Diagnosing Adhesion and Cohesion for BEOL Reliability: From Dieseals and Crack Stops to Cu and Low k

Low k Research
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Taek-Soo Kim, Nathan Stein

Chip/Package Interactions
Andrew Kearney, Bree Sharratt, Zhouyuan Zhu

Front End Structures
Ryan Birringer

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Collaborators at INTEL, AMD, IBM, Applied Materials, ASM and JSR.

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Work supported by the SRC, DOE, Device, Equipment and Materials Companies.

Outline

- Mechanical Reliability of Low-k Materials
  - what is the problem?
  - fracture properties and scaling with density/dielectric constant
- UV Curing Effects on Mechanical Properties
  - fracture path and effects on cohesive and adhesive properties
  - balancing film stress, modulus and fracture properties
- Non-Uniform UV Curing Phenomena
  - evidence for non-uniform curing
  - likely mechanism associated with UV light interference
- CMP Aqueous Chemistry Effects
  - accelerated cracking in aqueous CMP slurries and cleaning solutions
- Die Seal and Crack Stop Structures
  - fracture mechanics approach to preventing dicing damage
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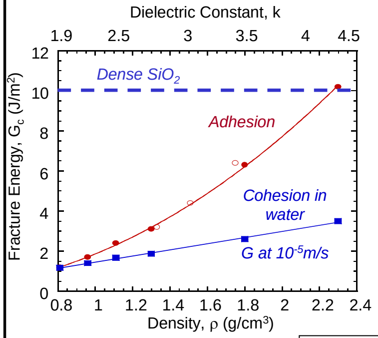
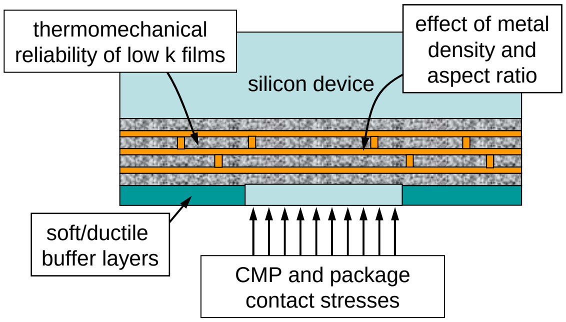
Reliability of Interconnect Structures



What is the problem….

highly stressed structures made from fragile glass layers



thermomechanical reliability of low k films

effect of metal density and aspect ratio

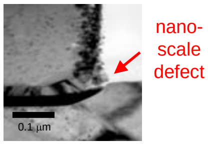
silicon device

soft/ductile buffer layers

CMP and package contact stresses

Evolution of Defects control Yield through Processing

- <u>Lower</u> driving force for cracking, G$_{total}$

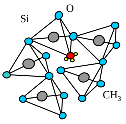


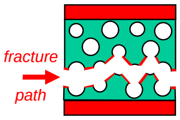
– thin film stresses

– CMP and packaging stress

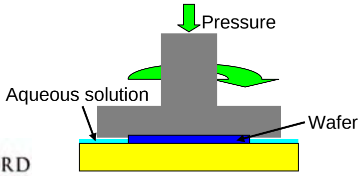
$$G_{total} \le G_c \; (J/m^2)$$

- <u>Optimize</u> resistance to cracking - glass composition, network and pore structure, UV curing





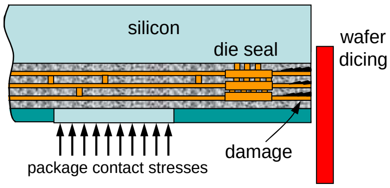
- <u>Control evolution</u> of defects during processing, packaging and service



Pressure

Aqueous solution

Wafer



silicon

die seal

wafer dicing

package contact stresses

damage

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Experimental Methods

Glass Structure

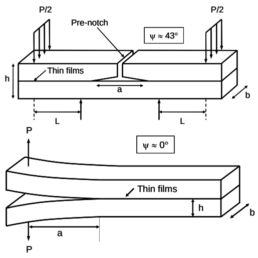
- ^{29}Si and ^{13}C magic angle spinning NMR (3.2 mm MAS rotor, 12-13 KHz spinning rates, 9.4 Tesla magnet)
- FTIR

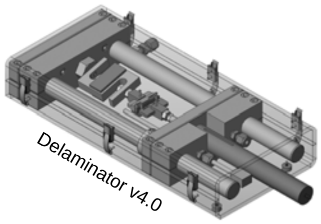
Fracture Mechanics Testing

- Four Point Bend (FPB) and Double Cantilever Beam (DCB) geometries

FPB adhesion

DCB cohesion





Fracture Surface Morphology/Composition

- AFM, XPS

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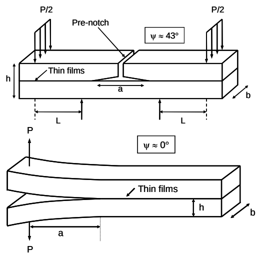
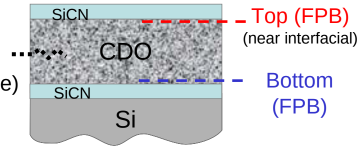


DCB center (cohesive)



