Process Control Systems – SPC in Practice

Semiconductor Manufacturing and Chemical Engineers – BYU Oct 2011

Who is IM Flash Technologies?

- **Joint venture company established January 6, 2006 between Intel Corporation and Micron Technology (IM).**

- **State-of-the-art 300-millimeter fabrication facility in Lehi, Utah (3-5 billion dollar investment)**
  - 2.3 Million Square Feet of Building (53 acres)
  - 160,000 sq ft. of Fab Manufacturing space
  - Site sits on 2100 acres
  - 2800 parking stalls, with underground tunnels
  - 8.5 million cu. yards of dirt excavated
  - Approximately 1450 employees

Formed to <u>manufacture</u>
NAND Flash memory!

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IMFT Core Values

IM Flash Technologies is a values-based organization and believes in operating with the highest degree of:

Commitment

The personal obligation of each employee to accomplish the goals and objectives of the team

Teamwork

The collaborative effort that leverages the strengths of each individual while working toward common goals

Integrity

Truth, respect, and confidentiality in our interactions with our fellow team members, community, suppliers, and custo

Execution

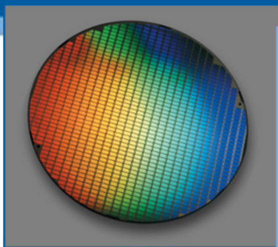
The achievement of shared goals through rigorous planning, tenacious follow-through,

Living these values will guide behaviors and define relationships

Why bring two leading companies together?

- **Create the best products in the world!**
- **Combine and leverage:**
  - Micron's leadership in NAND process and product technology
  - Intel's Multi-Level Cell technology (MLC) and history of innovation in Flash memory!!!
  - Existing investments in R&D and customer support
- **Lower process development and NAND design costs**
- **Allows greater productive use of prior investments in Lehi and Manassas**
- **Accelerate penetration into NAND, the highest growth memory product in the market**

NAND Replacing Hard Disk Drives



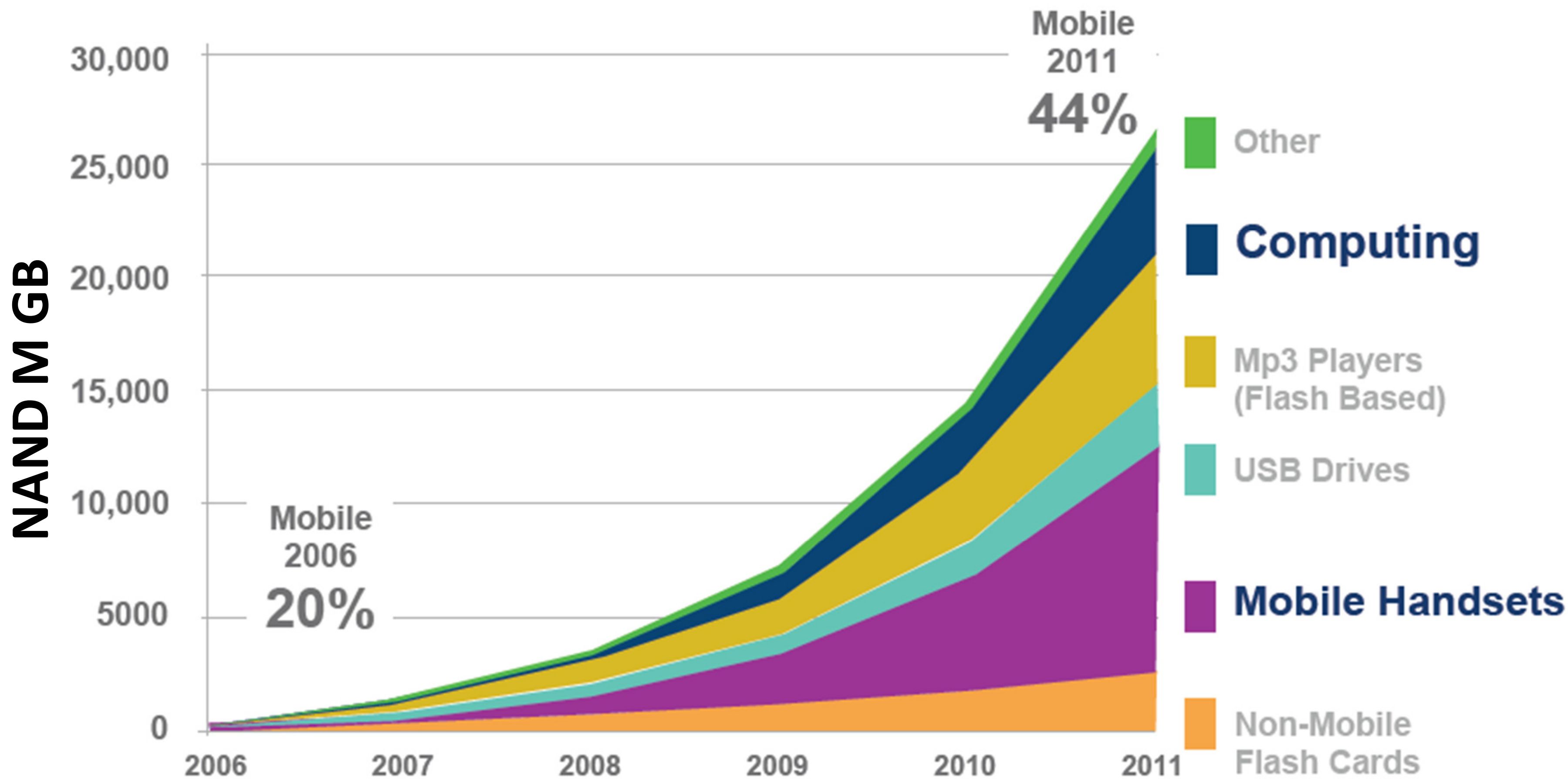
Primary applications where NAND competes with HDD

Current Applications		Emerging Applications	
			
Mobile Phones	MP3 Players	Laptop Computer	Handheld Gaming

NAND Flash memory is a solid-state, non-volatile (holds data in memory even when power is turned off), electrically-erasable memory that consumes less power and is used in many consumer products

Why is NAND so important to Intel and Micron?

Total NAND Market % by Application



Apple pre-paid $250 million to Micron and Intel in return for a portion of IM Flash Technologies NAND output.

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NAND Structure & Function

Basic Structure of a Flash Cell

Cell Architecture

I. **Control Gate** - The conductor of the wordline transistor whereby a row is selected and a voltage bias is applied

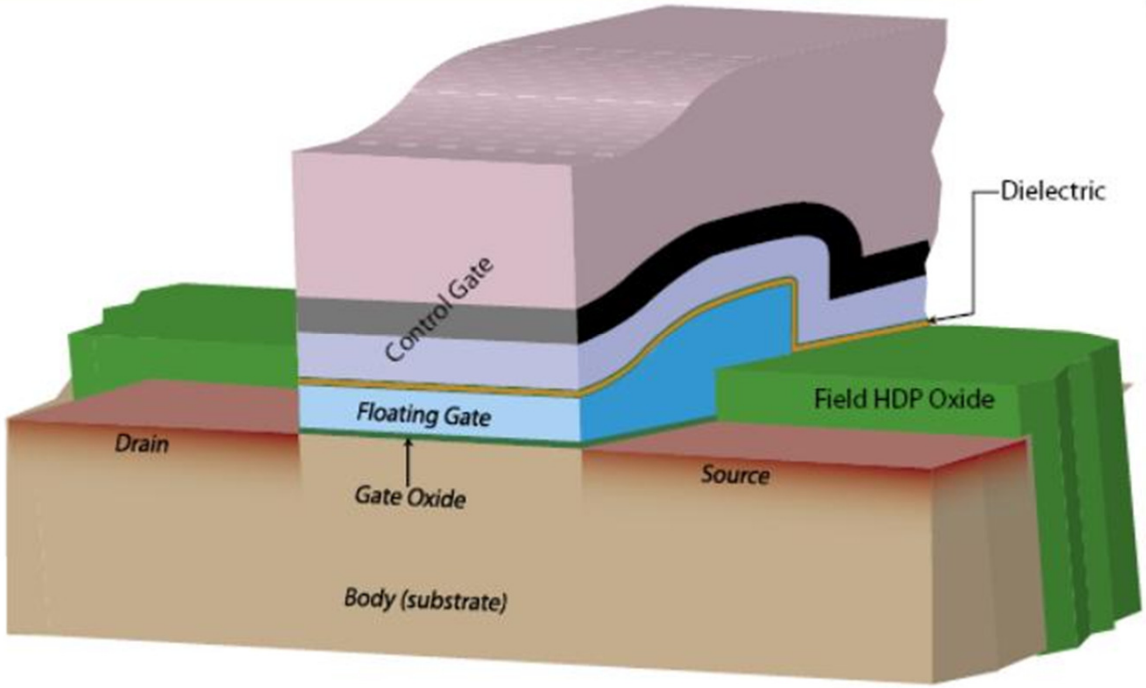
II. **Floating Gate** - Conducting or semiconduction layer that is completely surrounded by a dielectric used to store charge and alter the threshold coltage of the device.

