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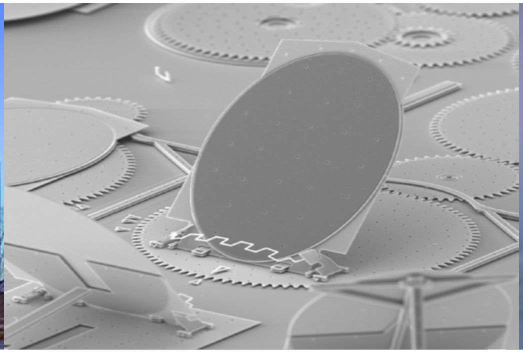

Contact Mechanics for Integrated Circuit Manufacturing

Jonatan A. Sierra Suarez PhD

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Outline

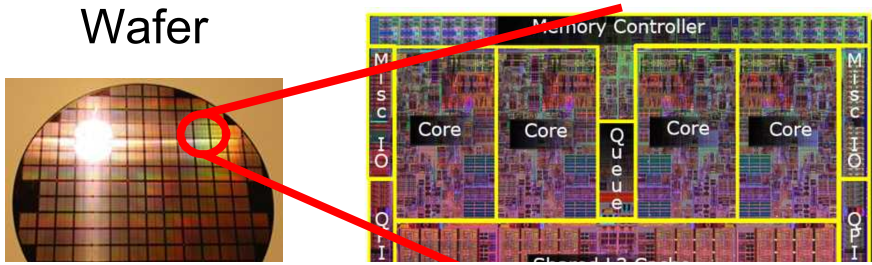
- Introduction to IC Manufacturing
- High Fidelity Contact Mechanics: General rough surface contact applied to CMP
- Contact Mechanics at the MESAfab

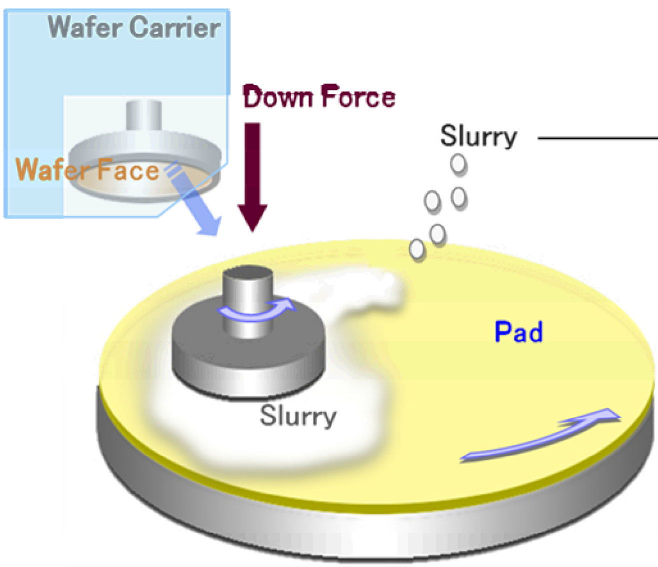
Chemical Mechanical Polishing (CMP): Basics

- CMP is used extensively to achieve planarity
- Leads to yield losses through systematic (dishing and erosion) and random defects (micro-scratches, particle contamination)

Wafer

Die

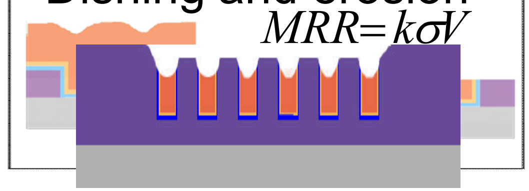




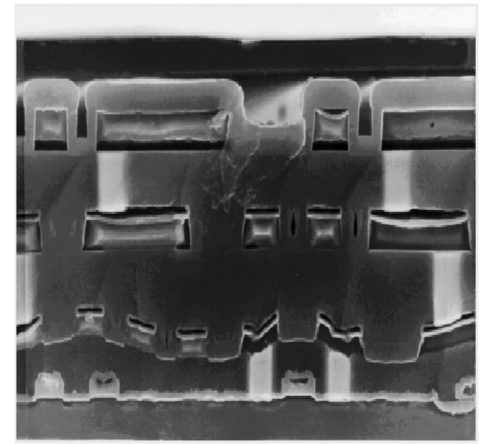
Slurry is chemically reactive fluid that also has nanoparticle abrasives

Dishing and erosion

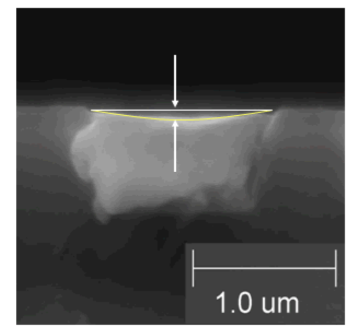
$MRR = k\sigma V$

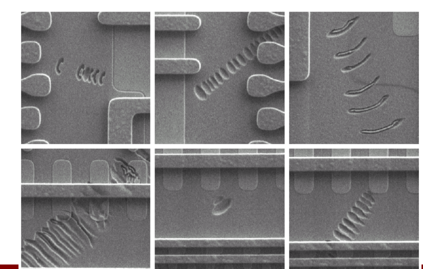


Defect SEM Images*



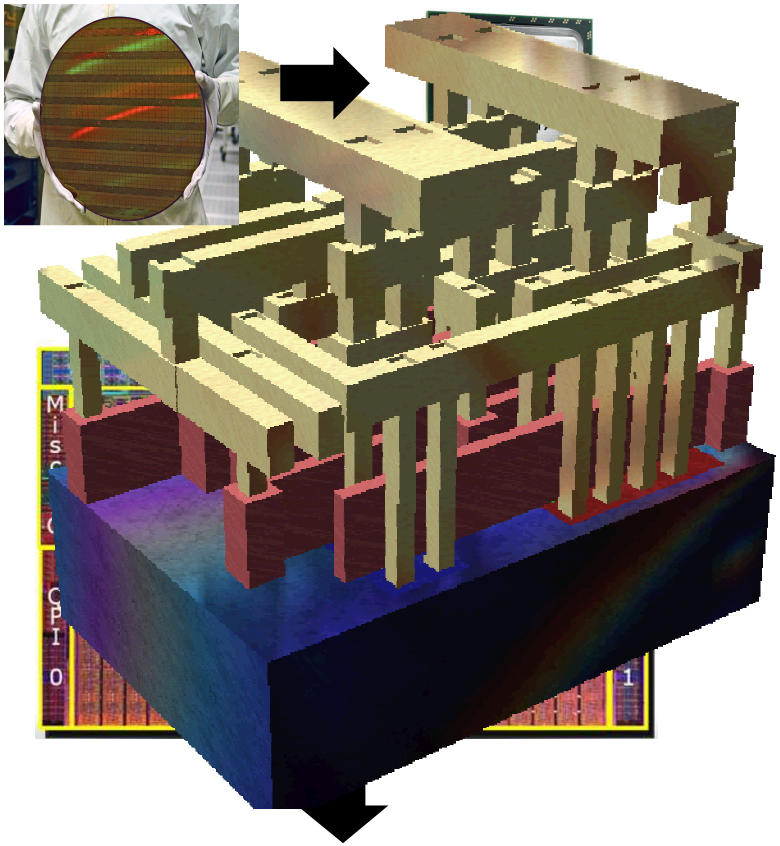
Courtesy 3M, Hitachi, TD- Perl

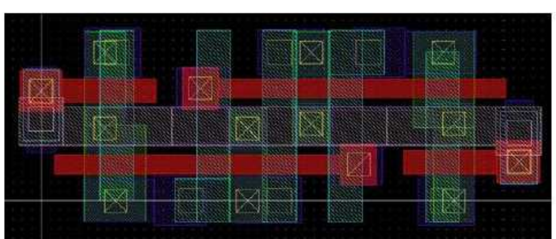


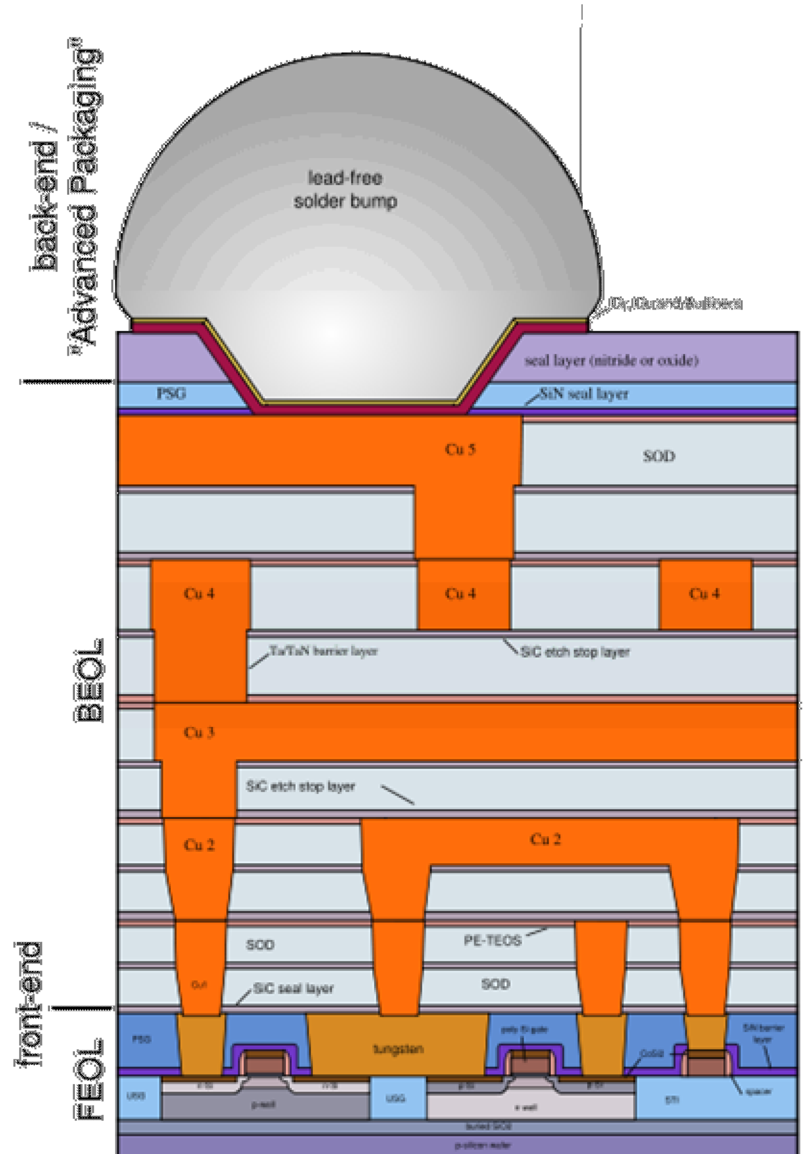


An In-Depth Look…

Sandia National Laboratories







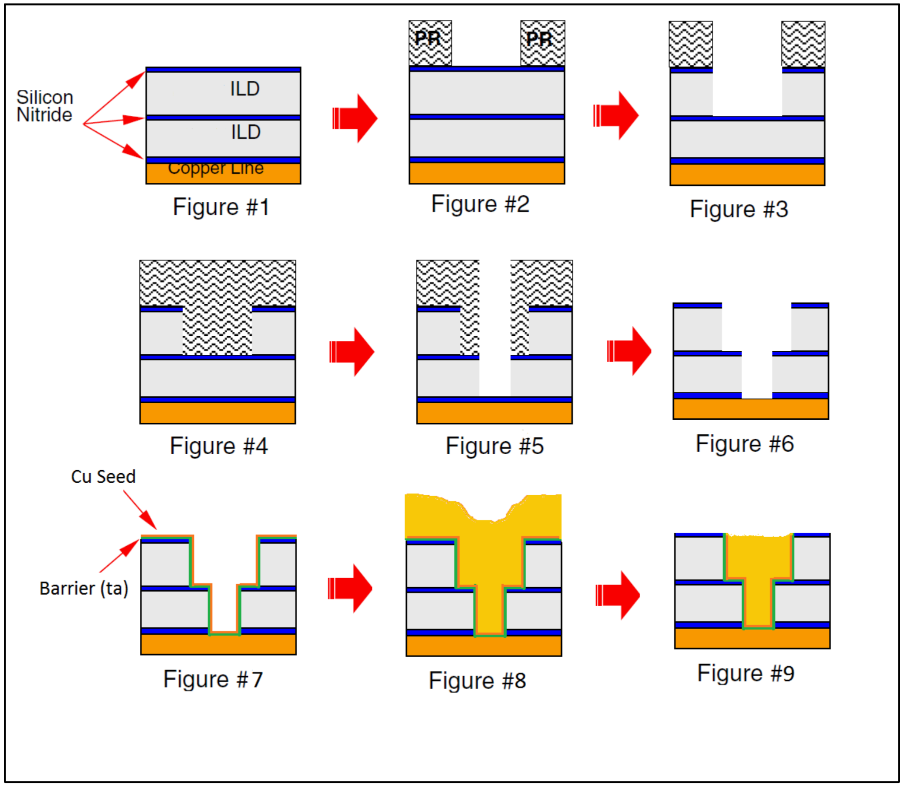
Images Courtesy of: Intel, Henrik Schumacher, David Carron

