Recent Trends in Super-Precision 3D Measurement Technology

- Innovative Algorithms for Optical Interferometry and their Applications -

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Contents

- Background: Conventional Interferometry & Its Problem
- New Algorithms:
  1. Speed improvement by sub-Nyquist sampling (SEST)
  2. Accuracy improvement by using phase information (WSI)
  3. Transparent film profiling
     1. Profiling of a transparent film on a substrate (KF/NF)
     2. Profiling of a freestanding film (TF)
     3. Simultaneous measurement of thickness and refractive index
  4. One-shot Interferometry
     1. One-wavelength
     2. Three-wavelength
How Small is a Nanometer?

1 m : 1 nm = 700 km: 0.7mm

Optics

CCD Camera
White Light
Beam Splitter
Piezo Actuator
Objective Lens
Michelson Interferometer
Conventional Techniques

- For flat surfaces
  - PSI (Phase-Shift Interferometry):
    --- Phase detection from 4-5 images

- For rough surfaces
  - VSI (Vertical Scanning Interferometry):
    --- Modulation peak detection from 20-100 images

VSI: White-Light Interferometry
VSI:
White-Light Interferometry

Objective Lens
Reference Mirror
Interference Plane
Object

VSI:
White-Light Interferometry

Intensity

Peak Position
Surface Height

$\lambda / 2 \approx 0.3 \mu m$
Motivation

- Toray Engineering:
  - Equipment supplier mainly for semiconductor & FPD industries

- Problem of Conventional Profiler:
  - Too slow or too narrow range
  - Error caused by a transparent film
  - Highly susceptible to vibration
  - Not applicable to moving object

Speed Improvement by Sub-Nyquist Sampling

- SEST algorithm -

SEST = Squared-Envelope function estimation by Sampling Theory
**SEST Algorithm (1)**

Sampled Data  

Reconstructed Waveform  

Sub-Nyquist Sampling  

Speed-up: Faster scan speed

**Bandwidth of Interferogram**

\[ f(z) = \int_{k_l}^{k_u} \psi(k) \cos 2k(z - z_p) dk \]  

Band-limited
Sampling Theorem for Band-limited Signal

When the frequency bandwidth of $f(z)$ is limited to $\lambda_c \pm \lambda_b$, $f(z)$ can be reconstructed from its sampled data $y_m$ *

$$f(z) = \sum_{m=1}^{M} y_m \phi_m(z)$$

where

$$\phi_m(z) = \text{sinc}\left[\frac{\pi(z - z_m)}{2\Delta}\right] \cos\left[\frac{4\pi(z - z_m)}{\lambda_c}\right]$$

Sampling interval $\Delta$:

$$\Delta_{max} = \left[\frac{\lambda_c + \lambda_b}{2\lambda_b}\right] \left[\frac{\lambda_c - \lambda_b}{4}\right]$$

SEST Algorithm (2)

Sub-Nyquist Sampling

Speed-up: Direct Calculation of Envelope
**Squared Envelope Function**

At the sampling points

\[
r(z_j) = \left\{ f(z_j) \right\}^2 + \frac{4}{\pi^2} \left\{ \sum_{n=-\infty}^{\infty} \frac{f(z_{j+2n+1})}{2n+1} \right\}^2
\]

At the non-sampling points

\[
r(z) = \frac{2\Delta^2}{\pi^2} \left[ \left( 1 - \cos \frac{\pi z}{\Delta} \right) \left\{ \sum_{n=-\infty}^{\infty} \frac{f(z_{2n})}{z - z_{2n}} \right\}^2 + \left( 1 + \cos \frac{\pi z}{\Delta} \right) \left\{ \sum_{n=-\infty}^{\infty} \frac{f(z_{2n+1})}{z - z_{2n+1}} \right\}^2 \right]
\]

---

**Surface Profiler**

**SP-500**

**Specifications (basic model)**

- **Range** : 100 μm
- **Resolution** : 0.01～1nm
- **Scan Speed** : max 60 μm/sec
  
  by the SEST algorithm

http://www.scn.tv/user/torayims/
Measurement Result of Step Height with 25.5 μm/sec Scan Speed