III. **Source/Drain** - locations of doped silicon where voltage bias is applied to achieve conduction under the gate of the transistor.

IV. **Dielectric** - insulator; typically ONO (Oxide Nitride Oxide).

V. **Gate Oxide** - insulator; typically SiO_2

VI. **Body (Substrate)** - Silicon Wafer



Function of a Flash Cell

Principles of Operation (High Level Overview)

The following section is dedicated to delivering a high level overview of the principles of operation of Nand Flash. Do not be concerned if the material in this section is foreign to you, as it is covered in depth throughout this manual. This sectioned is designed merely to give a brief overview of the material that will be covered throughout this manual.

Flash memory stores information

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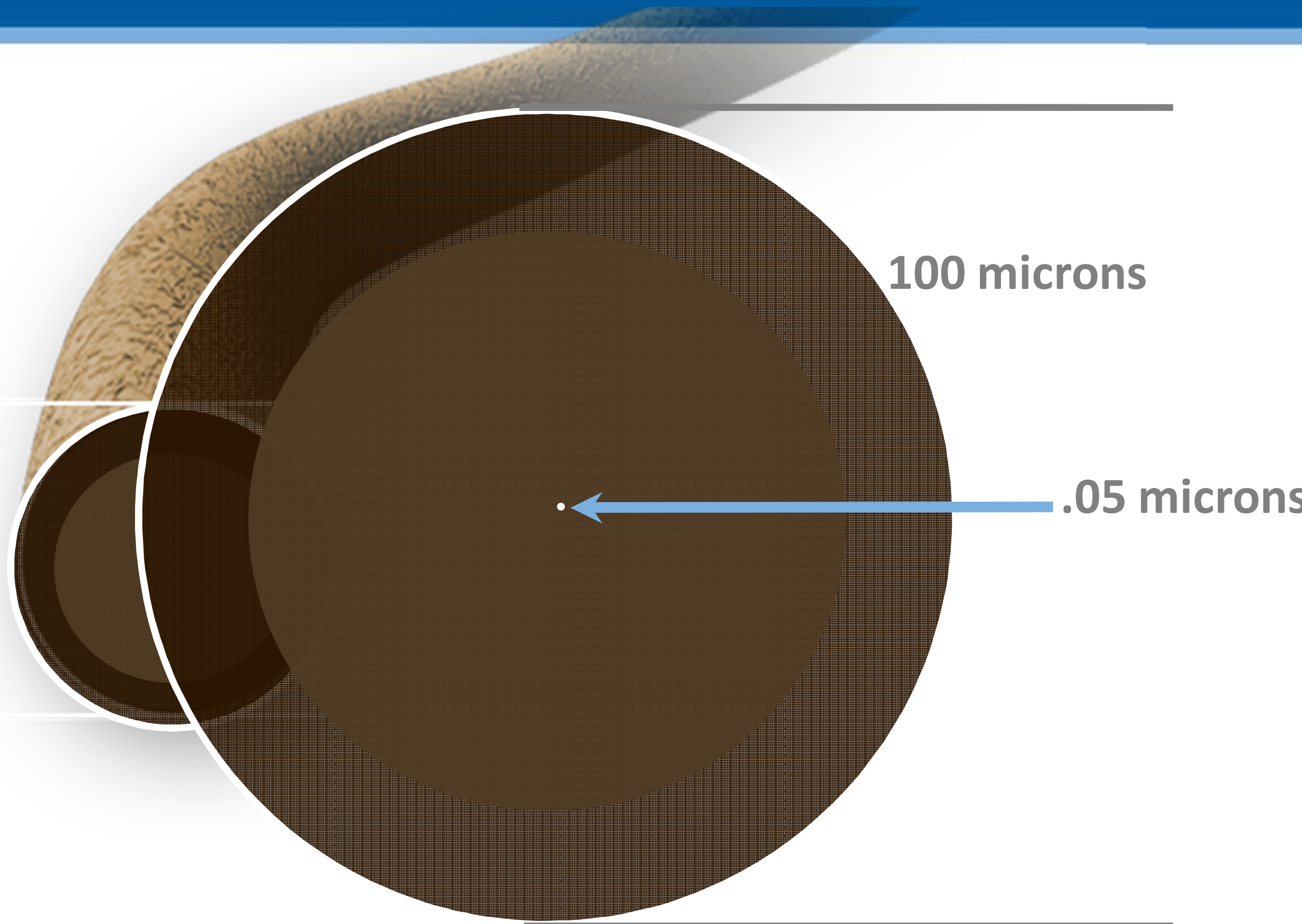
How Small is Small?



Cross-section of a human hair.

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IM Flash Strategy: Deliver The Right Technology Solution

20's → 40's → 50's → 60's → 70's

→ 80's (XXnm) → 90's+

- **90nm history**
  - 25nm problems were irrelevant OR…
  - 25nm problems were immeasurable

