Machine Learning based virtual metrology in advanced process control for improved high product mix manufacturing

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Outline

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  - Application: Chemical vapor deposition (CVD)
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- Approach
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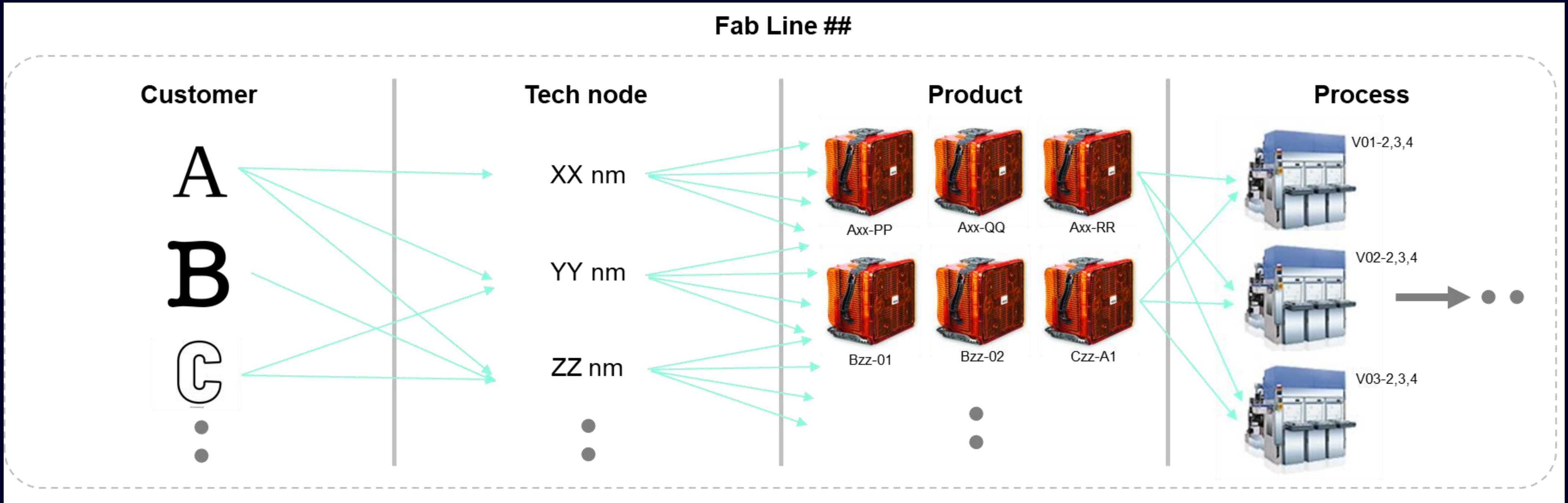
  - Calibre® design feature extraction
  - Calibre® Fab Insight VM modeling
  - VM modeling with and without incorporating design features and FDC data
- Results
  - APC system: R2R control with VM model
  - Control simulation result of APC system
- Conclusion

Background: High product mix manufacturing in semiconductor foundry



- Growing demand for **custom-designed products** from diverse customers requires increased manufacturing flexibility
- High product mix manufacturing involves coordination of various chambers and processes
- Complex operational challenges results in reduced yields and higher costs, requiring development of effective strategies

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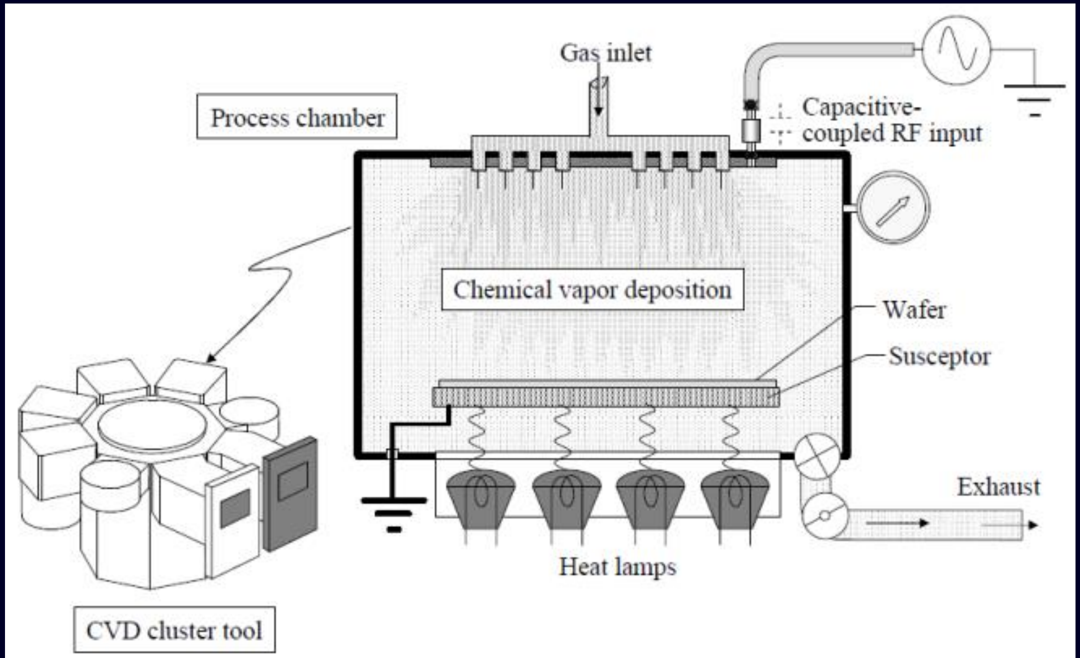
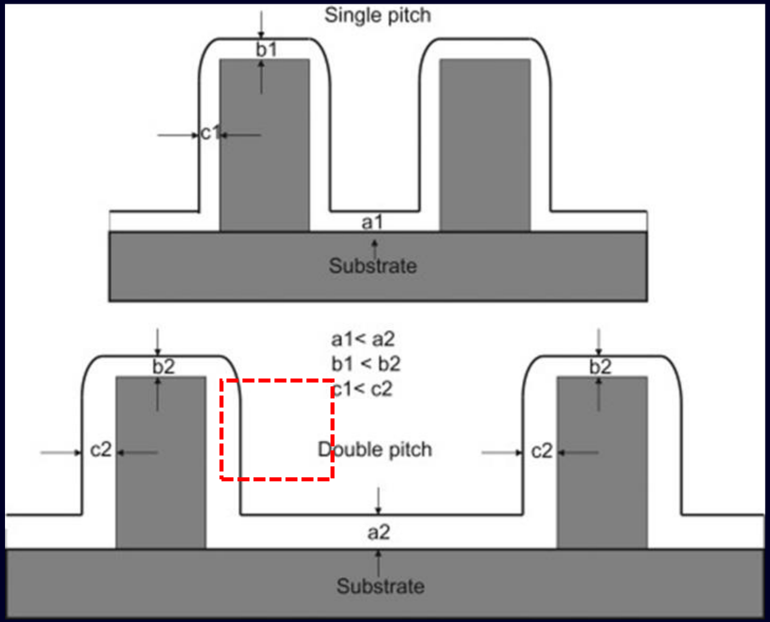
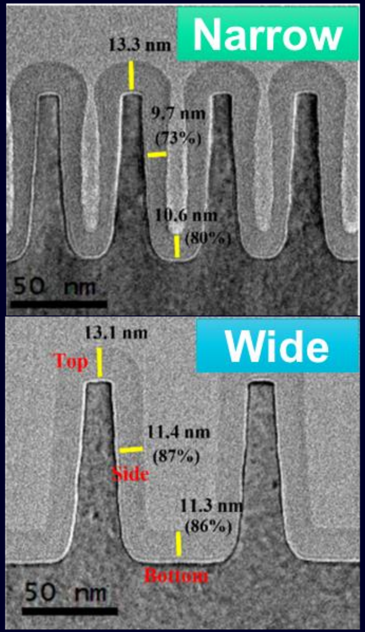
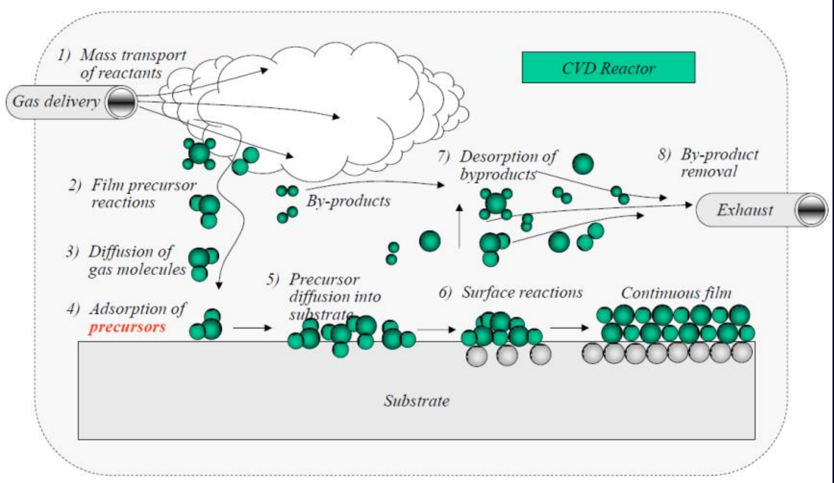
Application: Chemical vapor deposition (CVD) - Challenges









