Sensors and Metrology - 2
Optical Microscopy and Overlay Measurements

Optical Metrology

- Optical Microscopy
  - What is its place in IC production?
  - What are the limitations and the hopes?
- The issue of Alignment Control
  - Needs in the industry
  - Basic technology
  - Precision and Accuracy of existing tools
  - How the future looks

Optical Microscopy

- Optical Microscopes have limited resolution, but are still useful instruments for human (or even automated) inspection:

$$R = 0.61\lambda/NA$$

$$NA = n \sin\alpha$$

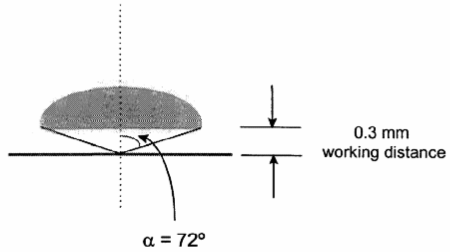


Fig. 2. Detail of 100x microscope objective with *NA* = 0.95.

Overview of Optical Microscopy and Optical Microspectroscopy , Joel W. Ager III, Characterization and Metrology for ULSI Technology, 1998 International Conference.

General Configuration

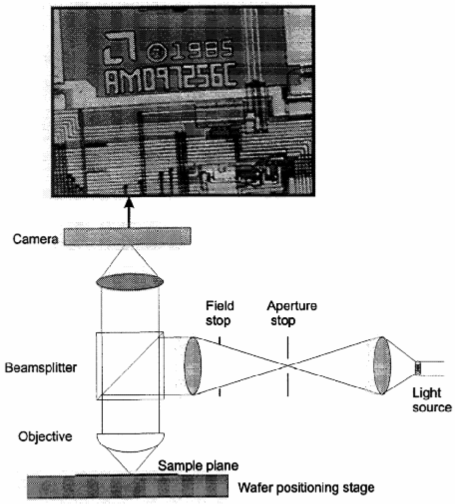


Fig. 1. Simplified block diagram of a semiconductor inspection microscope under brightfield illumination conditions. The image shown was taken with a 10x, *NA* = 0.25 microscope objective.

Practical magnification levels are limited by the diffraction-limited resolution...

Typical Resolution Limits

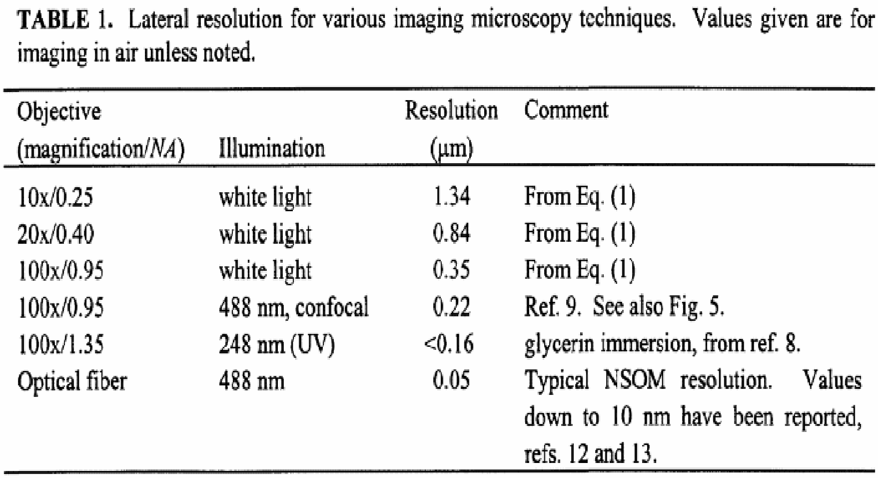


TABLE 1. Lateral resolution for various imaging microscopy techniques. Values given are for imaging in air unless noted.

Objective (magnification/*NA*)	Illumination	Resolution (μm)	Comment
10x/0.25	white light	1.34	From Eq. (1)
20x/0.40	white light	0.84	From Eq. (1)
100x/0.95	white light	0.35	From Eq. (1)
100x/0.95	488 nm, confocal	0.22	Ref. 9. See also Fig. 5.
100x/1.35	248 nm (UV)	<0.16	glycerin immersion, from ref. 8.
Optical fiber	488 nm	0.05	Typical NSOM resolution. Values down to 10 nm have been reported, refs. 12 and 13.