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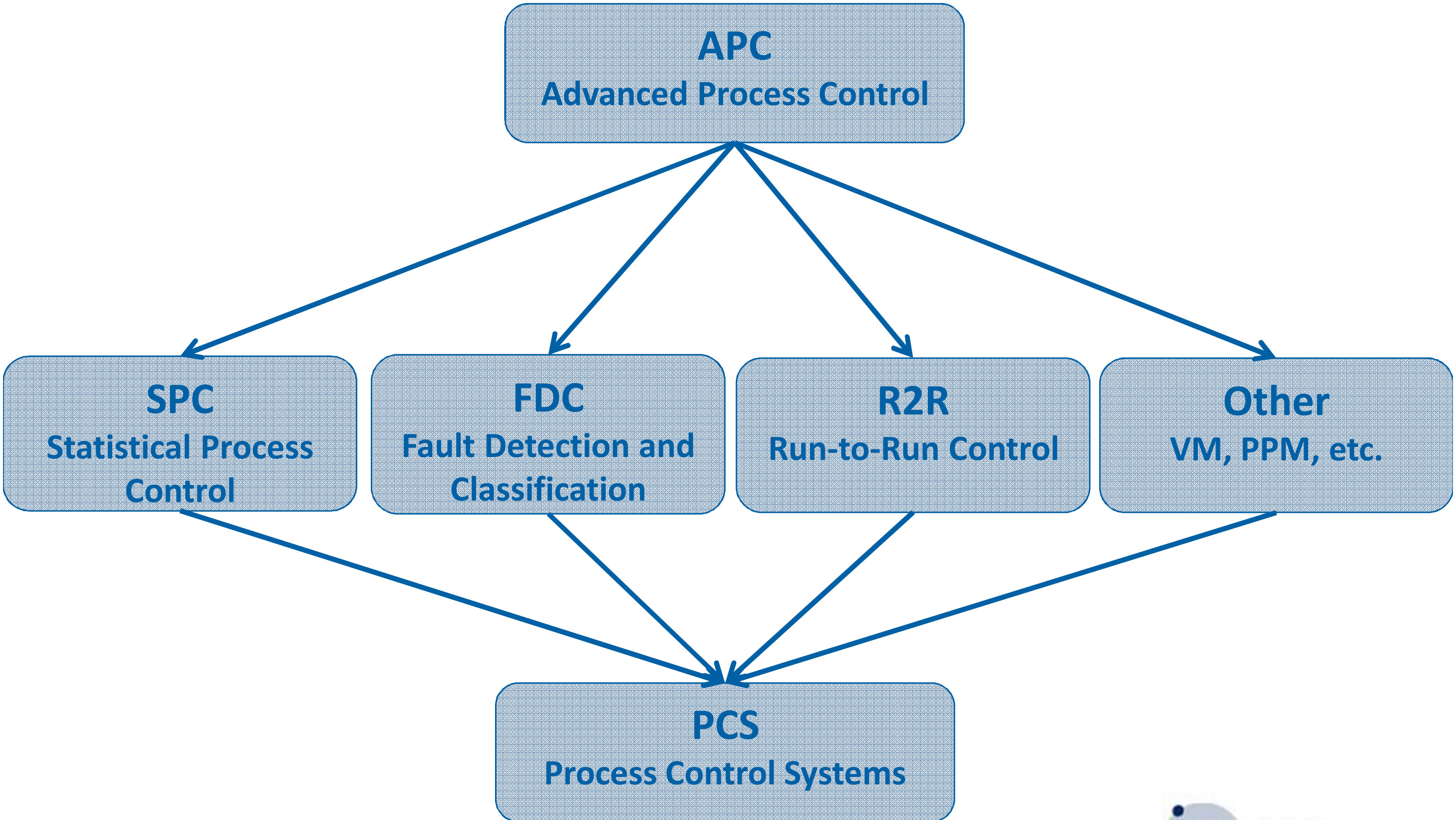
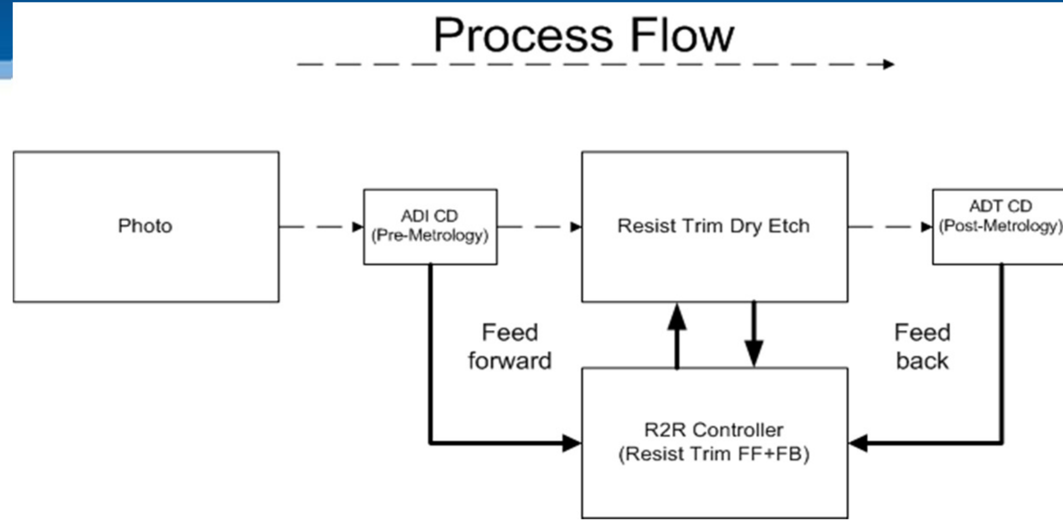
Process Control Systems Group (PCS)

MAINTAINING HIGH QUALITY NAND WAFERS IN A FAST-PACED MANUFACTURING ENVIRONMENT

TLA Guide

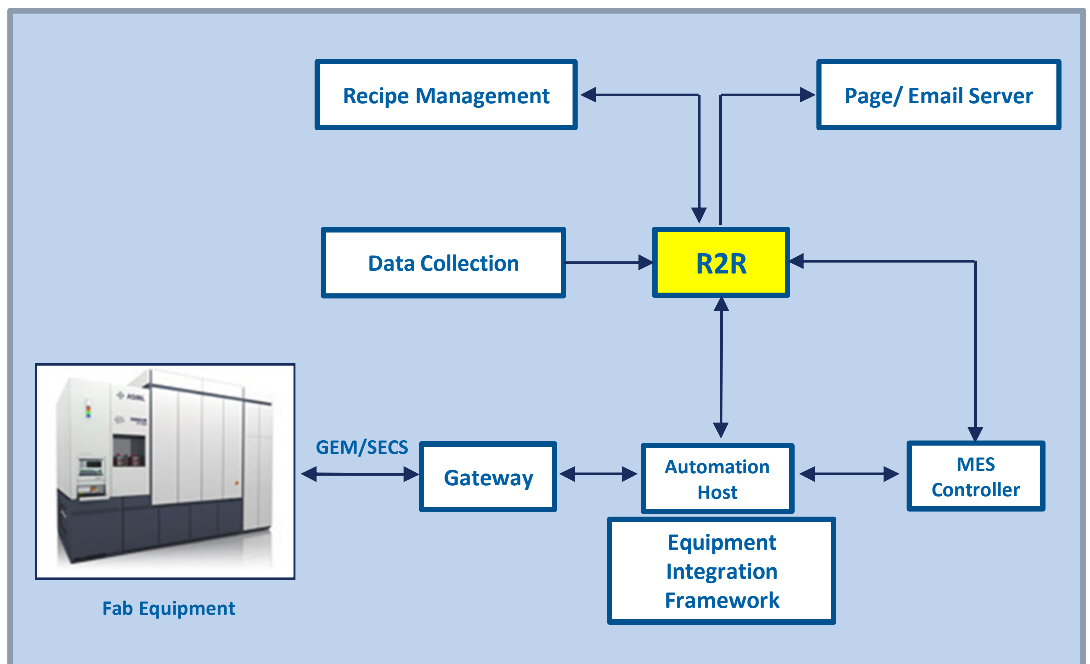

APC
Advanced Process Control
SPC
Statistical Process Control
FDC
Fault Detection and Classification
R2R
Run-to-Run Control
Other
VM, PPM, etc.
PCS
Process Control Systems

Run to Run (R2R) Overview



- R2R is the modification of process or equipment settings between machine runs to optimize output through the use of feed forward or feedback control methods

- The R2R system interacts with
  - Manufacturing Execution System
  - Recipe management
  - Automation host
  - Data collection
  - Page/email systems



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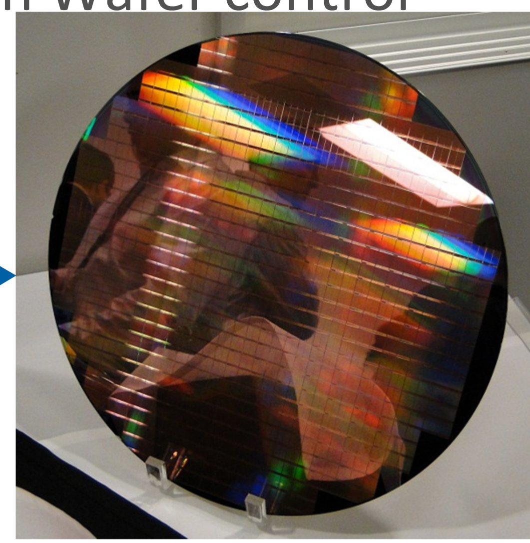
R2R Control Scenarios

- **Words to be aware of**
  - Run
  - Lot
  - Wafer
  - Die (Dice)

- **Types of Control**
  - Single input/Single output (SISO)
  - Multiple input/Multiple output (MIMO)
  - Lot-Level control
  - Wafer-level control
  - Within Wafer control



