CGS Interferometry as a Full-Field Wafer Inspection and Film Stress Measurement Tool:

Measurements in the Presence of Film thickness and Stress Discontinuities

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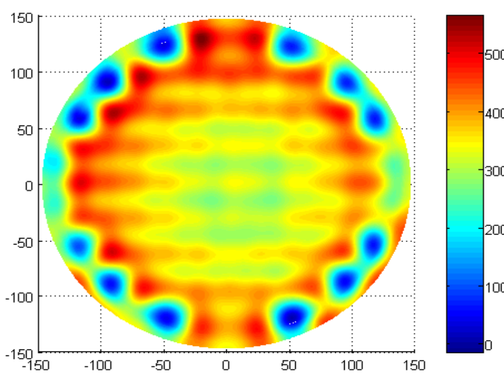
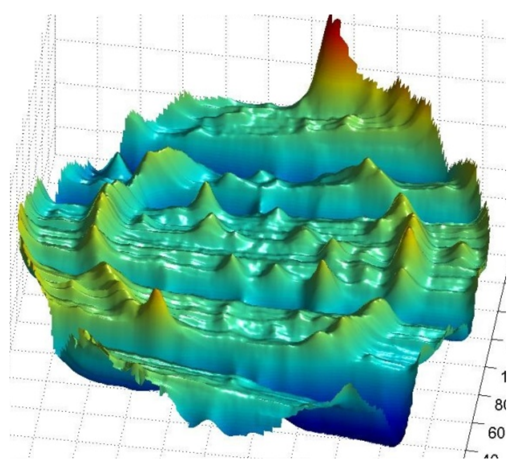
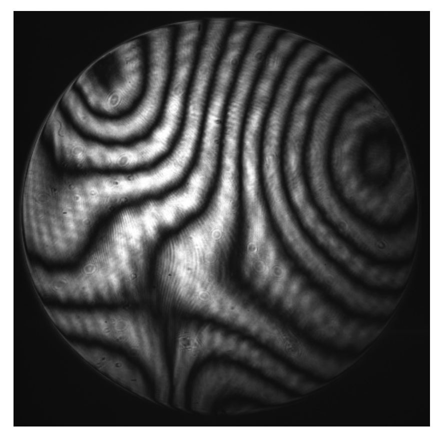
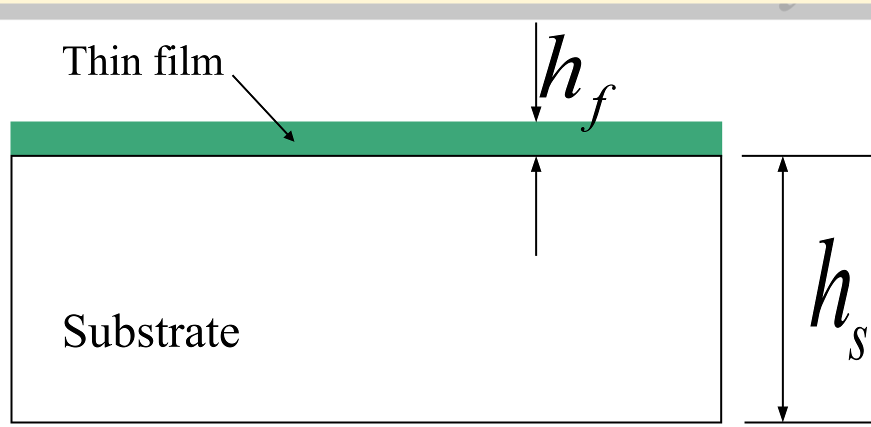






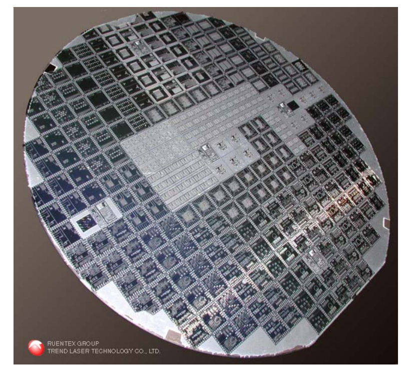
Thin-Film/Substrate Systems

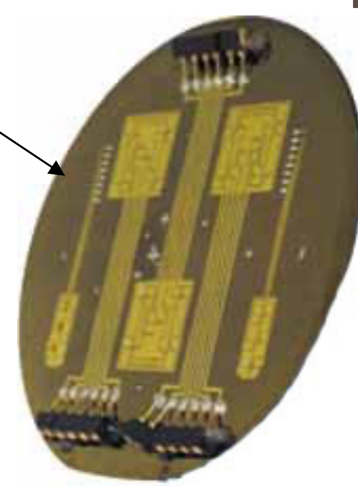


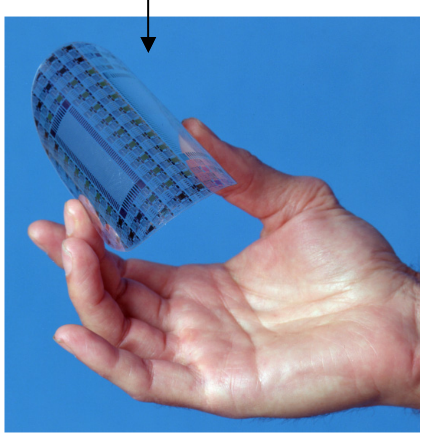
$$h_f \ll h_s$$

Applications:

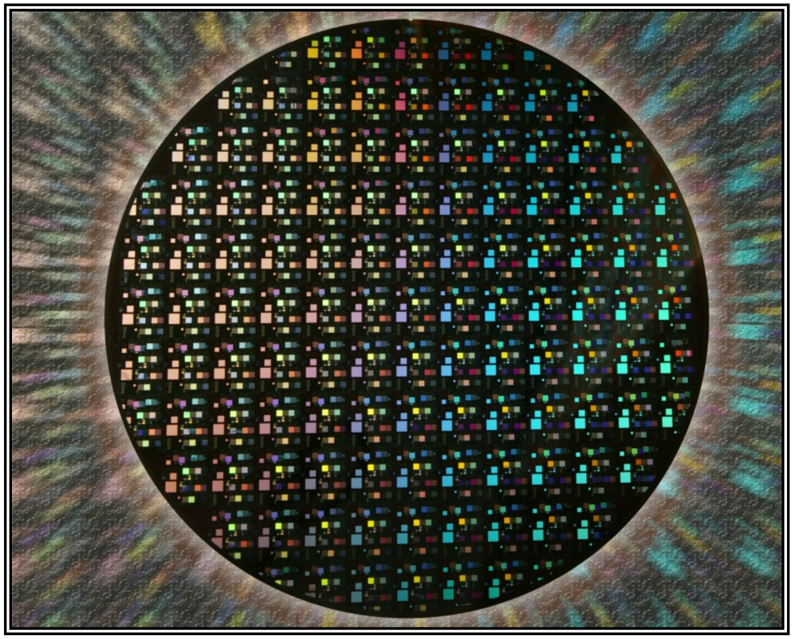
- *Integrated electronic, optical and optoelectronic circuits.*
- *MEMS deposited on wafers.*
- *Flat panel display systems.*







Motivation and Outline



- Materials, film thicknesses, misfit strain, stresses and curvatures across realistic wafers are non-uniform.
- Non-uniformities are often related to non-uniform processing conditions (e.g. due to deposition or thermal annealing non-uniformities)
- Existing metrology instruments do not provide a full-field measurement capacity and get confused by patterning.

⇒ A full-field curvature measurement technique is needed to record all three independent curvature component maps in large 300mm wafers, especially in the presence of non-uniformities

⇒ Advanced analysis methods which account for non-uniformities are needed in order to infer film stress from the full field curvature measurements

Stress in Thin-Film/Substrate Systems

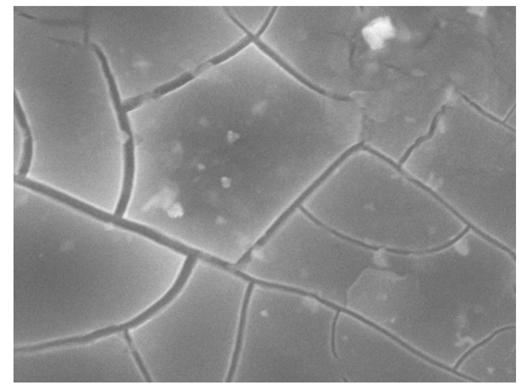
The fabrication of the film/substrate system involves many processing steps

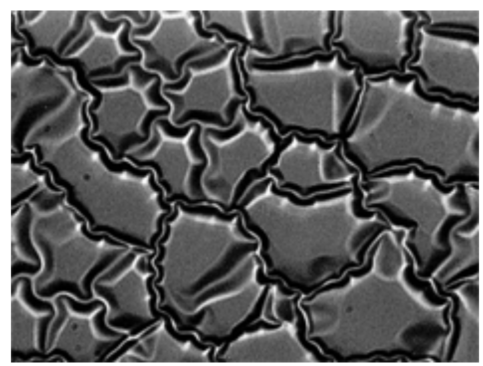
- ***Film deposition***
- ***Thermal anneal,***
- ***Natural or forced cooling***
- ***CMP, Etch steps***

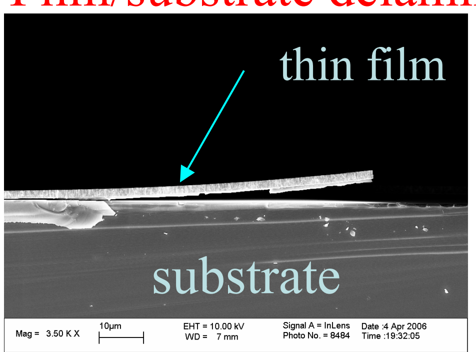
RESULT: Film thickness and misfit strain variations .

All these steps cause stresses in the film/substrate system, and may lead to structure failure.

- Stress-induced film cracking.
- Film buckling.
- Film/substrate delamination.

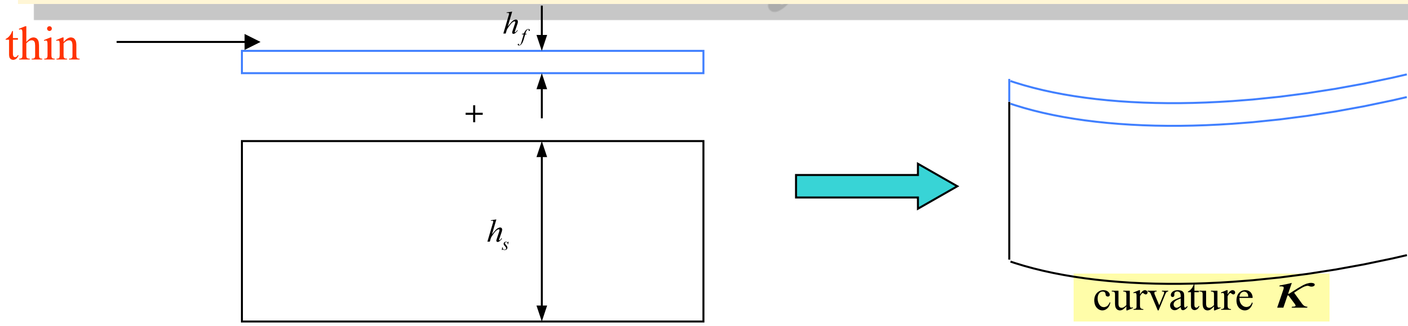






Need an accurate method to determine thin film stress

Stoney Formula



Stoney (1909) developed a simple method to infer film stress from system curvatures

Assumptions:

1) ***Uniform h_f , h_s and misfit strain (Thermal, epitaxial, etc.)***
2) ***Small strain and rotation***
3) ***Linearly elastic and isotropic film and substrate.***

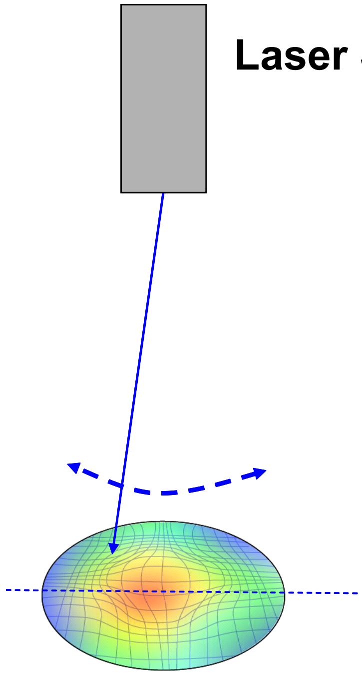
THIS IMPLIES:

1) ***Equi-biaxial film stress*** $\sigma_{xx}^{(f)} = \sigma_{yy}^{(f)} = \sigma$, ***others = 0***
2) ***Equi-biaxial system curvatures*** $\kappa_{xx} = \kappa_{yy} = \kappa, \kappa_{xy} = 0$
3) ***Uniform film stress and system curvature***

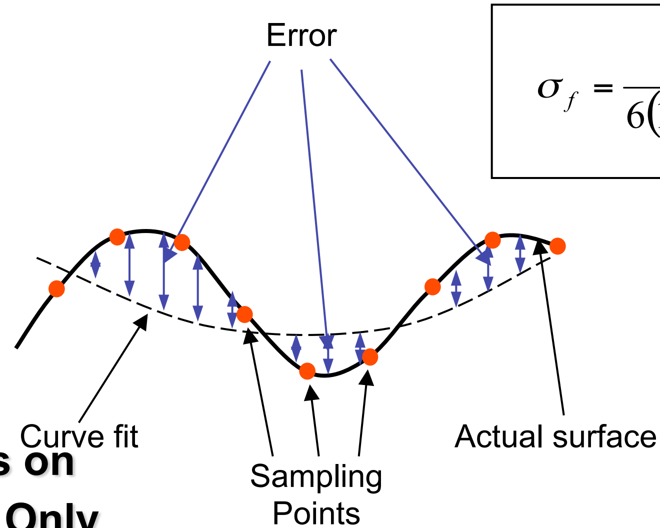
$$\sigma^{(f)} = \frac{E_s h_s^2 \kappa}{6 h_f (1 - \nu_s)}$$

System curvature $\Rightarrow$ film stress

Assumptions and limitations of classical Laser Scanning method
Freund & Suresh ,Thin Film materials 2003



Blanket (uniform) Films on Unpatterned substrates Only



Assume spatial uniformity and also:

$K_{11} = K_{22}$

$\sigma_{11} = \sigma_{22}$

$$\sigma_f = \frac{E_s h_s^2}{6(1-\nu_s)h_f}\kappa$$

Single, Average, In-plane, Stress Value

– Measurement misses curvature non-uniformities

– Accuracy is restricted by" Stoney's "Approximations of misfit strain, stress, curvature and thickness spatial uniformity

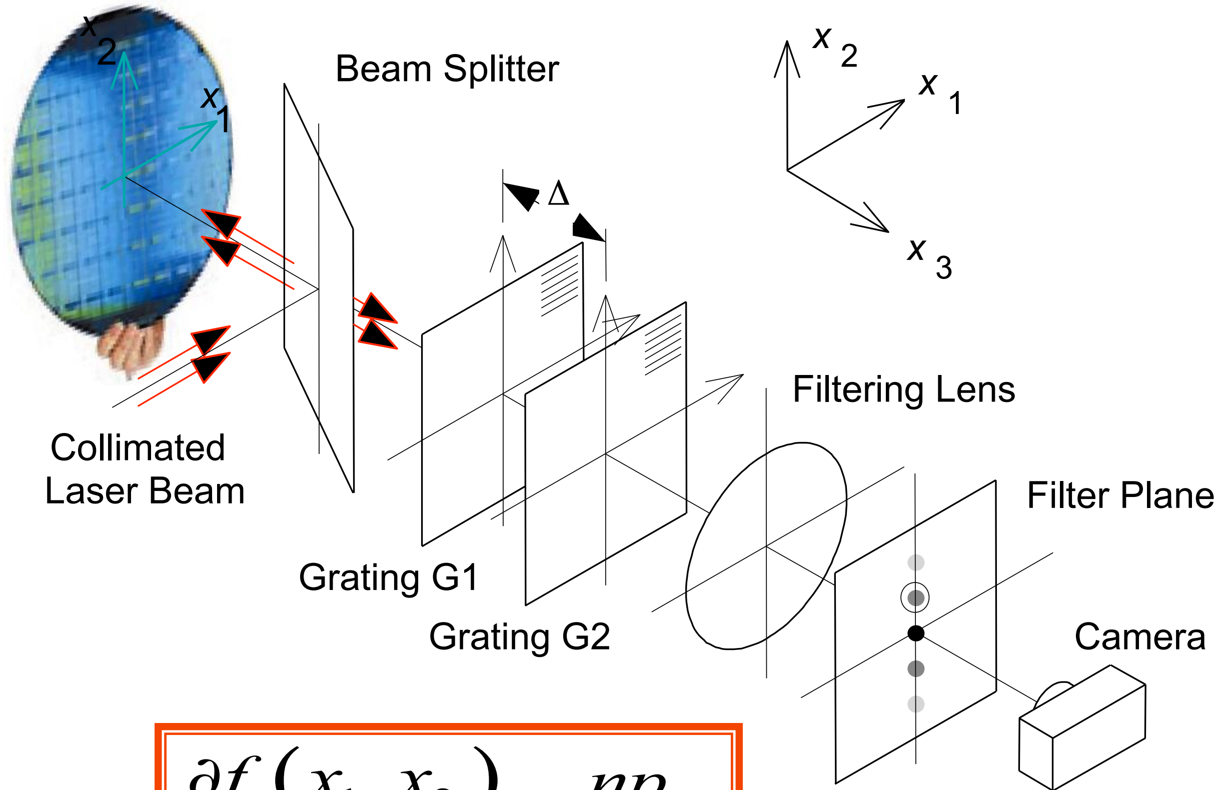
– Is confused by abrupt film thickness changes and patterns

Schematic of CGS Setup

* U.S. Patent Number: 6,031,611 (Rosakis *et. al.,Solid Thin Films* 2000)

CGS Instrument Schematic*

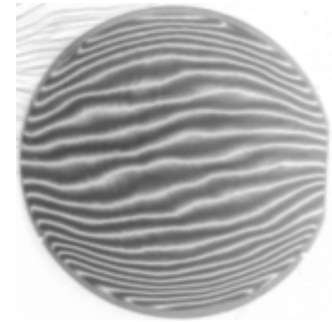
Specimen surface, $x_3 = f(x_1, x_2)$



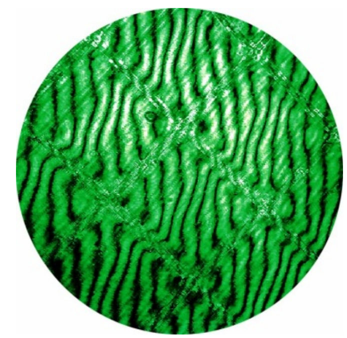
$$\Rightarrow \boxed{\frac{\partial f(x_1, x_2)}{\partial x_2} = \frac{np}{2\Delta}}$$

(no λ)

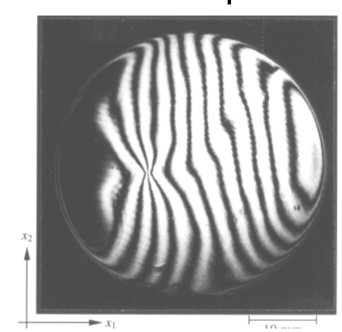
Polished Wafer



Patterned Wafer

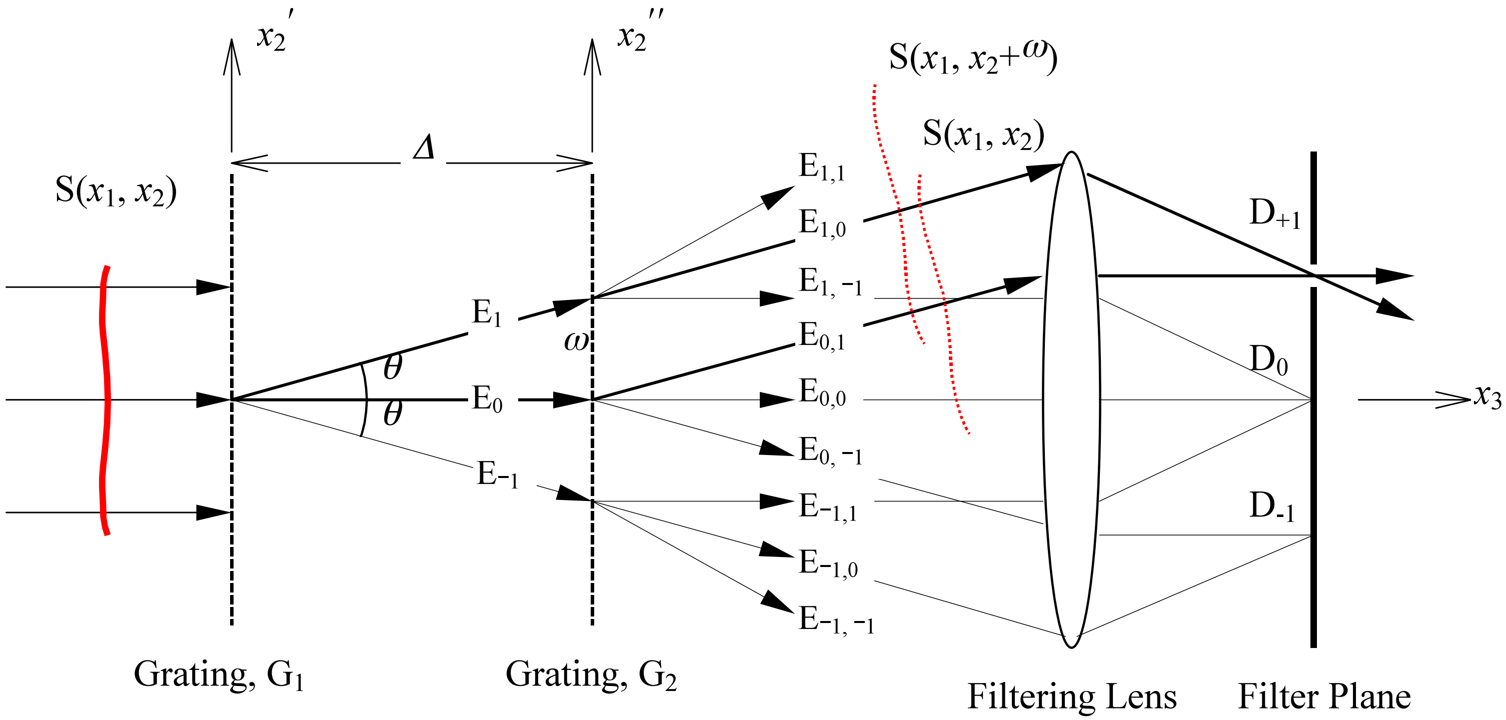


Wafer with a problem



vibration insensitive

The Shearing Action of Gratings for CGS (Optical Differentiation Process)



integer

Interference: $S(x_1, x_2+\omega) - S(x_1, x_2) = n\lambda$

Identical wavefronts shifted in space along x_2.

