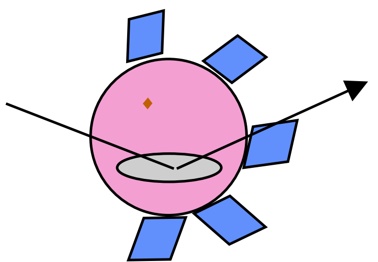
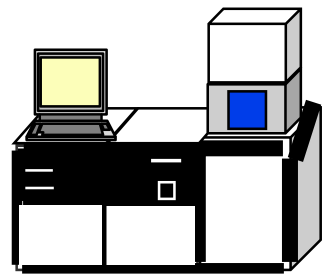
IN-SITU

IN-LINE

OFF-LINE / AT-LINE





1999 Metrology Roadmap

Europe	Alec Reader (Philips) Patrick Dussouillez (ST Microelectronics)
Japan	Fumio Mizuno (Hitachi)
Taiwan	Henry Ma (EPISIL) George Yen (ProMOS)
US	Bob Scace (NIST) Alain Diebold (SEMATECH)

Outline

- Changes from 1997
- Critical Challenges
- Lithography Metrology
- Front End Processes
- Interconnect Metrology
- Integrated Metrology
- Risks

Changes from 1997 NTRS

- Mask Metrology Expanded
- New needs from 157 nm Lithography
- Sensors now a part of Integrated Metrology

Difficult Challenges > 100 nm / Before 2005

- Metrology integration for in-situ and in-line metrology tools
- Particles, oxygen, and metallics detection at levels of interest for starting materials and reduced edge exclusion for metrology tools
- Measurement of the frequency-dependent dielectric constant of low k interconnect materials at 5x to 10x base frequency.
- Control of high-aspect ratio technologies such as Damascene challenges all metrology methods.
- Measurement of complex material stacks

Additional Difficult Challenges < 100 nm / Beyond 2005

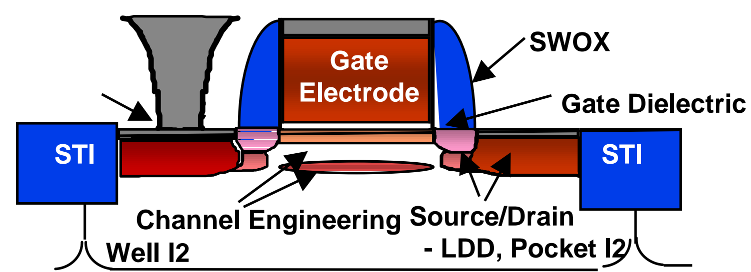
- Microscopy for critical dimension measurement, overlay, defect detection, and analysis
- Standard electrical test methods for reliability of new materials, such as ultra-thin gate and capacitor dielectric materials
- Statistical limits of sub-70 nm process control
- 3-D dopant profiling
- Production worthy, physical inline metrology for transistor processes that provides SPC required to achieve consistent electrical properties

Domestic vs International Points of View

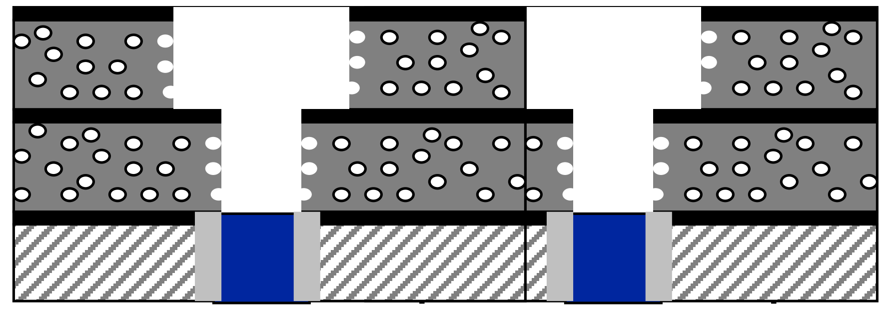
- Precision vs Accuracy
- Precision   US Centric
- Accuracy and Precision   Global Centric

