Understanding Stress, Chemistry and Molecular Diffusion for Optimized CMP of ULK Dielectrics

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ULK Thin-Film Materials
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Polymers and Nanomaterials
Mark Oliver, Jeffery Yang, Ruiliang Jia, Ani Kamer

Ultra-Thin Barrier Films
Ryan Birringer

Chip Package Interactions
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Photovoltaic and Flexible Electronic Materials
Vitali Brand, Fernando Novoa

Collaborators: T. Konno and T. Yamanaka
JSR Micro, Sunnyvale, CA

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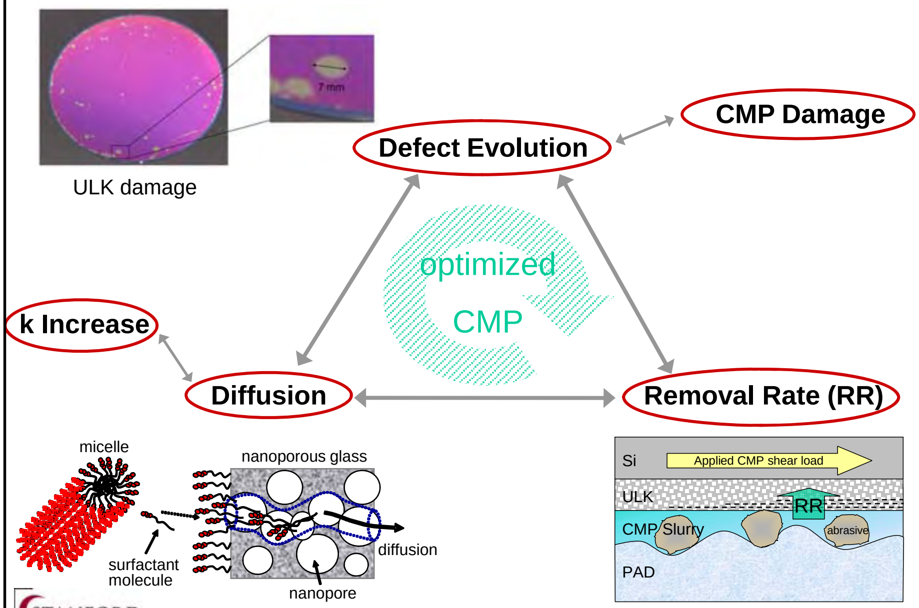
Road Map for Optimized CMP of Nanomaterials



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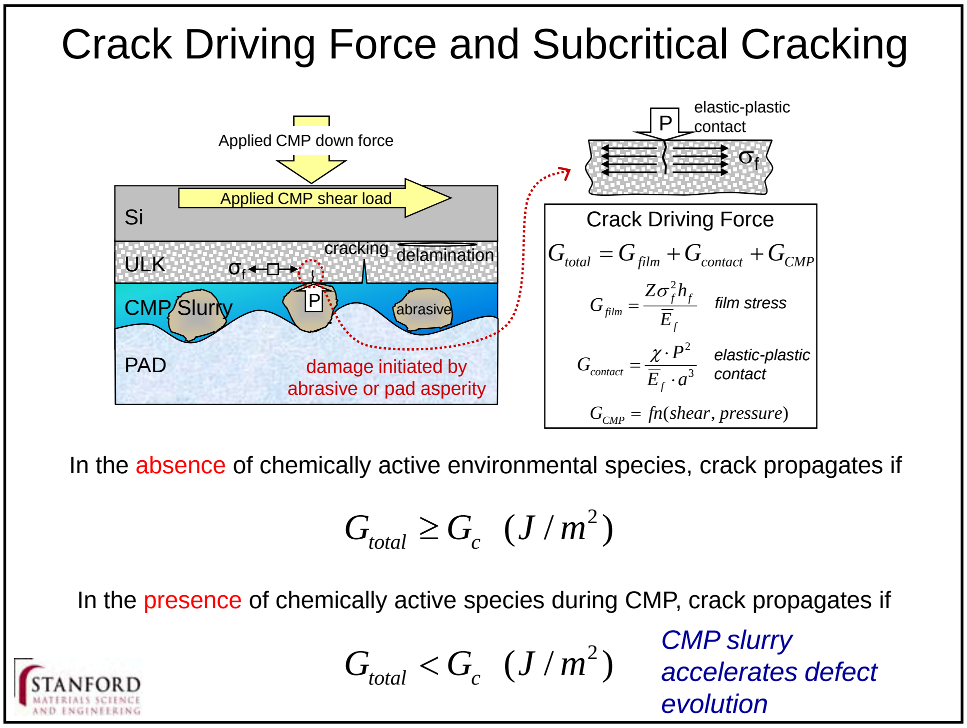


Crack Driving Force and Subcritical Cracking

Crack Driving Force

$$G_{total} = G_{film} + G_{contact} + G_{CMP}$$

$$G_{film} = \frac{Z\sigma_f^2 h_f}{\bar{E}_f}$$ *film stress*

$$G_{contact} = \frac{\chi \cdot P^2}{\bar{E}_f \cdot a^3}$$ *elastic-plastic contact*

$$G_{CMP} = fn(shear, pressure)$$

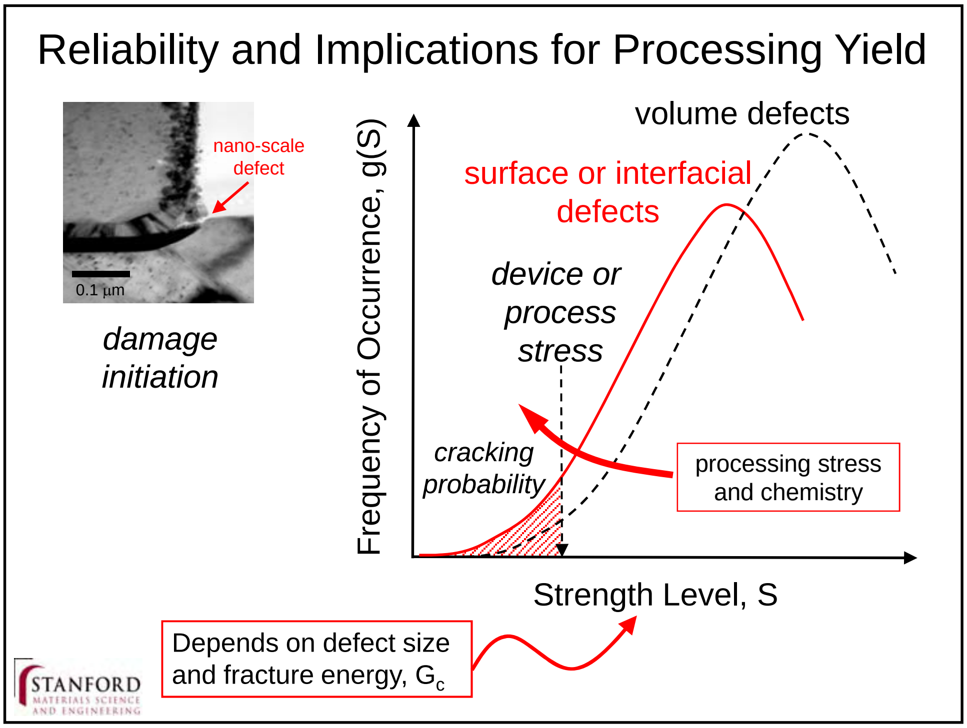
In the absence of chemically active environmental species, crack propagates if

