The measurement and control of process variation in High Volume Manufacturing semiconductor Fabs

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Introduction

- Intel in Ireland.
- What is High Volume manufacturing (HVM).
- The challenges of Process control in a high volume manufacturing environment.
- Use of tool parameters in tool diagnostics.
- Virtual Metrology.
- Future work

Intel Ireland Site - Wafer Fabrication facility

Challenges in High Volume manufacturing of IC's

- Many processing equipment spread across many fabs around the world.
- Many of the sources of variation in HVM factories are as a result of running large volumes of wafers with frequent intrusive maintenance to process chambers.
- Increase in the number of process steps and integrated effects.
- Increase in the complexity of the process chemistry and materials
- Product life cycle and ramp changes.
- Continued and relentless reducing in scale of silicon structures.

Logic Process Evolution

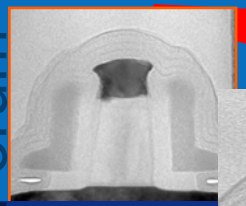
90nm Node
2003

65nm Node
2006

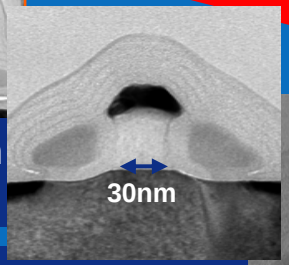
45nm Node
2007

32nm Node
2009

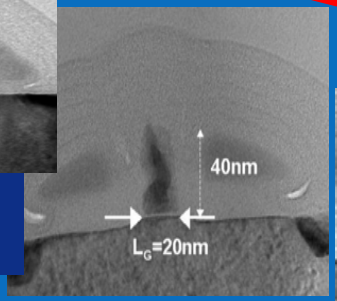
22nm Node
2011



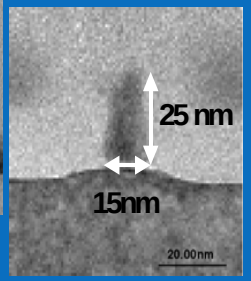
50nm Length
(Production)



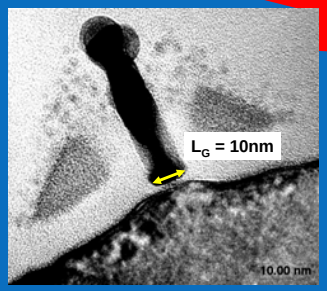
30nm Length
(Production)



20nm Length
(Development)



15nm Length
(Research)



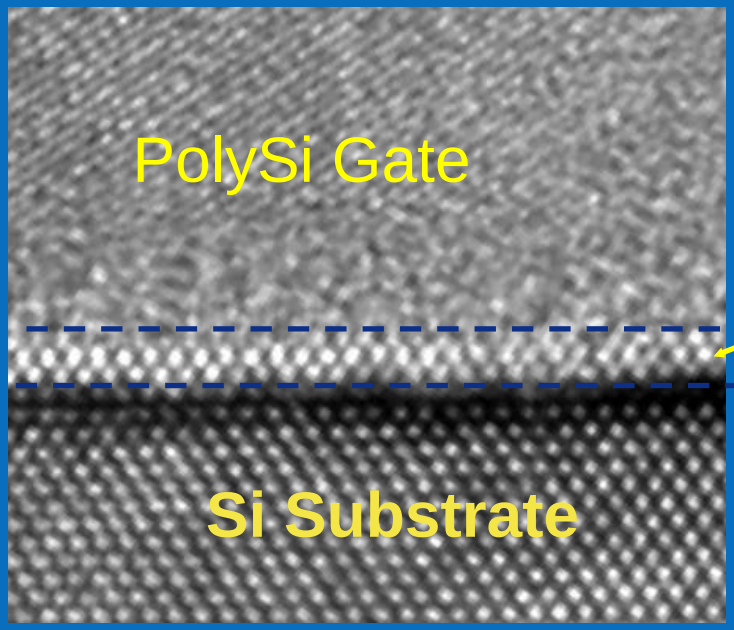
10nm Length
(Research)

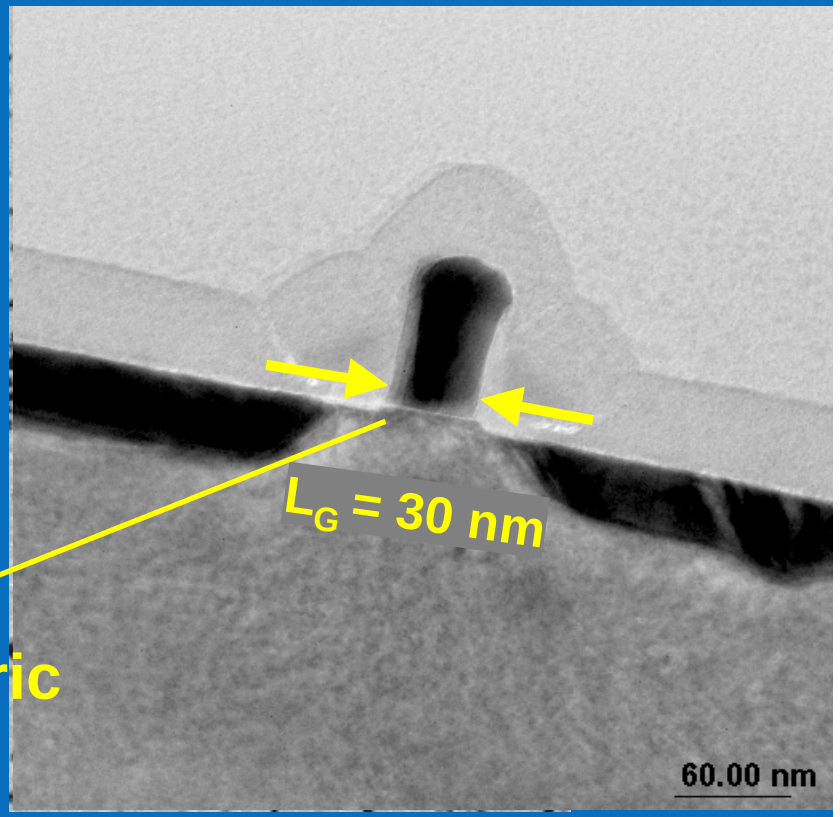
What kind of Process Control Systems do we need to develop to be able to manufacture these devices in high volumes at reduced cost per die?

Source: Intel

Challenges in Transistor manufacturing

How do we control these process?

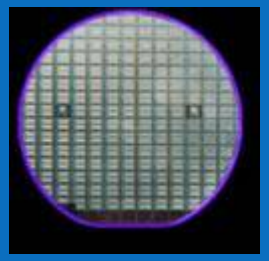


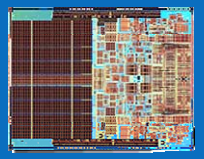


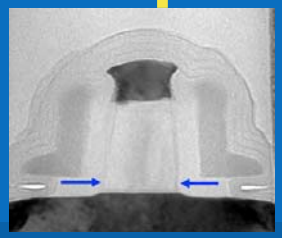
Reproducing these dimensions across all die

Source: Intel

CE! Challenges as we approach 10nm







How to make each transistor the same across in each fab across the world as we approach?