Lithography Metrology

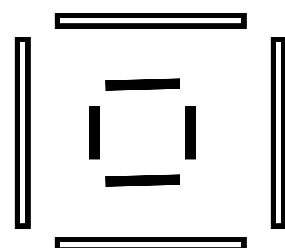
Gate Length Control



Damascene Line Width

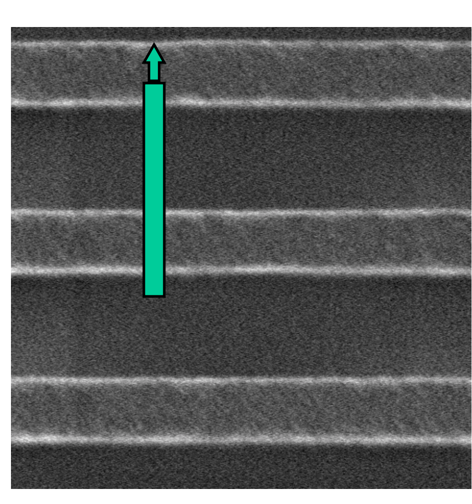


Overlay Control

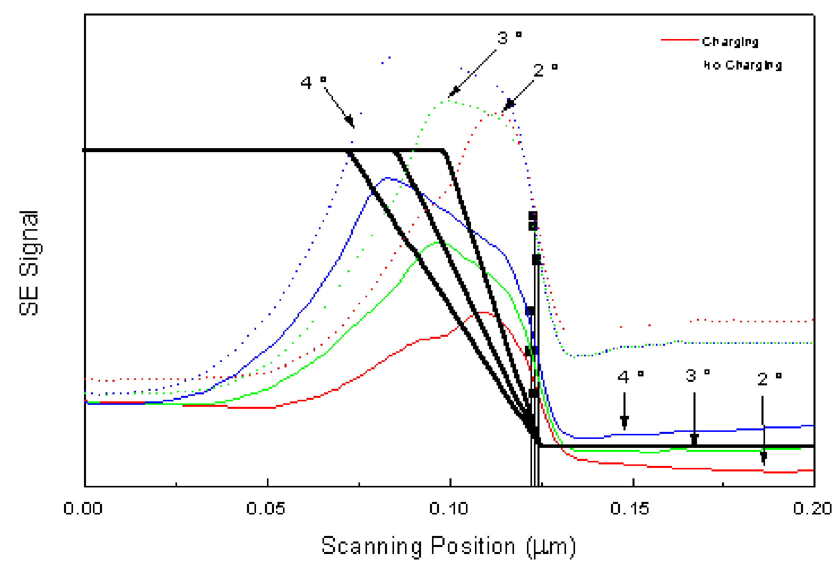


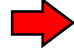
Lithography Metrology

Improve CD-SEM thru 100 nm node



top down
CD-SEM

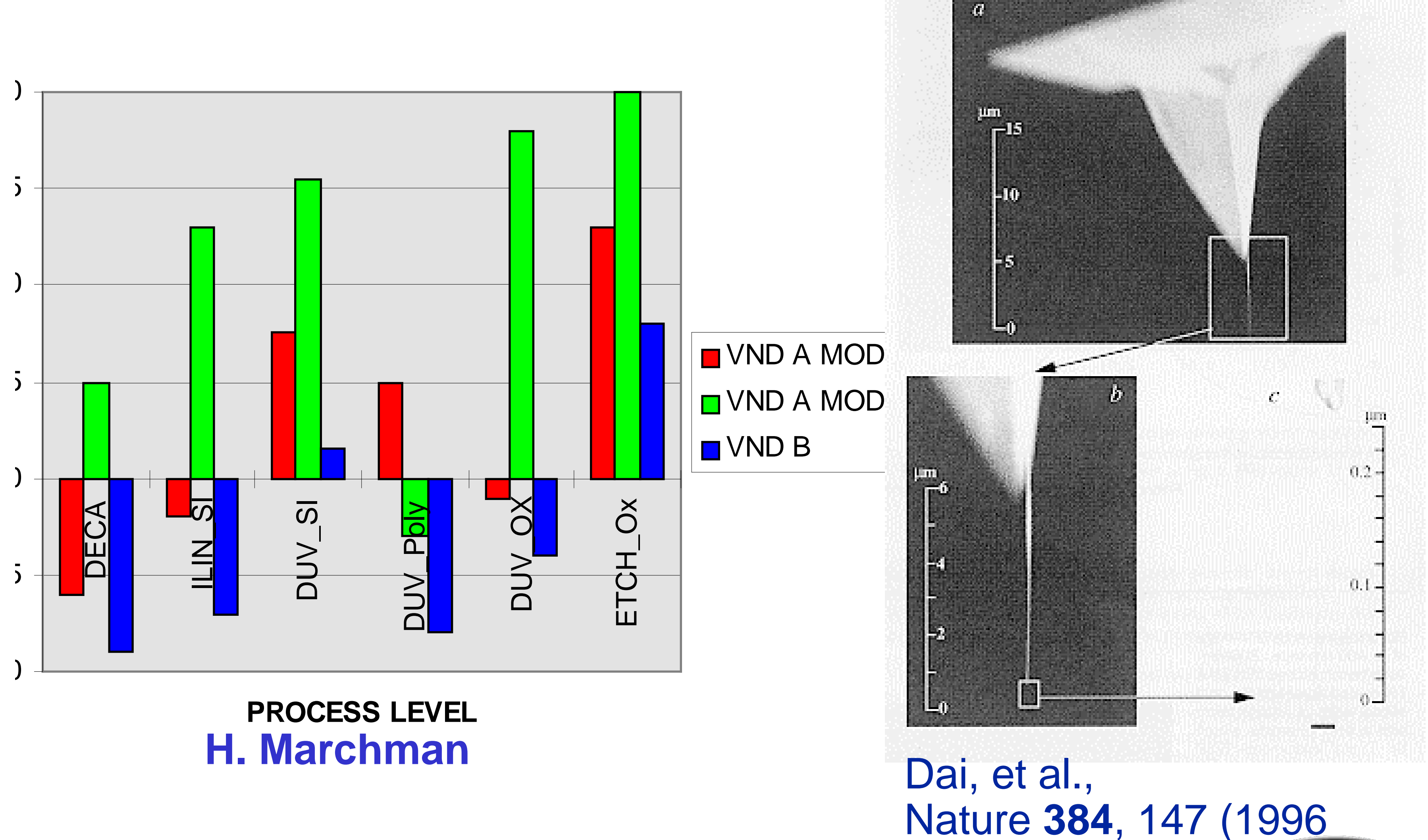


Signal  CD Value

NEED: Determine CD from Fundamental Model

Process Level Dependence of CD SEM

Calibration requires New Probe tips for CD-AFM



H. Marchman

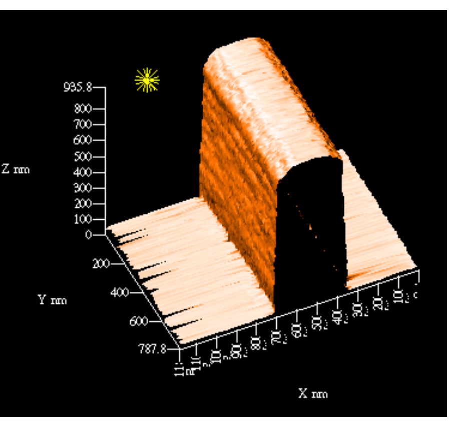
Dai, et al.,
Nature **384**, 147 (1996

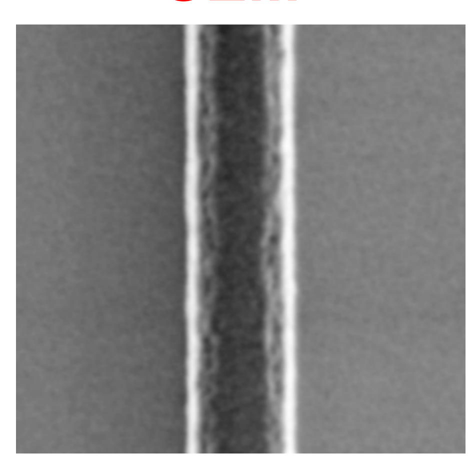
Microscopy Issues:

CD and Detection require new microscopy

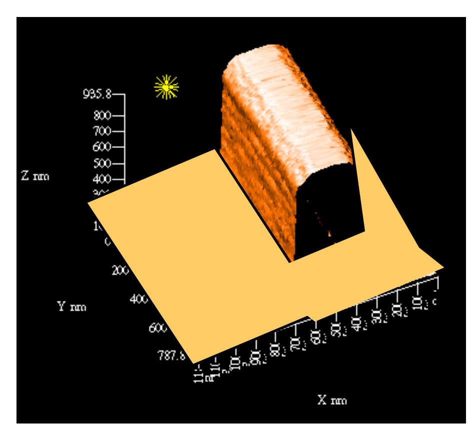
- SEM with resolution required for sub 100 nm has poor Depth of Focus
- 3D Information Required
- Improved throughput required

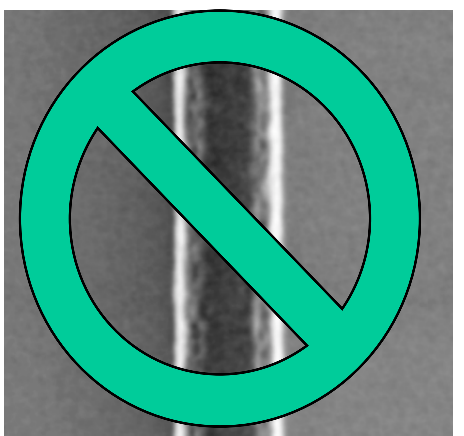
SEM





Today : Depth of focus > 1 micron





With Future Resolution:
Depth of focus << 1 micron

Microscopy and Lithography Metrology
Long Term Research and Development

Nanotip Field Emission source ~ 100eV

coherent electron beam

forward scattered electron beam

Projection Hologram forms in the overlap region between reference and scattered electrons