Resolution defined as the minimum distance at which two bright spots can be distinguished.

Confocal Microscopy for Enhanced Resolution

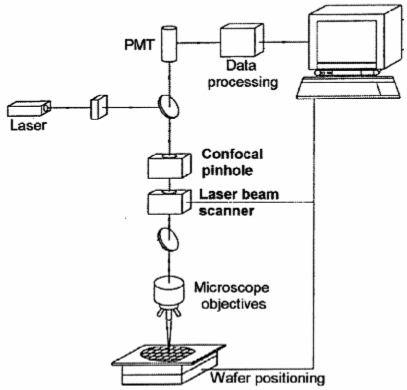


Fig. 3. Block diagram of a confocal laser microscope

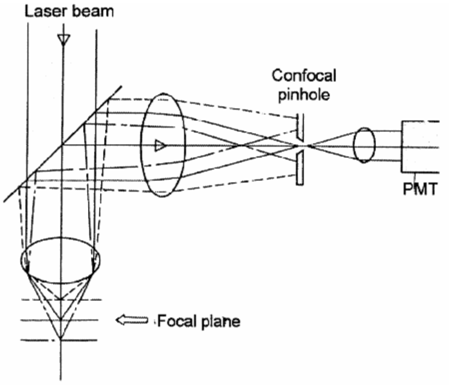


Fig. 4. Detail of rejection of light above and below the focal plane of the microscope objective. Dotted lines represent light emanating from above and below the focal plane that is blocked from reaching the detector by the confocal pinhole.

Focused laser beam is scanned across field of view, image is reconstructed electronically.

Ultraviolet Microscopy with NA>1 (!)

- UV illumination
- NA > 1 (achieved by immersing lens in high n medium (glycerin)
- Very high resolution, and very, very thin depth of focus.
  - Can be useful in detecting buried defects!
- Contamination concerns limit use in IC production

Near-field Scanning Optical Microscopy

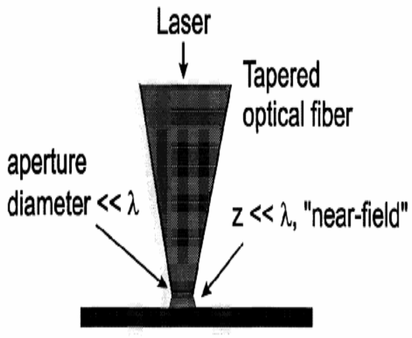


Fig. 6. Simplified picture of a near-field scanning optical microscope (NSOM). When tip to sample spacing is sufficiently small, lateral resolution is determined by the aperture diameter.

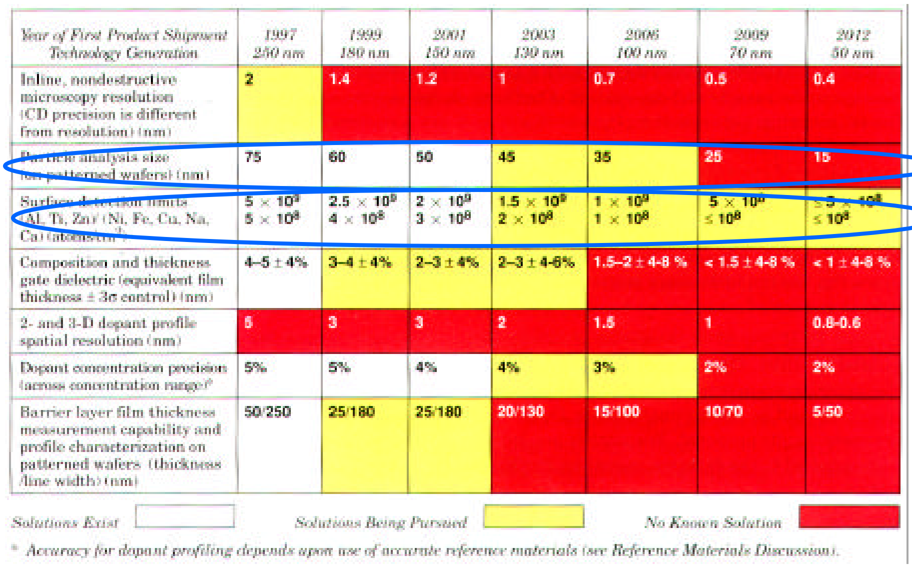
Use very narrow fiber (50-100nm) to illuminate at near field, and detect at far field,

or a focused laser to illuminate at far field and narrow fiber to detect at near field.

