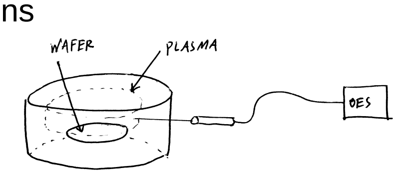
In-Situ Metrology

The Art of the Possible

A "Virtual Sensor" - Optical Emission Spectroscopy

- Measures concentration of various species present in plasmas
- useful in various plasma etch and plasma-enhanced deposition control applications
  - endpoint detection
  - impurity detection
  - etch rate monitoring
  - uniformity measurement



- provides real-time measurements (>1 Hz)
- simple installation on most plasma etchers
- Lets one "guess" about wafer condition, by looking at the environment around it.

OES (cont.)

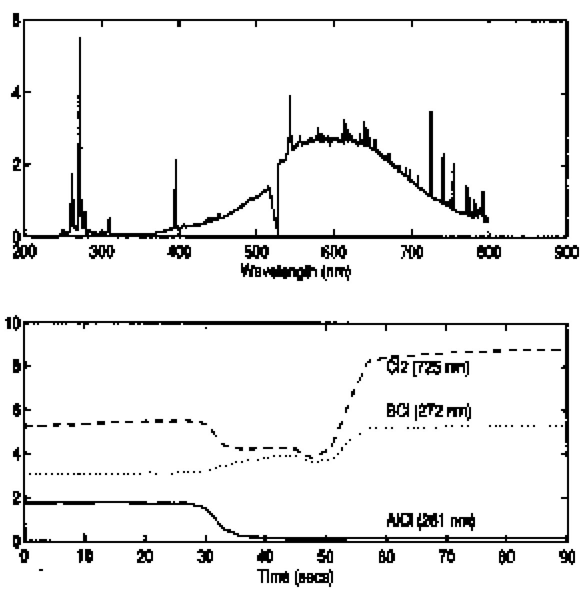
- operation principle
  - plasmas contain ions, neutral radicals, energetic electrons
  - plasma discharge light

$$A + e \rightarrow A^* + e,\ A^* \rightarrow A + h\nu$$

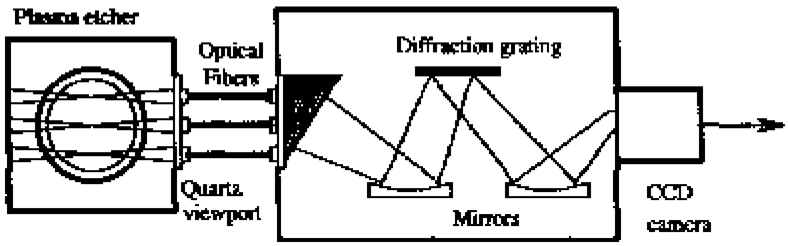
here A^* is the excited state of particle A

- frequency of emitted light
  - depends on allowable energy transitions
  - is characteristic of species
  - sometimes there is no useful emission signature in OES (ex: SiH_3 in PECVD with silane plasma)

OES (cont.)



OES (cont.)



- optical equipment options
  - photo-detector (possibly with scanning of diffraction grating)
  - photo-diode array
  - CCD camera
  - Choice depends on number of factors

    frequency resolution, spatial resolution, acquisition rates, bandwidth, sensitivity, etc.

OES (cont.)

- Signal Processing Issues
  - OES intensities depend on several factors in addition to species concentration, such as

    Excitation probability (strongly dependent on RF power), Optical collection efficiency (drifts over time due to residue build-up on window).
  - full-spectrum OES may require data compression and noise reduction.
  - signal intensity may be too weak in small area etches (vias and contact cuts in oxide, detection of trace Cu sputter targets in Al-Cu etches, etc.)

Laser-Induced Fluoresence

- basic idea

use a pulsed laser to excite plasma, observe induced emission

laser can be tuned to cause specific excitations

can detect species that have no natural emission SiH_3

can detect species in ground state

- details

Nd-YAG laser source @1064 nm used to pump tunable dye laser

pulsed lasers provide much more power in short excitation phase thus emission exceeds background

collection optics at 90º to source to minimize scattered light

can detect and measure CF,CF_2,SiO,SiN,BCl,Cl_2+,...

LIF (cont.), LAS

- issues
  - excellent spatial resolution (5 microns)
  - excellent temporal resolution (100nsec)
  - sensitivity 10^6-10^8 particles/cm^3
  - complex collection optics and signal processing
  - more complex than OES, but much more accurate
  - requires side viewing port
  - requires actinometry for calibration
  - limited to species with absorption in 200- 900nm range
- other option -- Laser absorption spectroscopy
  - tunable laser diode is used as source in IF range
  - absorption is very low here, so multiple passes are needed
  - path length is ~ 1Km
  - poorer resolution
  - qualitative tool

Actinometry

- objective: calibrate OES/LIF signals
- basic idea
  - introduce known amount of inert gas B (ex: Ar)
  - choose wavelength in inert gas emission spectrum whose excitation X-section, and excitation energy resembles species of interest A. Then,

$$\frac{I_a(l_a)}{I_b(l_b)} = K\frac{N_a}{N_b}$$

I_a, I_b measured

N_i = molar fraction of input gas i

K = constant

- issues
  - useful only for measurement *relative* species concentration
  - repeatability is a big issue: must ensure that emission lines go through same optical path, uniform temporal electron densities, etc.

