Thin Film Metrology at Applied Materials: Present and Future

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Real Content of Talk

- Thin Film Metrology tools that we have at Applied Materials
- Tools we don't have but would like to get someday
- Opinions about these tools
- What we do at the Defect & Thin Film Characterization Lab

Outline of Talk

- Acoustic Methods for film thickness
- Ellipsometers
- X-ray Reflectivity and Diffraction
- Non-contact electrical characterization
- Other tools
- DTCL capabilities
- Conclusion

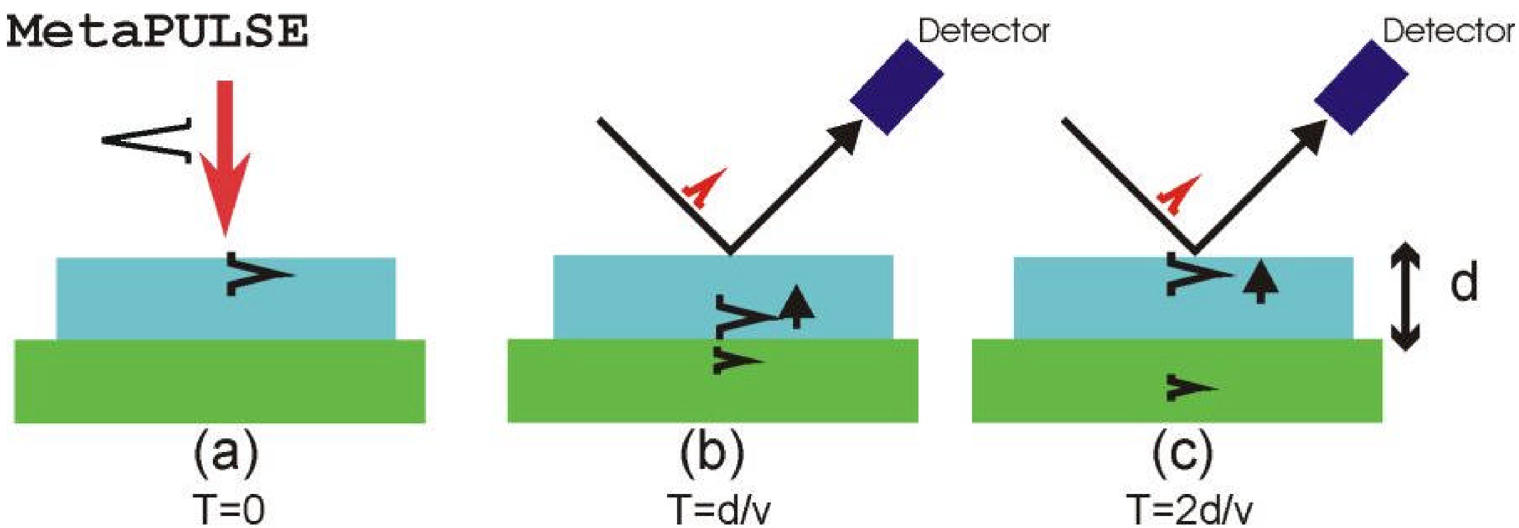
Acoustic Methods for Film Thickness

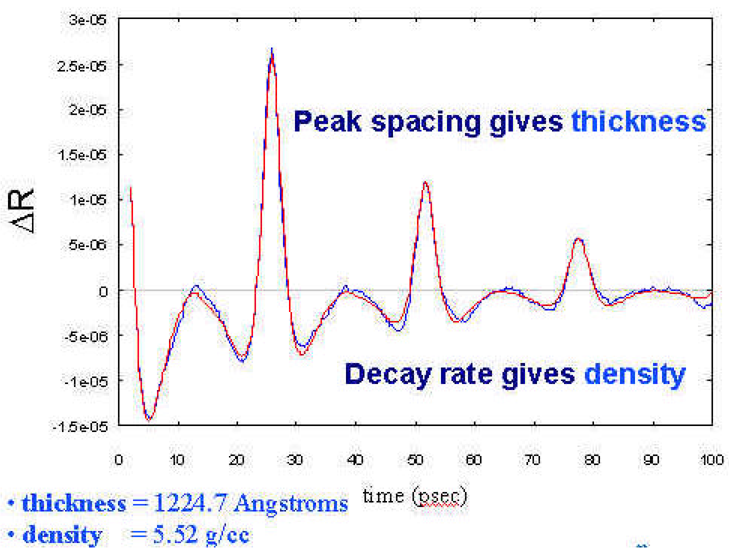
- Rudolph MetaPULSe
- Philip Analytical Impulse (PQ Emerald)
- At Applied Materials, we use both tools and exploit the advantages of each.

Acoustic Methods for Film Thickness Rudolph MetaPULSe

- Licensed technology from Brown U.
- Applications include
  - MOCVD TiN
  - ECP/CMP Cu
  - PVD Co, TiN, TaN, Ta, Ti, Al, + more
- Can measure other parameters such as adhesion, roughness, density, in special cases.