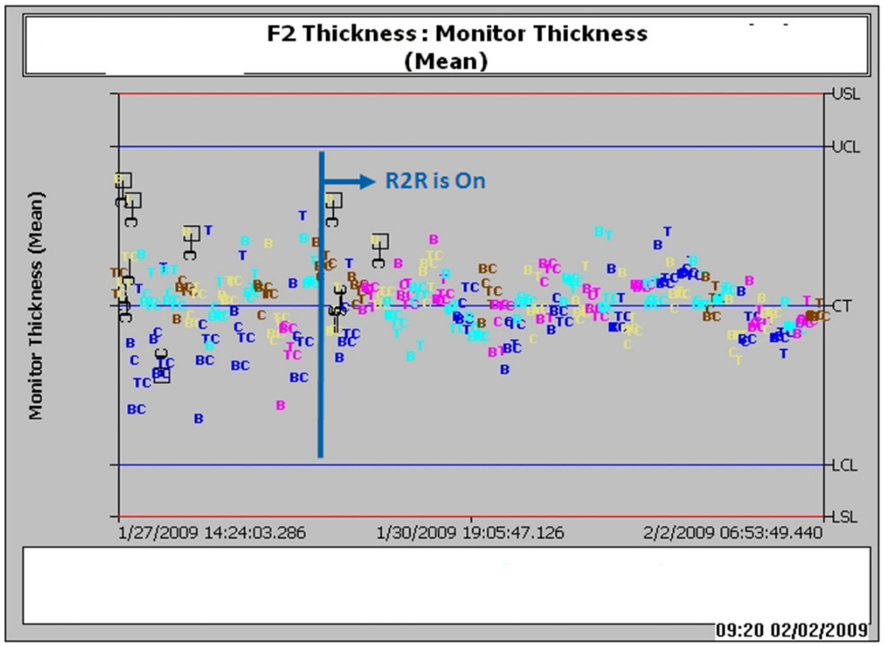
Steps to Building a Controller

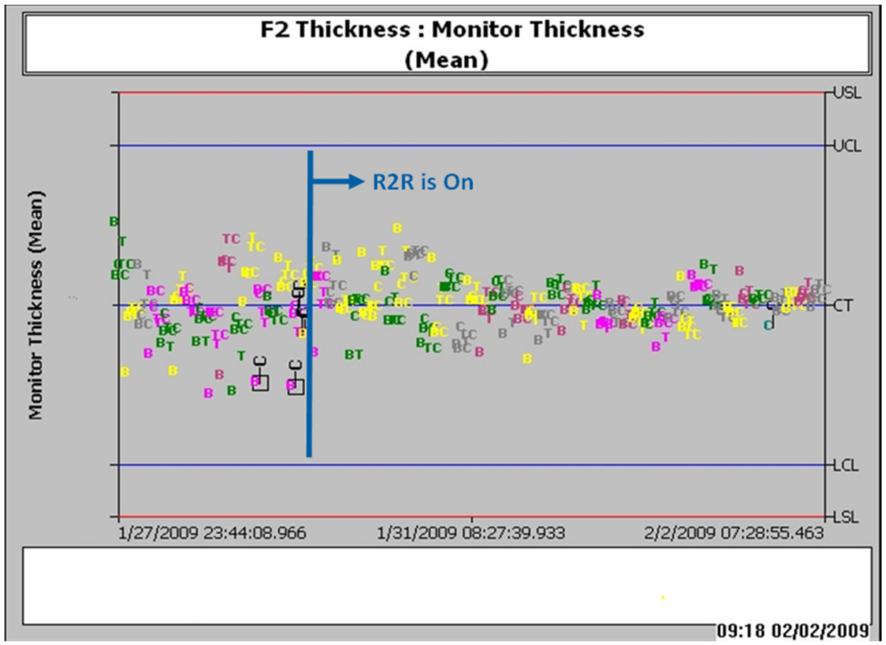
NEW CONTROLLER	
Controller Preparation	**Controller Testing**
Kickoff Meeting - WW Level	Controller Deployment Temporary ECN Submitted
FCT R2R Controller Tracking entry created	Test Server passive mode testing
Process Model Verification	Controller MES Lot Attribute requested
Software Modifications Submitted (if necessary)	Process Recovery and Escalation procedures defined and communicated
New Requirement Document Saved to MDM	Controller move to Production Server
Requirements Definition	Production Server Passive Mode Testing
PPA on R2R control for this process - Fab Level	**Deployment**
Completed Requirement Document Review - Fab level	FOAK Deployment Notification
Completed Requirement Document Review - WW Level	FOAK Testing Begin
Controller Development	FOAK Testing Complete
Changes in Mfg Software as Required by E3 (Sigma Specs, GeRM Params, etc.)	Full Deployment
Completed E3 Controller Peer Review - Fab Level	Controller and Dependencies Exported, Saved to MDM
Completed E3 Controller Peer Review - WW Level	**Post Deployment**
	Controller Description Doc
	Post Deployment Eval

R2R Controller Performance Analysis

Performance analysis

- R2R control systems have been deployed on several process steps
- Average of 40% Cpk improvement
- Example SPC charts before and after implementing R2R controllers for two different processes





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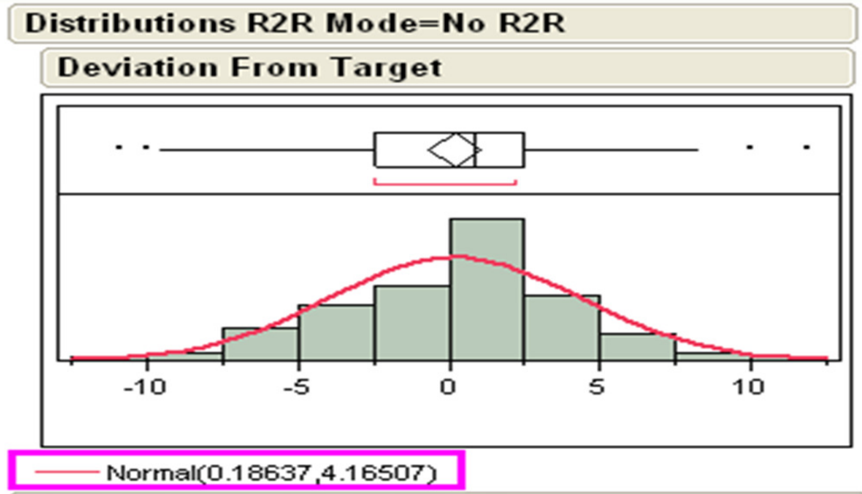
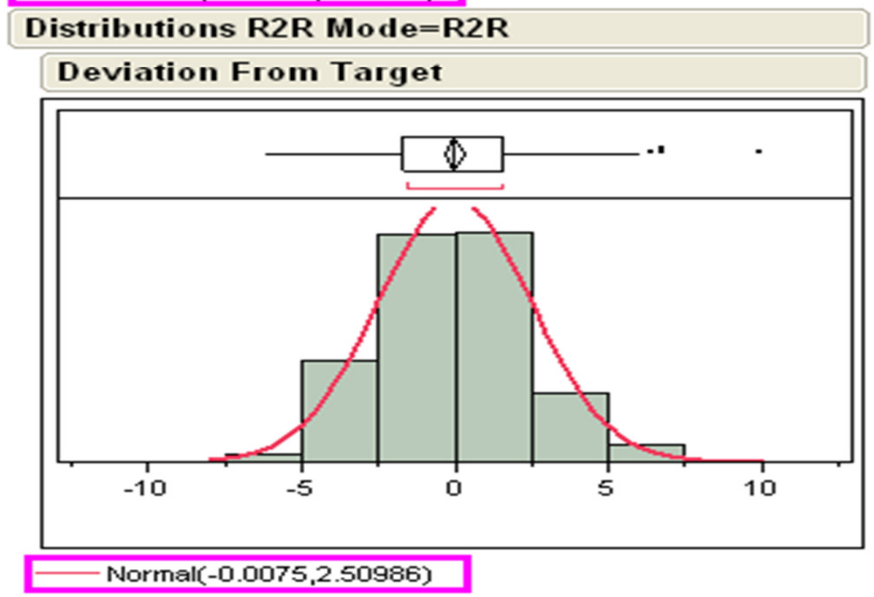
R2R Controller Performance Analysis Continued

- **R2R control drives the process mean towards target**
  - No R2R: μ = 0.18637
  - With R2R: μ = -0.0075

- **R2R control also reduces process variation**
  - No R2R: σ = 4.16507
  - With R2R: σ = 2.50986