$n = 1, 2, 3$...for destructive interference (black fringe centers)

$n = 1 + \frac{1}{2},\ 2 + \frac{1}{2}$...for constructive interference

The Governing Relations of CGS

wavelength of light

$$\frac{S(x_1, x_2 + \omega) - S(x_1, x_2)}{\omega} = \frac{n\lambda}{\omega} = \frac{np\theta}{\Delta\theta} = \frac{np}{\Delta}$$

take the limit as $\Delta \to 0$ *or* $\omega \to 0$.

$$\lim_{\omega \to 0} \left[\frac{S(x_1, x_2 + \omega) - S(x_1, x_2)}{\omega} \right] = \frac{\partial S(x_1, x_2)}{\partial x_2} = \frac{np}{\Delta}$$

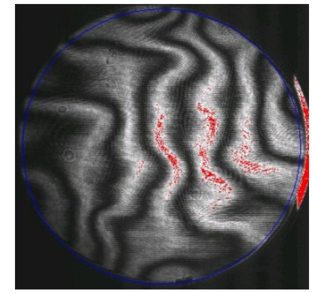
$$S(x_1, x_2) = S_0 + 2f(x_1, x_2).$$

$$\Rightarrow \frac{\partial S(x_1, x_2)}{\partial x_2} = \frac{np}{\Delta} = \frac{\partial (2f(x_1, x_2))}{\partial x_2}$$

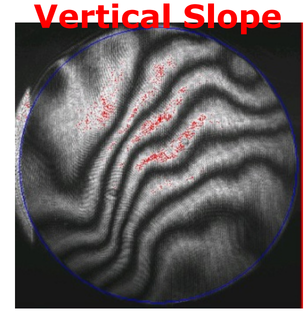
$$\Rightarrow \frac{\partial f(x_1, x_2)}{\partial x_2} = \frac{np}{2\Delta}$$

wafer slope map in x_2 direction.
R.H.S independent of wavelength.

(no λ)

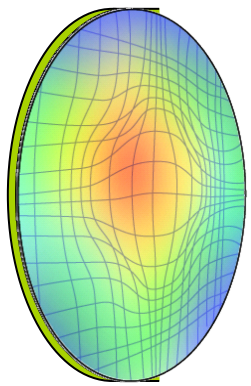


Vertical Slope

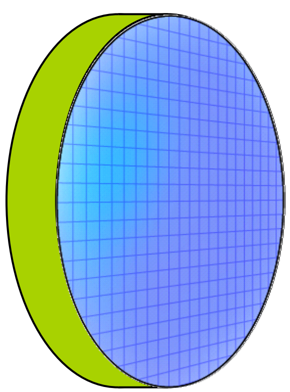


Horizontal Slope

Traditional Interferometers



Sample



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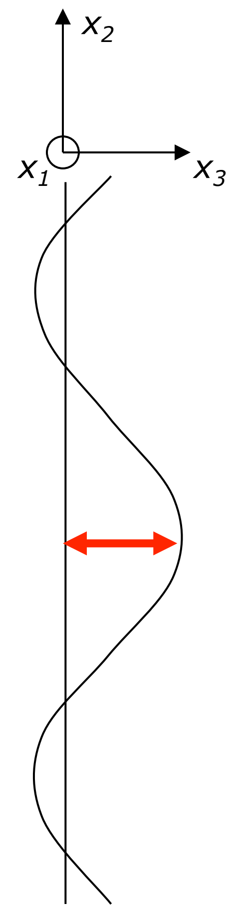
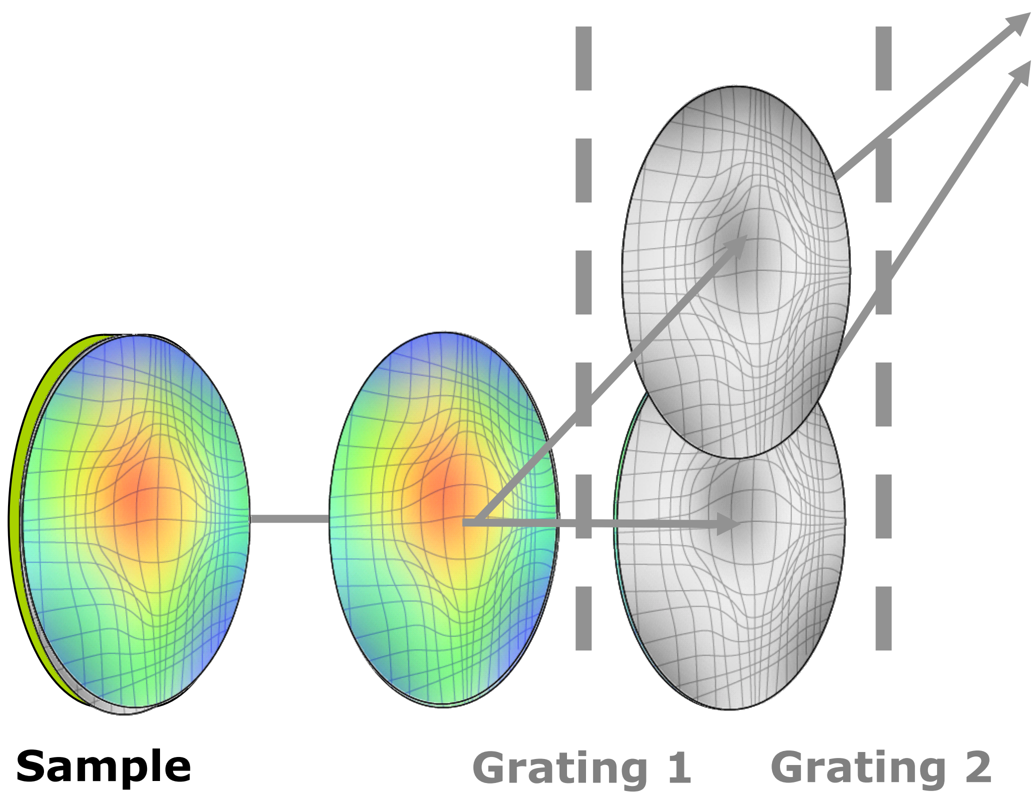


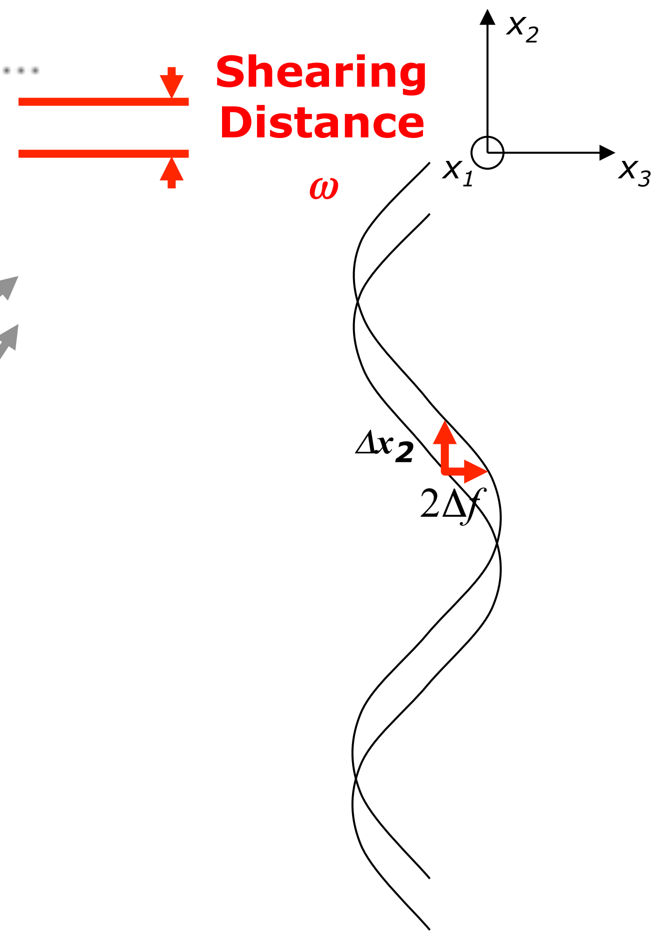
$$f = \frac{n\lambda}{2}$$

Advantage of CGS Interferometer

A Self Referencing Approach

$$\kappa_{\alpha\beta}(x_1,x_2) \approx \frac{\partial^2 f(x_1,x_2)}{\partial x_\alpha \partial x_\beta} \approx \frac{p}{2\Delta}\left(\frac{\partial n^{(\alpha)}(x_1,x_2)}{\partial x_\beta}\right), \quad n^{(\alpha)} = 0, \pm 1, \pm 2, \ldots$$





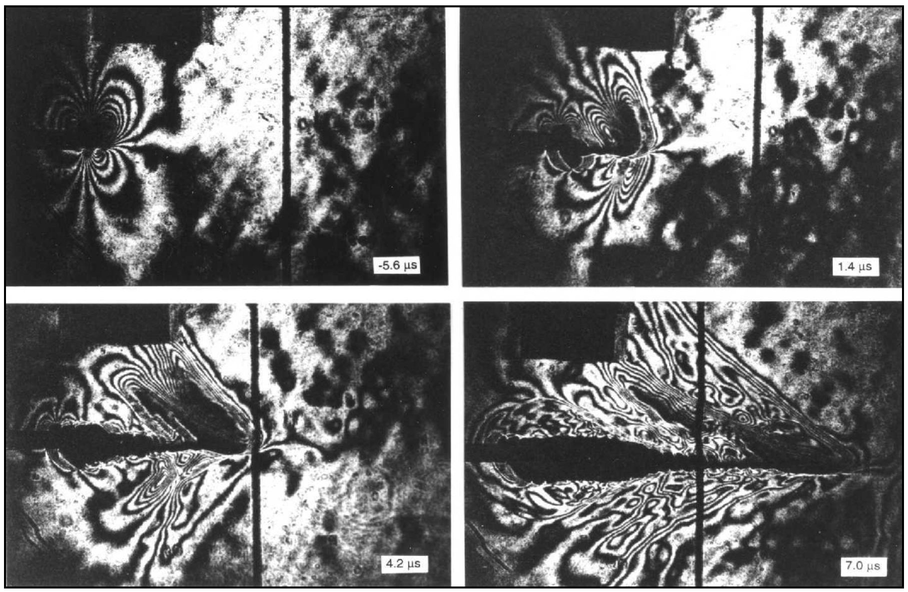
vibration insensitive

$$\frac{\partial f}{\partial x_2} = \frac{n\lambda}{2\omega} = \frac{np}{2\Delta}$$

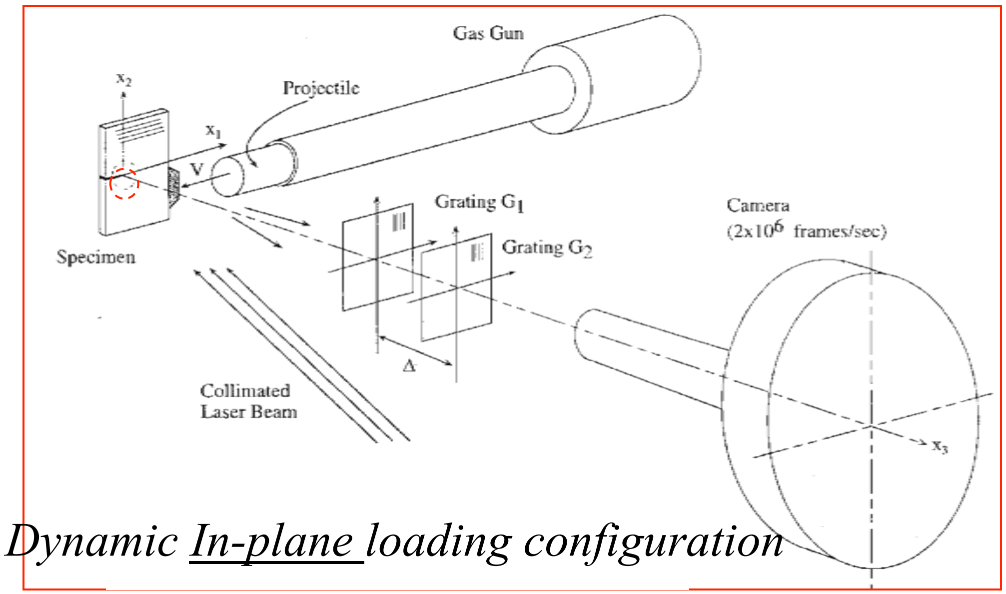
CGS Applied to Dynamic Testing

LEGACY CGS BASED IMPACT STUDIES

- ***Investigation of Dynamic Crack Tip Fields in Engineering Materials***
- ***Impact of Bi-materials & Composites***
- ***Dynamic Shear Band Formation***
- ***Dynamic Rupture of Frictional Interfaces***



•Coker, D. and Rosakis, A.J., "Experimental Observations of Intersonic Crack Growth in Axisymmetrically Loaded Unidirectional Composite Plates," Philosophical Magazine A, 81, 571-595, 2001.

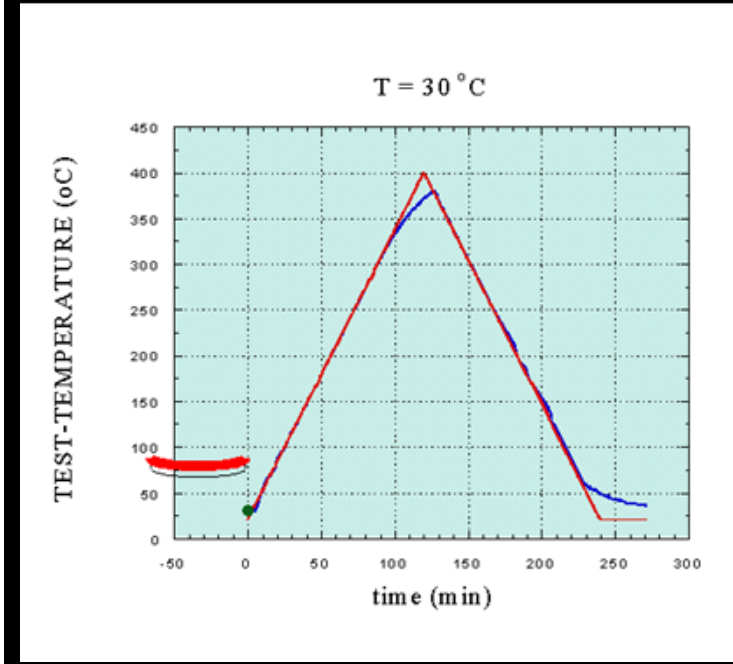


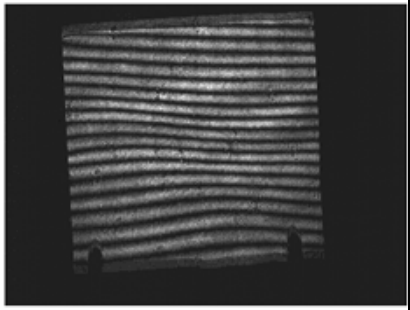
Dynamic In-plane loading configuration

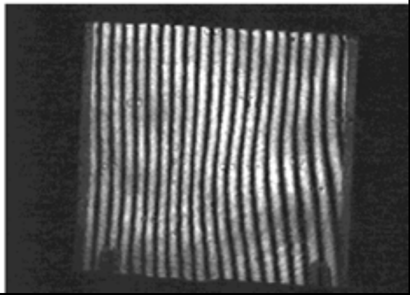
Reflection mode CGS: out-of-plane deformation field gradients

Transmission mode CGS: gradient of sum of principal (in-plane) stresses

CGS patterns during temperature cycling (in-situ measurement)

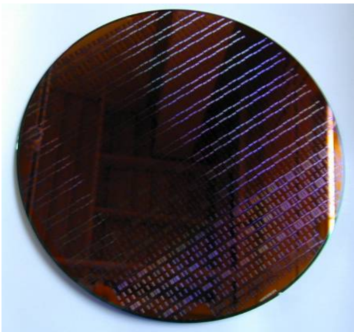




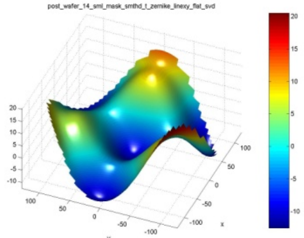


Click here to see movie

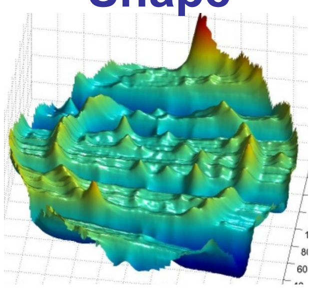
Micro Device Reliability Facility at GALCIT