Electron Holography

- Low damage
- Reduce Charging
- No aberration/diffraction
- 3D Information

David Joy, Univ. of TN

CD-Scatterometry :
Another Potential Solution

2-Θ scatterometer: CDS-2

- Developed as a Sensor at Sandia and UNM
- Available as an in-line system

Input laser beam

Detector

Θ Θ

Scattered light

Resist

ARC

Poly

All parameter combinations

Signature Generator Software

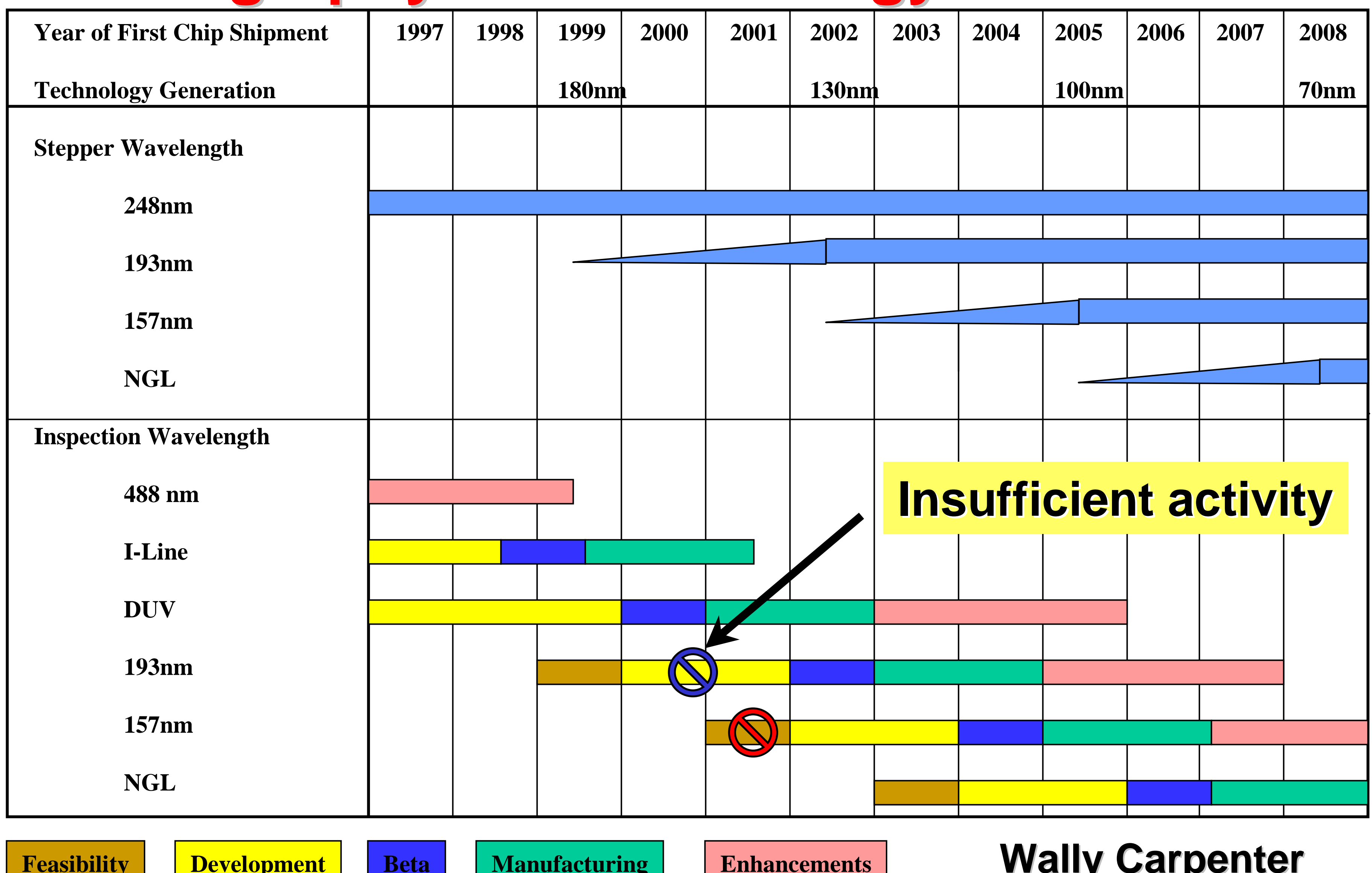
Parameters

Variables :
CD = 270 ± 60nm
Resist thickness = 725 ± 25nm
Poly thickness = 2500 ± 350nm
ARC thickness = 80 ± 10nm
Sidewall angle = 86 ± 2º

Fixed :
Pitch
Resist, Poly and ARC optical properties

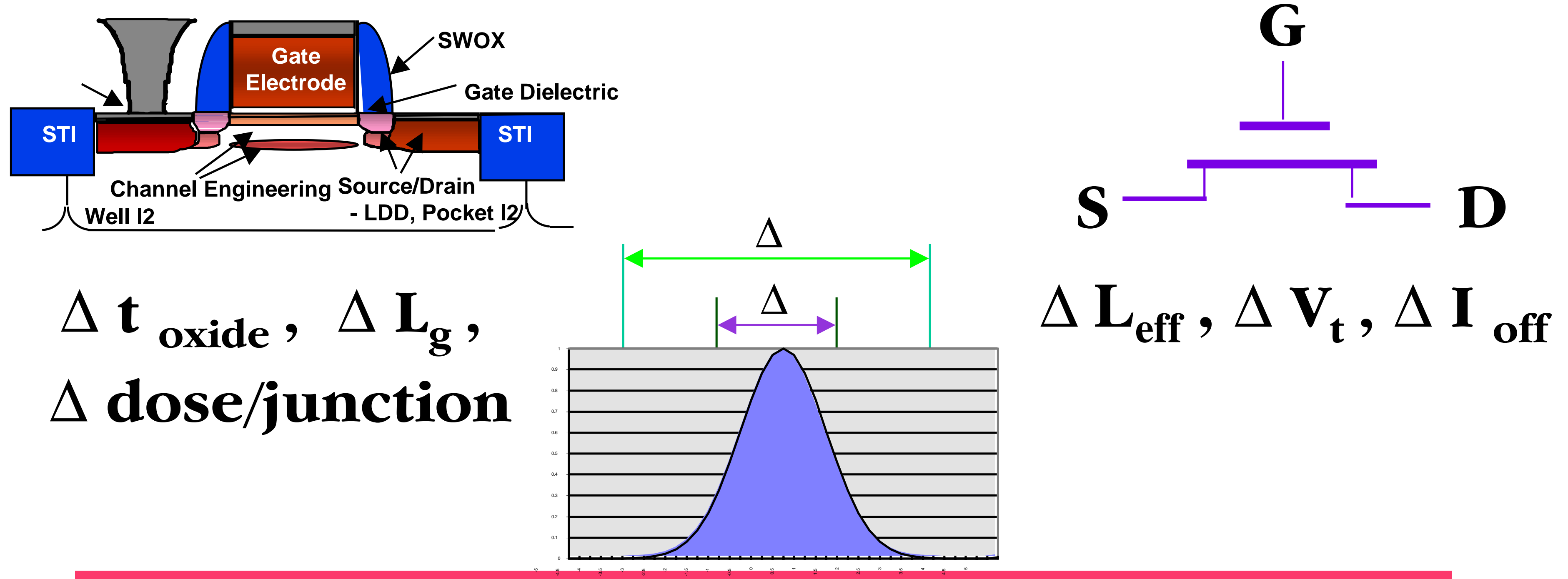
Figure courtesy BIO-RAD

Lithography Mask Metrology



Front End Processes

(Transistor & Capacitor Process) Metrology

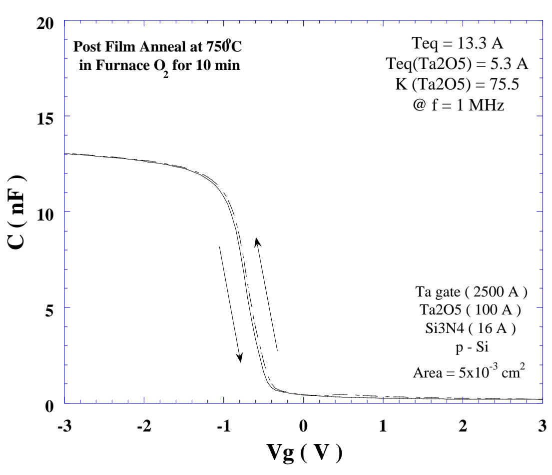


Electrical Measurement requires fabrication of a transistor.