Variation in deposition thickness in high product mix environment due to

- Device layout design
- Chamber condition drift

Design Features can influence film thickness by affecting key transistor parameters like threshold voltage and overlap capacitance, that impacts yield

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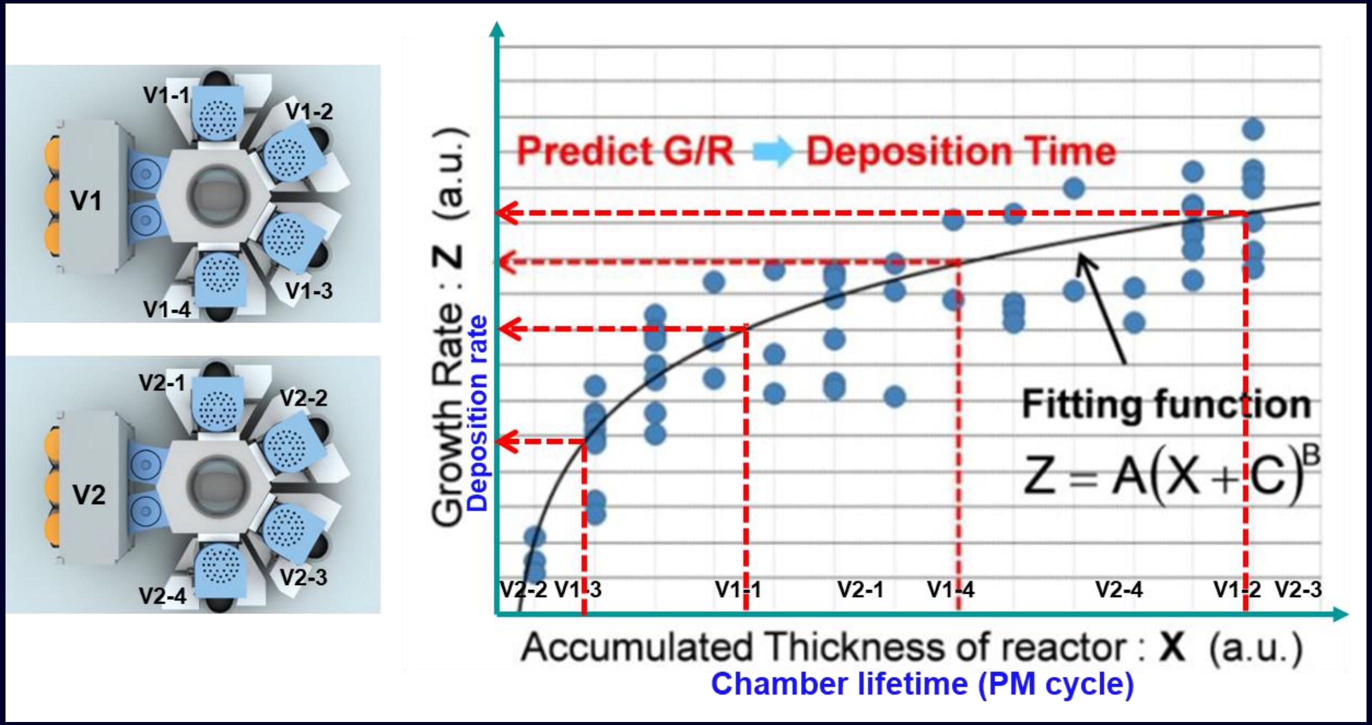
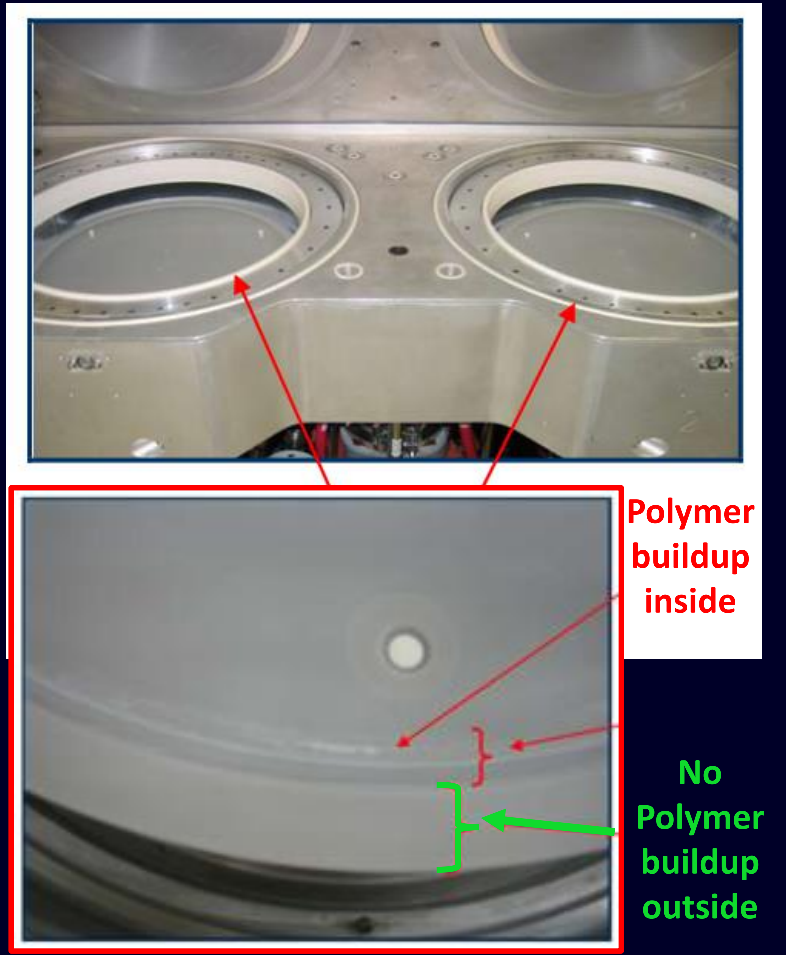
Application: Chemical vapor deposition (CVD) - Challenges