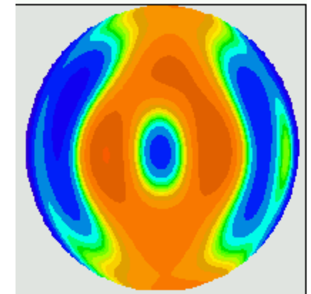


300 mm Wafer

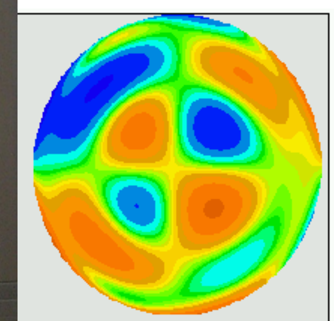


Shape



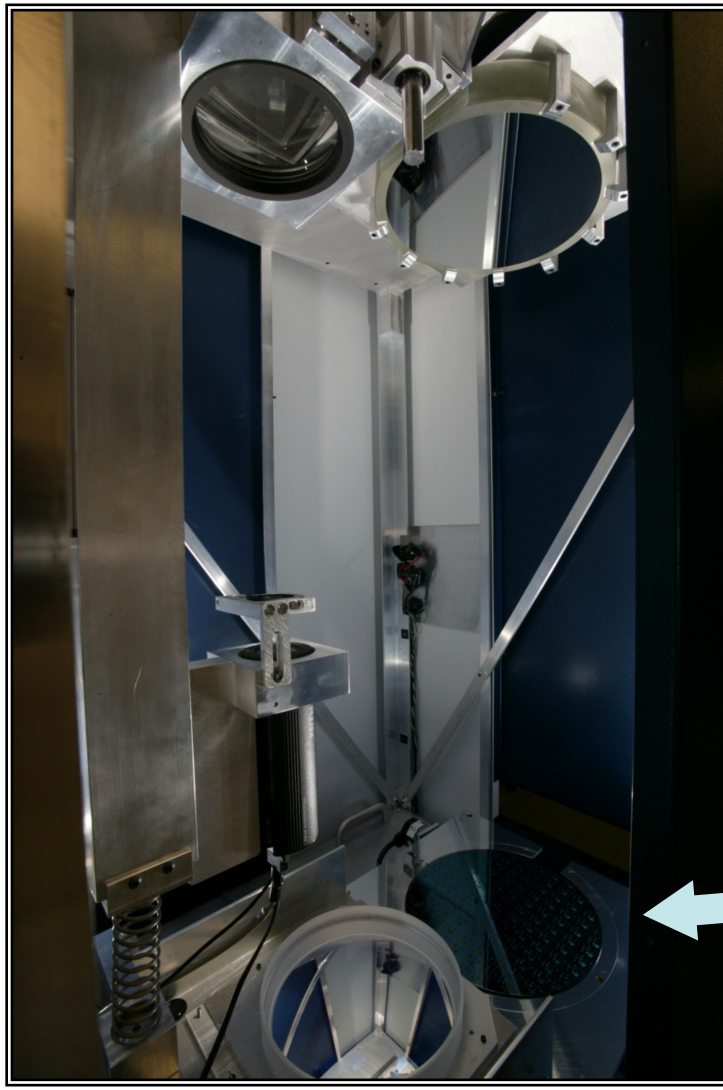


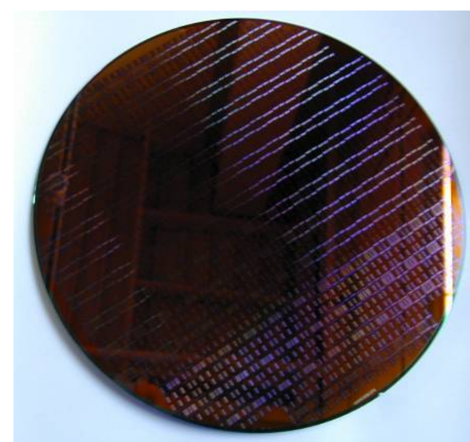
X Curvature, κ_{11}



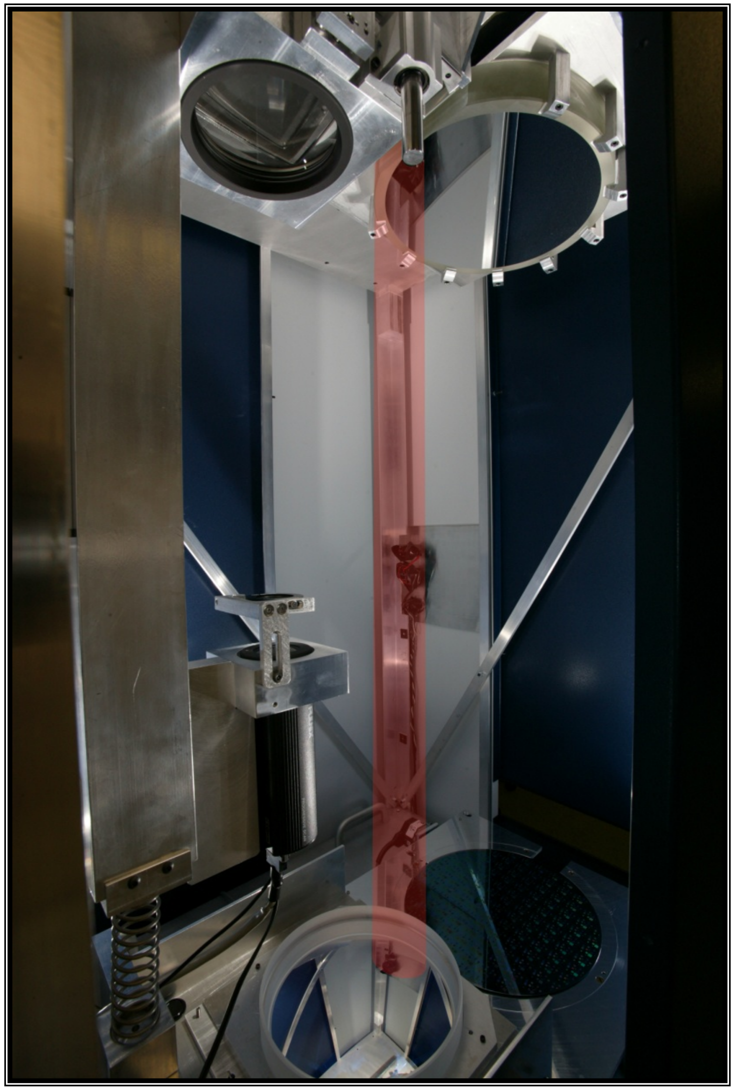
Twist Curvature, κ_{12}

Measuring 300mm wafers with CGS300

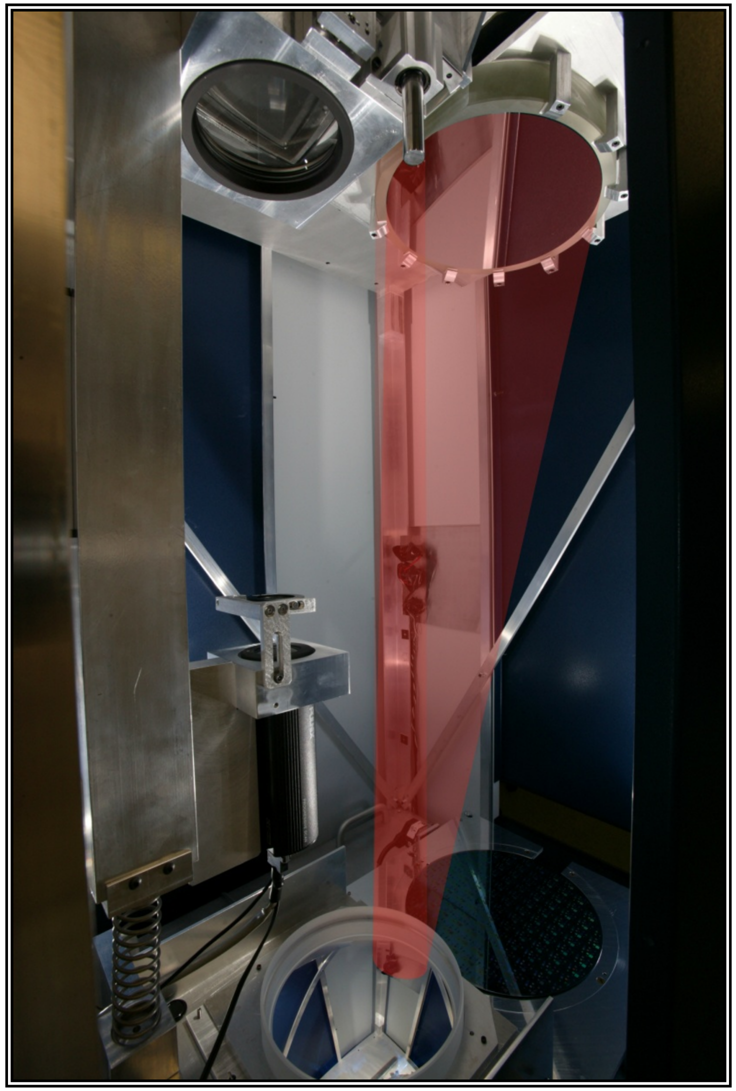




Measuring 300mm wafers with CGS300



Measuring 300mm wafers with CGS300

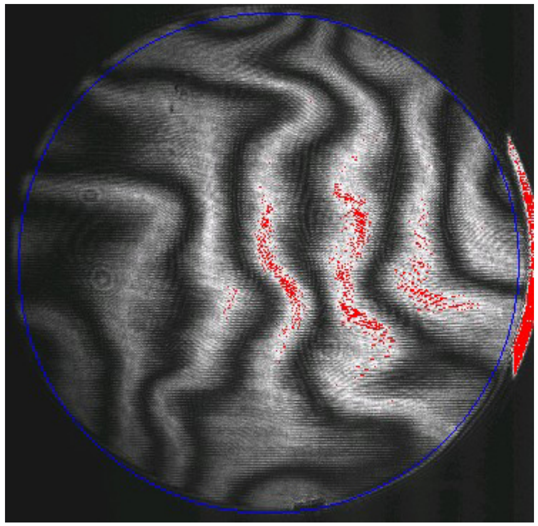


Measuring 300mm wafers with CGS300

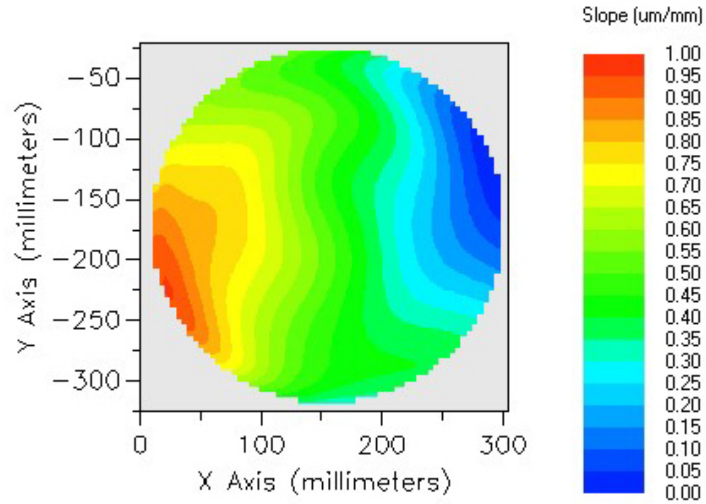
Measuring 300mm wafers with CGS300

Examples of CGS Data
Uniform film on a 300 mm Wafer: Interferograms & Slopes

$$\frac{\partial f}{\partial x_2}$$

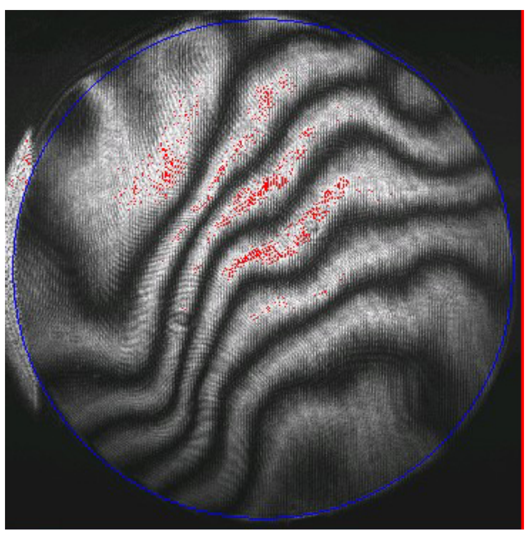


Interferogram: Vertical Slope

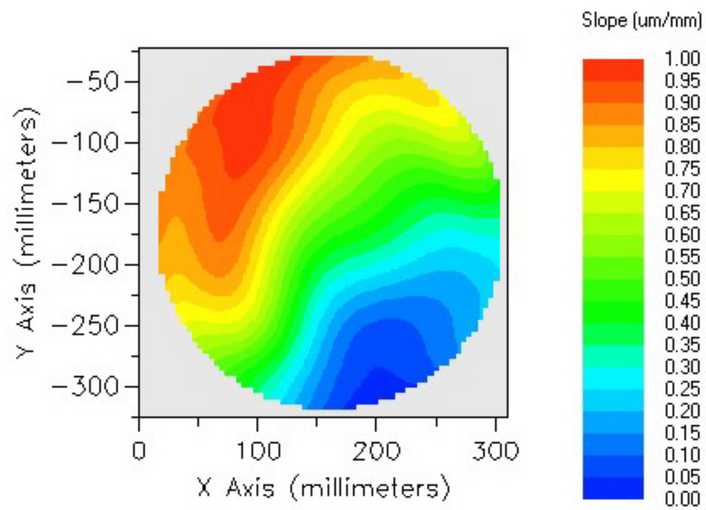


Vertical Slope Map

$$\frac{\partial f}{\partial x_1}$$



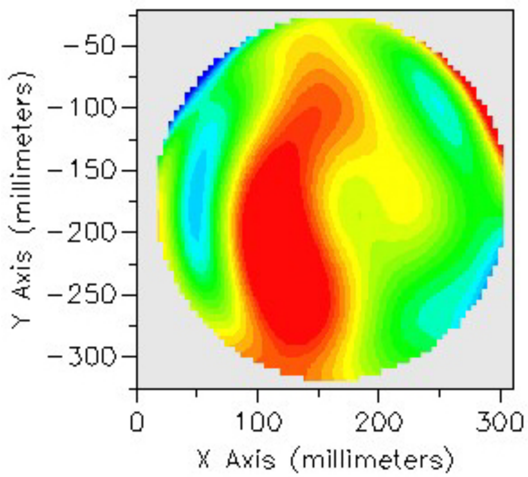
Interferogram: Horizontal Slope



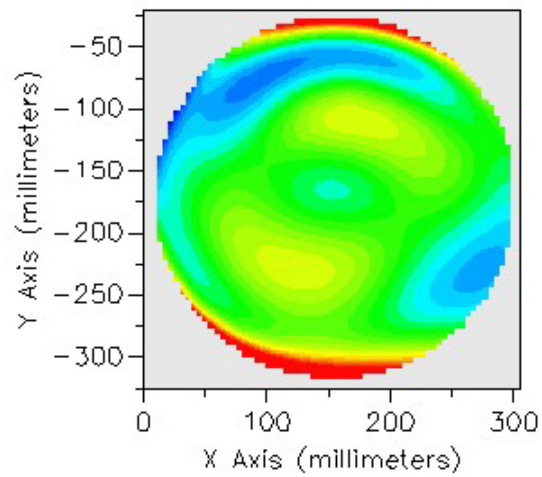
Horizontal Slope Map

Examples of CGS Data
Uniform film on a 300 mm Wafer: Curvature Change Maps

$$\kappa_{11} = \frac{\partial^2 f}{\partial x_1^2}$$



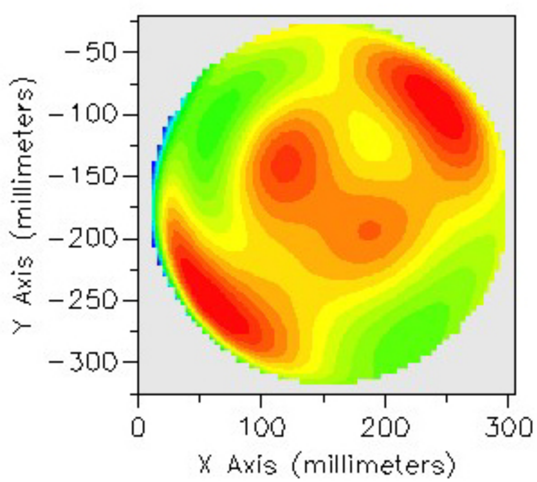
Horizontal Curvature



Vertical Curvature

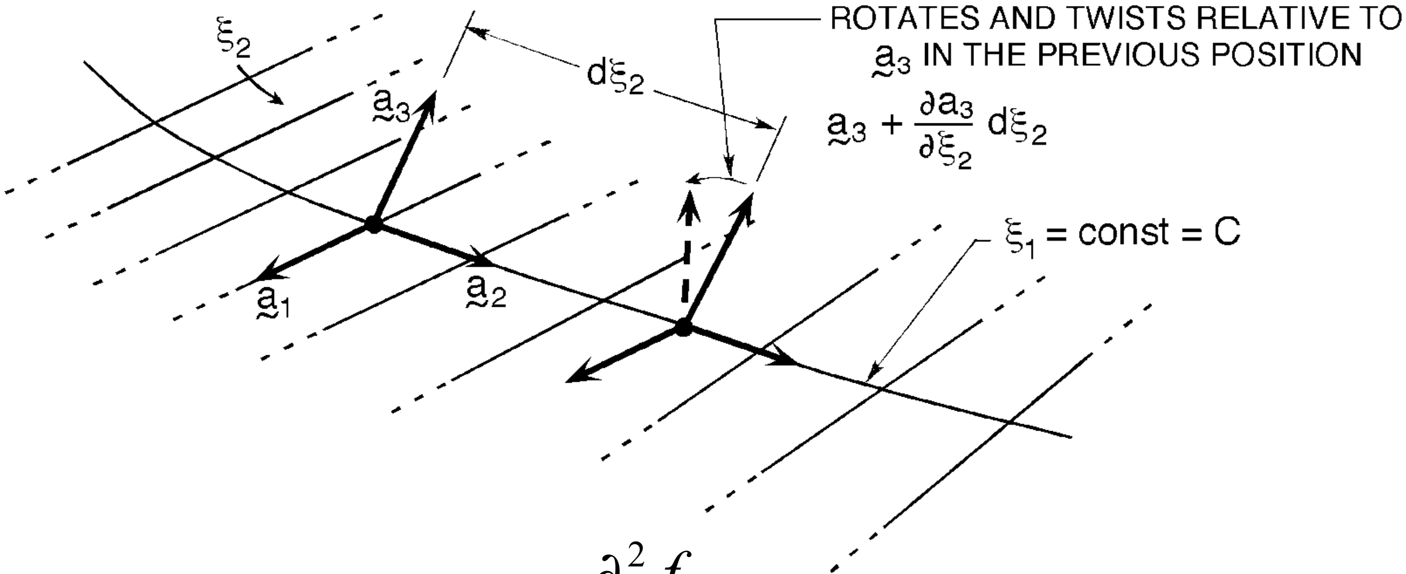
$$\kappa_{22} = \frac{\partial^2 f}{\partial x_2^2}$$

$$\kappa_{12} = \frac{\partial^2 f}{\partial x_1^2 \partial x_2}$$



(/m)	1/ (m)
0.0050	200
0.0045	222
0.0040	250
0.0035	286
0.0030	333
0.0025	400
0.0020	500
0.0015	667
0.0010	1000
0.0005	2000
0.0000	0
-0.0005	-2000
-0.0010	-1000
-0.0015	-667
-0.0020	-500
-0.0025	-400
-0.0030	-333
-0.0035	-286
-0.0040	-250
-0.0045	-222
-0.0050	-200

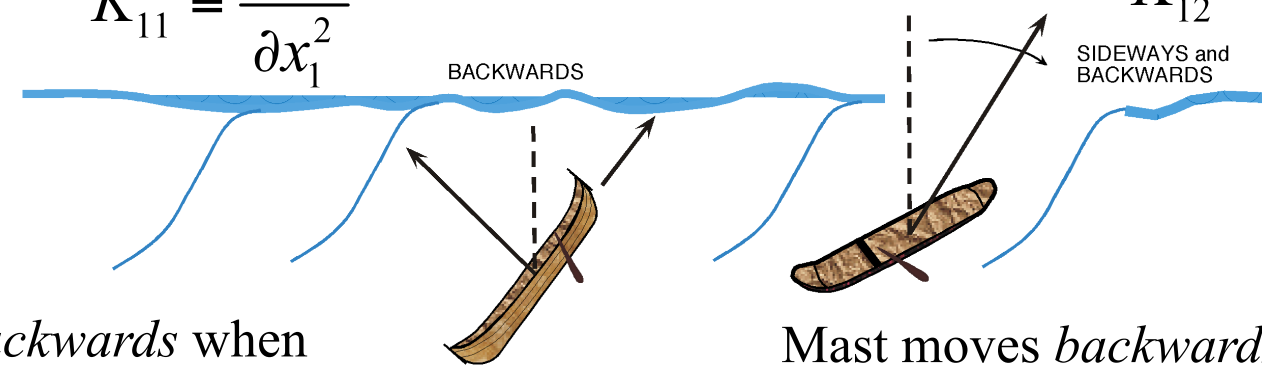
The Sailboat Analogy



$$K_{11} = \frac{\partial^2 f}{\partial x_1^2}$$

$$K_{12} = \frac{\partial^2 f}{\partial x_1^2 \partial x_2}$$

Analogy:
With boating



Mast moves *backwards* when boat meets wave head-on (directly).

Mast moves *backwards* and *sways* when boat meets wave obliquely.

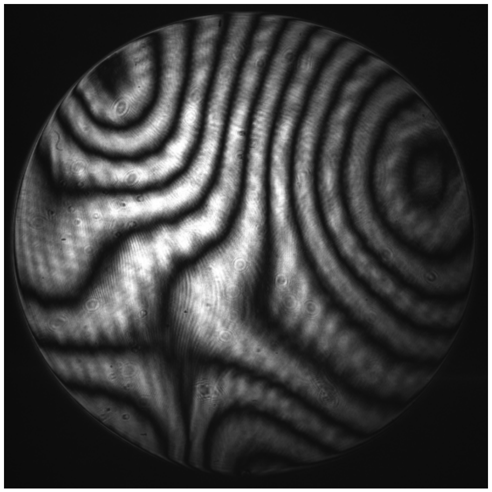
CGS slope and Curvature Management in 300mm wafers

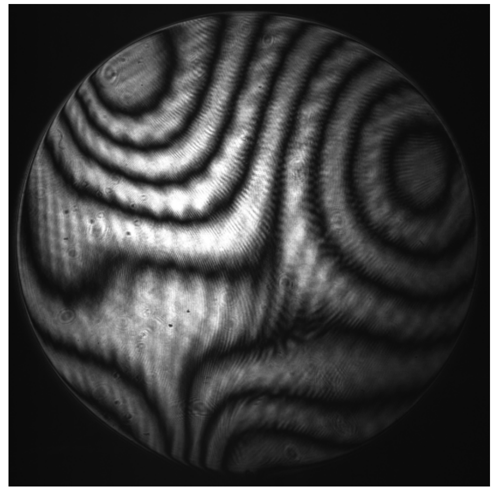
SiN Films: Comparison of Interferograms (Test and Patterned Wafer)

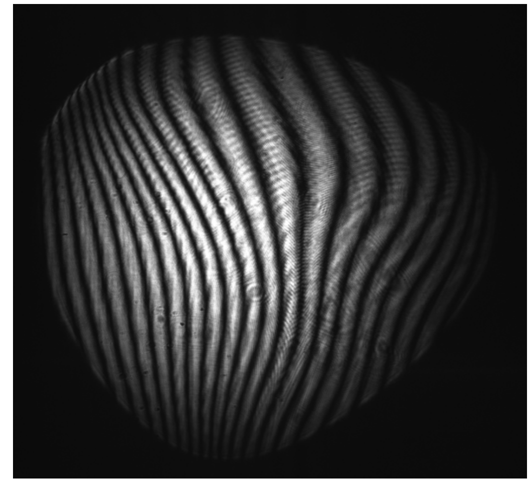
696Å Tensile SiN | **1250Å Compressive SiN** | **1200Å Highly Compressive SiN**

Uniform film on Si

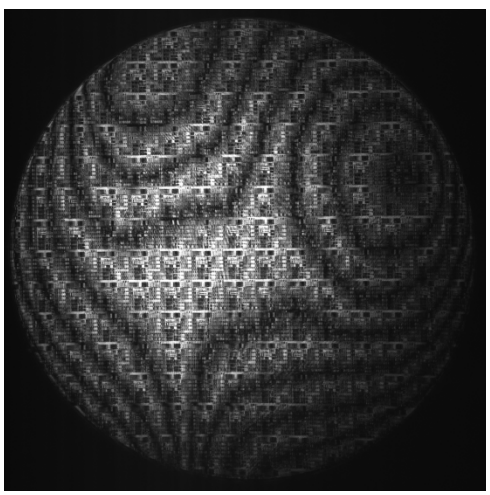
$$\frac{\partial f}{\partial x_2}$$

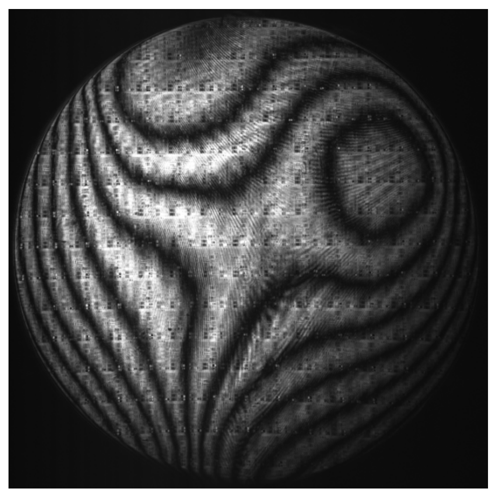


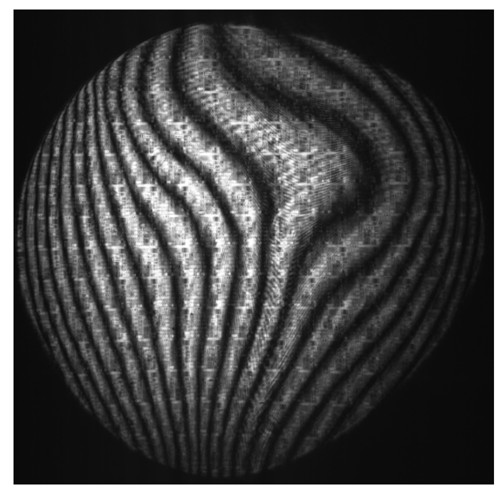




Pattern Wafer

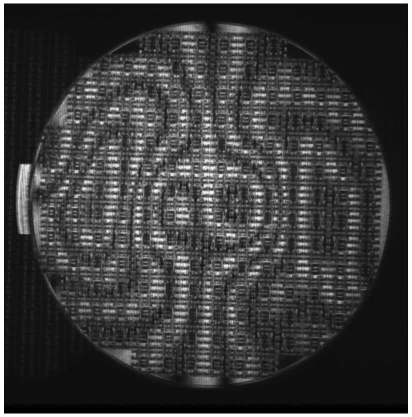




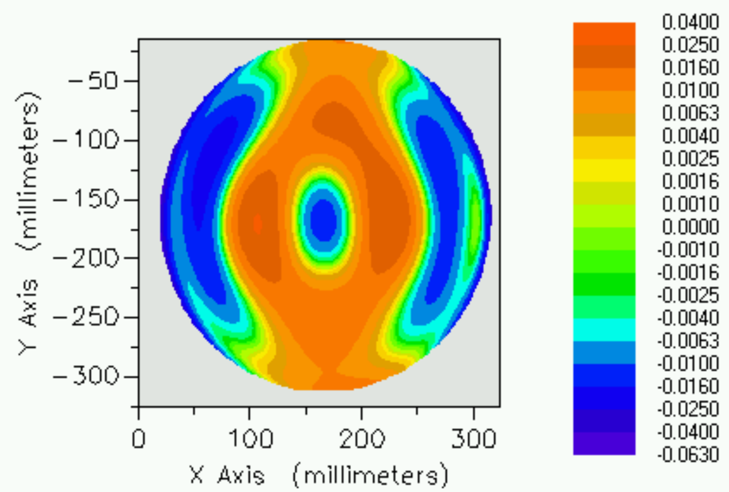


300mm Patterned Wafer (Curvature Maps)