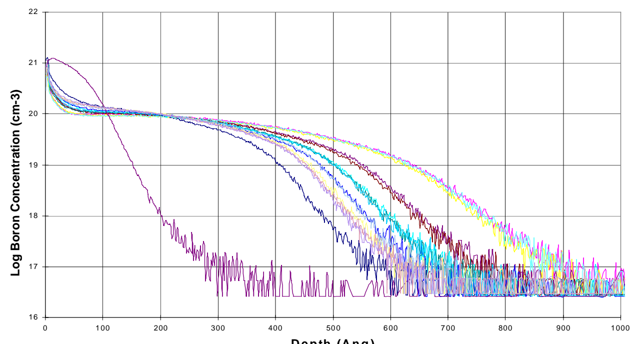
Will physical metrology be able to adequately control critical processes at 100 nm and

Transistor Process Metrology Challenges

New Materials & Ultra Shallow Junctions



SIMS Profile
Boron Concentration vs Junction Depth Xj

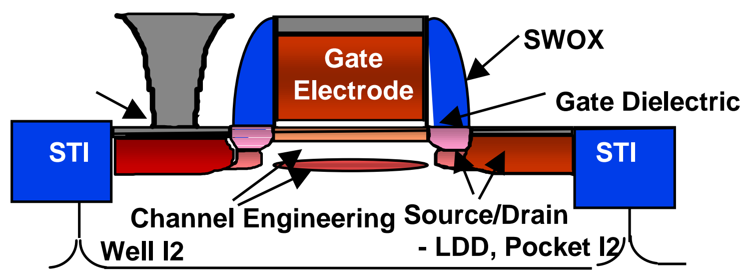


Gate metal / Ta_2O_5 /Oxynitride Dielectric

Ta_2O_5 Gate Dielectric

Oxynitride Interface

20 Å

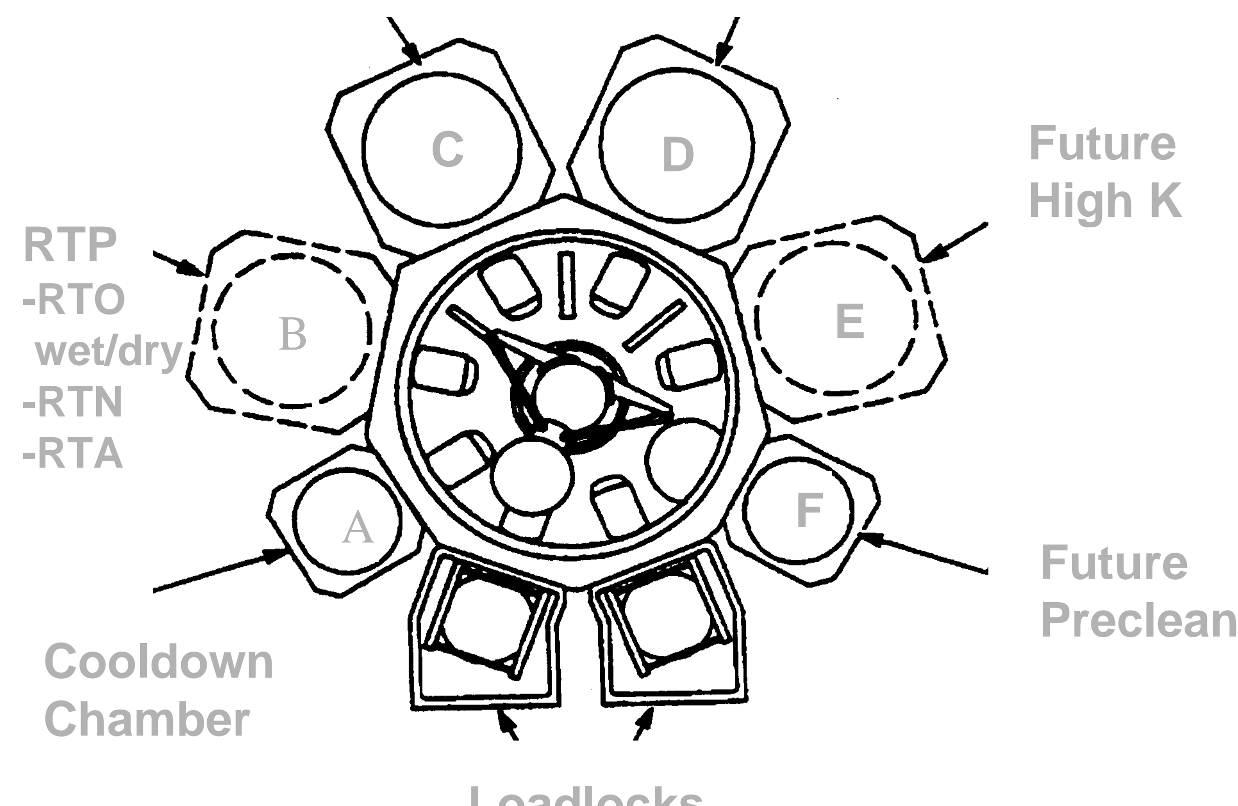


International Technology Roadmap for Semiconductors

Tokyo, Japan; November 1999

Front End Process Metrology

In-Situ Needs vs Integrated Metrology Trend



Clustered gate dielectric & electrode

e.g., Metal Gate forces in-situ metrology for dielectric

2D Dopant Profiling

Issue : Spatial Resolution

Experimental verification

properties

TCAD

Process flow

Mask set

BTotal
/cm3
+3.000e+20
+4.054e+19
+5.477e+18
+7.401e+17
+1.000e+17

500 nm

0.50
0
0 0.25 0.50 0.75 1.00

I_d [A]

V_{ds} [V]