$$G_{total} \geq G_c \quad (J/m^2)$$

In the presence of chemically active species during CMP, crack propagates if

$$G_{total} < G_c \quad (J/m^2)$$

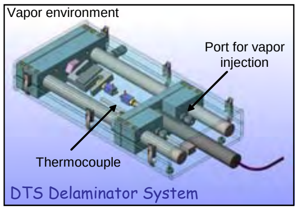
CMP slurry accelerates defect evolution

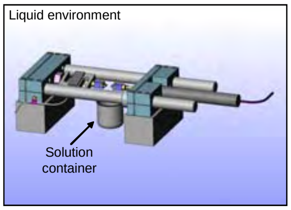


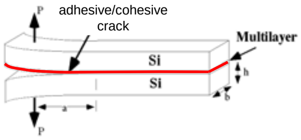
Reliability and Implications for Processing Yield

Depends on defect size and fracture energy, G_c

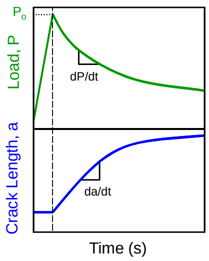
Automated Crack Velocity Testing



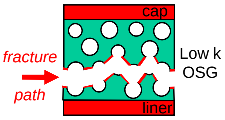




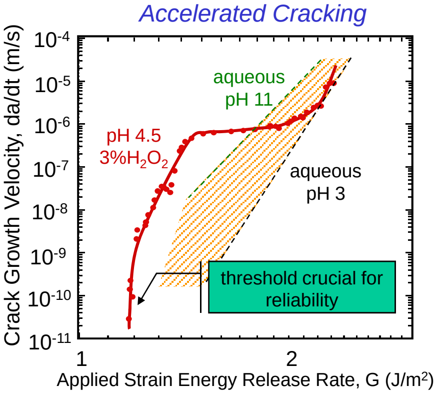
Load Relaxation Crack Growth Technique



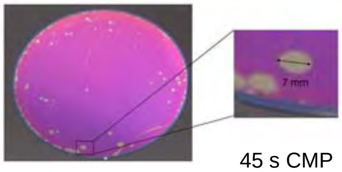
compliance analysis



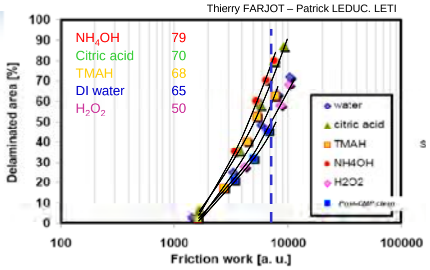
Accelerated Cracking



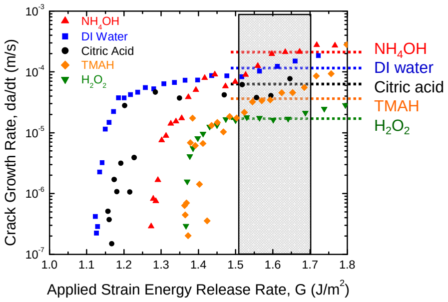
Relevance to CMP Damage

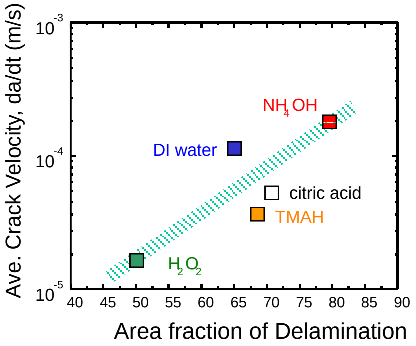


45 s CMP



Characterize crack growth rate to predict damage…

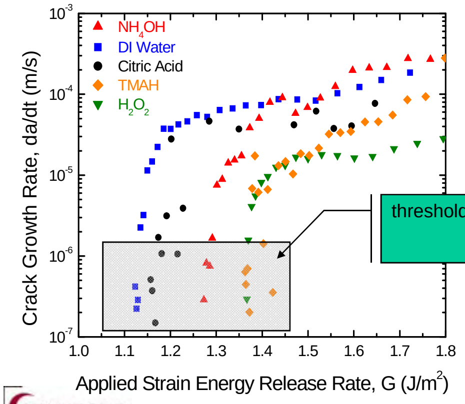




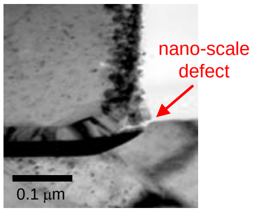
Relevance to CMP Damage

- Low crack growth rates critical for growth of nano-scale defects
- Dominated by threshold behavior in v-G curves

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



threshold crucial for CMP defects



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

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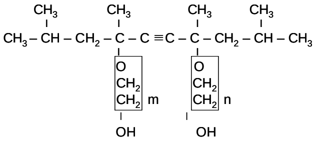
Surfactant Effects on Defect Growth and Diffusion

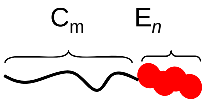
Dimeric (Gemini) surfactant

Low foaming (defoaming) and rapid surface wetting

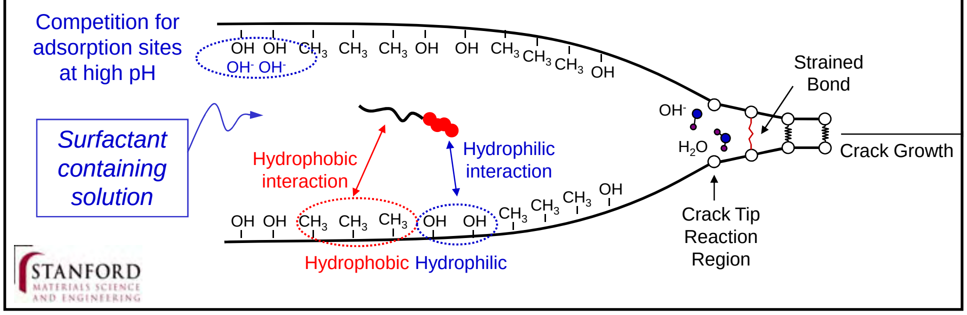


Linear (bridged) surfactant

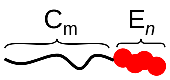
Polyoxyethylene Alkyl Ethers



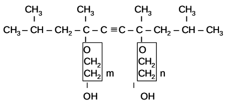
Effects of surfactant molecules on the defect evolution/crack growth are unknown!