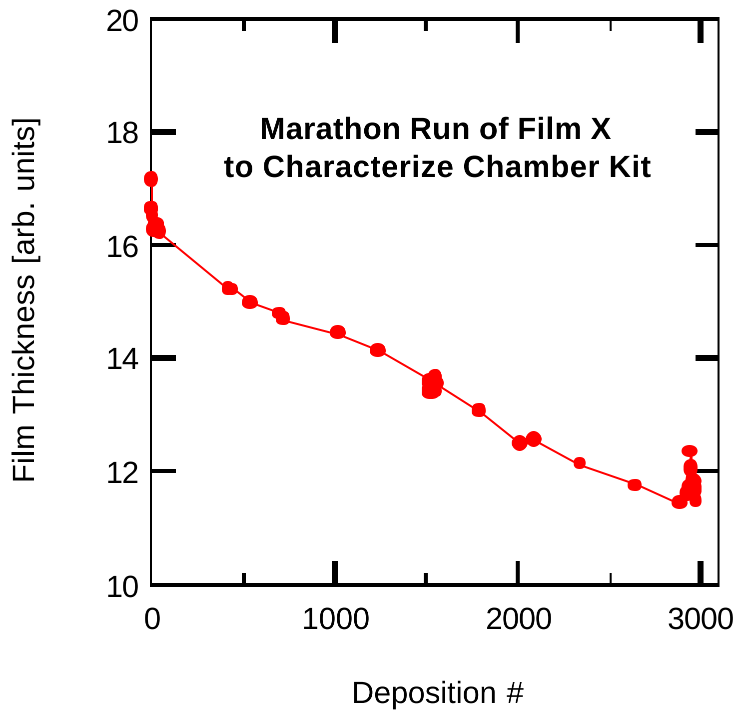
Rudolph MetaPULSe

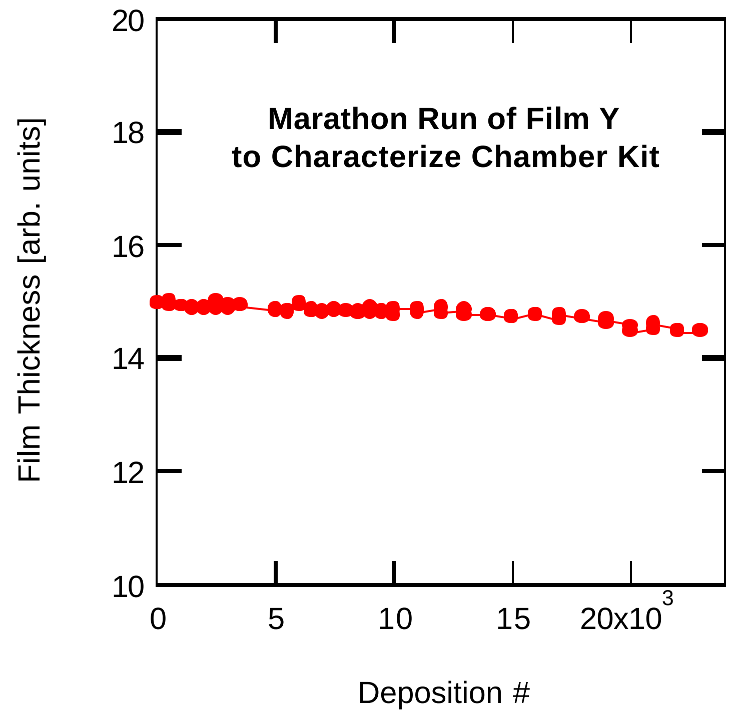




Works like Sonar. (a) Short-pulse laser on sample leads to energy absorption, thermal expansion, and thus the generation of a longitudinal wave. (b) Longitudinal wave propagates through sample and reflects at an interface. Probe laser tries to detect arrival of longitudinal wave. (c) On arrival of wave at the surface, it changes the optical constants. The reflectivity change is detected by the probe at time 2d/v.

MetaPULSe Application: characterization of chamber process kit life





- We can characterize the process kit life thickness and uniformity of a film

Rudolph MetaPULSe

- Advantages
  - Accepted in the industry
  - Easy to interpret data
- Disadvantages
  - Slow (>15 sec/point in some applications)
  - Lower limit of around 40Å (single layer)

Acoustic Methods for Film Thickness Philips Analytical Impulse

- Developed at MIT
- Applications at Applied Materials include:
  - ECP/CMP Cu
  - W
  - PVD Al
  - Patterned and blanket on all the above

Philips Analytical Impulse

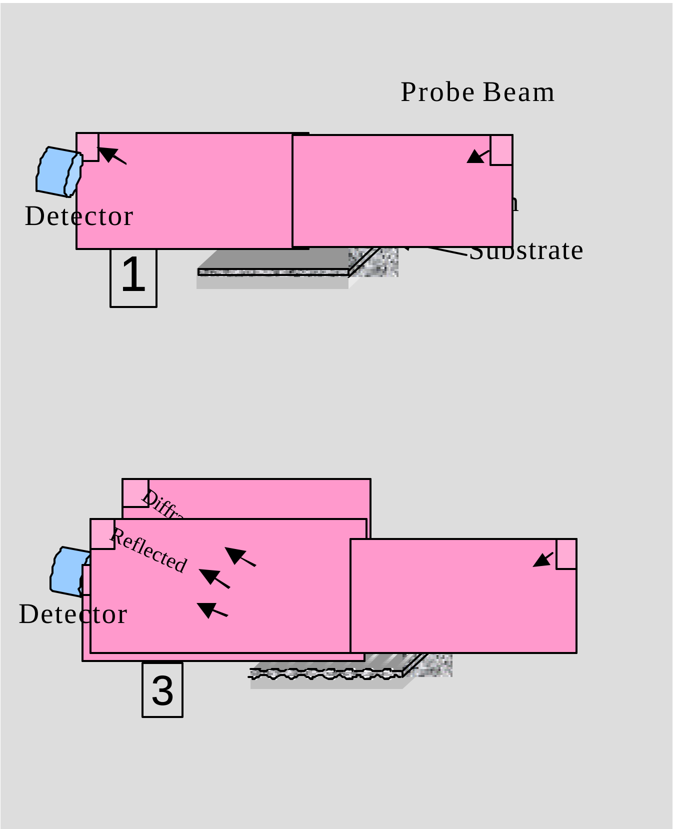
Analogy of throwing pebble in a still lake

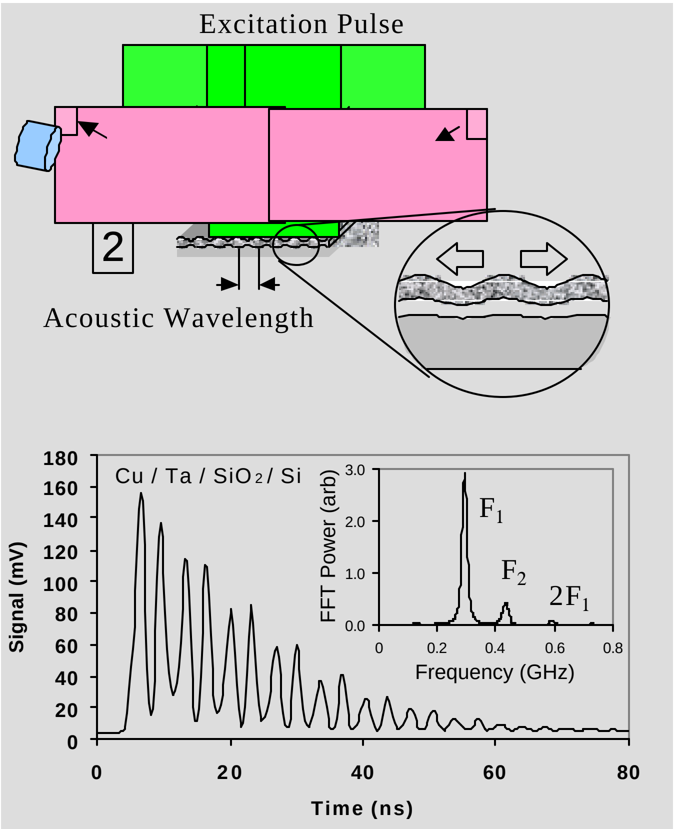
1) A probe beam is incident on the surface.

2) At the same spot, two laser pulses interfere, creating regions of light and dark, or regions of thermal expansion. The probe beam is diffracted.