Background: Manufacturing Processing Flow

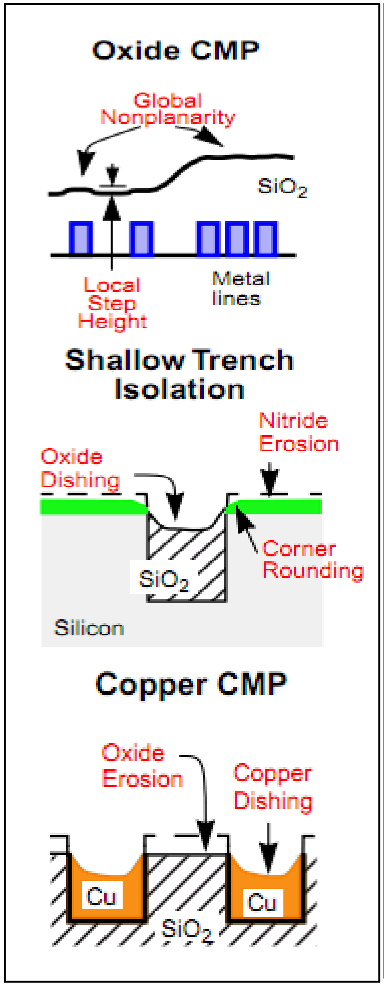
All unit processes below will be performed multiple times during the fabrication of IC devices

- CMP
- Deposition
- Etching
- Photolithography

Dual Damascene Process Steps (BEOL)

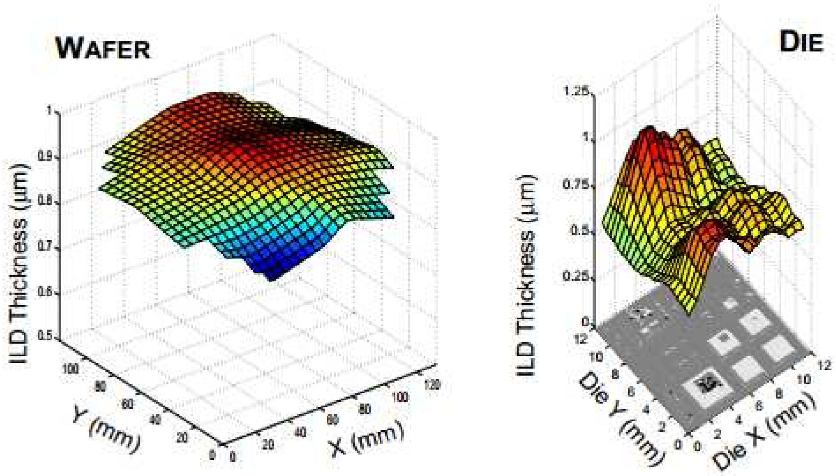


CMP Uses



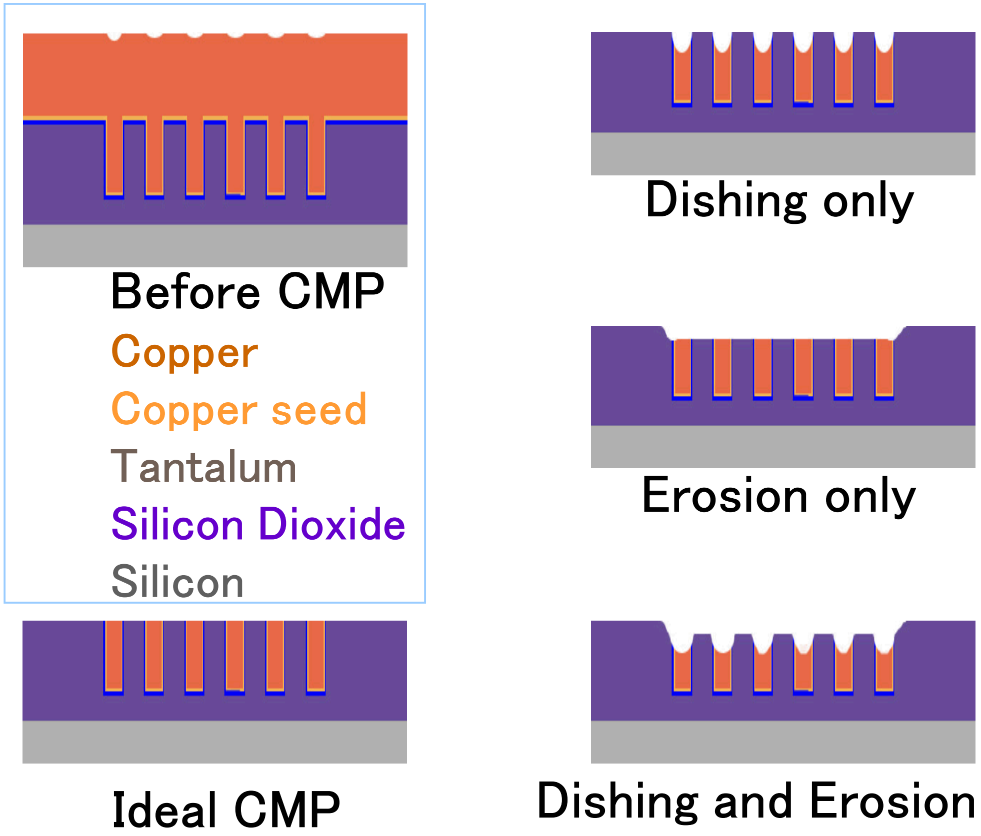
CMP : Non-Uniform Material Removal Rate (MRR)

Wafer and die non-uniformity



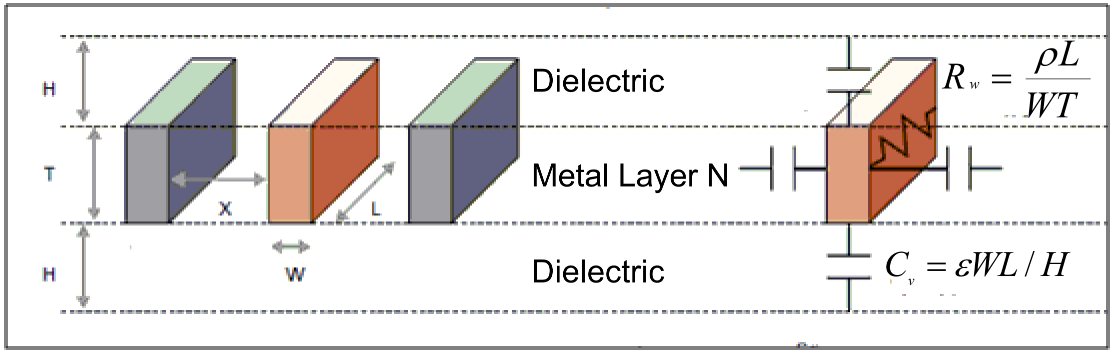
Non-uniformity across scales from Ouma et. al 2002

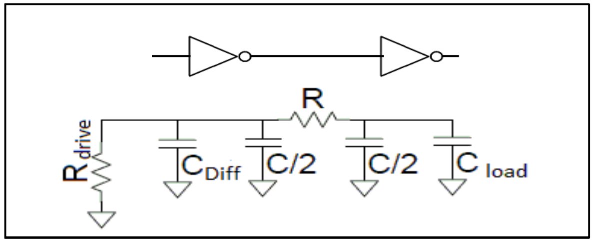
Feature non-uniformity



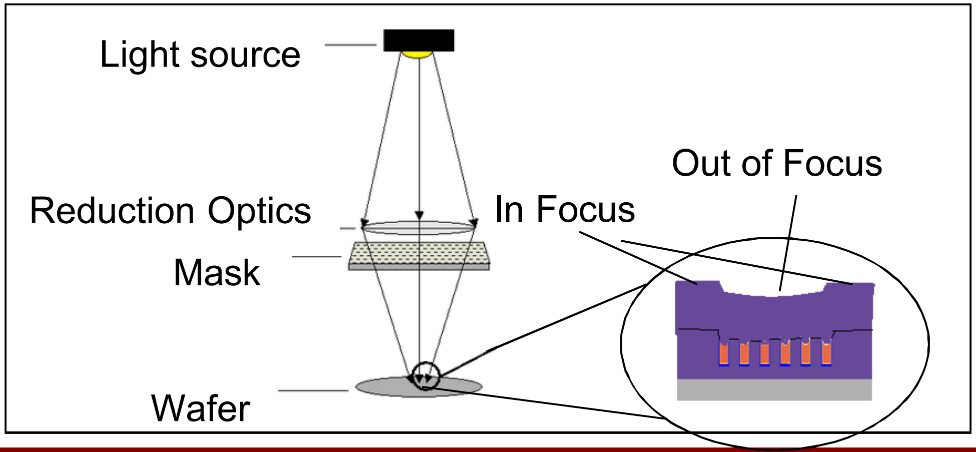
CMP: Manufacturing Impact

- Dummy fill, dishing, and erosion will raise resistance and capacitance
  - This affects timing and power





- Successful photolithography depends on low topography variation due to depth of focus (DOF)



Elastic Halfspace Contact Solution for CMP

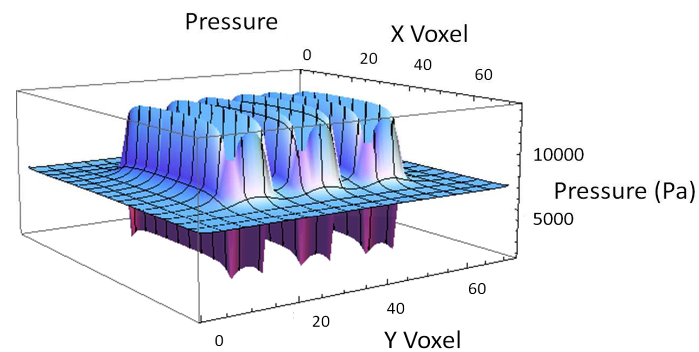
Deflection u_z at a point in an elastic halfspace due to applied pressure (Johnson 1985)**:**

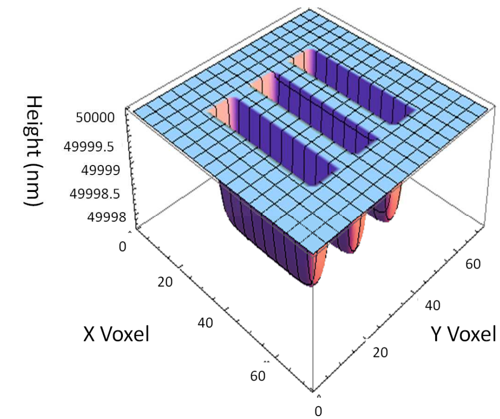
$$u_z(x,y) = \frac{1-\nu^2}{\pi E} \iint \frac{\sigma(x',y')}{\sqrt{(x-x')^2+(y-y')^2}}\, dx'dy'$$

Couple with Preston's wear equation to calculate material removal rate (MRR)

$$MRR = k\sigma V$$

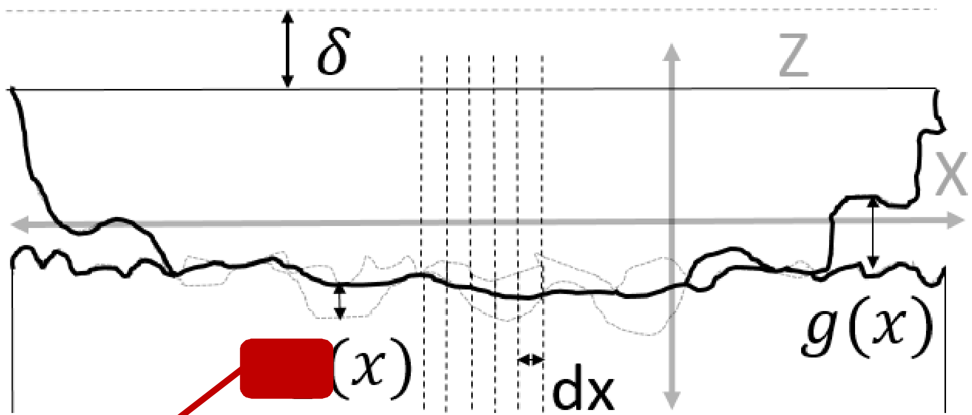
Nomenclature			
u	Surface Deflection	**σ**	Contact stress
v	Poisson ratio	**k**	Preston coefficient
E	Young's Modulus	**V**	Relative velocity