Surfactant Effects on Defect Growth and Diffusion

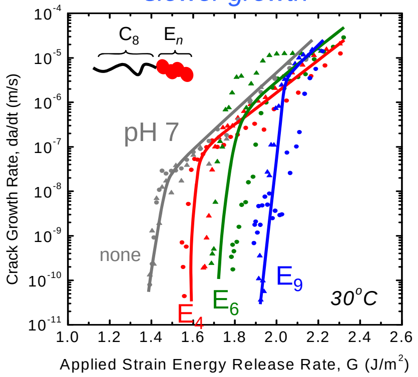


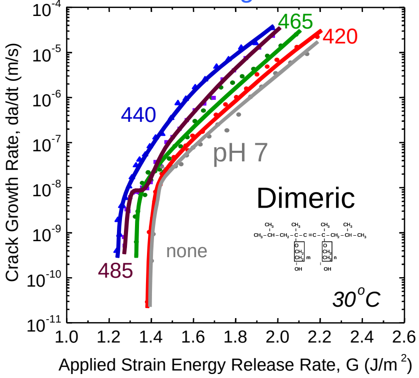
Linear (bridged) surfactant
Polyoxyethylene Alkyl Ethers



Dimeric (Gemini) surfactant

slower growth 0.1 wt. % surfactant solution *faster growth*





Dimeric surfactant accelerates crack growth

C_mE_n surfactants suppressed crack growth!

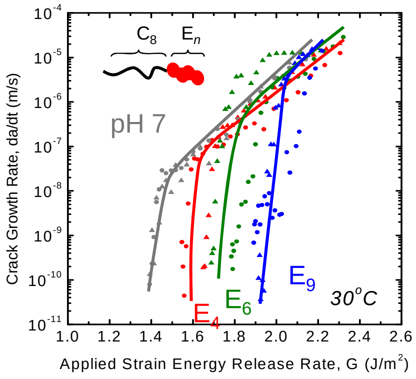
Dimeric surfactant decreases diffusion

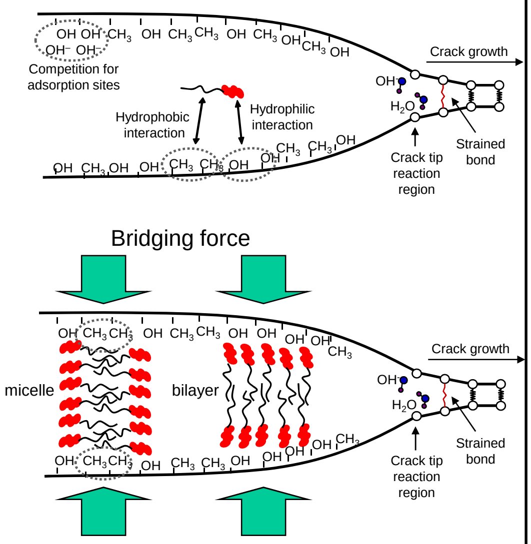
C_mE_n surfactants accelerate diffusion!

Micellar Bridging in Aqueous Solution

$$\boxed{G_{tip} = G_{applied} - G_{bridging}}$$

Micellar bridging reduces
crack tip driving force





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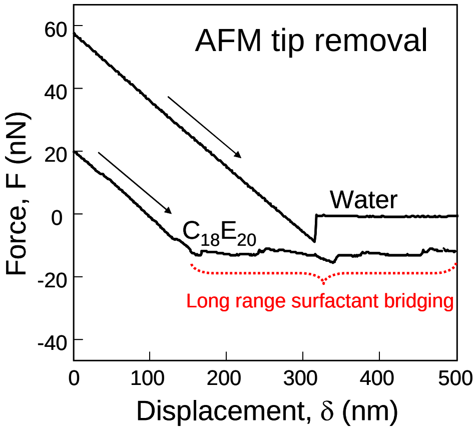
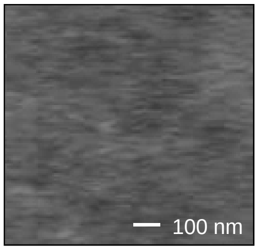
Probing Molecular Interactions with AFM

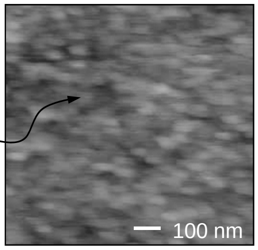


DI water pH10 (NH_4OH)