Fabs

VF

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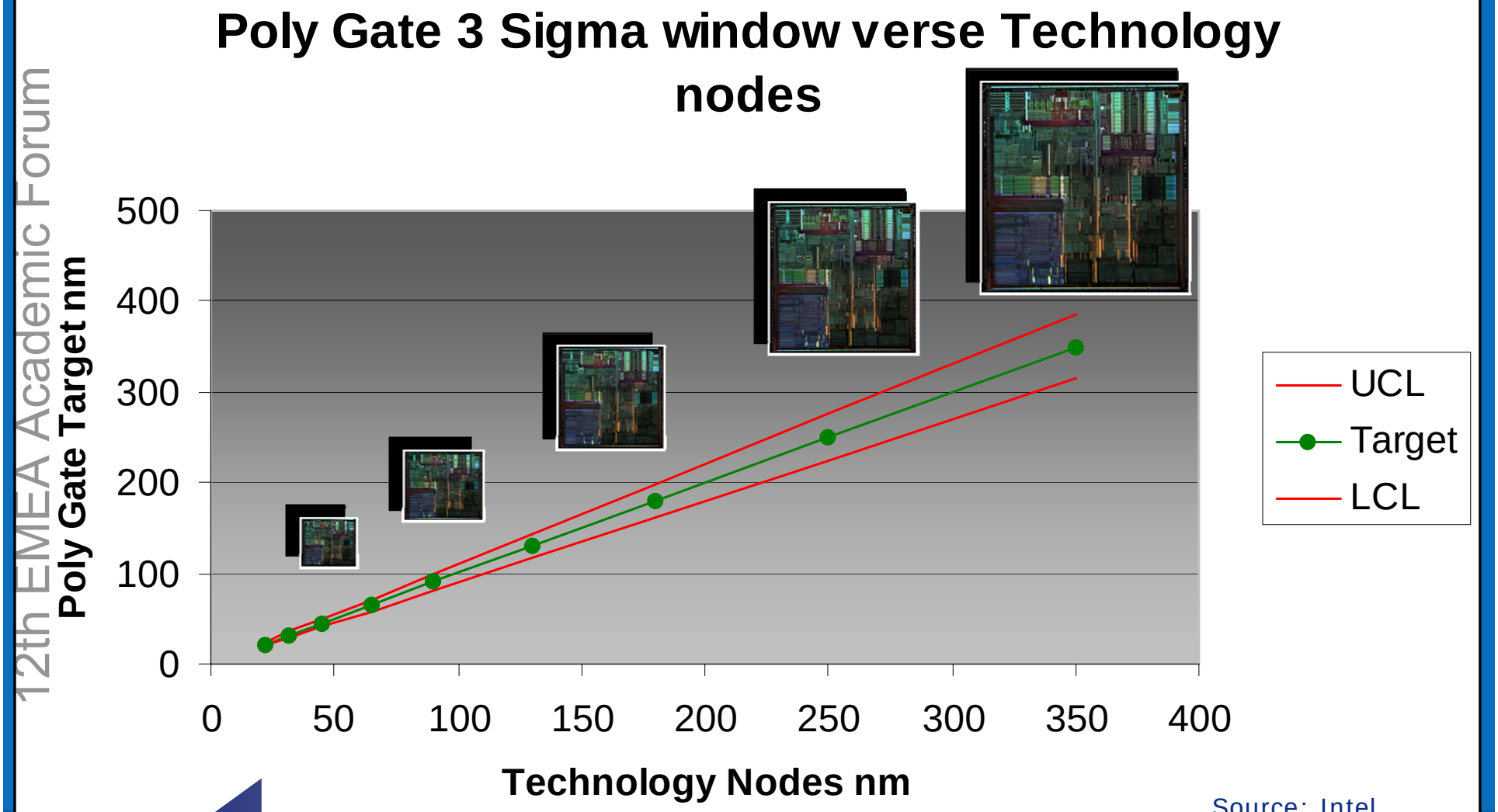
Smaller Process Windows need new Control Strategies



Source: Intel

Line Width Shrinks so does process window

Process Control requirements

- Yield
  - Optimise tool performance and drive solutions for process marginality
- Reduced excursions
  - Keep equipment under control at a hardware parameter level
- Tool Availability and MTTR
  - Tool side fault classification solutions.
  - Identify critical parameters that need to be controlled
- Reduce Costs
  - Sensor-based diagnostics and post-maintenance qualification
  - Increase productivity and effectiveness of Manufacturing technicians and engineers.
- Virtual Metrology
  - Being able to predict wafer metrology from tool and process state parameters.

Source :Fab Innovation - Integration of DFM and APC is Key for Yield Enhancement
Tokyo, April 24, 2006 Elder,Melody, Harner

Process Control Systems Integration

For operational efficiency
For better control
For variation reduction

Multi Step Control
Loop Level Control (e.g. FCCD Variation)
Control to EOL

APC Indicators
APC Application
Health Metrics

R2R Control

FF Metrology
Recommendation
Wafer Level Metrology
FB Metrology
Recommendation

SPC++

Metro Data
Sample Plan

Tool Data

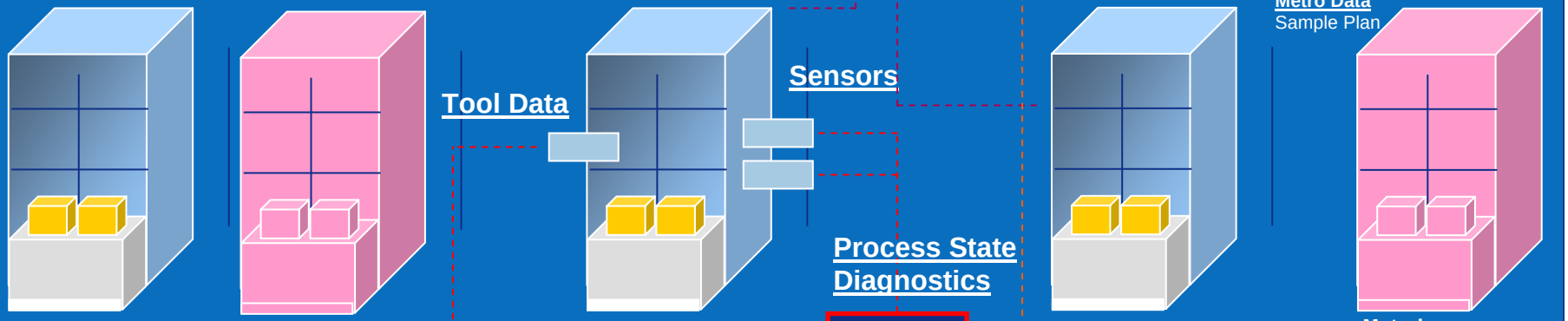
Sensors

Process State Diagnostics

Tool State Diagnostics

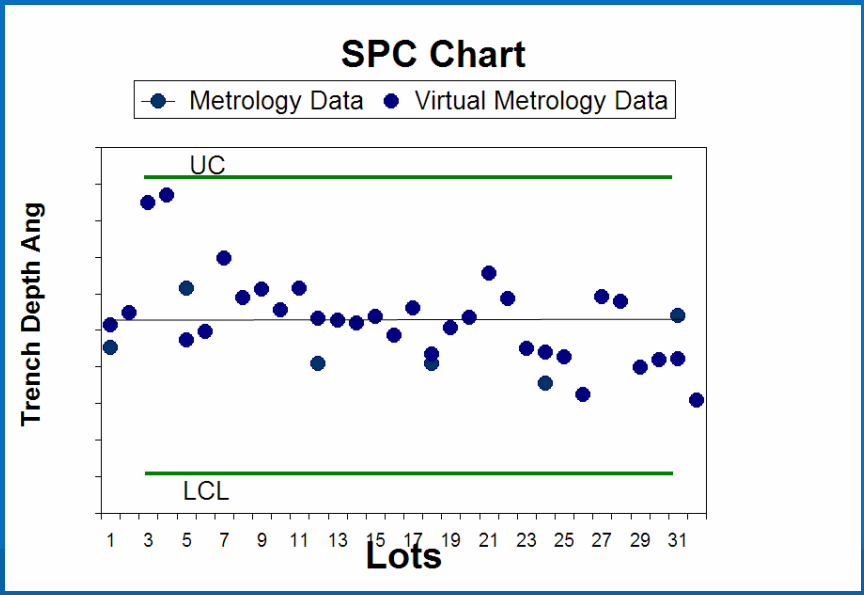
EP Indicators
EP Template
Health Metrics
& Optimization