Diffraction gratings

- used to spectrally resolve light
- operating principle
  - close parallel lines or steps etched on a surface
  - mechanically made gratings: etched glass or plastic
  - holographically patterned gratings: higher transmission, flatter response
  - modern gratings are blazed: periodic phase shifting across grating, concentrates light energy in a specific order
- performance characteristics

  peak location is at $sin\theta = m\lambda/d$

  resolving power $R = \lambda/\Delta\lambda = Nm$

  dispersion $D = \Delta\theta/\Delta\lambda = m/dcos\theta$

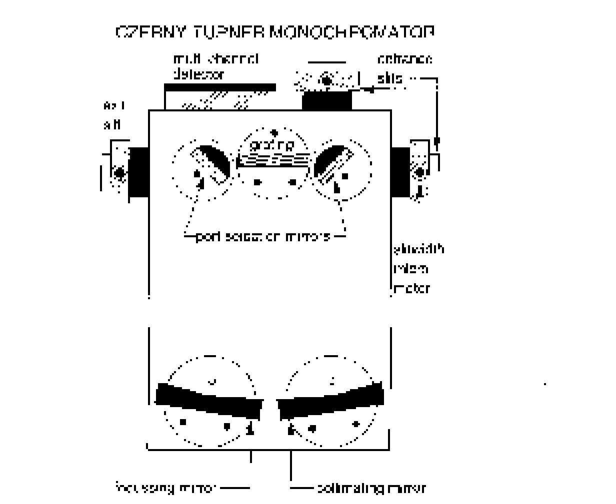
  d = spacing, N = number of lines, m = order

  λ = wavelength of incident light, θ = viewing angle

Monochromators

- basic idea
  - essentially a tunable narrow-band wavelength selective optical filter
  - uses a diffraction grating
- issues
  - accuracy of selected wavelength
  - calibration
  - efficiency (transmission ~ 10 %)
- Czerny-Turner monochromator
  - grating is rotated by a stepper drive
  - angle of rotation determines wavelength of light at exit slit
- dielectric bandpass filters
  - fixed wavelength applications
  - transmission ~ 50 - 70 %

Czerny-Turner monochromator



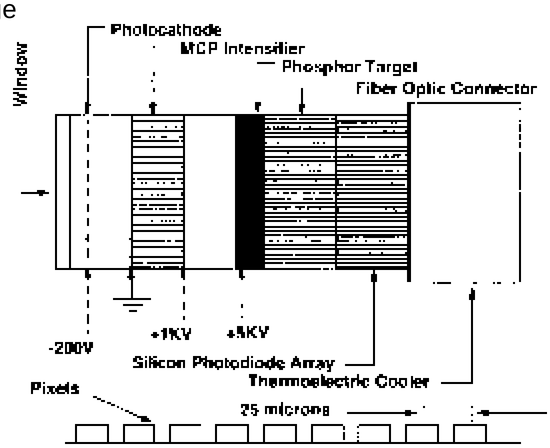
Design of a Czerny-Turner monochromator. The concave collimating and refocussing mirrors are at the bottom of the monochromator. The top left and right mirrors are used to reflect light into and out of the side slit assemblies. A photodiode array can be mounted on the top left exit port.

Light Detectors

- photo-multipliers
  - very high gain photon detectors -- rely on cascading
  - resolution 0.05 photons/sec
  - spectral characteristic are adjustable by choice of material
- photo-diode arrays
  - can be used directly to measure intensity vs. wavelength
  - lower resolution than a monochromator with pmt
  - wider spectral coverage than monochromator with pmt
  - light strikes a multi-channel intensifier plate and emits electrons
  - DC bias accelerates electrons towards a phosphor target
  - fiber optics connect to pixels (up to 1200)
  - need to be cooled to limit thermal photo-electron emissions
  - smaller dynamic range

Photodetectors (contd.)

- CCD arrays
  - similar operating principle as photo-diode arrays
  - no multi-channel intensifier plate
  - wider spatial coverage
  - lower resolution
  - very inexpensive



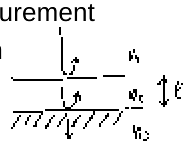
Optical Metrology

- Probe the wafer with a beam of light
- Analyze the resulting E&M field
- Extract thickness, n and k of thin films and stacks

- Reflectometry
  - Mostly “blanket” thin film analysis
- Ellipsometry
  - Mostly “blanket” thin film analysis, more difficult setup, many more degrees of freedom to analyze.
- Scatterometry
  - Novel, analysis of periodic gratings. CD metrology and full profile reconstruction.