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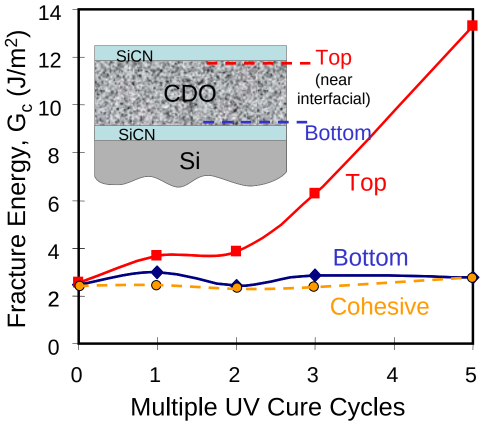
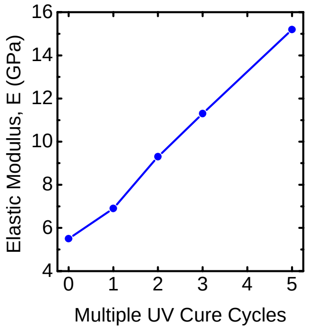
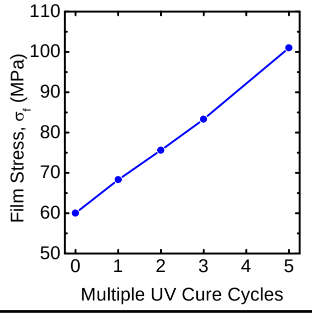
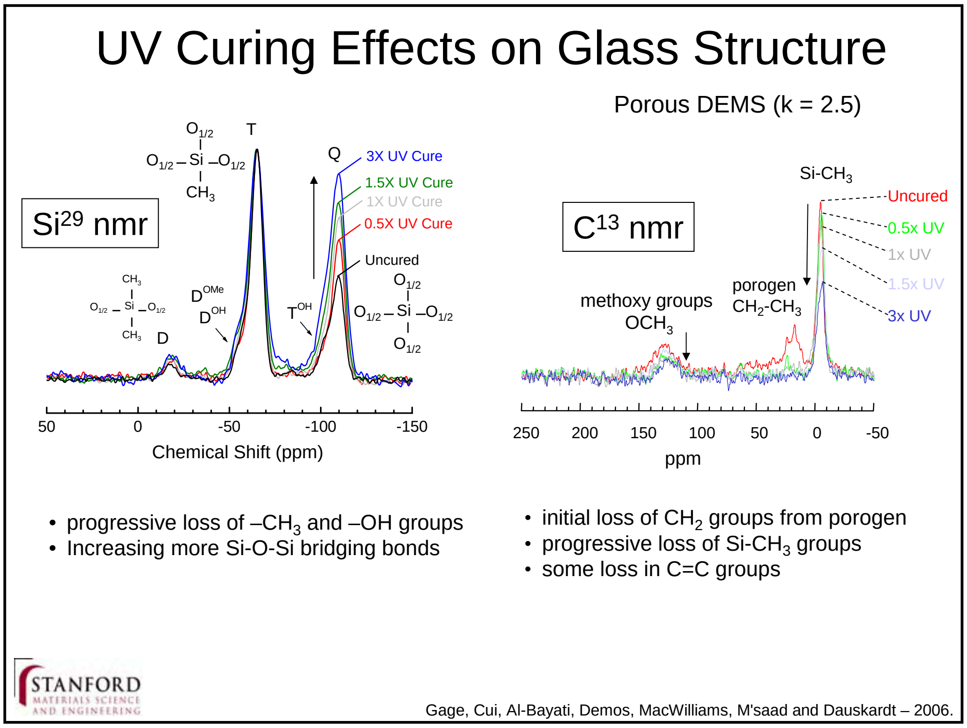
Role of UV Cure on Mechanical Properties







Treatment	Dielectric Constant	Elastic Modulus, $\bar{E}_f$ (GPa)	Residual Film Stress, σ_f (MPa)	Crack Driving Force, G (J/m^2)	Cohesive Fracture, G_c (J/m^2)
none	2.62	5.5	60	0.287	2.50
UVx1	2.59	6.9	68.3	0.296	2.40
UVx2	2.62	9.3	75.6	0.269	2.36
UVx3	2.66	11.3	83.3	0.269	2.34
UVx5	2.72	15.2	101	0.294	2.66



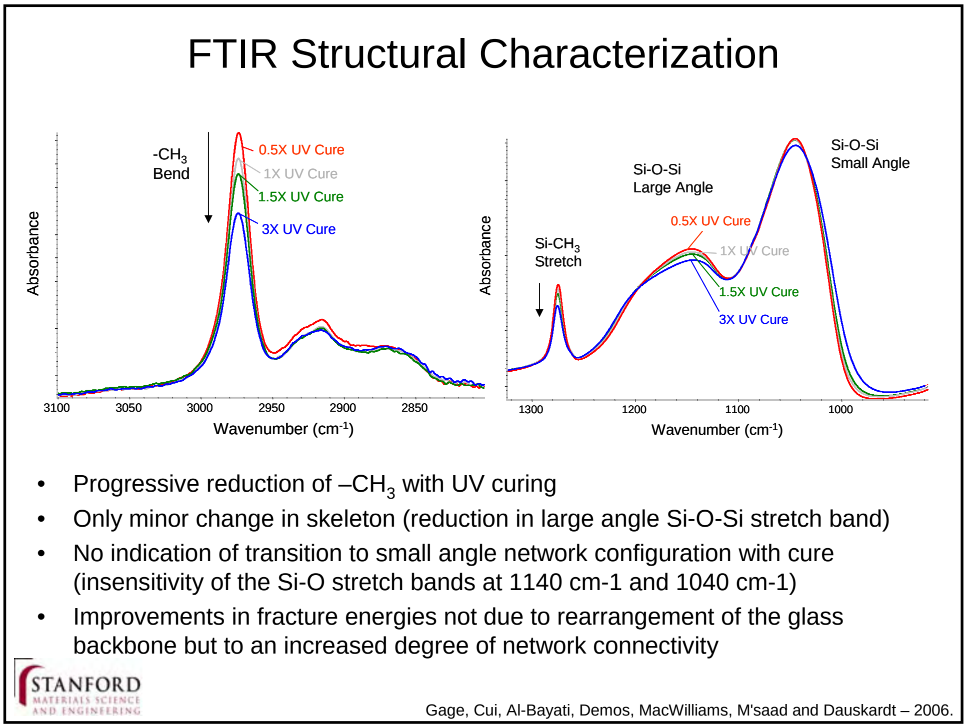
UV Curing Effects on Glass Structure

Porous DEMS (k = 2.5)

- progressive loss of $-CH_3$ and –OH groups
- Increasing more Si-O-Si bridging bonds

- initial loss of CH_2 groups from porogen
- progressive loss of $Si\text{-}CH_3$ groups
- some loss in C=C groups

Gage, Cui, Al-Bayati, Demos, MacWilliams, M'saad and Dauskardt – 2006.



FTIR Structural Characterization

- Progressive reduction of $-CH_3$ with UV curing
- Only minor change in skeleton (reduction in large angle Si-O-Si stretch band)
- No indication of transition to small angle network configuration with cure (insensitivity of the Si-O stretch bands at 1140 cm-1 and 1040 cm-1)
- Improvements in fracture energies not due to rearrangement of the glass backbone but to an increased degree of network connectivity

Gage, Cui, Al-Bayati, Demos, MacWilliams, M'saad and Dauskardt – 2006.