V
V
+0.000e+00
-5.000e-01
-1.000e+00
-1.500e+00
-2.000e+00

500 nm

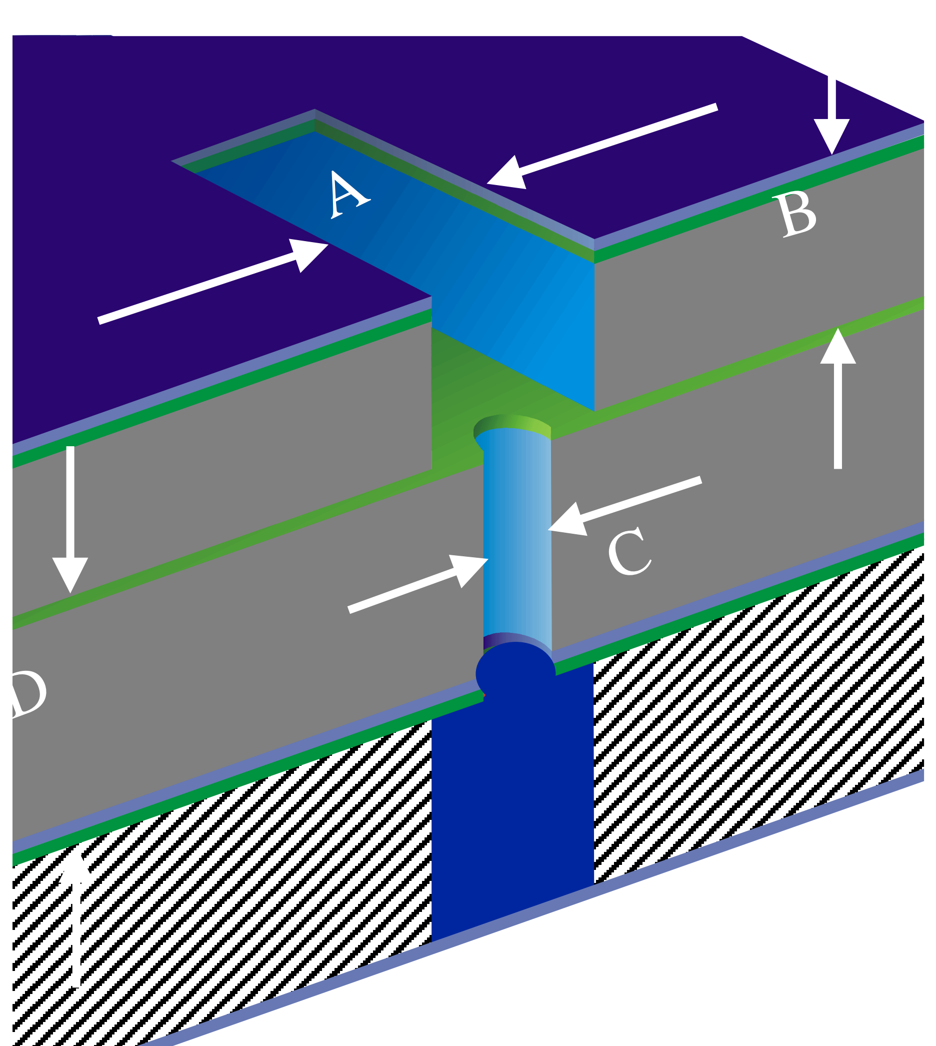
Nanopotentiometry

Processing

Device Simulation

imec - Vandervorst

Interconnect Metrology
New Materials and Processes



Copper/barrier Film Thickness

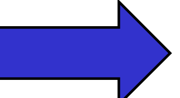
100 micron diameter size test areas by acoustic

Low k Dielectrics

High frequency dielectric testing needs development for > 40 GHz

Need optical models for porous materials

Developing Physical Properties and Delamination testing

SENSOR based  Integrated Metrology

Comments on :

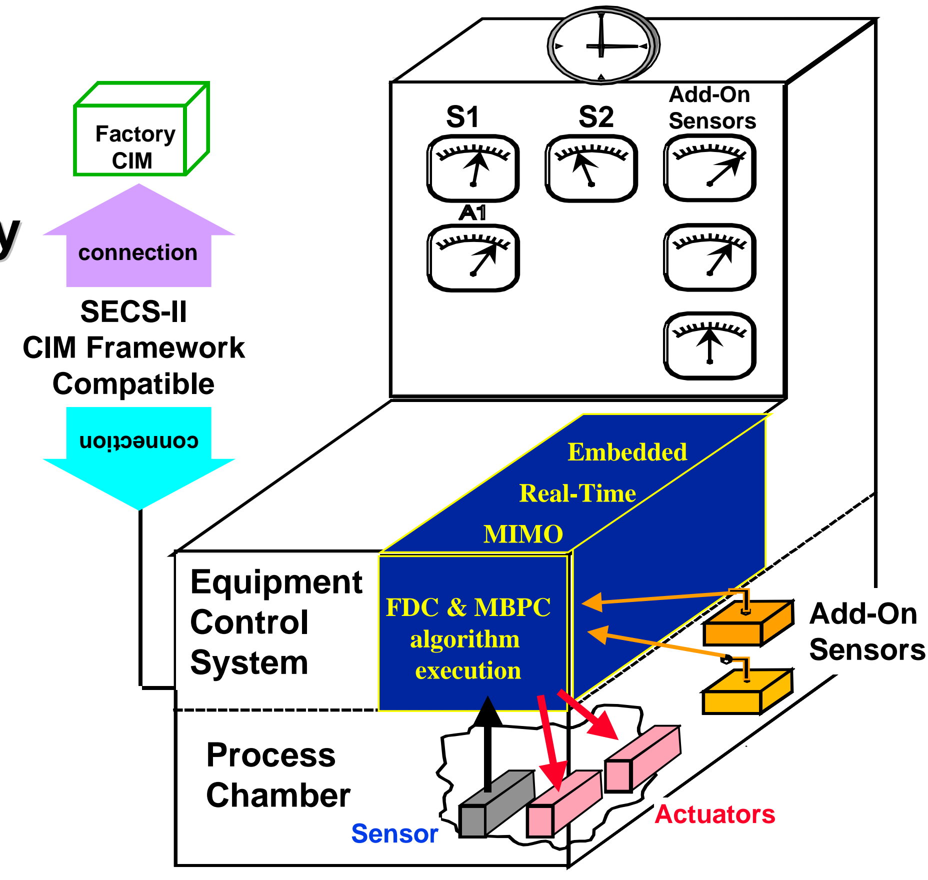
Advanced Process Control - Advanced Equipment Control

- **AEC/APC GOAL :**

model based predictive control based on process and metrology models using in-situ and in-line measurements

- **Momentum ?**

- **Now suppliers advocate Integrated Metrology**



RISKS

- Many Measurements have precision requirements that will be difficult to meet. This leads to a Lack of Metrology Tools for accelerated Technology Cycle
- Important New Approaches need additional funding for long term R+D (ex. - Electron Holography, arrayed AFM/SEM)
- Business Model for Metrology does not fit Industry needs
- Lack of methodology for Statistically Limited Processes and appropriate metrology
- Shrinking scribe lines limit test areas needed for adequate measurement precision

Background

In-line Metrology usage
400 + step Process Flow

180 nm

Poly-Silicon

6 metal levels

steps

~25 Overlay

~20 CD

<20 Defect/Particle

~ 6 Poly Si Control
ILD Thickness
Contact Etch
ILD Etch Control
Metal Thickness

~ 4 Implant Dose

1 Gate Ox Thickness

Messages from overview

- Infrastructure
- Requirements have too much RED
- Challenge Associated with Precision Requirements
- Microscopy Development
- Interfacial Measurements

Metrology Timing vs Infrastructure Capabilities

Gap in long term R&D Spending + Development Funding Model

Need for Metrology Tool

Need for Process Tool

Volume Sales of Metrology Tools

Process Tool Supplier Development

Pilot Line

FAB Startup & Volume Manufacture

Research Required

Development Underway

Qualification/ Preproduction

Typical Potential Solutions Time Line for Process Tool

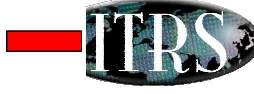
Too Many Metrology Technology Requirements are R