Either case requires AFM-like scanning and feedback control for position (terrain following).

Approach limited by speed and surface topography.

Microscopy can help in Contamination Analysis



Year of First Product Shipment Technology Generation	*1997 250 nm*	*1999 180 nm*	*2001 150 nm*	*2003 130 nm*	*2006 100 nm*	*2009 70 nm*	*2012 50 nm*
Inline, nondestructive microscopy resolution (CD precision is different from resolution) (nm)	2	1.4	1.2	1	0.7	0.5	0.4
Particle analysis size (on patterned wafers) (nm)	75	60	50	45	35	25	15
Surface detection limits (Al, Ti, Zn) (Ni, Fe, Cu, Na, Ca) (atoms/cm^2)	5×10^9 5×10^8	2.5×10^9 4×10^8	2×10^9 3×10^8	1.5×10^9 2×10^8	1×10^9 1×10^8	5×10^9 $\leq 10^8$	$\leq 5 \times 10^8$ $\leq 10^8$
Composition and thickness gate dielectric (equivalent film thickness ± 3σ control) (nm)	4–5 ± 4%	3–4 ± 4%	2–3 ± 4%	2–3 ± 4-6%	1.5–2 ± 4-8 %	< 1.5 ± 4-8 %	< 1 ± 4-8 %
2- and 3-D dopant profile spatial resolution (nm)	5	3	3	2	1.5	1	0.8-0.6
Dopant concentration precision (across concentration range)*	5%	5%	4%	4%	3%	2%	2%
Barrier layer film thickness measurement capability and profile characterization on patterned wafers (thickness /line width) (nm)	50/250	25/180	25/180	20/130	15/100	10/70	5/50

Solutions Exist ☐ *Solutions Being Pursued* 🟨 *No Known Solution* 🟥

* *Accuracy for dopant profiling depends upon use of accurate reference materials (see Reference Materials Discussion).*

Raman Microspectroscopy

- Microspectroscopy is considered a very promising technique for defect classification

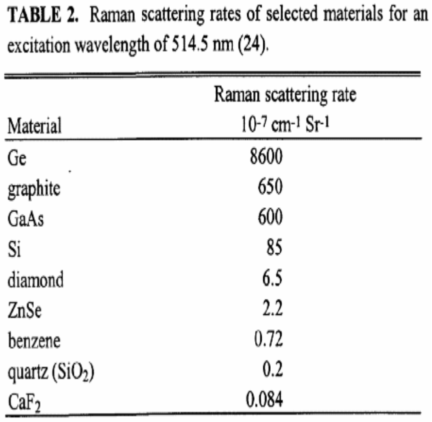
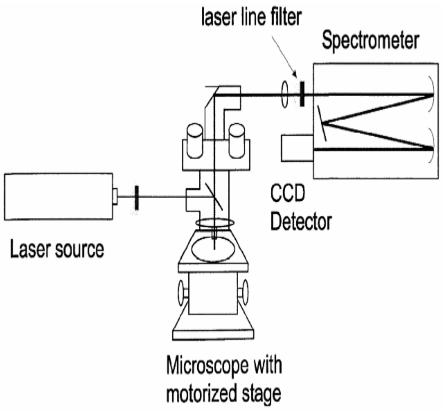


TABLE 2. Raman scattering rates of selected materials for an excitation wavelength of 514.5 nm (24).

Material	Raman scattering rate 10^{-7} cm^{-1} Sr^{-1}
Ge	8600
graphite	650
GaAs	600
Si	85
diamond	6.5
ZnSe	2.2
benzene	0.72
quartz (SiO_2)	0.2
CaF_2	0.084



Raman Spectroscopy for Defect Classification

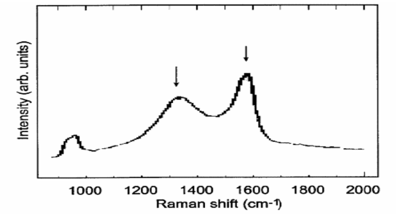


Fig. 8. Raman spectrum of 200 nm graphite particle obtained with prototype semiconductor inspection tool. Arrows mark the distinctive D-band (1360 cm^{-1}) and G-band (1580 cm^{-1}) features of microcrystalline graphite. The peak at 975 cm^{-1} is a 2nd-order feature from the Si substrate.