Pad Conformal Contact

Contact Mechanics Formulation



The composite vertical surface displacement:

$$u_z(x,y) = \frac{1-\nu^2}{\pi E}\iint \frac{\sigma(x',y')}{\sqrt{(x-x')^2+(y-y')^2}}dx'dy'$$

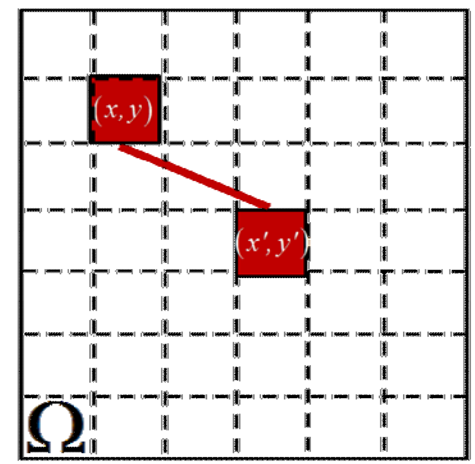
Every element has an influence on all other elements (Johnson, 1985)

Direct matrix multiplication $O[(N_x x N_y)^2]$

$$\mathbf{u}_z = \mathbf{C}\boldsymbol{\sigma}$$

Or leverage Fourier analysis $O[(2N_x x 2N_y)]$

*Discretized computational domain (view from top)



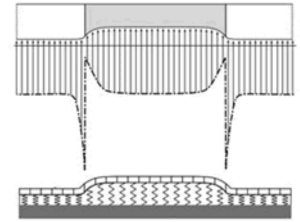
•N_x x N_y elements

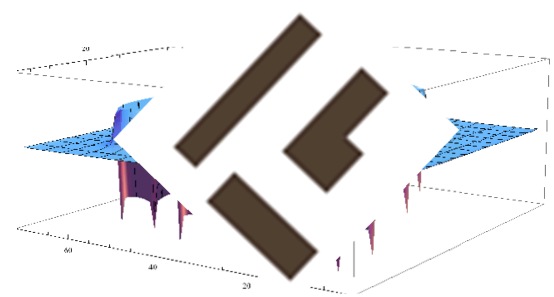
**Graphic*: Zenyuk, Kumbur, Litster (2013)

Sample Layout

3D Contact Stress

2D Contact Stress



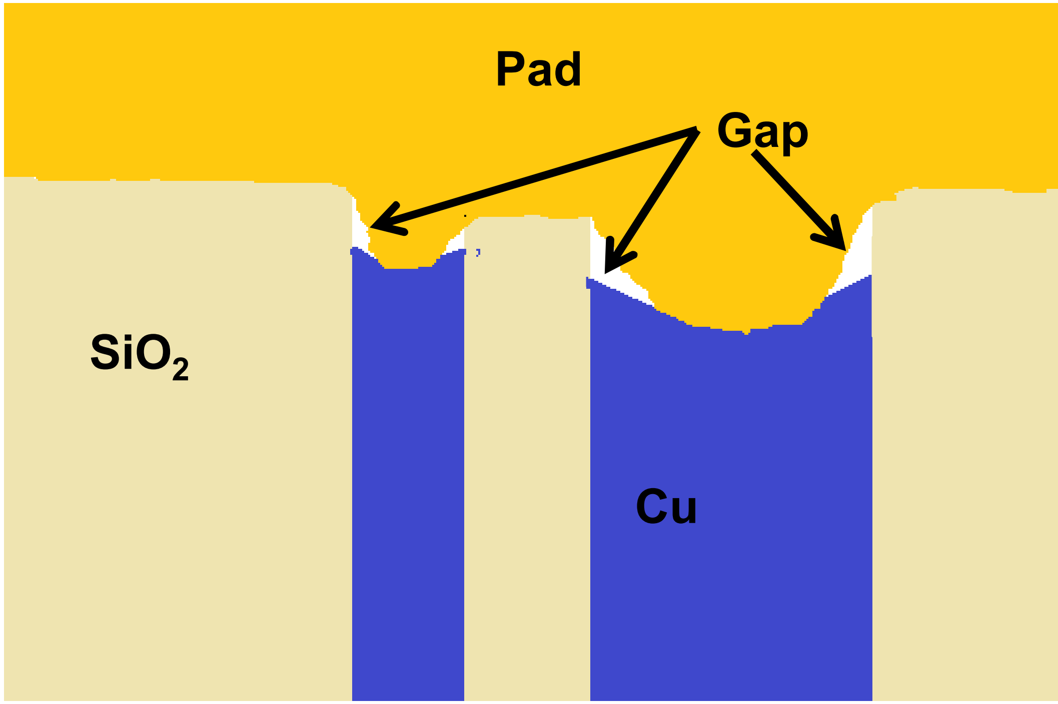


General rough surface contact: Higher Fidelity CMP

- Introduction to IC Manufacturing
- High Fidelity Contact Mechanics: General rough surface contact applied to CMP
- Contact Mechanics at the MESAfab

Conformal Assumption Removal: Two-Body Contact

- Contact is not necessarily conformal
- Remove conformal assumption by treating contact as a general two body problem.



Deterministic Two-Body Contact

- Two body contact is a linear complimentary problem
  - Multiple methods to solve (Alwood 2005)

$$\mathbf{g} = \mathbf{g}_0 - \delta + \mathbf{u}$$

$$\mathbf{u} = \mathbf{C}\boldsymbol{\sigma}$$

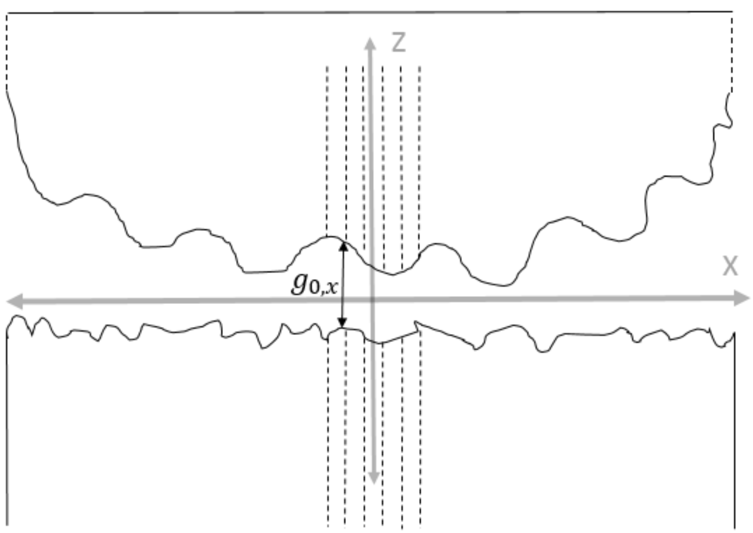
$$\mathbf{g} = \bar{\mathbf{g}} + \mathbf{C}\boldsymbol{\sigma}, \quad s.t.$$

$$\sigma_{x,y} = 0, \quad g_{x,y} \geq 0$$

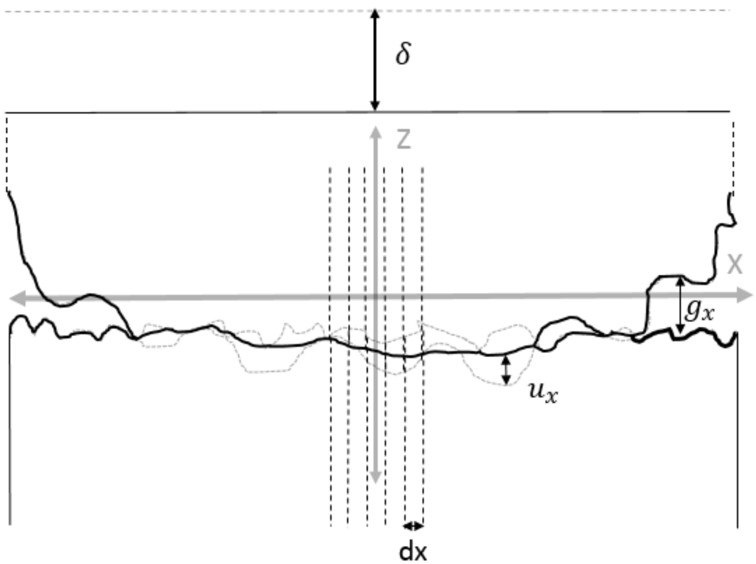
$$\sigma_{x,y} > 0, \quad g_{x,y} = 0$$

$$=> \boldsymbol{\sigma} \bullet \mathbf{g} = 0$$

Initial Surfaces

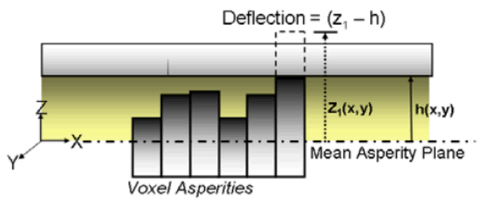


Deformed Surfaces



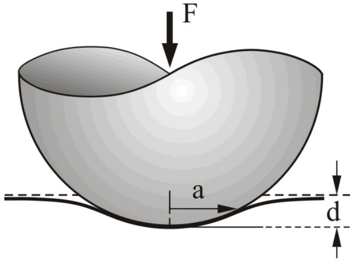
Contact Model Comparison

Winkler



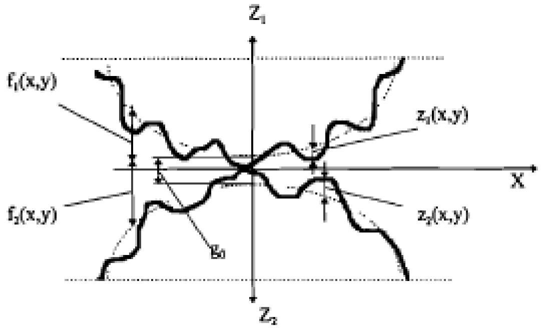
Elastic body is treated as set of linearly independent springs

Hertzian



Analytical model to conformal contact geometries such as sphere on sphere contact

Elastic halfspace with FFT, and constrained CGM (Hu et. al 1999)



Solves general two body contact by treating the problem as an optimization problem

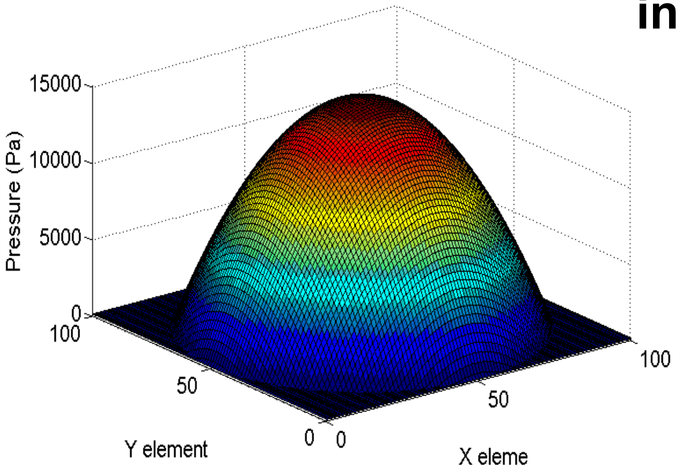
The CGM fits nicely with computationally efficient FFT

In collaboration with TPES (Prof. Shawn Litster & Prof. Iryna Zenyuk)

