Optimizing High-Product-Mix Manufacturing with Advanced Process Control through Machine Learning-Based Virtual Metrology

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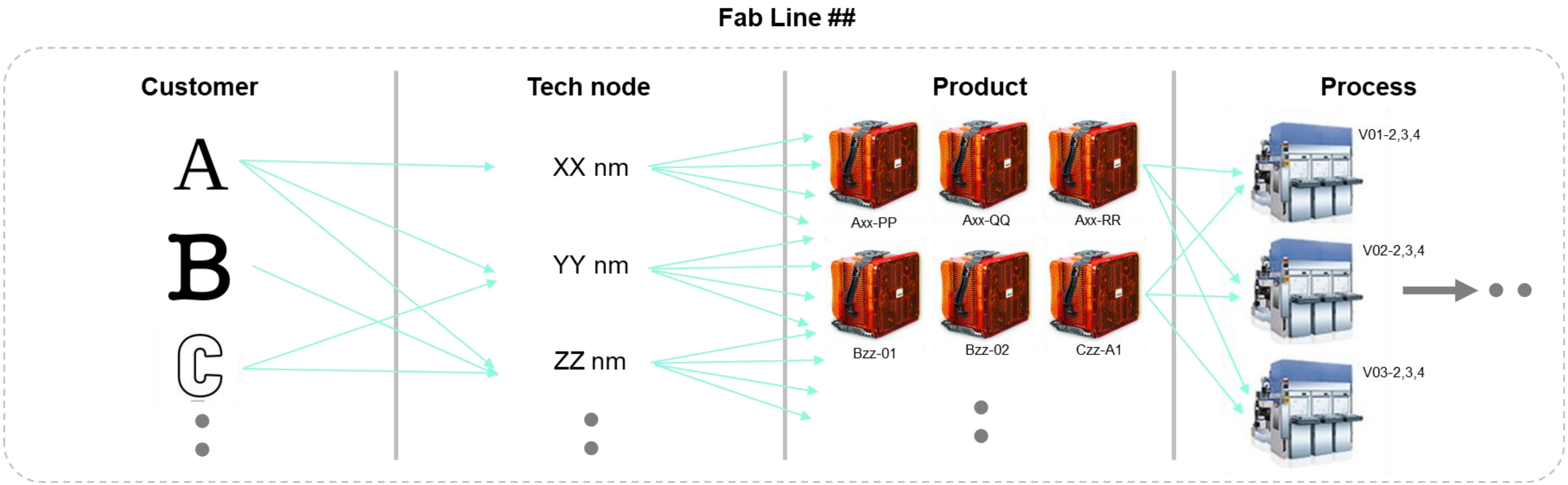
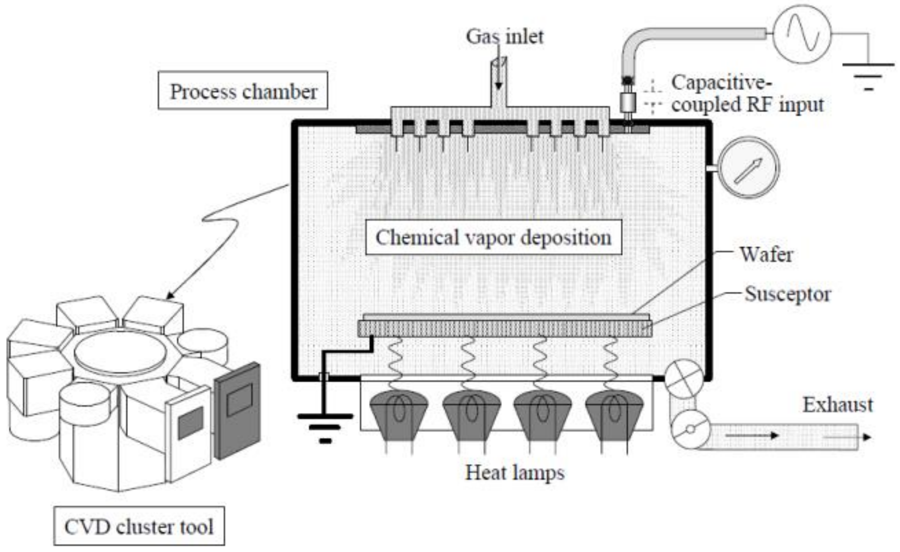
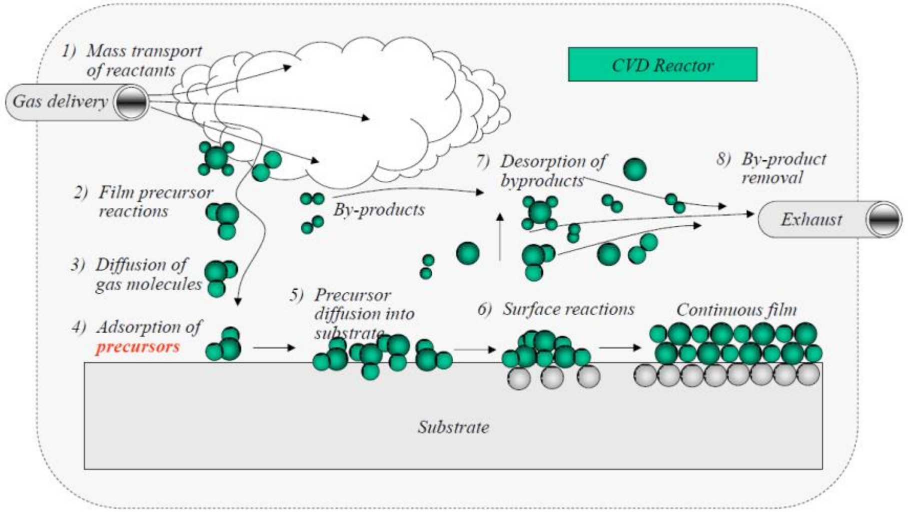
Background: High product mix manufacturing in semiconductor foundry