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- Mechanical Reliability of Low-k Materials
  - what is the problem?
  - fracture properties and scaling with density/dielectric constant
- Studies of Glass Network Structure
  - NMR and FTIR reveal glass network structure
  - UV cure reactions and changes in network structure
- UV Curing Effects on Mechanical Properties
  - fracture path and effects on cohesive and adhesive properties
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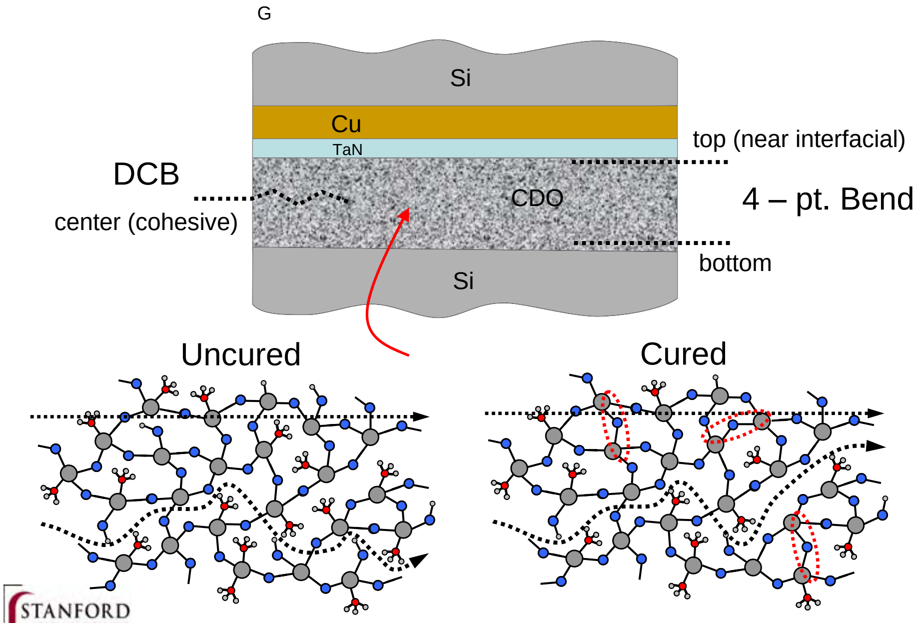
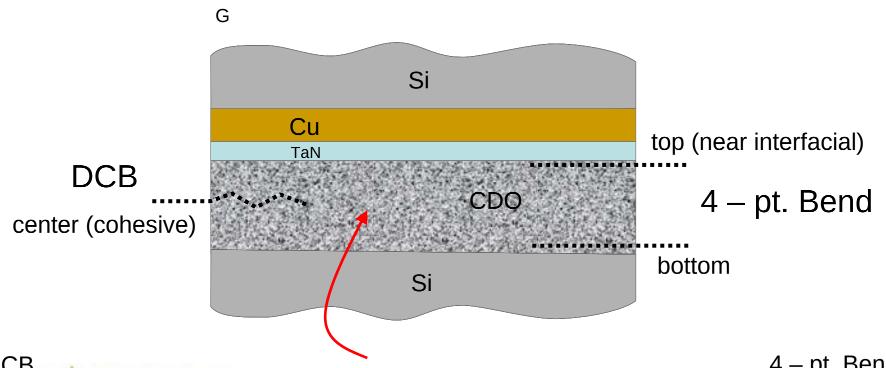
Low k Fracture Path

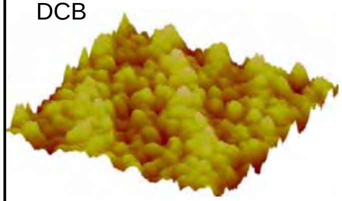


Low k Fracture Path

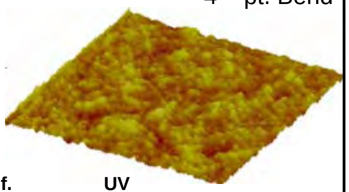


variation in glass composition or structure
↓
weak fracture path??

DCB



4 – pt. Bend



Ref.	UV
1.2nm	1.13nm

Ref.	UV
0.12nm	0.16nm

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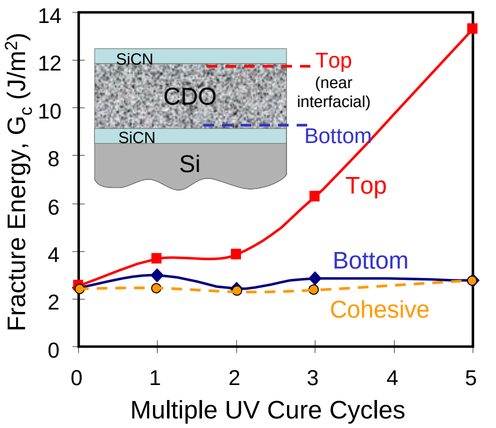
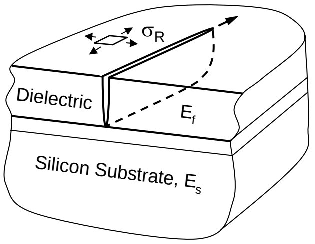
Role of UV Cure on Mechanical Properties



Issues and Tradeoffs:

- crack “driving force” and “material properties”



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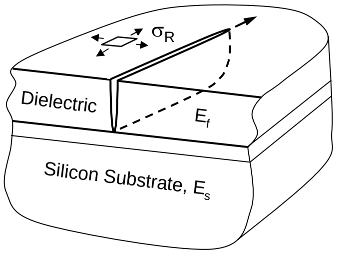
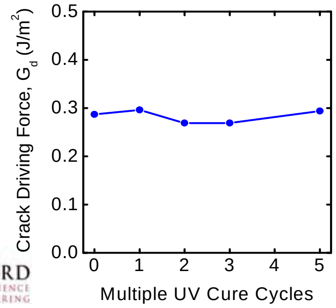
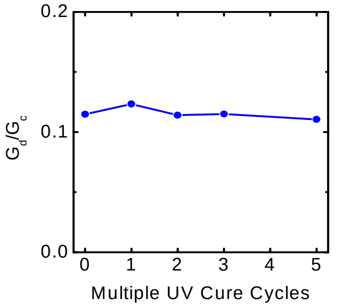


$$\underbrace{G_d = \frac{Z\sigma_f^2 h_f}{\bar{E}_f}}_{\text{crack driving “force”}} \le \underbrace{G_c}_{\text{fracture resistance}}$$

G_d vs. UV Cure Cycles



G_d/G_c vs. UV Cure Cycles



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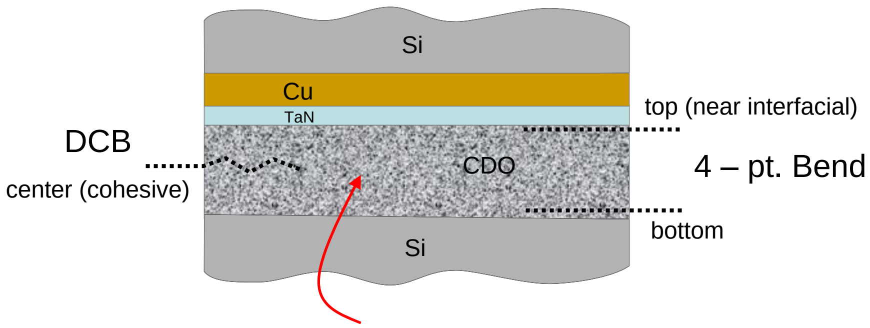
Non-Uniform Curing Phenomena



variation in glass composition or structure

↓

weak fracture path??