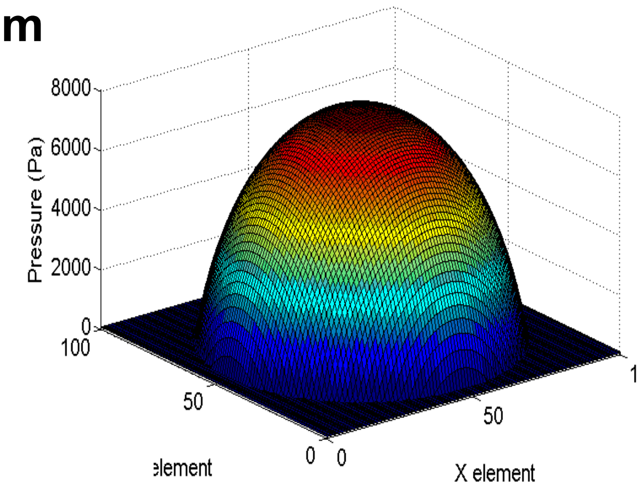
Error Analysis Between Three Contact Models

Pin-On-Disk indentation of 0.5um

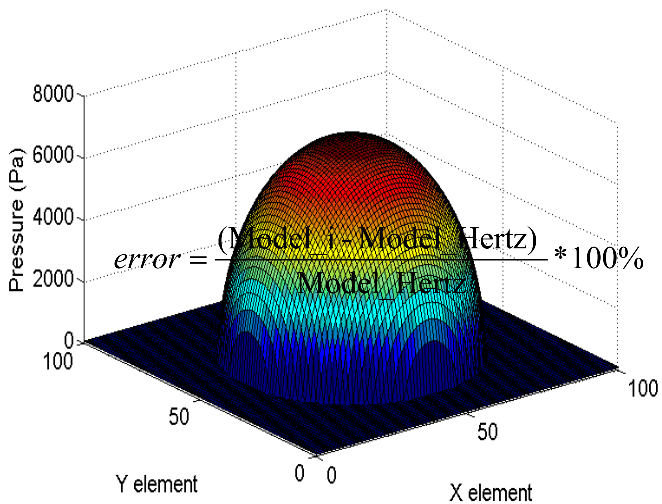
Winkler



Hu

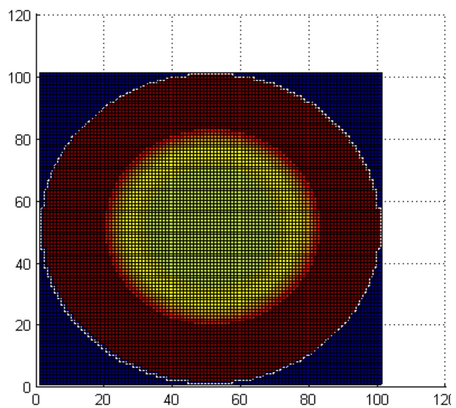


Hertz

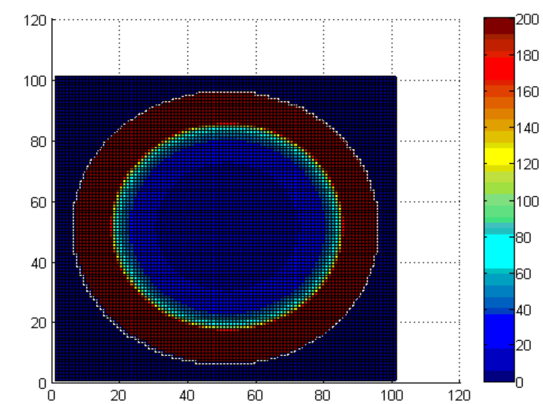


$$error = \frac{(Model\_i - Model\_Hertz)}{Model\_Hertz} * 100\%$$

Error Percent



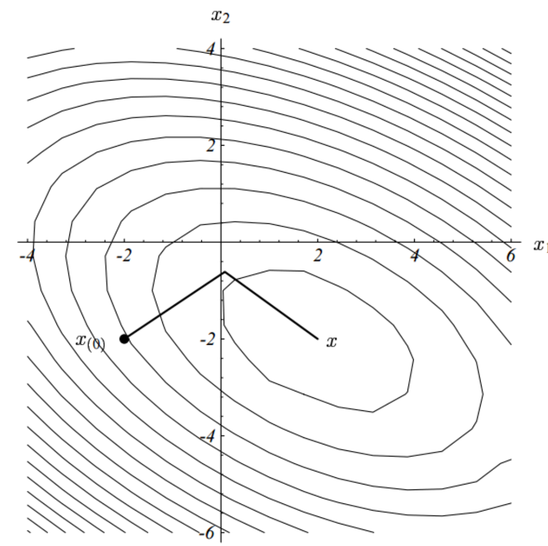
Error Percent

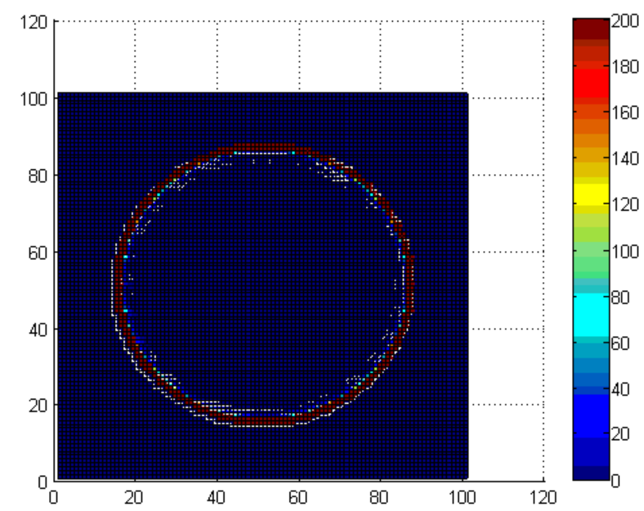


Improving upon Hu model

- Hu's constrained CGM method was replaced by a constrained *non-linear* CGM with a Newton Raphson line search

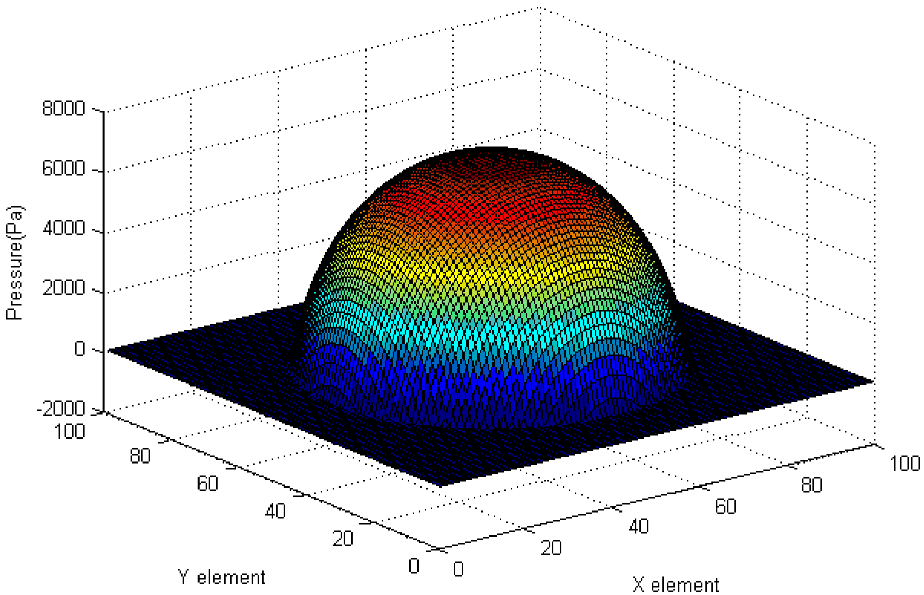
- This improves convergence (as shown by Schewchuk (1993)) and accuracy





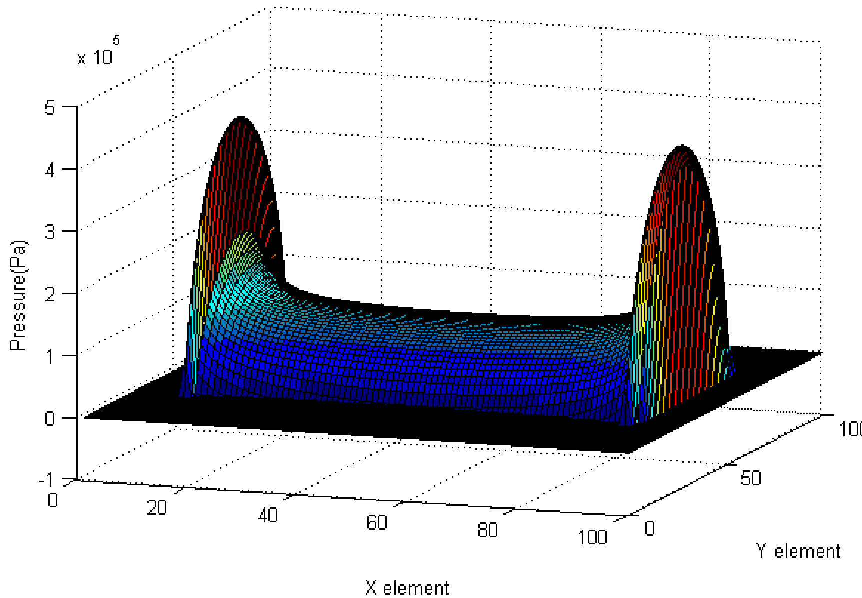
NL-CGM Results: Circular & Line Contacts

Pin on Disk



Numerical error at center element as compared to Hertzian Solution		
Winkler	Hu	NL-CGM
100.14%	18.05%	.35%

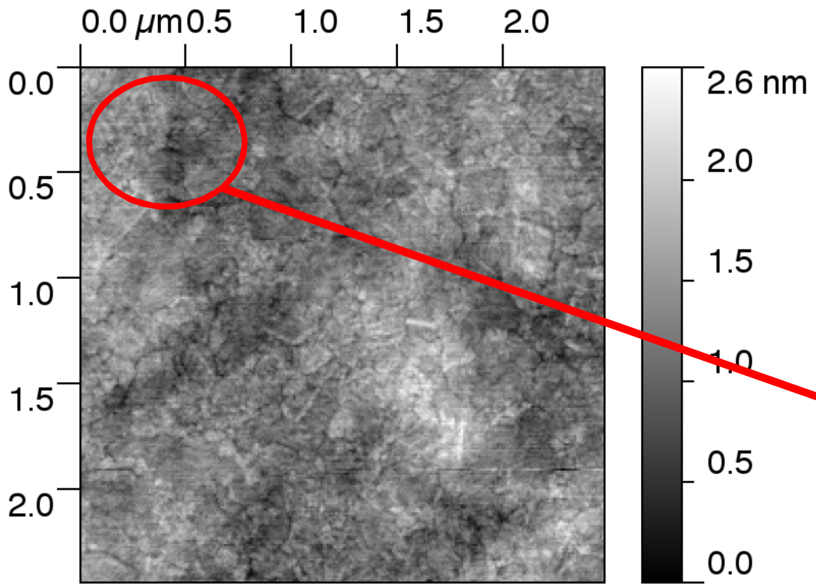
Cylinder



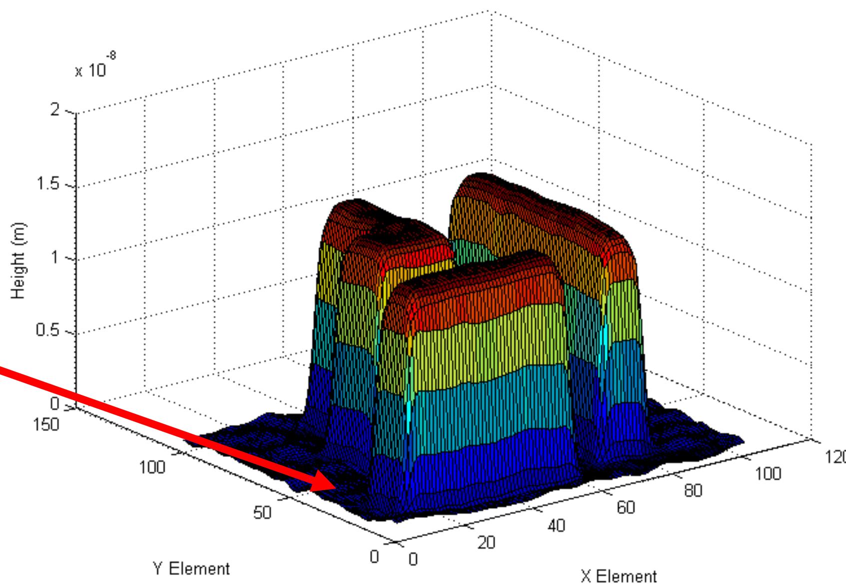
Numerical error at center element as compared to Hertzian Solution		
Winkler	Hu	NL-CGM
64.7%	NA	2.56%