Process Data Visualization & Analysis

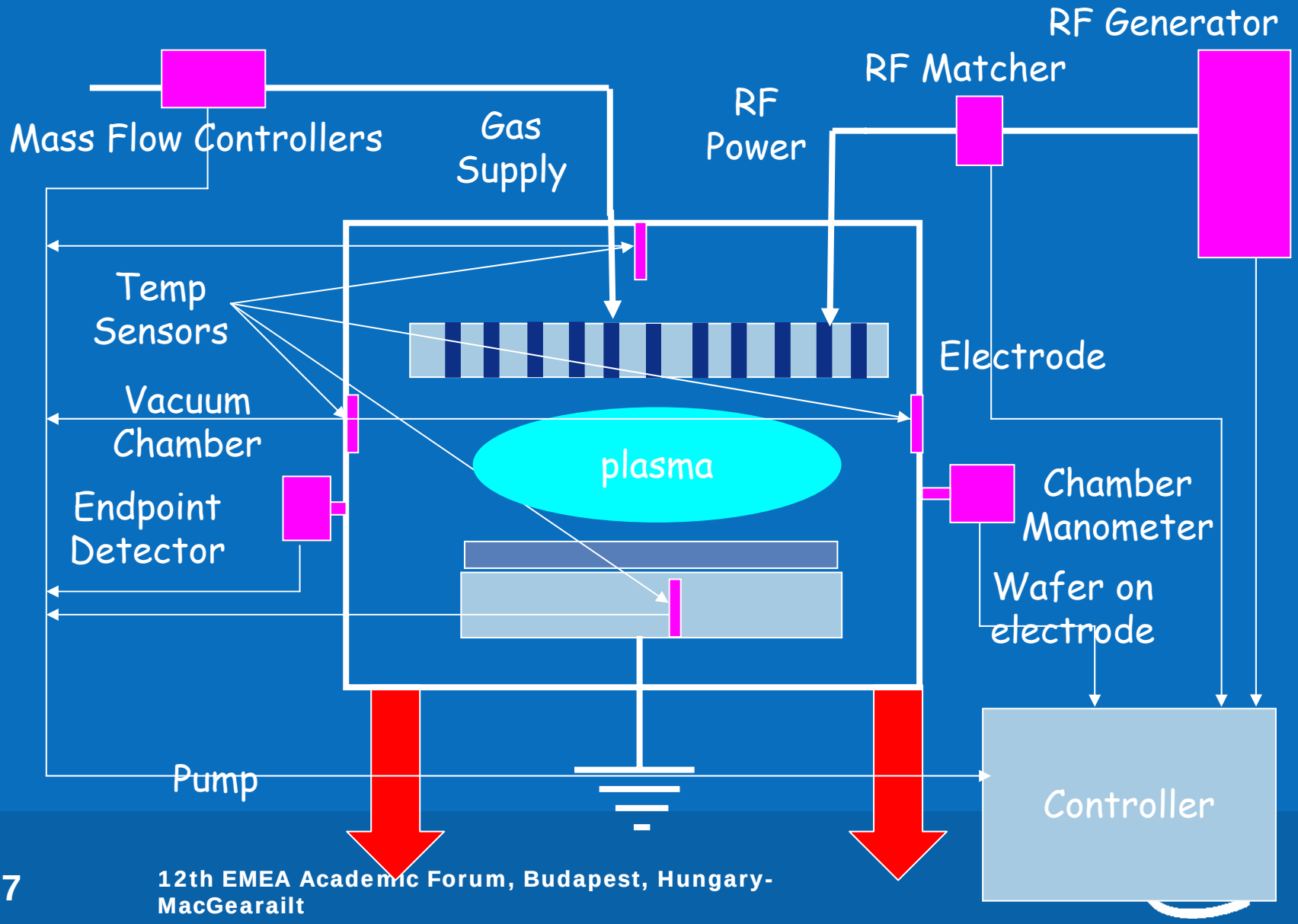


Statistical Process Control: Example

- One of the most effective ways of influencing the quality of our products is to ensure consistency and reproducibility in the manufacturing process.
- SPC is a valuable tool to compare previous performance of key parameters with present performance and differentiating between normal statistical variation and process deviation.
- Traditionally SPC has been based on Metrology measurements from the wafer.