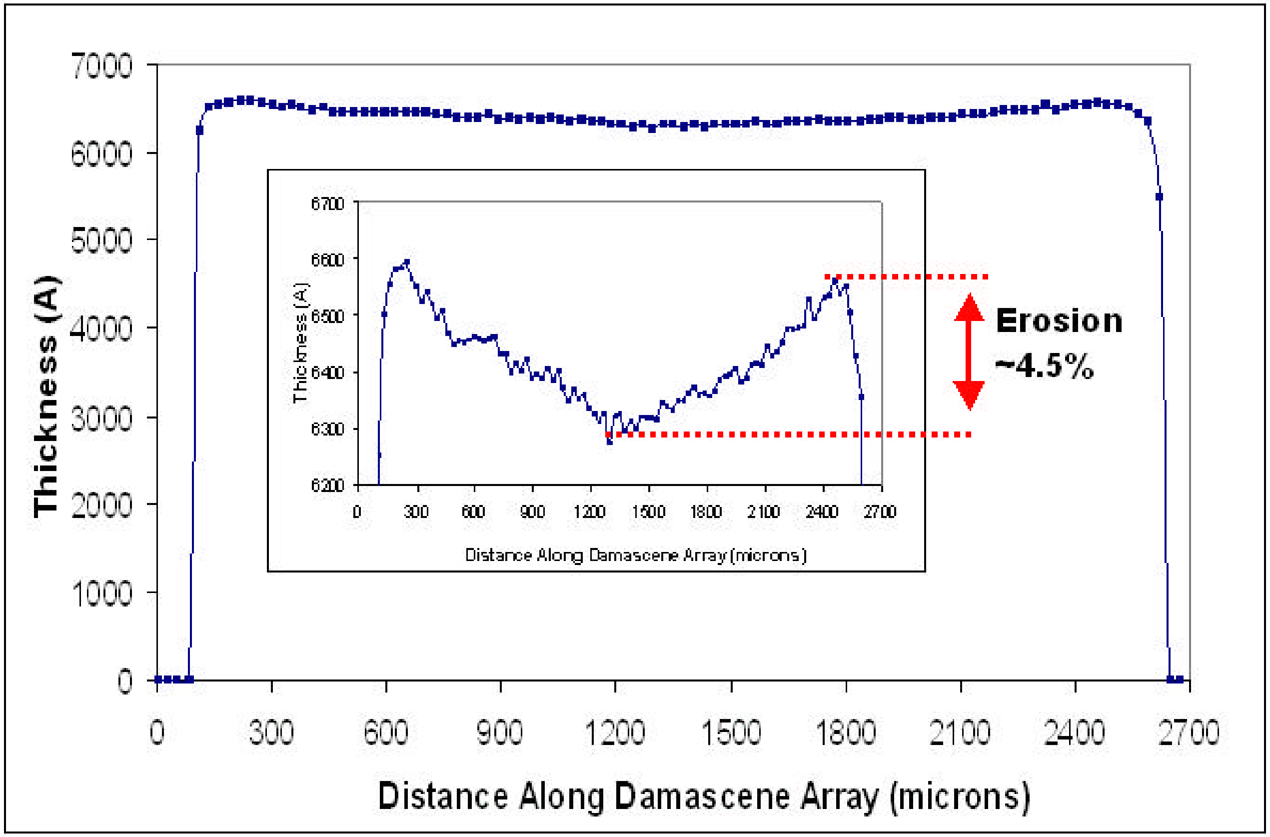
3) In the diffraction, the probe beam comes in and out of the detector as the “grating,” or acoustic wave, travels.

4) Output of detector. Fourier Transform, acoustic wave, is correlated to the thickness.

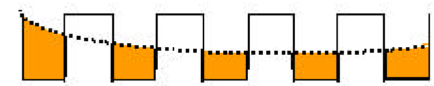




Erosion - Line Scan Across Damascene Wire Array



SEMATECH 926 Test Pattern



Philips Analytical Impulse

- Advantages
  - Very fast (2 to 3 sec/point)
  - Can measure blanket wafers and patterned features (vias, line arrays, etc.)
- Disadvantages
  - Lower limit of around 250 Å in thickness (Version 1, in use at AMAT), but Philips claims around 100 Å, depending on the application, for Version 2.
  - Single layer only. Philips claims two layers for Version 2.

Ellipsometers

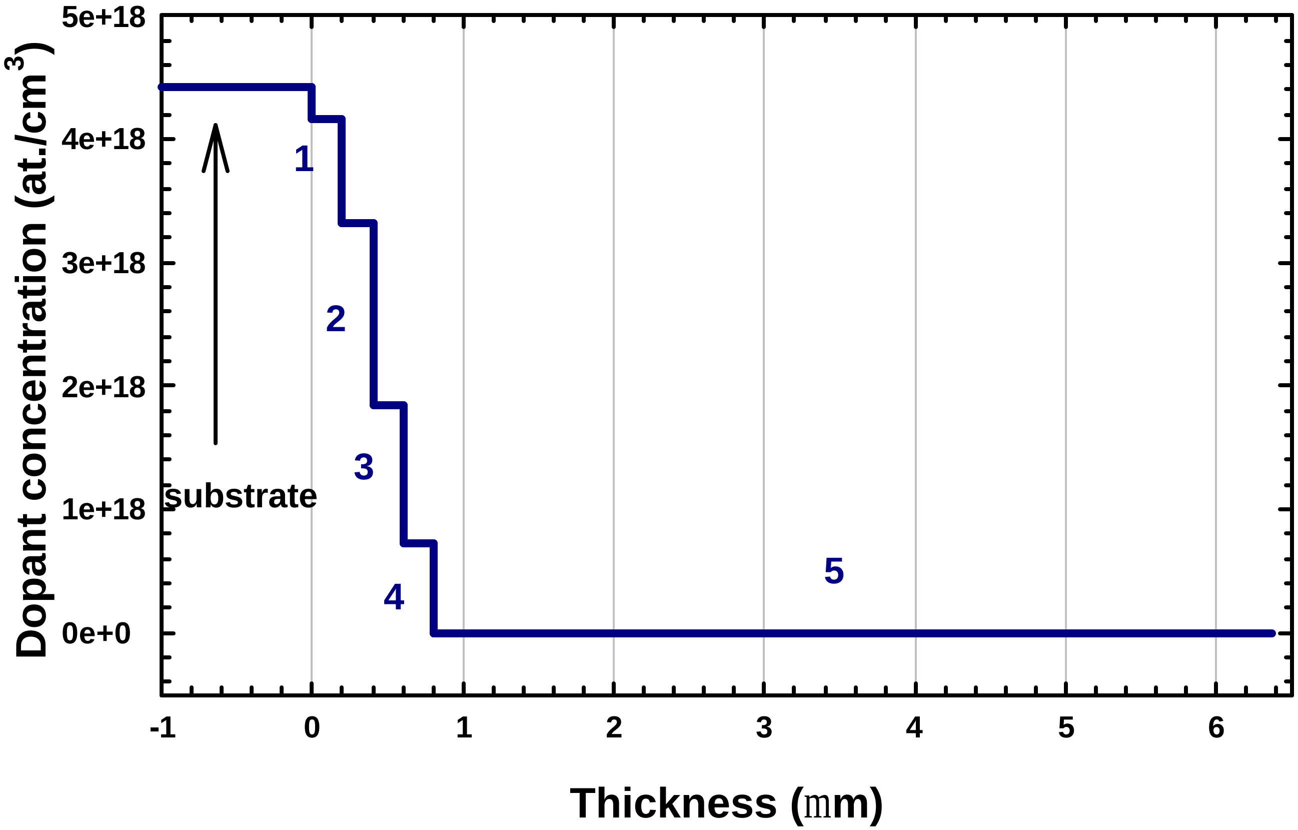
- Ellipsometers are a commodity
  - Technical capability and performance of the major vendors are similar
- Two types/classes of note in ellipsometer development
  - Sopra's SE300
    - UV to IR ellipsometer
  - High-resolution ellipsometers
    - 8 million points/map
    - fast mapping
    - Candela
    - HDI

Sopra's SE300

- Spectroscopic ellipsometer (UV to visible, + IR)
- In UV to visible range, includes a scanning mode (slit + photomultiplier) for superior signal to noise. F5 or Optiprobe does not.
- Essentially identical to the F5. KLA-Tencor licensed the technology from Sopra.
- Applications include
  - High-k gate materials
  - Thick oxides and other dielectrics
- Includes an IR ellipsometer, especially good for
  - low-k materials
  - Epi Si
  - SiGe

