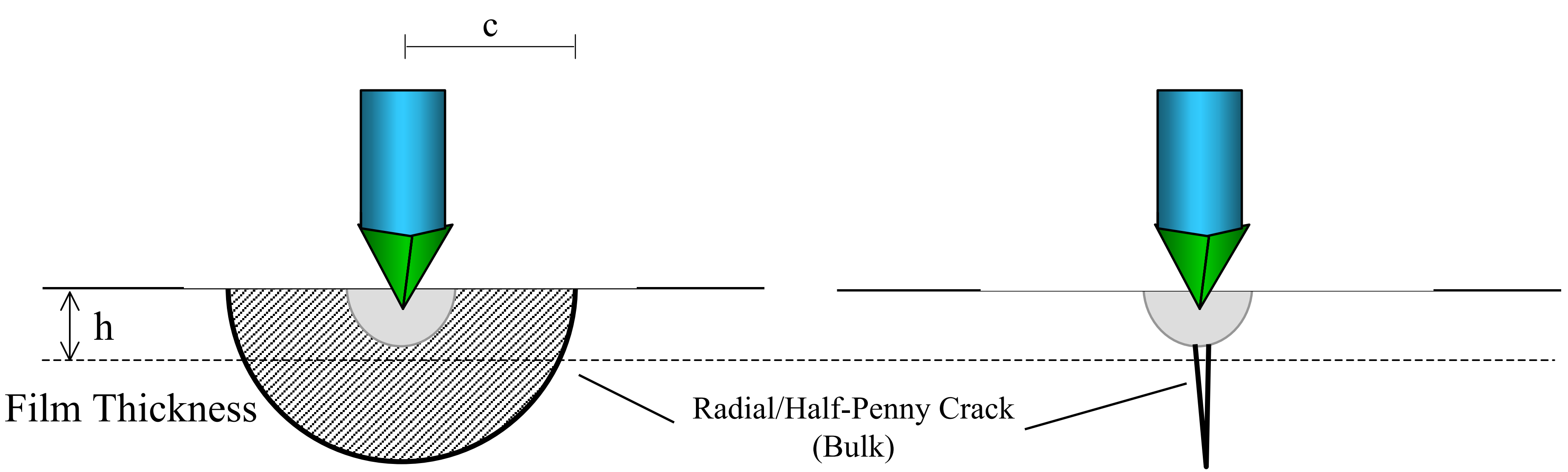
E ~ 10 GPa

H ~ 1.5 GPa

4 kÅ Low-k


E-Beam
20.0 kV
Det
CDM-E
Spot
2
Scan
H 90.52 s
FWD
4.69
Mag
12.0 kX
5 µm
20 um
Low-K
TiW
Low-K

Fracture Toughness Measurement



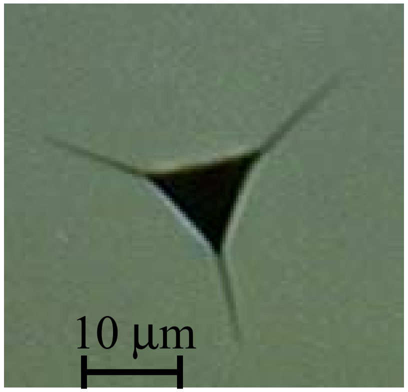
$$K_{c\ Bulk} = \alpha \left(\frac{E}{H} \right)^{1/2} \left(\frac{P_{max}}{c^{3/2}} \right)$$ 40% Accuracy

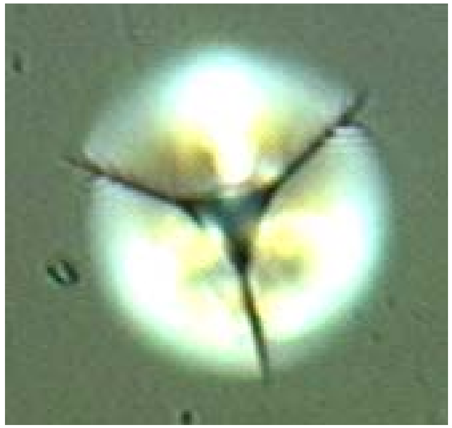
$$K_{c\ Thin\ Film}(h,H,E) = ?$$

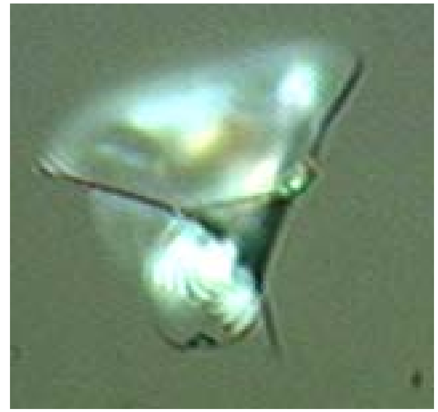
Lawn, B.R., Evans, A.G., and Marshall, D.B. (1980) ‘Elastic/Plastic Indentation Damage in Ceramics: The Median/Radial Crack System’, *J. Amer. Cer. Soc.* 63, 574-581.