Reflectometry

- operating principle
  - interference between light reflected from top surface and from surfaces in underlying stack
  - intensity at detector is ~ sinusoidal in thickness of top layer and in wavelength
  - provides thickness/index/composition measurement of top layer
  - typically near-normal incidence
- applications
  - etch-rate measurement
  - develop-rate measurement
  - end-point detection



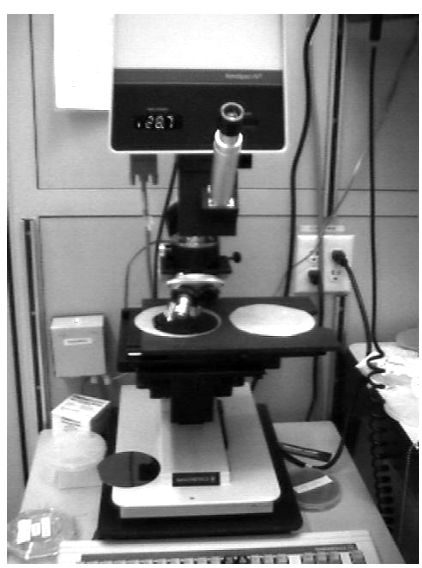
$$Z_{L1} = \eta_2 \left(\frac{\eta_3 \cos k_2 \ell + j\eta_2 \sin k_2 \ell}{\eta_2 \cos k_2 \ell + j\eta_3 \sin k_2 \ell} \right)$$

$$\rho = \frac{Z_{L1} - \eta_1}{Z_{L1} + \eta_1} \qquad k_2 = 2\pi f \sqrt{\mu_2 \epsilon_2} \qquad \eta_1 = \sqrt{\frac{\mu_1}{\epsilon_1}}$$

Reflectometry (contd.)

- single-wavelength
  - pulsed laser source is preferred
  - detected light is filtered at pulsing frequency to reduce noise
  - thickness accuracy +/-20A
- spectral reflectometry
  - broad band incoherent source for scan-wavelength
  - more noisy, but can solve for more unknowns (index and composition)
- issues
  - absolute intensity measurement is hard, need to model optics
  - need underlying stack geometry and indices
  - multiple internal reflections
  - phase shifts at stack boundaries
  - surface roughness
  - patterned wafers

Clasic Off-line Reflectometer



Ellipsometry

- operating principle

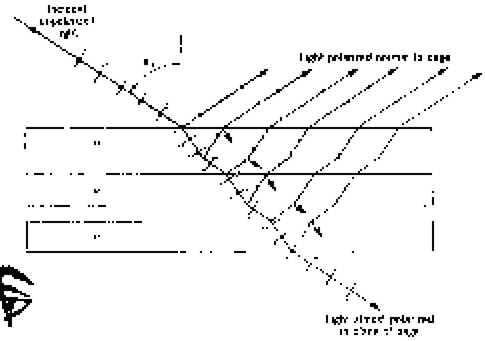
  circularly polarized incident light

  TE and TM components undergo different reflections

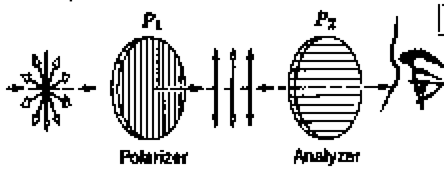
  Fresnel reflection coefficients

$$r_{12}^{TE} = \frac{n_2 \cos j_1 - n_1 \cos j_2}{n_2 \cos j_1 + n_1 \cos j_2}$$

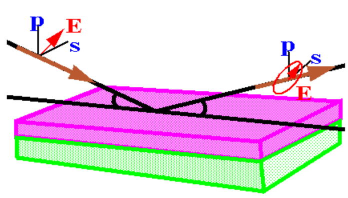
$$r_{12}^{TM} = \frac{n1 \cos j_1 - n_2 \cos j_2}{n_1 \cos j_1 + n_2 \cos j_2}$$



received light is elliptically polarized

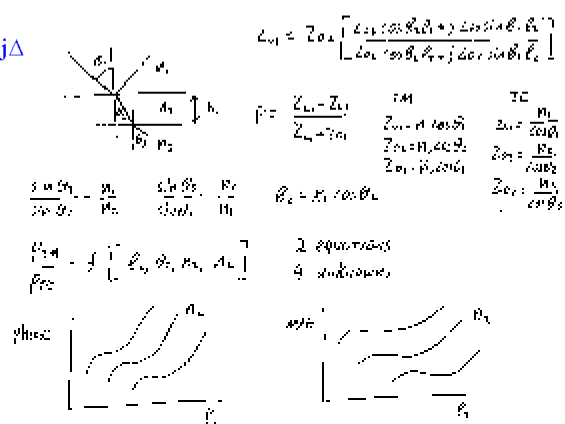


Ellipsometry (cont.)