X Interferogram

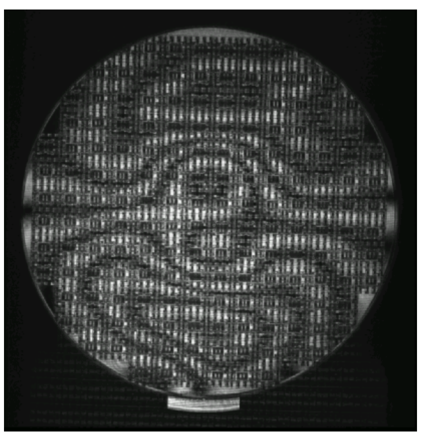


X Curvature

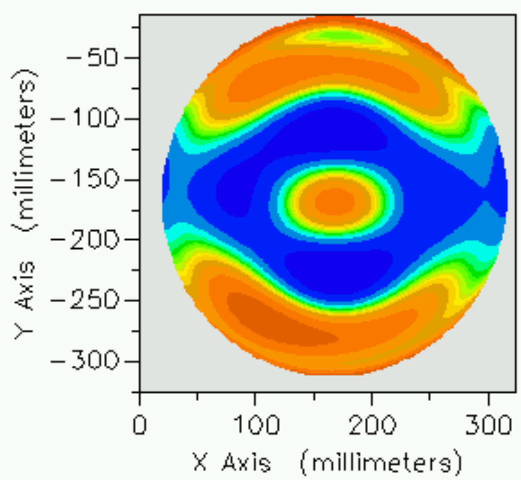


$$K_{11} = \frac{\partial^2 f}{\partial x_1^2}$$

Y Interferogram

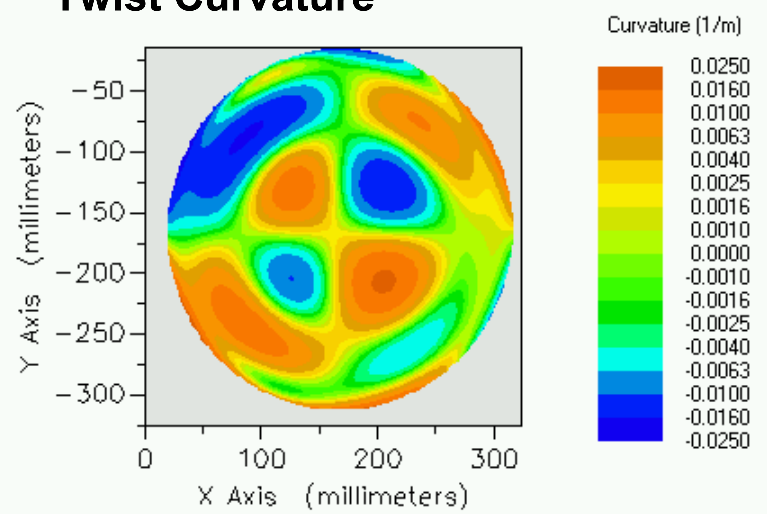


Y Curvature



$$K_{22} = \frac{\partial^2 f}{\partial x_2^2}$$

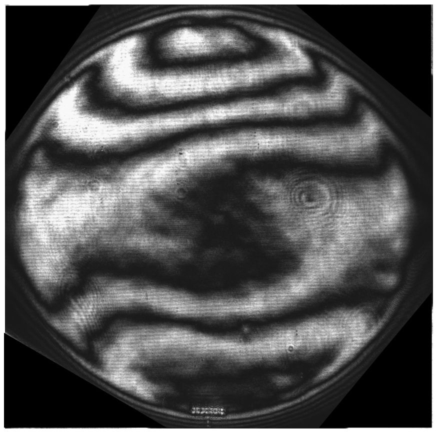
Twist Curvature

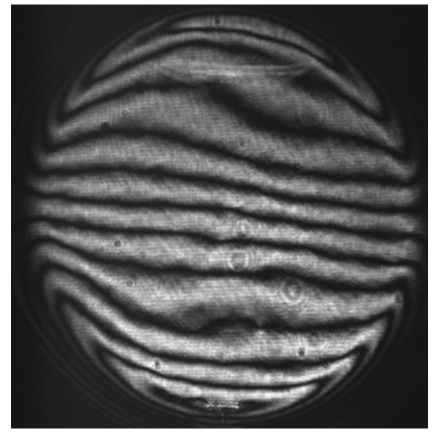


$$K_{12} = \frac{\partial^2 f}{\partial x_1 \partial_2}$$

Curvature Changes Before and After Deposition Process

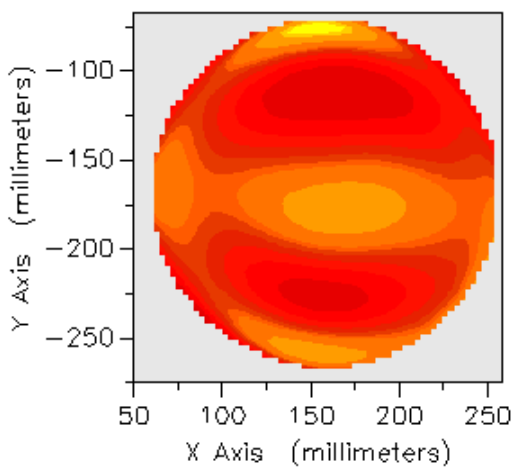
Interferograms

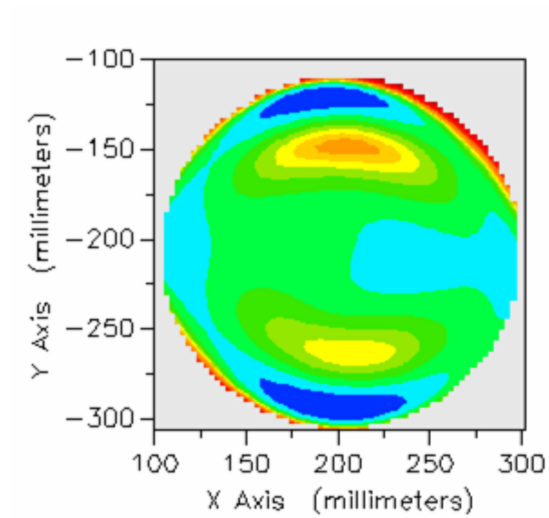




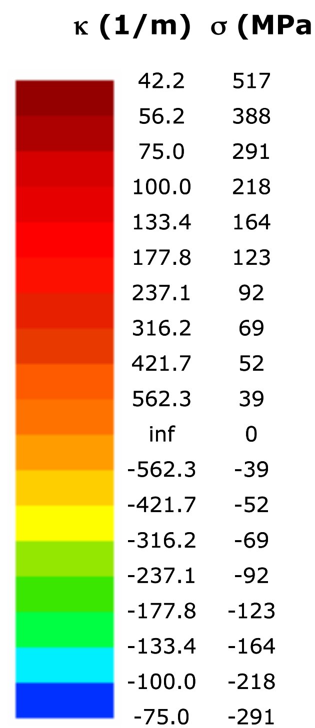
Prior to deposition **After deposition**

Vertical Curvature





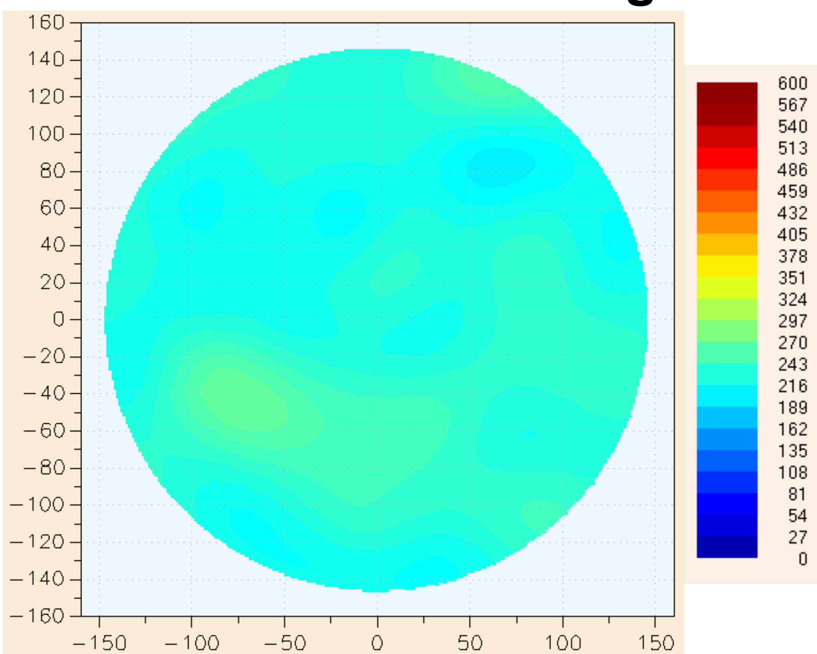
1 μm film / 775 μm substrate



Comparison of Stress Non-Uniformity and level

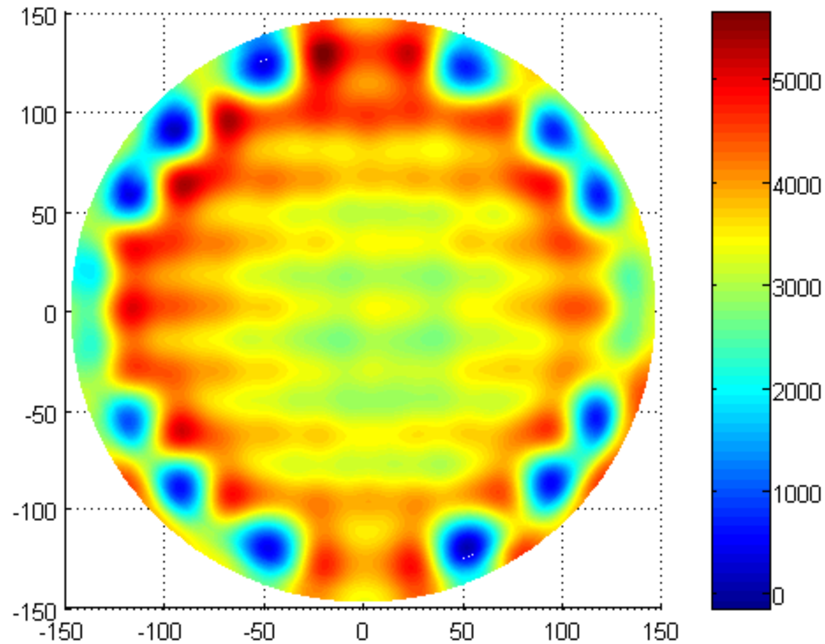
LSA vs. Flash Anneal

LSA - Localized heating



σ_{max} = 240 ± 11.2 MPa

Flash Anneal – Global Heating

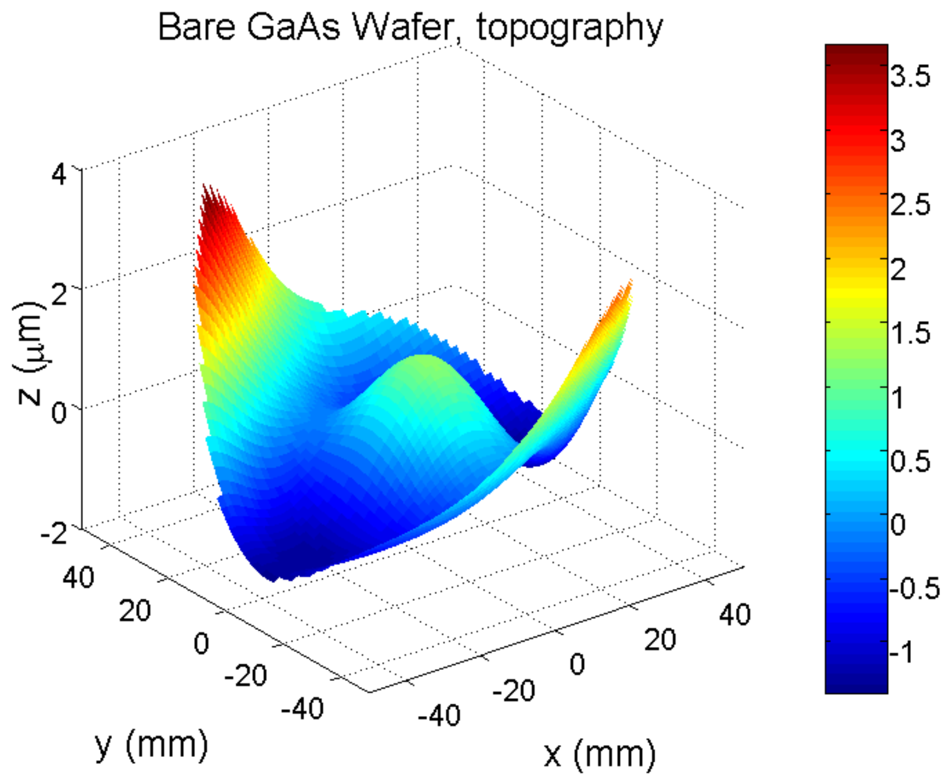


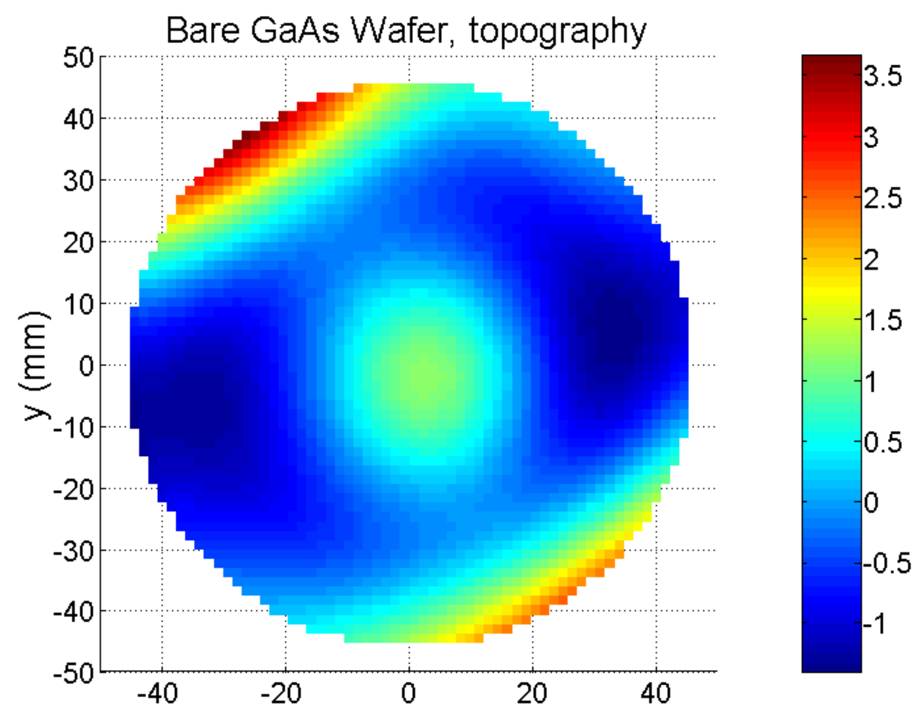
σ_{max} = 3377 ± 874 MPa

Global Heating leads to increased residual stress and wafer curvature and as a result to litho yield loss

GaAs Substrate Shape

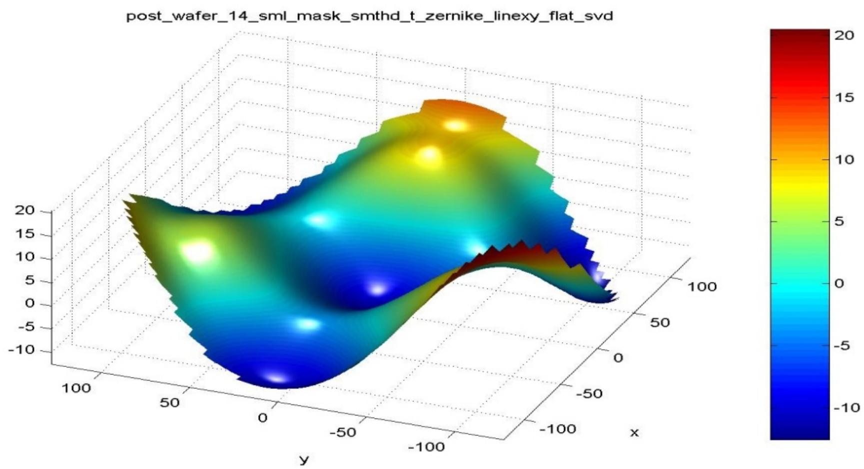
635 μm GaAs

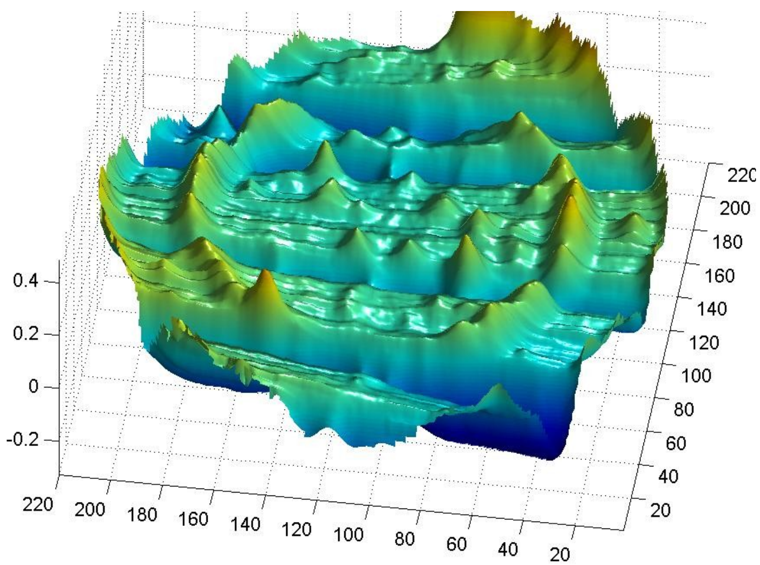




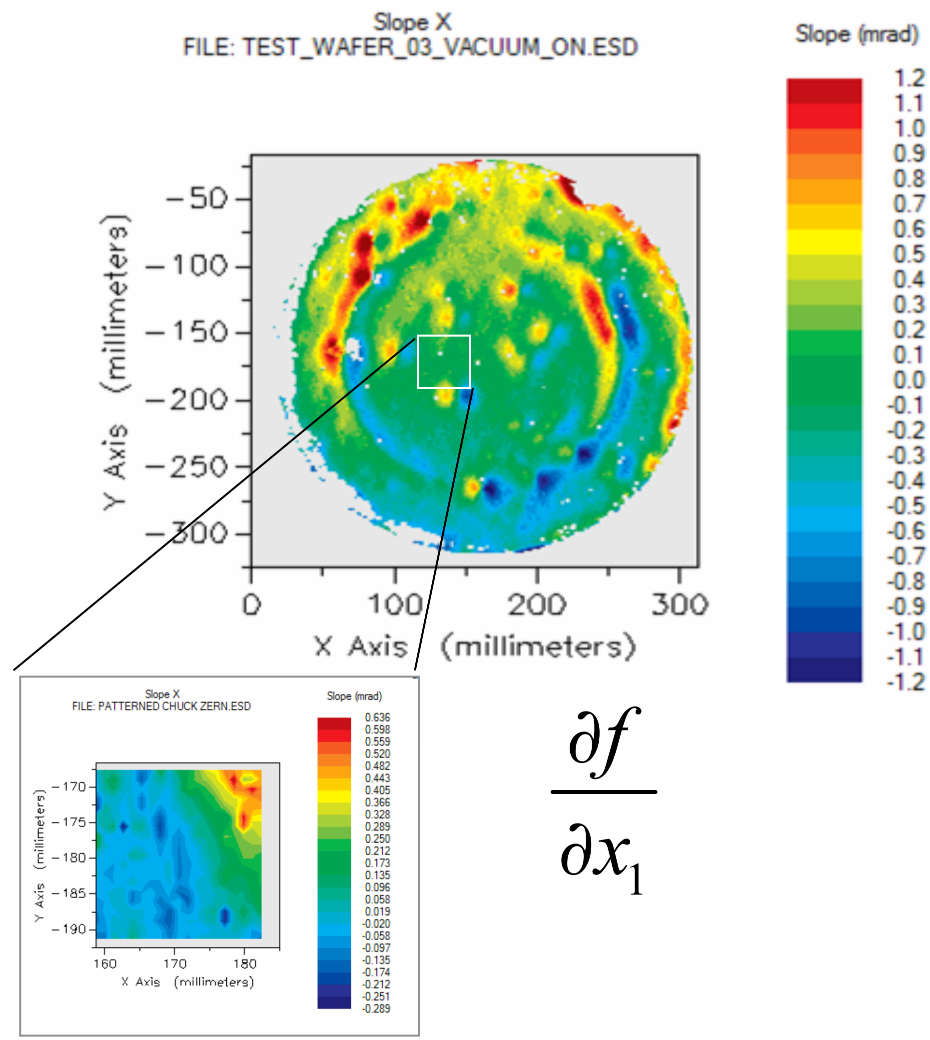
NGC wafers

Topography for Lithography





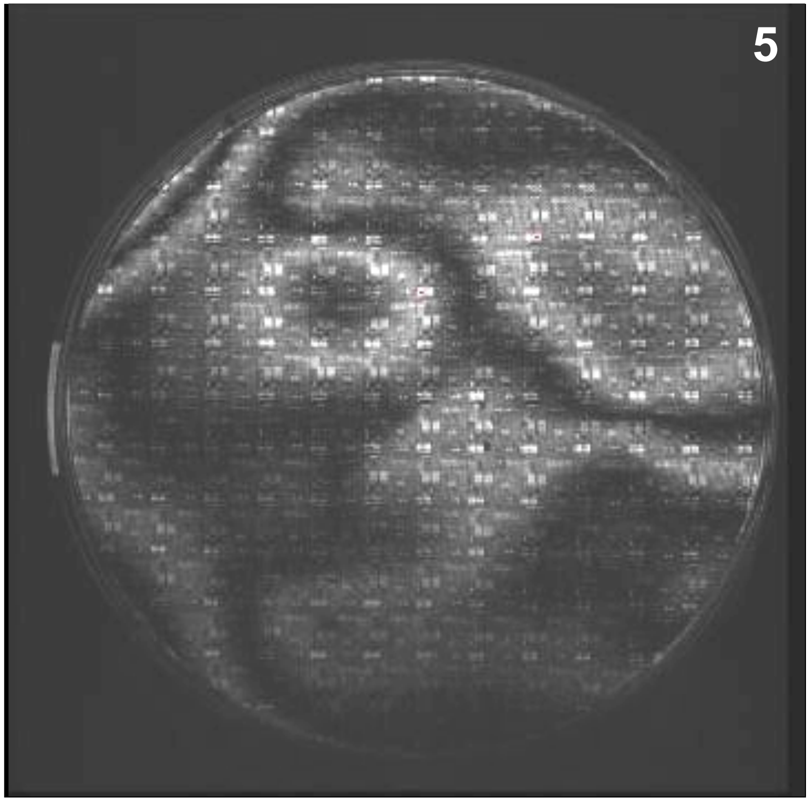
Topography of
a chucked wafer



$$\frac{\partial f}{\partial x_1}$$

Slope map
(resolution ~ O.1μrad)