pH10 (NH_4OH) +0.1wt% $C_{18}E_{20}$

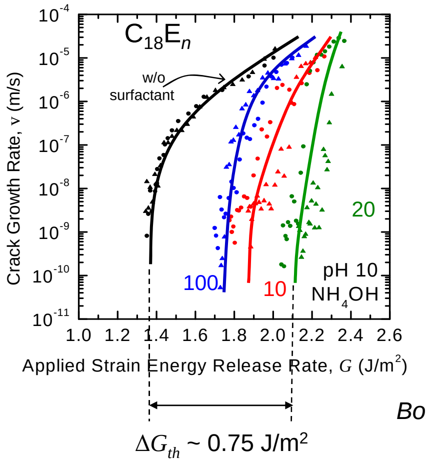
surfactant self-assembly

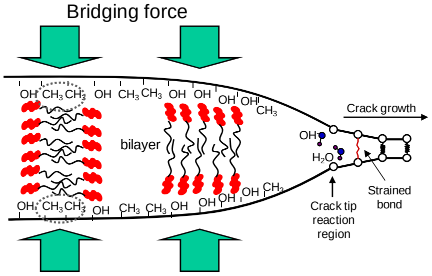


- Si_3N_4 tips
- Spring constant ~ 0.22N/m
- Images taken in soft contact mode

Molecular Bridging Contribution

$$G_{tip} = G_{applied} - G_{bridging}$$





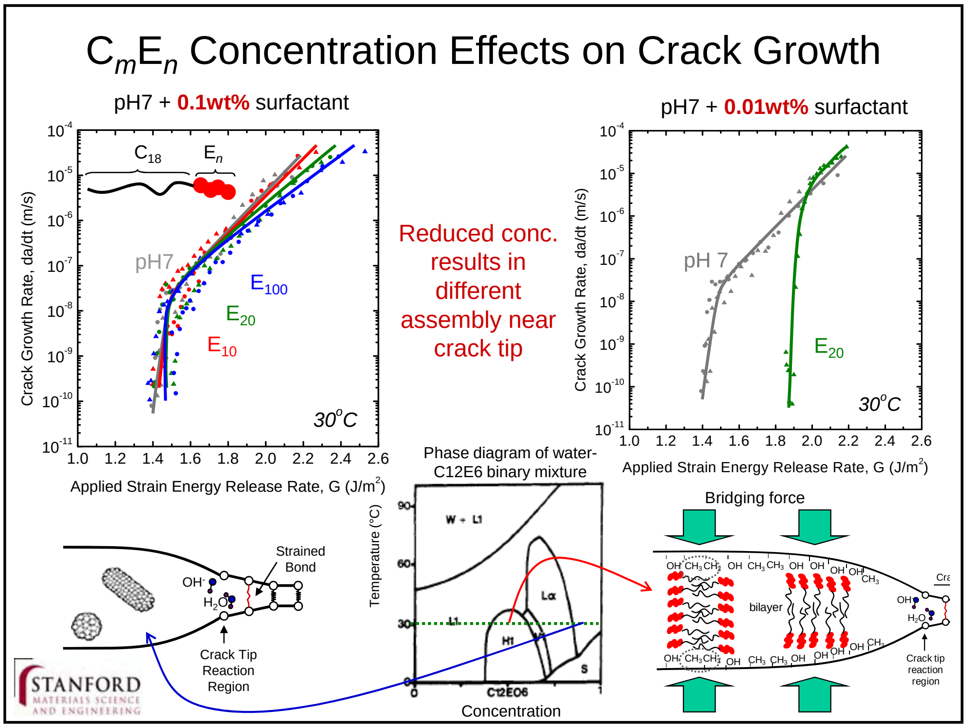
From AFM measurements:

F_{max} ~ 13.3 pN

Bridging stress: $\sigma_o = F_{max} \cdot A = 2.6$ pN/nm^2

Bond Areal density: $A \sim 1/[(\pi\cdot(C\cdot r)^2] \sim 2 \cdot 10^{-4}$ nm^{-2}

$$G_{bridging} = \sigma_o \delta_o \int_0^1 \chi(\varepsilon)\, d\varepsilon = 0.93\,\mathrm{J/m^2}$$



C_mE_n Concentration Effects on Crack Growth

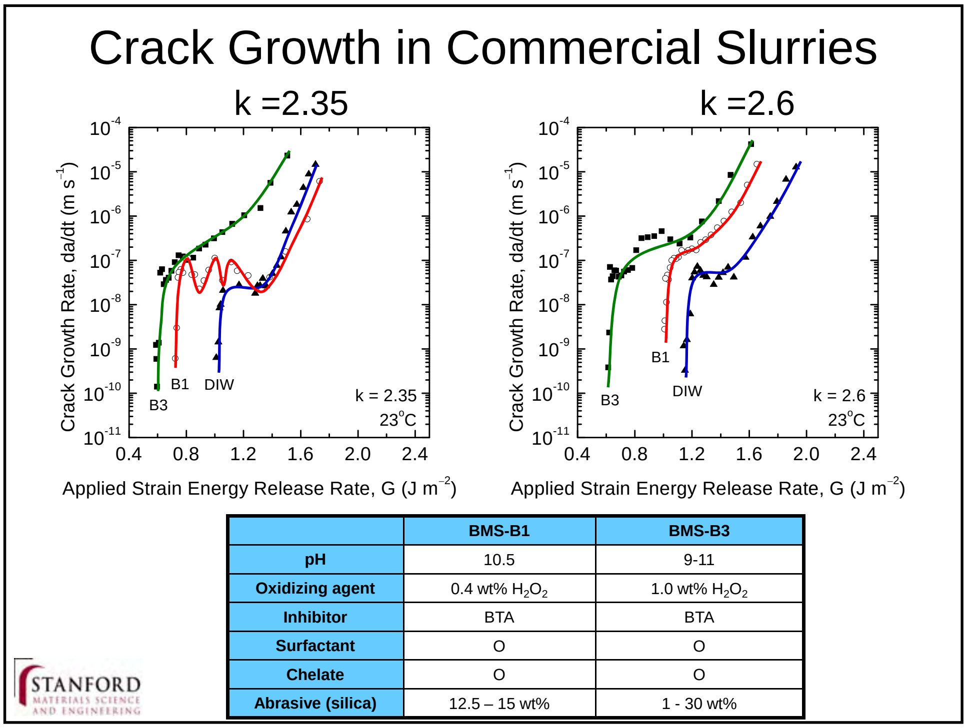
pH7 + **0.1wt%** surfactant

pH7 + **0.01wt%** surfactant

Reduced conc. results in different assembly near crack tip

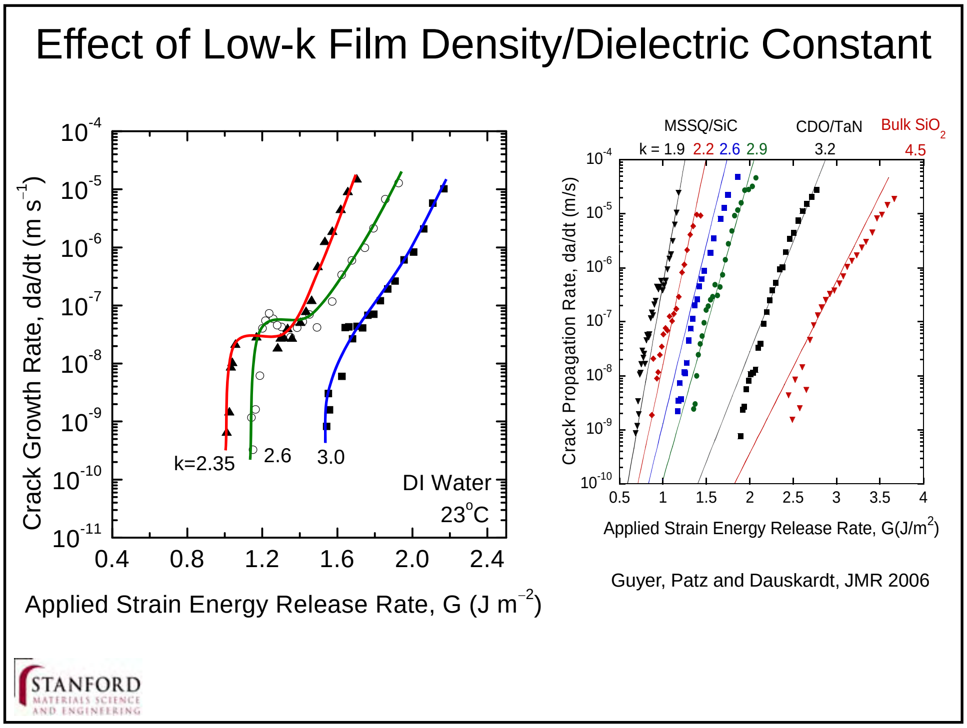
Phase diagram of water-C12E6 binary mixture