Ellipsometry

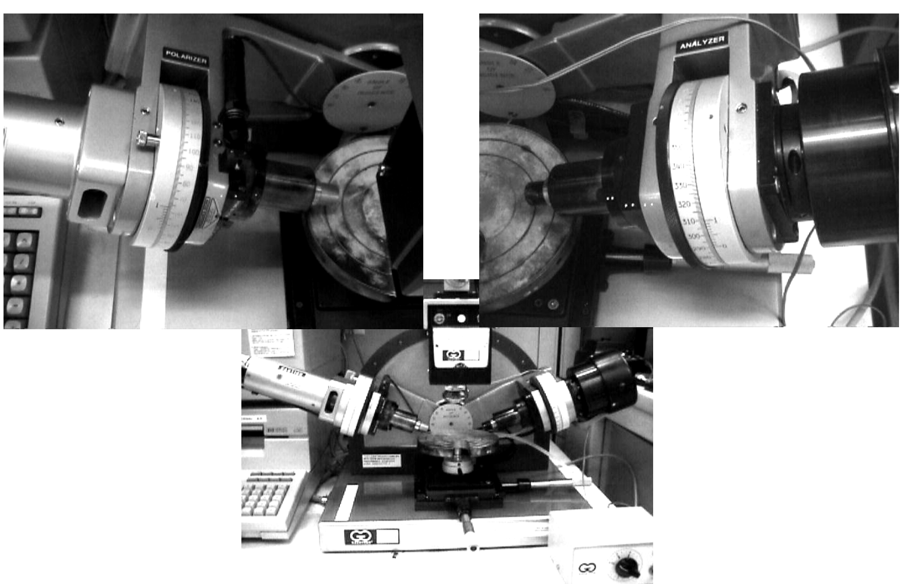
$$\rho = r_p / r_s = \tan \Psi e^{j\Delta}$$



Ellipsometry (contd.)

- issues
  - polarization of detected light is measured by nulling
  - no need to have intensity measurements
  - polarized light source
- comments
  - can measure 2 quantities -- typically index and film thickness
  - spectrally and spatially resolved ellipsometry
  - extremely accurate -- index +/-.1%, thickness +/- 4A
  - more expensive and delicate than reflectometry

Classic Ellipsometer

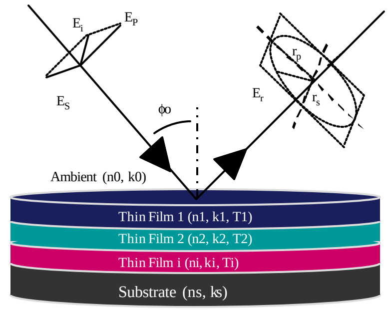


Principle of Spectroscopic Ellipsometry

$$\rho = \frac{r_p}{r_s} = \mathrm{Tan}(\Psi).e^{j(D)}$$

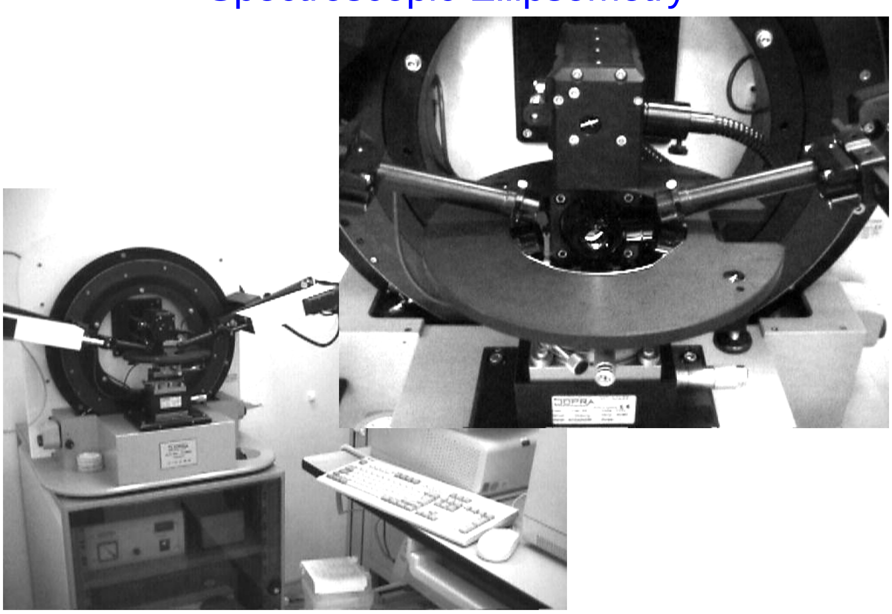
Measured Parameters

TanΨ and CosD



Issue: must know at least the form of the dispersion equation of material $n = f_1(\lambda)$, $k = f_2(\lambda)$.