CVD Process variability (Drift in CVD film growth rate) during Preventive Maintenance (PM) cycles and chamber-to-chamber variations

Caused by decreasing surface area and reactive gas consumption within the CVD chamber because of accumulated film thickness

PM cycles: the entire process cycle between PMs

Efficient management of PM cycle variation and chamber matching can help reduce fab line efficiency and throughput loss

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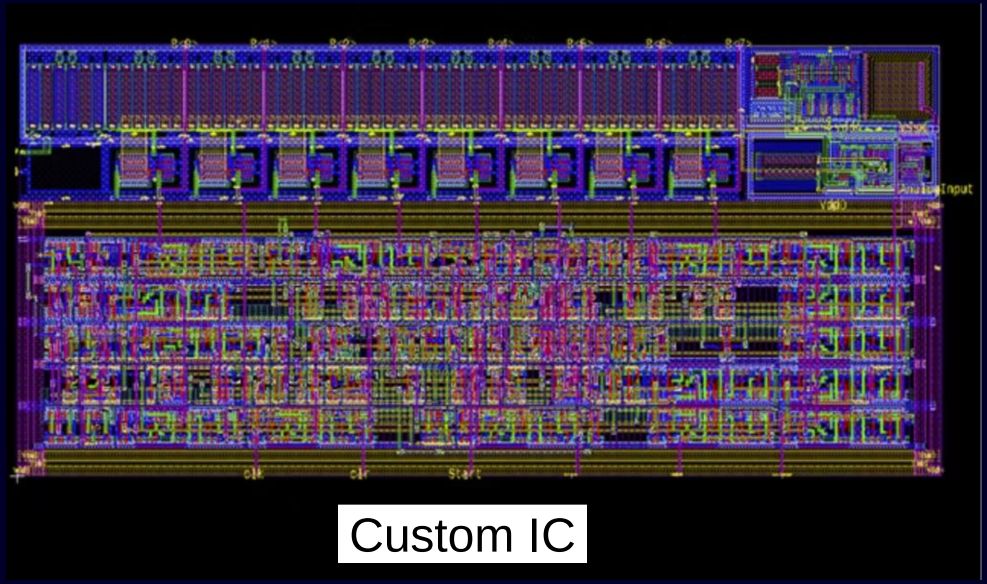
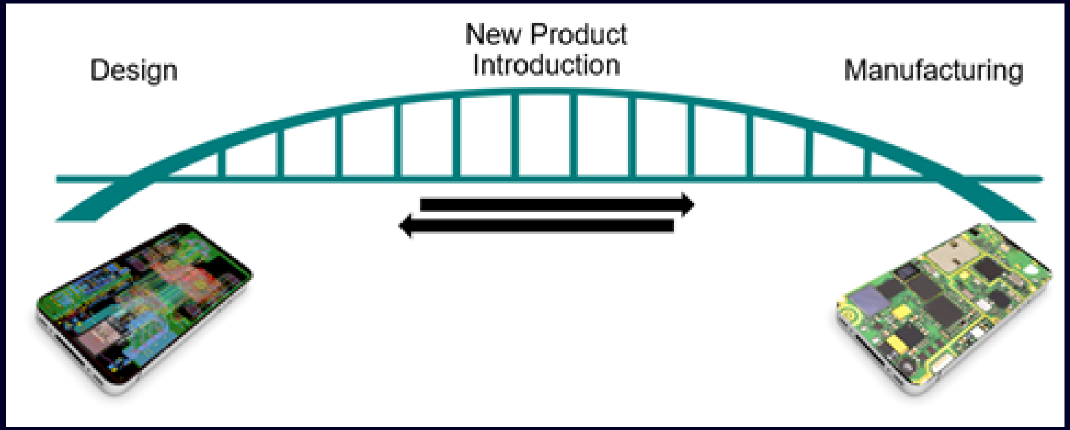
New product introduction (NPI)





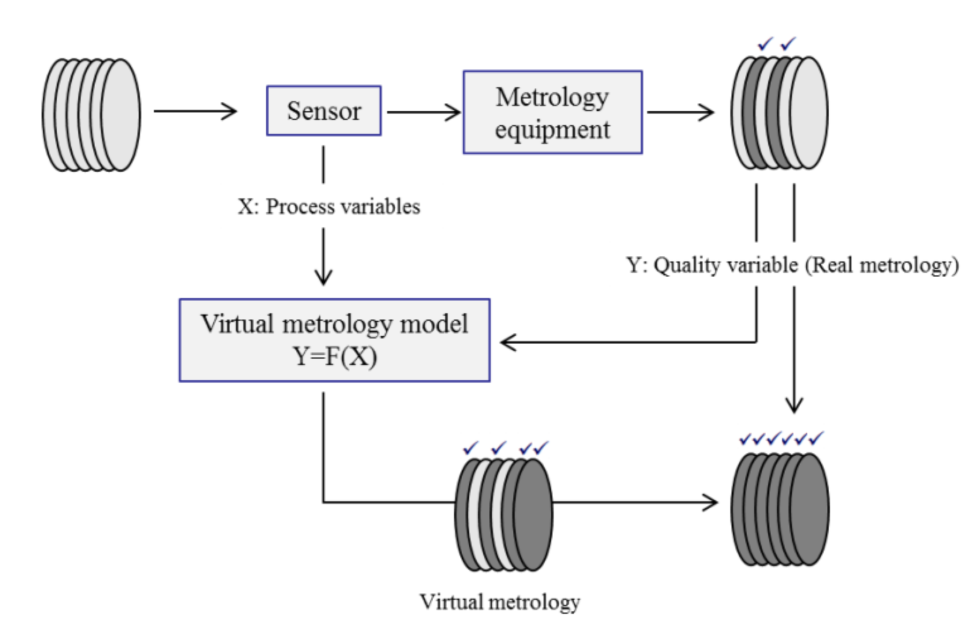
High Mix Production → Frequent **New Product Introductions (NPI)**