Bridging force



Crack Growth in Commercial Slurries

	BMS-B1	BMS-B3
pH	10.5	9-11
Oxidizing agent	0.4 wt% H_2O_2	1.0 wt% H_2O_2
Inhibitor	BTA	BTA
Surfactant	O	O
Chelate	O	O
Abrasive (silica)	12.5 – 15 wt%	1 - 30 wt%



Effect of Low-k Film Density/Dielectric Constant

Guyer, Patz and Dauskardt, JMR 2006

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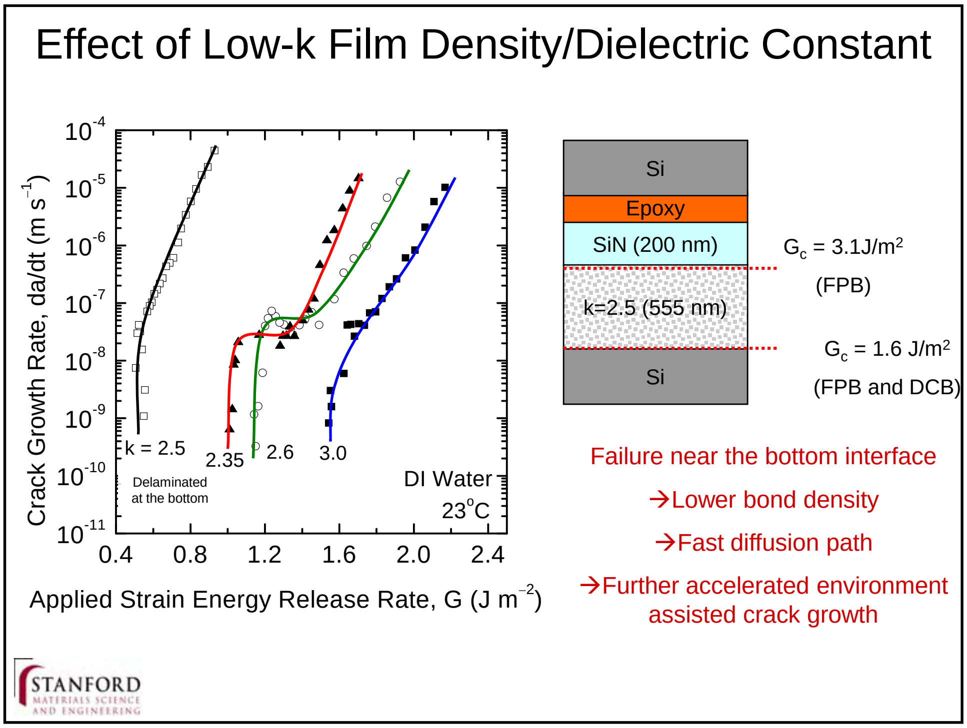

Effect of Low-k Film Density/Dielectric Constant

Failure near the bottom interface

→Lower bond density

→Fast diffusion path

→Further accelerated environment assisted crack growth

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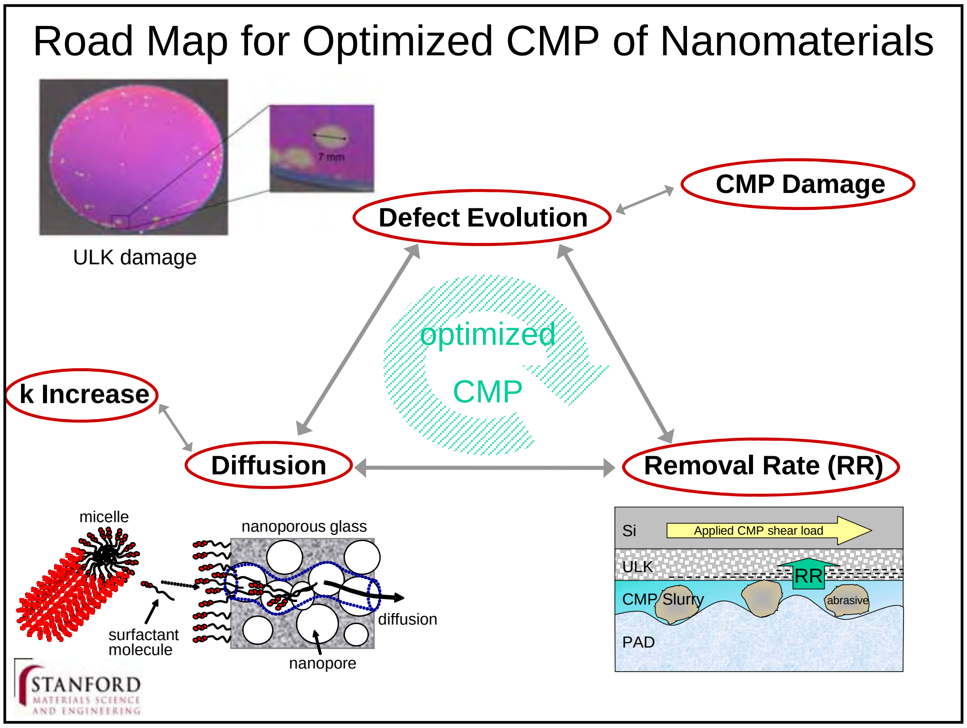
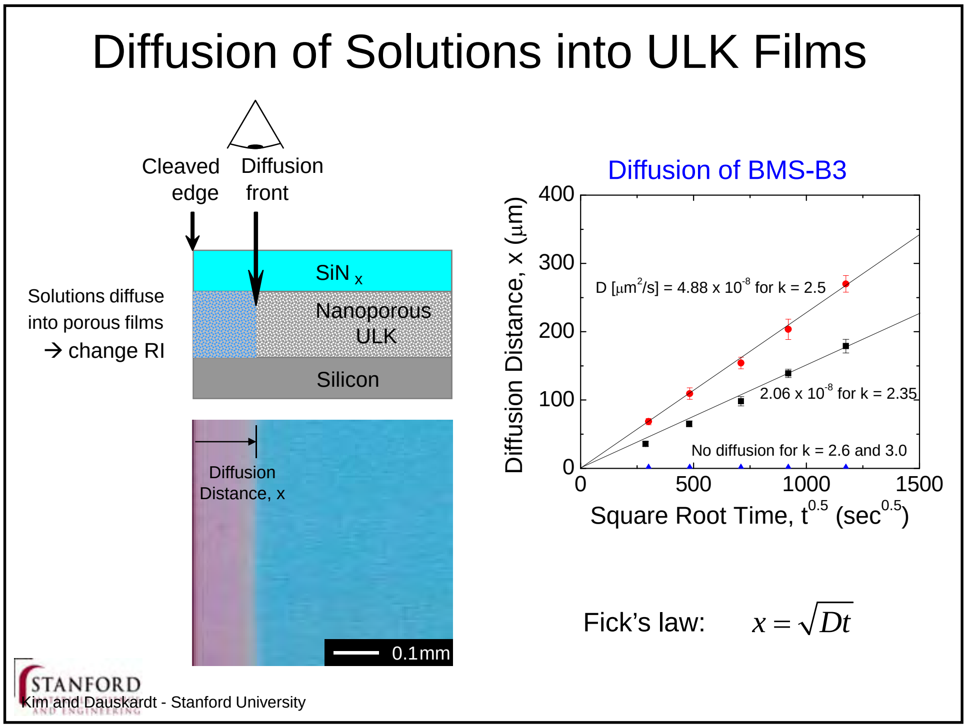