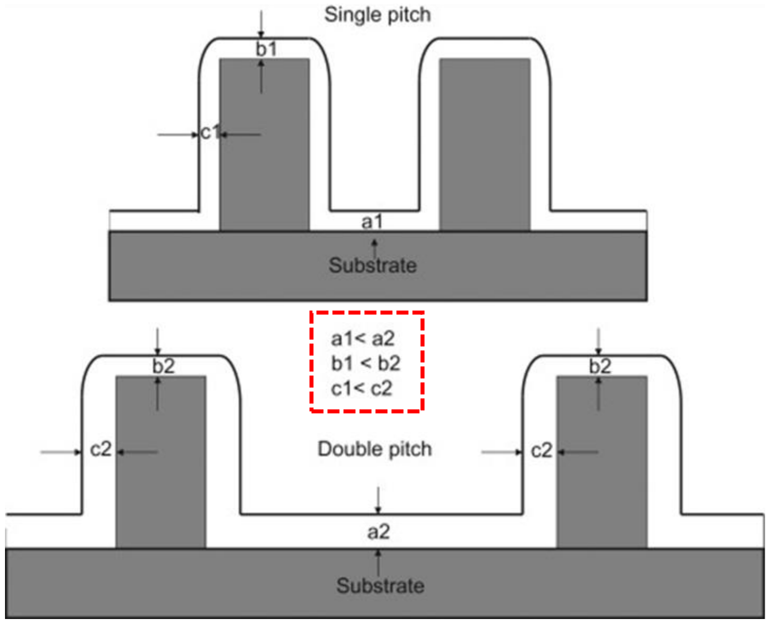


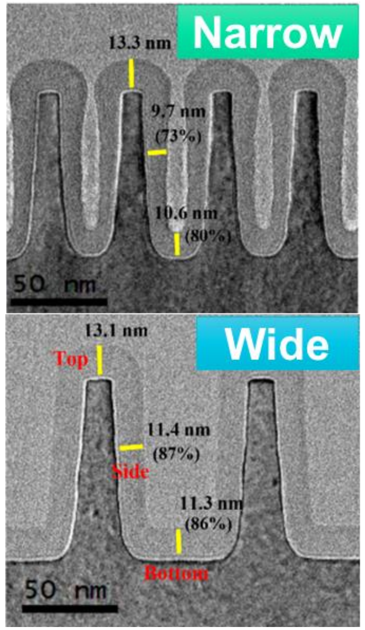
- Semiconductor foundry industry has evolved significantly, emphasizing high product mix manufacturing
- Growing demand for **custom-designed products** from diverse customers requires increased manufacturing flexibility
- Managing multiple products in a single facility involves coordination of various chambers and processes, leading to complex operations
- High product mix manufacturing challenges can result in reduced yields and higher costs, necessitating the development of effective strategies

Application: Chemical vapor deposition (CVD)



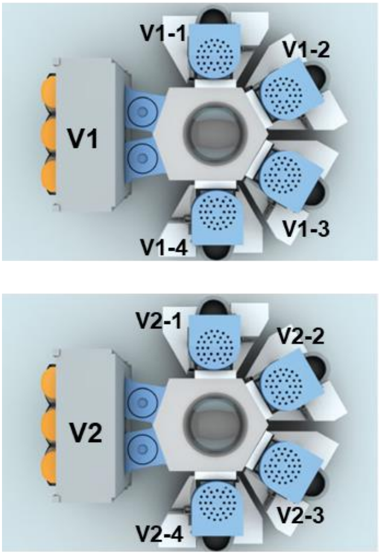


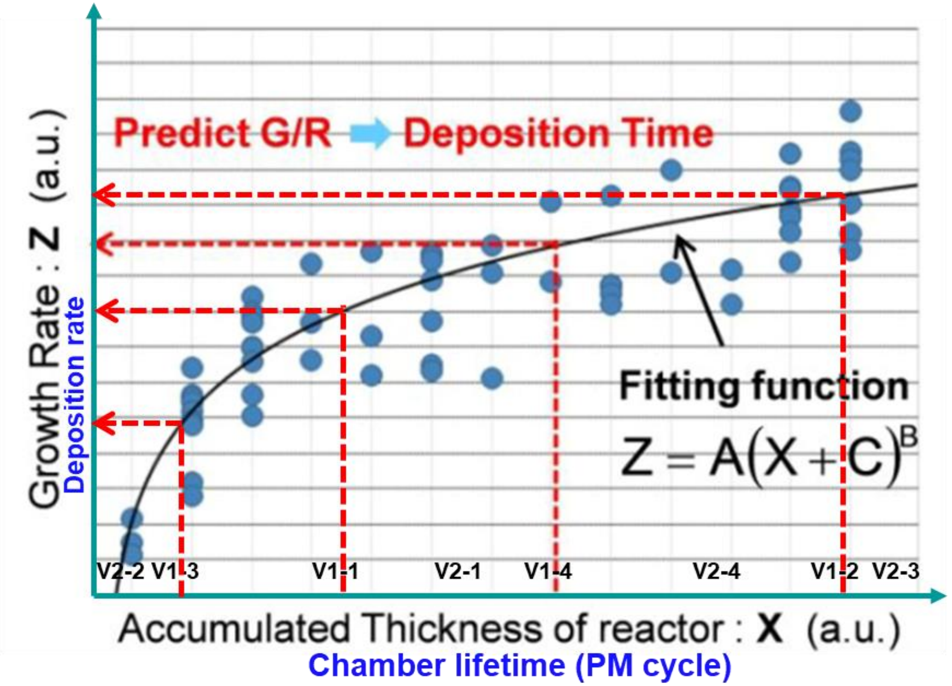


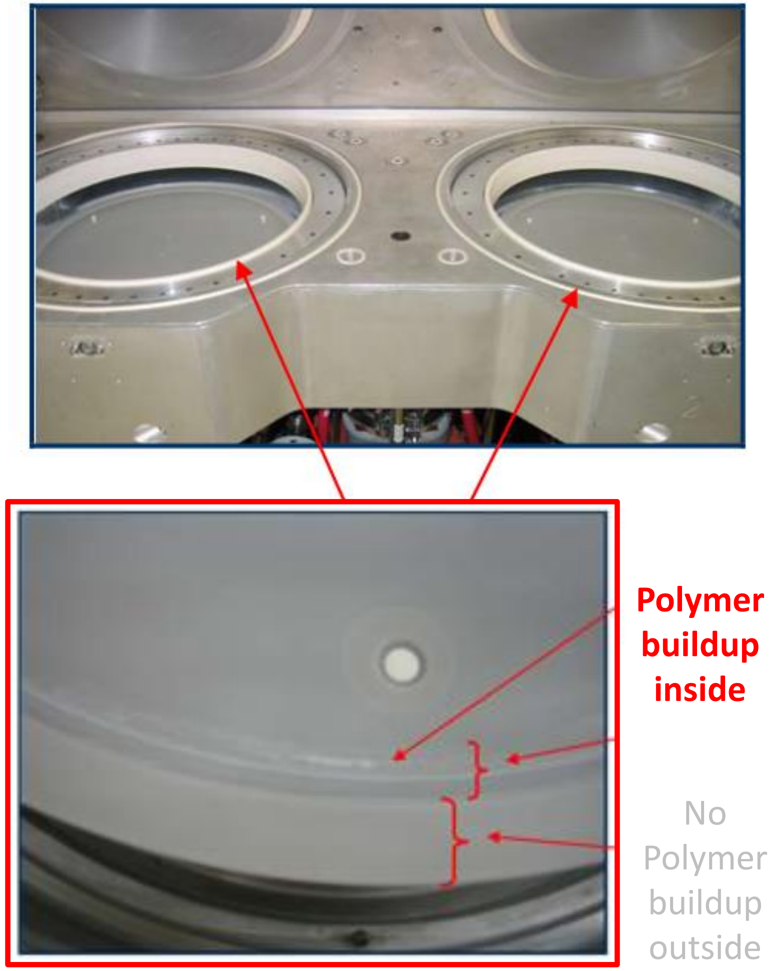


- Chemical vapor deposition (CVD) is one of critical processes in semiconductor manufacturing
- CVD also faces challenges related to high product mix including deposition thickness variations due to
  - Device layout design
  - Chamber condition drift
- Various design features can influence film thickness, affecting key transistor parameters like threshold voltage and overlap capacitance, ultimately impacting yield