Sampled Data, Reconstructed Waveform and Envelope

Sampled Data with 0.85 μm interval
Reconstructed waveform
Calculated envelope
Demo: IC bumps
with 58.5 μm/sec scan speed

Accuracy Improvement by Using Phase Information
- WSI algorithm -
WSI Algorithm

- Sometimes called WLPSI
- At first finds the envelope peak frame \(N_p\)
- Then calculates the relative phase \(\varphi_r\) at the position
- Obtains the height (\(z\)) by
  \[ z = N_p \cdot \Delta - (\lambda/4\pi)\varphi_r \]
  where
  \(\Delta = \) sampling interval,
  \(\lambda = \) the wavelength

Comparison of three methods

<table>
<thead>
<tr>
<th>Method</th>
<th>VSI</th>
<th>PSI</th>
<th>WSI</th>
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<tbody>
<tr>
<td>Light</td>
<td>White</td>
<td>Monochro</td>
<td>White</td>
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<tr>
<td>Principle</td>
<td>Peak</td>
<td>Phase</td>
<td>Peak &amp; Phase</td>
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<td>Surface</td>
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<td>Smooth only</td>
<td>Any</td>
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<td>Accuracy</td>
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<td>0.01 nm typ.</td>
<td>1 nm typ.</td>
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<tr>
<td>Scan Speed</td>
<td>Any</td>
<td>---</td>
<td>2.4 um/sec typ.</td>
</tr>
<tr>
<td>Calc. Time</td>
<td>Long</td>
<td>Short</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Industry’s #1 performance
Test Results: 1 μm Step Height

Profiling of a Transparent Film
Problem Caused by a Transparent Film

- Reflection from back surface interferes
- False profile obtained

Film Profiling

- Thick vs Thin

KF Method (2002)
Profiling of a Thick Transparent Film

- KF Algorithm -

**Principle**

- Surface and Back-surface Profiles are obtained from the interferogram
- Film thickness is calculated with known refractive index (n)

![Optical Thickness (n*t)](image)

<p>| | | |</p>
<table>
<thead>
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<tr>
<td>HR[um]</td>
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<tr>
<td>n*t[um]</td>
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<td>n</td>
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<tr>
<td>t[um]</td>
<td>4.227</td>
<td></td>
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</table>

Front Surface  Back Surface
Reported Technologies

- Measurement of a thick transparent film
  - Flournoy: Film thickness gauge (1967)
  - Tsuruta, Ichihara: Lens thickness (1972)
  - Nakamura, Toyoda: Subsurface profile (1991)
  - Itoh, Yamada et al.: Film Thickness (1995)
- No practical algorithm proposed
- No product commercially available

KF Algorithm

Interferogram

Squared AC components

Optimum Threshold

Separated peaks
Peak Separation Method

- Automatic Threshold Selection Algorithm for Image Analysis
- Otsu's method is adopted
  \[ f = \omega_1 \sigma_1^2 + \omega_2 \sigma_2^2 \rightarrow \min \]

- \( \omega_1, \omega_2 \): frequency of classes
- \( \sigma_1, \sigma_2 \): variance of classes

Test Results: Film Step

Oxide Film
4 µm Thick

1 µm Thick

Si Wafer
Test Results: Film Step

Measurement of Resist Film with Unknown Refractive Index

Front Surface Step (Thickness $t$) = 1.6 μm
Film Thickness Calculated with \( n=1 \)

\[
\text{Optical thickness}(n \times t) = 3.0 \mu m
\]

Estimation of Refractive Index

- **Method 1**: Refractive index (\( n \)) = Optical thickness(\( n \times t \)) / Surface step(\( t \))
  
  \[
  = 3.0 / 1.6 \\
  = 1.9
  \]

- **Method 2**: Visual estimation from the back surface profiles calculated with different refractive indexes

  \( n = 1.88 \)  \hspace{1cm}  \( n = 1.90 \)  \hspace{1cm}  \( n = 1.92 \)
Measurement Result of Resist Film