YEAR TECHNOLOGY NODE	2008 70 nm	2011 50 nm	2014 35 nm
Wafer gate CD control*	4.0	3.0	2.0
Wafer dense line CD control*	7.0	5.0	3.5
Wafer contact CD control*	8.0	5.5	4.0
Wafer CD metrology tool precision* P/T=.2 for isolated lines**	0.8	0.6	0.4
Wafer CD metrology tool precision* P/T=.2 for dense lines**	1.4	1.0	0.7
Wafer CD metrology tool precision* P/T=.2 for contacts**	1.6	1.1	0.8
Maximum CD measurement bias (%)	10	10	10
Mask CD control isolated lines*	7	5	3.3
Mask CD control dense lines*	11	8	5.6
Mask contact area control Normalized to ρ of area*	12	9	6.4
Mask CD metrology tool precision* P/T=.2 for isolated lines**	1.4	1.0	0.7
Mask CD metrology tool precision* P/T=.2 for dense lines**	2.2	1.6	1.1
Mask area metrology tool precision for contact normalized to ρ of area–ρ of target for P/T=.2	1.6	1.8	1.3
Wafer overlay control (nm)	25	20	15
Wafer overlay output metrology precision (nm, 3 sigma)* P/T=.1	2.5	2.0	1.5
Final mask image placement	15	12	9
Mask image placement metrology precision P/T=.1	1.5	1.2	0.9
Mask phase (in degrees)	1	NA	NA
Phase metrology precision P/T=.2 (in degrees)	0.2	NA	NA
Variation in attenuated mask film transmission % of deviation from nominal (%)	4	NA	NA
Transmission metrology precision % of nominal attenuated PSM transmission P/T=.2 (%)	0.8	NA	NA

* *All precision values are 3 sigma in nm and include metrology tool matching.*

** *Measurement tool performance needs to be independent of line shape, line materials, and density of lines.*

Solutions Exist | *Solutions Being Pursued* | *No Known Solutions*



Examples of Precision Requirements

Year of First Product Shipment Technology Generation	*1999 180 nm*	*2000*	*2001*	*2002 130 nm*	*2003*	*2004*	*2003 100 nm*	*Driver*
DRAM 1/2 Pitch	*180*	*165*	*150*	*130*	*120*	*110*	*100*	D½
Logic Isolated Lines	*140*	*120*	*100*	*85*	*80*	*70*	*65*	M Gate
Microscopy and Lithography								
Microscopy resolution (nm) for P/T=0.1	1.4	1.2	1.0	0.85	0.8	0.7	0.65	MPU
Wafer Gate CD Control*	13	12	10	8.5	8	7	6.3	MPU
Wafer CD Tool Precision* P/T=.2 Isolated Lines**	2.6	2.4	2.0	1.8	1.6	1.4	1.3	MPU
Mask Area Metrology Tool Precision P/T=.2	4.8	4.2	3.4	2.8	2.6	2.4	2.2	MPU

Front End Processes								
Logic Dielectric Thick Precision 1σ (nm) [B]	0.0075	0.0075	0.006	0.006	0.006	0.005	0.004	MPU Gate
2D Dopant Profile Spatial Resolution (nm)	3	3	3	2	2	2	1.5	MPU Gate

Interconnect								
Barrier layer Thick (nm) process range ($\pm 3\sigma$) Precision 1σ (nm)	17 10% <0.06	16 10% 0.05	14 10% <0.05	13 10% 0.04	12 10% 0.04	11 10% <0.04	10 10% 0.03	MPU

Effect of P/T on Process $C_P = (UL\text{-}LL) / 6\sigma$

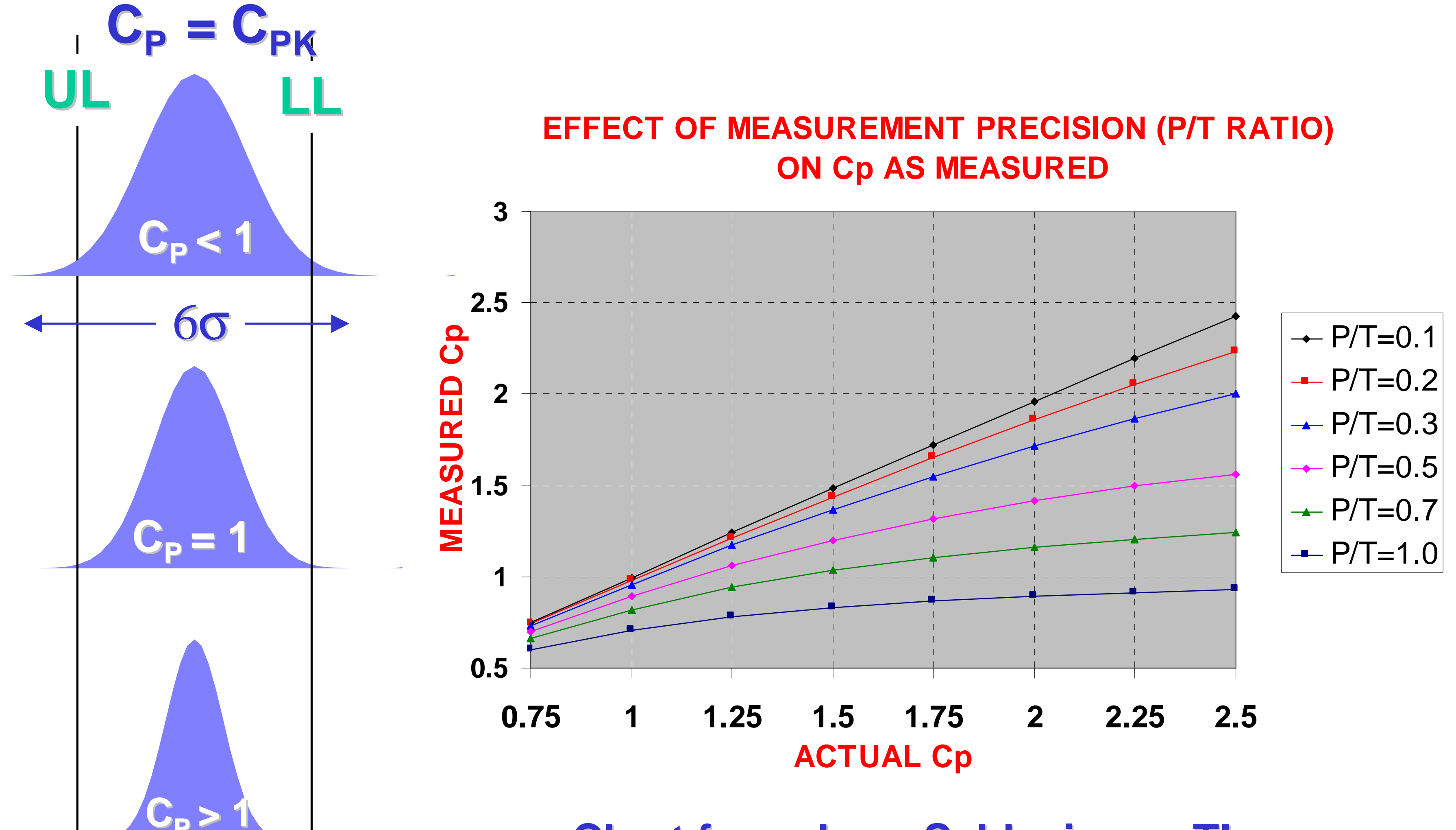


Chart from Jerry Schlesinger, TI

Calibration of CD-SEM
Intensity Profiles From CD-AFM / SEM

SEM

CD-AFM
Stylus
Nano
Profilometer

159.00
0.00
0
Pixels
164

1.00
0.00
0
Pixels
164

Thanks to Joe Griffith

Systematic Failure Modes in Dual Damascene Processes

CMP Slurry
Pad Residue
CMP Ripout
Metal Dishing
Undercut
Barrier Layer Defect
Corrosion
CMP Scratches
Erosion/ Metal Smear
Spikes and Pinholes
Side Wall Roughness
Dielectric
Copper
Undercut
CMP/ Etch Barrier
Etch Residue
Metal Voids
Dielectric
Metal n-1
Dielectric
Metal n-1