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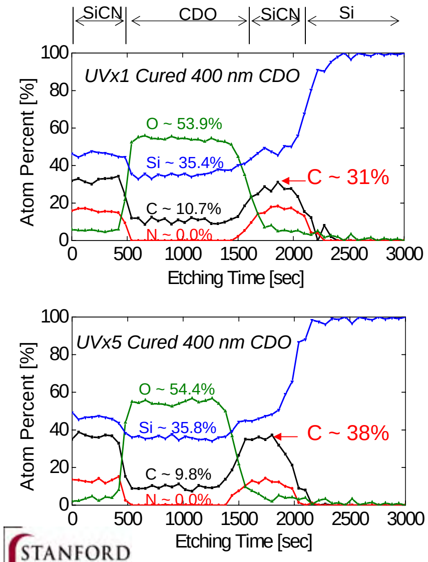
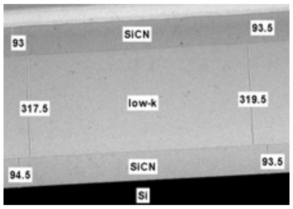
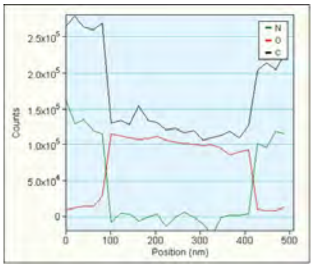
No Evidence of Compositional Variation

XPS Depth Profiling





EELS composition profile taken in STEM mode



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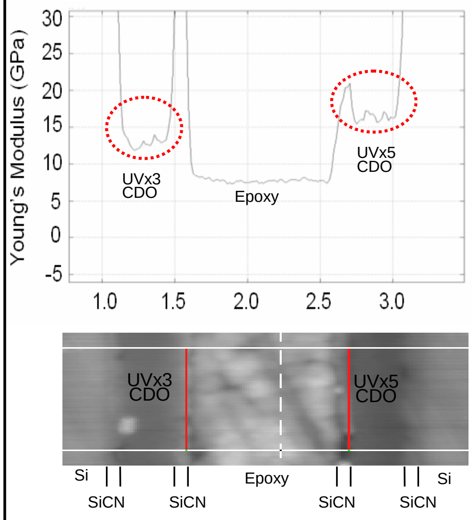
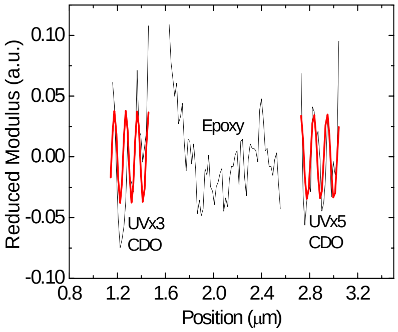
T. Kim, N. Tsuji, N. Kemeling, K. Matsushita, D. Chumakov, E. Zschech, and R. H. Dauskardt, AMC2006.

FM-AFM Measurements of Modulus Variations



sine wave fitting of modulus variations



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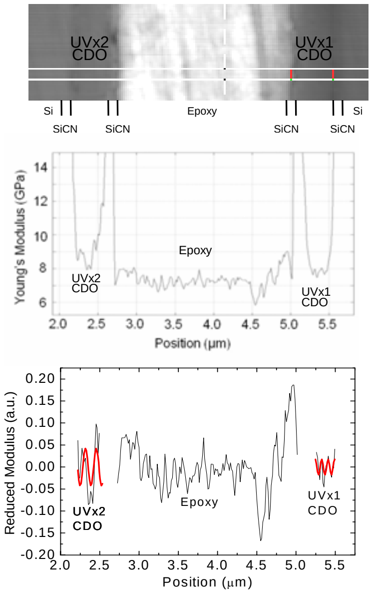