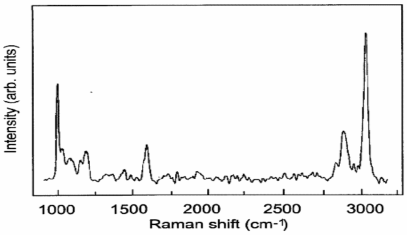


Fig. 9. Raman spectra from 1 μm polystyrene sphere. The features at 1000 cm^{-1} and 1600 cm^{-1} are due to C-H out of plane motion and aromatic ring breathing, respectively. The strong features at 2900 - 3100 cm^{-1} are due to C-H stretches.

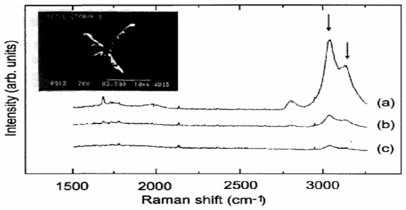


Fig. 10. Raman spectra from a series of NH_4Cl defects (example shown in inset) of decreasing size: (a) 2.5 μm; (b) 1.0 μm; (c) 0.5 μm. The peaks at 3040 and 3320 cm^{-1} (arrows) are due to the symmetric and asymmetric N-H stretches in the NH_4^+ cation. The position of these peaks established that the defect is NH_4Cl.

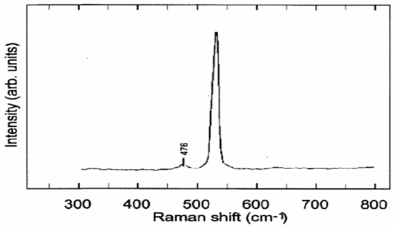
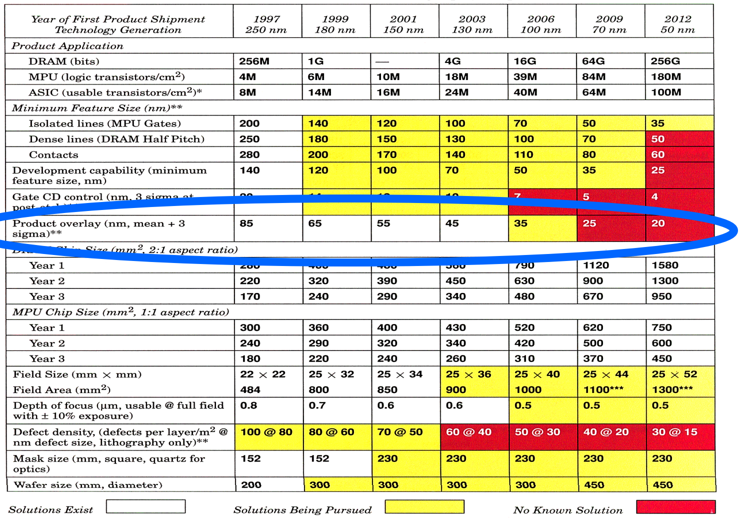


Fig. 11. Raman spectra from 1.5 μm quartz (SiO_2) particle on a Si wafer. The peak at 476 cm^{-1} is due to the quartz; the strong peak at 520 cm^{-1} is from the Si substrate which, because the quartz particle is transparent, is also in the field of view of the microscope objective.