Application: Chemical vapor deposition (CVD)

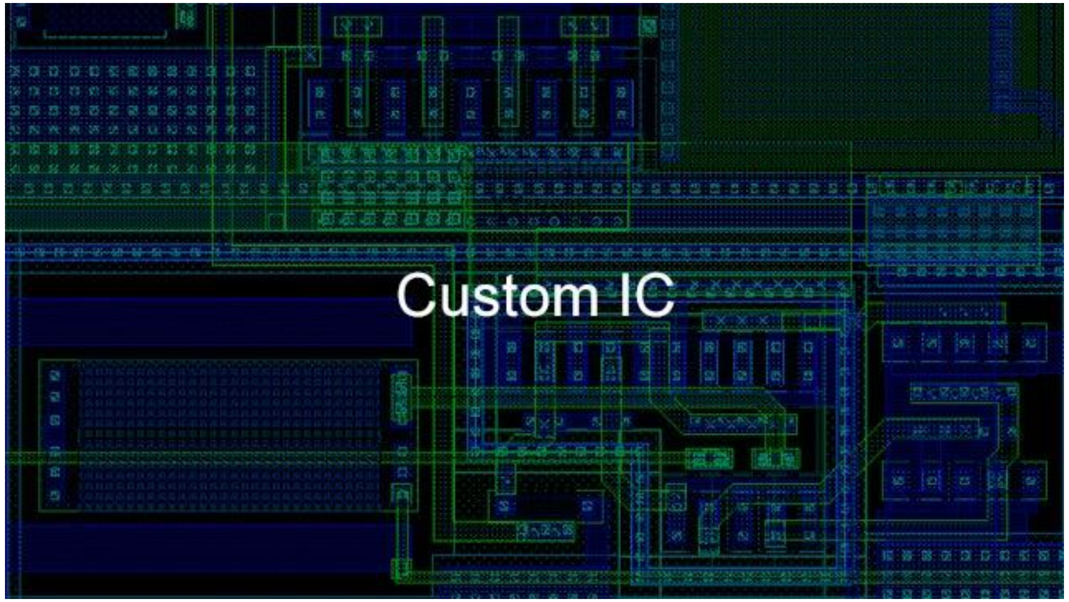


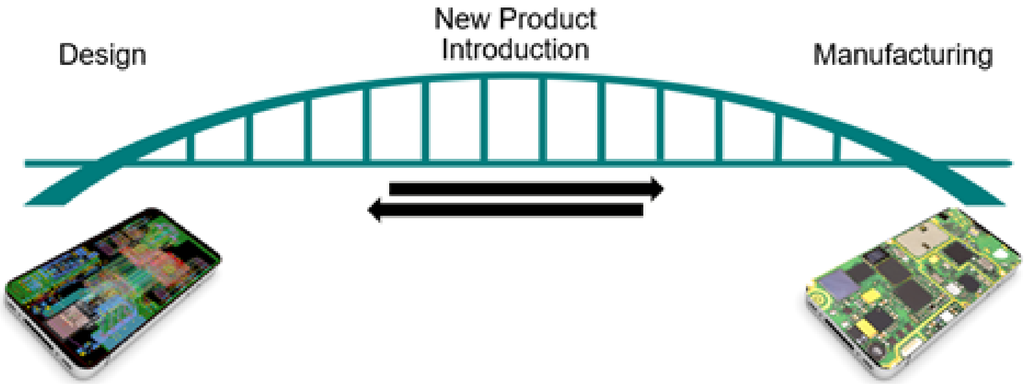




- CVD process variability (the drift in CVD film growth rate) during preventive maintenance (PM) cycles and chamber-to-chamber variations PM cycles: the entire process cycle between PMs
  - Caused by decreasing surface area and reactive gas consumption within the CVD chamber because of accumulated film thickness
- Insufficient solutions for managing PM cycle time-series variation and achieving chamber matching can result in reduced fab line efficiency and throughput loss

New product introduction (NPI)





- High mix production often requires frequent **new product introductions (NPI)**, which can be time-consuming if not optimized
- The complexity of high product mix manufacturing poses challenges for traditional run-to-run (R2R) advanced process control (APC) methods

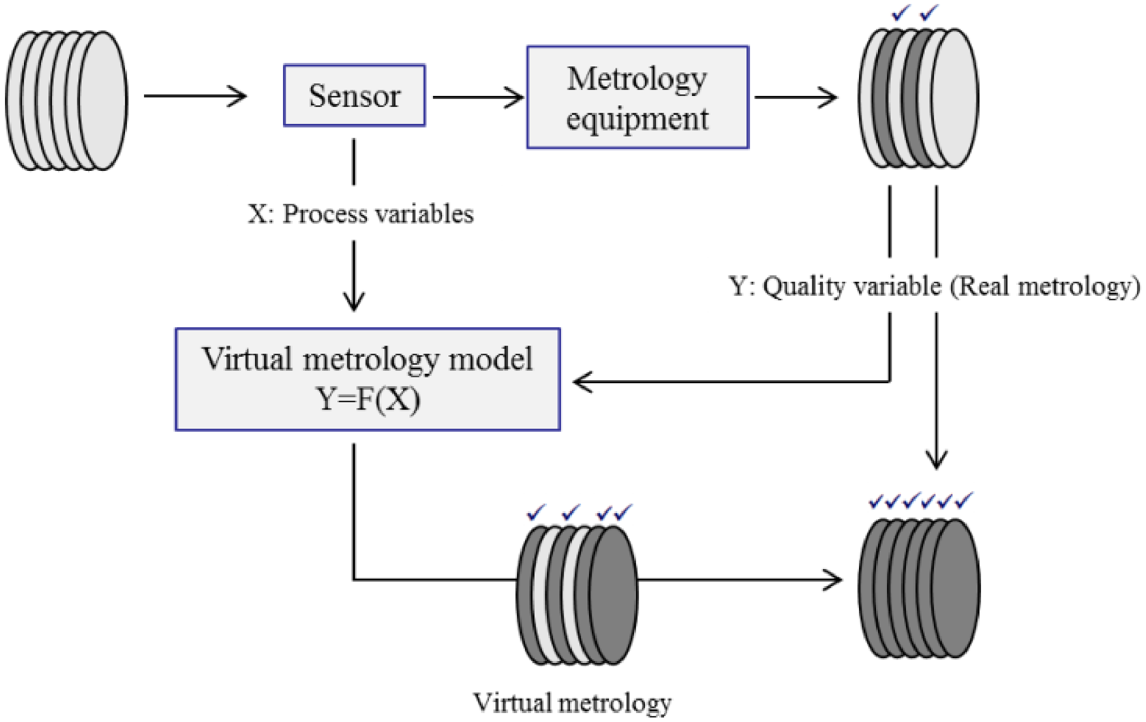
→ Machine learning (ML) based virtual metrology (VM) approach is proposed as an effective process control solution for high product mix manufacturing