Spectroscopic Ellipsometry



In-situ spectroscopic ellipsometry

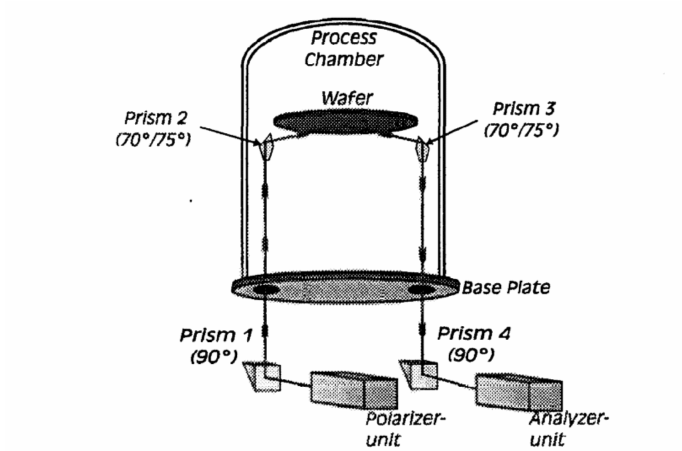


FIGURE 1: The *in situ* ellipsometer arrangement with the beam guiding system (1)

Another in-situ example...

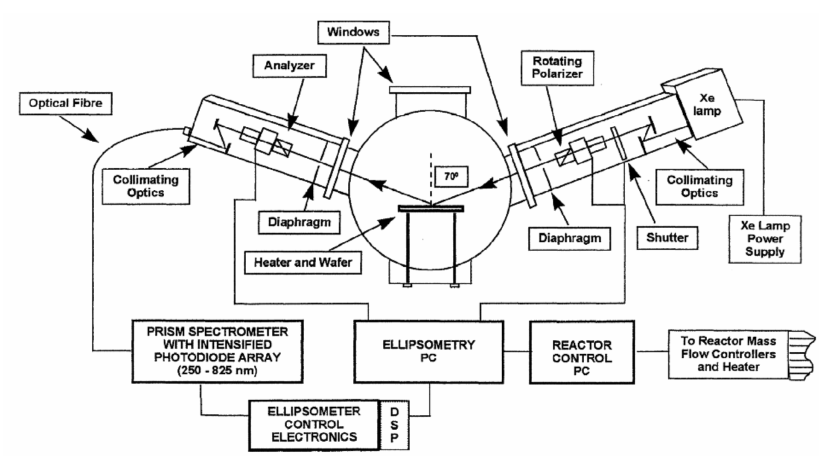
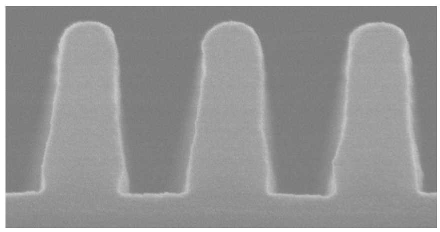


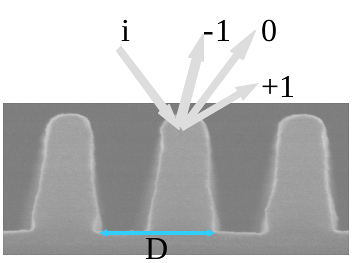
FIGURE 2. Schematic diagram of real-time spectroscopic ellipsometry equipment interfaced to Si/SiGe CVD system.

Scatterometry

- The objective is to find a fast and economic way to characterize patterns.
- Another objective is to relieve/bypass the heavy work-load of CD-SEM and CD-AFM in the fab.
- Periodic gratings can be both theoretically and experimentally characterized.



Scatterometry Principle



$$\sin\theta_m = \sin\theta_i + m\frac{\lambda}{D}$$

$$|\sin\theta_m| < 1$$

--Propagating orders

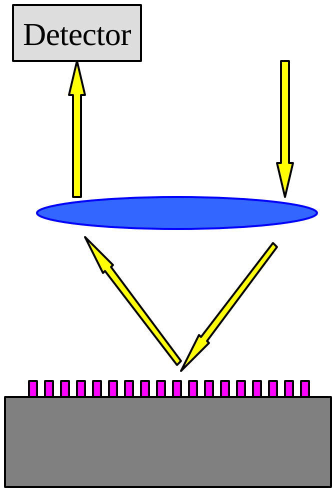
$$|\text{Sin}\,?_m| > 1$$

--Evanescent orders

λ	Cut-Off Pitch	
600	300	
400	200	
250	125	(in nm)