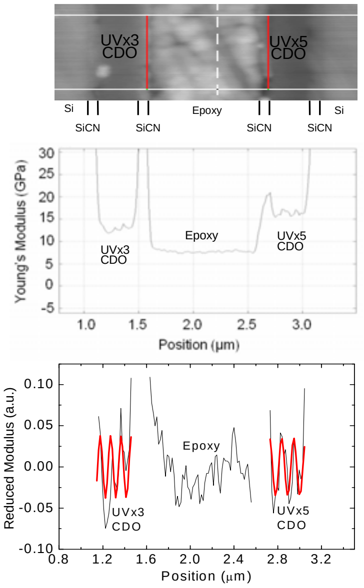

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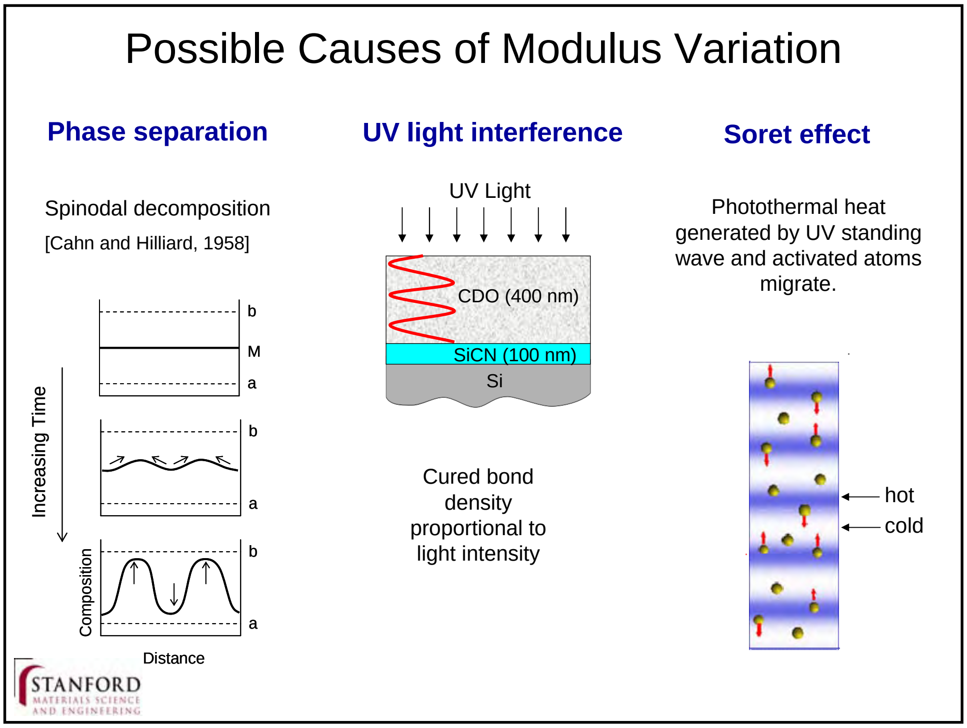


Possible Causes of Modulus Variation

Phase separation

Spinodal decomposition

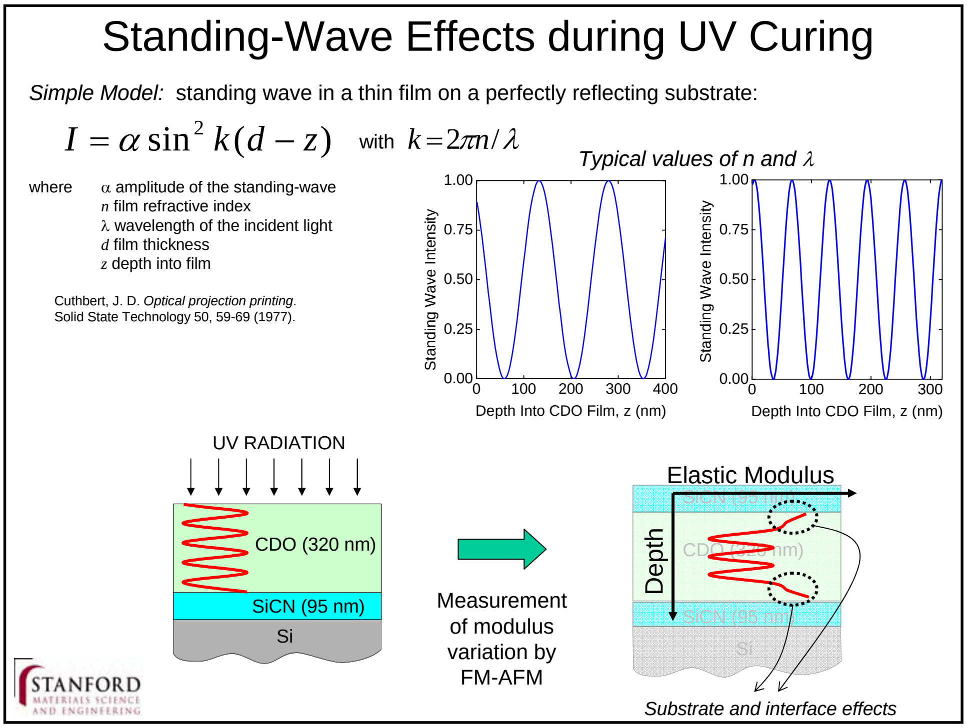
[Cahn and Hilliard, 1958]

UV light interference

Cured bond density proportional to light intensity

Soret effect

Photothermal heat generated by UV standing wave and activated atoms migrate.



Standing-Wave Effects during UV Curing

Simple Model: standing wave in a thin film on a perfectly reflecting substrate:

$$I = \alpha \sin^2 k(d - z) \quad \text{with} \quad k = 2\pi n / \lambda$$

where
α amplitude of the standing-wave
n film refractive index
λ wavelength of the incident light
d film thickness
z depth into film

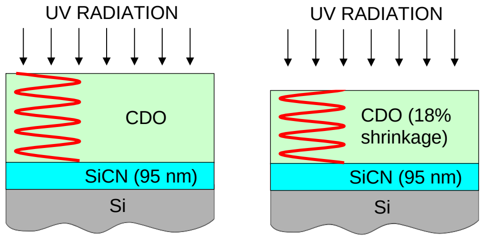
Cuthbert, J. D. *Optical projection printing*. Solid State Technology 50, 59-69 (1977).