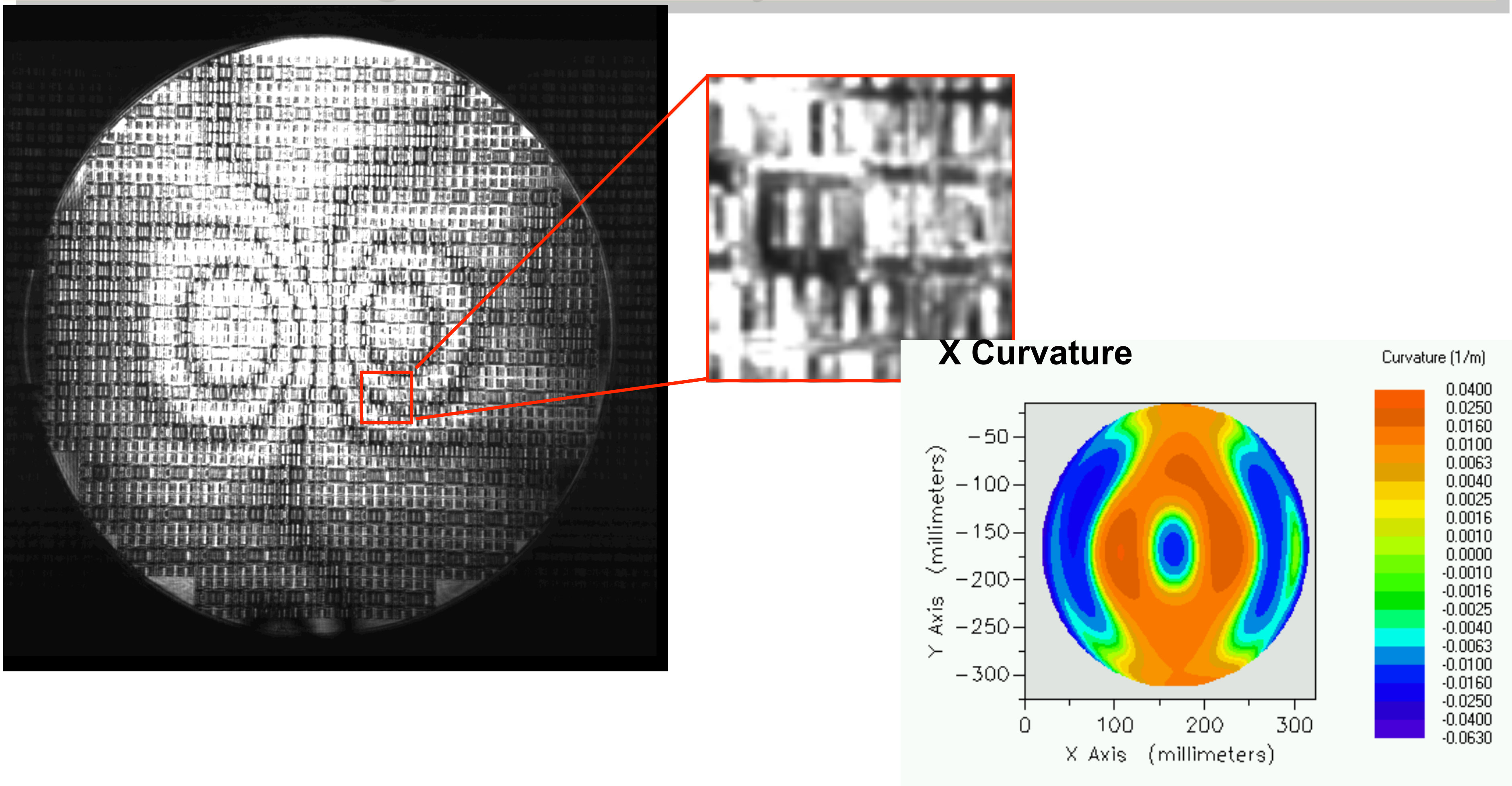
Advantage of CGS Interferometer Patterned Wafer Measurement



Click here to see movie in slideshow mode

- **Phase shifting is a common inteferometric technique**
  - Multiple images are obtained at discrete offsets in phase
  - Measures relative phase of each location on the wafer, NOT relative intensity thus enabling patterned wafer measurements and high resolution

CGS Advantage – Phase Shifting
Enabling Patterned Wafer Stress Measurement

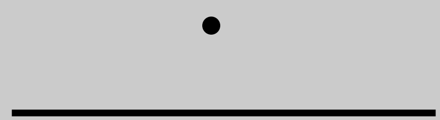


- Phase shifting reduces the impact of intensity variability across the wafer by eliminating background noise since relative phase (not intensity) is measured .This facilitates patterned wafer measurement.

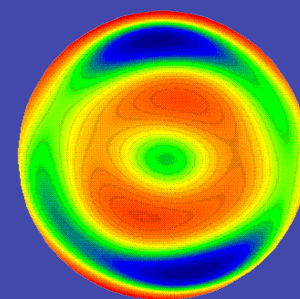
Enabling, Innovative Technology

Existing Metrology	**CGS Breakthroughs**
Single Data Points	**Full Wafer and all curvatures Instantly**
Blanket films	**Bare AND Patterned Wafers**

Single Data Points

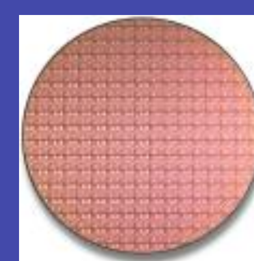


Full Wafer and all curvatures Instantly



Blanket films

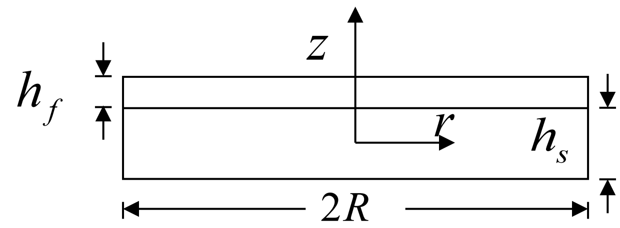
Bare AND Patterned Wafers



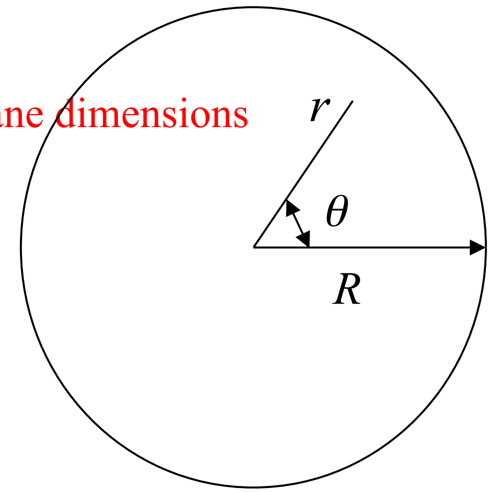
Inferring Film Stress: The Classical Stoney Formula

(Thin film Materials, Freund and Suresh, 2003):

$$\sigma^{(f)} = \frac{E_s h_s^2 \kappa}{6h_f(1-\nu_s)}$$



A) ASSUMPTIONS



$h_f << h_s << R$

(1.) UNIFORM film and substrate thickness. INFINITE in-plane dimensions

(2.) INFINITESIMAL strains and rotations of plate system.
(no large deformations or bifurcation allowed)

(3.) HOMOGENEOUS, ISOTROPIC MISFIT STRAIN ε_m
LINEAR-ELASTIC (or THERMOELASTIC) substrates.

(4.) EQUI-BIAXIAL (or in-plane isotropic) film stress state with
VANISHING interfacial shear stress and out of plane direct stresses.

⟹ **ONE STRESS COMPONENT**

(5.) EQUI-BIAXIAL curvature states (two equal direct curvatures and no twist)

(6.) SPATIALLY CONSTANT stresses and curvatures .No variation over surface.

⟹ **SPHERICAL WAFER SHAPES**

THE CLASSICAL STONEY FORMULA

A) ***ASSUMPTIONS*** *(Cont'd)*

(4) (5) and (6) → *One stress number, one curvature number, spherical wafer shape.*

B) ***THE CLASSICAL STONEY:***

$$\kappa = \kappa_{rr} = \kappa_{\theta\theta} = 6\frac{E_f h_f}{1-\nu_f}\frac{1-\nu_s}{E_s h_s^2}\varepsilon_m . \qquad \sigma^{(f)} = \sigma_{rr}^{(f)} = \sigma_{\theta\theta}^{(f)} = \frac{E_f}{1-\nu_f}\varepsilon_m$$

$$\sigma^{(f)} = \frac{E_s h_s^2 \kappa}{6h_f(1-\nu_s)}$$

EXISTING EXTENSIONS OF STONEY(Thin film Materials, Freund and Suresh, 2003):

Freund, Suresh, Park and their co-workers *have relaxed assumptions (1),(4) and (5) extending Stoney to thick films and anisotropic systems (bare, encapsulated and passivated periodic lines, etc).*

Rosakis, Park and Suresh *have extended it to include vertical stresses on vias in multilevel structures.*

Suresh, Freund and Their co-workers *have also relaxed assumptions (2) allowing bifurcated curvature states.*

All of the above still require spatial uniformity or assume that a local relation between curvature and stress is valid.

Evidence of radial Non-Uniformities on a Real Wafer, $\varepsilon_m(r)$

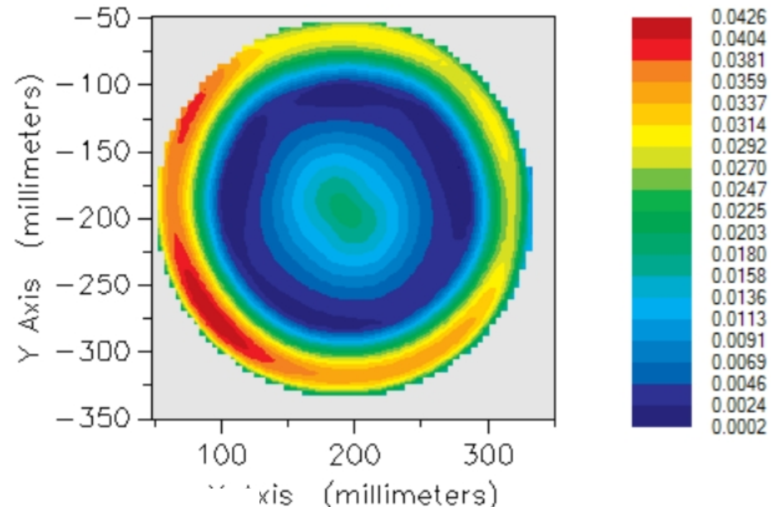
Huang & Rosakis JMPS 05 ;

SOURCES OF SPATIAL NON-UNIFORMITIES

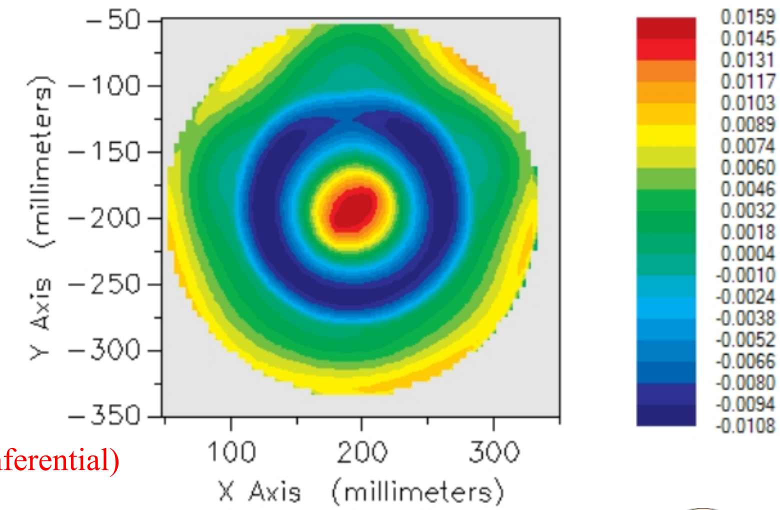
Fabrication and processing steps:

- *Film deposition*
- *Thermal anneal,*
- *Natural or forced cooling*
- *CMP, Etch steps*
- *Film thickness variations, etc.*

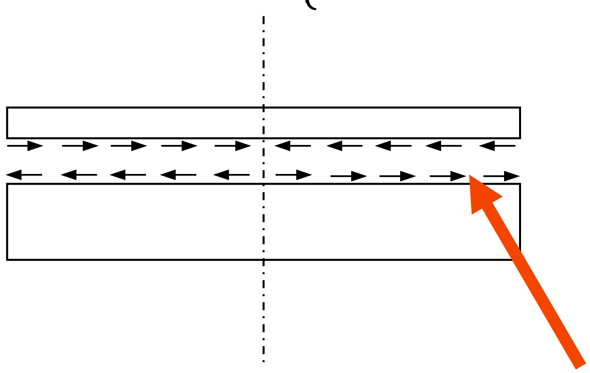
$$\kappa_{1,2} = \frac{\kappa_{\theta\theta} + \kappa_{rr}}{2} \pm \left\{ \left(\frac{\kappa_{rr} - \kappa_{\theta\theta}}{2} \right)^2 + \kappa_{r\theta}^2 \right\}^{1/2}$$



Maximum (radial)



Minimum (circumferential)



Curvature non-uniformity is expected to result in interfacial shears.

HR STRESS/CURVATURE RELATIONS [$\varepsilon_m = \varepsilon_m(r)$]

"Local" Stoney: $\sigma_{rr} + \sigma_{\theta\theta} = \dfrac{E_s h_s^2}{6(1-\nu_s)h_f}(\kappa_{rr} + \kappa_{\theta\theta})$

Stress/curvature relations for axisymmetric misfit strain, $\varepsilon_m(r)$:

- $$\sigma_{rr}^f + \sigma_{\theta\theta}^f = \frac{E_s h_s^2}{6(1+\nu_s)h_f}\left\{\kappa_{rr} + \kappa_{\theta\theta} + \frac{1-\nu_s}{1+\nu_s}\left[\kappa_{rr} + \kappa_{\theta\theta} - \overline{\kappa_{rr} + \kappa_{\theta\theta}}\right]\right\}$$

where $$\overline{\kappa_{rr} + \kappa_{\theta\theta}} = \frac{1}{\pi R^2}\int\int_A (\kappa_{rr} + \kappa_{\theta\theta})\eta d\eta d\theta$$
$$= \frac{2}{R^2}\int_0^R \eta(\kappa_{rr} + \kappa_{\theta\theta})d\eta$$

h_f is non-uniform, $h_f = h_f(r)$

- $$\sigma_{rr}^f - \sigma_{\theta\theta}^f = -\frac{2E_f h_s}{3(1+\nu_f)}(\kappa_{rr} - \kappa_{\theta\theta})$$

Because now $\kappa_{rr} \neq \kappa_{\theta\theta}$,
there is a stress difference

"Non-local", axisymmetric portion: depends on difference over **average curvatures**

Huang & Rosakis JMPS 05 ; Huang, Ngo & Rosakis, AMS 05.

INTERFACIAL SHEAR $[\varepsilon_m = \varepsilon_m(r)]$

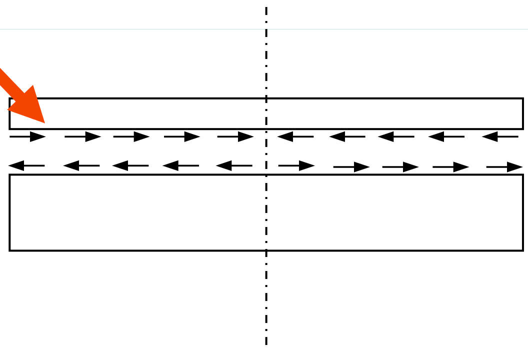
Recall that Stoney has no interfacial shear since the curvature is spatially uniform.

In the HR analysis, however, curvature may be non-uniform

This curvature non-uniformity is expected to result in interfacial shears

These depend on curvature GRADIENTS:

$$\sigma_{rz} = \tau = \tau(r) = \frac{E_s h_s^2}{6(1-\nu_s^2)} \frac{d}{dr}(\kappa_{rr} + \kappa_{\theta\theta})$$



Stoney has no interfacial shear,
$\tau(r) = 0$

Huang, Y., Ngo, D., Rosakis, A.J, *Acta Mech Sinica,* (2005).

HR RELATIONS [$\varepsilon_m = \varepsilon_m(r,\theta)$]

First define coefficients as

$$C_n = \frac{1}{\pi R^2}\iint_A (\kappa_{rr} + \kappa_{\theta\theta})\left(\frac{\eta}{R}\right)^n \cos n\varphi \, dA,$$

$$S_n = \frac{1}{\pi R^2}\iint_A (\kappa_{rr} + \kappa_{\theta\theta})\left(\frac{\eta}{R}\right)^n \sin n\varphi \, dA,$$

Stress/curvature relations for misfit strain, $\varepsilon_m(r,\theta)$:

Stoney → $\kappa_{rr} + \kappa_{\theta\theta}$

Axisymmetric → $\frac{1-\nu_s}{1+\nu_s}\left(\kappa_{rr} + \kappa_{\theta\theta} - \overline{\kappa_{rr} + \kappa_{\theta\theta}}\right)$

$$\sigma_{rr}^{(f)} + \sigma_{\theta\theta}^{(f)} = \frac{E_s h_s^2}{6h_f(1-\nu_s)}\left[\kappa_{rr} + \kappa_{\theta\theta} + \frac{1-\nu_s}{1+\nu_s}\left(\kappa_{rr} + \kappa_{\theta\theta} - \overline{\kappa_{rr} + \kappa_{\theta\theta}}\right) - \frac{1-\nu_s}{1+\nu_s}\sum_{n=1}^{\infty}(n+1)\left(\frac{r}{R}\right)^n \left(C_n \cos n\theta + S_n \sin n\theta\right)\right]$$

h_f is non-uniform, $h_f = h_f(r,\theta)$

where $\overline{\kappa_{rr} + \kappa_{\theta\theta}} = C_0 = \iint_A (\kappa_{rr} + \kappa_{\theta\theta})\, dA / \pi R^2$

Fully non-uniform portion: integrals of curvature also have position dependence in their integrants

Ngo, D., Feng, X., Huang, Y., Rosakis, A.J., and Brown, M.A, *IJSS,* (2006).

HR RELATIONS [$\varepsilon_m = \varepsilon_m(r,\theta)$]

Stress/curvature relations for misfit strain, $\varepsilon_m(r,\theta)$, contd:

Axisymmetric

$$\sigma_{rr}^f - \sigma_{\theta\theta}^f = -\frac{E_f h_s}{6(1+\nu_f)}\left\{ 4(\kappa_{rr} - \kappa_{\theta\theta}) - \sum_{n=1}^{\infty}(n+1)\left[n\left(\frac{r}{R}\right)^n - (n-1)\left(\frac{r}{R}\right)^{n-2}\right](C_n \cos n\theta + S_n \sin n\theta)\right\}$$

Fully non-uniform portion depends on integrals of curvature

$$\sigma_{r\theta}^f = -\frac{E_f h_s}{6(1+\nu_f)}\left\{ 4\kappa_{r\theta} + \frac{1}{2}\sum_{n=1}^{\infty}(n+1)\left[n\left(\frac{r}{R}\right)^n - (n-1)\left(\frac{r}{R}\right)^{n-2}\right](C_n \sin n\theta - S_n \cos n\theta)\right\}$$

Fully non-uniform relations allow a twist curvature component for the first time

Ngo, D., Feng, X., Huang, Y., Rosakis, A.J., and Brown, M.A, *IJSS,* (2006).

INTERFACIAL SHEAR [$\varepsilon_m = \varepsilon_m(r,\theta)$]

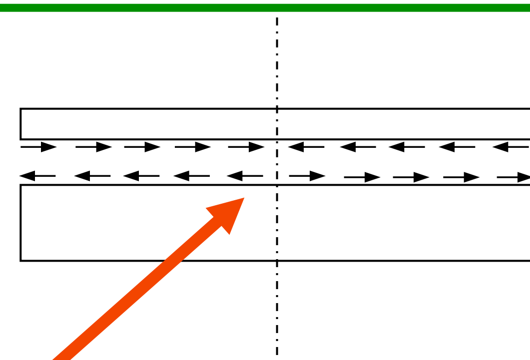
Axisymmetric

$$\tau_r = \frac{E_s h_s^2}{6\left(1-\nu_s^2\right)}\left[\frac{\partial}{\partial r}\left(\kappa_{rr}+\kappa_{\theta\theta}\right) - \frac{1-\nu_s}{2R}\sum_{n=1}^{\infty} n(n+1)\left(C_n \cos n\theta + S_n \sin n\theta\right)\left(\frac{r}{R}\right)^{n-1}\right],$$

Fully non-uniform portion

$$\tau_\theta = \frac{E_s h_s^2}{6\left(1-\nu_s^2\right)}\left[\frac{1}{r}\frac{\partial}{\partial \theta}\left(\kappa_{rr}+\kappa_{\theta\theta}\right) + \frac{1-\nu_s}{2R}\sum_{n=1}^{\infty} n(n+1)\left(C_n \sin n\theta - S_n \cos n\theta\right)\left(\frac{r}{R}\right)^{n-1}\right].$$

The lack of radial symmetry allows for a circumferential shear component

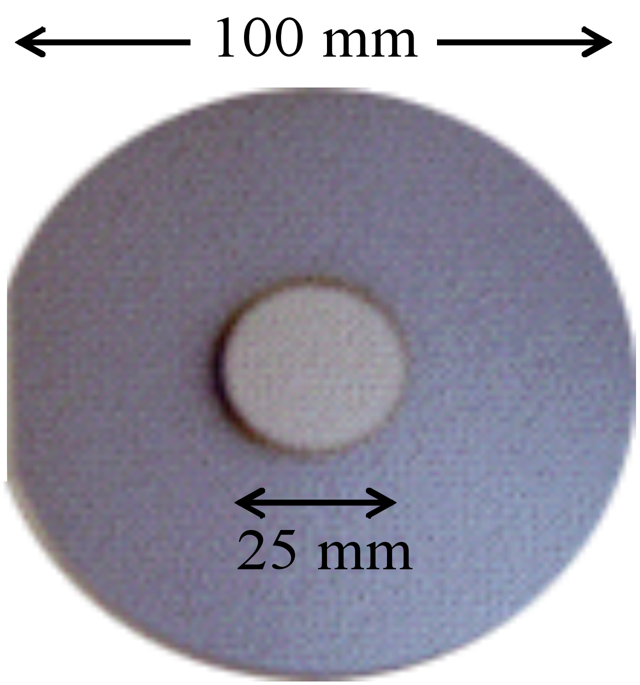


Curvature non-uniformity is expected to result in interfacial shears

Ngo, D., Feng, X., Huang, Y., Rosakis, A.J., and Brown, M.A, *IJSS,* (2006).