- Complex setup, time-consuming if not optimized
- Challenges for traditional run-to-run (R2R) advanced process control (APC) methods

Machine learning (ML) based virtual metrology (VM) approach proposed as an effective process control solution

Virtual metrology (VM) development and utilization for control system

Metrology used for monitoring wafers to update control models. Effective metrology systems can help achieve precision during CVD Process.



Reliance on metrology tools can

- Extend processing times
- Raising costs
- Trade-off between cost and quality

Virtual metrology (VM) optimizes control in the CVD process, striking a balance between cost and quality

- Traditional VM uses process chamber data, including fault detection and classification (FDC), to predict metrology results
- VM seamlessly integrates predictions into real-time, high-volume manufacturing control systems, especially in run-to-run (R2R) settings

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Digital Twin Product: Understanding impact of product design

Visualizing impact of product design features on the model using SHAP analysis

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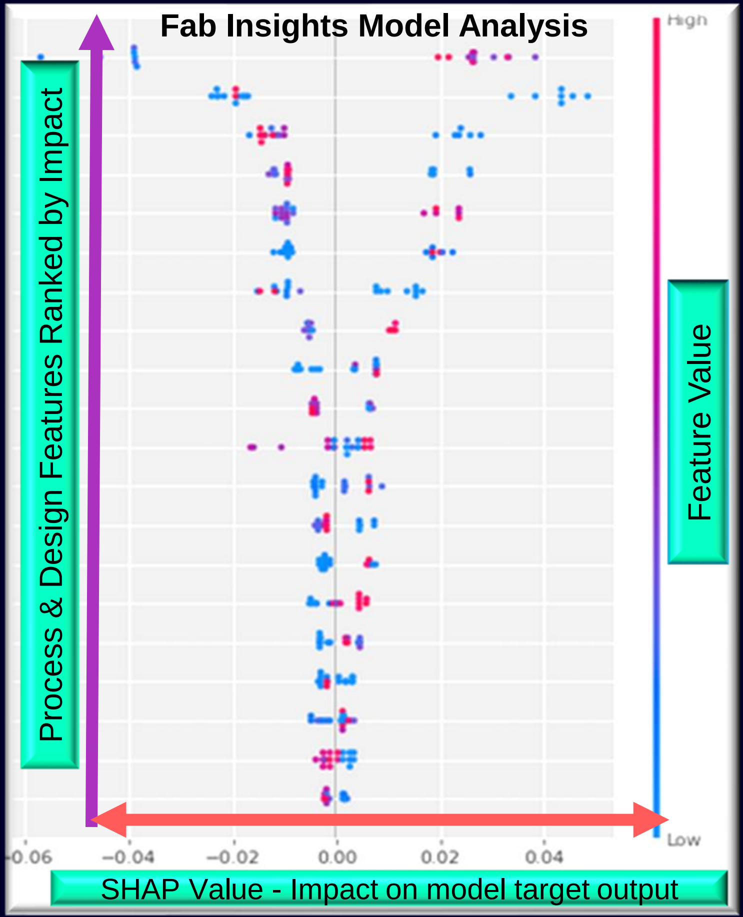
Process Characterization

Process

Metrology



Design, simulate, and verify products digitally

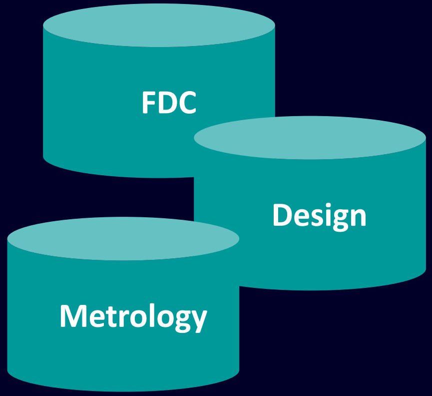
Leverage physical design understanding to capture sensitive product characteristics

- VM can utilize specific design features extracted for better predictions across various layouts and technologies

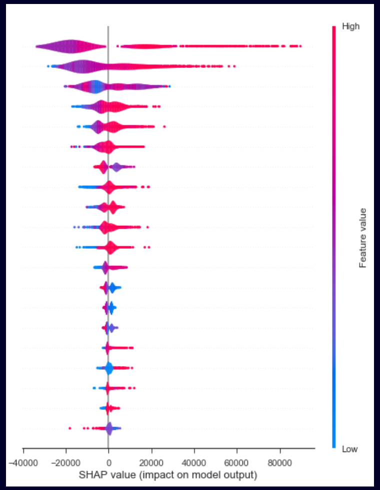
  Extended VM model for enhancing control performance especially high product mix manufacturing

Calibre® Fab Insights - VM model overview

Training dataset

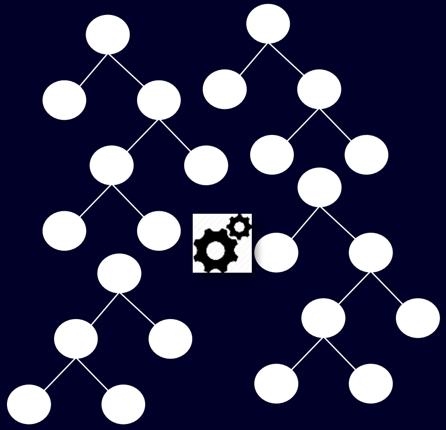


Feature selection



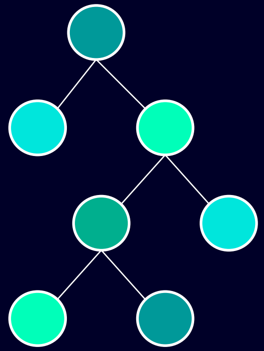
Shap analysis used to rank and select features (top N) for training to prevent model from overfitting