Application: doping profile of an P/P+ epilayer

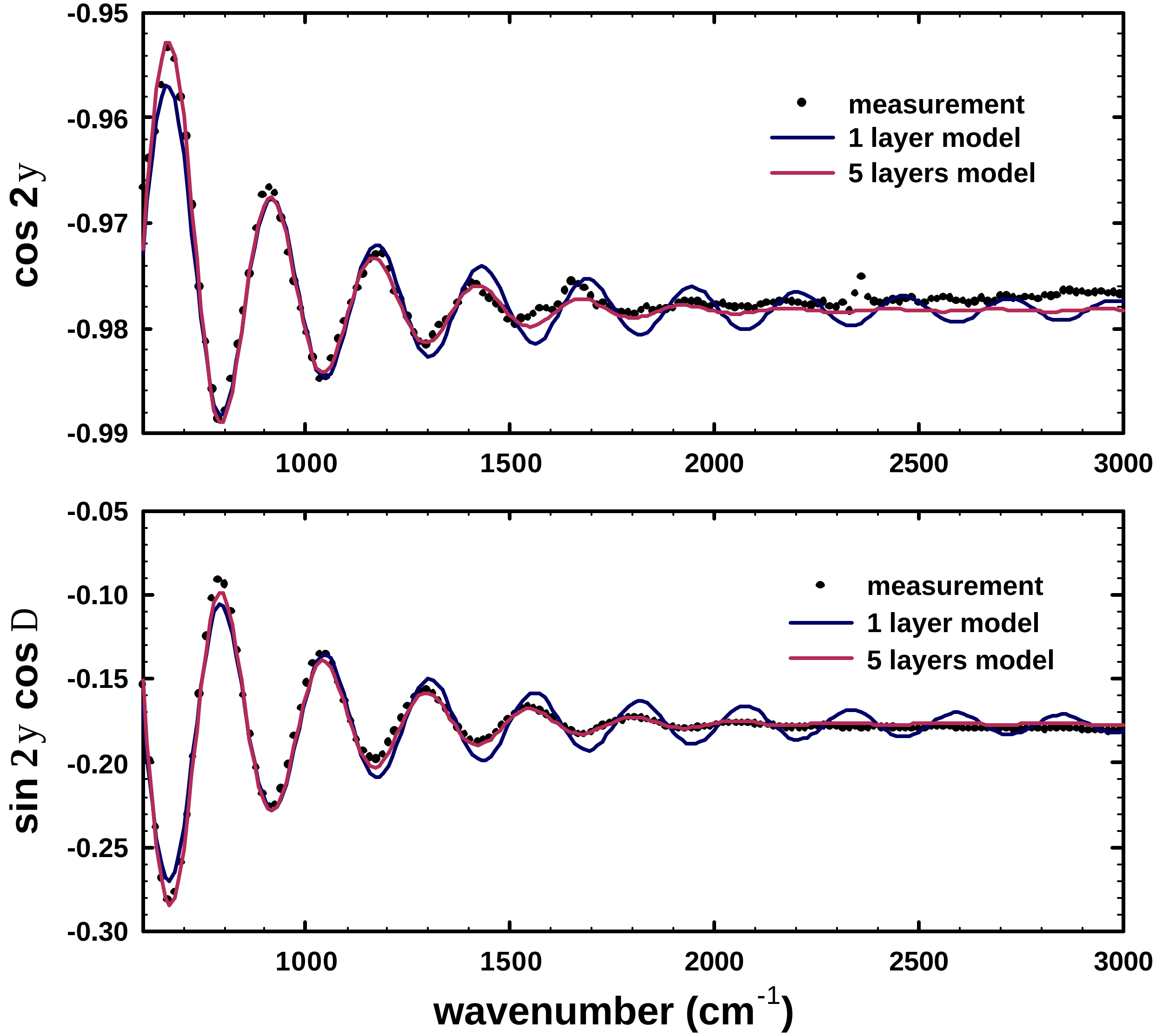
Epilayer consists of a undoped layer and a transition layer (described by four 0.2 mm thick layers with unknown doping concentration).

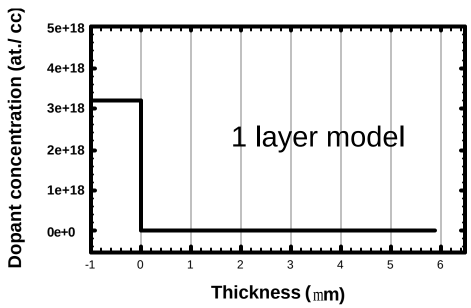


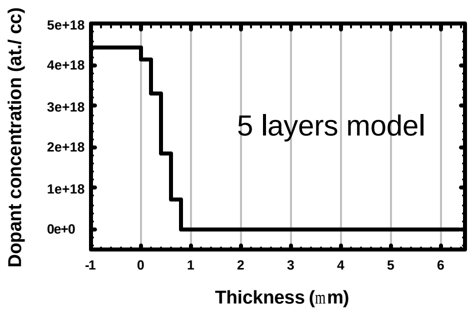
Model parameters

- layer thickness
- doping concentration of the substrate
- doping concentration of the four layers used to describe the transition layer