Virtual metrology (VM) development and utilization for control system

- Achieving precision in CVD processes requires effective metrology systems for monitoring wafers and updating control models
- But increased reliance on metrology tools can extend processing times and raise costs, creating a trade-off between cost and quality

→ To address this challenge, the concept of **virtual metrology (VM)** has been developed

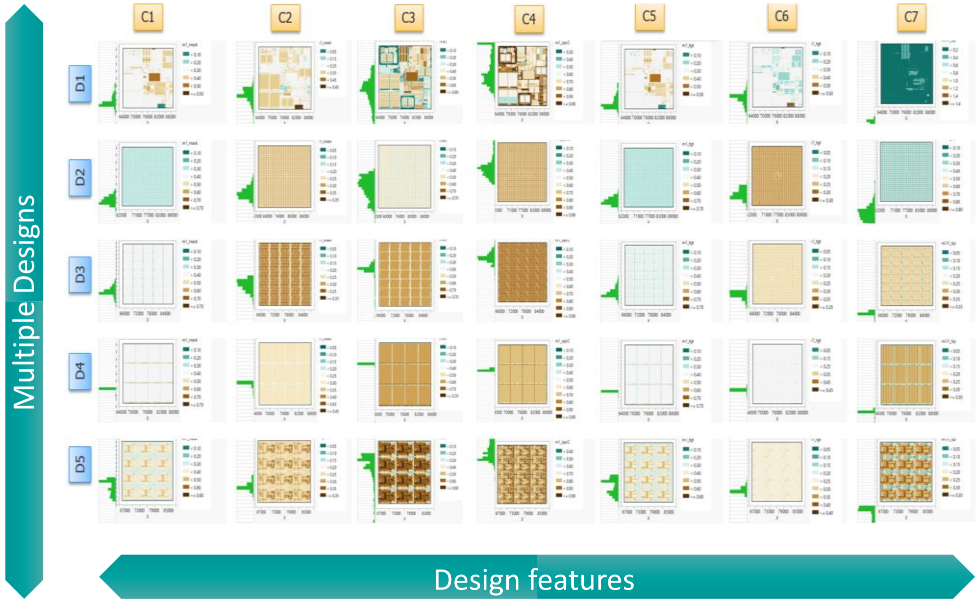
(VM optimizes control in the CVD process, striking a balance between cost and quality, making it a valuable solution)



- 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

Calibre® design feature extraction

Design feature extraction



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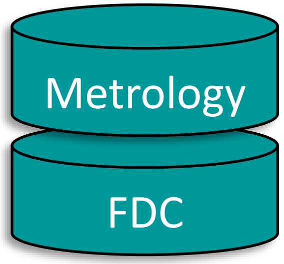
Traditional VM model



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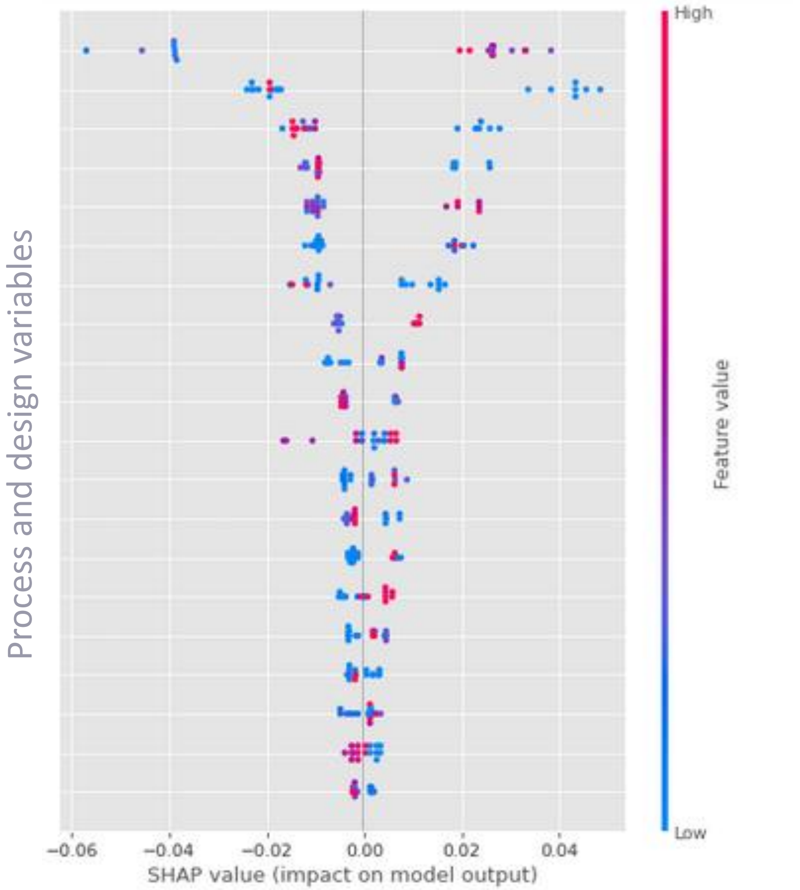
Extended VM model



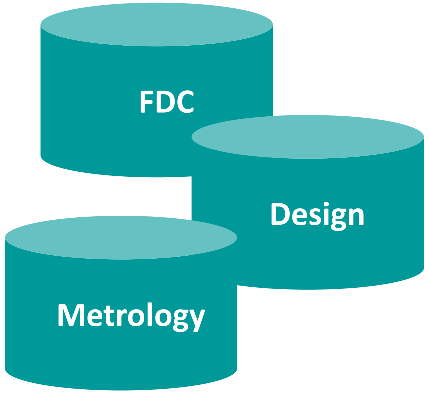
- VM can utilize specific design features extracted for better predictions across various layouts and technologies

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

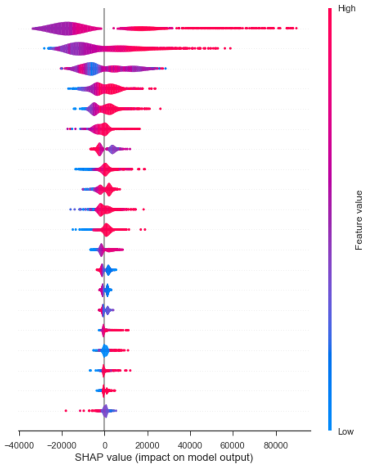
From S.Schuler et al, "Virtual metrology: how to build the bridge between the different data sources", Proc. SPIE 11611, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXV, 2021