David Jensen - AMD/SEMATECH

Depth of Focus Requirements for Litho

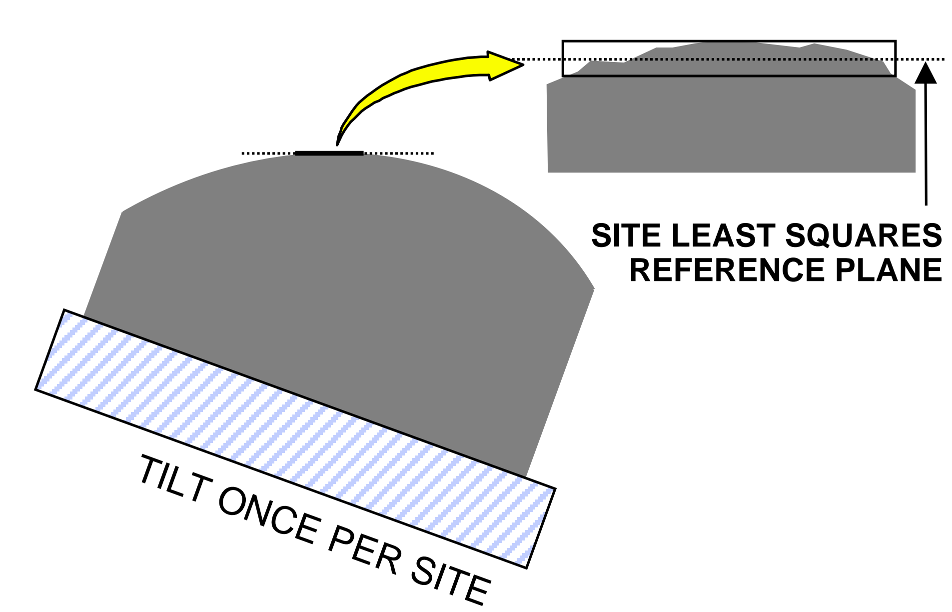
CMP Metrology tool should measure what litho tool “sees”