Ensemble Model

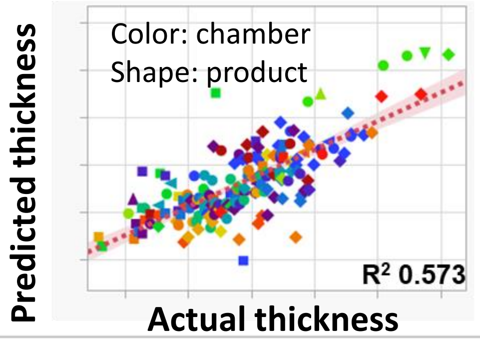
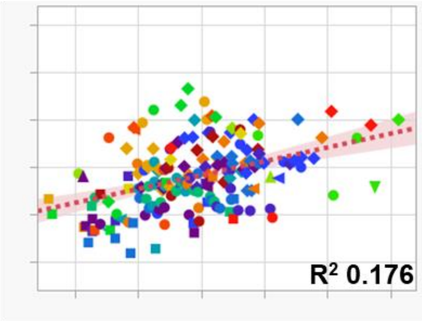
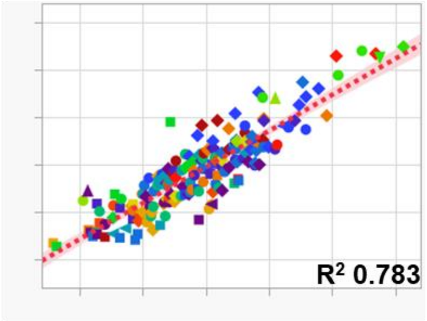
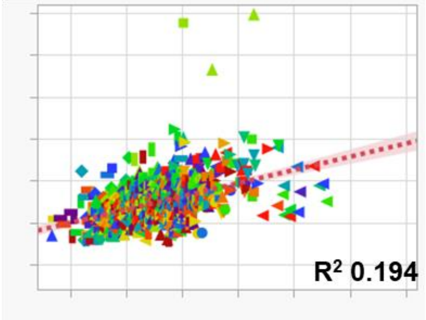
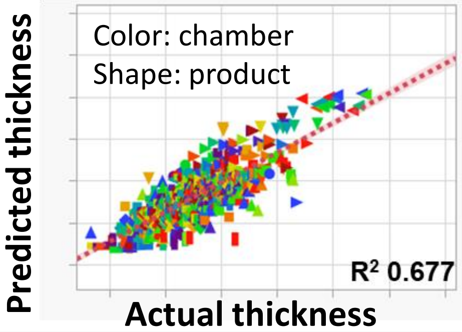
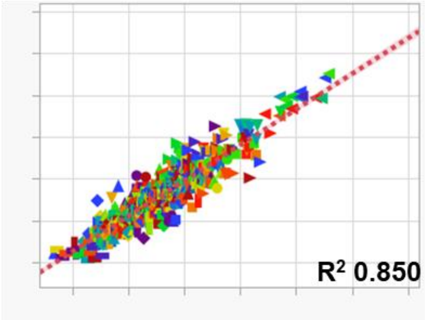
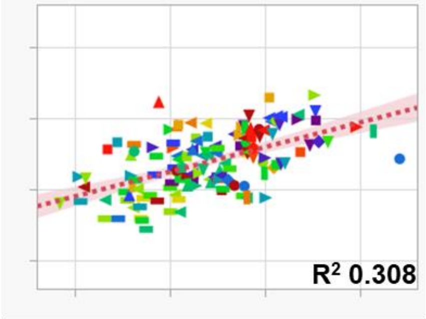
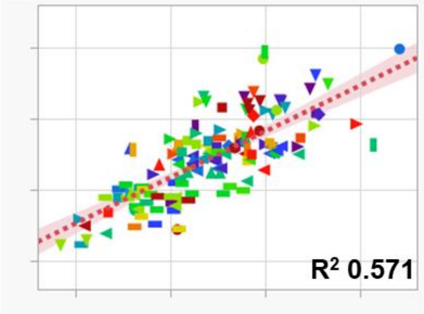
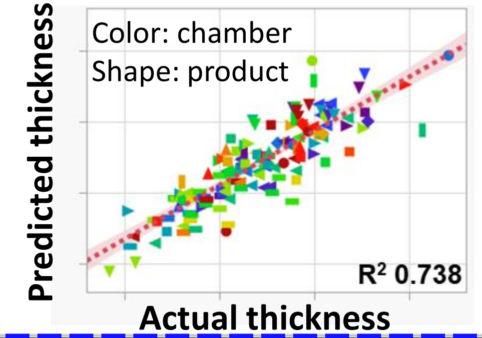


Ensemble model based on LightGBM
(Based on Decision tree algorithms)
Focus on performance and scalability
OPTUNA's hyperparameter optimization

Final Virtual Metrology Model



VM modeling with and without incorporating design features and FDC data

Tech node	Without Design features	Without FDC	With Design features & FDC
XX nm			
YY nm			
ZZ nm			

Data for modeling
- Tech nodes: 3
- Product: 70
- Chambers: 15
  5 equipment units
  Each with 3 chambers

VM modeling: -
Training: 70% - Testing: 30%

※ Specific thickness targets for each technology node have been omitted due to confidentiality concerns

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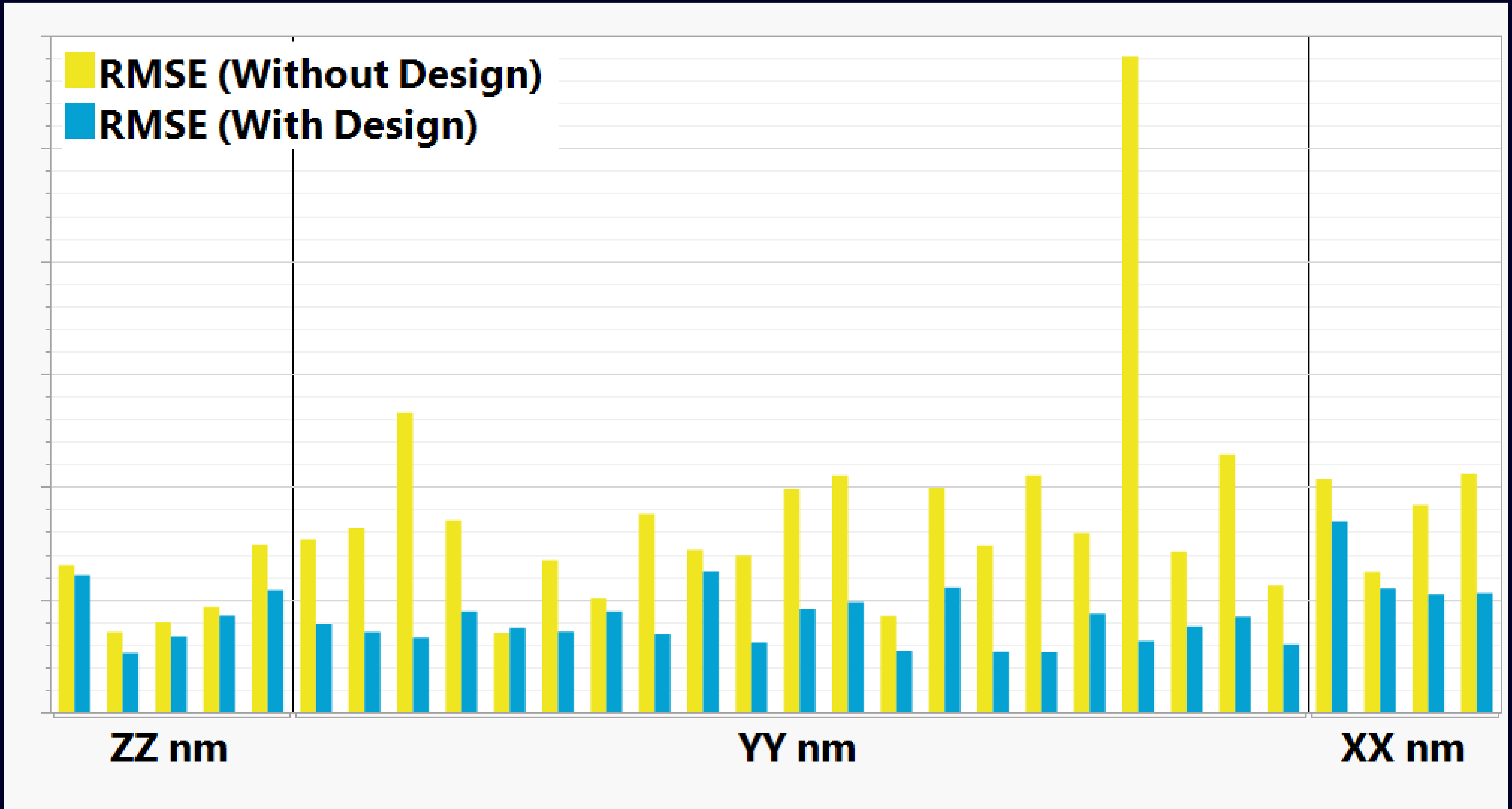
VM modeling with and without incorporating design features by product