Introducing Metrology Data: Real Surface

AFM Data

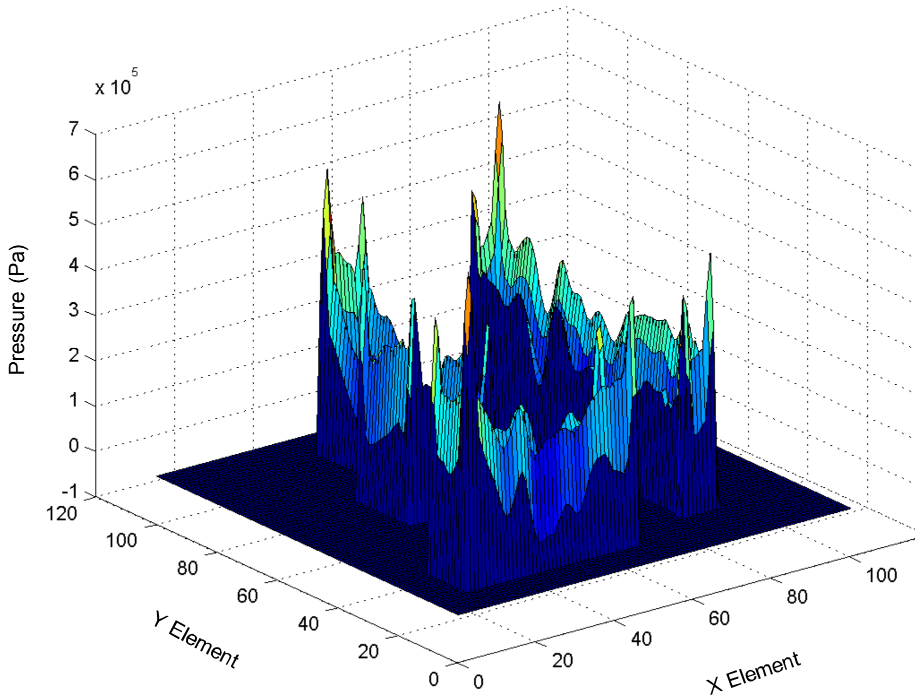


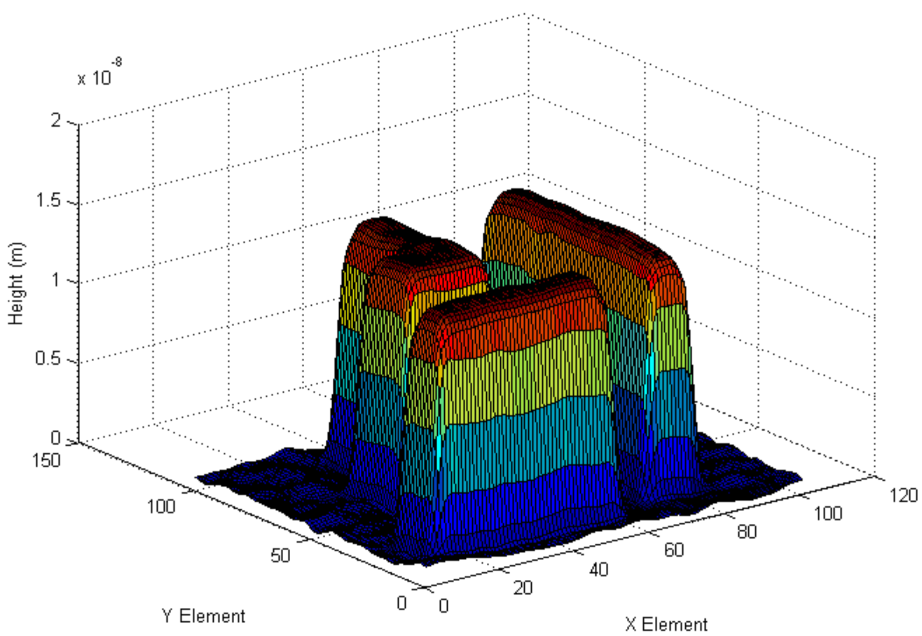
Raised surface prior to CMP using AFM data



NL-CGM Results: Extending to IC Feature Geometries

Average Load	5 psi	**Relative velocity**	.3 m/s
Simulation time step	.01s	**Preston coefficient**	60 MPa^{-1}
Element Size	10nm x 10nm	**Error tolerance**	1%





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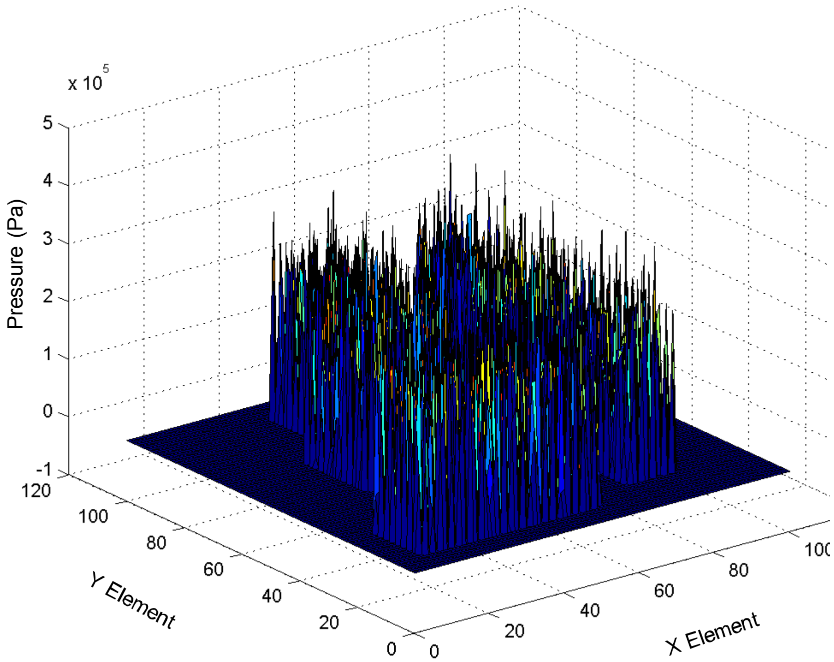
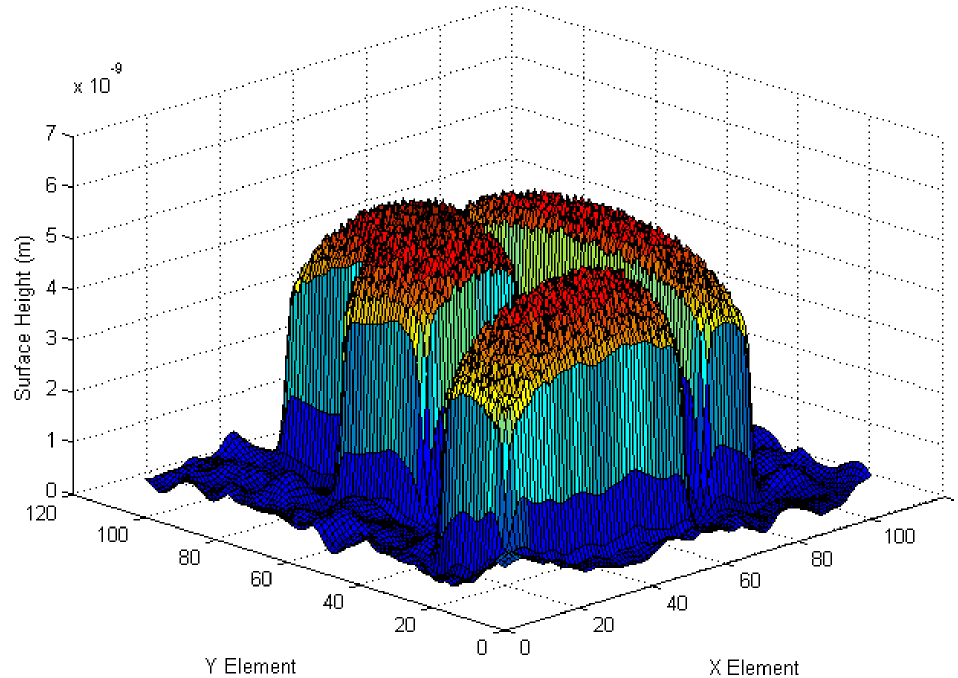




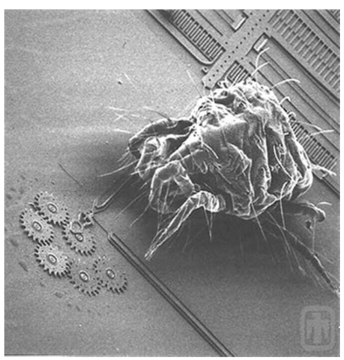
SNL: MESA Complex

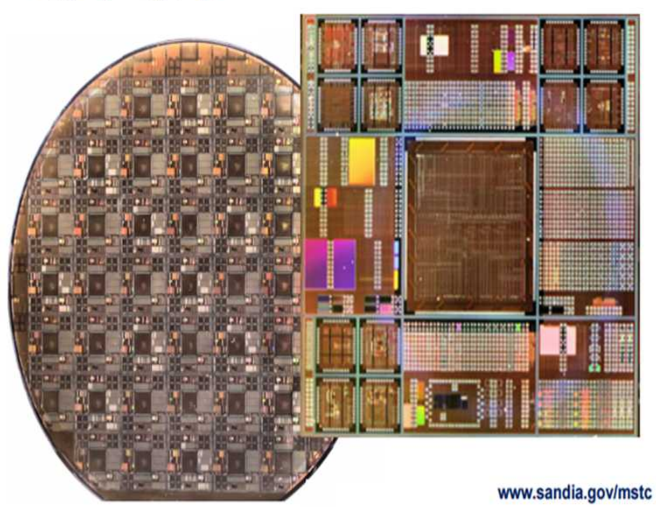
Silicon Fab

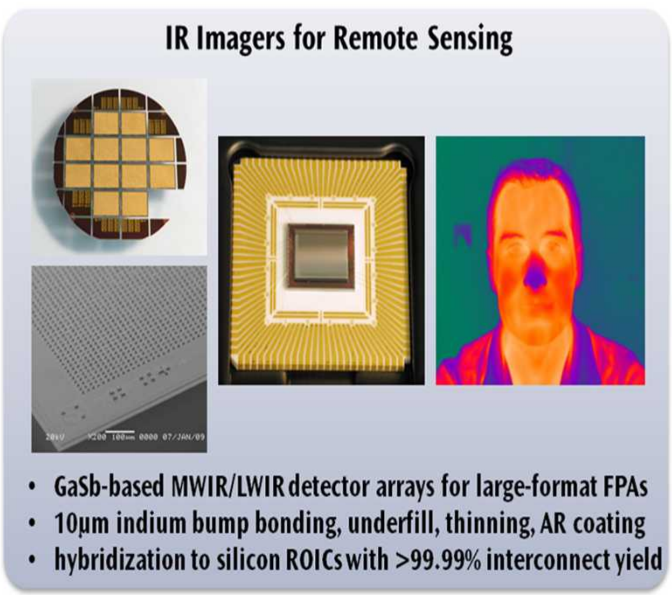
Trusted Rad-Hard application specific integrated circuits (ASIC)
Micro Electromechnical Systems (MEMS)
Photonics & more...