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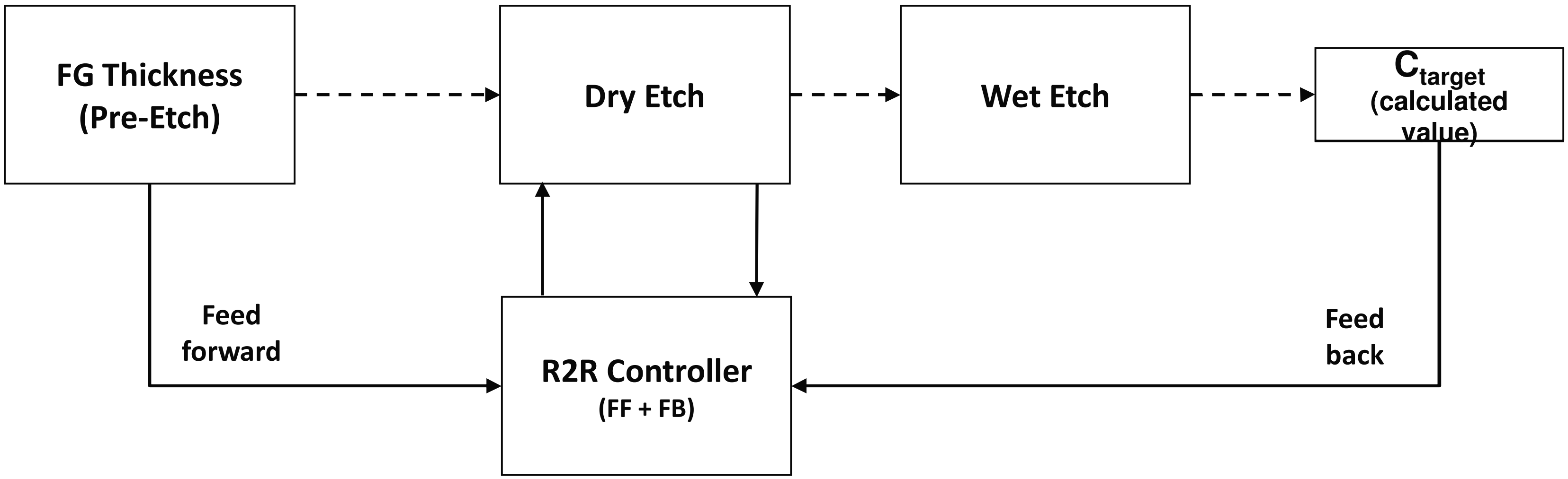
Dry Etch Process Control

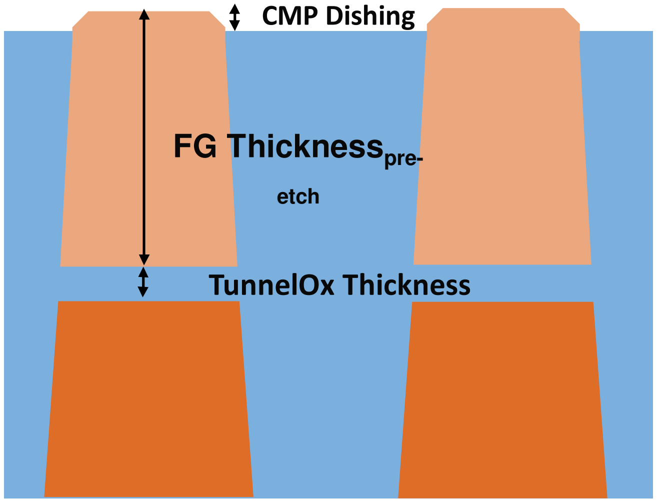
Process Control Schematic

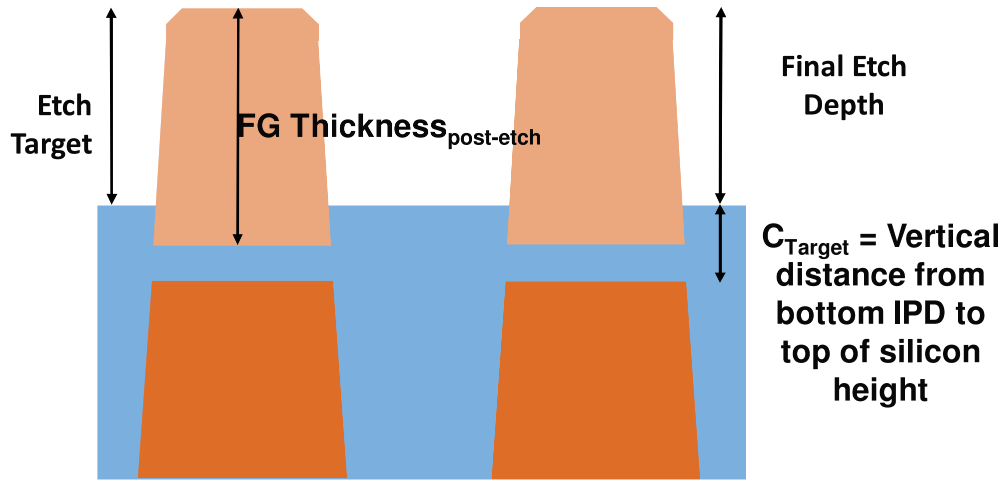


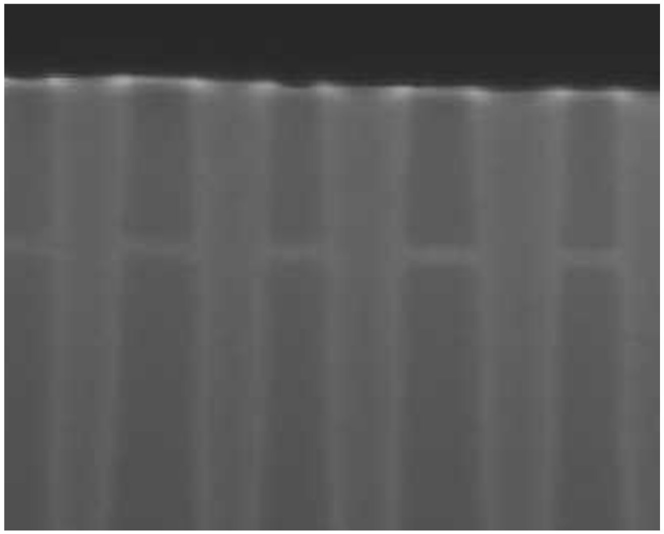
- **Etch Controller with Feed-Forward and Feed Back Components**

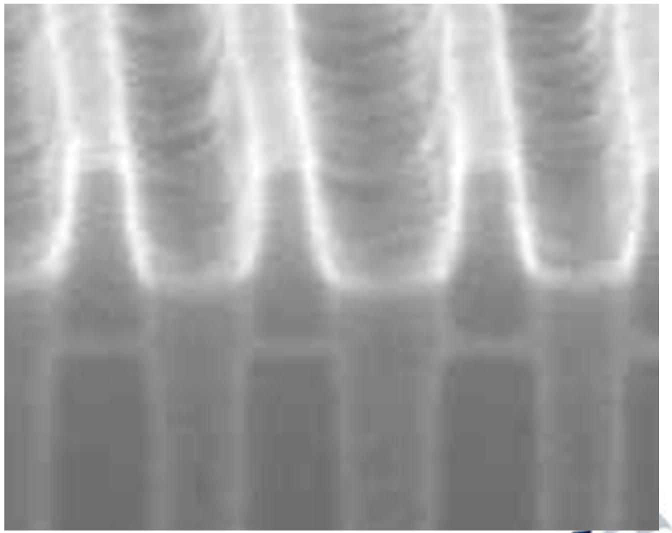
Feed-Forward	Feed-Back	Control Knobs
FG $\text{Thickness}_{\text{pre-etch}}$	FG $\text{Thickness}_{\text{post-etch}}$	Etch Time
CMP Dishing	Final Etch Depth	Gas flow (Etch Rate)
	CG-AA Delta	