The Issue of Image Placement

Table 24 Product Critical Level Lithography Requirements



Year of First Product Shipment Technology Generation	*1997 250 nm*	*1999 180 nm*	*2001 150 nm*	*2003 130 nm*	*2006 100 nm*	*2009 70 nm*	*2012 50 nm*
Product Application							
DRAM (bits)	256M	1G	—	4G	16G	64G	256G
MPU (logic transistors/cm^2)	4M	6M	10M	18M	39M	84M	180M
ASIC (usable transistors/cm^2)*	8M	14M	16M	24M	40M	64M	100M
*Minimum Feature Size (nm)***							
Isolated lines (MPU Gates)	200	140	120	100	70	50	35
Dense lines (DRAM Half Pitch)	250	180	150	130	100	70	50
Contacts	280	200	170	140	110	80	60
Development capability (minimum feature size, nm)	140	120	100	70	50	35	25
Gate CD control (nm, 3 sigma at post-etch)**	20	14	12	10	7	5	4
Product overlay (nm, mean + 3 sigma)**	85	65	55	45	35	25	20
DRAM Chip Size (mm^2, 2:1 aspect ratio)							
Year 1	280	400	480	560	790	1120	1580
Year 2	220	320	390	450	630	900	1300
Year 3	170	240	290	340	480	670	950
MPU Chip Size (mm^2, 1:1 aspect ratio)							
Year 1	300	360	400	430	520	620	750
Year 2	240	290	320	340	420	500	600
Year 3	180	220	240	260	310	370	450
Field Size (mm × mm)	22 × 22	25 × 32	25 × 34	25 × 36	25 × 40	25 × 44	25 × 52
Field Area (mm^2)	484	800	850	900	1000	1100***	1300***
Depth of focus (μm, usable @ full field with ± 10% exposure)	0.8	0.7	0.6	0.6	0.5	0.5	0.5
Defect density, (defects per layer/m^2 @ nm defect size, lithography only)**	100 @ 80	80 @ 60	70 @ 50	60 @ 40	50 @ 30	40 @ 20	30 @ 15
Mask size (mm, square, quartz for optics)	152	152	230	230	230	230	230
Wafer size (mm, diameter)	200	300	300	300	300	450	450

Solutions Exist ☐ *Solutions Being Pursued* 🟨 *No Known Solution* 🟥

* *ASIC will use maximum available field size*
** *Requirements scale with resolution for shrinks*
*** *Field size requirements are based on Year 2 chip sizes, the year demanding the full field size for high volume production*

Overlay Requirements

- 0.5µm technology needed 150nm of overlay
- 0.25µm technology needs <100nm of overlay
- 3-5% of overlay budget can be allowed for metrology errors.
  - Systematic (lens aberrations, illumination problems, wafer related problems, resist slope, processing asymmetry, etc.)
  - Random (pattern dependent, CMP effects, etc.)
  - Ugly (interactions among process steps, strange sensitivity to focus position, etc.)

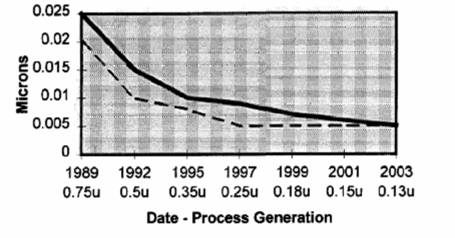


FIGURE 3. Performance of Overlay metrology equipment relative to SIA process error budget requirements.

Image Placement

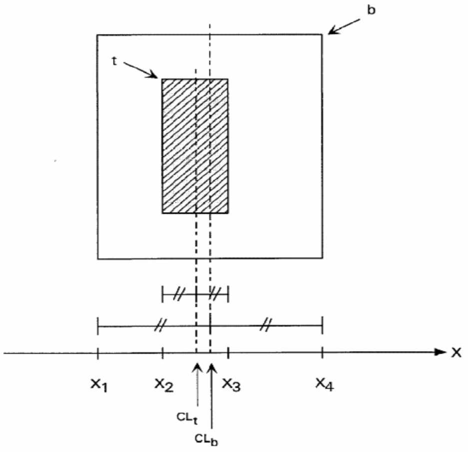


FIGURE 1. Illustrating the ground rule definitions of linewidth, centerline overlay and edge-to-edge overlay.

Metrology of Image Placement, Alexander Starikov, Ultratech Stepper, Inc., San Jose, California 95134

CP449, Characterization and Metrology for ULSI Technology: 1998 International Conference, edited by D. G. Seiler, A. C. Diebold, W. M. Bullis, T. J. Shaffner, R. McDonald, and E. J. Walters