VM model incorporates design features consistently exhibits significantly better performance

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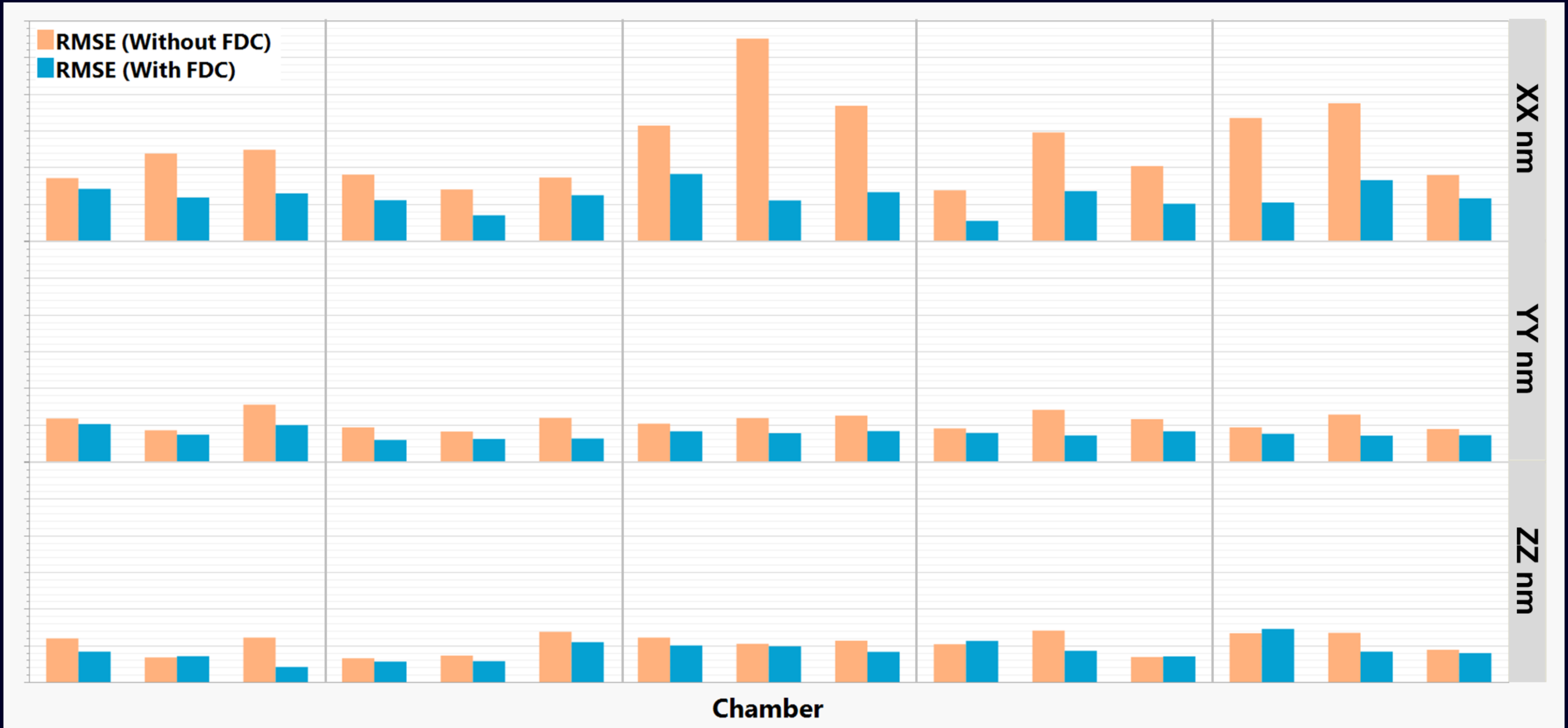
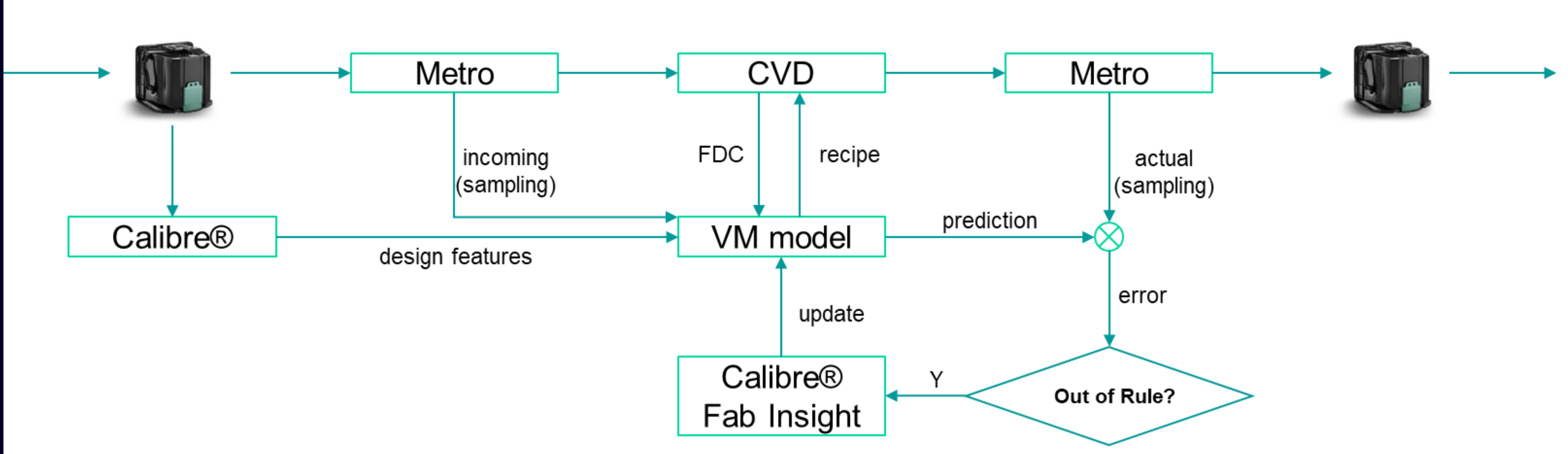
VM modeling with and without incorporating FDC data by chamber