Application: P/P+ epilayer





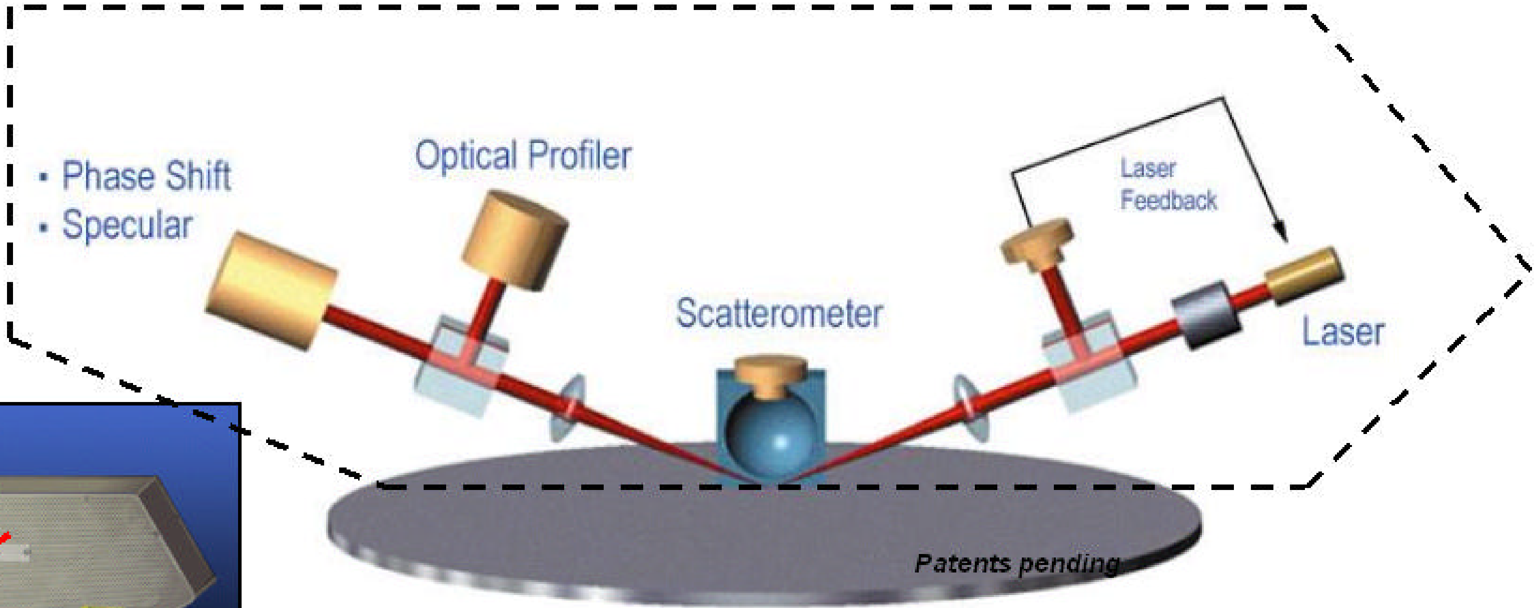


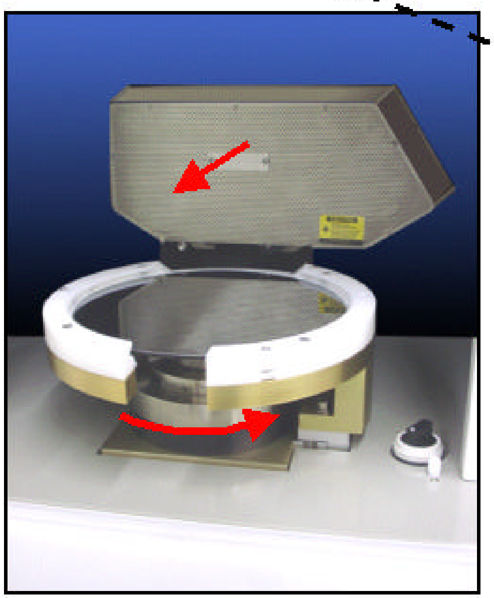
Comparison between the fit obtained with

- 1 layer model
- 5 layers model

High-Resolution Ellipsometers

- Candela (manufacturer) has the OSA
- HDI (manufacturer) has the SRA
- Traditionally in hard disk business, used to characterize uniformity of layer
- Moving to semiconductor industry
- Potential applications in:
  – High-resolution mapping of thickness for uniformity
  – Defect detection
  – Process control for very thin layers





Multi-channel detection technology combines ellipsometer, reflectometer, scatterometer, and optical profiler

Measurements can be made independently or *simultaneously*

Multiple applications for lower cost-of-ownership compared to single-function systems

Slot 1

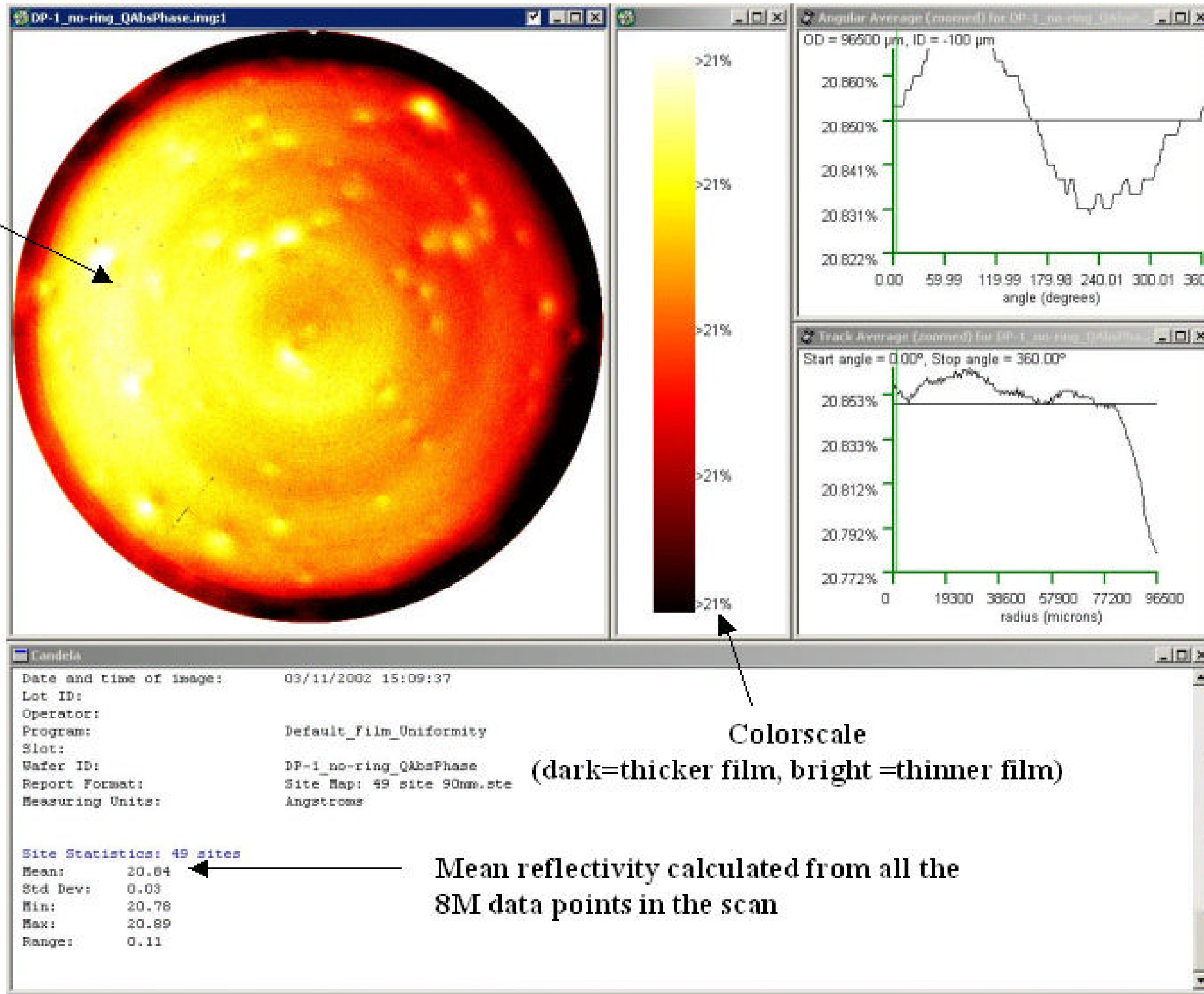
Film Uniformity Image (consists of about 8 million data points)

Angle Average Cross Section

Shows the average variation of the film thickness around the wafer

Track Average Cross Section

Shows the average variation of the film thickness from ID to OD



Data header

Colorscale
(dark=thicker film, bright =thinner film)

Mean reflectivity calculated from all the 8M data points in the scan

Log File

Contains summary as well as site statistics Can be saved as a text file

High-Resolution Ellipsometers

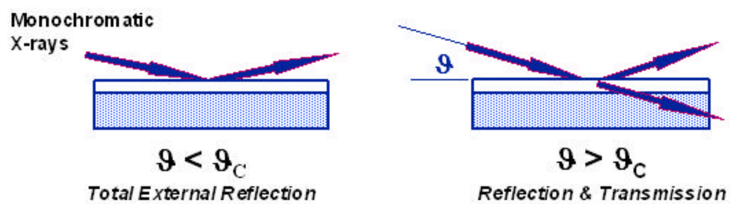
- Candela's OSA
- HDI's SRA
- Potential applications in
  - High-resolution mapping of thickness for uniformity
  - Defect detection
  - Process control for very thin layers
- Advantages
  - High precision