Pre/Post Etch Comparison









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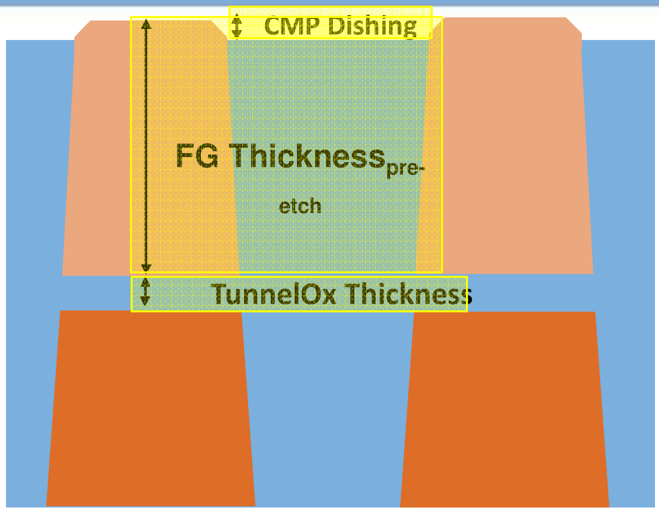
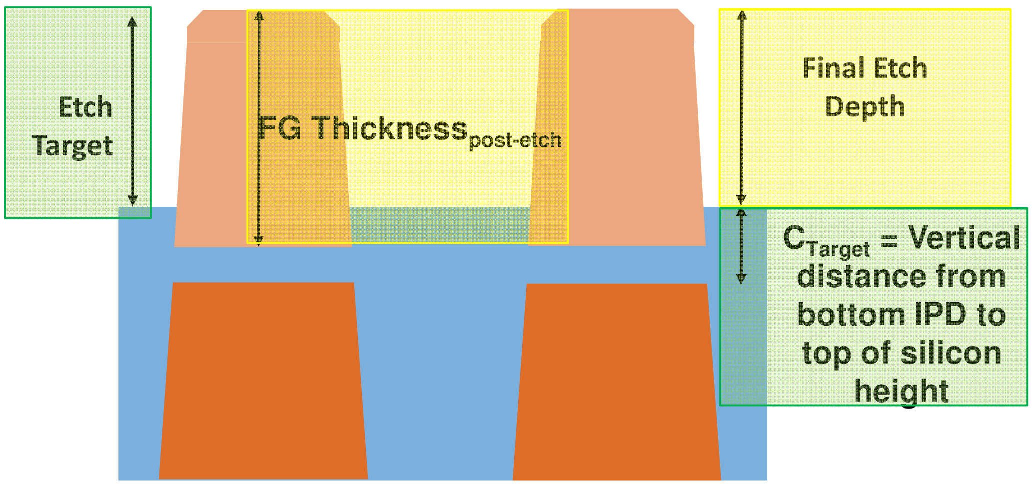
Pre/Post Etch Comparison





- **For pre Etch – FF calculation**
  - Etch Target = $\text{FG Thickness}_{pre\text{-}etch}$ - CMP Dishing - C_{Target} + TunnelOx Thickness
  - Etch time is determined by the Etch Target and Etch Rate for tool
- **For post Etch – FB calculation**
  - C_{actual} = $\text{FG Thickness}_{post\text{-}etch}$ – Final Etch Depth + TunnelOx Thickness
  - Feed back delta between C_{target} and C_{actual} for adjustment
  - $\text{Etch Amount}_{post\text{-}etch}$ = Etch Rate * Etch Time + Bias (constant)
  - C_{delta} and Etch Rate determine gas flow and etch time adjustments

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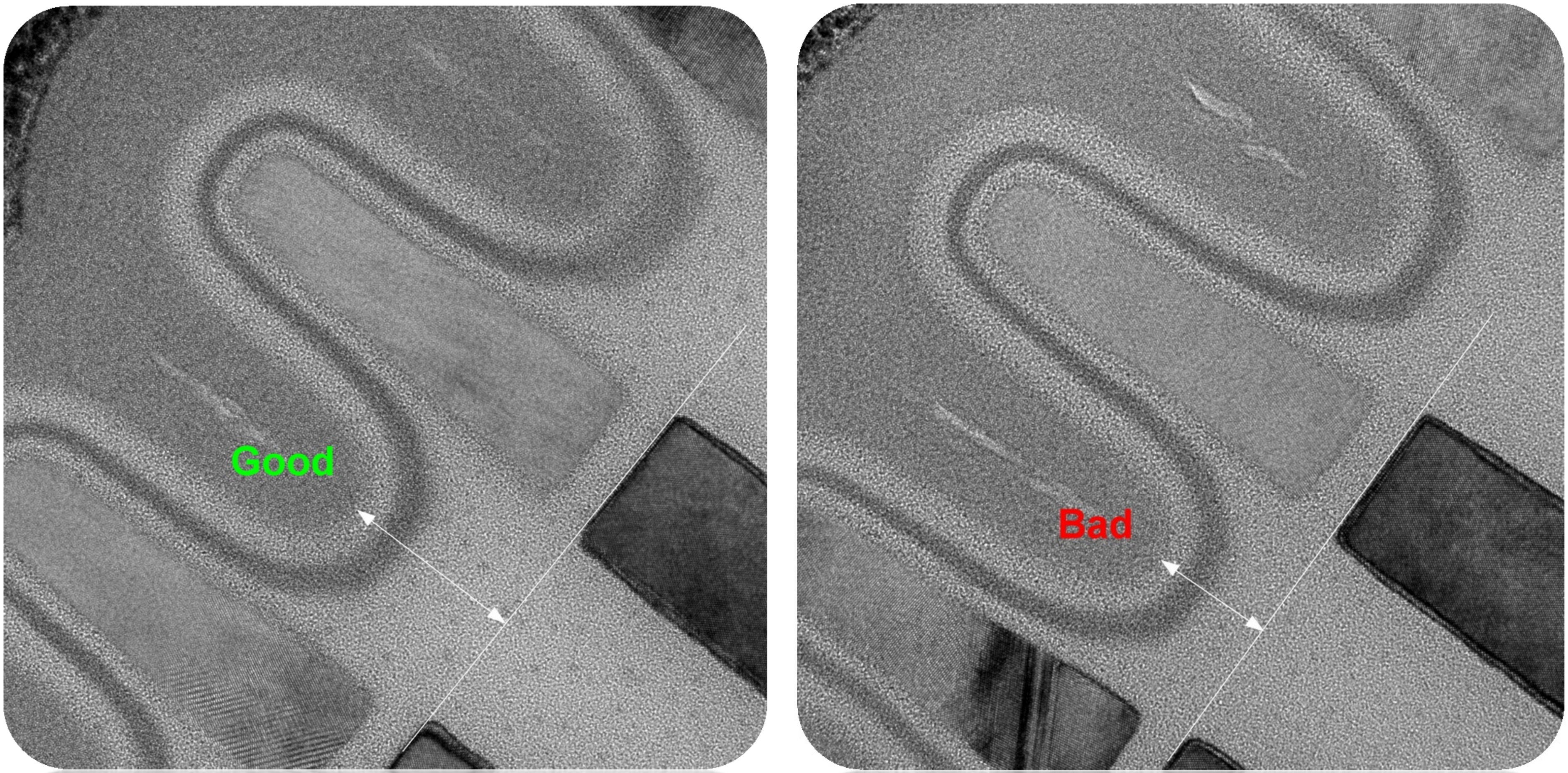
Post CGAA Delta Good vs. Bad

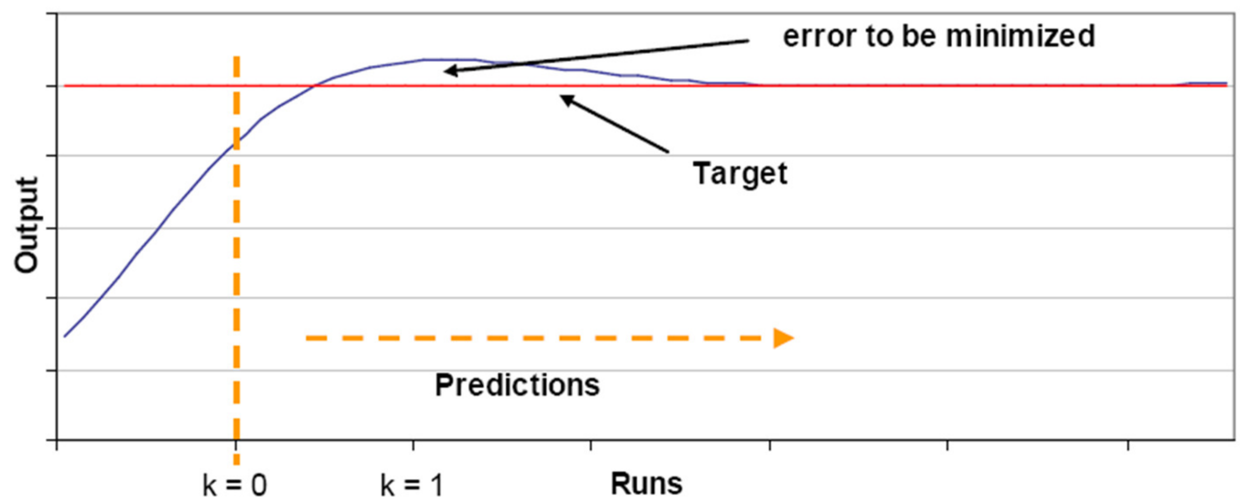


Cross Wafer Uniformity Control

- **A multiple inputs and multiple outputs (MIMO FF+FB) solution has been implemented to improve Center to Edge profile and uniformity**

$$\begin{bmatrix} CGAA\_Center \\ CGAA\_Edge \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} EtchTime \\ GasFlow \end{bmatrix} + \begin{bmatrix} g_1 \\ g_1 \end{bmatrix} \begin{bmatrix} FF\_Disturb \end{bmatrix} + \begin{bmatrix} b1 \\ b2 \end{bmatrix}$$