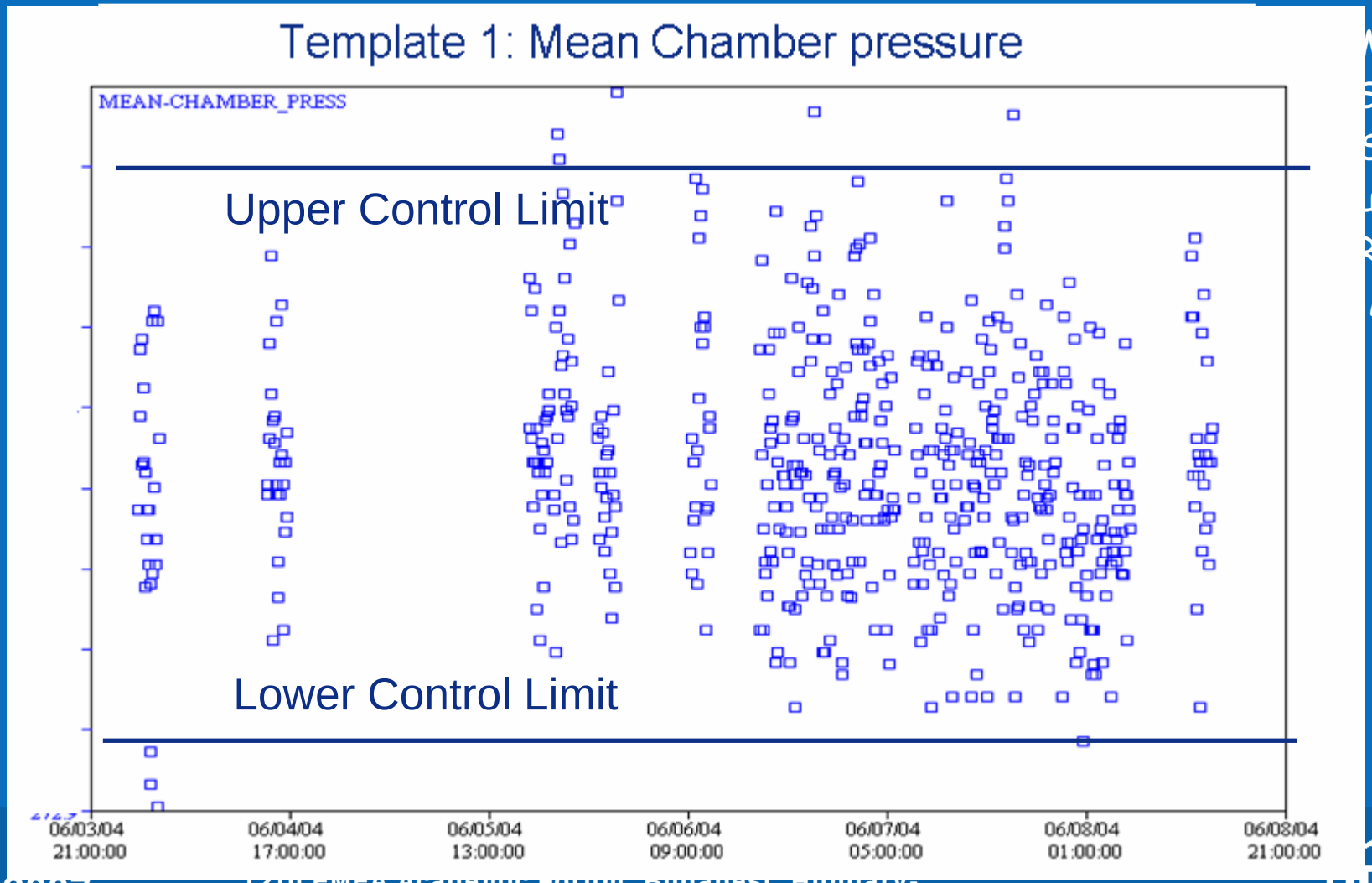


Advanced Equipment Control



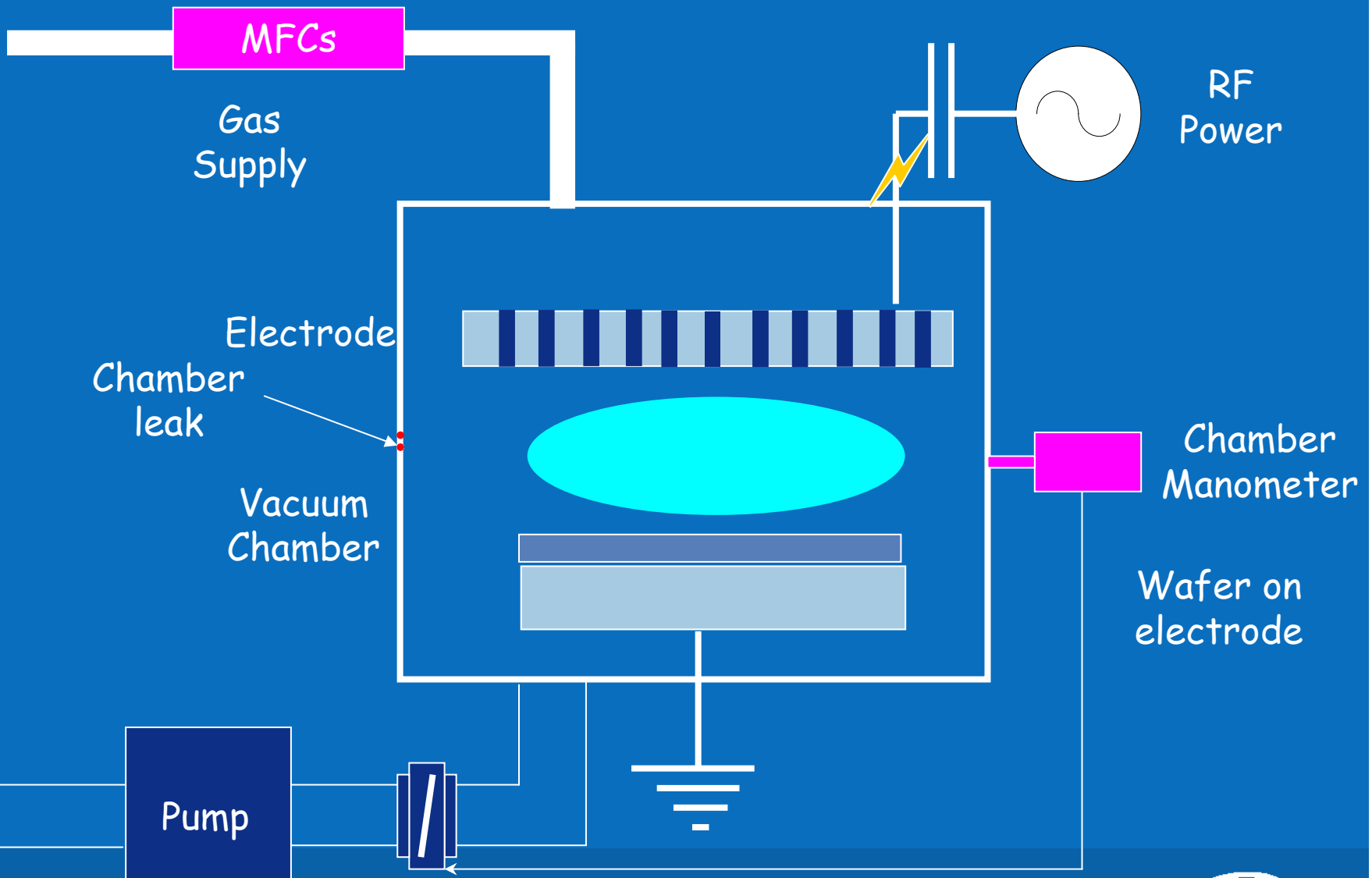
Advanced Equipment Control

summary statistics are calculated from the raw data :