Road Map for Optimized CMP of Nanomaterials



Diffusion of Solutions into ULK Films

Solutions diffuse into porous films → change RI

Fick's law: $x = \sqrt{Dt}$

Kim and Dauskardt - Stanford University

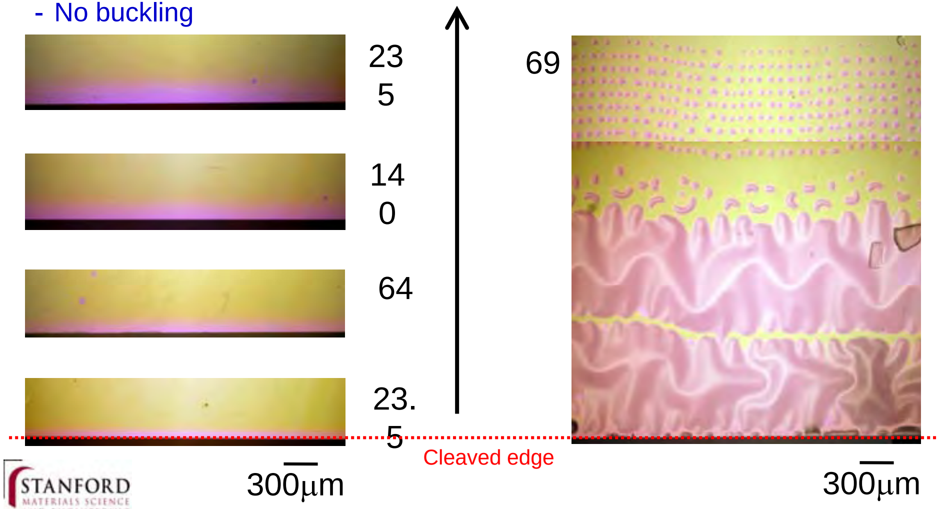
Diffusion of CMP Slurry: Effect of H_2O_2 Addition

With H_2O_2 (1 wt.%)