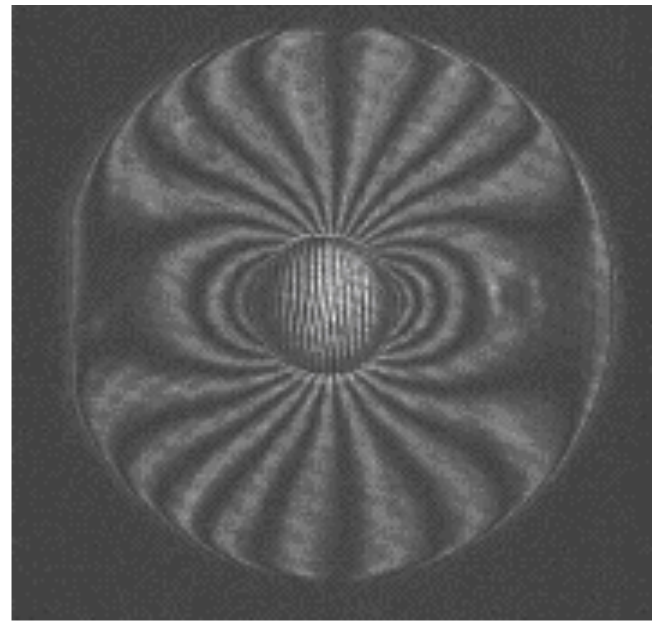
Experiments involving severe non-uniformities

THICKNESS AND FILM STRESS



The system has:

- Axisymmetric misfit strain
- Non-uniform film thickness

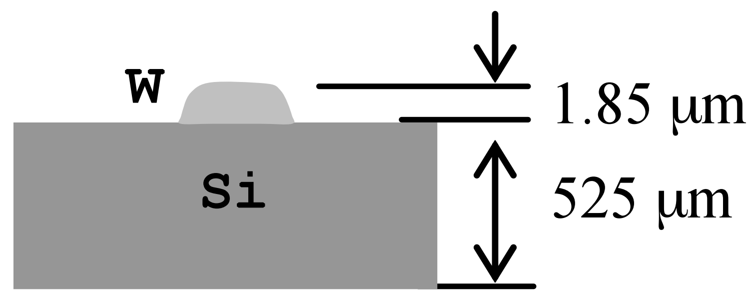


top view

Material Properties:

W film: E_f= 411 GPa, ν_f=0.28

Si substrate: E_s=130 GPa, ν_s=0.28

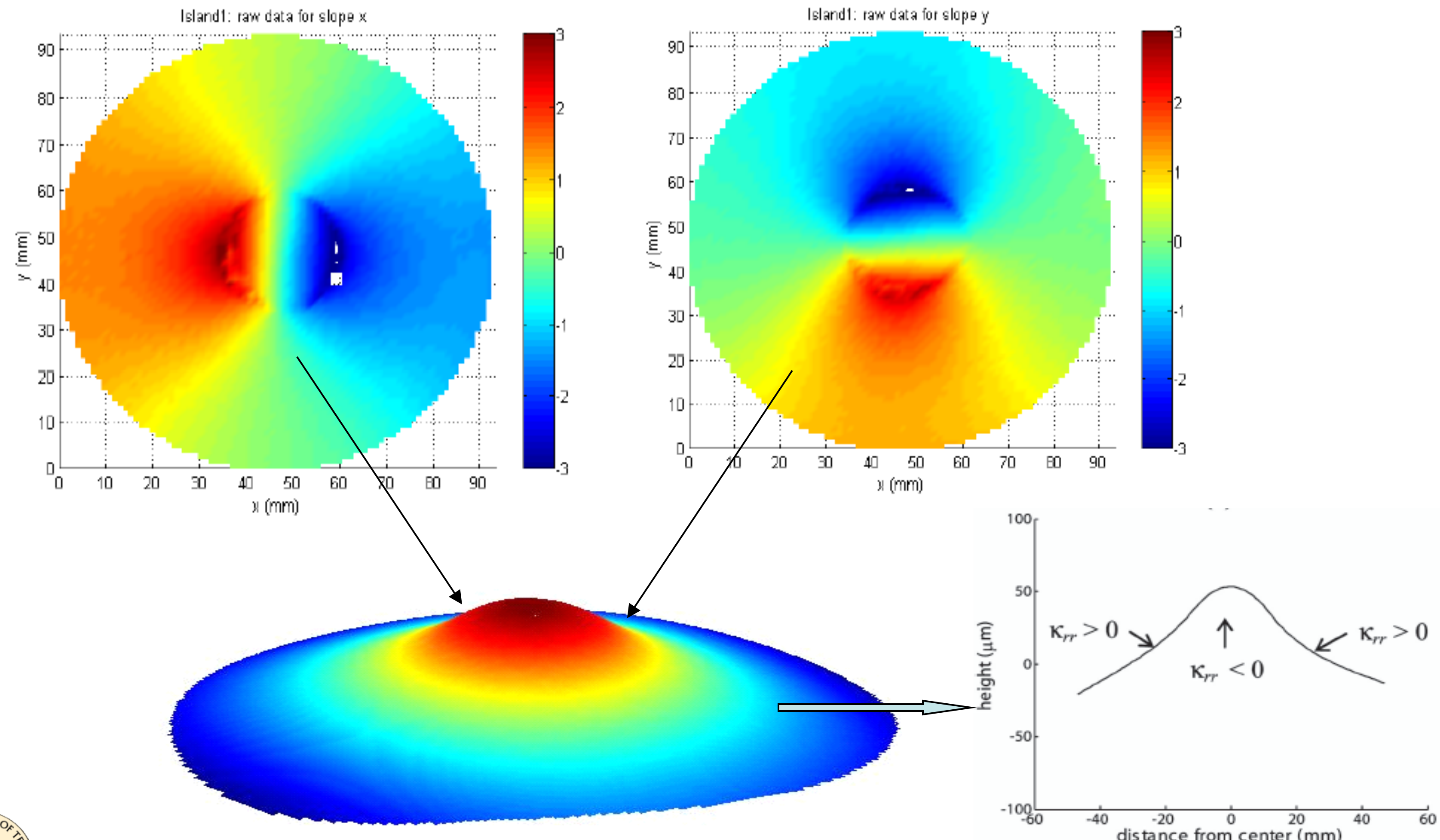


cross section

Verification of Axisymmetry

Slope $(\frac{\partial f}{\partial x_1})$ from CGS

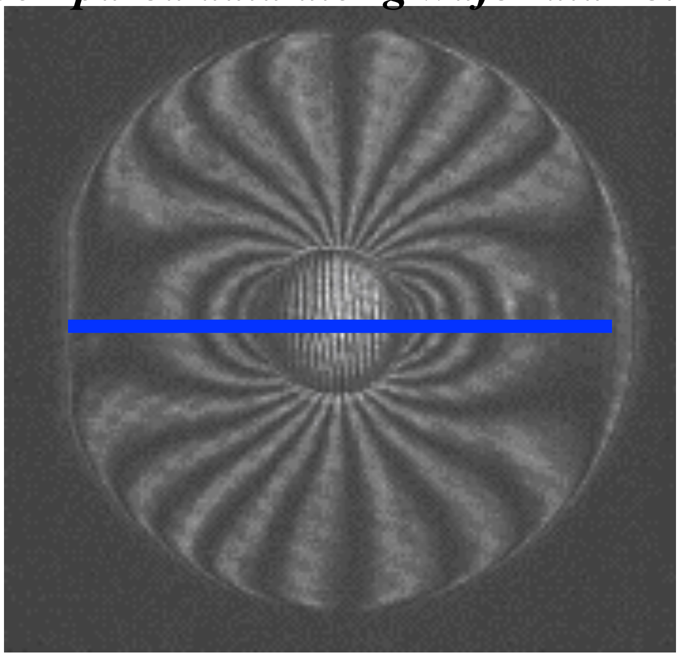
Slope $(\frac{\partial f}{\partial x_2})$ from CGS

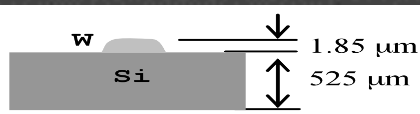


(a)

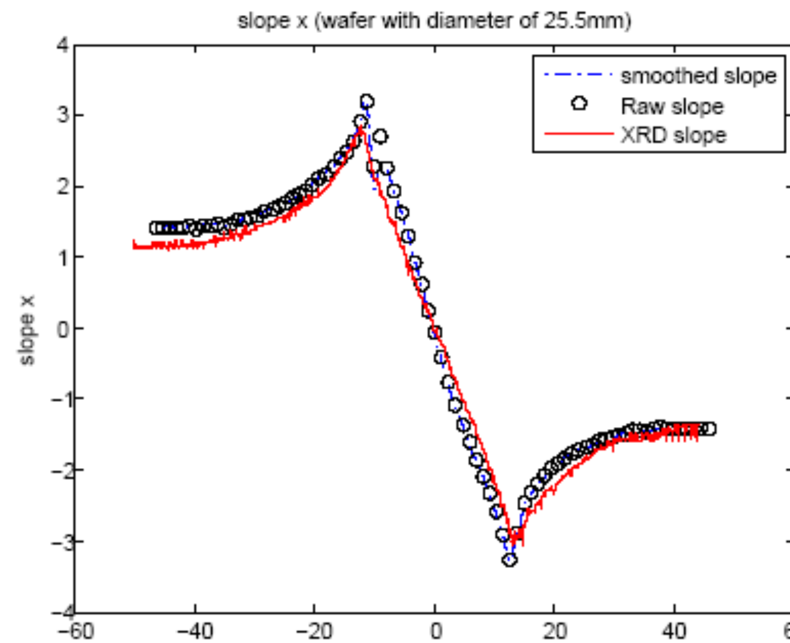
Two simultaneous micro-XRD measutements: At ALS (LBNL)

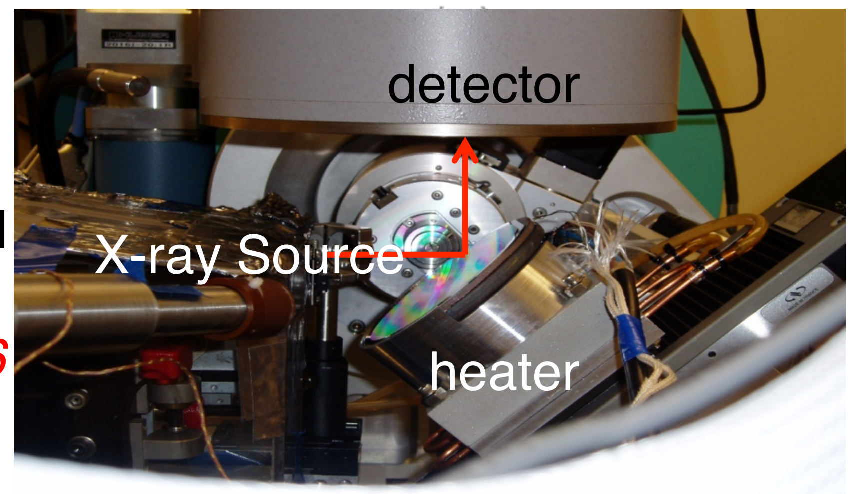
Compared data along wafer diameter





Comparison of CGS and XRD Slope

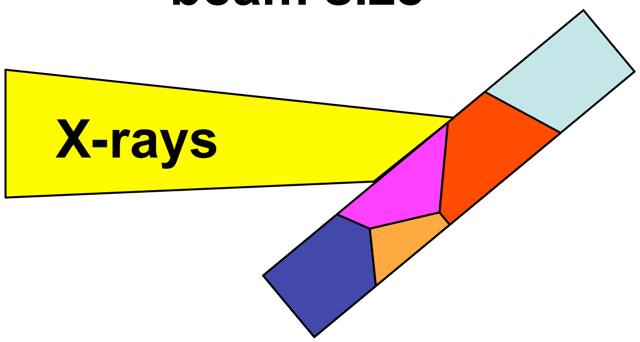




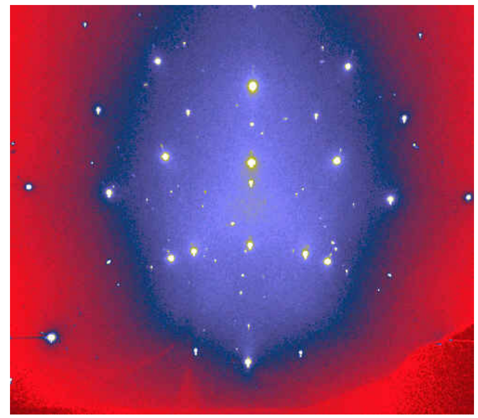
• beam size is order of 1µm ⇒ direct stress/curvature measurement of small volume structures ⇒ validation of analysis. *Brown et. al. JAM 05,IJSS,06*

X-Ray Microdiffraction

Grain size > or ~ beam size



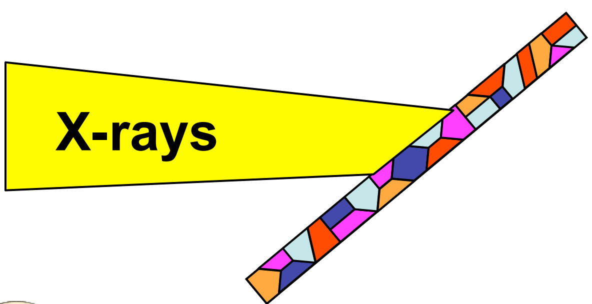
White beam



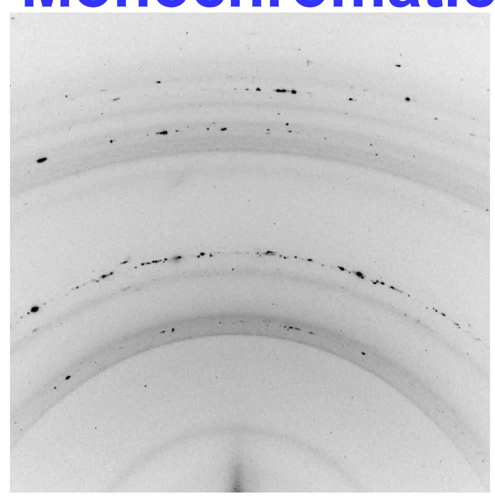
Single Crystal or Large Grain

- Orientation imaging for Si substrate slope measurement
- Strain/Stress map (3D)
- Micro-topography
- Dislocation mapping

Grain size << beam size



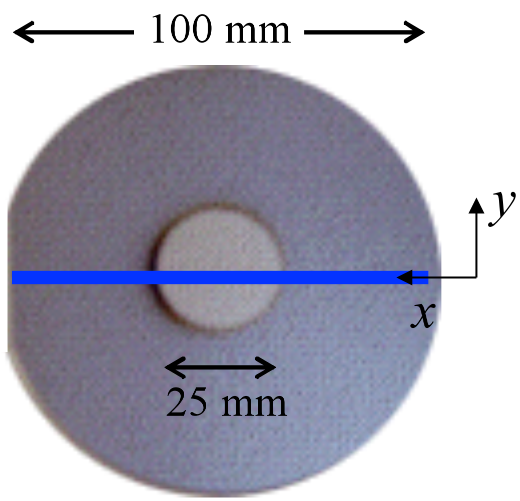
Monochromatic



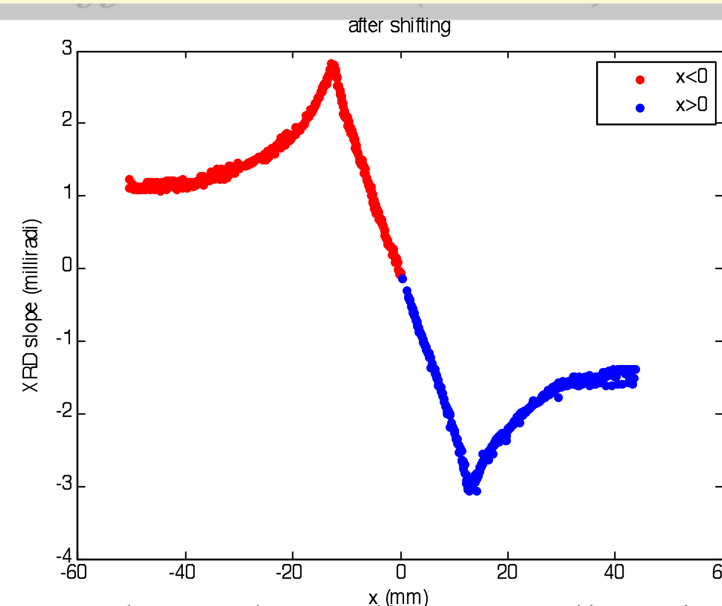
Polycrytalline with small grains

- Phase distribution
- Film stress mapping (averaged biaxial stress)

Slope measured by X-Ray Diffraction (XRD)

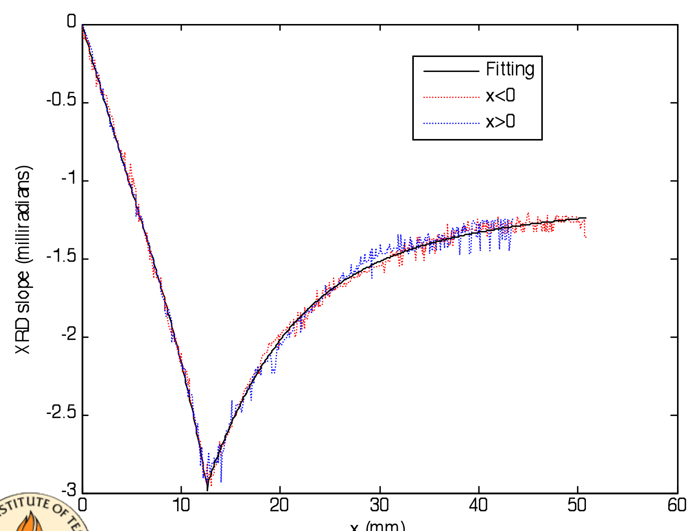


top view



XRD slope along diameter direction

XRD slope is axisymmetric



fitting

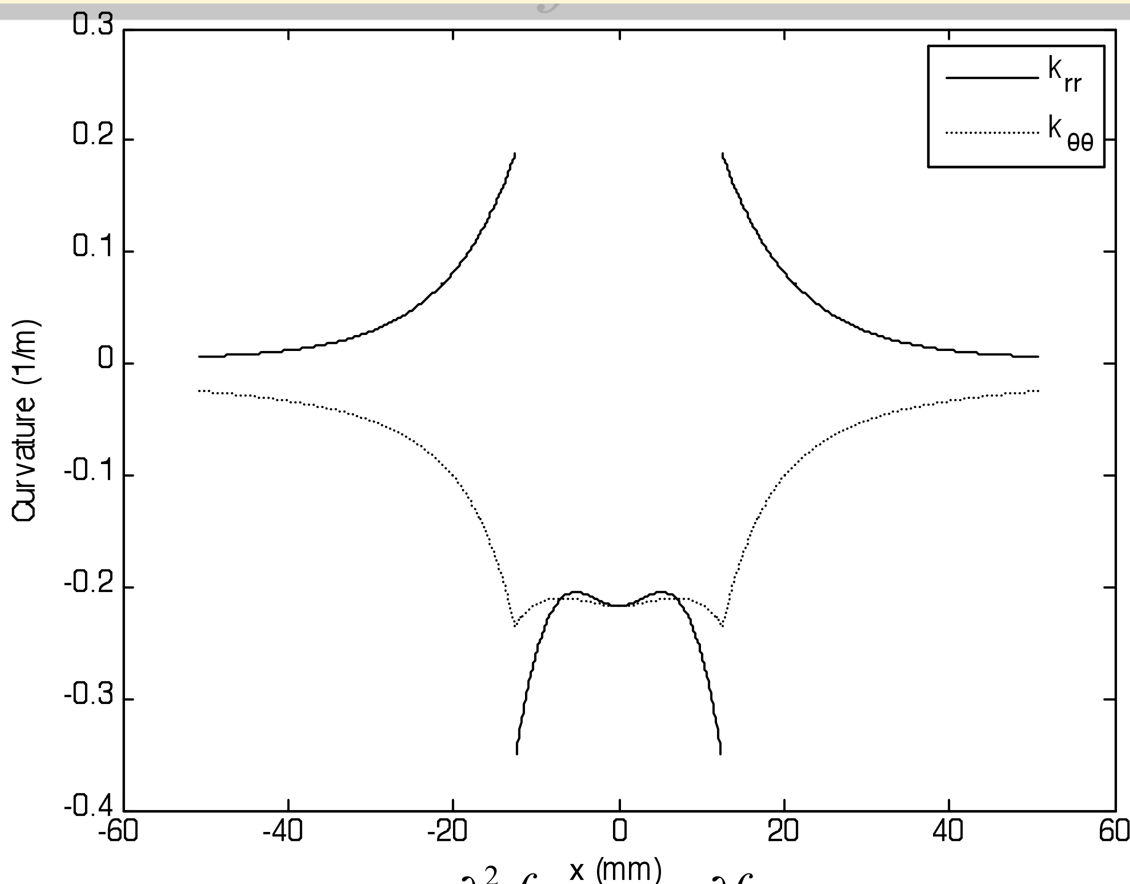
$$\left.\frac{\partial f}{\partial r}\right|_{island} = p_1 r^4 + p_2 r^3 + p_3 r$$

$$\left.\frac{\partial f}{\partial r}\right|_{outside} = a e^{b \cdot r} + c e^{d \cdot r}$$

$$p_1 = -4.599E-5;\ p_2 = 0.0004727;\ p_3 = -0.2173$$

$$a = -6.72;\ b = -0.115;\ c = -1.44;\ d = -0.00329$$

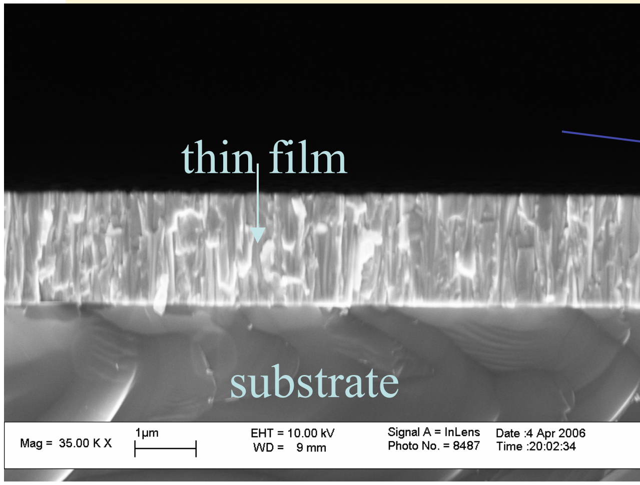
Curvatures from XRD slope



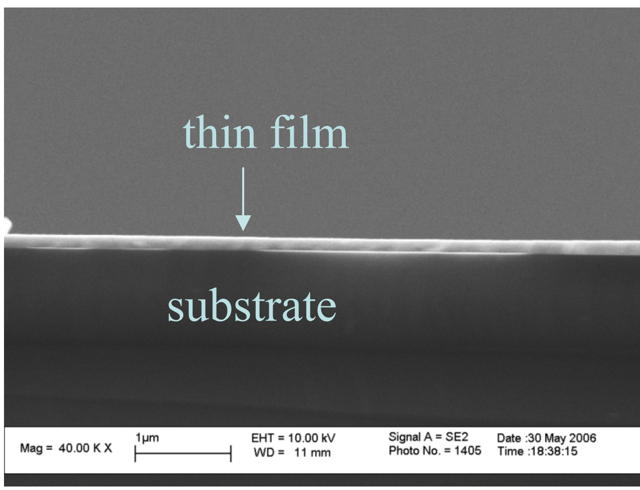
$$\kappa_{rr} = \frac{\partial^2 f}{\partial r^2}; \kappa_{\theta\theta} = \frac{\partial f}{r \partial r}$$