Specular variable angle scatterometry

-- Bio-Rad CDS1 Scatterometer

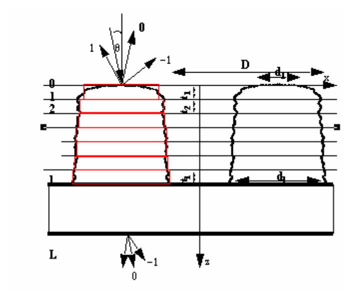


- He-Ne laser is used as light source
- Maximum incident angle is 38 degree due to the optics setup
- Simulation software only works for TE case

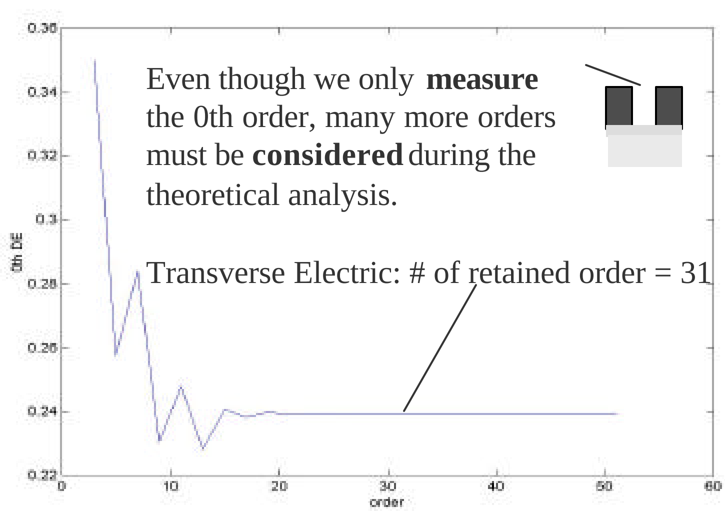
The ex-situ scatterometer

Rigorous Coupled Wave Analysis

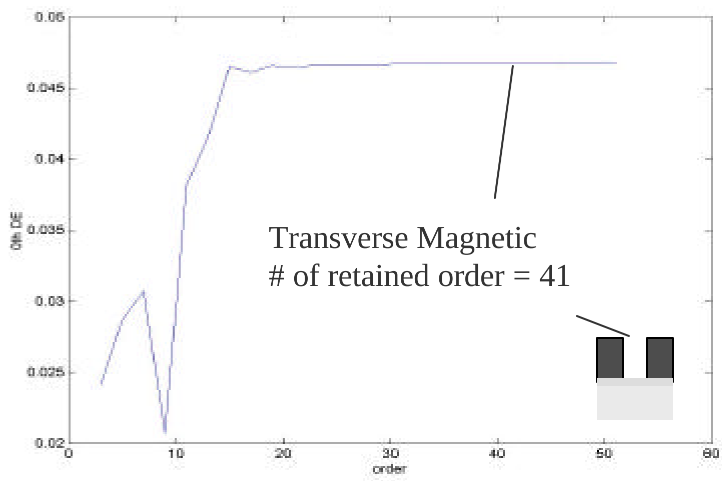
- Fourier expansion of the grating profile.
- Eigensystem formulation.
- Linear system solution of E&M field.
- In theory, this approach is “rigorous”.



RCWA Accuracy

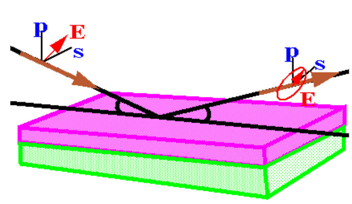


Accuracy of RCWA (cont'd)



Specular Spectroscopic Scatterometry

- We are only collecting the 0th order.
- We use Spectroscopic ellipsometry (200nm~800nm), and 1-D gratings.



