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

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 (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**

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

System curvature $\Rightarrow$ film stress
Assumptions and limitations of classical Laser Scanning method

Freund & Suresh, Thin Film materials 2003

Assume spatial uniformity and also:

\[ K_{11} = K_{22} \]
\[ \sigma_{11} = \sigma_{22} \]

\[ \sigma_f = \frac{E_s h_s^2}{6(1-v_s)h_f} \]

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, $x_3 = f(x_1, x_2)$

---

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

(no $\lambda$)

- **Polished Wafer**
- **Patterned Wafer**
- **Wafer with a problem**

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

Interference:

\[ S(x_1, x_2 + \omega) - S(x_1, x_2) = n\lambda \]

Identical wavefronts shifted in space along \( x_2 \).

\( n = 1, 2, 3 \ldots \) for destructive interference (black fringe centers)

\( n = 1 + \frac{1}{2}, 2 + \frac{1}{2} \ldots \) for constructive interference
The Governing Relations of CGS

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

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 \( \lambda \))
Traditional Interferometers

Sample

Reference

\[ f = \frac{n\lambda}{2} \]
Advantage of CGS Interferometer
A Self Referencing Approach

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

Shearing Distance \( \omega \)

Sample

Grating 1

Grating 2

vibration insensitive

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


Reflection mode CGS: out-of-plane deformation field gradients
Transmission mode CGS: gradient of sum of principal (in-plane) stresses
Micro Device Reliability Facility at GALCIT

300 mm Wafer

Shape

X Curvature, $\kappa_{11}$

Twist Curvature, $\kappa_{12}$
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

\[ \frac{df}{dx_2} \]

Interferogram: Vertical Slope

\[ \frac{df}{dx_1} \]

Interferogram: Horizontal Slope

Vertical Slope Map

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

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

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

\[ \kappa_{12} = \frac{\partial^2 f}{\partial x_1 \partial x_2} \]
**The Sailboat Analogy**

Analogy: With boating

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

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

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

\[
K_{12} = \frac{\partial^2 f}{\partial x_1^2 \partial x_2}
\]
CGS slope and Curvature Management in 300mm wafers
SiN Films: Comparison of Interferograms (Test and Patterned Wafer)

Uniform film on Si

\[
\frac{\partial f}{\partial x_2}
\]

Pattern Wafer

696Å Tensile SiN

1250Å Compressive SiN

1200Å Highly Compressive SiN
300mm Patterned Wafer (Curvature Maps)

X Interferogram

Y Interferogram

X Curvature

Y Curvature

Twist Curvature

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

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

\[ K_{12} = \frac{\partial^2 f}{\partial x_1 \partial x_2} \]
Curvature Changes Before and After Deposition Process

Interferograms

Prior to deposition

After deposition

Vertical Curvature

$k (1/m)$  $\sigma (MPa)$

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<th>$\sigma$ (MPa)</th>
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$1 \mu m$ film / $775 \mu m$ substrate
Comparison of Stress Non-Uniformity and level
LSA vs. Flash Anneal

\[ \sigma_{\text{max}} = 3377 \pm 874 \text{ MPa} \]

\[ \sigma_{\text{max}} = 240 \pm 11.2 \text{ MPa} \]

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

Bare GaAs Wafer, topography

635 μm GaAs

NGC wafers
Topography for Lithography

Topography of a chucked wafer

Slope map (resolution ~ 0.1μrad)
Advantage of CGS Interferometer
Patterned Wafer Measurement

- Phase shifting is a common interferometric 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
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**

- Single Data Points

**CGS Breakthroughs**

- 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

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 \( \varepsilon_m \)
   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.

\[ h_f \ll h_s \ll R \]

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
A) **ASSUMPTIONS (Cont’d)**

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

B) **THE CLASSICAL STONEY:**

\[
\kappa = \kappa_{rr} = \kappa_{\theta\theta} = 6 \frac{E_f h_f}{1 - \nu_f} \frac{1 - \nu_s}{E_s h_s^2} \varepsilon_m. \quad \sigma^{(f)} = \sigma^{(f)}_{rr} = \sigma^{(f)}_{\theta\theta} = \frac{E_f}{1 - \nu_f} \varepsilon_m
\]

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

**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.

Maximum (radial)

Minimum (circumferential)

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

\[
K_{1,2} = \frac{K_{\theta\theta} + K_{rr}}{2} \pm \left\{ \left( \frac{K_{rr} - K_{\theta\theta}}{2} \right)^2 + K_{r\theta}^2 \right\}^{1/2}
\]
**HR STRESS/CURVATURE RELATIONS** \[ \varepsilon_m = \varepsilon_m(r) \]

**“Local” Stoney:**
\[
\sigma_{rr} + \sigma_{\theta\theta} = \frac{E_s h_s^2}{6(1 - \nu_s) h_f} \left( \kappa_{rr} + \kappa_{\theta\theta} \right)
\]

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

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

\[ \text{where} \quad \kappa_{rr} + \kappa_{\theta\theta} = \frac{1}{\pi R^2} \int_0^1 \int_0^{2\pi} (\kappa_{rr} + \kappa_{\theta\theta}) \eta d\eta d\theta \]

\[ = \frac{2}{R^2} \int_0^K \eta (\kappa_{rr} + \kappa_{\theta\theta}) d\eta \]

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

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

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.*
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:

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

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

First define coefficients as

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

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

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

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

\[
- \frac{1 - \nu_s}{1 + \nu_s} \sum_{n=1}^{\infty} (n+1) \left( \frac{r}{R} \right)^n \left( C_n \cos n\theta + S_n \sin n\theta \right)
\]

where \( \kappa_{rr} + \kappa_{\theta\theta} = C_0 = \int_A \int (\kappa_{rr} + \kappa_{\theta\theta}) dA / \pi R^2 \)

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

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

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

Fully non-uniform portion depends on integrals of curvature

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

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

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

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

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

The lack of radial symmetry allows for a circumferential shear component.