$\kappa_{\theta\theta}$ is continuous, but κ_{rr} is discontinuous at the film edge

Measurement of film thickness

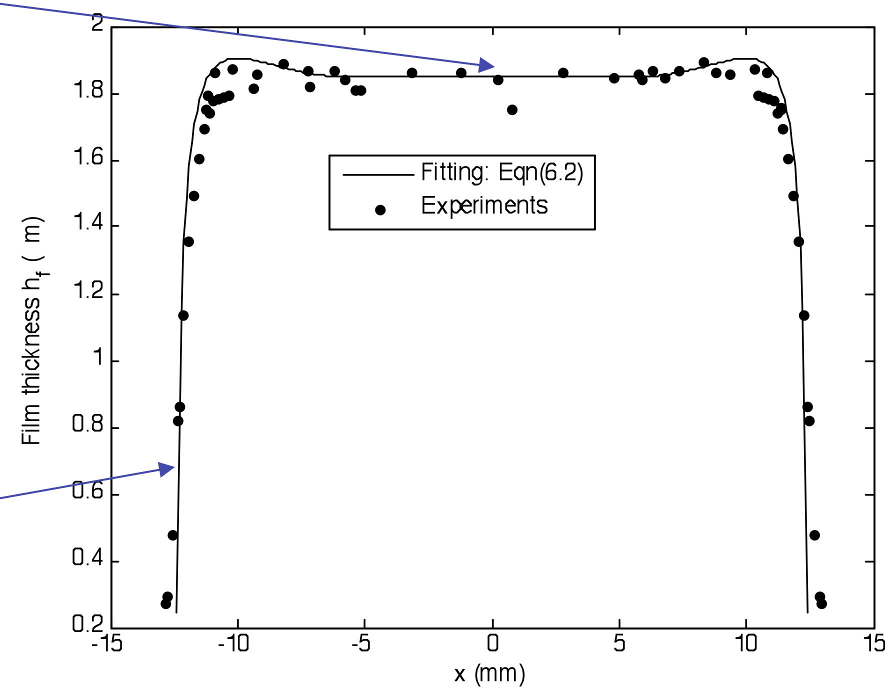


Middle of island



Edge of island

(SEM)

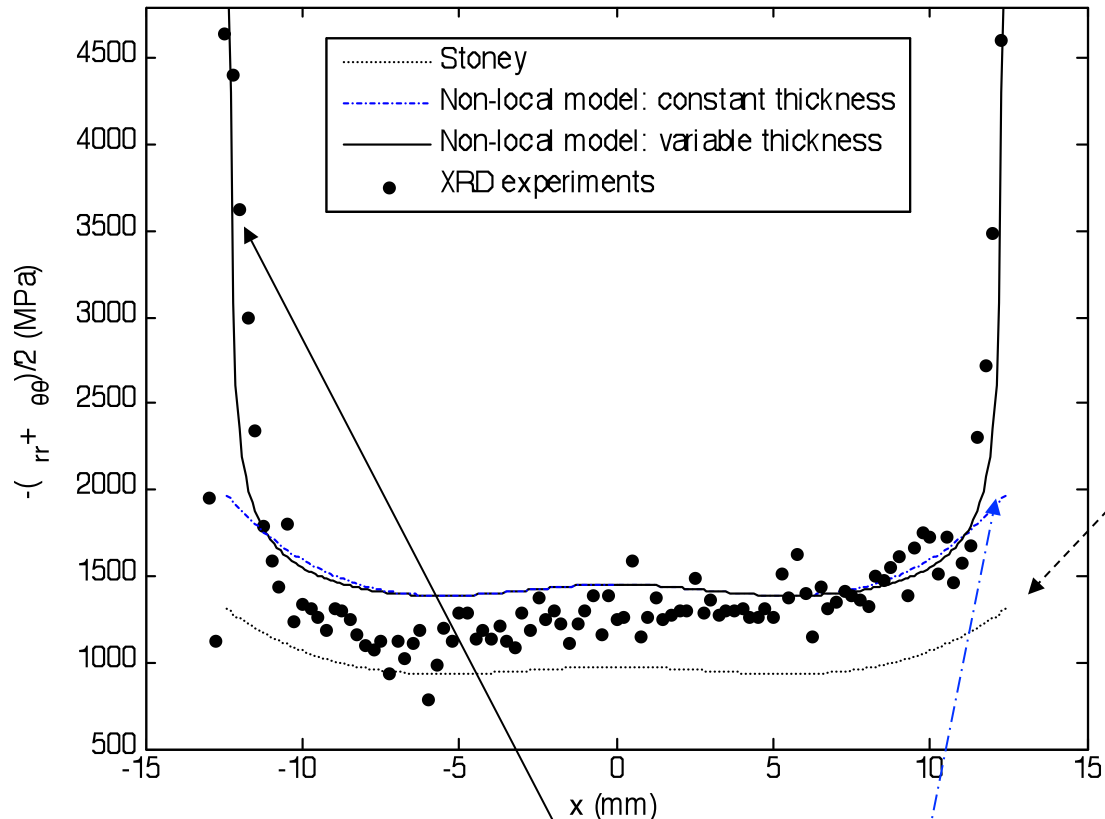


$$h_f = 1.85 + 0.00713\left(1 + \frac{1.49}{r - 12.62}\right)(r - 5.815)H(r - 5.815)$$

Film thickness is non-uniform!

Comparison of Theories and Experiment

Discrete points obtained directly from lattice spacing (Monochromatic XRD). Curves calculated from lattice rotation (white Beam XRD) and various analyses. NO AJUSTABLE CONSTANTS



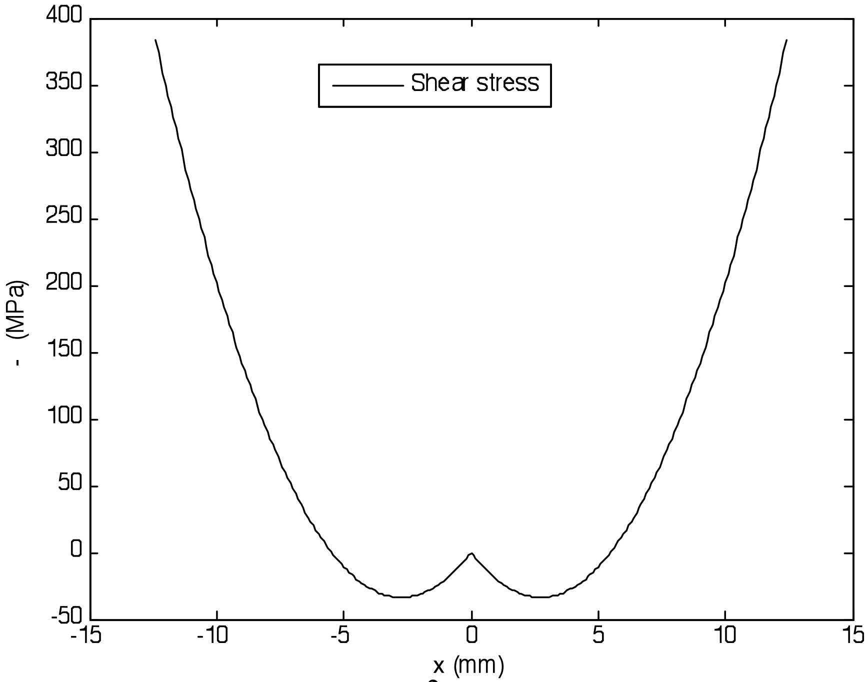
Stoney: $h_f = const$

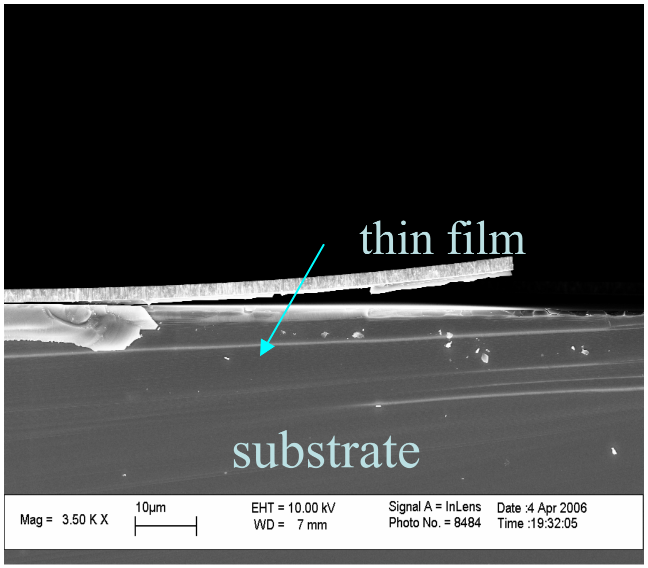
$$\sigma = \frac{E_s h_s^2}{6(1-\nu_s)h_f}\kappa$$

Non-local model with $h_f = const$: $\sigma_{rr}+\sigma_{\theta\theta} = \frac{E_s h_s^2}{6(1-\nu_s)h_f}\left\{\kappa_{rr}+\kappa_{\theta\theta}+\frac{1-\nu_s}{1+\nu_s}\left[\kappa_{rr}+\kappa_{\theta\theta}-\overline{\kappa_{rr}+\kappa_{\theta\theta}}\right]\right\}$

Non-local model with $h_f = h_f(r)$: $\sigma_{rr}+\sigma_{\theta\theta} = \frac{E_s h_s^2}{6(1-\nu_s)h_f}\left\{\kappa_{rr}+\kappa_{\theta\theta}+\frac{1-\nu_s}{1+\nu_s}\left[\kappa_{rr}+\kappa_{\theta\theta}-\overline{\kappa_{rr}+\kappa_{\theta\theta}}\right]\right\}$

Shear Stress On the Interface

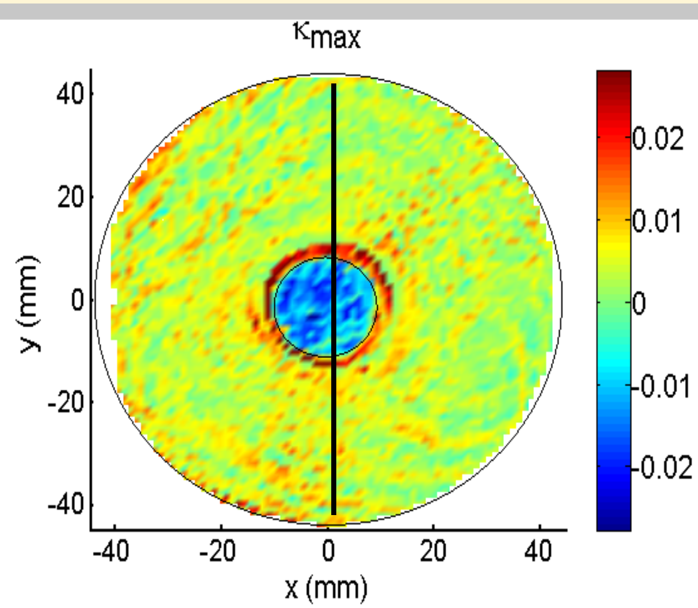


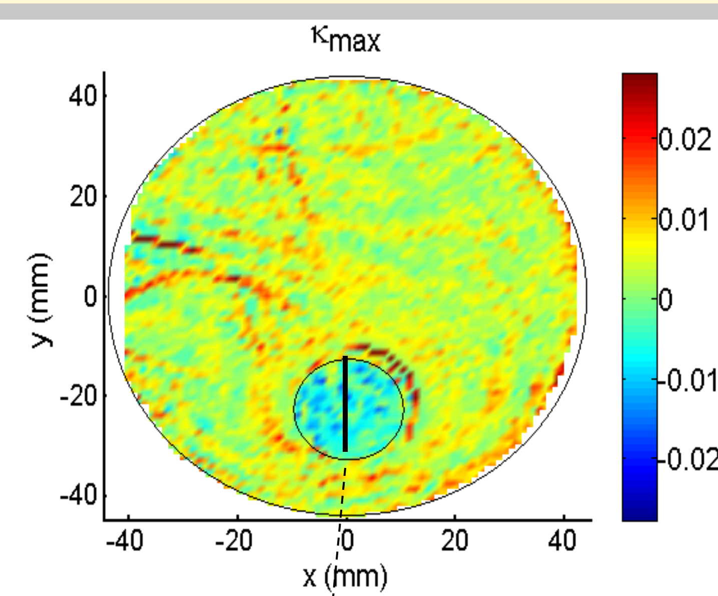


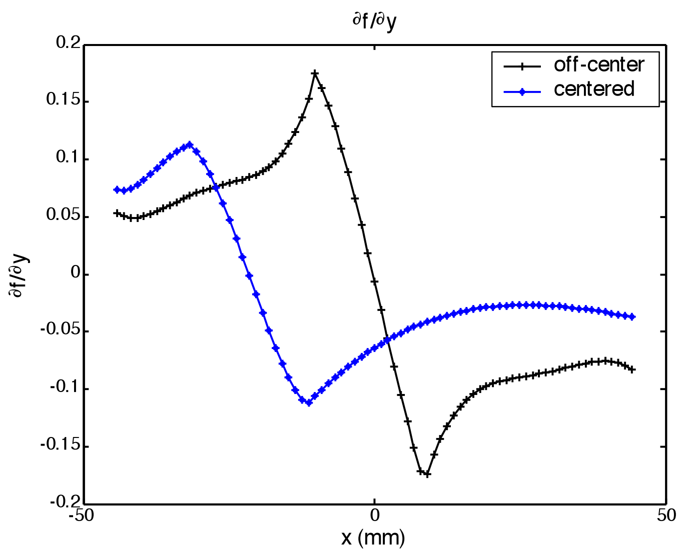
$$\tau = \frac{E_s h_s^2}{6\left(1-\nu_s^2\right)} \frac{d}{dr}\left(\kappa_{rr} + \kappa_{\theta\theta}\right)$$

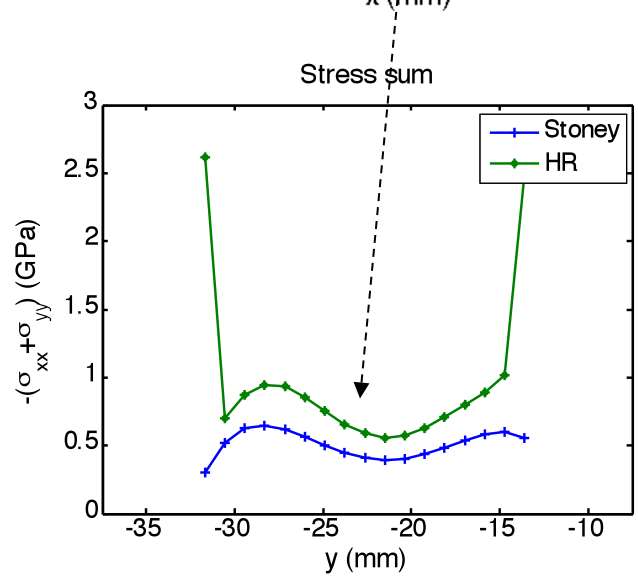
Shear stress on the edge is up to 400MPa. Delamination may occur !

Relying on CGS:CENTRAL AND OFF-CENTER ISLAND









CONCLUSIONS

X-ray micro-diffraction has validated the new analysis

A) CHARACTERISTICS OF THE NON-UNIFORM MISFIT STRAIN ANALYSIS:

Each stress component at a specific point depends on:

1. All curvature components at the same point (local dependence).
2. All curvature components at all other points (Non-local dependence)

The importance of the local effect is increased with more pronounced curvature non-uniformities and vanishes for spherical wafer shapes.

Shear stresses on the film/substrate interface depend on gradients of the curvature maps.

B) METROLOGY REQUIREMENTS TO IMPLEMENT NEW ANALYSIS

- Measurement over the ENTIRE wafer (full-field information).
- All curvature components should be measured

PERFECT FIT FOR CGS

A) DISCUSSION

Each stress component at a specific point depends on

1. All curvature components at the same point (local dependence).
2. All curvature components at all other points (Non-local dependence)
   The importance of the local effect is increased with more pronounced curvature non-uniformities and vanishes for spherical wafer shapes.
3. Shear stresses on the film/substrate interface depend on gradients of the curvature maps.

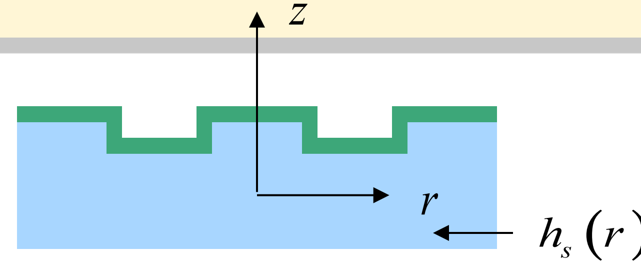
B) METROLOGY REQUIREMENTS TO IMPLEMENT NEW ANALYSIS

- Measurement over the ENTIRE wafer (full-field information).
- All curvature components should be measured.

Implications:

- A curvature measurement of all components over a small area is not enough.
- A radial scan is not sufficient since it only provides the radial curvature component.

Extension of Stoney Formula: Non-Uniform Substrate Thickness and Misfit Strain



- Thin film: same as before
- Substrate:

  Equilibrium:

$$\frac{dN_r^{(s)}}{dr}+\frac{N_r^{(s)}-N_\theta^{(s)}}{r}+\tau=0 \qquad \frac{dM_r}{dr}+\frac{M_r-M_\theta}{r}-\frac{h_s}{2}\tau=0$$

same as uniform substrate thickness

non-uniform substrate thickness terms

$$\Rightarrow \begin{cases} \dfrac{d}{dr}\left[h_s\left(\dfrac{du_s}{dr}+\dfrac{u_s}{r}\right)\right]-\left(1-\nu_s\right)\dfrac{dh_s}{dr}\dfrac{u_s}{r}=-\dfrac{1-\nu_s^2}{E_s}\tau \\ \dfrac{d}{dr}\left[h_s^3\left(\dfrac{d^2w}{dr^2}+\dfrac{1}{r}\dfrac{dw}{dr}\right)\right]-\left(1-\nu_s\right)\dfrac{1}{r}\dfrac{dh_s^3}{dr}\dfrac{dw}{dr}=\dfrac{6\left(1-\nu_s^2\right)}{E_s}h_s\tau \end{cases}$$

- Interface: same as before

Extension of Stoney Formula: Non-Uniform Substrate Thickness and Misfit Strain

(Feng et al., JAM, submitted)

- $h_s = h_{s0} + \Delta h_s$ ← thickness variation

  (h_{s0}: average thickness)

- Film stress:

uniform thickness terms

$$\sigma_{rr}^{(f)} + \sigma_{\theta\theta}^{(f)} = \frac{E_s}{3(1-\nu_s^2)h_f}\left\{ h_s^2\kappa_\Sigma - \frac{1-\nu_s}{2}\overline{h_s^2\kappa_\Sigma} + \frac{1}{2}\int_r^R \left[(1-3\nu_s)\kappa_\Sigma(\eta) - 3(1-\nu_s)\kappa_\Delta(\eta)\right] h_s^2(\eta)\frac{h_s'(\eta)}{h_{s0}}d\eta - \frac{1-\nu_s}{R^2}\int_0^R \eta^2\left[\kappa_\Sigma(\eta) - \kappa_\Delta(\eta)\right]h_s^2(\eta)\frac{h_s'(\eta)}{h_{s0}}d\eta \right\}$$

$$\sigma_{rr}^{(f)} - \sigma_{\theta\theta}^{(f)} = -\frac{2E_f h_{s0}}{3(1+\nu_f)}\kappa_\Delta$$

non-uniform thickness terms

where:

$$\kappa_\Sigma \equiv \kappa_{rr} + \kappa_{\theta\theta}$$

$$\kappa_\Delta \equiv \kappa_{rr} - \kappa_{\theta\theta}$$

- Interface shear stress:

$$\tau = \frac{E_s}{6(1-\nu_s^2)}\left\{ \frac{d}{dr}\left(h_s^2\kappa_\Sigma\right) - \frac{1}{2}\left[(1-3\nu_s)h_s^2\kappa_\Sigma - 3(1-\nu_s)h_s^2\kappa_\Delta\right]\frac{h_s'}{h_{s0}} \right\}$$

The film stresses depend on both local curvatures and non-local curvatures

Full Wafer Mapping

Performance specifications

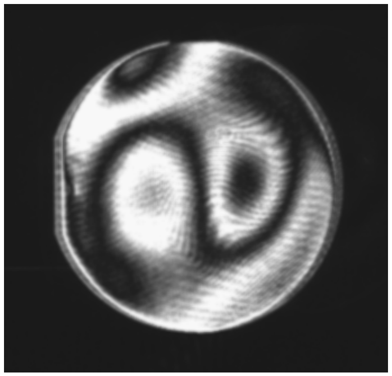
	Topography P-V (nm)	Slope (μrad)	Curvature (m^{-1})	Stress (MPa)
Sensitivity (Calc)	0.15 nm	0.1	1.25×10^{-6}	0.25
Repeatability (1σ)	30	4	1×10^{-5}	2
Accuracy (95% confidence)	greater of 1% or 10 nm	1%	1.5%	2%

- Relevant values for establishing specifications
  - *Laser wavelength: 632.8 nm*
  - *Slope sensitivity: 105 μrad/Half fringe (divide by gray scales)*
  - *Grayscale sensitivity of imaging array: 10-bit (1024 grayscales)*
  - *In-plane resolution / Pixel size: 300 μm (1024x1024 imaging array)*
  - *Film & substrate thickness (stress): 1000Å & 775 μm, respectively*
- Notes

GaAs Substrate Slope (courtesy of Patrick Chin and Dwight Streit NGC)