VM model incorporates FDC data exhibits better performance across the majority of segmented cases

APC system: R2R control with VM model



Advanced process control (APC) system, utilizing the VM model for run-to-run (R2R) control

- CVD process recipe is derived from the VM model, which integrates design features, fault detection and classification (FDC), and incoming measurements to achieve the target thickness
- After post-measurement, the prediction error calculated by comparing the predicted thickness with the actual thickness after processing
- If the error surpasses predefined rules, such as specifications or a 20% threshold, the VM model is triggered to update, incorporating additional data within a predefined time frame

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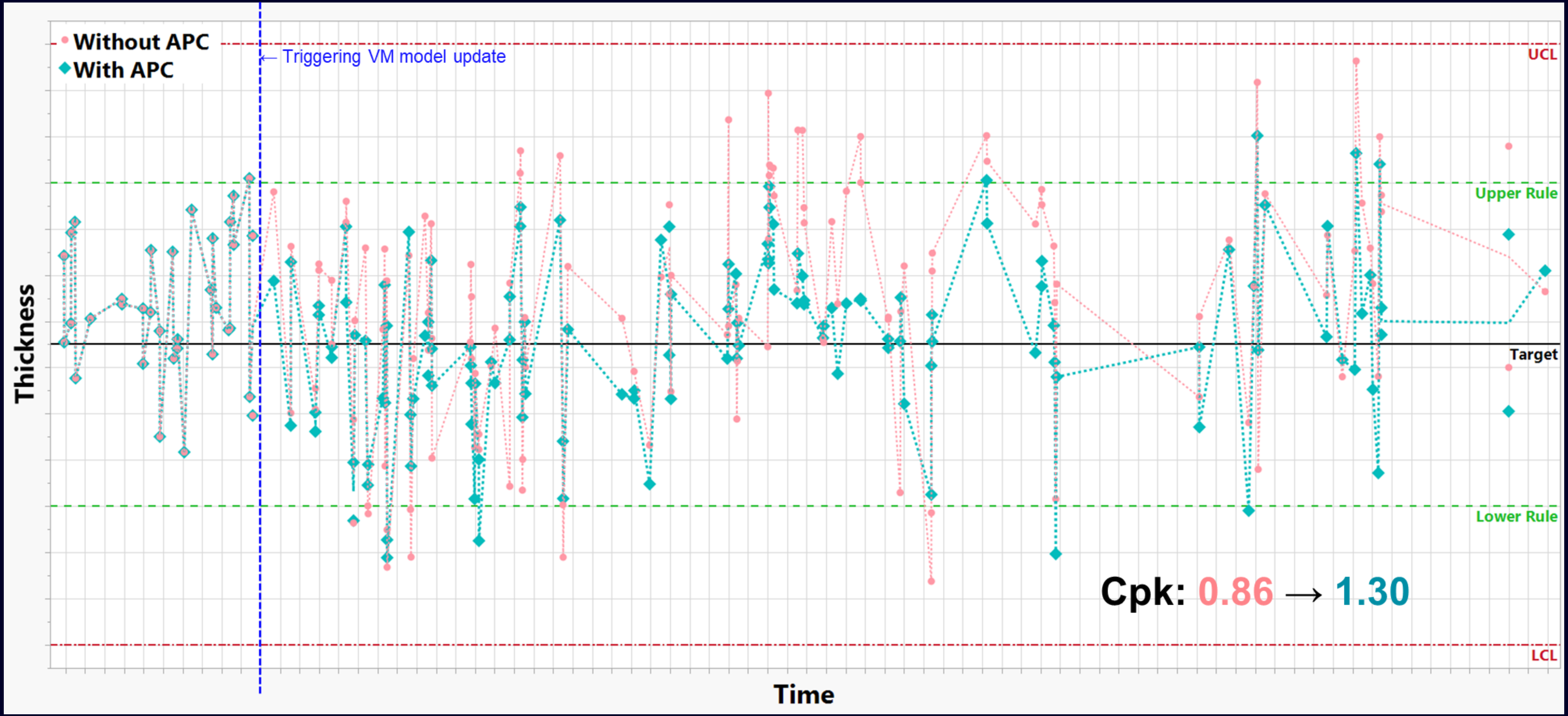
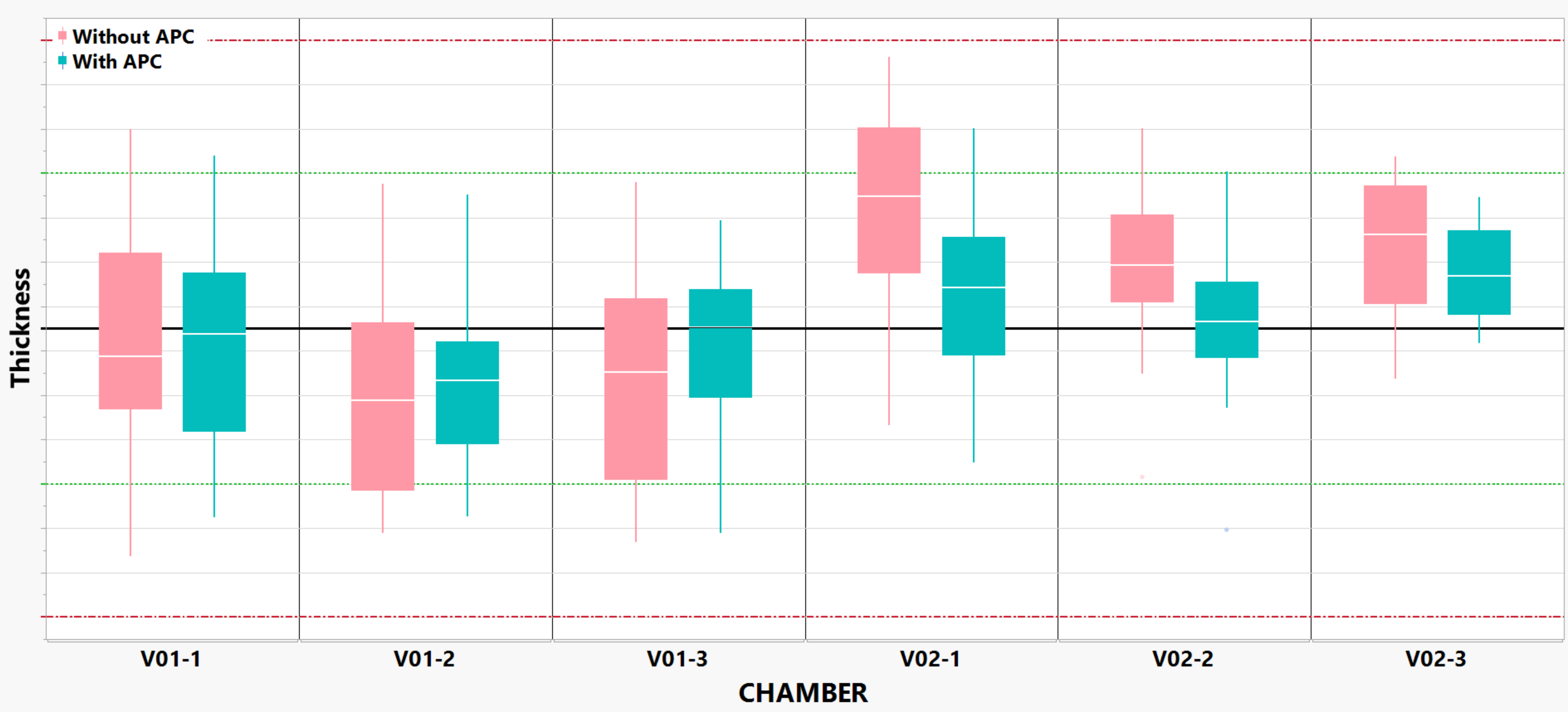
Control simulation result of APC system