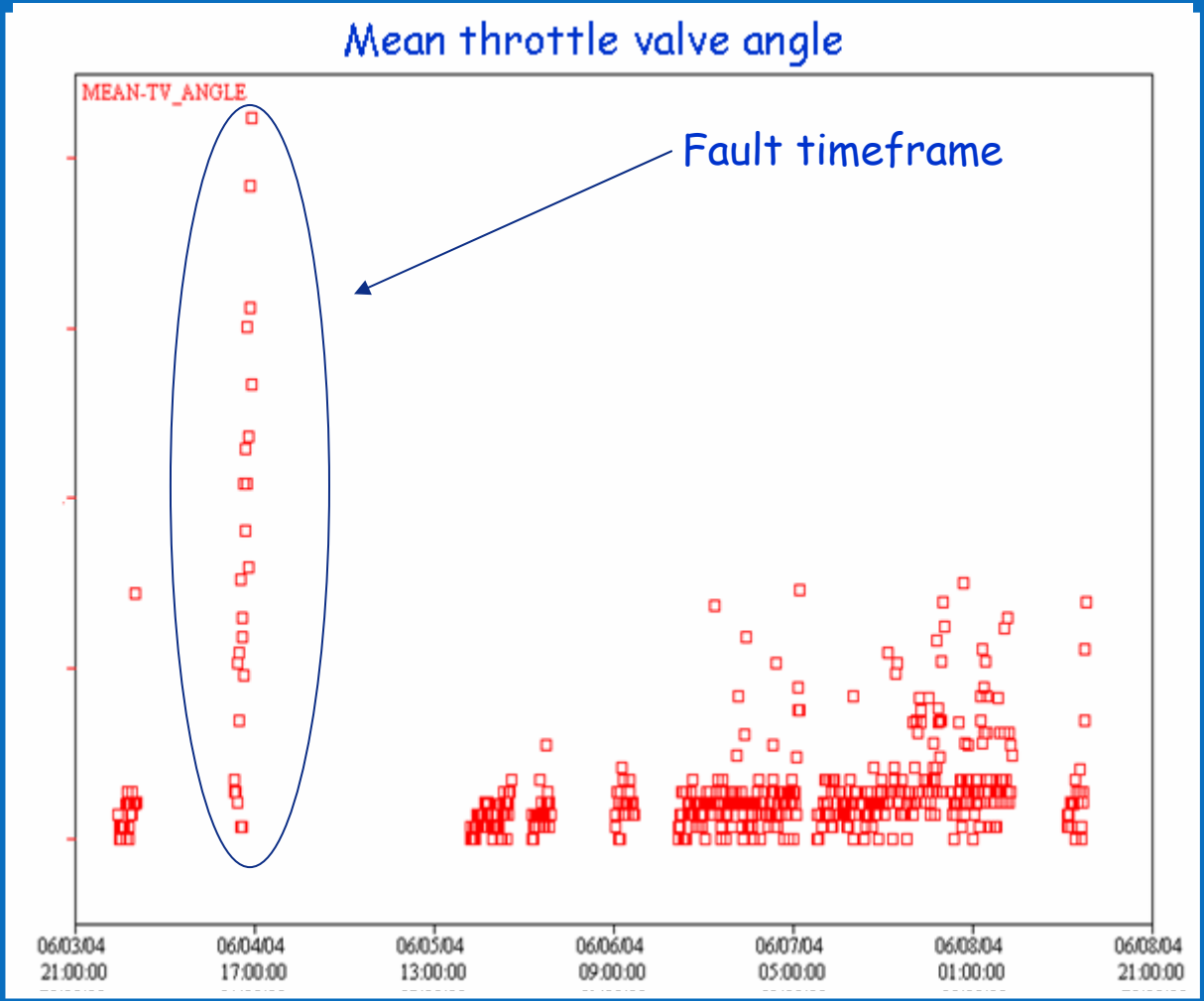
Mean
Stdev
Slope
uration
Range
Max
Min

Pressure Fault Example



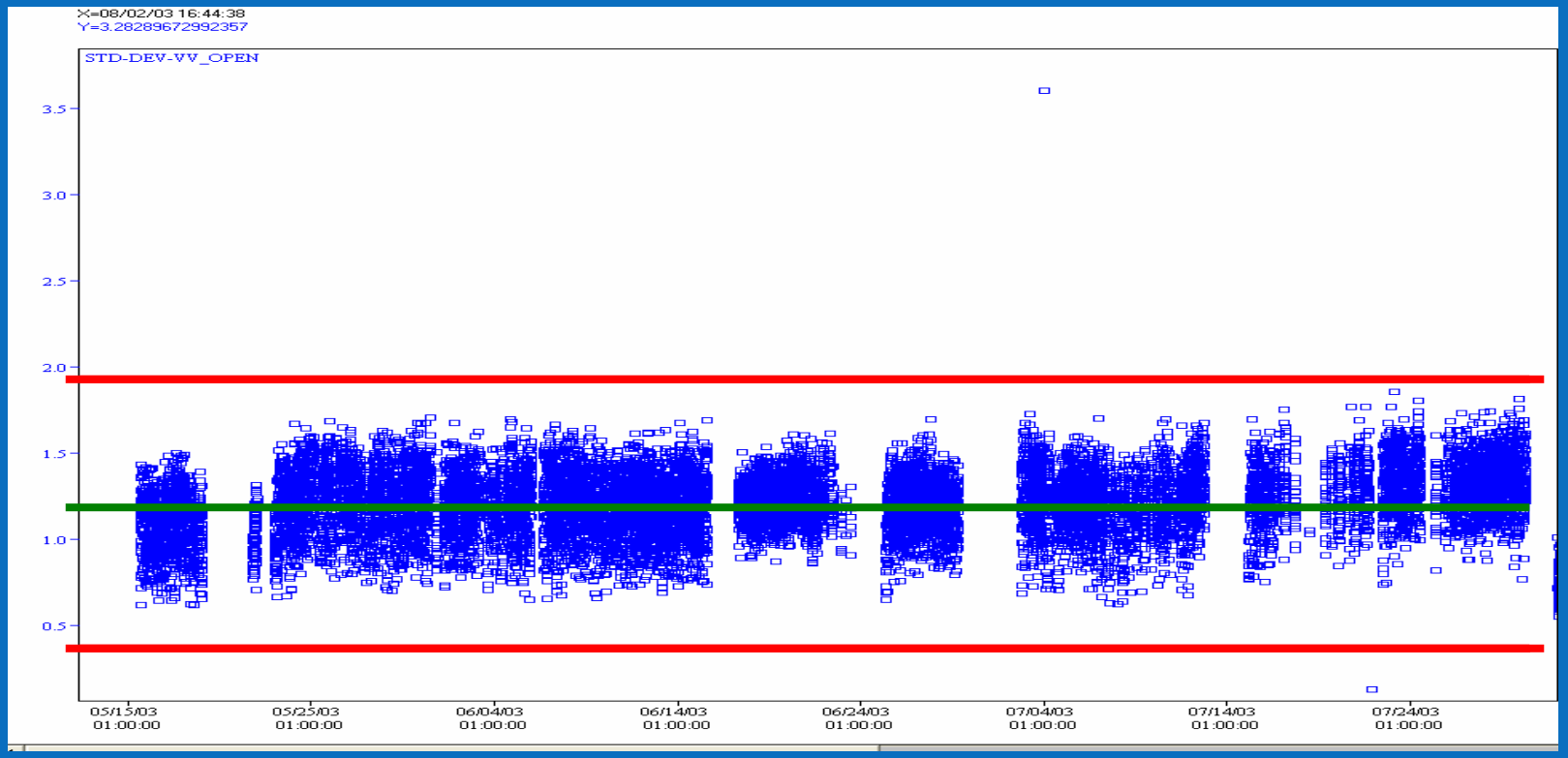
Throttle valve compensates to maintain chamber pressure

Pressure fault summary data



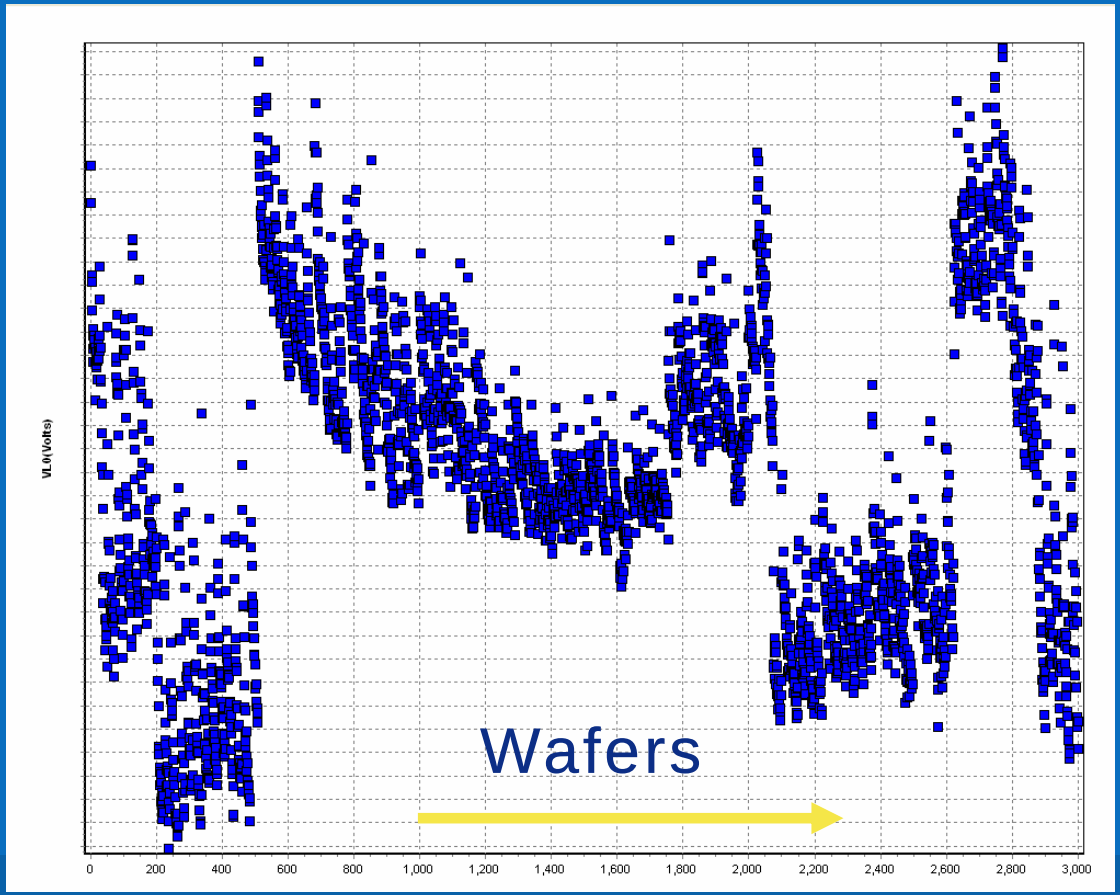
Univariate Statisical Limits on Tool parameters.