- **Model Predictive Control is used in MIMO control system**
  - MPC is one of the most advanced control technologies
    - Optimizes tuning knobs to get multiple outputs all closest to target
    - Takes into account all tuning knobs' constraints
    - Allows operation closer to constraints
    - Fully optimize use of tuning knobs within process windows
    - Minimize under and overshoot of target and hits targets in fewest runs



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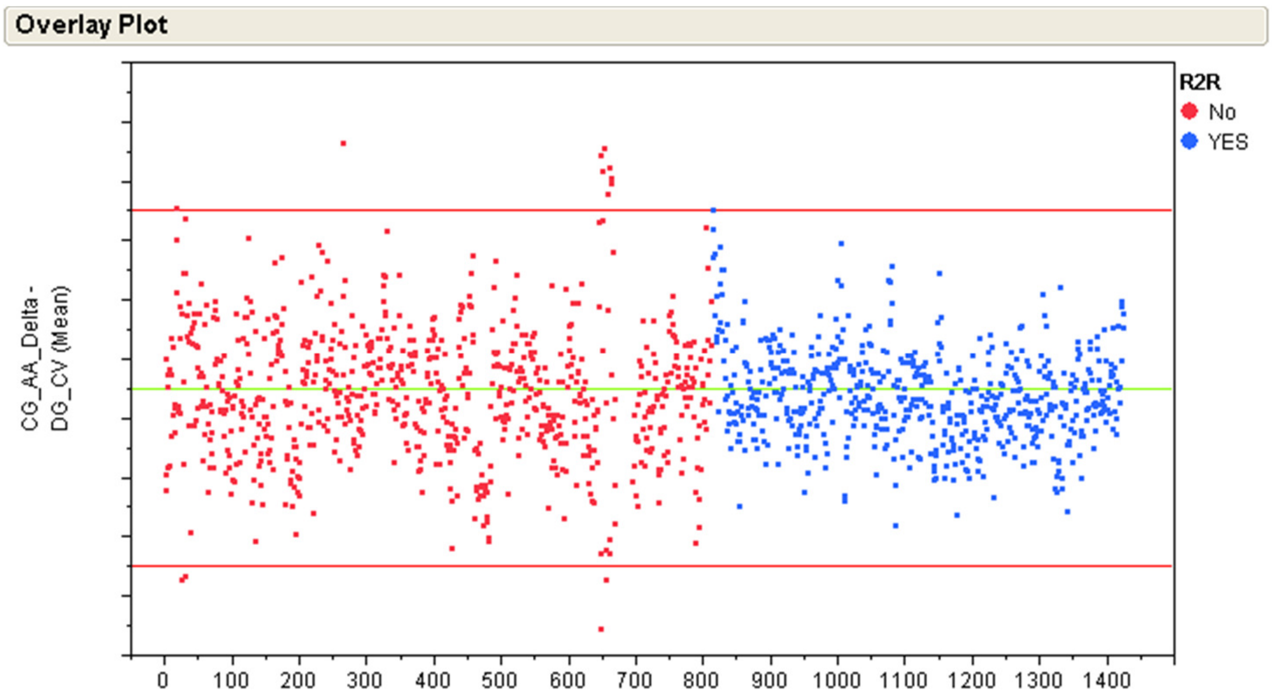
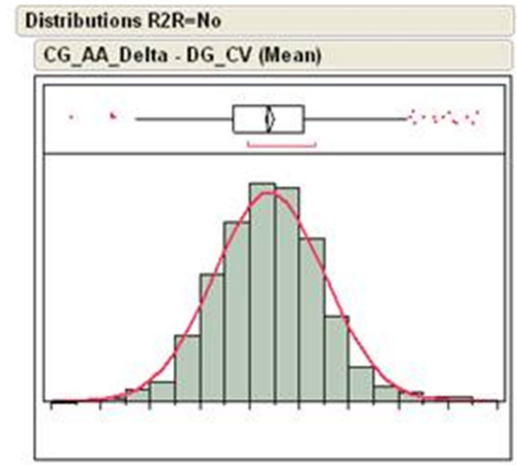
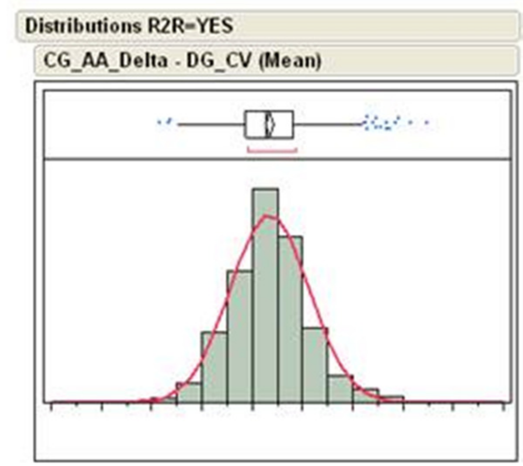
Data Comparison

- **CG_AA Delta before and after controller implementation**
  - 38% Cpk improvement







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The Furnace R2R Input - Output Model

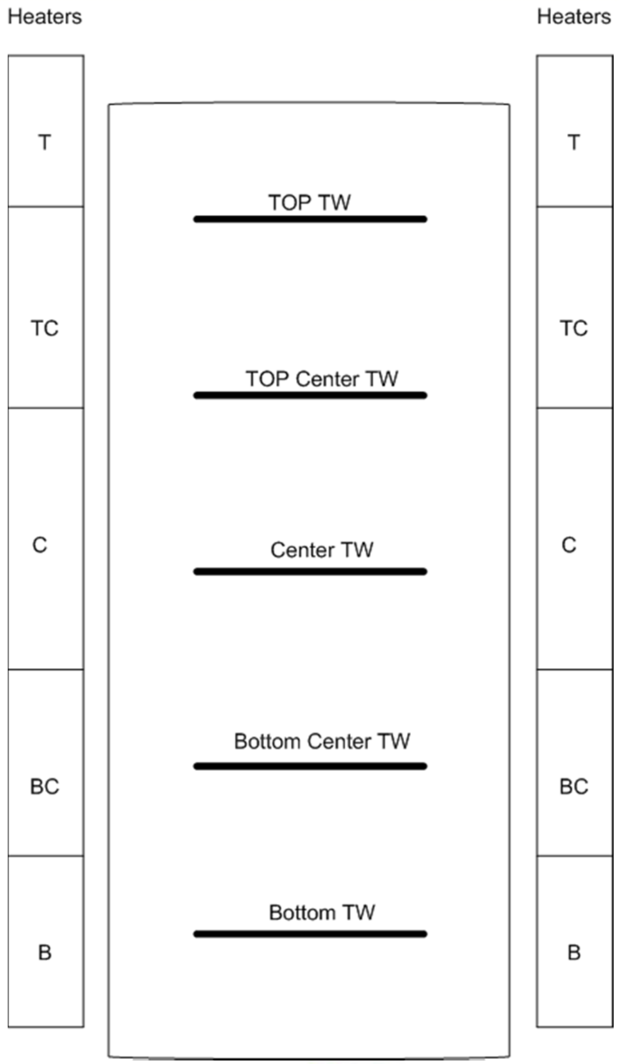
The Input - output model for the furnace can be described as below,

$$y_k = Cu_{k-1} + b_{k-1}$$

or,

$$\begin{bmatrix} Top\_Thick. \\ TopCenter\_Thick. \\ Center\_Thick. \\ BottomCenter\_Thick. \\ Bottom\_Thick. \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} \\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} \\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} \\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} \end{bmatrix} \begin{bmatrix} Temp1 \\ Temp2 \\ DepTime \\ Temp4 \\ Temp5 \end{bmatrix} + \begin{bmatrix} b1 \\ b2 \\ b3 \\ b4 \\ b5 \end{bmatrix}$$

Note: **the slope matrix (c11, c12, c13….. C55) was obtained via experiment. Significant non-diagonal terms were observed (i.e. $C_{54} \neq 0$), believed to be due to test wafer positions relative to heater elements, and due to reactor/recipe design.**