Full Field Steppers

SEMI STD

Site Frontside least-sQuared site reference

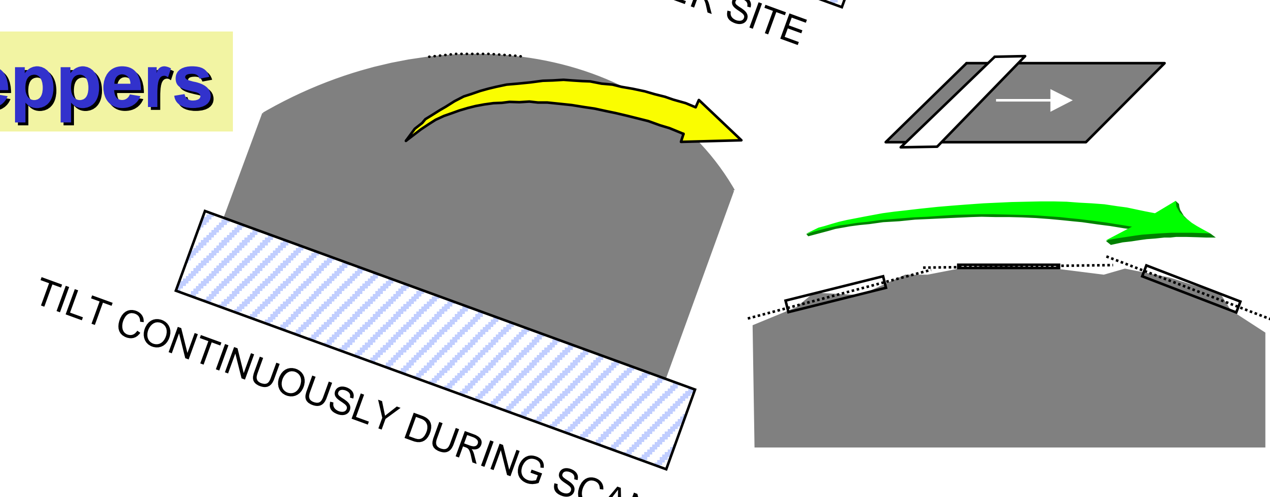
Range = SFQR
Deviation = SFQD



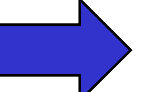
Scanning Steppers

SEMI STD

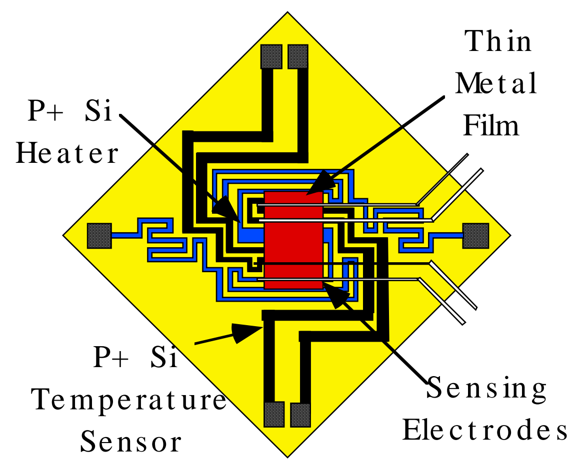
Site Frontside Scanning* site reference



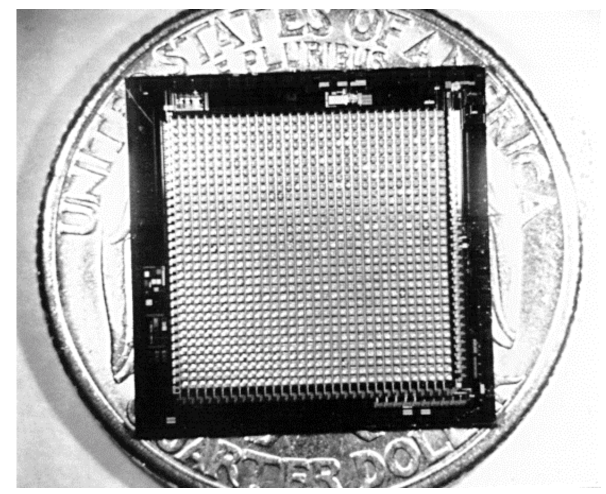
Range = SFSR
Deviation = SFSD

SENSOR based  Integrated Metrology

MEMS : Sensor Technology of the Future

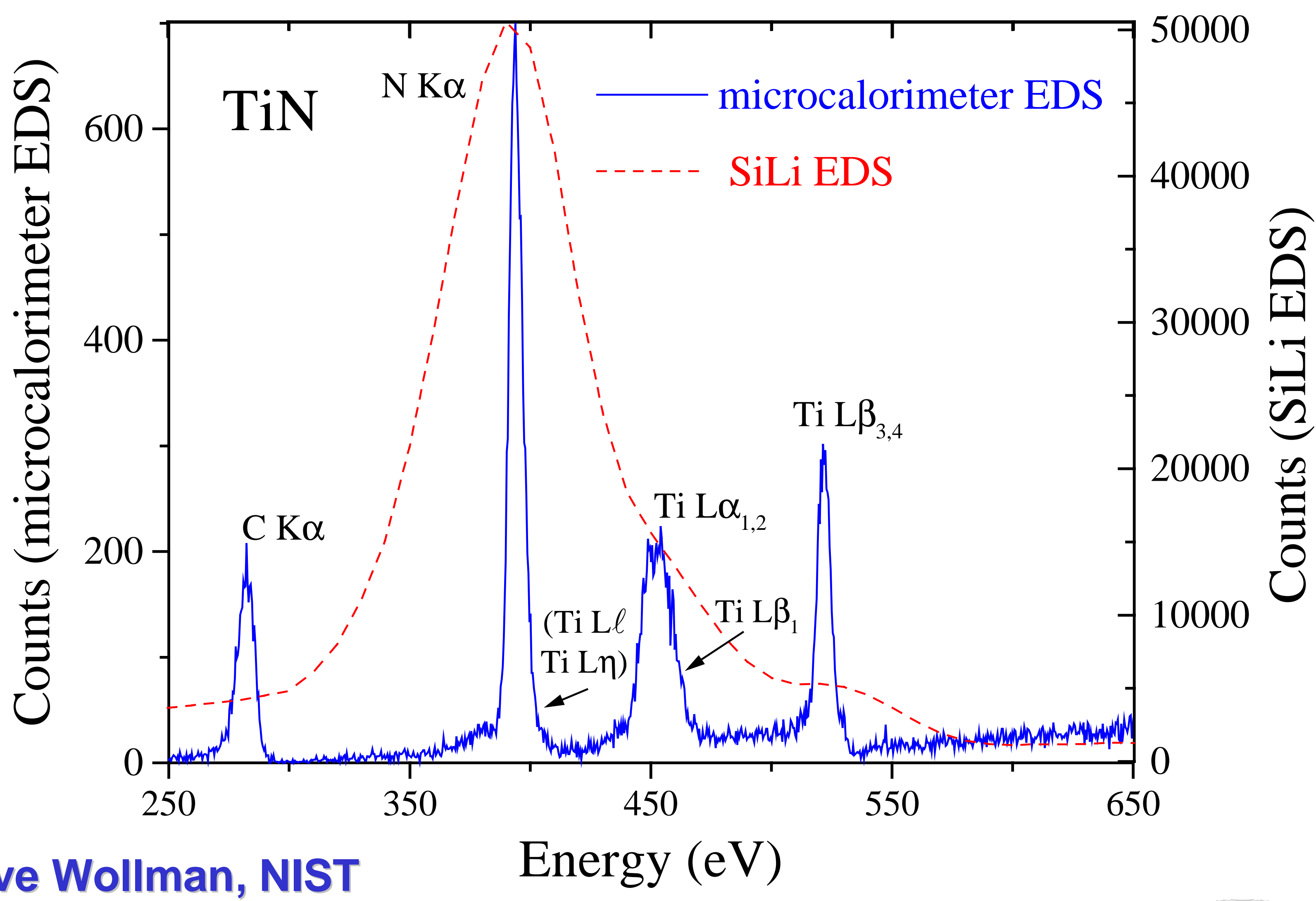


A MONOLITHIC DETECTOR
FOR PROCESS GAS PURITY



Infrared Imager for RTP
GOAL:
measure temp & uniformity
$\pm 1^{\circ}$ C to 1000° C

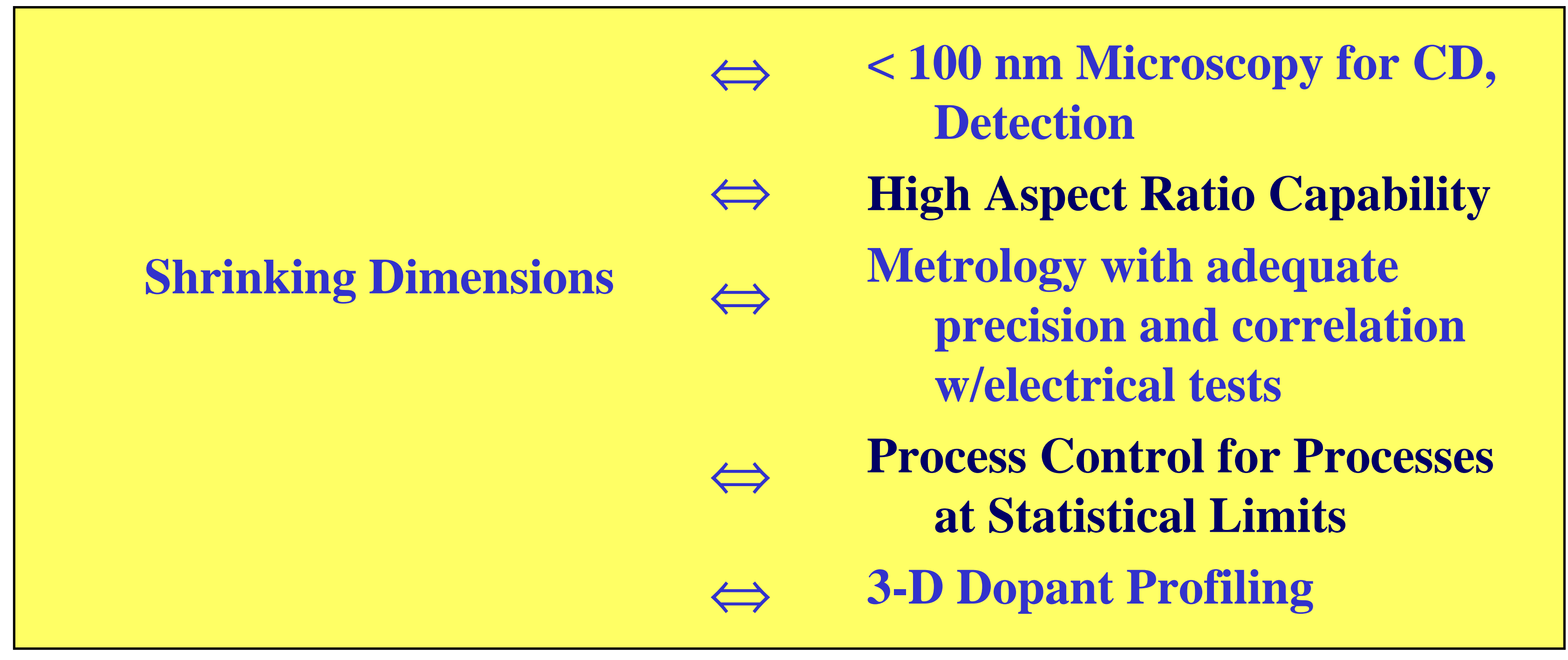
Microcalorimeter EDS vs EDS



Dave Wollman, NIST

Accelerated MPU Gate impacts all GAPS

Key Drivers ⇔ GAPS



Key Drivers		GAPS
New Materials in Transistor, Capacitor, and Interconnect	⇔	Measure High Frequency Dielectric Constant
	⇔	Measurements and standards for new materials stacks