- The aim of classical SPC is to insure that observations are within control limits
- Indicators are considered to be independent and are analyzed one by one.
- Control limits are defined by statistics (using a historical population) or are based on the process knowledge

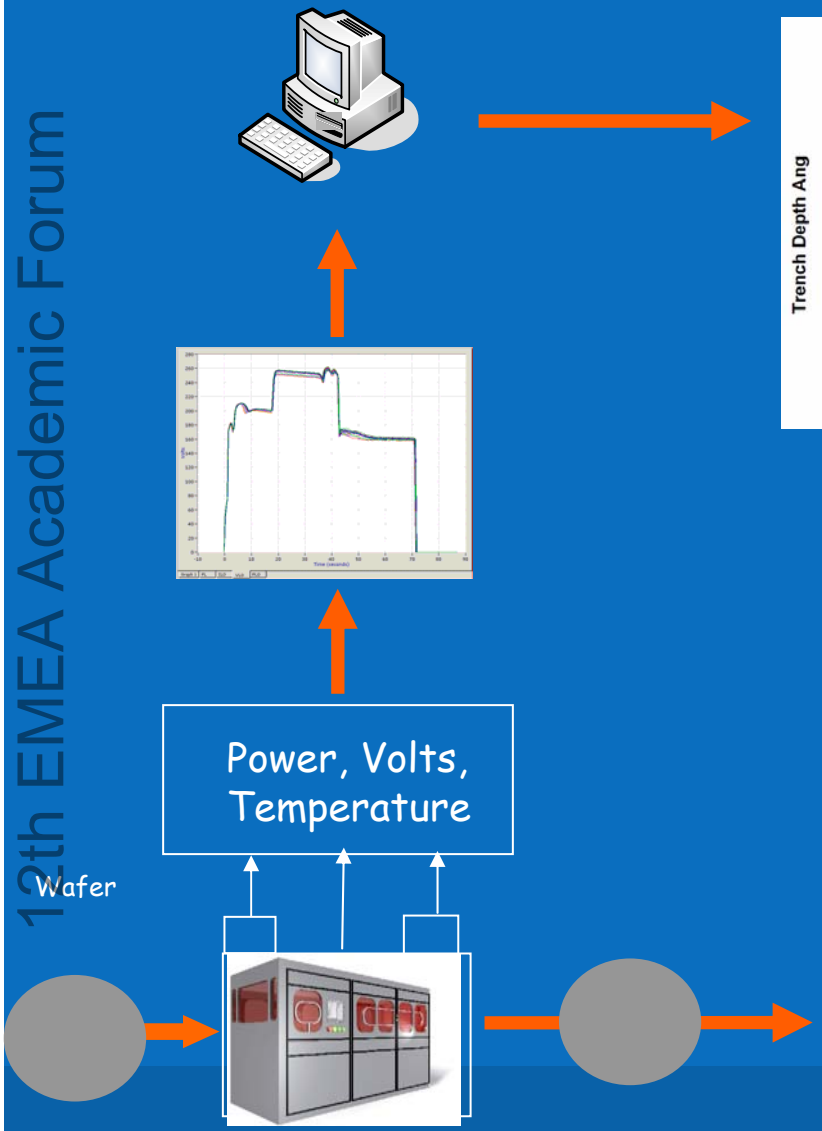


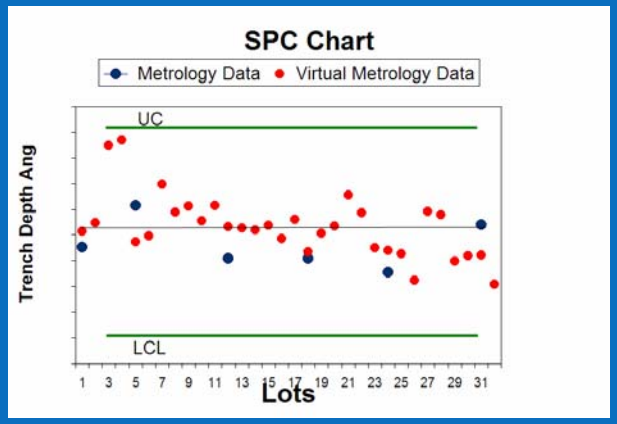
Univariate control limitations wont work on plasma parameters

- Parameter behaviour is not stable and drift across due to PM cycle due to conditioning effects, Parts wear, Chamber Hardware changes etc.
- Need new techniques to identify real faults from benign faults.



Virtual metrology (VM) is a novel technology to predict wafer performance from process state variables.



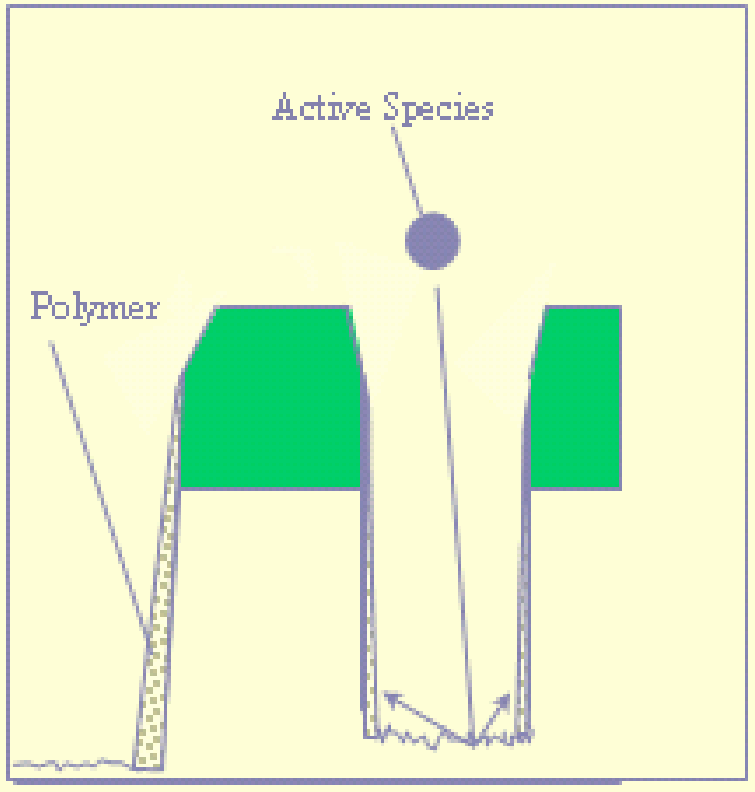


- Sensor data (voltage, power etc) collected from process chamber.
- Data filtered pretreated.
- Statisical / Machine learning (ML) model applied to data to predict metrology based on learned relationships between sensor data and metrology.
- Estimate of metrology data calculated for every wafer.

Plasma Etch Challenges

- Dimensions of the etched lines are dependant on plasma parameters- But which ones???
  - Ion Energy.
  - Plasma density
  - Chemical Conditions of plasma and chamber walls.
  - Temperature of substrate. Etc…….

- Tool state sensors have poor correlation with these plasma parameters.
- High resolution sensors are required to detect changes in the plasma chamber which affect wafer parameters.