Calibre® Fab Insight VM modeling overview

Training dataset

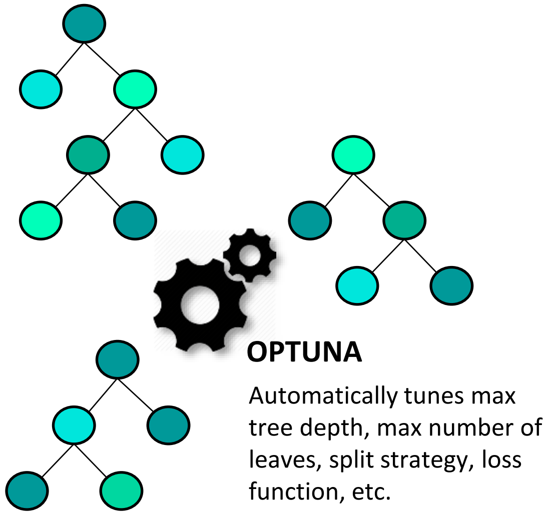


Feature selection



Based on Shapley analysis, select subset of input features (top N important features) for training to prevent model from overfitting

LightGBM training

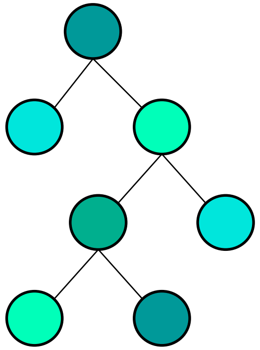


OPTUNA

Automatically tunes max tree depth, max number of leaves, split strategy, loss function, etc.

Using OPTUNA's hyperparameter optimization, train LightGBM model based on best set of hyperparameters.

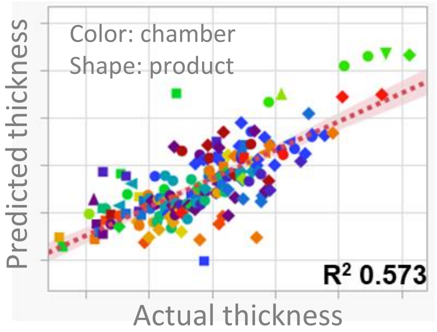
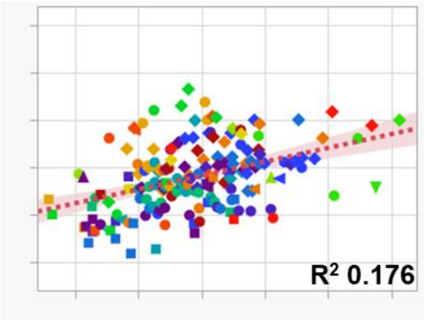
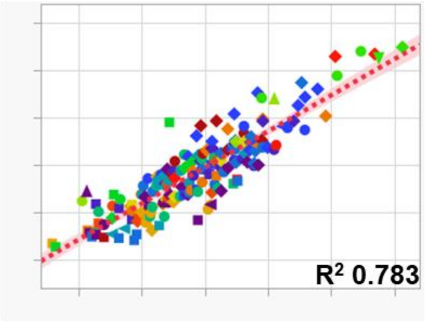
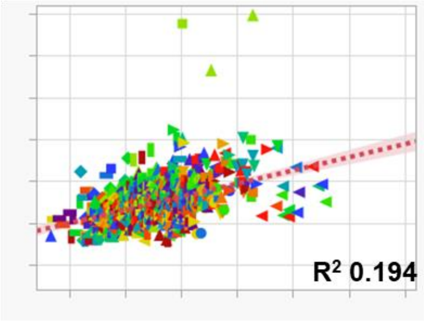
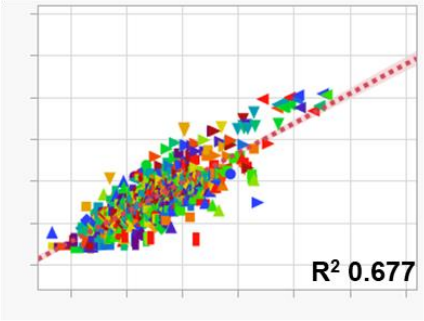
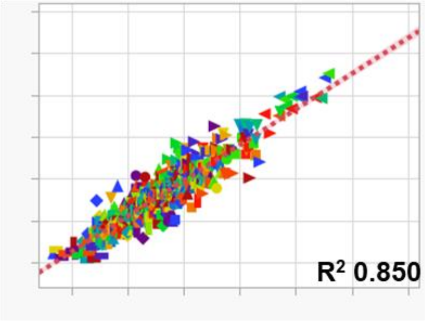
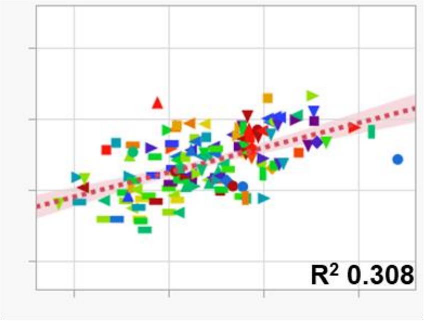
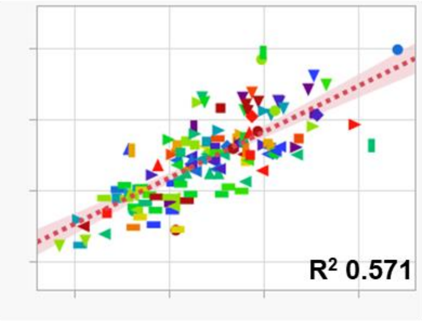
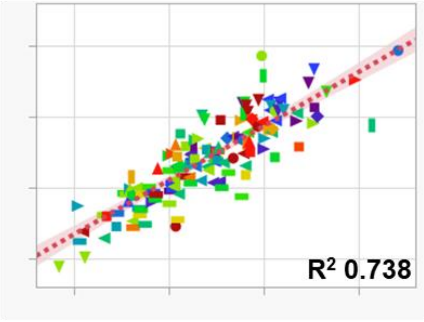
Final VM model