Micro Fab

III-V Compound Semiconductor Devices
Power Electronics
Advanced packaging







Advanced packaging

More functionality, Less Power, Faster performance…. More complexity

Failure analysis requires precise removal layer by layer

Stresses need to be considered at a micro scale

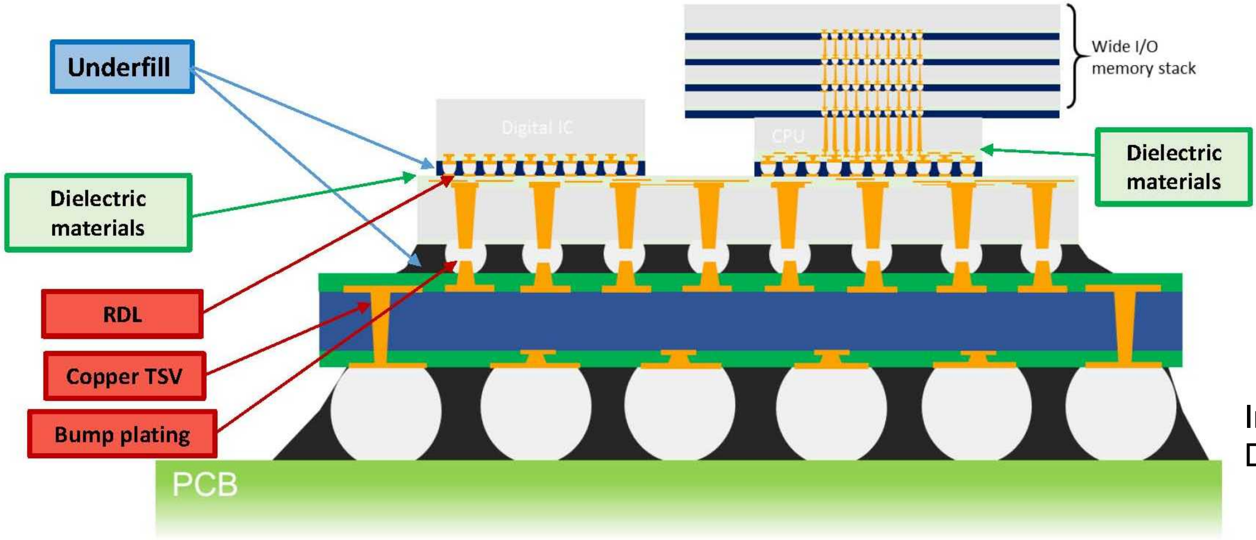
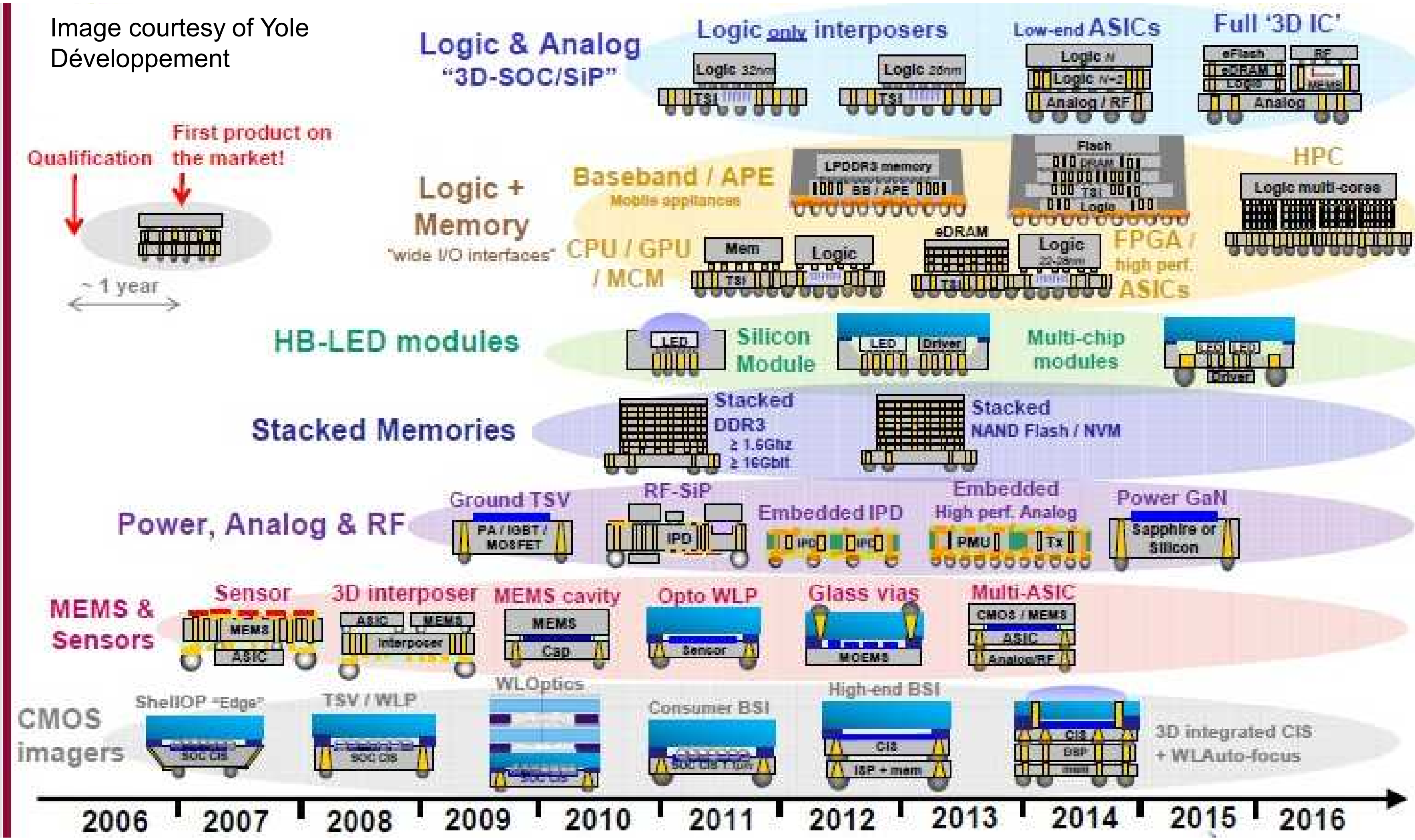


Image courtesy of Yole Développement

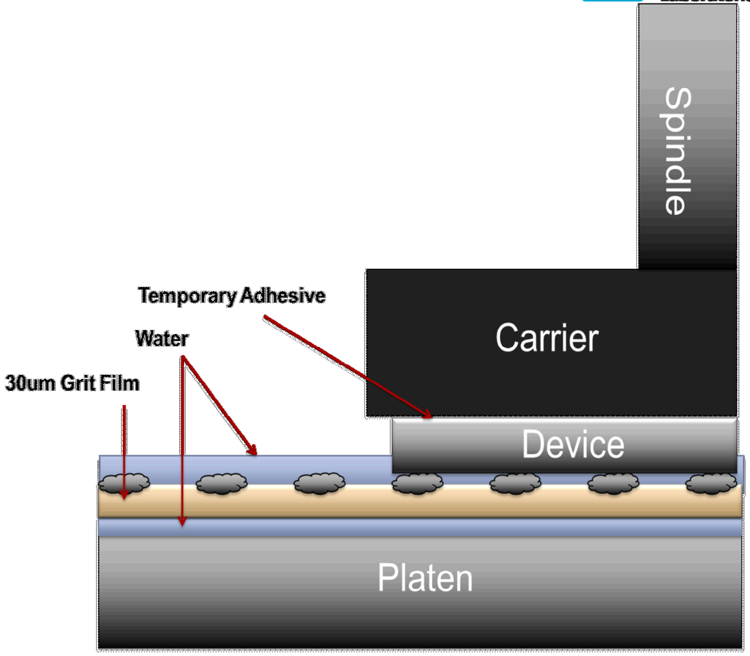
Advanced Packaging strategies

Image courtesy of Yole Développement



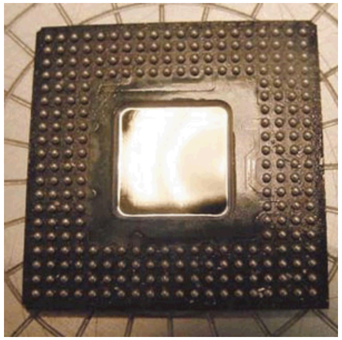
Device Thinning

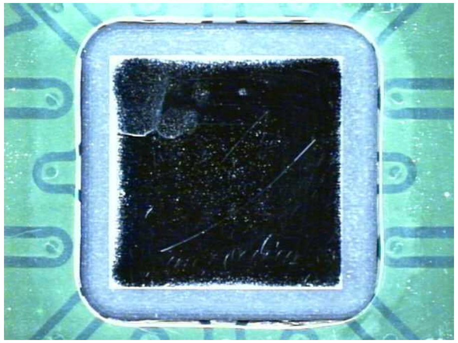
Devices are often thinned for failure analysis or manufacturing purposes on a CMP-like tool



Challenges to consistency include:

- Debris affects removal rate and selectivity
- Water-Film-Water stack
- Film Slippage





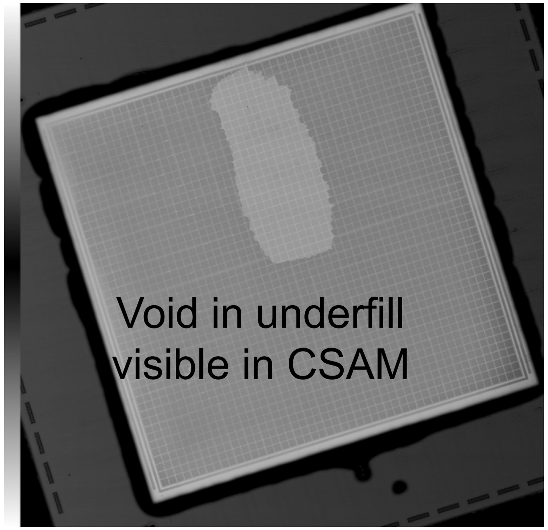


Image courtesy of Filmetrics

Source: Wu et. Al 2005

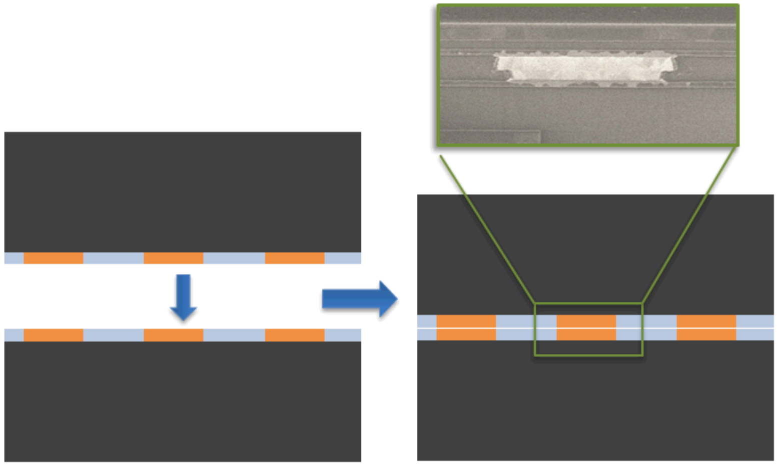
Wafer Bonding

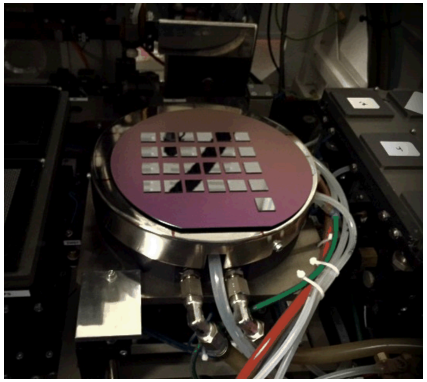
Two silicon wafers, or die can be bonded at low temperatures and form a hermatic seal

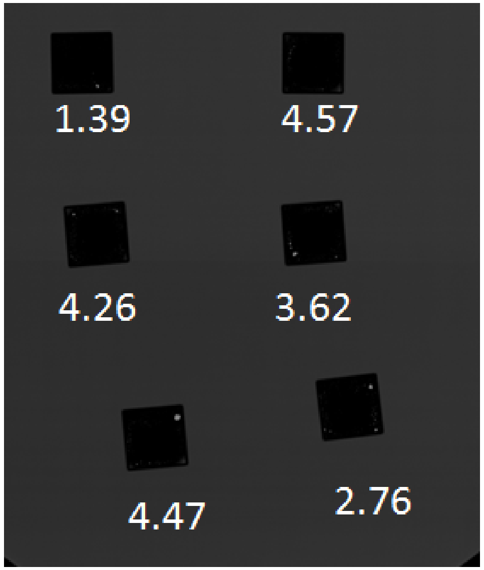
The bonded wafers/die can have functional patterned interconnect with the right materials and minimal dishing

Challenges:

- Contact points affect the bond quality
- Grain boundaries in metals
- Non Selective CMP







Percent Area uncontacted under each die

Conclusion

- Presented a high fidelity and accuracy CMP-focused contact mechanics approach capable of resolving wear and nano-topography
- IC fabrication is evolving to include extremely complex 3D structures
- Plenty of niche areas which could benefit from robust contact mechanics frameworks

Acknowledgements

- Prof. C. Fred Higgs III
- Prof. Shawn Blanton (ACTL)
- Prof. Shawn Litster (TPES)

- Sandia 1740 Group,
- MesaFab CMP Team
- HTS Team
- Dr. Sara Jensen
- Dr. Adam Jones

THANK YOU

Extra Slides

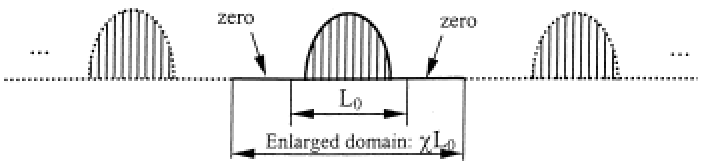
Contact Mechanics Implementation

- Direct matrix multiplication is too expensive.