Pharr, G.M., Harding, D.S., and Oliver, W.C., Mechanical Properties and Deformation Behavior of Materials Having Ultra-Fine Microstructures, 449-461. M Nastasi et al. (eds.), Kluwer, Netherlands, 1993.

Cube Corner Indents



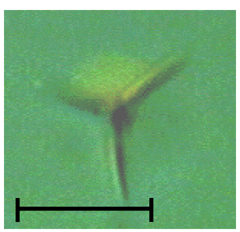




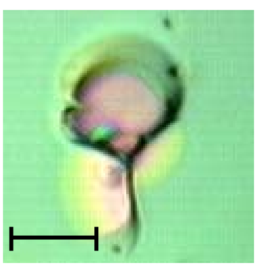
Silica:
$K_c \sim 0.5\ MPa \cdot m^{1/2}$
vs. literature:
$K_c \sim 0.75\ MPa \cdot m^{1/2}$

1 um LowK

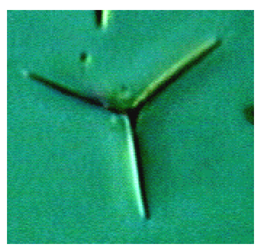
2 um LowK

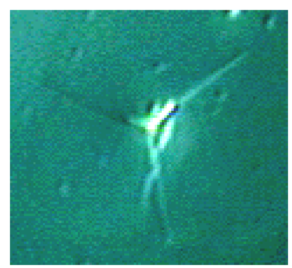


5 um



5 um





$K_c \sim 0.01\text{-}0.05\ MPa \cdot m^{1/2}$

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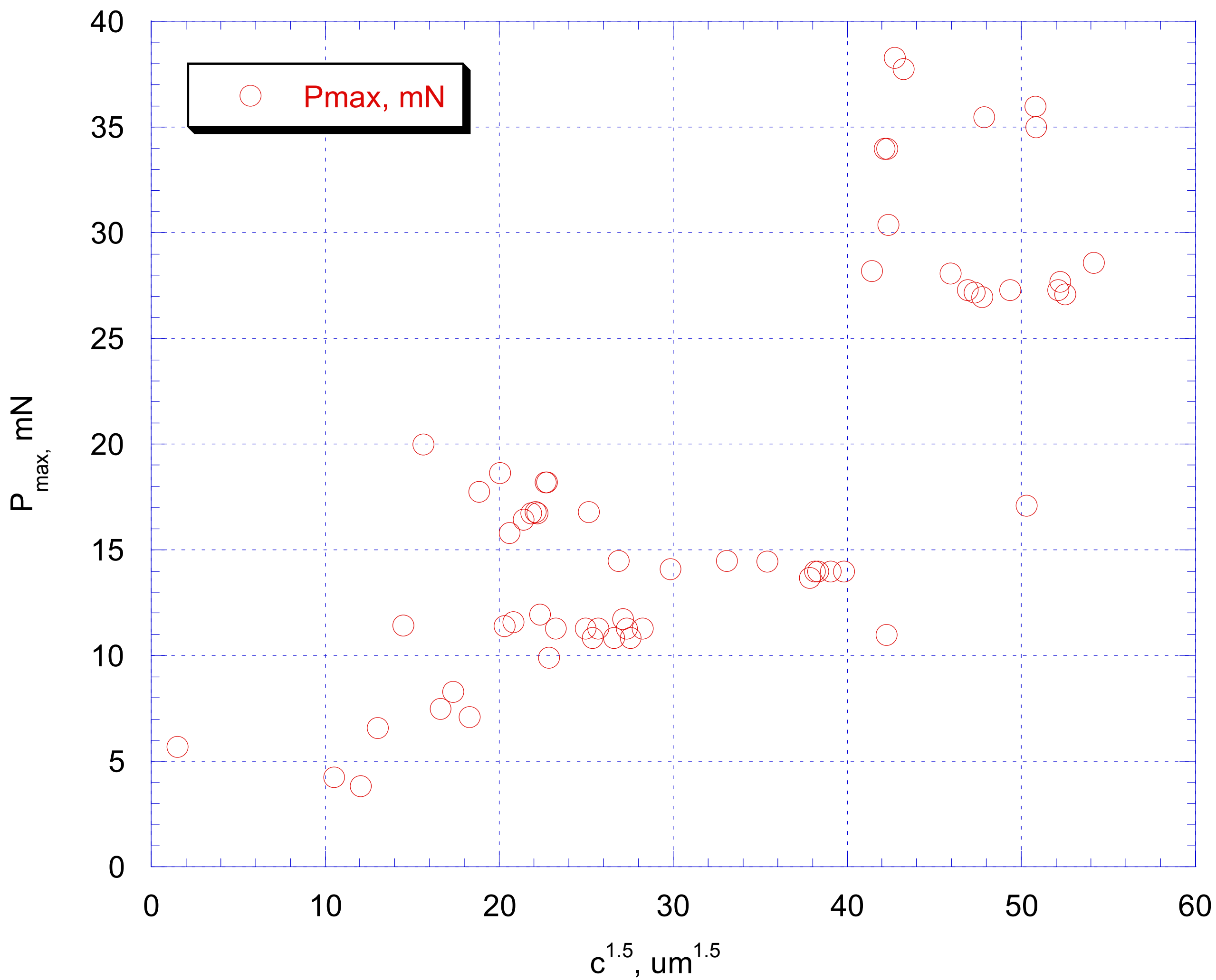
Linear relationship for P_{max} vs. $c^{3/2}$