X-ray Reflectivity, Diffraction, Fluorescence

- Manual XRD Tools at Applied Materials
  - Bede D1 (R&D version)
    - Has automated (wafer loading) version
  - Philips MRD
  - Typical applications include
    - Phase
    - Grain size
    - Texture
    - SiGe

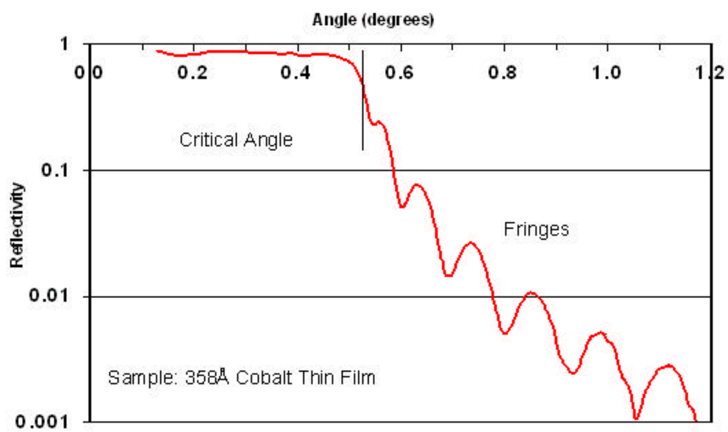
Basics of x-ray reflectivity (XRR)

Meta-Probe X is based on XRR



$\vartheta_C \propto \lambda \cdot (\rho)^{1/2}$

… use critical angle to determine density



$\sin^2 \vartheta_{max} = \sin^2 \vartheta_C + [i + ½]^2 \cdot [\lambda/2 \cdot T]^2$

for

$i = 1, 2, …$

… use fringe spacing to determine thickness

$R = R_{ideal} \times \exp(-[4\pi \sin \varphi\, \sigma/\lambda]^2)$

… use slope of curve and fringe attenuation to determine interface roughness

THERMA-WAVE The Fab Productivity Enhancement Company

X-ray reflectivity

- Thickness, no calibrations/standards needed
- Density
- Interface roughness

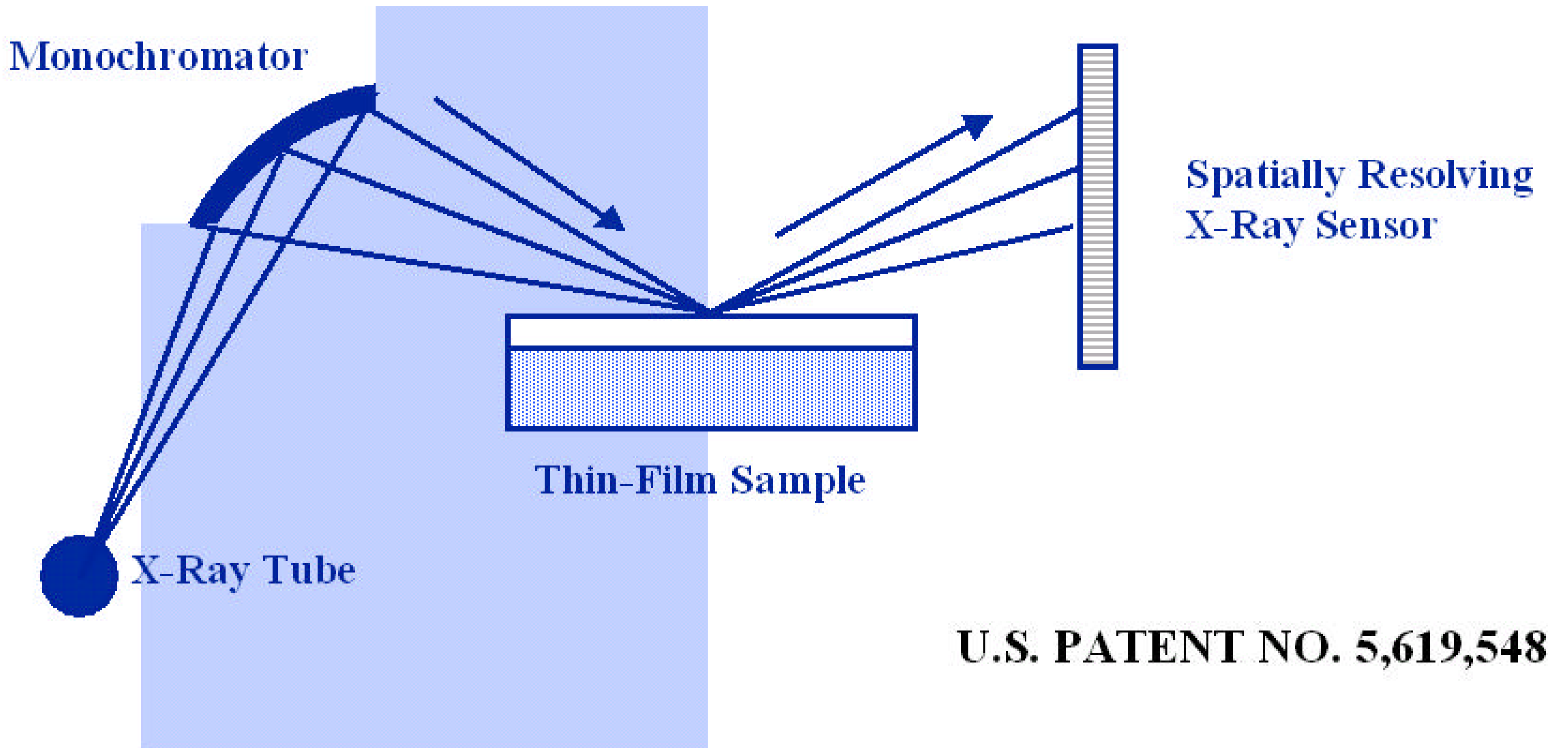
Automated x-ray tools

- Therma-Wave Meta-Probe X (MPX)
  - rapid XRR
  - installed at Applied Materials
- Technos S-MAT
  - XRR and XRF
- Jordan Valley JVX
  - rapid XRR and XRF
- Rigaku (new ?)

Therma-Wave Meta-Probe X

- Rapid x-ray reflectivity
- No scanning; measures range of incident angle simultaneously