Profiling of a Thin Transparent Film - NF Algorithm -
Reported Technologies

- Measurement of a thin film using interferometry
  - S.W. Kim and G.H. Kim (1999)
  - D. Kim et al. (2002)
- No practical algorithm proposed for white-light interferometry
- No product commercially available

Test Results: Film Thickness Standards

Graph showing the relationship between nominal thickness (nm) and measured thickness (nm) for a range of values from 0 to 800 nm.
Test Results: Thin Film Step

Etched Depth
200nm

Oxide Film
300nm Thick

Si Wafer

Test Results: Thin Film Step

Front Surface

Thickness

Back Surface
Film Profiler SP-700

- Based on the KF & NF Algorithm
- Simultaneous Measurement of Front and Back Surface Profiles
- Plus Film Thickness Distribution
- World’s First Product (released in 2002 & 2006)

Film Thickness Profiling by Pseudo-Transmission Interferometry (TF Method)
**Problems of Freestanding Films**

- Film on Substrate:
  - KF method
  - NF method

- Freestanding Film:
  - Unstable
  - Not flat

**Principle of TF method**

Optical path difference ($D$) between air and the film

$$D = (n-1)t$$

Sample Film ($t$, $n$) (positioned out of range)
**Test Result: PET Film**

- PET Film (nominal 0.9μm; n=1.65)

Average height difference $D = 0.581 \mu m$

Thickness $t = \frac{D}{n-1} = 0.894 \mu m$

---

**Correlation between the measured values and the nominal values**

![Graph showing correlation between measured and nominal thickness values. The equation $y = 1.089x - 0.089$ with $R = 0.999$.]
Simultaneous Measurement of Thickness and Refractive Index

Principle

- Combine the results of two measurements:
  1) the optical thickness $T$ by the KF method,
  2) the optical path difference $D$ by the TF method

- Since $T = n \times t$ and $D = (n - 1) \times t$,
  the thickness ($t$) and the refractive index ($n$) can be obtained by the following equations;

  $t = T - D$
  $n = T/(T - D)$
**Test Results: PET Film**

- Refractive index and thickness are obtained from the results of the KF and TF methods

![Graph showing refractive index and thickness](image)

**Test Results: Glass Plate**

Sample: Nominal thickness 30μm

- thickness
- refractive index

![Graphs showing thickness and refractive index](image)
One-Shot Interferometry

Motivation

- Toray Engineering Co.:
  - Equipment supplier mainly for semiconductor & FPD industries

- Problems of conventional surface profiling
  - Too slow
  - Highly susceptible to vibration
  - Not applicable to moving objects
**Spatial Carrier Interferometry**

- Tilted reference surface
- Fringe analysis

![Interferogram with carrier fringes]

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**Reported Algorithms of Fringe Analysis**

- Fourier method [Takeda et al., 1982]

**Problems:**
- High frequency components filtered out
- High calculation cost
- Phase ambiguity problem resulting in low measurement range

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**Local Model Fitting (LMF) Algorithm**

**LMF Algorithm (1)**

- The observed signal is given by
  \[ g(x_i) = a(x_i) + b(x_i) \cos \left( 2\pi f_x x_i + \phi(x_i) \right) \]

\[ i = 1, \ldots, k \]

- \( a(x_i) \) : bias
- \( b(x_i) \) : amplitude
- \( f_x \) : carrier frequency
- \( \phi(x_i) \) : phase
**LMF Algorithm (2)**

- Model for LMF

Assumption: Locally \( a(x_i), b(x_i), \phi(x_i) \) are constant.