Typical “redundant” target

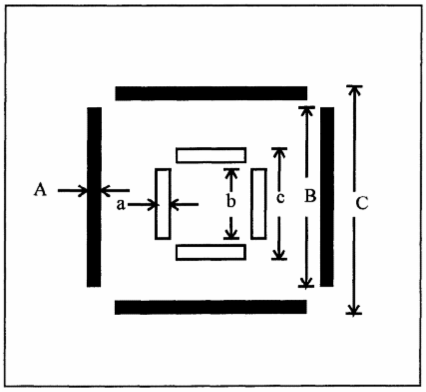


FIGURE 6. Typical automated overlay structure design

Overlay Metrology: The systematic, the random and the ugly, Neal Sullivan, Jennifer Shin, Advanced Process Tool Development Group, Digital Semiconductor, Hudson, MA 01749
CP449, Characterization and Metrology for ULSI Technology: 1998 International Conference edited by D. G. Seiler, A. C. Diebold, W. M. Bullis, T. J. Shaffner, R. McDonald, and E. J. Walters 0 1998 The American Institute of Physics l-56396-753-7/98/$15.00

Standard SEMI Targets

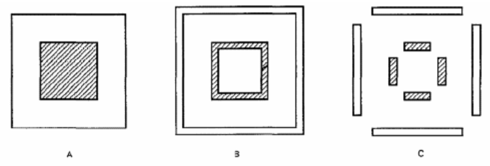


FIGURE 3. Typical O/L metrology structures.

Modern targets exploit dimensional redundancy
TIS (Tool Induced Shift) can be measured by comparing readings to 180 degree rotation.
WIS (Wafer induced Shift) is subject to topography and other target problems. It is much harder to measure.

Target Asymmetry can be a Problem

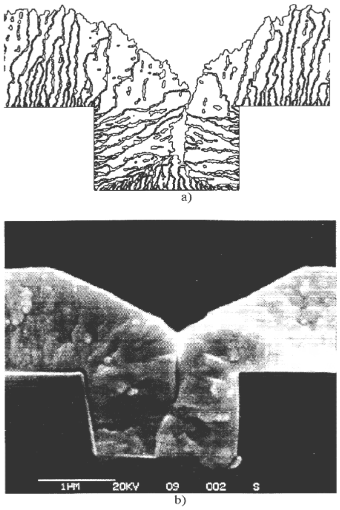
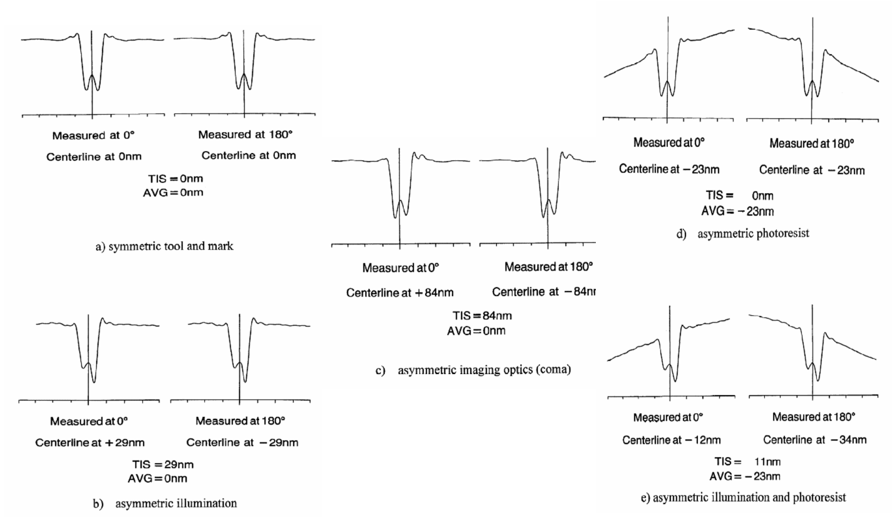


FIGURE 13. Illustrating properties of W sputtered over a trench: SIMBAD model (a) and SEM cross-section (b).

An Illustration of TIS and WIS effects



Modern Tools are big, dedicated and expensive

The **5200XP Overlay Metrology System** performs fully automated overlay measurements on multilayer integrated circuit product and test wafers. The system features measurement capability for 0.18 µm technology, including coherence probe measurement capability which is optimized for planarized layers. It also features optional KLASS 4.0 for Windows analysis software for stepper-specific registration control. The 5200XP is also available in a SMIF configuration.