VM modeling with and without incorporating design features and FDC data

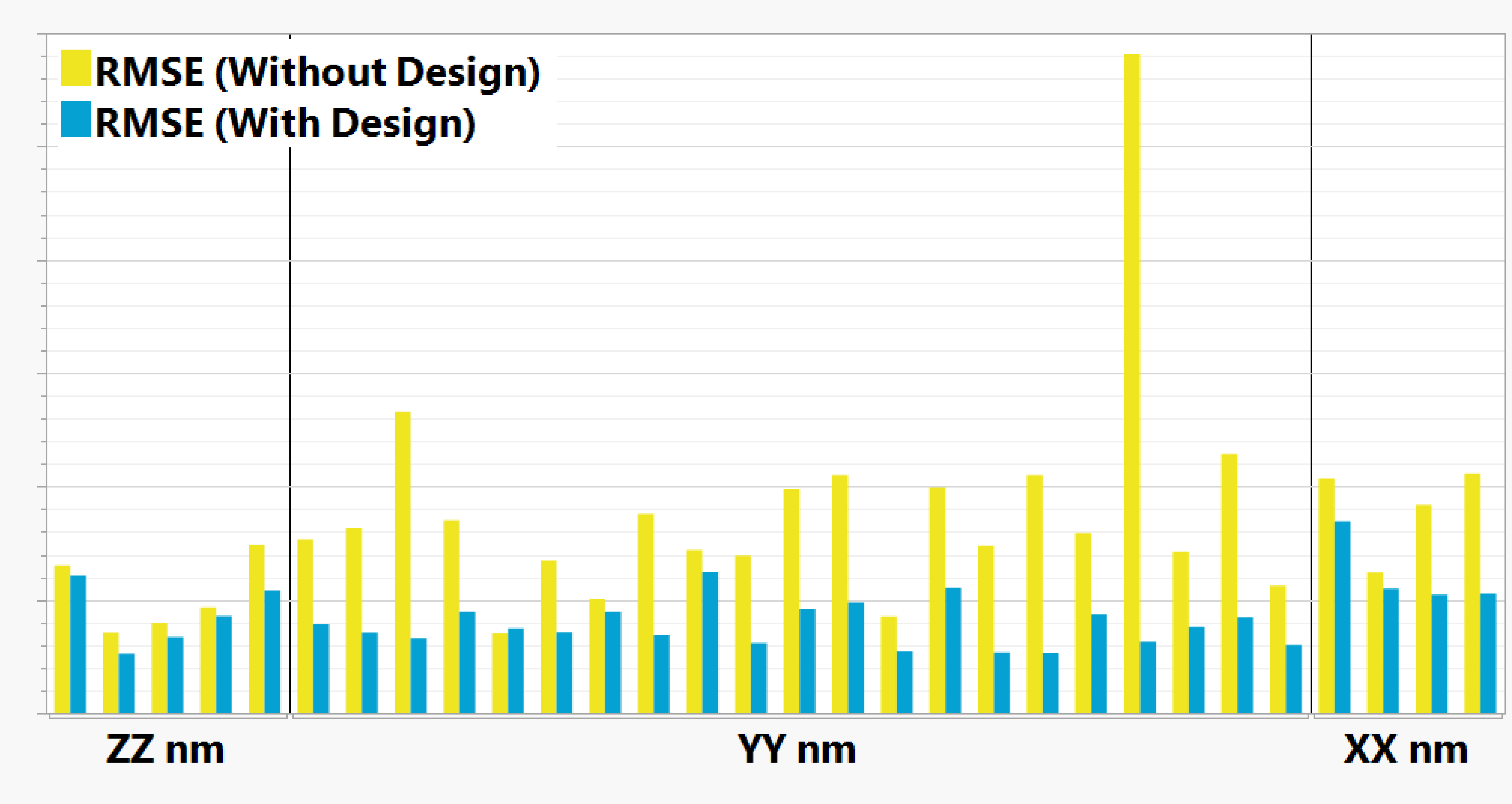
※ Dataset for modeling
(HVM foundry fab)
- Tech node: 3
- Product: 70
- Chambers: 15
(with 5 equipment units, each equipped with 3 chambers)

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

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

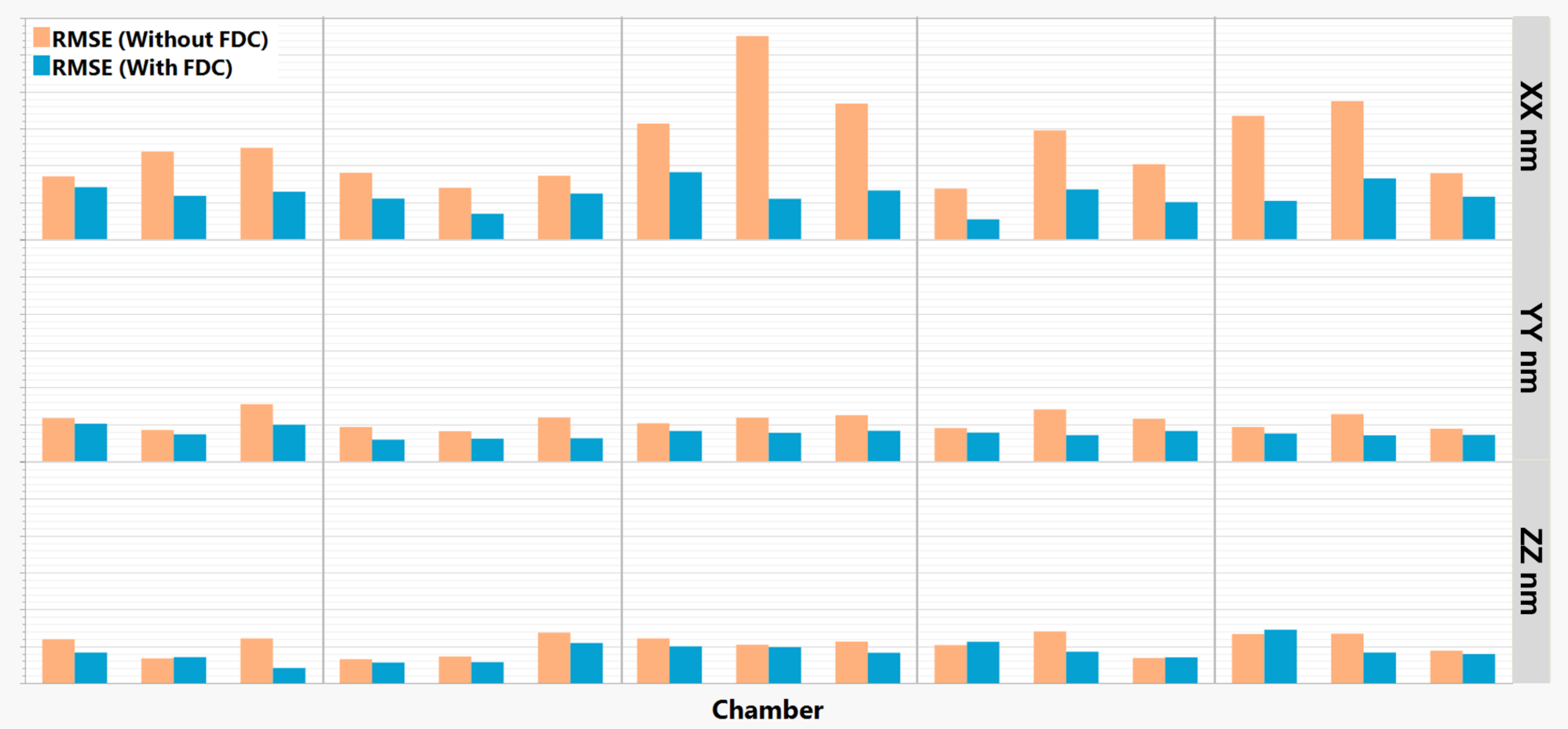
※ Specific thickness targets for each technology node have been omitted due to confidentiality concerns