‘Virtual Metrology’ for Trench Depth estimation in HVM Etch

Problem:

- Lack of Timely Process Monitors in Etch
- EOL Correlation Unclear in Daily Processing

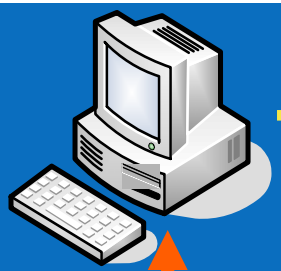
Solution:

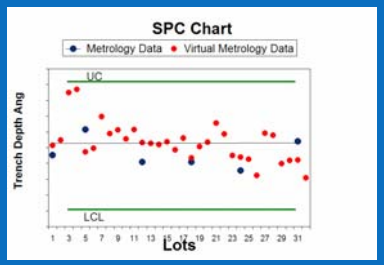
- Prediction of Trench Depth and Sensor Data
  - Use Linear Model For Prediction
  - System Prescreens Using MVA
  - Predicts When the Data is Within the MVA Distribution

Results:

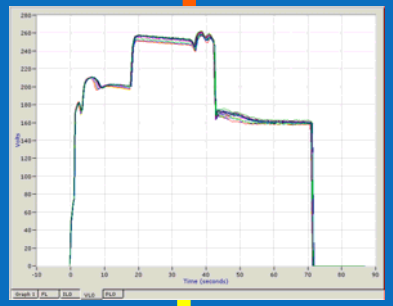
- Productivity
  - Reduced False Fails, Send ahead's, Test Wafers
- Increase in Yield due to:
  - Greater correlation with EOL parameters, detection of process chamber excursions

Source :Fab Innovation - Integration of DFM and APC is Key for Yield Enhancement Tokyo, April 24, 2006 Elder,Melody, Harner





$(X_1, X_2, \ldots\ldots X_n)$



$y = f(x)$

(y)