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

Experiments involving severe non-uniformities

THICKNESS AND FILM STRESS

The system has:
- Axisymmetric misfit strain
- Non-uniform film thickness

Material Properties:
- W film: $E_f = 411 \text{ GPa}, \nu_f = 0.28$
- Si substrate: $E_s = 130 \text{ GPa}, \nu_s = 0.28$

100 mm

25 mm

cross section

1.85 \mu m
525 \mu m

top view
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 measurements: At ALS (LBNL)

Compared data along wafer diameter

- beam size is order of $1\mu$m ⇒ direct stress/curvature measurement of small volume structures ⇒ validation of analysis. Brown et. al. JAM 05, IJSS, 06

Comparison of CGS and XRD Slope

![Graph showing comparison of CGS and XRD slopes.](image-url)
X-Ray Microdiffraction

**White beam**

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

**Monochromatic**

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

**X-rays**

- Grain size > or ~ beam size
- Single Crystal or Large Grain

- Grain size << beam size
- Polycrystalline with small grains
Slope measured by X-Ray Diffraction (XRD)

XRD slope along diameter direction

\[
\begin{align*}
\frac{\partial f}{\partial r}_{\text{island}} &= p_1 r^4 + p_2 r^3 + p_3 r \\
\frac{\partial f}{\partial r}_{\text{outside}} &= a e^{br} + c e^{dr}
\end{align*}
\]

\[
\begin{align*}
p_1 &= -4.599E - 5; p_2 = 0.0004727; p_3 = -0.2173 \\
a &= -6.72; b = -0.115; c = -1.44; d = -0.00329
\end{align*}
\]
Curvatures from XRD slope

\[ \kappa_{rr} = \frac{\partial^2 f}{\partial r^2}, \quad \kappa_{\theta\theta} = \frac{\partial f}{r \partial r} \]

\( \kappa_{\theta\theta} \) is continuous, but \( \kappa_{rr} \) is discontinuous at the film edge
Measurement of film thickness

Film thickness is non-uniform!

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

\[ \sigma = \frac{E_s h_s^2}{6(1-v_s) h_f} \kappa \]

Stoney: \( h_f = \text{const} \)

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

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

\[
\frac{dN_r^{(s)}}{dr} + \frac{N_r^{(s)} - N_\Theta^{(s)}}{r} + \tau = 0
\]

\[
\frac{dM_r}{dr} + \frac{M_r - M_\Theta}{r} - \frac{h_s}{2} \tau = 0
\]

- 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
  
  average thickness

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

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

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

  where:

  \( \kappa_{\Sigma} = \kappa_{rr} + \kappa_{\theta\theta} \)

  \( \kappa_{\Delta} = \kappa_{rr} - \kappa_{\theta\theta} \)

The film stresses depend on both **local** curvatures and **non-local** curvatures
### Full Wafer Mapping

**Performance specifications**

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<tr>
<th></th>
<th>Topography P-V (nm)</th>
<th>Slope (μrad)</th>
<th>Curvature (m⁻¹)</th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (Calc)</td>
<td>0.15 nm</td>
<td>0.1</td>
<td>1.25x10⁻⁶</td>
<td>0.25</td>
</tr>
<tr>
<td>Repeatability (1°)</td>
<td>30</td>
<td>4</td>
<td>1x10⁻⁵</td>
<td>2</td>
</tr>
<tr>
<td>Accuracy (95% confidence)</td>
<td>greater of 1% or 10 nm</td>
<td>1%</td>
<td>1.5%</td>
<td>2%</td>
</tr>
</tbody>
</table>

- 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 grayscale)
  - 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

\[ \frac{\partial f}{\partial x_1} \]

CGS fringes in x-direction

Digitized Slope Maps

\[ \frac{\partial f}{\partial x_2} \]

CGS fringes in y-direction
GaAs Substrate Curvature tensor components

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

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

\[ K_{22} = \frac{\partial^2 f}{\partial x_2^2} \]
GaAs Substrate Shape

Bare GaAs Wafer, topography

635 μm GaAs

NGC wafers
Stress from Single GaAs Layer  NGC wafers

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

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

Nonlocal Stress, \( \sigma_x + \sigma_y \) (MPa)

Subtracted \( \kappa_{xx} \) (1/m)

Subtracted \( \kappa_{yy} \) (1/m)

0.6 \( \mu \)m GaAs

635 \( \mu \)m GaAs
Effect of Non-Local Analysis
(Stress in Single GaAs Film)

Local Stress, $\sigma_x + \sigma_y$ (MPa)

Nonlocal Stress, $\sigma_x + \sigma_y$ (MPa)

0.6 $\mu$m GaAs
635 $\mu$m 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, \textit{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.