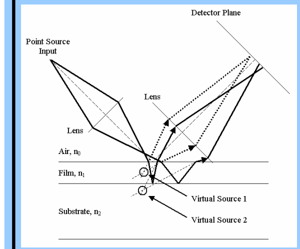
Thin film optical metrology using principles of wavefront sensing and interference.

D.M. Faichnie, I. Bain and A.H. Greenaway
School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh

Aberration Modelling

Measurement Principle



Illumination of film structure results in Fresnel reflection from each film interface. Associated wavefronts are analysed simultaneously.

- **Illumination of a thin film with a converging laser beam results in aberrations being introduced into reflected fields.**
- **The analysis of such aberrations allows a measure of film thickness and surface shape in a single measure.**
- **A thickness retrieval algorithm based on Moore – Penrose pseudo-inverse can be formulated to retrieve film thickness and surface tilt from aberration mode strengths.**

Each aberration coefficient can be written as a combined linear function of thickness (d) and tilt (t) :

$$s_m = a_m d + b_m t$$

By selecting various Zernike coefficients this can be expressed in matrix form :

$$\Sigma = Mu$$

where :

$$M = \begin{bmatrix} a_{m_1} & b_{m_1} \\ a_{m_2} & b_{m_2} \\ . & . \\ a_{m_n} & b_{m_n} \end{bmatrix} \qquad \Sigma = \begin{bmatrix} s_{m_1} \\ s_{m_2} \\ . \\ s_{m_n} \end{bmatrix} \qquad u = \begin{bmatrix} d \\ t \end{bmatrix}$$

Thickness and tilt are then calculated using :

$$u = M^{\dagger}\Sigma$$

Example calculation: 100µm film, 1mrad tilt

$$M = \begin{bmatrix} 0.007452 & -2.559405 \\ 0.002820 & -3.777644 \\ -0.017464 & 7.561416 \\ 0.003660 & -1.282303 \end{bmatrix} \qquad \Sigma = \begin{bmatrix} -1.8246472 \\ -3.512169 \\ 5.8394112 \\ -0.9215989 \end{bmatrix}$$

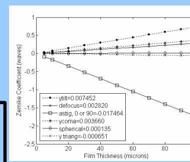
Values gained from gradients of straight line fits in plots.

$$u = \begin{bmatrix} d \\ t \end{bmatrix} = M^{\dagger}\Sigma = \begin{bmatrix} 100.48 \\ 1.0045 \end{bmatrix}$$

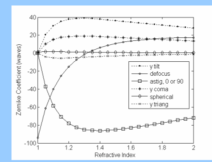
Effect of Refractive Index.

- **Aberration mode strength has dependency on refractive index.**
- **A non-linear relationship exists between mode strength and refractive index from plot.**
- **This non-linear relationship could be used to indicate a change in material refractive index.**
- **Refractive index has limited impact on thickness measurement when refractive index limited to 1.4 to 1.7.**

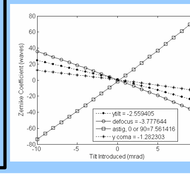
Thickness Variation



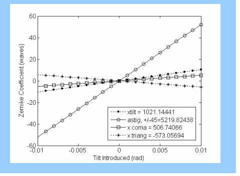
Refractive Index Variation



Horizontal Tilt Variation

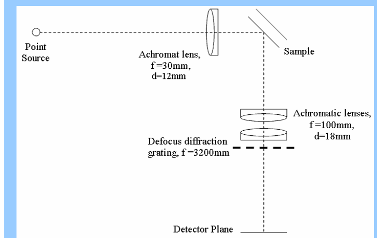


Vertical Tilt Variation



Wavefront sensing for thin film metrology

Experimental set-up

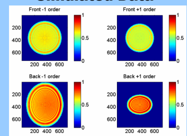


- **Sample under test illuminated with focused laser beam with focus nominally set at the first film interface.**
- **Wavefront sensor consists of lens, grating and detector.**
- **Wavefront sensor analyses each Fresnel reflection from each film interface.**
- **Wavefront reconstruction allows measurement of film thickness and surface tilt to be made simultaneously (from analysis above).**
- **Measurement of interface profile possible.**
- **Distorted diffraction grating used to implement phase diversity wavefront sensing.**
- **Experimental results match simulated data.**
- **Measurements made on thick laminates (1-2mm).**
- **Accuracy of 50nm achieved to date.**
- **Dynamic range of instrument from 10µm to 8mm.**

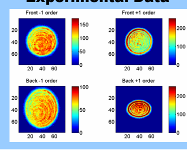
System Simulation

- **System simulated using extended source analysis using Optalix ray tracing software package.**
- **Simulated data allowed size of diffraction order images to be calculated and used to develop thickness retrieval algorithm.**
- **Simulated data was compared with experimental results as shown with sizes differing by <1 pixel.**
- **Phase retrieval can be carried out on simulated data to reconstruct wavefront.**
- **Full wavefront analysis of simulated and experimental data will allow film thickness and interface profile to be measured simultaneously.**

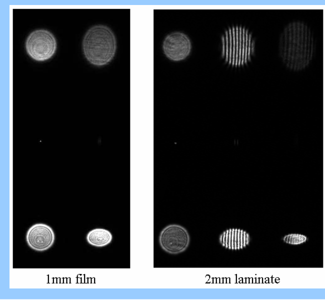
Simulated Data



Experimental Data

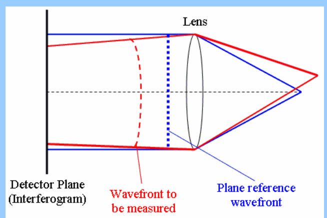


Experimental Detector Output



Film thickness using interference

Measurement Principle.



- **Reflected wavefronts from film under measurement produce interferogram.**
- **Retrieval of phase gives measure of wavefront difference, i.e. aberrations introduced by the film structure.**
- **Monitoring of such interferograms allows film thickness to be measured.**
- **Suitable for very thin films and laminates.**

Reference wavefront can be expressed as:

$$a(x,y) = |a(x,y)|\exp[-jf(x,y)]$$

Wavefront to be measured can be expressed as:

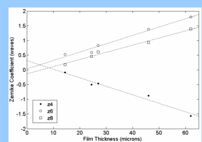
$$A(x,y) = |A(x,y)|\exp[-j\gamma(x,y)]$$

The intensity at the detector plane is then expressed as a combination of both wavefronts:

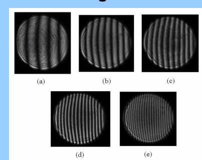
$$I(x,y) = |A(x,y)|^2 + |a(x,y)|^2 + 2|A(x,y)||a(x,y)|\cos[\gamma(x,y) - f(x,y)]$$

Phase Unwrapping.

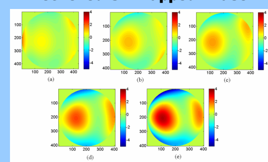
- **The interferogram data must be interpreted to retrieve wrapped phase.**
- **Phase retrieved by use of FFT method to isolate sideband data and re-centring.**
- **Wrapped phase is then unwrapped using common techniques to identify dislocations in the wrapped phase.**



Interferogram Data



Retrieved Unwrapped Phase



A Zernike fit is then carried out on the unwrapped phase to determine aberration mode strengths

A linear relationship exists between retrieved mode strengths and film thickness as shown. A measurement of film and laminate thickness possible using such methods.

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E.R.P.