The Status and Future of Metrology: Challenges from the ITRS Metrology Roadmap

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Center for Nanoscale Metrology (NC)3
ITRS Process
www.itrs.net

Overall Roadmap Characteristics
Gbits, CD, Speed

Focused Roadmaps
Litho, FEP, Interconnect, PIDS, Packaging, Test, Design, Wireless, ERM, ERD

Metrology
ESH
Yield Enhancement
Modeling and Simulation

2011 – Text & Requirements Update

2012 – Requirements Update

3 Meetings/year

Spring Europe

Summer US – Semicon West

Winter – Japan/Taiwan/Korea
Extreme CMOS

NanoElectronics – NanoTechnology – NanoScale Science

15 year Horizon
Non-classical CMOS

High $\kappa$/interface & Metal Gate Metrology

The Future

Yesterday
90 nm $\frac{1}{2}$ Pitch

CMOS pMOS FINFET

New Materials

UTB SOI

Strain Metrology

Today
<32 nm $\frac{1}{2}$ pitch

Non-classical CMOS

Metrology For New Structures

Strain Enhanced Mobility
## 2010 Metrology Roadmap

<table>
<thead>
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<td>Double Exposure and Etch - Process Range (nm)</td>
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<td><strong>Spacer PEE process</strong></td>
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<td>First pass CD control (after etch) - Process Variation (nm)</td>
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<td><strong>Front End Processes Metrology</strong></td>
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<td>High Performance Logic EOT equivalent oxide thickness (EOT), nm</td>
<td>0.65</td>
<td>0.5</td>
<td>0.5</td>
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<td>Logic Dielectric EOT Precision 3σ, nm</td>
<td>0.0026</td>
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<td>Barrier layer thick (nm)</td>
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<td>Void Size for 1% Voiding in Cu Lines</td>
<td>4.5</td>
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<td>Detection of Killer Pores at (nm) size</td>
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AGENDA

• Lithography Metrology
• FEP Metrology
• Interconnect Metrology
• Beyond CMOS
• Conclusions
Patterning via EUV Lithography

Reticle stage
C4 element
Projection optics
Wafer stage
Drive laser beam
C1 collector
Gas jet assembly
Laser-produced plasma
C2, C3 pupil optics
Spectral purity filter
Patterned Absorbers
~ 100 nm thick (e.g. Al, Cr, TaN, W)

Buffer Layer
~ 50 nm thick (e.g. SiO$_2$)

Reflective Multilayers
~ 300 nm thick (Mo - Si = 13.5nm)
40 - 50 Pairs
Phase and Amplitude Defects

"Phase defects"

Incident EUV

Wafer plane image

Mo/Si

Substrate

"Amplitude defects"

Incident EUV

Wafer plane image

Mo/Si

Substrate

Phil Seidel  2003
EUV Lithography Metrology

**Mask Substrate Defect Inspection**
- Glass

**Mask Blank Inspection**
- Absorber Layer
- Mo-Si Multi Layer
- Glass

**AIMS**
- Project what mask will print onto a detector

**Patterned Mask Inspection**
Self Assembly Patterning

Block co-polymers

Stoykovich, et al, Science 308 (2005), 1442
Lithography Metrology

Dual Patterning

Line Edge Roughness

CD Metrology Extendibility

CD-SAXS

Litho Metrology for 3D Devices

Contour vs Design

MuGFET
MuCFET

Mueller Matrix Ellipsometry
## Lithography Metrology Requirements

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**Gate**

**Dense Lines**
Typically - Line Edge has Higher Intensity
NIST Research Finds 3D info

Before 2000

Cross section
Video signal
SE yield
SE edge effect

IC structure
Raw video linescan
Beam geometry corrected
Monte Carlo corrected

Andras Vladar, Mike Postek, & John Villarrubia
Scatterometry Was Introduced

Real Time Calculation of line width & shape & Libraries

See – Scatterometry by Chris Raymond in Handbook of Silicon Semiconductor Metrology

cnse.albany.edu
Grating - periodic in x direction

\[ \varepsilon(x) = \sum_{h} \varepsilon_h \exp\left( j \frac{2\pi}{\Lambda} hx \right) \]