Tool-to-Tool matching is an issue

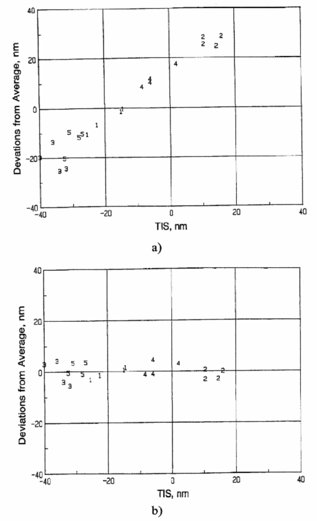


FIGURE 5. Tool-to-tool matching in a set of five systems of the same type from a population average on four sites on one wafer: a) using only the data taken at 0° and b) using an average of the data taken at 0° and 180° (that is, calibrated for TIS).

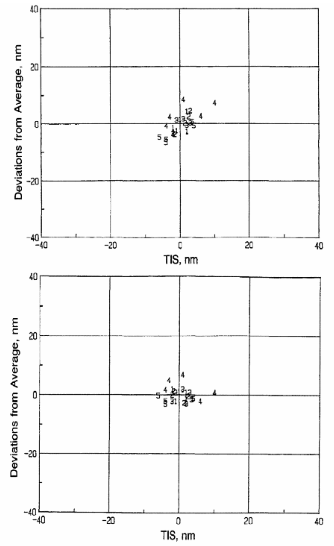
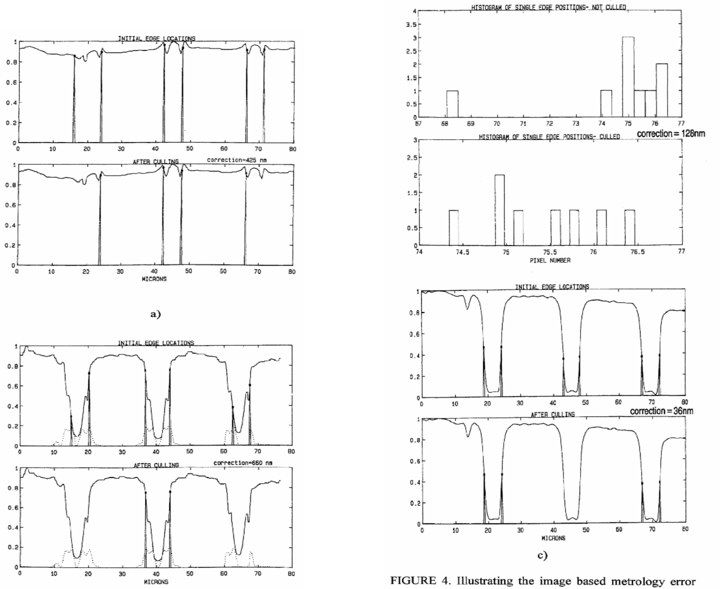


FIGURE 6. Tool-to-tool matching of the same tools as in Fig. 5, but when TIS is small.

Imaged-based Error Correction helps...



a)

b)

c)

FIGURE 4. Illustrating the image based metrology error diagnostics and culling by detecting: failure of redundancy (a), asymmetry (b) and spatially localized anomaly (c).

Other issues contribute to variability

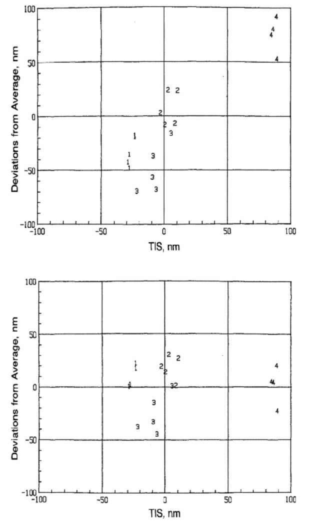


FIGURE 8. Tool-to-tool matching of four conventional optical bright field polychromatic systems with different optical configurations, focus and edge/centerline estimation criteria.

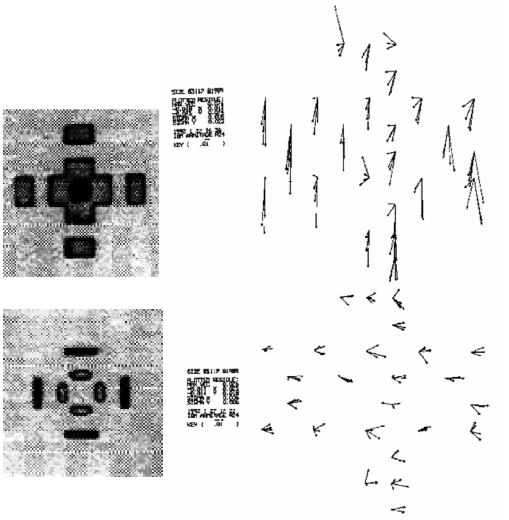


FIGURE 10a. Assessment of O/L metrology error in metrology process integration: large errors due to topography and SLR.