E3 State Space Model

The State Equation and Output Equation,

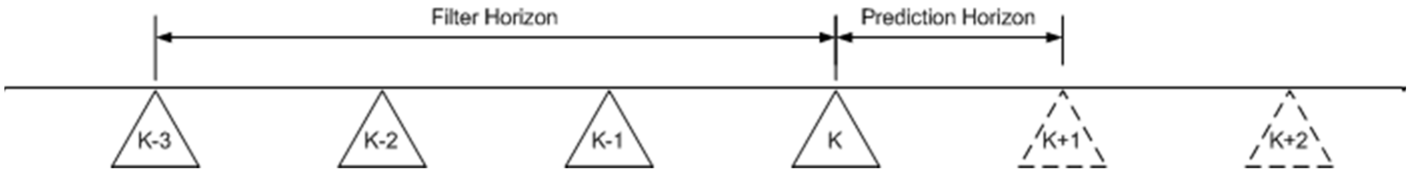
- State Equation: $x_{k+1} = Ax_k + Bu_k + Fw_k$
- Output Equation: $y_{m,k} = Cx_K + Gf_k + v_k$

where x_k is state vector; w_k is state noise vector; v_k is measurement noise vector and f_k is feed forward components vector. A, B, C, F, G are state model parameters.

State Space mapping allows modeled disturbances to linearized and added to the control model as a separate term

State Estimation Horizon and Controller Horizon

The E3 R2R framework used for R2R is the Model Predictive Control (MPC)



- Batches K-3 through K have processed in the furnace reactor and have post-metrology measurements. The Filter Horizon (or State Estimation Horizon) consists of a fixed number historical runs where the model state is known.

- Batch K+1 has not yet been processed, and constitutes the Prediction Horizon (or Controller Horizon).

- The Filter Horizon is used to estimate the model states, while the Prediction Horizon is the range over which the controller set points are tuned via the controller block.

States Estimation – Filter Horizon

$$\min_{\{w_k, v_k\}} \left(J = \sum_{k=-1}^{N-1} w_k' Q w_k + \sum_{k=0}^{N} v_k' R v_k \right)$$

$$Subject\_to:$$

$$x_0 = \overline{x_0} + w_{-1}$$

$$x_{K+1} = Ax_k + Bu_k + Fw_k$$

$$y_k = Cx_K + Gf_k + v_k$$

$$x_{\min} \le x_k \le x_{\max}$$

$$w_{\min} \le w_k \le w_{\max}$$

$$v_{\min} \le v_k \le v_{\max}$$

- Q and R are configurable weighting matrices used as part of the optimization cost function (analogous to lambda in EWMA control).
- The optimization function allows states to be calculated such that state noise and measurement noise are minimized while remaining within established model constraints.
- The state estimation block updates model states based on historical run data using the control model and the state estimation optimization equation.

Controller - Prediction Horizon

$$\min_{\{u_k \ldots u_{k+p-1}\}} \left(\sum_{i=k+1}^{k+p} (y_i - y^t)' Q (y_i - y^t) + u_i' R u_i \right)$$

$$Subject\_to:$$

$$x_{i+1} = Ax_i + Bu_i$$

$$y_i = Cx_i + Gf_i$$

$$u_{\min} \le u_i \le u_{\max}$$

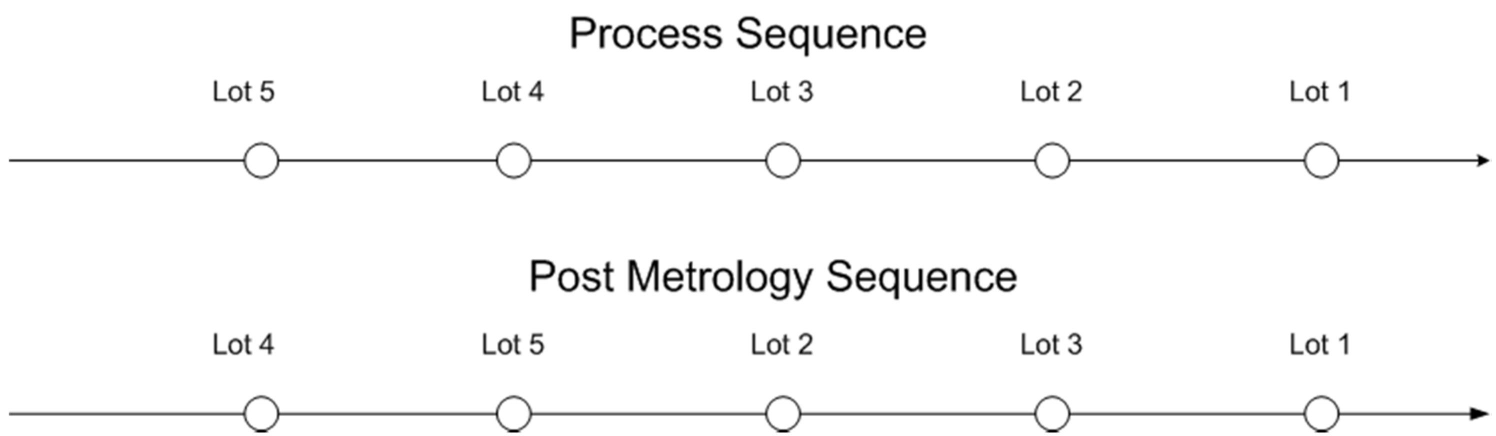
$$u_{-Delta} \le (u_i - u_{default}) \le u_{+Delta}$$

$$y_{\min} \le y_i \le y_{\max}$$

- Q and R are additional configurable weighting matrices allowing additional dampening by minimizing the predicted output errors and input moves.
- There are cases where it is necessary to use optimization based on higher cost of input moves when an explicit control model solution is outside of operating window constraints.
- In short, the controller block calculates the new recipe settings by driving the predicted metrology towards target for the Prediction Horizon, based on the model states.

Selected Topic Discussion – Out-of-Order Metrology

- **Wafers are not always measured at post-metrology in the same sequence in which they were processed in a given furnace.**
- **State estimation uses the process run sequence to estimate the furnace states instead of the post-metrology run sequence. Such a method is critical for processes with large or rapidly changing state disturbances.**



Future R2R Control at IMFT

- **Non threaded Run to Run control**
  - Sharing information among different threads (e.g. minority part states could be continuously updated through majority part.)
- **Performance monitoring and self tuning**
  - Good controller performance monitoring metric can alert potential need for R2R tuning, which is the key to maintaining near optimal performance
  - Controller's weighting factors can also be changed dynamically based on performance metric
- **Run to run control through virtual metrology**
  - Virtual Metrology (VM): FDC data and upstream metrology information can be utilized to predict metrology data

What We Look for in a Process Control Engineer

- **Group Demographics**
  - 54% ChE
  - 23% EE
  - 15% ME
  - 8% Other
  - 15% PhD
  - 23% MS
  - 62% BS

- **Demonstrated dedication to IMFT's core values of commitment, integrity, teamwork, and execution**
- **Enthusiasm for SPC, process control, and data**
- **Proven ability to be effective in verbal and written communication**
- **Strong knowledge of DOE and data analysis**
- **Detailed understanding of control loops and control systems**
- **Thorough knowledge of fab processes and tools**
- **Proven ability with fab software applications**
- **Strong analytical, problem-solving skills**
- **Self-Starter/Strong Work Ethic**
- **Ability to develop, teach, present, and understand technical subjects**
- **Understanding of fab data flow and tool/host communication**
- **Programming ability**

Where do I go from here?

- **Look into potential of working with IMFT engineer as a mentor for a project, or better yet work toward an internship at IMFT**
- **Shore up your statistical knowledge. Especially helpful are applied/DOE type statistical classes**
- **Look into advanced control classes. Industry trend is leaning heavily toward state space solutions, which are not covered to great extent in introductory control classes**

Q & A (freebie time)

1. **Which two companies combined to form IMFT?**
2. **What type of memory does IMFT produce?**
3. **What does 'PCS' stand for?**
4. **What's feature size of current technology in mass production at IMFT?**
5. **What do SISO and MIMO stand for?**
6. **What's feed back control?**
7. **What's feed forward control?**
8. **What's the indicator for performance analysis?**

Bonus: Name one of the core values at IMFT.

Making the Memory that Makes the World Mobile