Typical values of n and λ

Measurement of modulus variation by FM-AFM

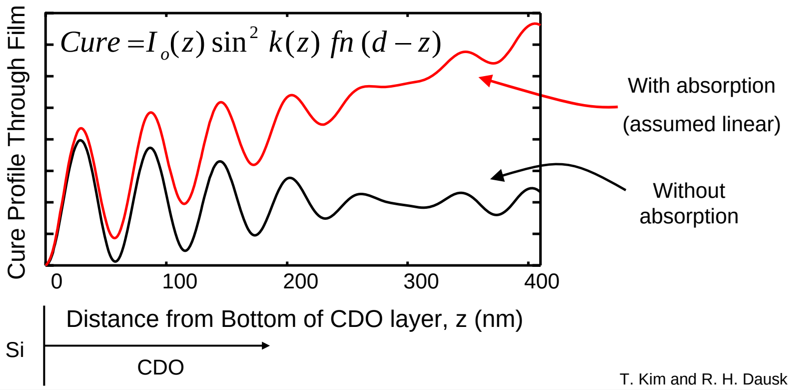
Substrate and interface effects

New Interference Model



Superposition of the effects of standing waves in the shrinking film over time

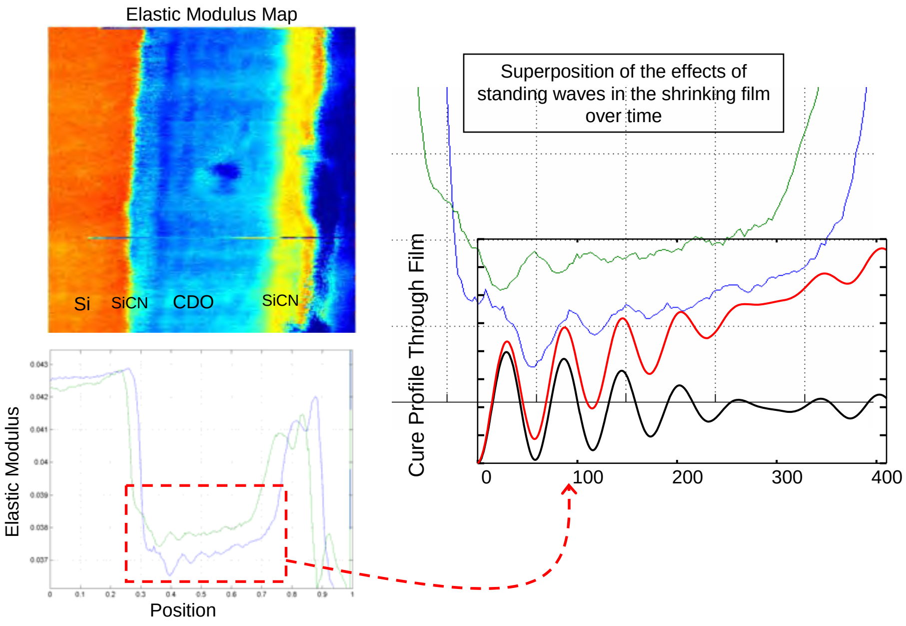
$$I = I_o \sin^2 k(d - z)$$



$$Cure = I_o(z) \sin^2 k(z)\ fn\,(d - z)$$

T. Kim and R. H. Dauskardt, 2007.

New Interference Model Predictions



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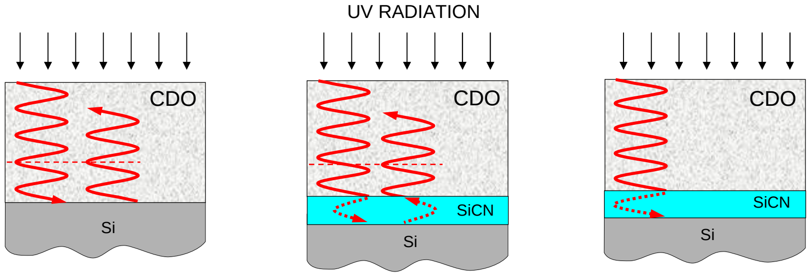
Role of the Bottom SiCN Layer



perfectly reflecting

intensified
standing wave

partially reflecting

decreased
standing wave

fully absorbing

no
standing wave

- Reflectivity of bottom interface strongly dependent on underlying layer.
- SiCN thin film can significantly absorb high energy UV light depending on its carbon content

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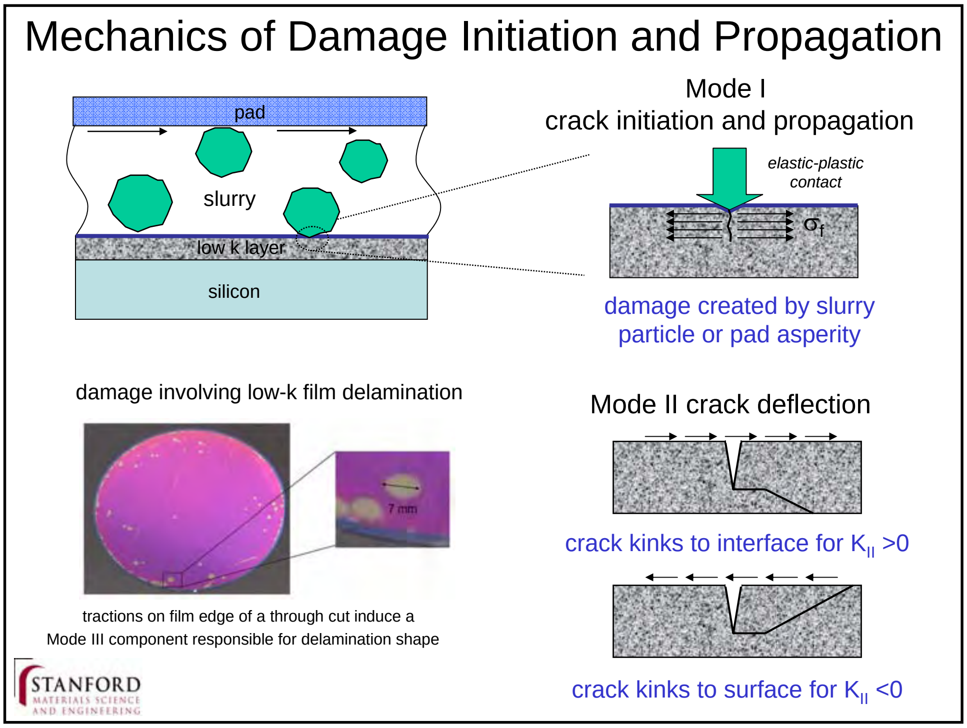

Mechanics of Damage Initiation and Propagation

Mode I
crack initiation and propagation

damage created by slurry particle or pad asperity

damage involving low-k film delamination

tractions on film edge of a through cut induce a Mode III component responsible for delamination shape

Mode II crack deflection

crack kinks to interface for $K_{II} > 0$

crack kinks to surface for $K_{II} < 0$

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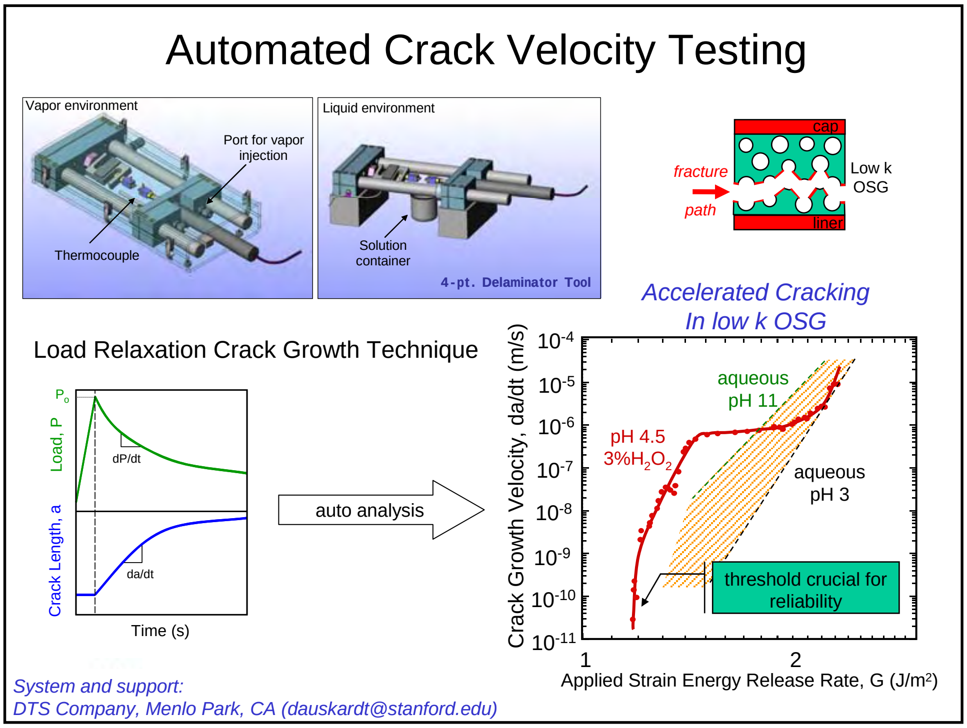