W CMP Case Study

CMP is meant to planarize

We need visible edges to measure centerlines and adjust position.

Some undesirable CMP artifacts help us find position.

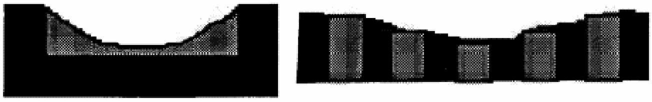


FIGURE 7. Dishing (left) and erosion (right) 18

Optical and Electronic Tricks help

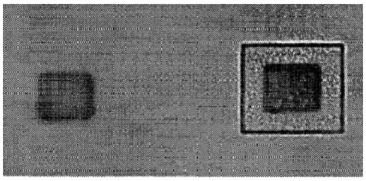


FIGURE 10. Contrast Improvements due to Image Enhancement 22

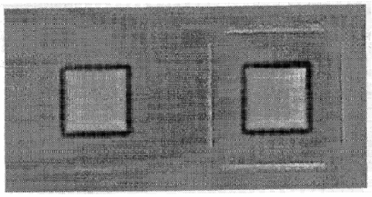


FIGURE 12. Contrast Improvements due to a priori Target data26

Placement error is proportional to square root of noise...

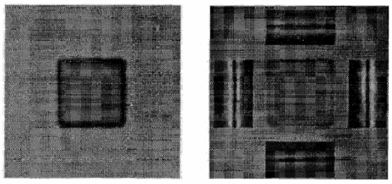
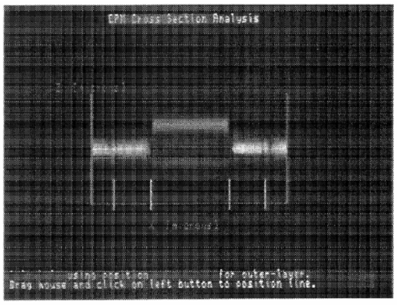


FIGURE 11. Contrast Improvements due to Phase Imaging 24

Results of W CMP study



[illegible] using position [illegible] for outer-layer.
Drag mouse and click on left button to position line.

FIGURE 14. "Cloud Plot" of W CMP Overlay Target.

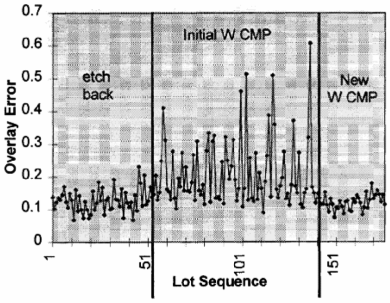


FIGURE 15. Manufacturing Data Demonstrating Overlay Target Performance.

W-CMP Study

1) Substrate bar formed by isolated space to avoid erosion.
2) Maximize edge definition by maximizing post W CMP Step height:
    a) Minimized deposited W thickness
    b) Optimize trench width to 6 - 8 times minimum feature size (Max width determined by dishing).
    c) maximize trench depth (remove etch stops).

Note conflicting process/metrology requirements!

Approach for Metrology Improvement

- use a comprehensive (systems) approach;
- analyze processes, sub-processes and points of hand-off;
- establish quantitative measures of metrology quality;
- automate gathering and analyses of quality feedback;
- assess quality of typical metrology (benchmarking);
- assess the failures of control (frequency and magnitude);
- establish the absolute values of error (to standard);
- account for technology limitations;
- rank the impact and cost to remove (Pareto analysis);
- remove the largest detractors first and re-assess.

Metrology

“The ultimate goal of IC manufacturing is to make high quality product at reasonable cost, so that the people in metrology and processing make their living. When the social contract of the various groups involved in IC manufacture is seen this way, a solution is always found.”

What is next

- In-situ possibilities
- Reflectometry, Ellipsometry and Scatterometry
- OES, Temperature, Pressure Sensors
- What is the future in process/wafer sensors?