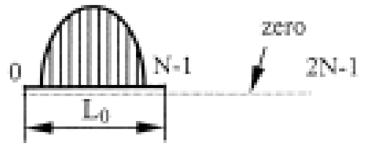
$$u = C \cdot p$$

- Implemented through a memory saving Fast Fourier Transform (FFT) approach.
- In order to meet periodic and infinite domain conditions of FFT, zero padding and domain wrap around are employed
  - Liu et al. 2000

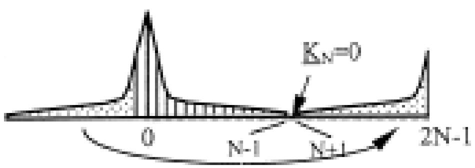
Extended Periodic Domain



Zero Padding



Wrap Around



Three Contact Model Comparison

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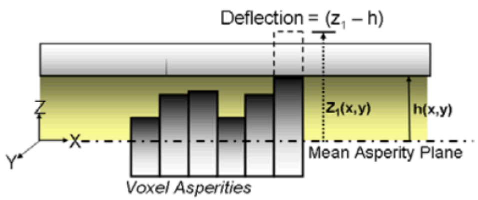
Winkler

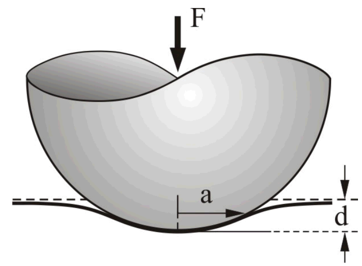


$$\Delta H_{x,y} = \frac{\sigma_{x,y}}{E} \frac{(1-2v)(1+v)}{(1-v)} t$$

$$\sigma_{x,y} = \frac{E_v}{t} \Delta H_{x,y}$$

$$\frac{E_v}{t} = 1.35 \frac{E^*}{a}$$

Hertzian



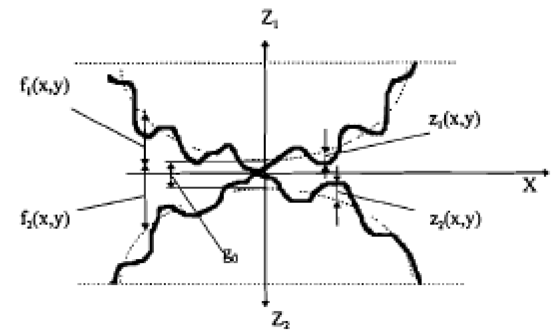
$$a = \left(\frac{3WR}{4E^*}\right)^{1/3}$$

$$\delta = \frac{a^2}{R}$$

$$\sigma = \sigma_0 \{1 - (\frac{r}{a})^2\}^{.5}$$

$$\sigma_0 = \frac{3W}{2\pi a^2}$$

Elastic halfspace with FFT, and constrained CGM (Hu et. al 1999)



$$Minimize\ F(\sigma) = \hat{g}\sigma + \frac{1}{2}\sigma C \sigma$$

$$subject\ to: \sigma \geq 0$$

KKT condition:

$$\sigma_{x,y} = 0 \quad \frac{\partial F}{\partial \sigma} \geq 0$$

$$\sigma_{x,y} > 0 \quad \frac{\partial F}{\partial \sigma} = 0$$

=> $\frac{\partial F}{\partial \sigma} = \bar{g} + C\sigma = g$

Non-Linear CGM

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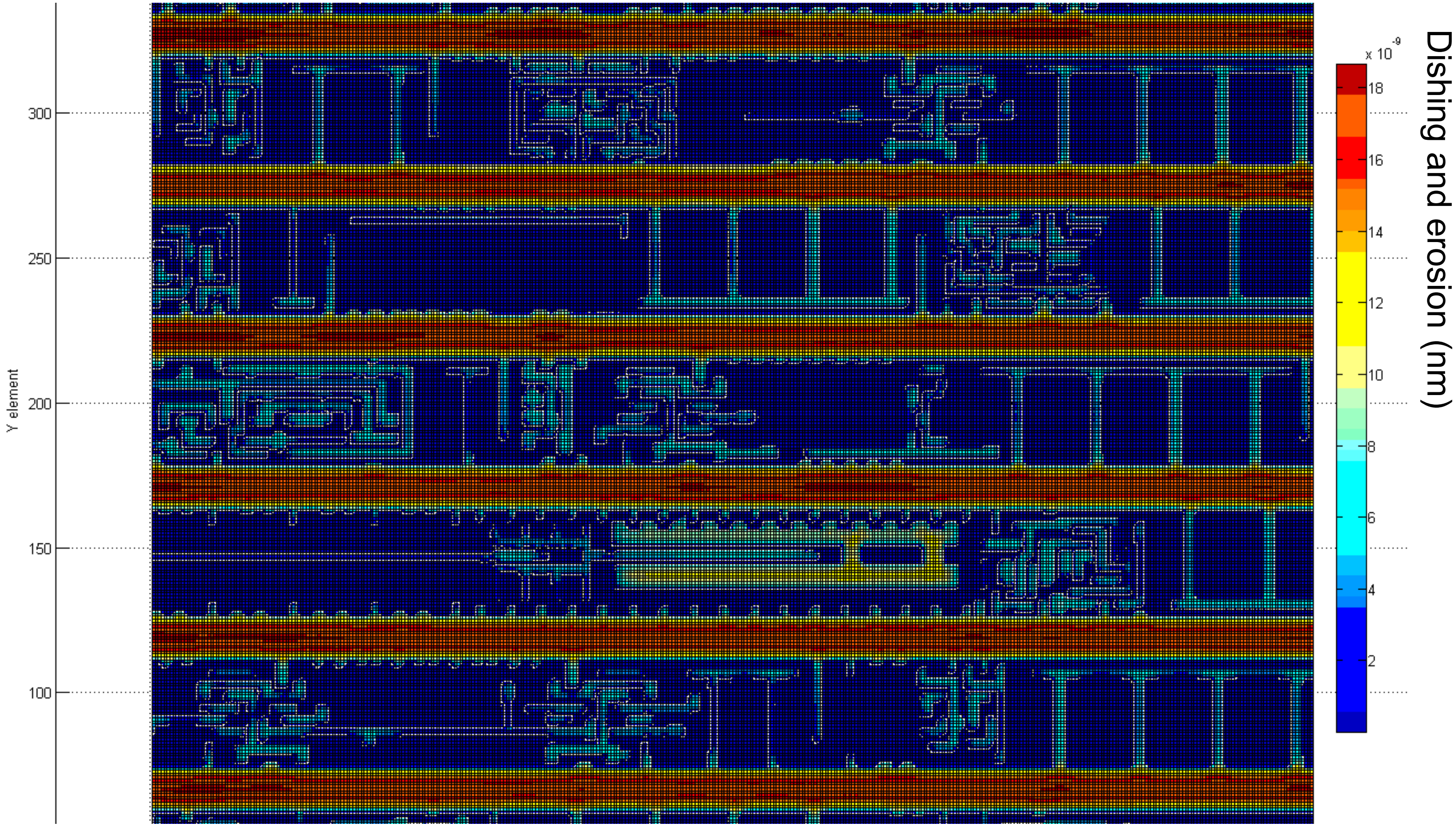
$i \Leftarrow 0$
$k \Leftarrow 0$
$r \Leftarrow -f'(x)$
$d \Leftarrow r$
$\delta_{new} \Leftarrow r^T r$
$\delta_0 \Leftarrow \delta_{new}$
While $i < i_{max}$ and $\delta_{new} > \varepsilon^2 \delta_0$ do
    $j \Leftarrow 0$
    $\delta_d \Leftarrow d^T d$
    Do
        $\alpha \Leftarrow -\frac{[f'(x)]^T d}{d^T f''(x) d}$
        $x \Leftarrow x + \alpha d$
        $j \Leftarrow j + 1$
    while $j < j_{max}$ and $\alpha^2 \delta_d > \epsilon^2$
    $r \Leftarrow -f'(x)$
    $\delta_{old} \Leftarrow \delta_{new}$
    $\delta_{new} \Leftarrow r^T r$
    $\beta \Leftarrow \frac{\delta_{new}}{\delta_{old}}$
    $d \Leftarrow r + \beta d$
    $k \Leftarrow k + 1$
    If $k = n$ or $r^T d \leq 0$
        $d \Leftarrow r$
        $k \Leftarrow 0$
    $i \Leftarrow i + 1$

CMP on Post litho M1 (10s simulation)



Process-Aware CMP-Focused DFM framework

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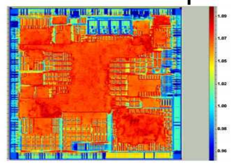
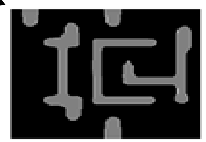
Current DFM (segregated)

CMP Hotmap





Litho model

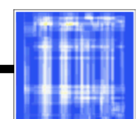
Rule Check

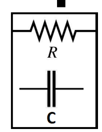
Final Design To Fab

Process-Aware CMP Focused DFM

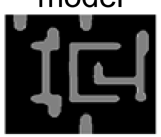
RC Info for timing

Hot Spot Info

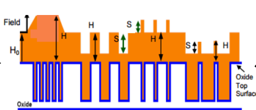


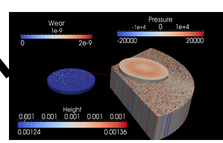


Litho model

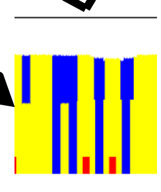


Depo model





CMP model

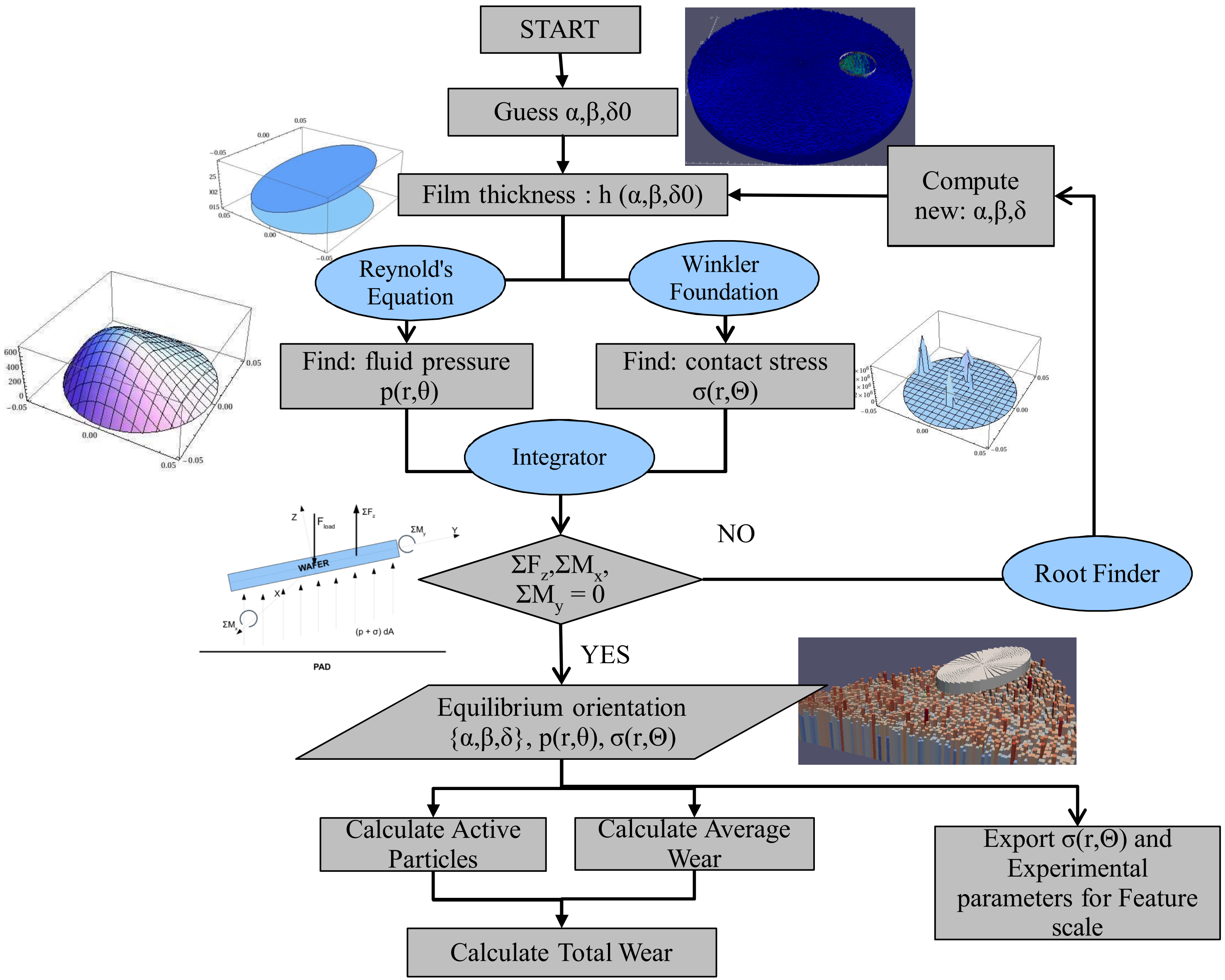


3D Virtual Chip

Final Design To Fab

Useful to:
Chip Design, Manufacturing & Test Engineers

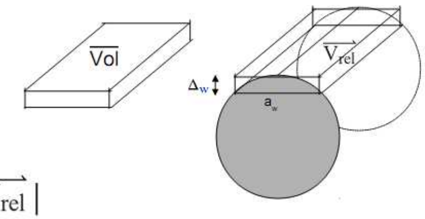
Wafer-Scale Topography Simulation Flowchart (PAML-lite)