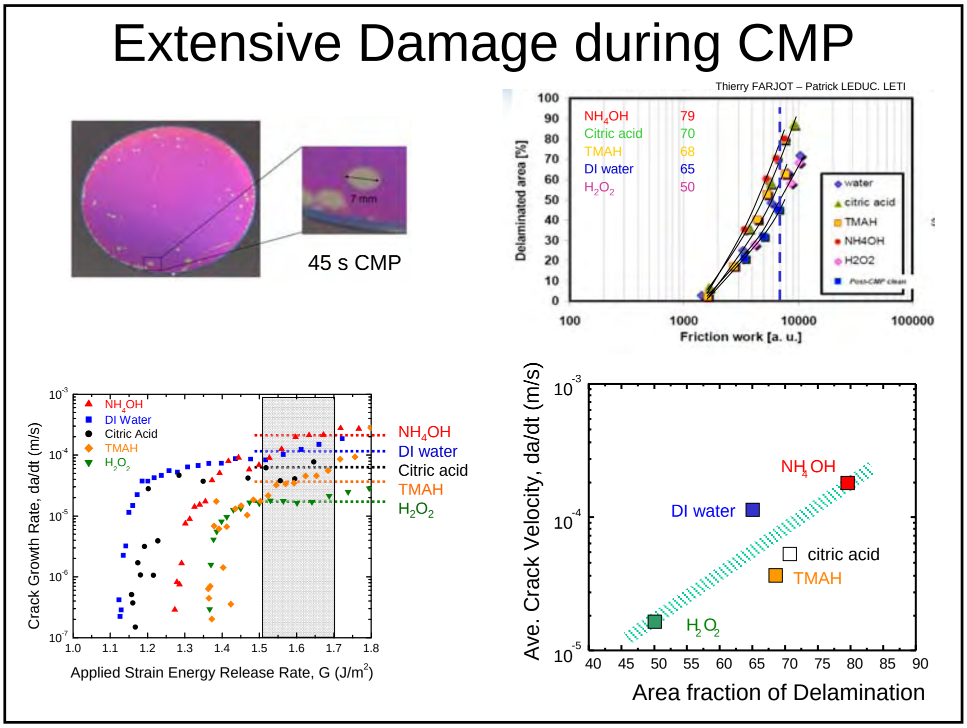
Automated Crack Velocity Testing

Accelerated Cracking In low k OSG

Load Relaxation Crack Growth Technique

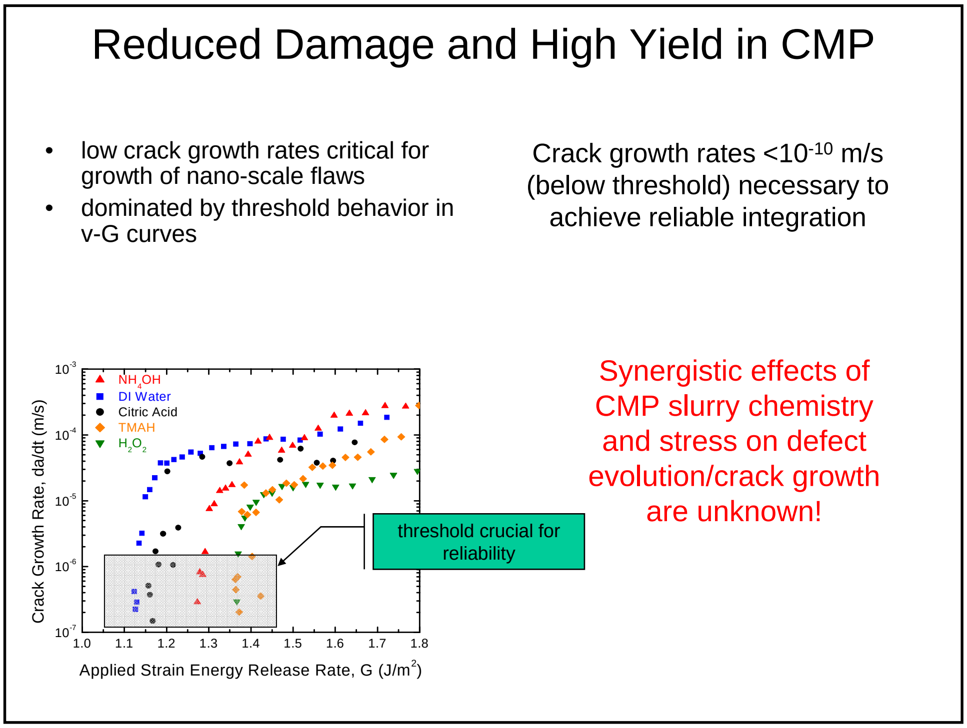
threshold crucial for reliability

System and support:
DTS Company, Menlo Park, CA (dauskardt@stanford.edu)



Extensive Damage during CMP

Thierry FARJOT – Patrick LEDUC. LETI



Reduced Damage and High Yield in CMP

- low crack growth rates critical for growth of nano-scale flaws
- dominated by threshold behavior in v-G curves

Crack growth rates $<10^{-10}$ m/s (below threshold) necessary to achieve reliable integration

threshold crucial for reliability

Synergistic effects of CMP slurry chemistry and stress on defect evolution/crack growth are unknown!