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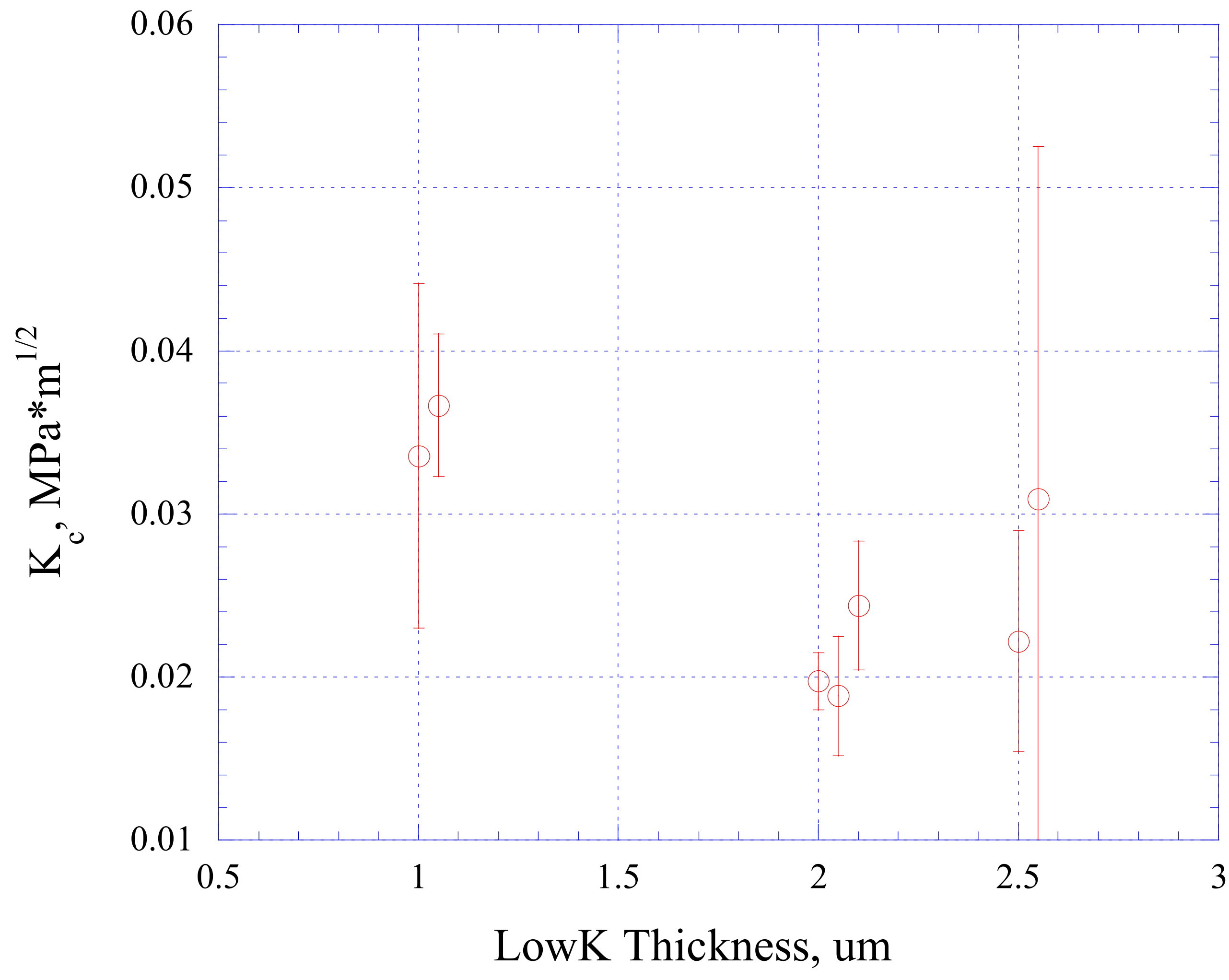
Low-k Fracture Toughness