Feature-Scale Wear Modeling of CMP

- Soft pad model given by Luo and Dornfeld (2003) implemented.
- Wear depends on:
  - Number of active particles (Particles participating in the wear event)
  - Average wear (Material removed by a average active particle
  - Local Contact Stress
  - Local Material Hardness

Average Wear per Particle



- Abrasive wear,

$$\overline{\mathrm{Vol}} = \Delta_w \, a_w \, |\overrightarrow{V_{rel}}|$$

$$\Delta_w = \sqrt{\frac{2F}{\pi H_w}}$$

$$|\overrightarrow{V_{rel}}| = |\overrightarrow{V_p} - \overrightarrow{V_w}|$$

$$a_w = \frac{2F}{\pi \, x_{avg-a} H_w}$$

$$F = \sigma * \pi x^2$$

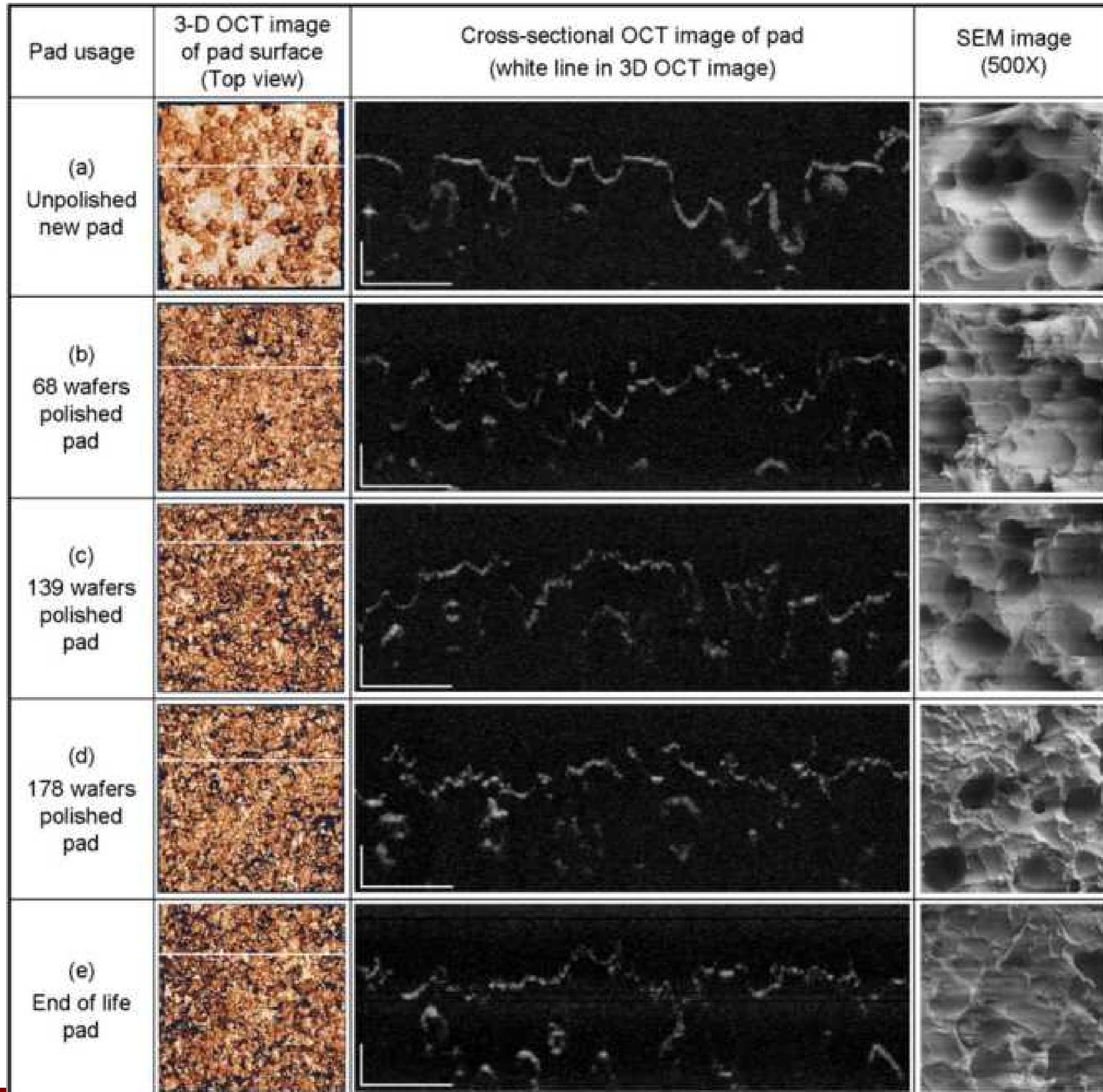
Reduces to the following equation

$$\overline{\mathrm{Vol}} = \frac{1}{2\sqrt{2}} x_{avg-a}^{2} \left(\frac{\sigma}{H_w}\right)^{3/2} V_{rel}$$

MRR Equation at Feature Scale:

$$\frac{dh_{vox}}{dt} = \frac{1}{2\sqrt{2}} x_{avg-a}^{2} \left(\frac{\sigma(x,y)}{H_w(x,y)}\right)^{3/2} V_{rel}(x,y) \frac{Nact(x,y)}{A_{vox}}$$

CMP Pad Magnification



Modeling Parameters

Pad Properties	
Model Simulated	IC 1000
Hardness	5.0 MPa
Elastic Modulus	12 MPa
Asperity Distribution	Random Gaussian
Pad Thickness	1.3 mm
Roughness	10 µm
Poisson's Ratio	0.4
Wafer Properties	
Hardness	2.0 Gpa (SiO2), .38 Gpa (Cu)
Elastic Modulus	110 GPa
Poisson's Ratio	0.16
Slurry Properties	
Particle Material	Silica
Particle Density	2000 kg / m3
Particle Size Distribution	Gaussian
Mean Particle Radius	150 nm
Standard Deviation of Particle Radius	15 nm
Fluid Density	1000 kg / m3
Fluid Viscosity	0.001 Pa - s
Concentration	2% (wt/wt)

Operating Parameters	
Load	4psi
Wafer RPM	50
Pad RPM	90
Layout	3x5 SRAM Array
Layout Size	1.5 μm^2

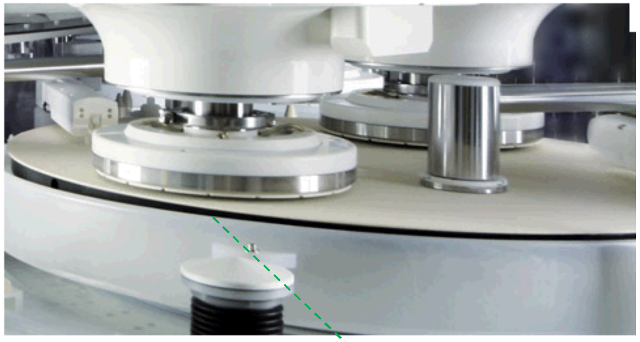
CMP Modeling: Literature Across the Scales

Select CMP Models

Wafer Scale	Die Scale	Feature Scale	Multi Scale
Sundararajan et al. (1999) Zhao & Chang (2001) Luo & Dornfeld (2001) Shan et al. (2001) Fu et al. (2001) Higgs et al. (2005) Jin et al. (2005) Beschorner et al. (2009) Srivastava & Higgs (2013) Sierra-Suarez et al. (2013)	Stine et al. (1997) Tugbawa et al. (1999) Ouyang et al. (2000) Ouma et al. (2002) Luo & Dornfeld(2003) Xie et al. (2003)	Runnels et al (1994) Chekina et al. (2000) Zhao et al. (2003) Vlassak (2004) Saxena et al. (2004) Terrell & Higgs(2009) Comes et al. (2010)	Seok et al. (2003) Tripathi et al. (2007) Wang et al. (2007) Kasai & Bushan (2008) Sierra-Suarez et al. (2013)

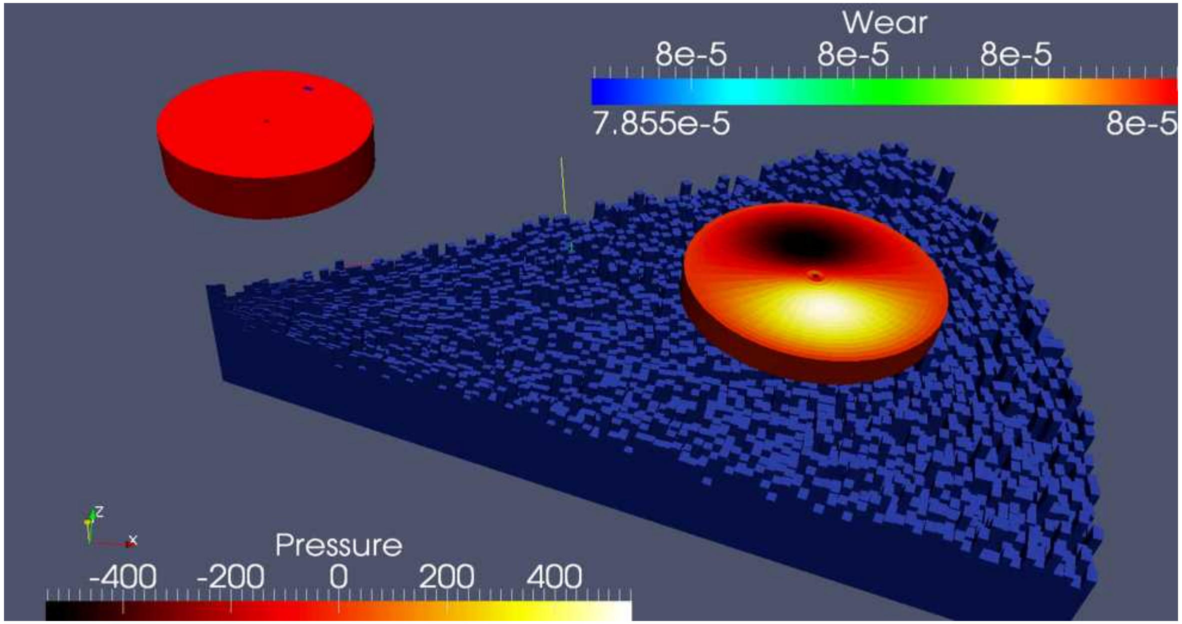
Wafer-Scale Model: PAML-lite

Application: CMP



Virtual CMP

(Multiphysics fluid structure interaction & Wear)



- Wafer-scale mixed lubrication model from Srivastava & Higgs (2013)
- The evolution of wear, fluid pressure, and contact stress is monitored

CMP Simulation: From Wafer to Layout Features