- Uniform Fickian diffusion
- No buckling

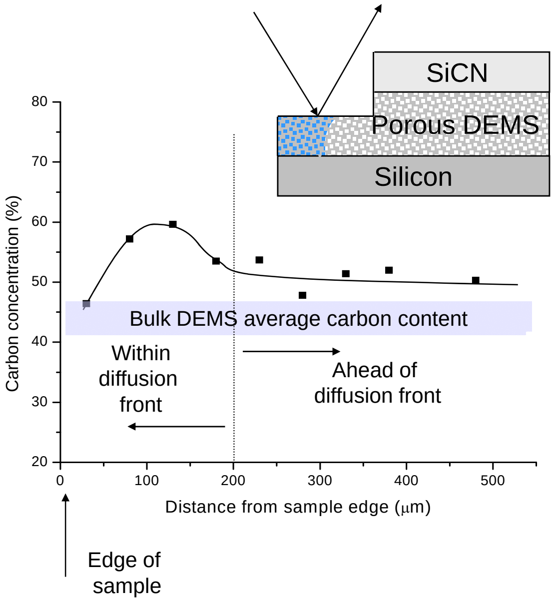
Without H_2O_2

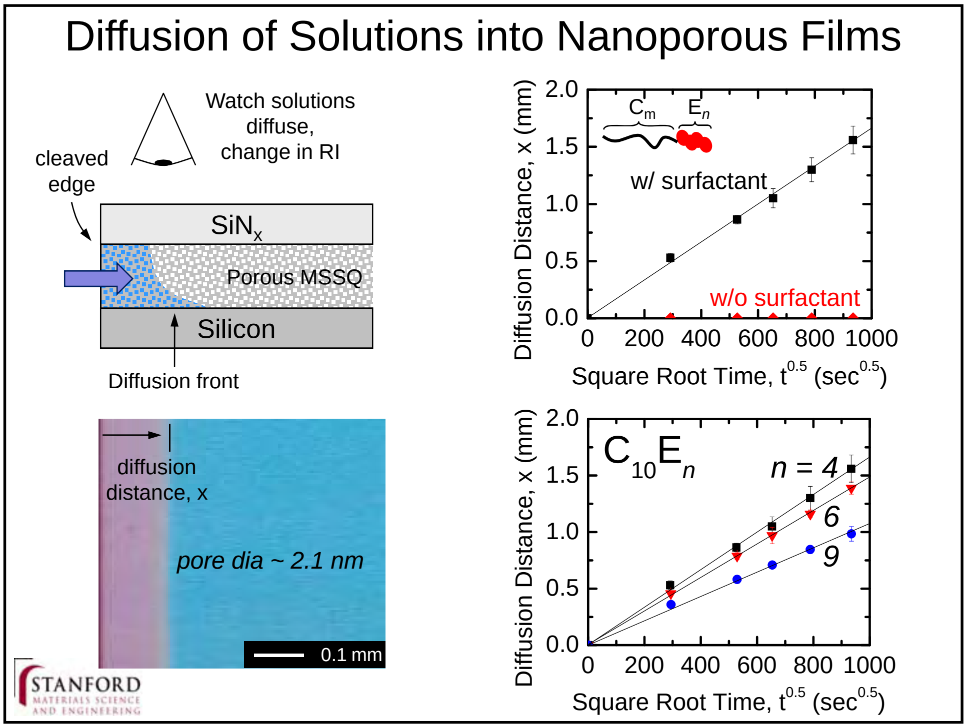
- Severe buckling



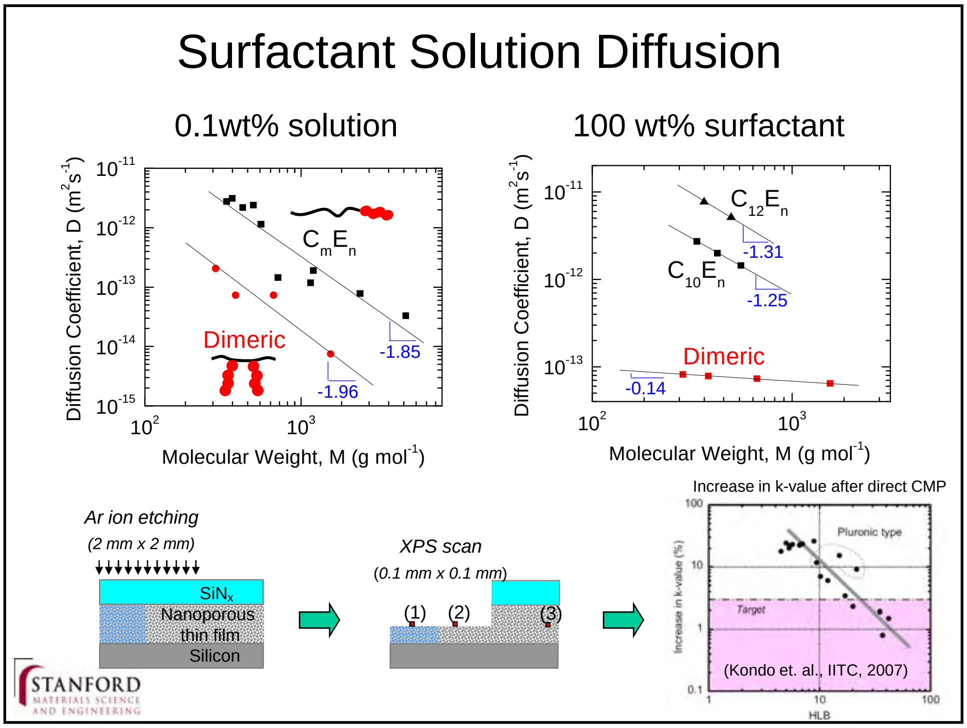
Analyzing Diffusion Front with XPS

- Carbon content is used to track extent of slurry infiltration
- Chemical analysis shows a clear carbon maximum in the middle of the diffusion front
- Due to complexity of slurry the exact diffusing species cannot be determined using XPS



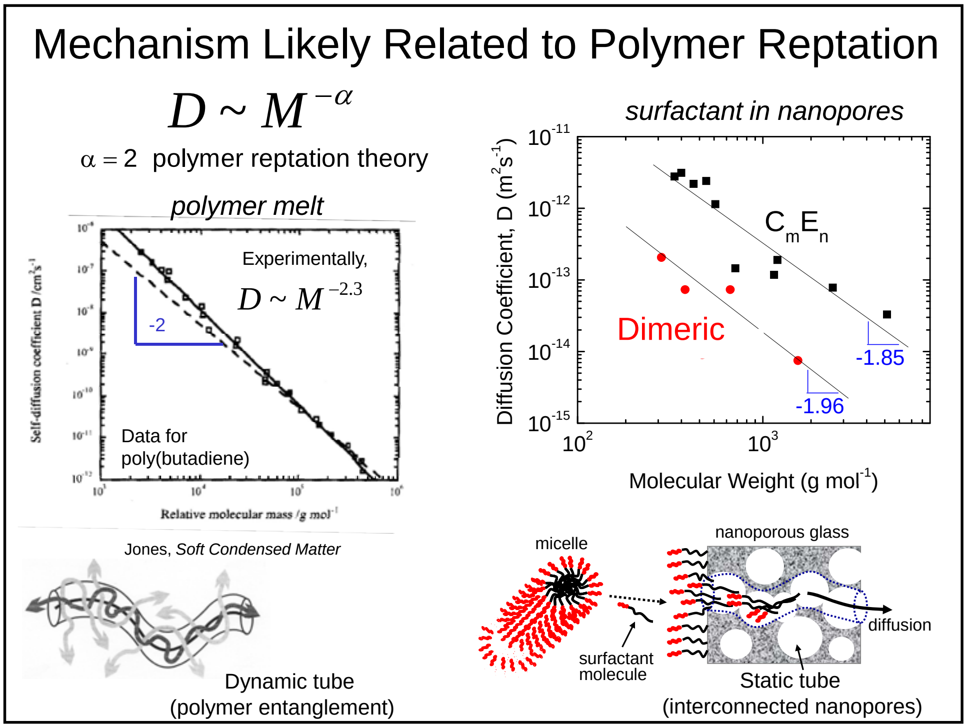


Diffusion of Solutions into Nanoporous Films



Surfactant Solution Diffusion

Mechanism Likely Related to Polymer Reptation



$$D \sim M^{-\alpha}$$

$\alpha = 2$ polymer reptation theory

polymer melt

Experimentally,

$D \sim M^{-2.3}$

Data for poly(butadiene)

Jones, *Soft Condensed Matter*

Dynamic tube
(polymer entanglement)

surfactant in nanopores

Static tube
(interconnected nanopores)

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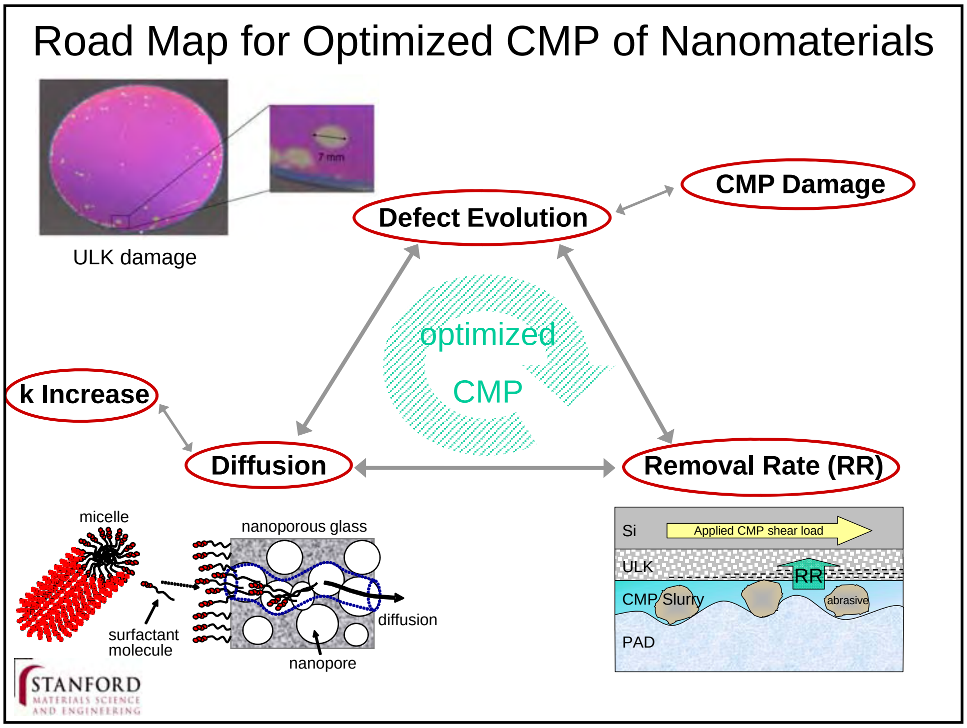
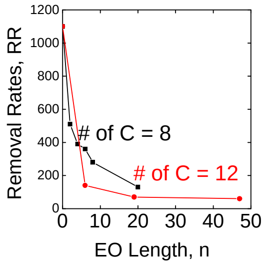
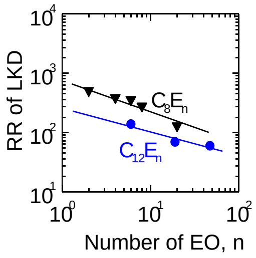