VM modeling with and without incorporating design features by product



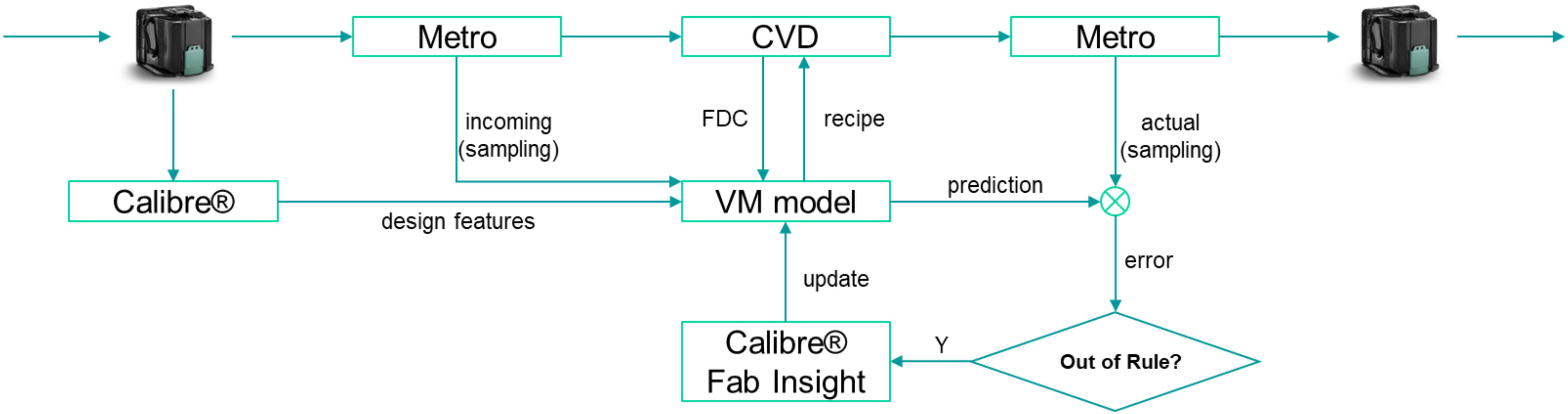
- VM model incorporates design features consistently exhibits significantly better performance