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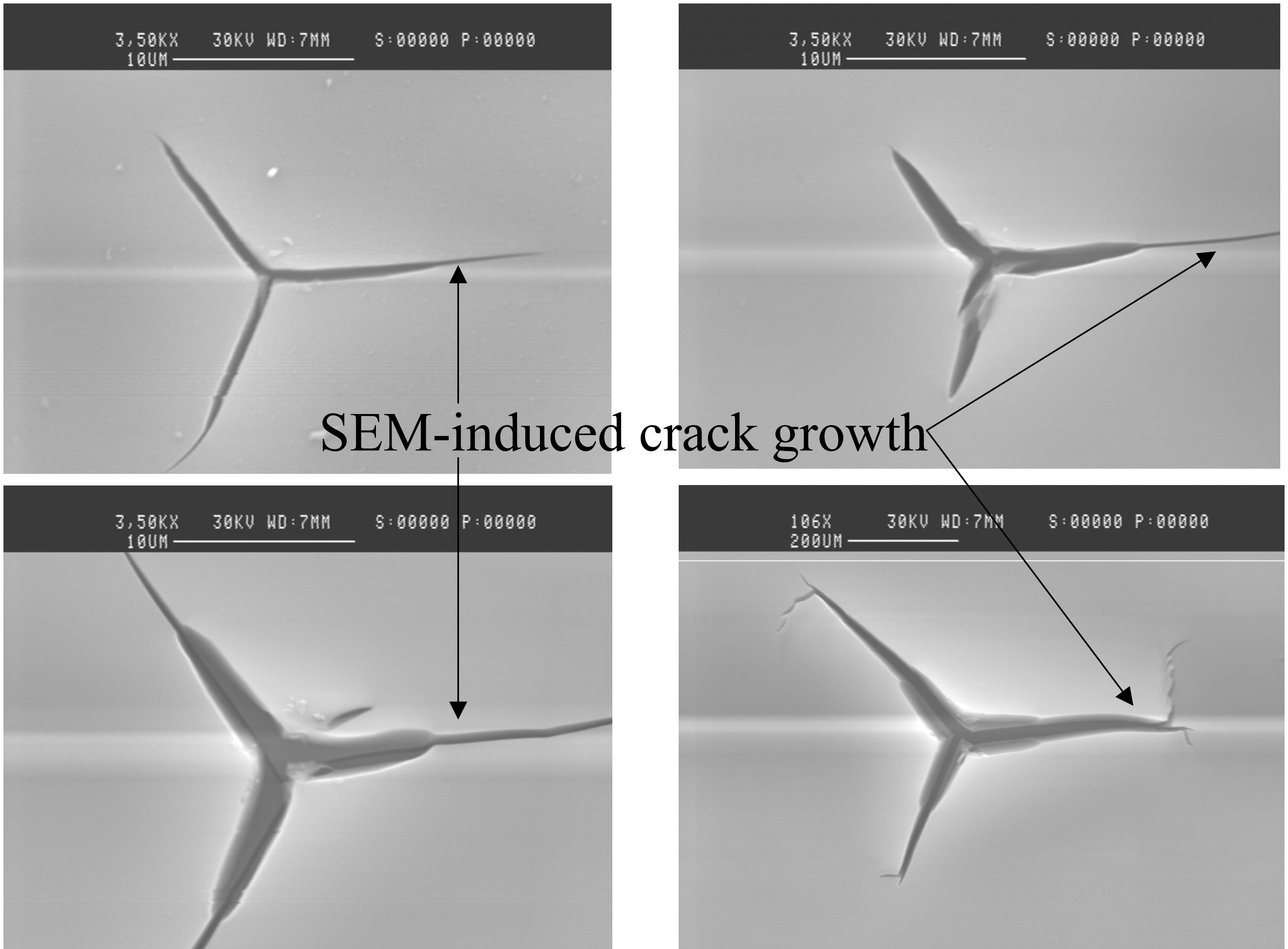
Si/20KÅ LowK Cracking in SEM



Summary

Nano-Indentation was able to successfully address some of the metrology challenges in development and integration of low k materials

Technique is also capable of identifying adhesion issues and provide selection for optimum process conditions

Currently investigating the compatibility of low k materials during assembly and packaging using Nano-Indentation

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