ULK damage

Correlations with CMP Removal

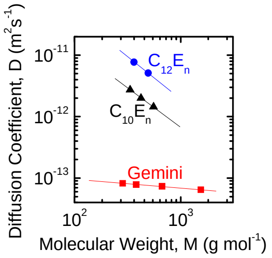
RR is inversely proportional to D. ***RR is inversely proportional to G_{TH}.***

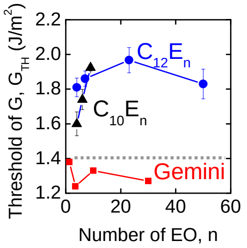




$$RR \sim D^{-c}M^{-d}$$

$$RR \sim G_{th}^{-\beta}$$





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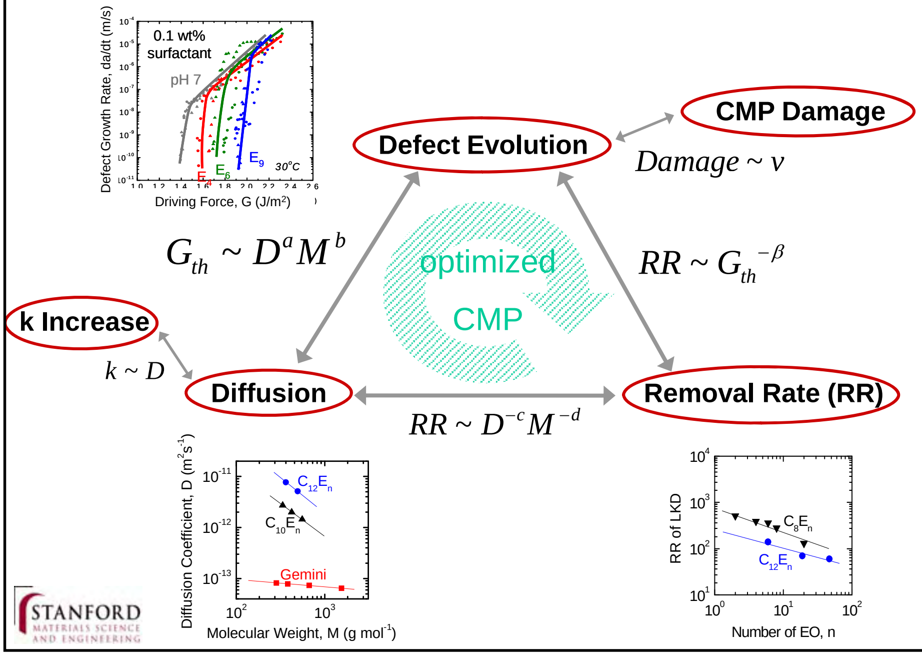


CMP Damage

Defect Evolution

$Damage \sim v$

$$G_{th} \sim D^a M^b$$

$$RR \sim G_{th}^{-\beta}$$

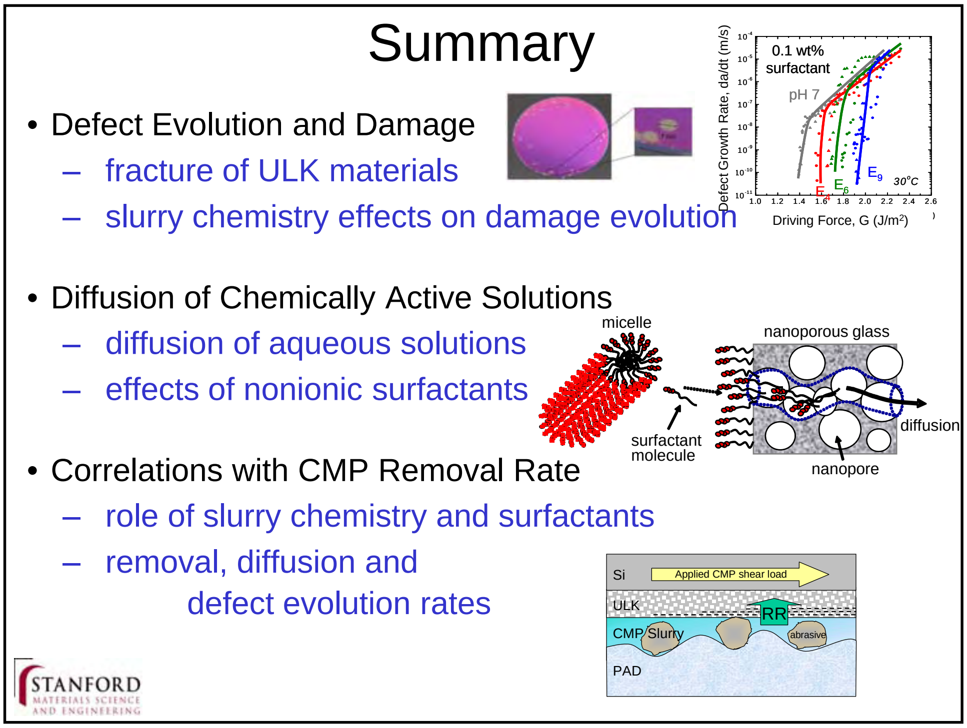
k Increase

$k \sim D$

Diffusion

Removal Rate (RR)

$$RR \sim D^{-c}M^{-d}$$



Summary

- Defect Evolution and Damage
  - fracture of ULK materials
  - slurry chemistry effects on damage evolution
- Diffusion of Chemically Active Solutions
  - diffusion of aqueous solutions
  - effects of nonionic surfactants
- Correlations with CMP Removal Rate
  - role of slurry chemistry and surfactants
  - removal, diffusion and defect evolution rates

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