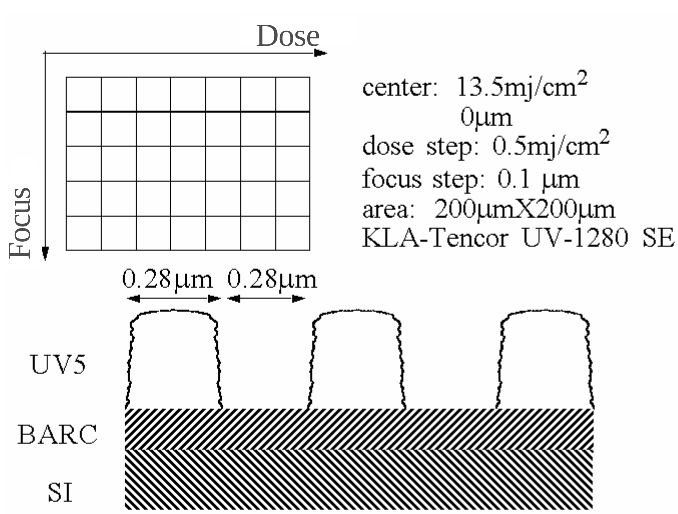
Ellipsometry

$$\rho = r_p / r_s = \tan\Psi e^{j\Delta}$$

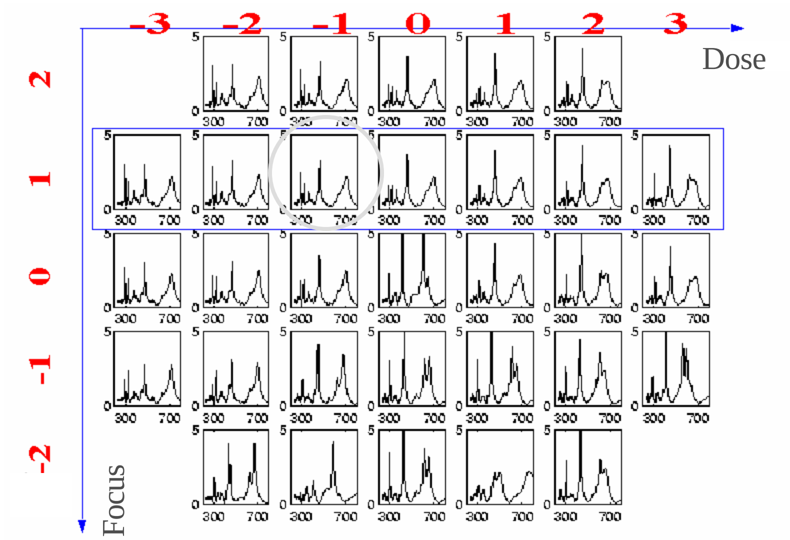
Experimental Verification

- Verification of the forward diffraction grating simulation is done using given CD profiles.
- Verification of the inverse CD profile extraction is done from given Spectroscopic Ellipsometry measurements.

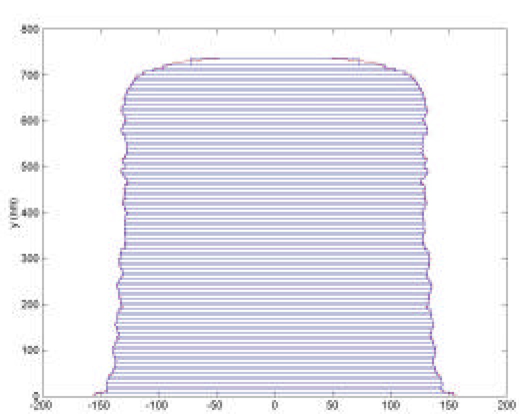
Focus-exposure Matrix Experiment for 1-D grating



tanΨ of the entire F-E Matrix



CD AFM Profile Segmentation



UV5:

100 layers

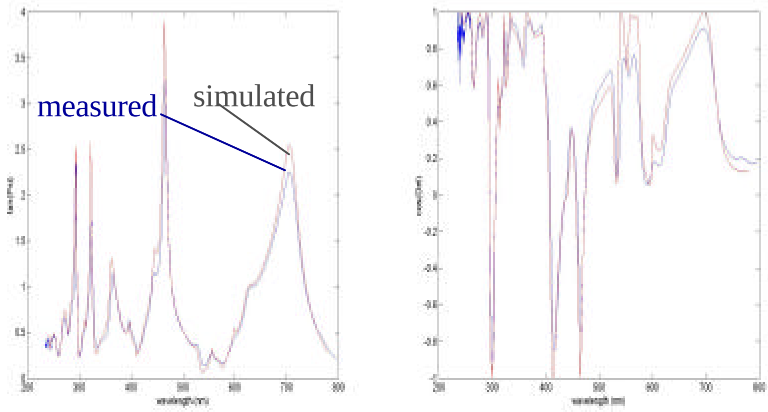
739.75nm

ARC:

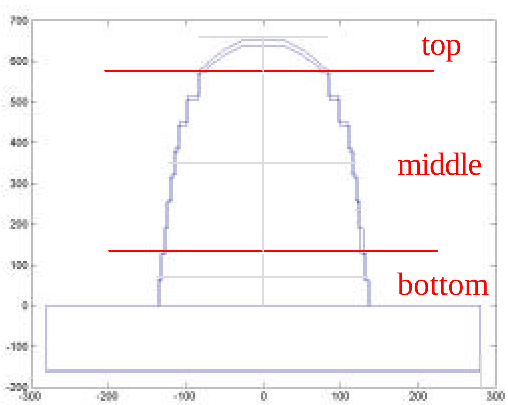
1 layer

162.9nm

Measured and Simulated tan(Ψ) and cos(Δ)