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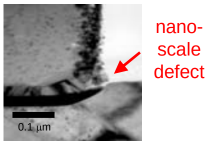
Evolution of Defects control Yield through Processing

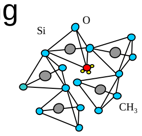
- Lower driving force for cracking, G_{total}

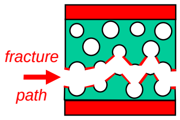


  - thin film stresses
  - CMP and packaging stress

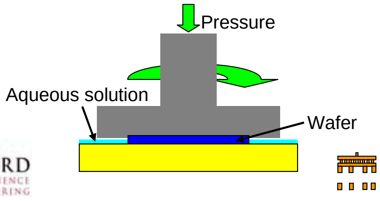
$$G_{total} \le G_c \; (J/m^2)$$

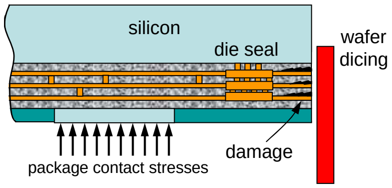
- Optimize resistance to cracking - glass composition, network and pore structure, UV curing

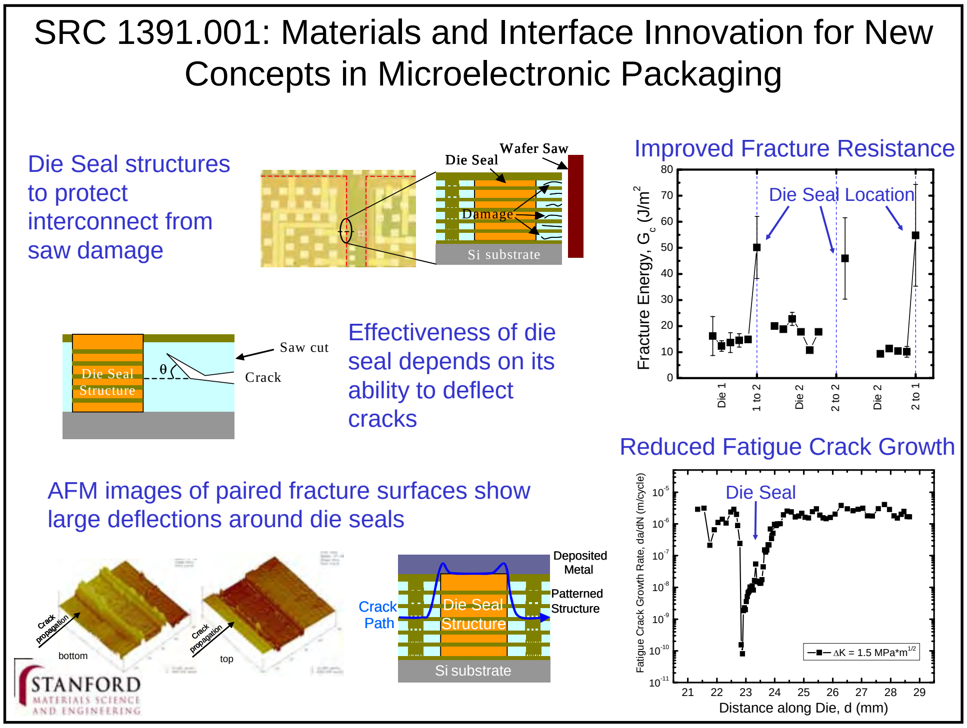




- Control evolution of defects during processing, packaging and service







SRC 1391.001: Materials and Interface Innovation for New Concepts in Microelectronic Packaging

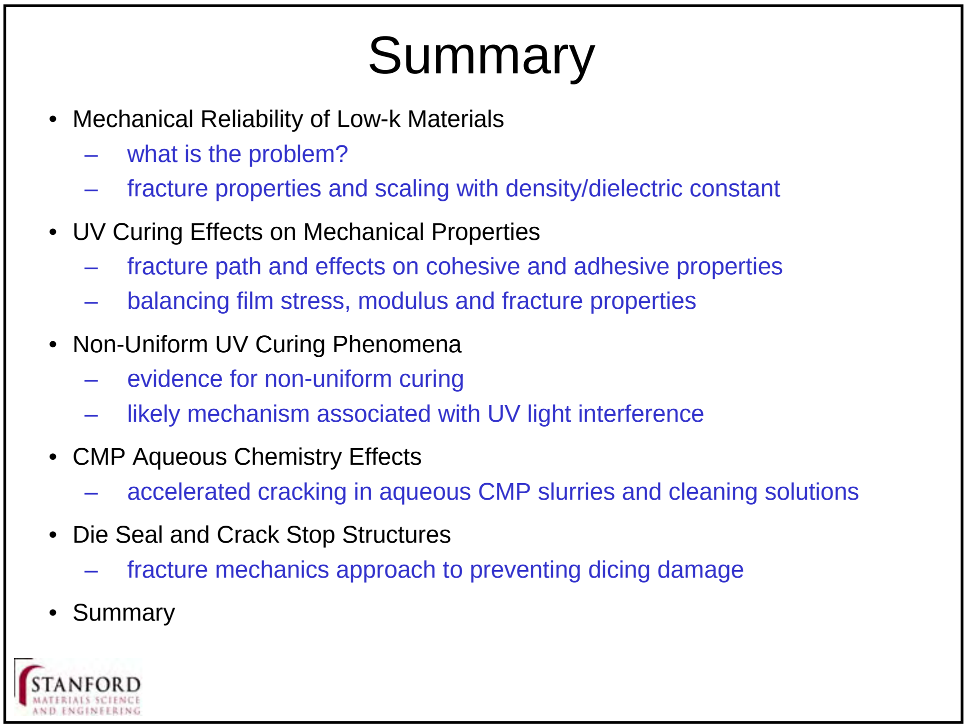
Die Seal structures to protect interconnect from saw damage

Effectiveness of die seal depends on its ability to deflect cracks

AFM images of paired fracture surfaces show large deflections around die seals

Improved Fracture Resistance

Reduced Fatigue Crack Growth



Summary

- Mechanical Reliability of Low-k Materials
  - what is the problem?
  - fracture properties and scaling with density/dielectric constant
- UV Curing Effects on Mechanical Properties
  - fracture path and effects on cohesive and adhesive properties
  - balancing film stress, modulus and fracture properties
- Non-Uniform UV Curing Phenomena
  - evidence for non-uniform curing
  - likely mechanism associated with UV light interference
- CMP Aqueous Chemistry Effects
  - accelerated cracking in aqueous CMP slurries and cleaning solutions
- Die Seal and Crack Stop Structures
  - fracture mechanics approach to preventing dicing damage
- Summary