Then

\[
g(x_i) = a + b \cos\{2\pi f_x x_i + \phi\}
\]

\( a, b, \phi \) : three unknown variables

**LMF Algorithm (3)**

- \( a, b, \phi \) are estimated by least-square fitting

\[
\min_{(a,b,\phi)} \sum_{i=1}^{k} [g(x_i) - a - b \cos(2\pi f_x x_i + \phi)]^2
\]

Nonlinear with respect to \( \phi \)

- Reparameterization

\[
\xi_x = b \cos \phi \quad \xi_s = b \sin \phi
\]

\[
\min_{(a,\xi_x,\xi_s)} \sum_{i=1}^{k} [g(x_i) - a - \xi_x \phi_c(x_i) - \xi_s \phi_s(x_i)]^2
\]

\( \phi_c(x) = \cos(2\pi f_x x) \quad \phi_s(x) = -\sin(2\pi f_x x) \)

Linear with respect to \( a, \xi_x, \xi_s \)
**LMF Algorithm (4)**

- \( a, \xi_c, \xi_h \) are obtained by the linear simultaneous equations:

\[
A \begin{pmatrix} \hat{a} \\ \hat{\xi}_c \\ \hat{\xi}_h \end{pmatrix} = g,
A = \begin{pmatrix}
\pi & \sum \phi_i(x_i, y_i) & \sum \phi_i(x_i, y_i) \\
\sum \phi_i(x_i, y_i) & \sum \phi_i(x_i, y_i) \rho_i(x_i, y_i) & \sum \phi_i(x_i, y_i) \rho_i(x_i, y_i) \\
\sum \phi_i(x_i, y_i) \rho_i(x_i, y_i) & \sum \phi_i(x_i, y_i) \rho_i(x_i, y_i) & \sum \phi_i(x_i, y_i) \rho_i(x_i, y_i)
\end{pmatrix},
\]

\[
g = \begin{pmatrix}
\sum \mu_i(x_i, y_i) \\
\sum \mu_i(x_i, y_i) \rho_i(x_i, y_i) \\
\sum \mu_i(x_i, y_i) \rho_i(x_i, y_i)
\end{pmatrix}.
\]

- Since \( \xi_h / \xi_c = \tan \phi \), \( \hat{\phi} = \arctan(\hat{\xi}_h / \hat{\xi}_c) + 2m\pi \quad (m:\text{integer}) \)

- Then \( h = \left( \hat{\phi} / 2\pi + m \right) \left( \lambda / 2 \right) \)

---

**Test Result:**

**67nm Step Height**

*Captured Image*

*Measured Surface by LMF Algorithm (k=7)*
Problem of One-Wavelength Interferometry

- Phase ambiguity problem
  - Caused by phase wrapping
  - Needs phase unwrapping
  - $\lambda/4$ limit between neighboring pixels
  - Narrow measurement range
  - Common with PSI
- Multi-wavelength technique in PSI is applicable to one-shot method
- However, simultaneous multi-wavelength imaging is essential

Three-Wavelength One-Shot Method
Three-Wavelength Optics

Features:
- Low cost
- Compact

<table>
<thead>
<tr>
<th>Color</th>
<th>Center Wavelength (nm)</th>
<th>Bandwidth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>627</td>
<td>20</td>
</tr>
<tr>
<td>G</td>
<td>530</td>
<td>35</td>
</tr>
<tr>
<td>B</td>
<td>470</td>
<td>25</td>
</tr>
</tbody>
</table>

Spectral Curves of LEDs and Color Camera

Crosstalk is not negligible
Experimental Setup

- Color camera
- Microscope
- Objective lens
- LED illuminator
- Sample stage

Experiments

- Sample: 1 μm nominal step height

Surface profile by white-light interferometry
**Flow Chart**

1. Captured Image
2. Color Decomposition
   - B
   - G
   - R
3. Crosstalk Correction \((B,G,R)\)
4. Frequency Estimation \((f_B, f_G, f_R)\)
5. Phase Calculation \((\phi_B, \phi_G, \phi_R)\)
6. Unwrapping
7. Height \(h(x,y)\)

---

**Color Decomposition**

1. Captured Fringe Image
2. Decomposition
3. B Image
4. G Image
5. R Image
Crosstalk Correction

- Crosstalk model:
  
  \[
  \begin{align*}
  B' &= B + aG + bR \\
  G' &= cB + G + dR \\
  R' &= eB + fG + R
  \end{align*}
  \]
  
  where \((B', G', R')\) are observed intensities, \((B, G, R)\) are true intensities and \(a, b, c, d, e, f\) are parameters.