Therma-Wave Rapid XRR



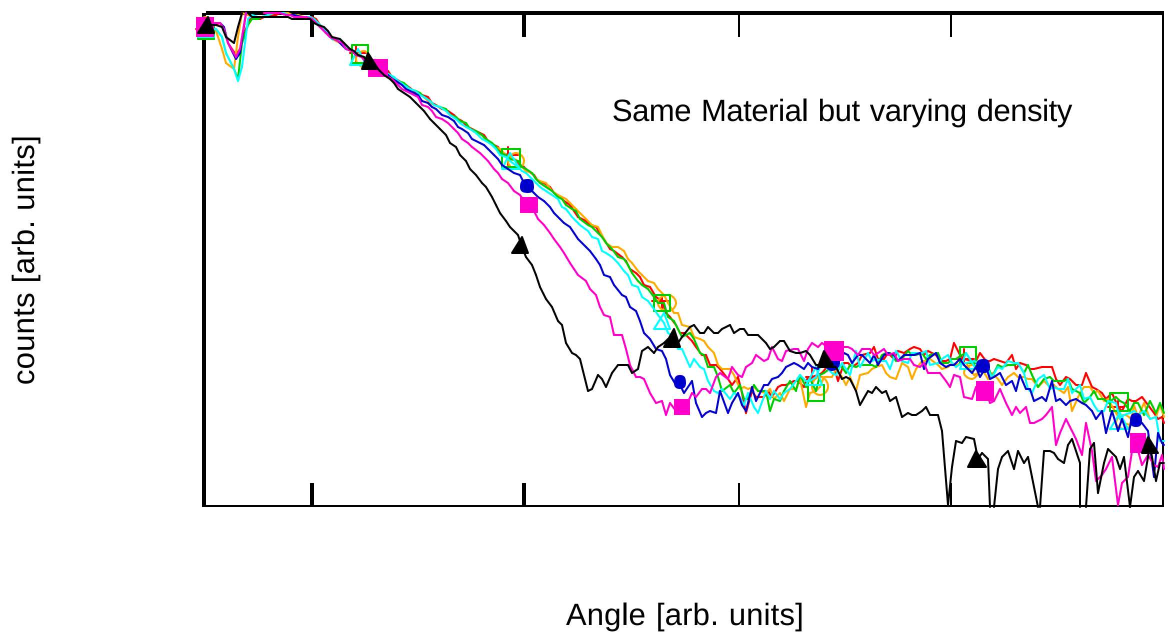
U.S. PATENT NO. 5,619,548

- Rapid Data Collection *...measurements in seconds*
- No Moving Parts or Complex Lasers *... simple and robust*

THERMA-WAVE
The Fab Productivity Enhancement Company

Meta-Probe X: example application

Density changes could be detected quickly. Process conditions were optimized according to the measured density.



Therma-Wave Meta-Probe X

- Applications at Applied Materials include
  - Liner/barrier MOCVD TiN
  - novel high-k materials (calibrate on MPX, measure on ellipsometer for speed)
  - Can measure multilayer film stack
- Advantages
  - Fast, range of angles simultaneously, no scanning
  - No moving parts
- Disadvantage
  - Limited range of angles
  - Therma-Wave roadmap is to increase the range
  - Lower limit of around 30 Å in thickness

Jordan Valley JVX

- Rapid x-ray reflectivity; also x-ray fluorescence
- Potential applications at Applied Materials
  - MOCVD TiN
  - novel high-k dielectrics for gate
  - Liner/barrier for Cu
  - ECP/CMP Cu, both patterned and blanket
- Advantages
  - Wide range of angles
  - high flux of x-rays
  - Small spot size
  - fast

Technos S-MAT

- Scanning x-ray reflectivity and fast XRF
- XRR for calibration, XRF for fast measurements
- Potential applications at Applied Materials
  - MOCVD TiN
  - novel high-k dielectrics for gate
  - Liner/barrier for Cu
- Advantages
  - Two tools in one (XRR and XRF)
  - Fast XRF
  - Can measure very thin films for process control (< 20 Å)
- Disadvantages
  - Slow, scanning XRR

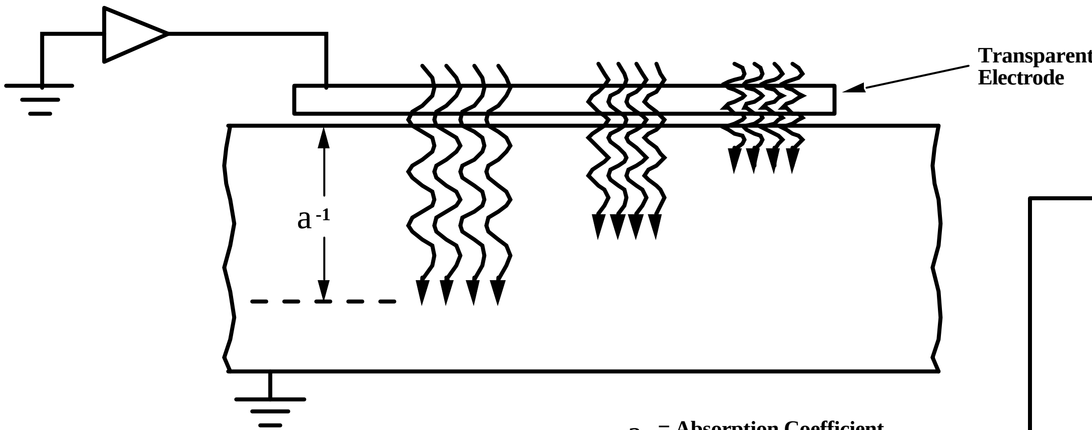
Non-contact Electrical Characterization

- Characterizes electrical properties of films
- Measures
  - Electrical oxide thickness
    - K-value (dielectric constant)
  - Heavy metal contamination in Si
    - Fe, Cu
    - This causes device degradation
    - Measurement principle is surface photovoltage (SPV)
  - Mobile ion contamination in dielectrics
    - Na, K, Li, Cu
    - This causes device degradation
    - Measurement principle is bias thermal stress (BTS)
  - Twenty other parameters
    - Density of interface traps, flatband voltage, etc.

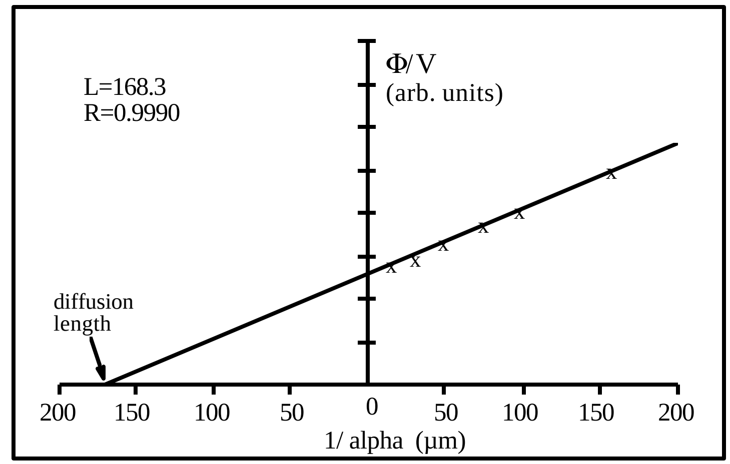
Tools at Applied Materials

- FAaST-330 from Semiconductor Diagnostics, Inc.
- Quantox from KLA-Tencor

Schematic of SPV Analysis Principle



a = Absorption Coefficient



Distribution of Generated Photo-Carriers is Determined by Wavelength of Light
DN(x) ~ exp (-ax) where 'x' is distance from illuminated surface

From the Values of the Surface Photo Voltage Signal (SPV) for Various Wavelegths, the Diffusion Length (L) is Calculated:

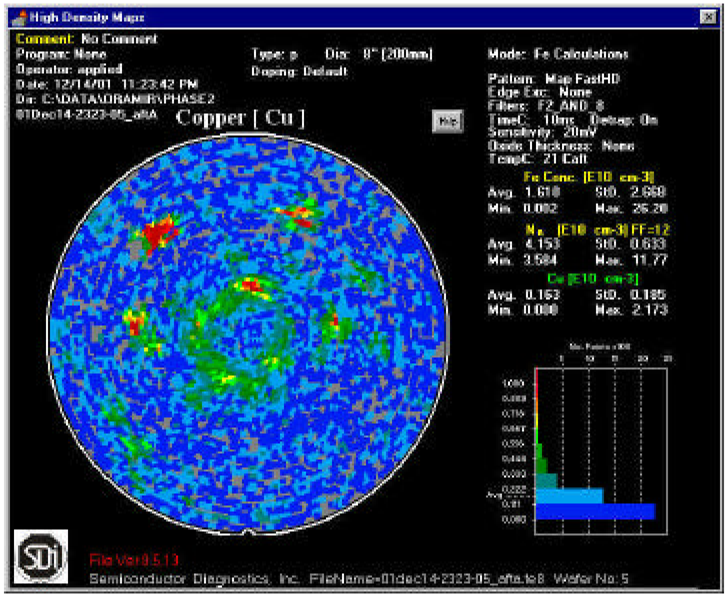
$$\frac{F}{D\,\mathbf{SPV}} = \mathbf{A}\left(1 + \frac{\mathbf{sL}}{\mathbf{D}}\right)\left(\frac{1}{a} + \mathbf{L}\right)\mathbf{exp}\left(\frac{\mathbf{qV}}{\mathbf{kT}}\right)$$

D = Diffusion Constant
S = Surface Recombination
a = **Absorption Coefficient for Given Wavelength**

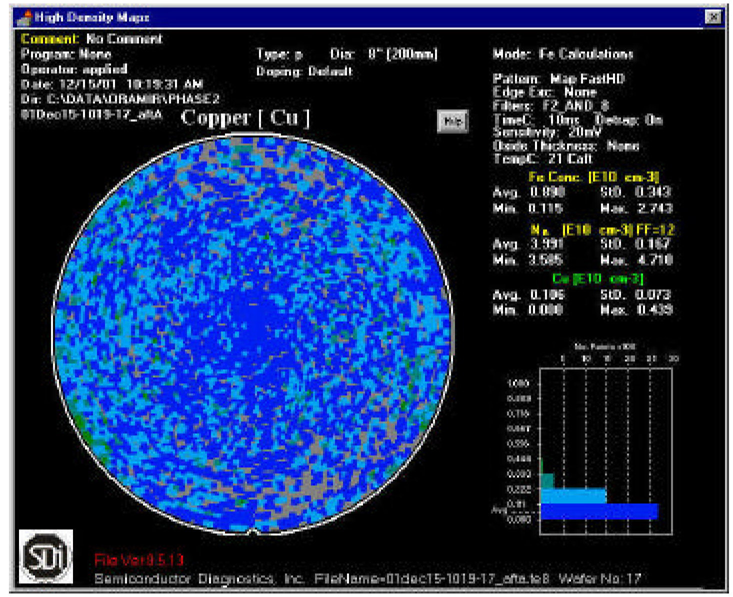
Solve Eq. For L

Bulk [Fe] and [Cu] concentration in Si originated from pre-aligner contamination

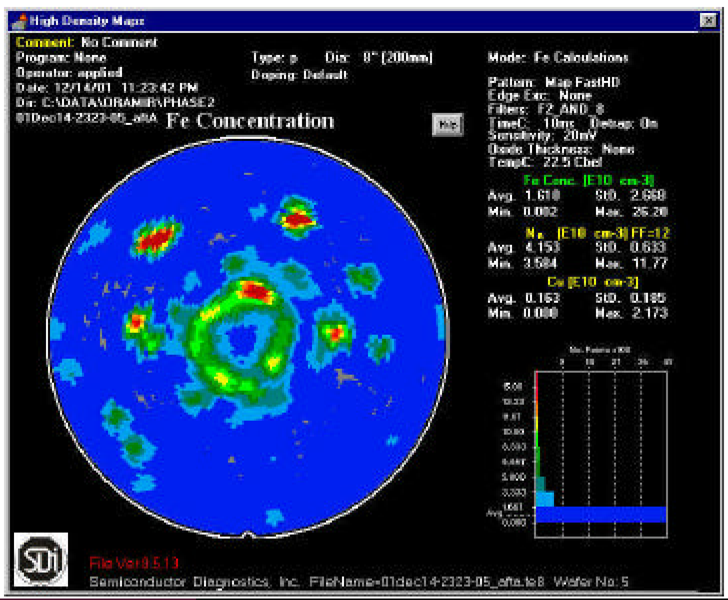
[Cu]



After Pre-aligner Clean



[Fe]



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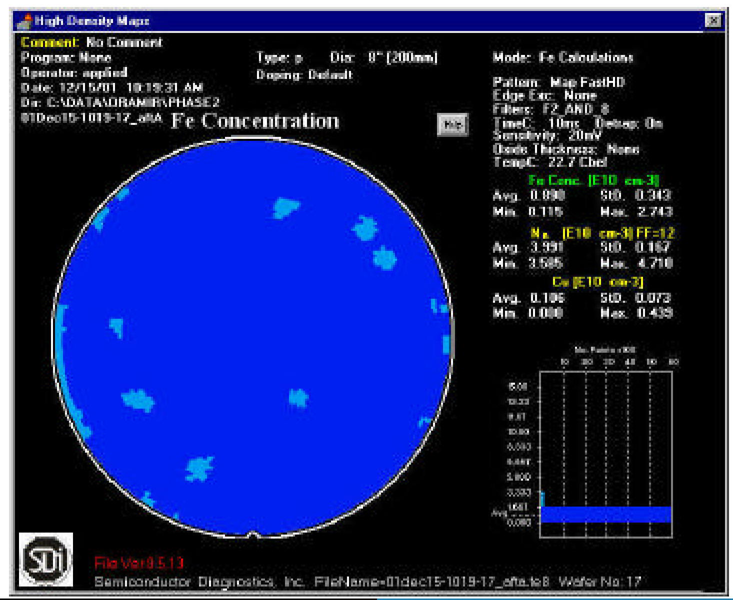

Metrology Tool Owners at Applied Materials

- Defect & Thin Film Characterization Lab (DTCL)
  - Centralized organization
  - Supports all the product business groups
- Individual Product Business Groups (PBG)
  - For example: CMP, Epi, etc.

DTCL in Applied Materials

- Owns and operates metrology tools for thin films and defects
- Mission of
  - Enabling faster time-to-market for product groups
  - Enhance customer satisfaction by quick turnaround resolution of field issues

DTCL Capabilities

Tool	Applications	Thin Film	Defect
FIB/SEM	film thickness, TEM sample prep	X	X
SEMVision	defect ID		X
Raman	phase, defect ID	X	X
FTIR	phase, defect ID	X	X
Auger	defect ID	X	X
Boxer Cross	junction depth, implant damage	X	
SP1	particle detection		X
Excite	particle detection		X
Compass	particle detection		X
MetaPULSe	thickness	X	
Impulse	thickness	X	
SDI FAaST	electrical properties	X	
KLA-Tencor Quantox	electrical properties	X	
AFM	surface roughness	X	X
Hardness Testing	film hardness	X	
Nano Scratch	adhesion	X	
Philips XRD	XRD, thickness, density	X	
Bede D1	XRD, thickness, density	X	
Metaprobe-X	thickness, density	X	

Challenges and Directions in Applied Materials Metrology

- Defect detection and characterization of smaller particles
- Very thin (< 15 Å) film measurement, including accuracy
- Detection of very low contamination levels (TXRF, VPD-ICPMS)
- Integrated metrology

Disclaimer

Mention of vendors does not necessarily mean that Applied Materials endorses them or their products

Acknowledgements

- Valery Komin
  - DTCL's guru on electrical characterization
- Yuri Uritsky
  - DTCL Manager
- Vendors who provided slides and other comments