635 μm GaAs

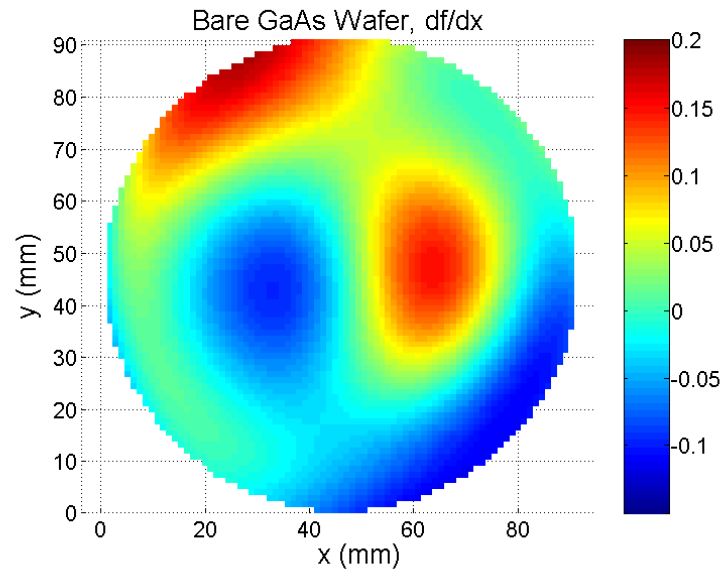
NGC bare wafer

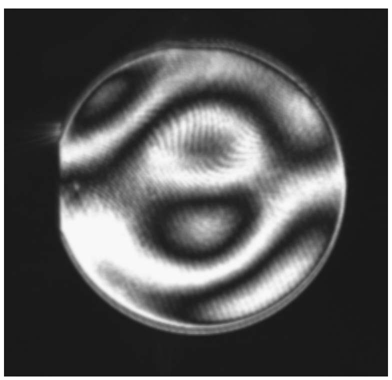


CGS fringes in x-direction

$$\frac{\partial f}{\partial x_1}$$

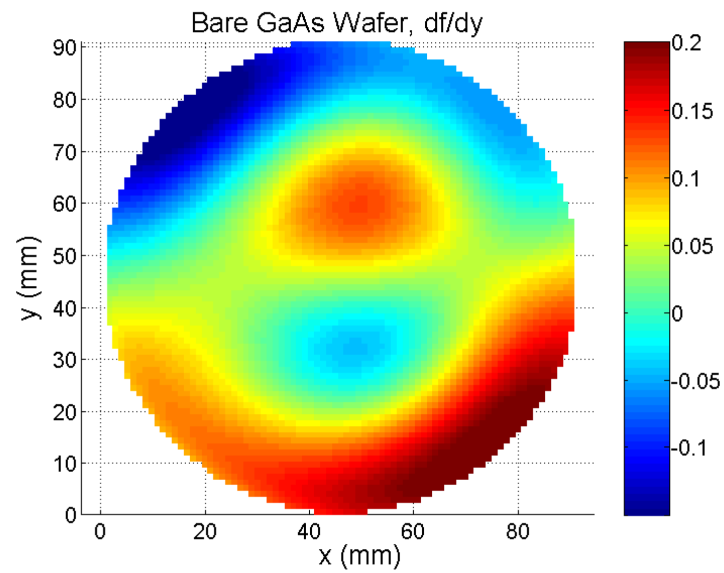
Digitized Slope Maps



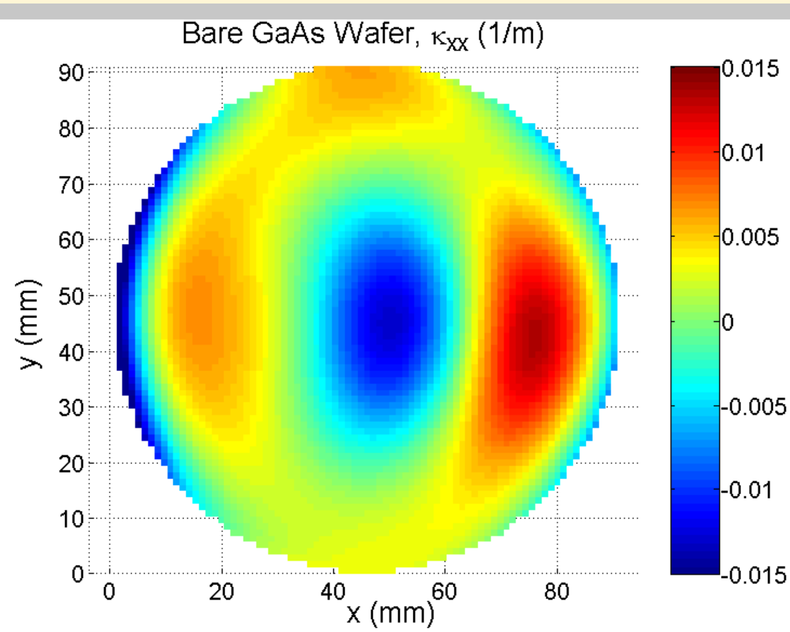


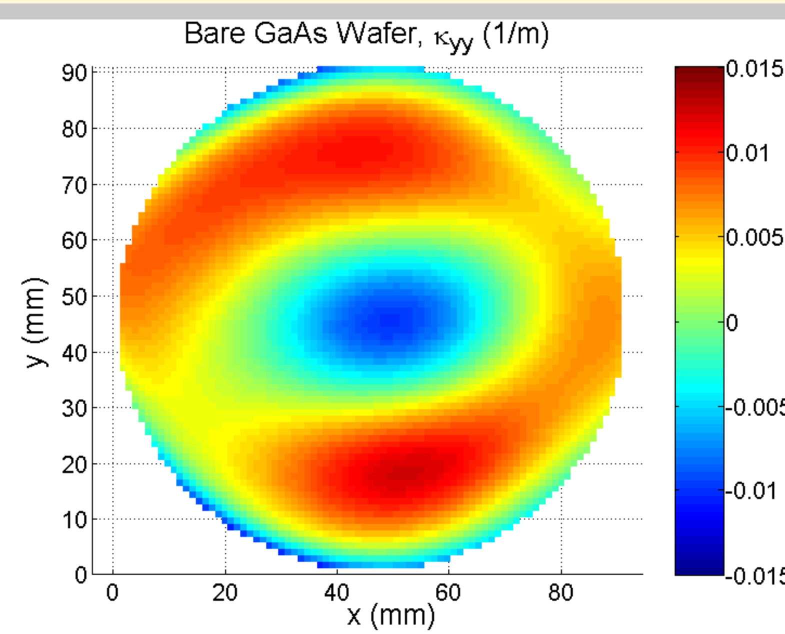
CGS fringes in y-direction

$$\frac{\partial f}{\partial x_2}$$

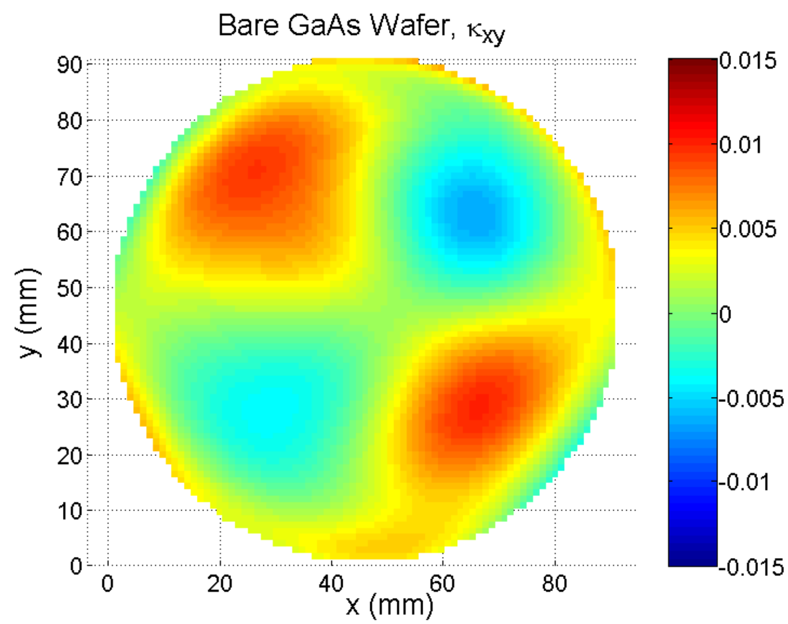


GaAs Substrate Curvature tensor components





$$K_{11} = \frac{\partial^2 f}{\partial x_1^2}$$



$$K_{22} = \frac{\partial^2 f}{\partial x_2^2}$$

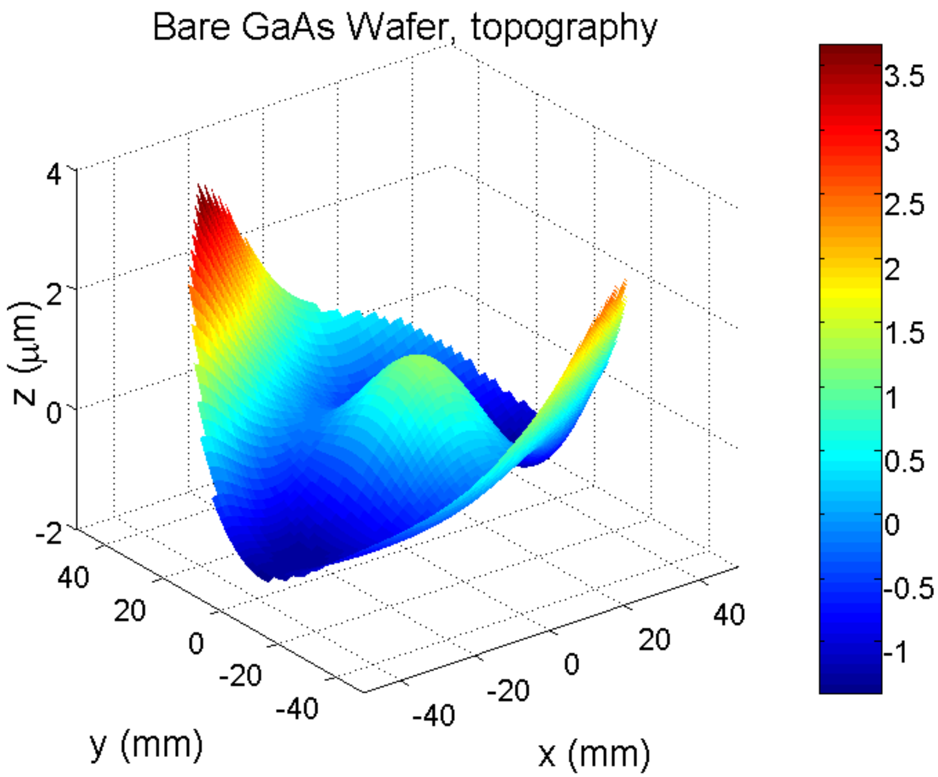
$$K_{12} = \frac{\partial^2 f}{\partial x_1 \partial x_2}$$

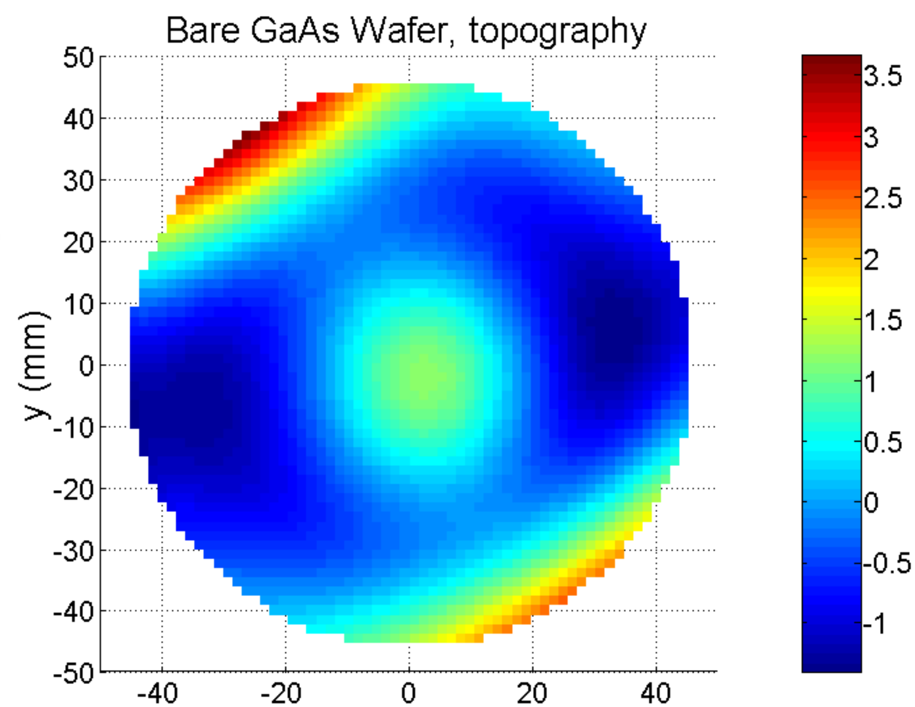
635 μm GaAs

NGC wafer

GaAs Substrate Shape

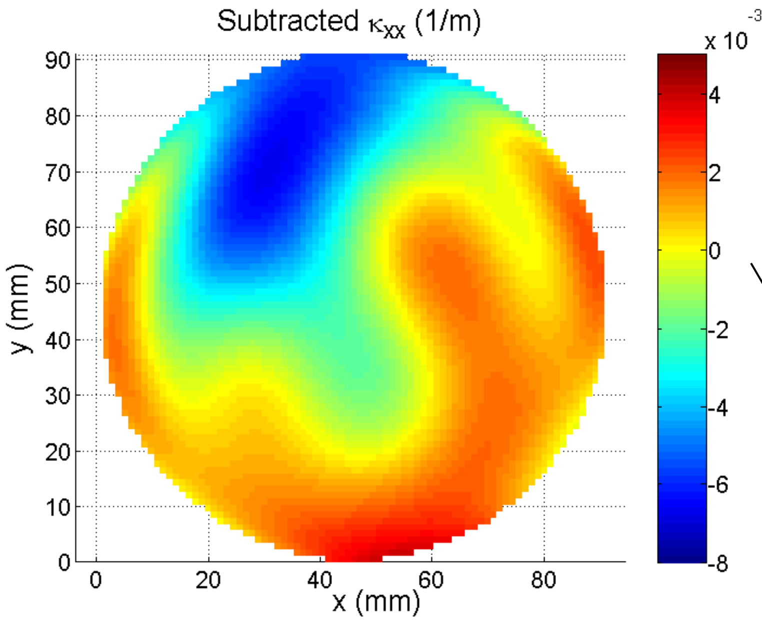
635 μm GaAs



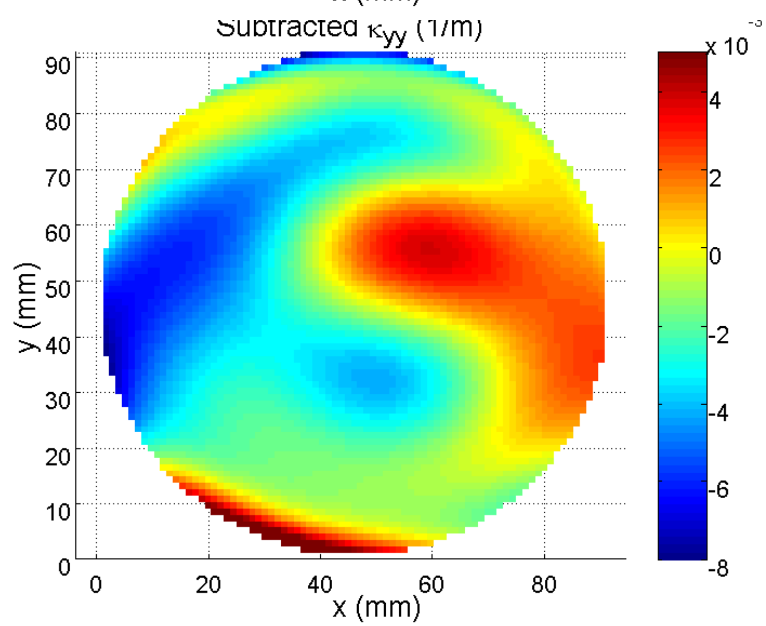


NGC wafers

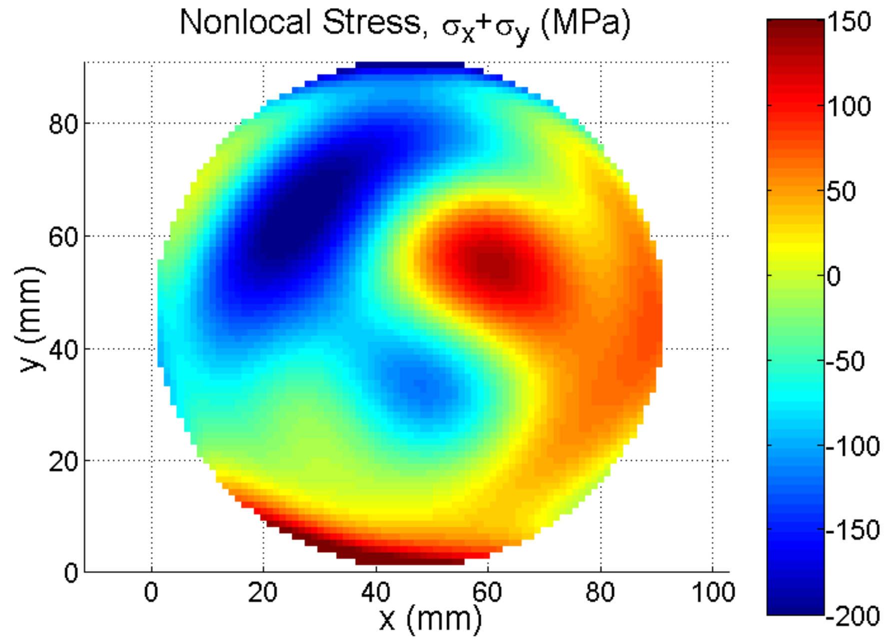
Stress from Single GaAs Layer *NGC wafers*



$$K_{11} = \frac{\partial^2 f}{\partial x_1^2}$$

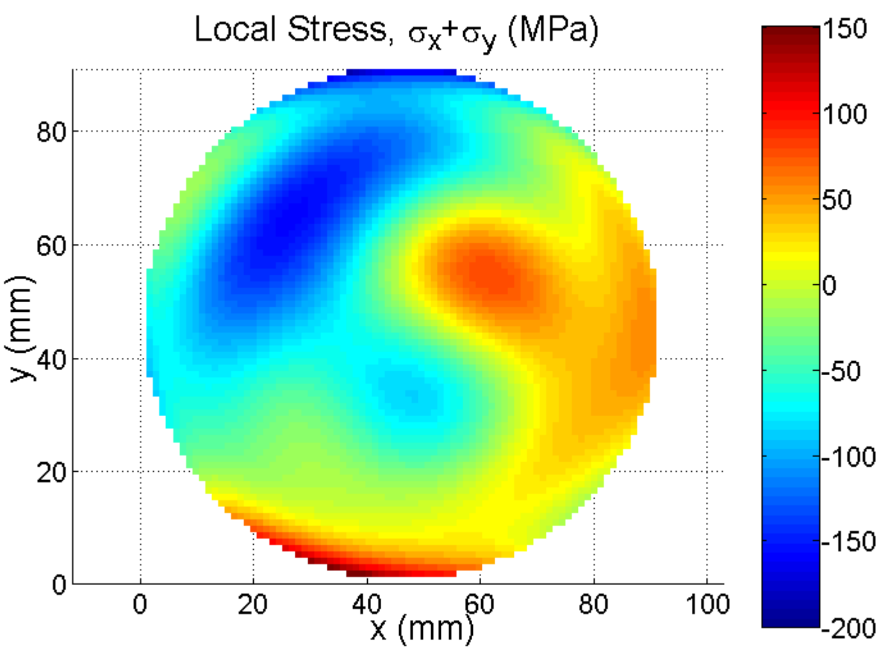


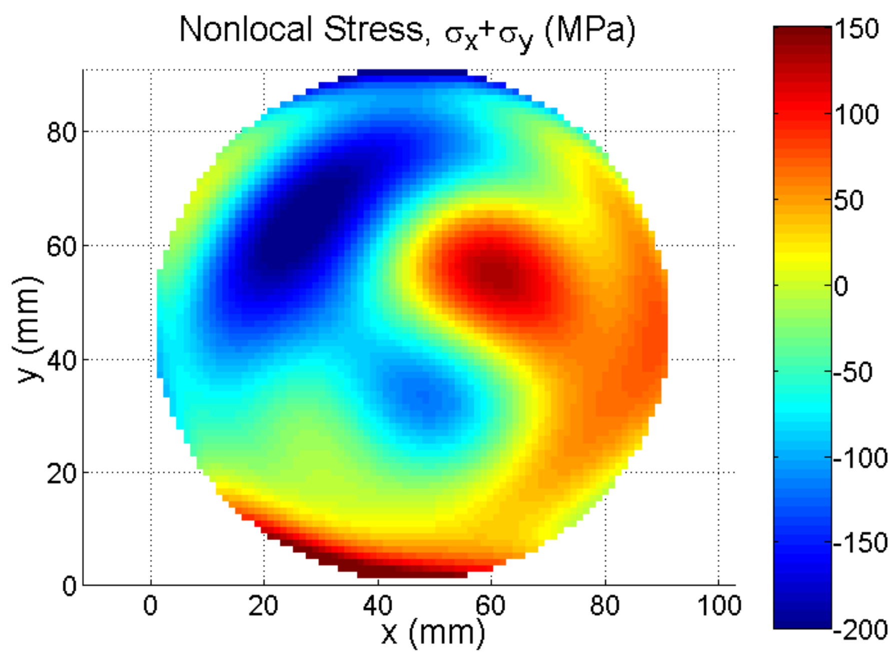
$$K_{22} = \frac{\partial^2 f}{\partial x_2^2}$$



0.6 μm GaAs
635 μm GaAs

Effect of Non-Local Analysis (Stress in Single GaAs Film)





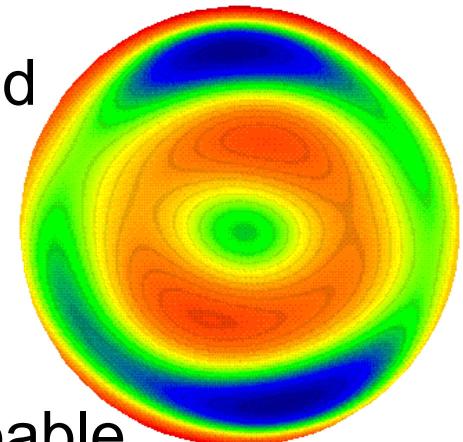
0.6 μm GaAs

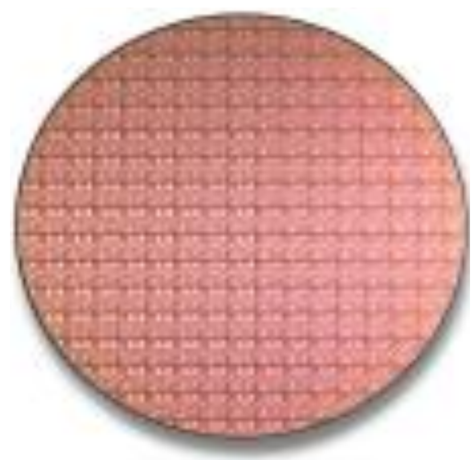
635 μm GaAs

NGC wafers

CGS Overview

- Full field Wafer Mapping. All curvature and stress components available.
    - > 95% of wafer surface analyzed
- Production Capable
    - Front-end and back-end process capable
    - Patterned and blanket wafer measurement
- Instantaneous measurement
- High Throughput
    - All of the above at 25 wph





Only Curvature/Stress Measurement System Designed for In-Line Product Process Monitoring

CONCLUSIONS

- Coherent Gradient Sensing (CGS) interferometry provides a full-field, real-time, *in-situ* slope and curvature measurement over the entire wafer surface

- Non-uniform deformations and stresses have been measured using CGS interferometry in both patterned and unpatterned wafers

- X-ray Microdiffraction has been used to validate the technology

•CGS metrology may be a robust method for the in situ measurement and characterization of wanted or unwanted surface deformations in mirrors used in space systems