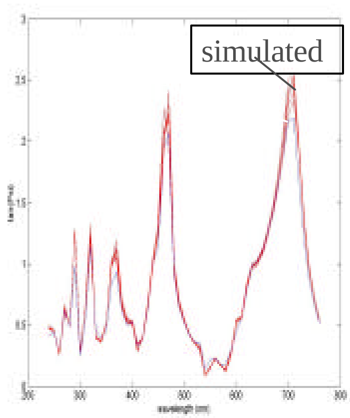
Monte Carlo Profile Library

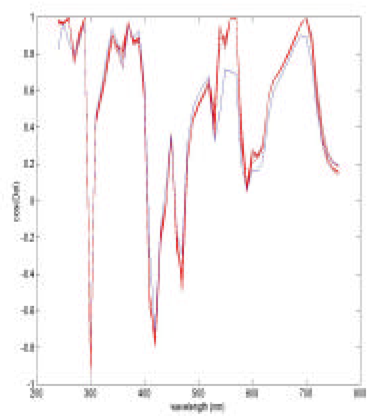


- Primitives
- 180000 profiles index
- 53 wavelength
- 22 layers
- 2 min/profile on a SUN Ultra 170 workstation

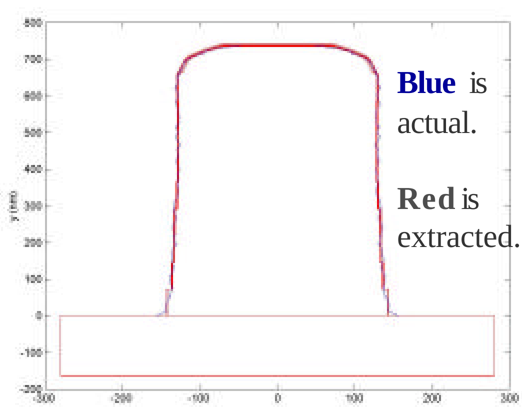
6000hrs

Matching on tan(Ψ) and cos(Δ)

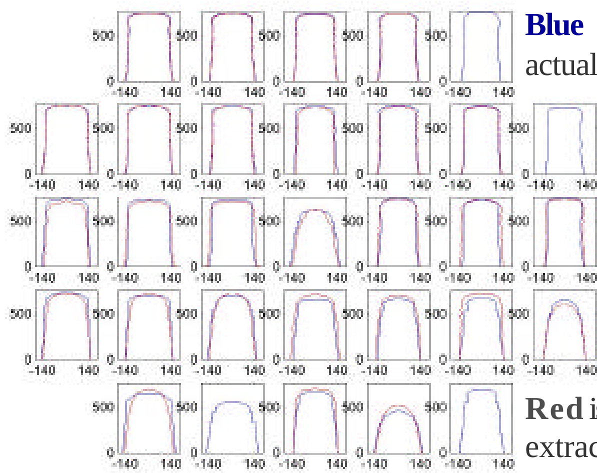




Example of CD Profile Extraction



Profile Extraction over the entire FEM

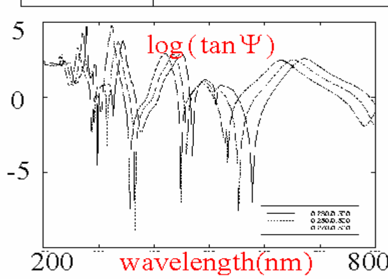


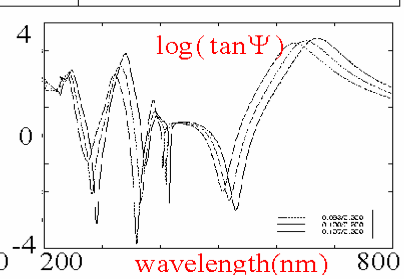
Blue is actual.

Red is extracted.

Applicability to Future Technology

	Feature in 1997, 250nm	Feature in 2006, 100nm
CD	250nm	100nm
$CD_{3\sigma}$	230, 250, 270nm	93, 100, 107nm
thickness	800nm	400nm





Conclusions, so far

- OES is an example of a “virtual” wafer sensor.
- Reflectometry, Ellipsometry and Scatterometry can be real, in-situ, direct wafer sensors.
- Implementation and commercialization has started:
  - CMP (reflectometry)
  - furnace operations (ellipsometry, reflectometry)
  - CD-control (scatterometry on the wafer track)
  - Big issue in in-situ metrology: cost/complexity of the sensor, relationship between suppliers.

Next time: chamber and on-wafer sensors.

An Update on Scatterometry

- During the last three years, CD-scatterometry (now known as Optical CD) has spread rapidly in IC production.
- TEL (the largest equipment vendor for Lithography and Plasma) acquired Timbre Tech (the leader in OCD and a Berkeley startup) and is now selling an in-line OCD solution for their tracks.
- Applied has partnered with Nanometrics.
- Others have partnered with KLA-Tencor.
- It is widely expected to be a $1B/year industry.