The system effectively mitigates variations in the R2R deposition film thickness and accurately adjusts the thickness to the desired target value

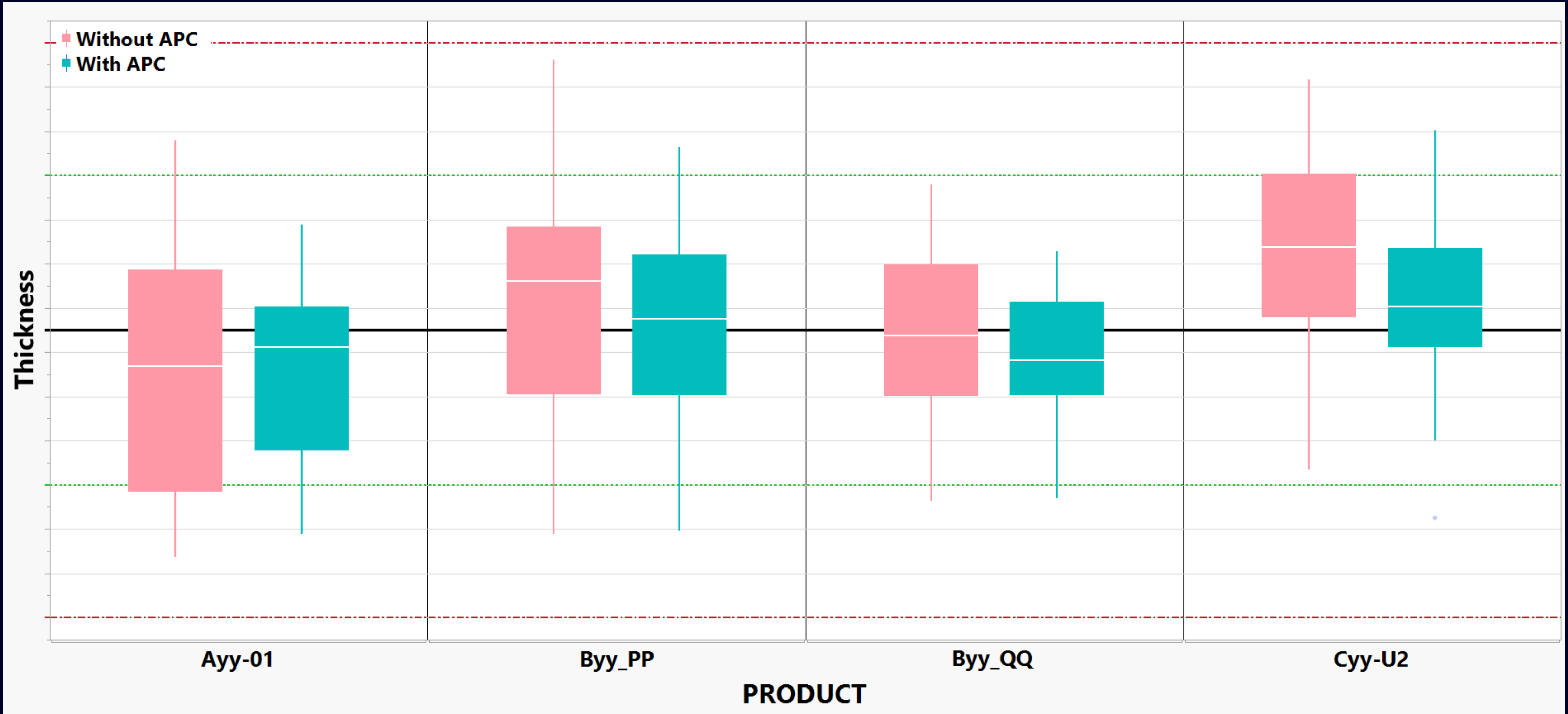
※ Due to the limited size of the dataset, the control simulation primarily focuses on a single technology node (YY nm)

Control simulation result of APC system by chamber



Improvement in chamber-to-chamber thickness variation with the implementation of the APC system

Control simulation result of APC system by product



Improvement in product-to-product thickness variation with the implementation of the APC system

Conclusion

- Growing demand for custom-designed products from diverse customers requires increased manufacturing flexibility and frequent NPI
- ML based VM approach is proposed as an effective process control solution for high product mix manufacturing
  - Formulate VM model with incorporating design features and FDC data
  - Employ most advanced and optimized ML methodology to build VM model
  - Integrate VM model to APC system for R2R control
- Simulation results confirm the effectiveness of integrating the APC system with the VM model into the CVD process, particularly within a high product mix foundry fab
- Further R&D being done to enhance the solution to better align with the demands and requirements of foundry customers

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