- Crosstalk correction matrix:
  
  \[
  \begin{pmatrix}
  B \\
  G \\
  R
  \end{pmatrix} =
  \begin{pmatrix}
  B' \\
  G' \\
  R'
  \end{pmatrix}
  \]
  
  \[
  \begin{pmatrix}
  1 & 0.05 & 0.00 \\
  0.28 & 1 & 0.04 \\
  0.01 & 0.04 & 1
  \end{pmatrix}
  \]
  
  (Simplified under the assumption that the parameters are small)

Determination of Crosstalk Parameters

- From color images with one LED illumination

![Graph] Correlations between G, R and B when only B-LED is on

Obtained crosstalk parameters
Effect of Crosstalk Correction (1)
- Comparison of G value waveforms

Effect of Crosstalk Correction (2)
- Correlation between RGB color values after the correction

Crosstalk correction algorithm is proved correct.
Effect of Crosstalk Correction (3)

- Spectral comparison

![Graph showing amplitude vs. wavelength with raw and compensated data.]

Fringe Frequency Estimation

- Essential for correct multi-wavelength unwrapping
- Conventional methods
  - FFT
  - Zero-cross detection
  - Peak counting
  - Prony method
  - Parameter fitting

- "Phase gradient method"
  ① High precision
  ② Fast
  ③ Two dimension
**Phase Gradient Method**

Observed data with freq. $f$: $g(x) = A \cos(2\pi f x + \phi(x))$

Model with initial freq. $f_0$: $g'(x) = A' \cos(2\pi f_0 x + \phi'(x))$

Obtained phase: $\phi(x) = 2\pi(f - f_0)x + \phi(x)$

In a flat surface area, where $\phi(x) =$constant,

$f = f_0 + (d\phi / dx) / 2\pi$

Phase gradient depends on the frequency error.

---

**Computer Experiment**

**[Conditions]**
- Observed data: $g(x) = \cos(2\pi f x)$
- Added noise: uniform (-0.1, +0.1)
- Model: $g'(x) = A' \cos(2\pi f_0 x + \phi'(x))$
- True freq. $f$: 0.020
- Initial freq. $f_0$: 0.019 (relative error 5%)
- Number of data: 25 pixels

**[Results]**
- Phase gradient: 0.00628
- Estimated freq.: $0.019 + 0.00628/2\pi = 0.02000$
- Relative error: <1/2000
**Frequencies Estimation of Actual Fringe Pattern**

- By the phase gradient method
- At the flat area (400 × 200 pixels)
- Phase calculation by LMF method (25 × 5 pixels)

**Estimated Frequencies**

<table>
<thead>
<tr>
<th>Color</th>
<th>( f_x ) (1/pix)</th>
<th>( f_y ) (1/pix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.0394</td>
<td>0.0005</td>
</tr>
<tr>
<td>G</td>
<td>0.0343</td>
<td>0.0005</td>
</tr>
<tr>
<td>R</td>
<td>0.0301</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

**Three-wavelength Phase Unwrapping**

- Based on the exact fractions method
- The integral orders are determined so that the three heights coincide best

\[
h_1(n_1) = (\phi_1 / 2\pi + n_1) \cdot (\lambda_1 / 2)
\]
\[
h_2(n_2) = (\phi_2 / 2\pi + n_2) \cdot (\lambda_2 / 2)
\]
\[
h_3(n_3) = (\phi_3 / 2\pi + n_3) \cdot (\lambda_3 / 2)
\]

Minimum Error
Profiles of Intensity, Phases and Height

Intensity (R)

Phases

Height

Measurement Result
Measurement Result in 3D

Surface profile by one-shot method

Demo: 1 μm Step Height

By this PC (1.6GHz cpu)
Conclusions

- Recent rapid advances in electronics and computer technology now allow the incorporation of newly developed, sophisticated algorithms in interferometric profilers, with dramatic results.
- These advances indicate the superb future potential of this technology and signal the beginning of a ‘2nd generation of interferometry’.

Thank you!

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