SPC

Voltage, power, OES etc

3 Days

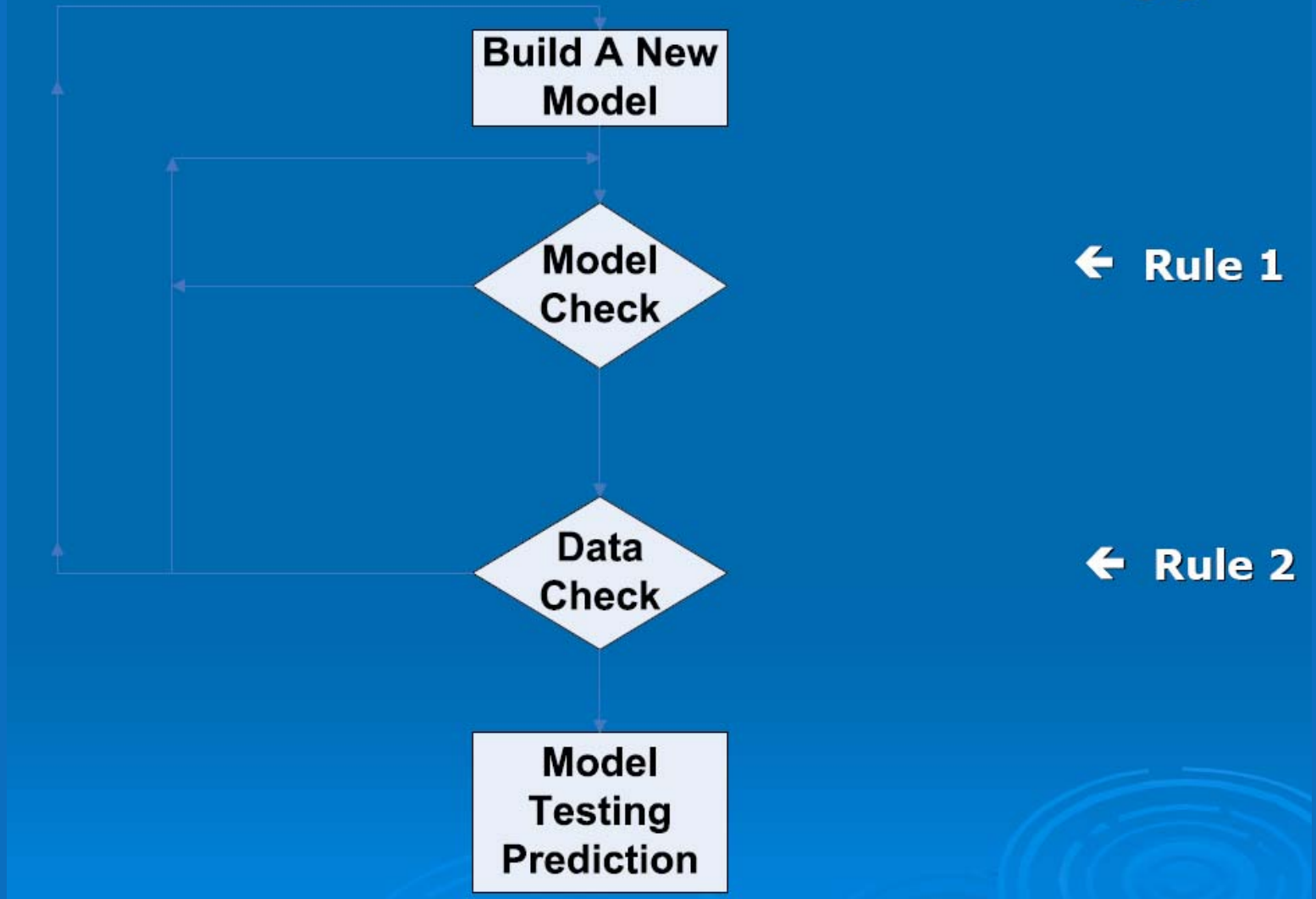
Wafer

Etch

Source: Wang, MacGearailt, Mao, Raulefs- ISMI 2006

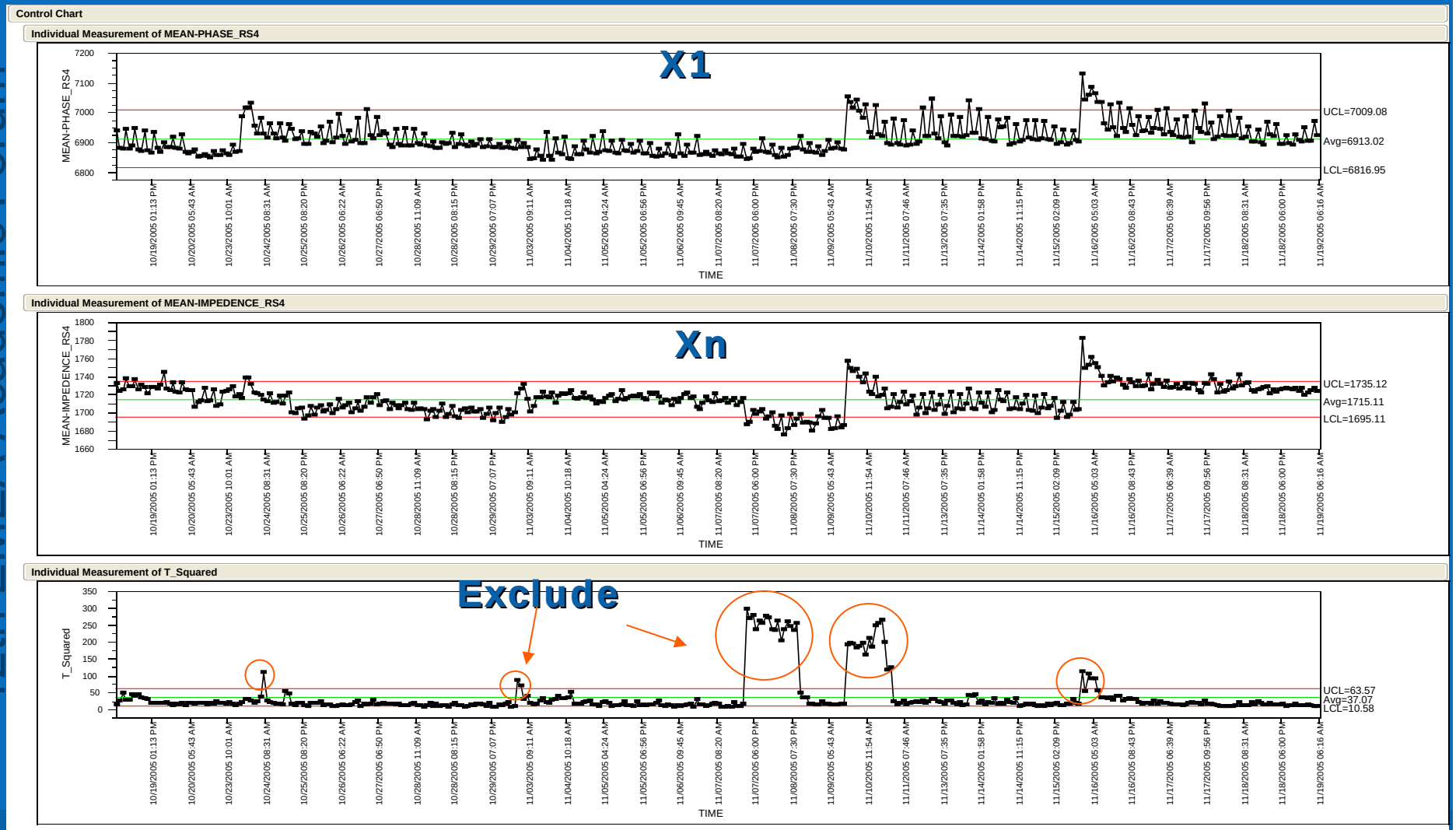
intel

Solution: Virtual Metrology



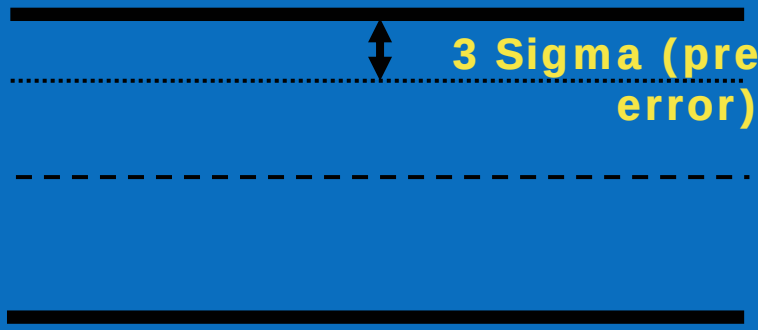
Source: Wang, Mac Gearailt, Mao, Raulefs- ISMI 2006

Screening Using Predictability Indicator

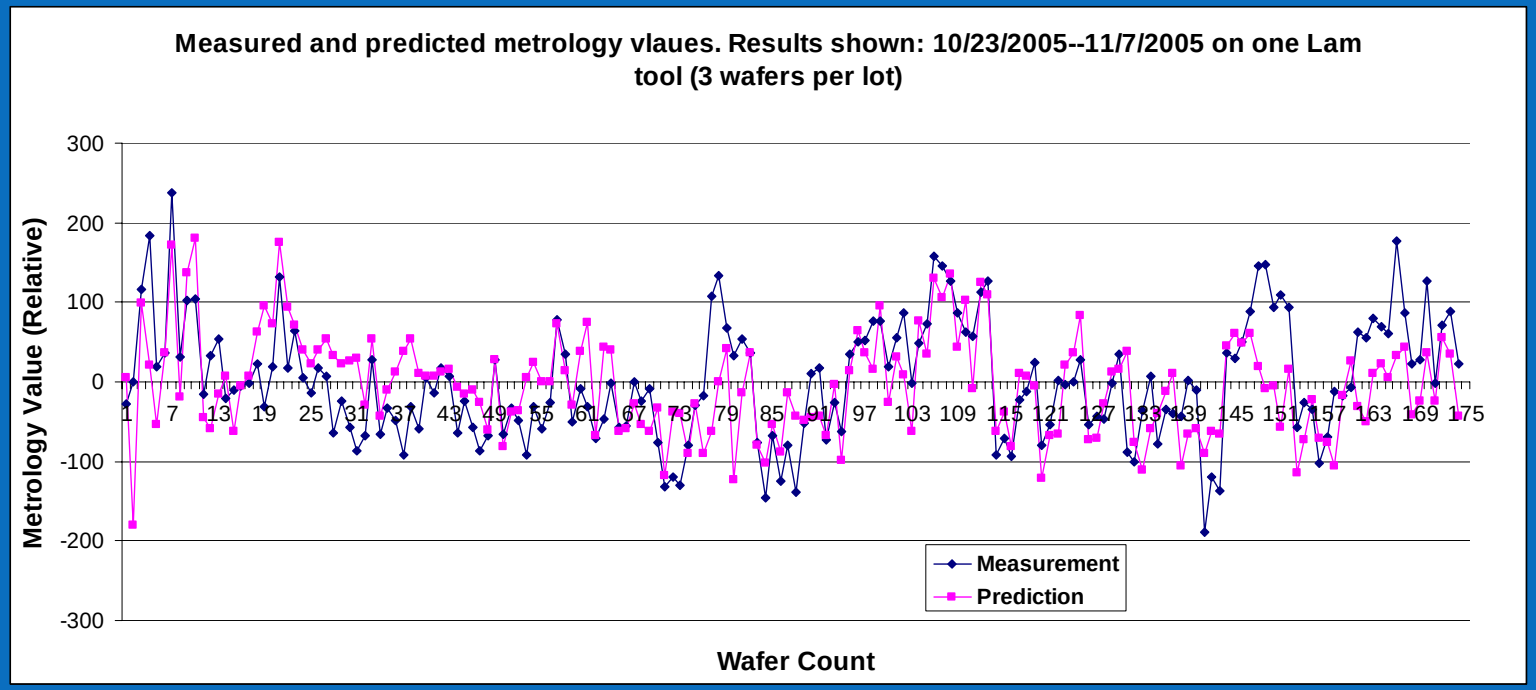


Source: Wang, Mac Gearailt, Mao, Raulefs- ISMI 2006

Results on Etch Prediction



Rule 3 ➔



Source: Wang, Mac Gearailt, Mao, Raulefs- ISMI 2006

Benefits Of Virtual Metrology

- Reduce the sampling needed at inline Metrology.
- Reduce in TPT due to dynamic sampling.
- Reduce overall cost at Metrology (H.C & tools).
- Tool availability-reduced false fails
- Test wafers usage reduction
- Increase in yields due to:
- Greater correlation with EOL parameters
- Greater detectability on the process chamber excursions
- Potential for feed into Run 2 Run Controller for
- improved tool control.

Source: Wang, Mac Gearailt, Mao, Raulefs- ISMI 2006

Summary

- The future of High Volume manufacturing present significant challenges as Moore's Law is pursued.
- In addition the challenges for low costs and high productivity is driving the need for new process control tools.
- Automated control systems are increasingly becoming the process of record in HVM fab.
- Virtual Metrology is demonstrating it’s ability to remove non-value added operations while maintaining the ability to control critical processes.
- On going research with academic partners in exploiting more advanced diagnostic measurement techniques coupled with plasma and profile simulations will potentially lead to more accurate silicon feature prediction.