Solve coupled wave equations by ordinary matrix techniques with matched boundary conditions in the interface of air and substrate.

\[ \frac{\partial S_{yi}}{\partial z} = k U_{xi} \]

\[ \frac{\partial U_{xi}}{\partial z} = \left( \frac{k_{xi}^2}{k} \right) S_{yi} - k \sum_{p} \varepsilon_{(i-p)} S_{yp} \]
High K Optical Model Requirement
Variability with Composition and Process

25 Å Hf-Silicate

- 30 %
- 45 %
- 60 %

Wavelength (nm)

Bandgap (nm)

Silicate %
What are you measuring?

Measurement Convergence - CD-SEM measurement of multiple lines in same image and Scatterometry determined Average Value
Potential New CD Methods

CD-SAXS

He Ion Microscope
New Imaging Physics

Winli Wu  NIST
More Signal from Existing Methods

- Mueller Matrix Ellipsometry

- 3D Dimensional SEM Metrology
Drift-corrected frame averaging

Better CD SEM
Via Small Improvements

3D model determines all structure dimensions

Andras Vladar, NIST
Rotating-polarizer ellipsometry (PRSA)

One example from many types of ellipsometers
Great for Isotropic Samples & No Depolarization

\[
\begin{align*}
S &= \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} I_x + I_y \\ I_x - I_y \\ I_{\pi/4} - I_{-\pi/4} \\ I_{\text{LCP}} - I_{\text{RCP}} \end{bmatrix} \\
\begin{bmatrix} s_0,_{\text{out}} \\ s_1,_{\text{out}} \\ s_2,_{\text{out}} \\ s_3,_{\text{out}} \end{bmatrix} &= \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} s_0,_{\text{in}} \\ s_1,_{\text{in}} \\ s_2,_{\text{in}} \\ s_3,_{\text{in}} \end{bmatrix}
\end{align*}
\]

\[
\tan \Psi e^{i\Delta} = \frac{r^P}{r^S}
\]
Dual Rotating Compensator Ellipsometer (RC2)

Laboratory Ellipsometer
Great for All Types of Samples

Unpolarized incident light

Rotating Compensator

Sample

Elliptically polarized light

Rotating Compensator

Rotating Analyzer

\[
S = \begin{bmatrix}
    s_0 \\
    s_1 \\
    s_2 \\
    s_3 \\
\end{bmatrix} = \begin{bmatrix}
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\end{bmatrix}
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Stokes Vector

\[
\begin{pmatrix}
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    S_{1,\text{out}} \\
    S_{2,\text{out}} \\
    S_{3,\text{out}} \\
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    M_{41} & M_{42} & M_{43} & M_{44} \\
\end{pmatrix} \begin{pmatrix}
    S_{0,\text{in}} \\
    S_{1,\text{in}} \\
    S_{2,\text{in}} \\
    S_{3,\text{in}} \\
\end{pmatrix}
\]

Mueller Matrix
Diffraction Effects and Scatterometry

K. Suzuki & B.W. Smith, 
Microlithography: Science and Technology, 
Part III Chapter 14

Blossom target in 
(a) full view and (b) center detail

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• Interconnect Metrology
• Beyond CMOS
• Conclusions
Metrology for New Structures

EOT & Defects for Alternate Channel Materials

CD/Sidewall/Height/Stress Metrology for 3D Devices

New Memory Materials
Phase Change Memory

Metrology for Generation II and III Metal Gate/High k stacks

Nano-topography & Local Stress measurements

ITRS
New Materials impact CD Metrology

Optical Properties of next Gen High k

Measuring Interfacial Layer is more challenging
Optical Model for NanoScale Metal Film

Drude Oscillator - Free Electron

Lorentz Oscillator - Bound Electron

\[ E = \hbar \omega \]

\[ \varepsilon_1 = \varepsilon_1^f + \varepsilon_1^b \]

\[ \varepsilon_2 = \varepsilon_2^f + \varepsilon_2^b \]

\[ \tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2 = (\tilde{N})^2 = (n + ik)^2 = (n^2 - k^2) + 2ink \]
\[
\frac{1}{\tau_f} = \frac{1}{\tau_{bulk}} + \frac{\nu F}{\lambda}
\]

\[
\lambda = \left[\frac{2(1-\Re)}{3\Re}\right]R_g
\]