VM modeling with and without incorporating FDC data by chamber



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

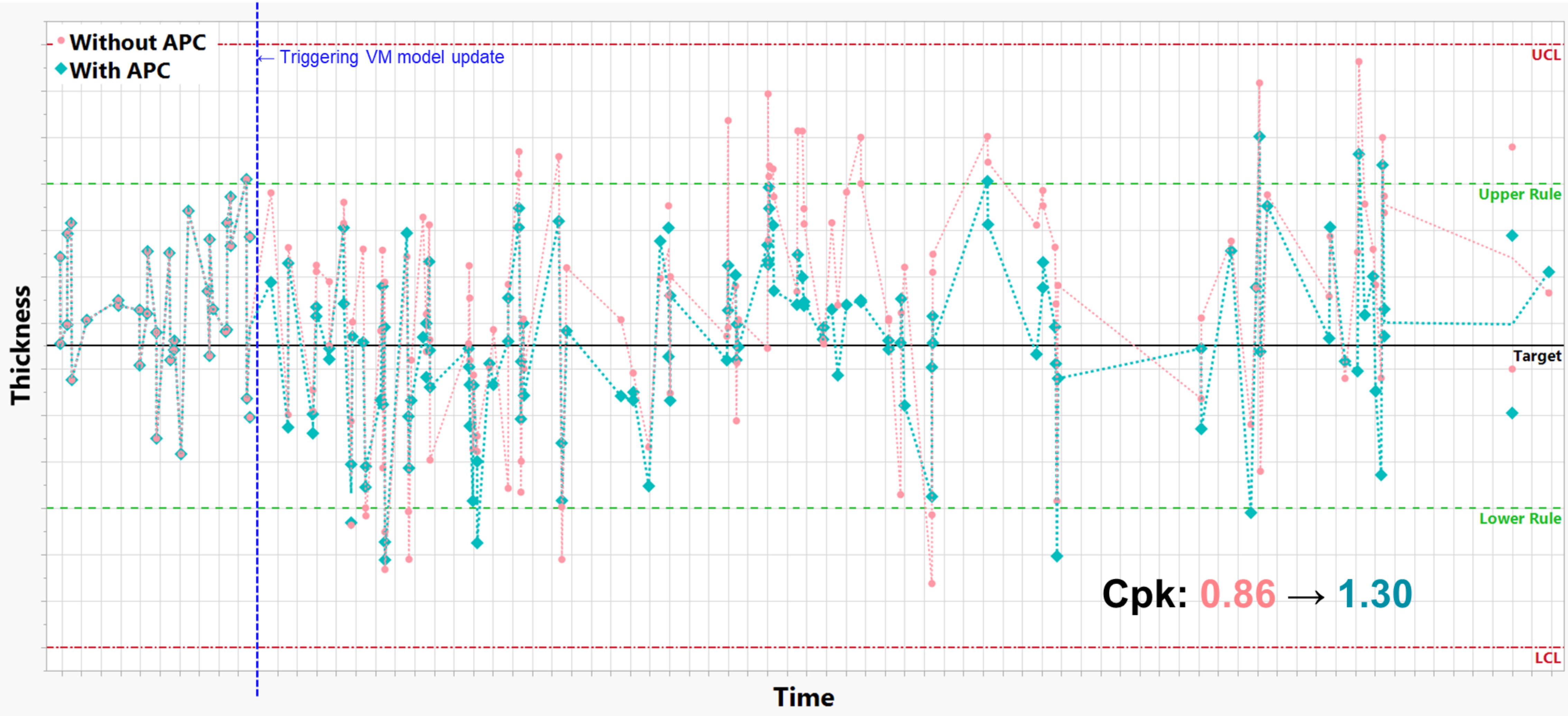
APC system: R2R control with VM model



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

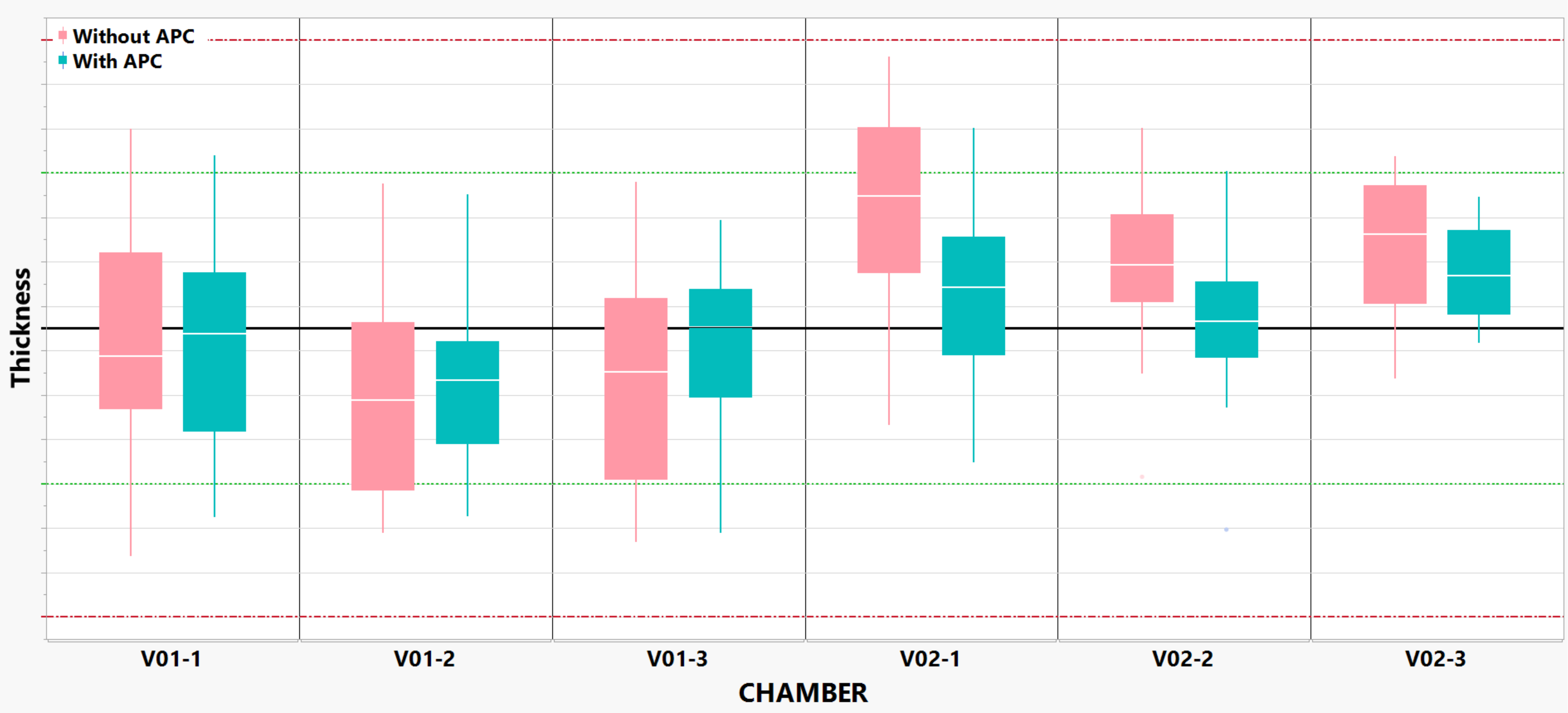
Control simulation result of APC system



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

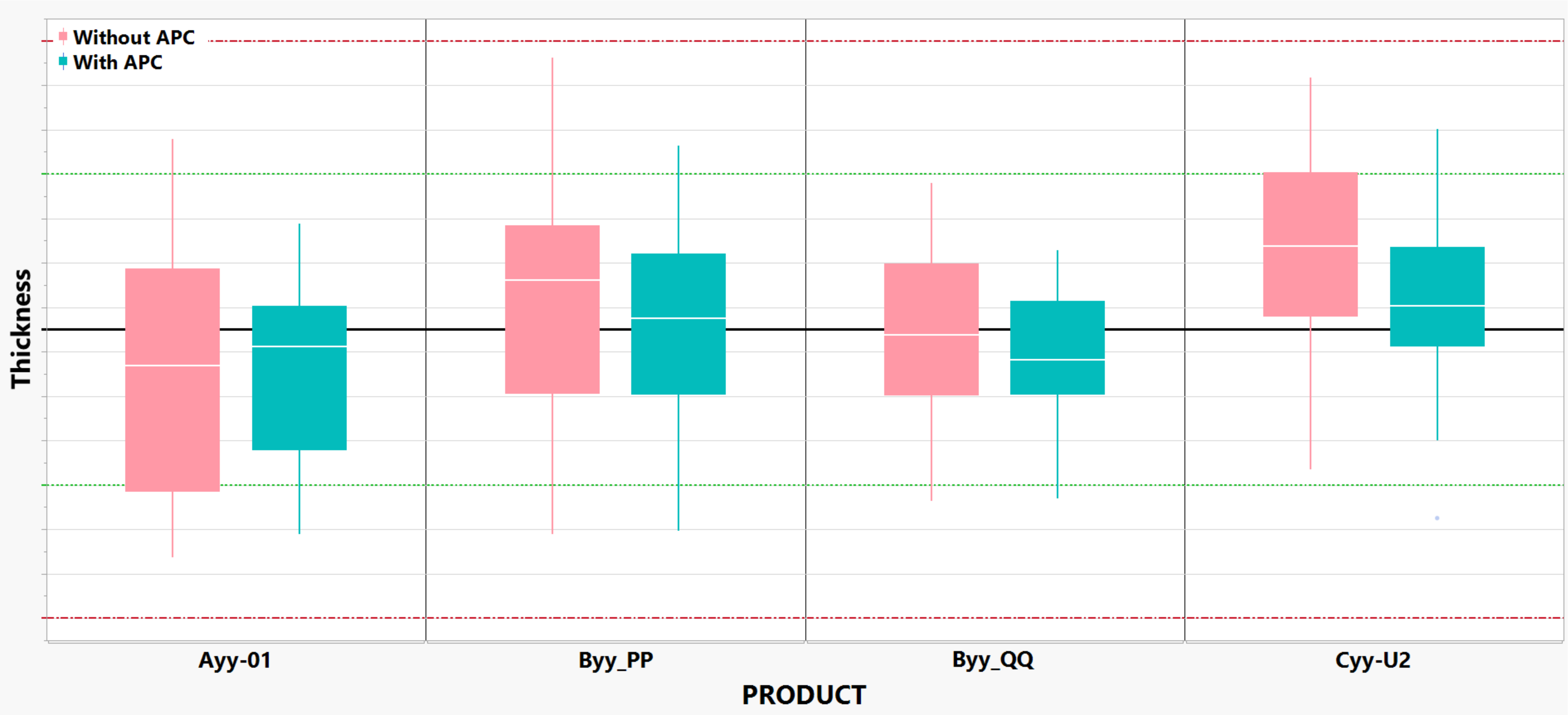
※ Due to the limited size of the dataset, the control simulation primarily focuses on a single technology node (YY nm)

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 remarkable effectiveness of integrating the APC system with the VM model into the CVD process, particularly within a high product mix foundry fab
- Further research and development is actively conducted to enhance the solution and better align it with the demands and requirements of foundry customers

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