Real part of refractive index of Ni films

Refractive index of 800 Å Ni film

Refractive index of 50 Å Ni film

Vimal Kamineni - CNSE
Gap in Dopant Metrology

• Emphasis on Dopant Metrology
  – USJ Conference

• SOI impacts methods such as photomodulated optical reflectance

• Start with the Theory – see JOURNAL OF APPLIED PHYSICS 108, 104908 (2010)
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Overlay – IR Microscopy

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X-Ray Microscopy

Bonding Defects – SAM Scanning Acoustic Microscopy

Stress Metrology Raman Microscopy
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Extreme and Beyond CMOS

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Non-classical CMOS

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CMOS
pMOS FINFET

New Materials

High $\kappa$/interface & Metal Gate
Metrology

Is Graphene THE material?

Strain
Enhanced Mobility

Metrology
For New
Switches

UTB SOI

Beyond CMOS

Strain
Metrology
Transition to Beyond CMOS

Nanowire Electronics (Lieber - Nature)

NanoTube Electronics (Avouris – Chen, Science)

18 um long
Carbon nanotube

Ring Oscillator
5 CMOS inverters
= 10 FETs
INDEX – Metrology for Graphene

High carrier mobility and structural robustness have driven a considerable effort in Graphene research

How many Layers? Raman, LEEM, Ellipsometry

Measurement of Bi-layer Mis-orientation Aberration corrected TEM

Quantum Hall Effect observes the Berry Phase

Magnetic Field

\[ V = 0 \]

Hall Voltage

Current

\[ \rho_{xx}, \rho_{xy} \]
DF TEM of CVD Graphene

Method described in Muller groups 2011 Nature pub
Counting Atomic Columns in a FiN

Beyond CMOS Materials
Graphene

NIST Traceable Standard
Ron Dixon – NIST
George Orji - NIST
Ben Bunday - SEMATECH

Figure Courtesy
C. Kisielowski - Nano Lett.8, (2008), 3582–3586
Optical Absorption at Critical Points

Nano-Dimensional Optical Properties
Blue shift for E1 transition – First Explanation was Quantum Confinement.
Nano-Dimensional Optical Properties

Ultra-Thin Silicon

Blue shift for E1 transition. – Phonon confinement Plays a Role

Low Temperature Data shows that electron-phonon scattering strongly influences optical properties
Electron and phonon confinement change optical properties

Vimal Kamineni - CNSE
5 nm SOI with different top dielectric layers

- Hafnium oxide (5.1 nm)
- Native oxide (5.1 nm)
- Silicon dioxide (4.8 nm)
5 nm SOI with different top dielectric layers

Acoustic and optical phonon modes have a strong effect on E1 Critical Point energy and broadening of E1, i.e. the refractive index.

Our Modeling of acoustic phonon modes show that they change with film thickness and presence of a dielectric layer above the SOI.

This implies that optical properties of Nanoscale Semiconductors depend on Materials and Structure.
Metrology needs to measure the distribution of a property that is changing at Nano-Scale Dimensions across a large area such as stress across an SRAM Cell.

We need more than CD to control Electrical Properties.

Final Stress in SRAM Cell

Sentaurus TCAD simulations from Synopsys – TCAD News Dec 2010
Conclusions

• Changes in Metrology Requirements often outpace R&D of new methods

• Old methods often find new life: Measurements Require Nanoscale Materials Properties

• New Materials & Beyond CMOS drive most R&D
Acknowledgements

• ITRS Metrology TWG

• My research group - Vimal Kamineni, Florence Nelson, Josh LaRose, Lay Wai Kong, Ilyssa Wells, Eric Bersch and Tianhao Zhang

• Theme VI team
  – Ray Ashouri, Karl Berggren, Robert Geer, Julia Greer, Tony Heinz, Robert Hull, Philip Kim, Charlie Marcus

• NRI – NERC – INDEX Funding