# How AI and ML can save $38bn for semiconductor manufacturers

**Atonarp's CEO Prakash Murthy explains how artificial intelligence and machine learning can be used for semiconductor manufacturing equipment and process co-optimization.**

Today, increasing throughput is the number-one priority for semiconductor fabs, as they work to overcome the challenges of the global chip shortage.

Looking beyond throughput, there are significant opportunities for long-term cost savings from optimizing, simplifying or removing processing steps. We call this approach EPCO – Equipment and Process Co-Optimization. It is a combination of good engineering and applying data-driven machine learning (ML) to the manufacturing process and equipment.

A 2021 paper by McKinsey argued that semiconductor manufacturing optimization, using artificial intelligence (AI) and machine learning (ML), could save $38bn, through improved yields and increased throughput.

Real-time, accurate and actionable data is vital to achieving this potential. McKinsey highlighted that the single most important point to address is the real-time, run-to-run adjustment of tool parameters, using live in-situ tool sensor data. This enables AI/ML algorithms to optimize the nonlinear relationship between process operations.

## The problem: increasing process complexity

Today's high-volume, advanced logic processes — including Fin-FET and gate-all-around (GAA) transistors, as well as high-aspect-ratio etch techniques used in 3D-NAND memories — require a new approach to the established standards based on Intel's CopySmartly! methodology.

As process nodes have shrunk, new variables have emerged that affect process yield, and can cause deviations even on the exact same equipment. In Figure 1, shared in a study of machine learning for high-volume manufacturing metrology challenges, chamber-based effects on process critical dimensions (CD) can be clearly seen.

Some of these critical variables that can affect process performance include localized virtual vacuum leaks, subtle reaction gas partial pressure variations, wafer surface saturation due to changes in pumping performance, surface reactivity due to changing wafer temperature, chamber clean end-point, and chamber seasoning profile.

Additional challenges — inter-layer adhesion, 300mm wafer mechanical stresses, new atomic-level deposition

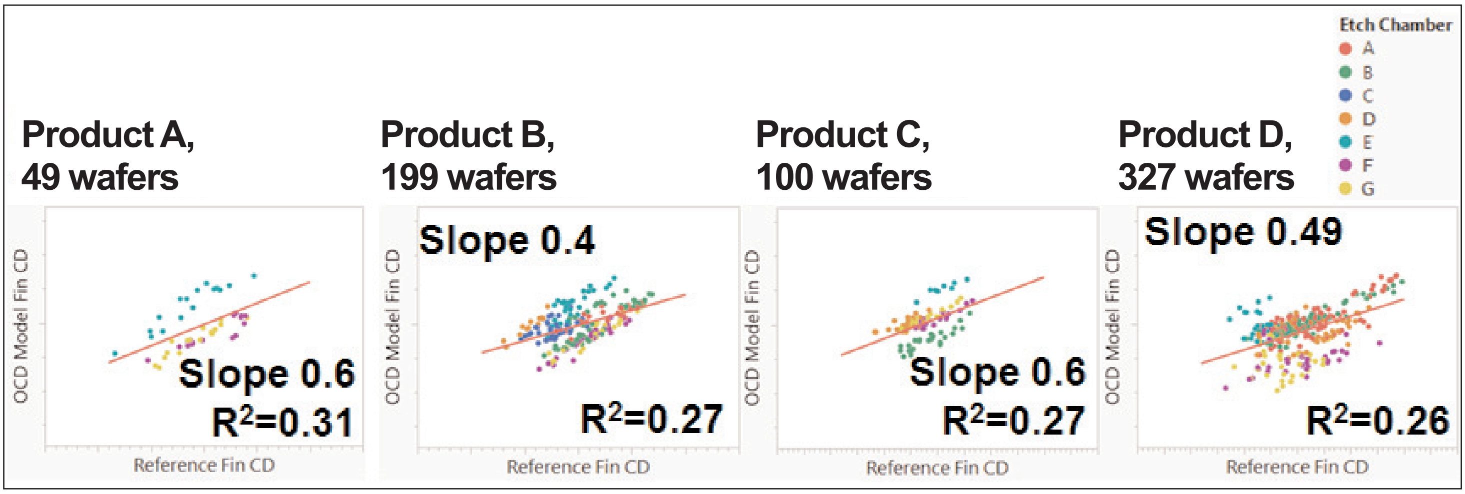

**Figure 1. Wafers of four different products from eight process chambers were evaluated above. Each chamber is represented by a different colored dot. Based on the colored dot clustering, some chambers demonstrate significant variation in CD values between wafers, clearly showing a chamber-related effect on the unit process.**

and etch chemistries, exotic low-resistance contact and fill metals, stringent cross-contamination protocols, and maximizing throughput — all require greater insight into how the process and equipment are interacting. Optimizing advanced processes such as these now demand higher-accuracy metrology tools and add a new layer of in-situ molecular complexity.

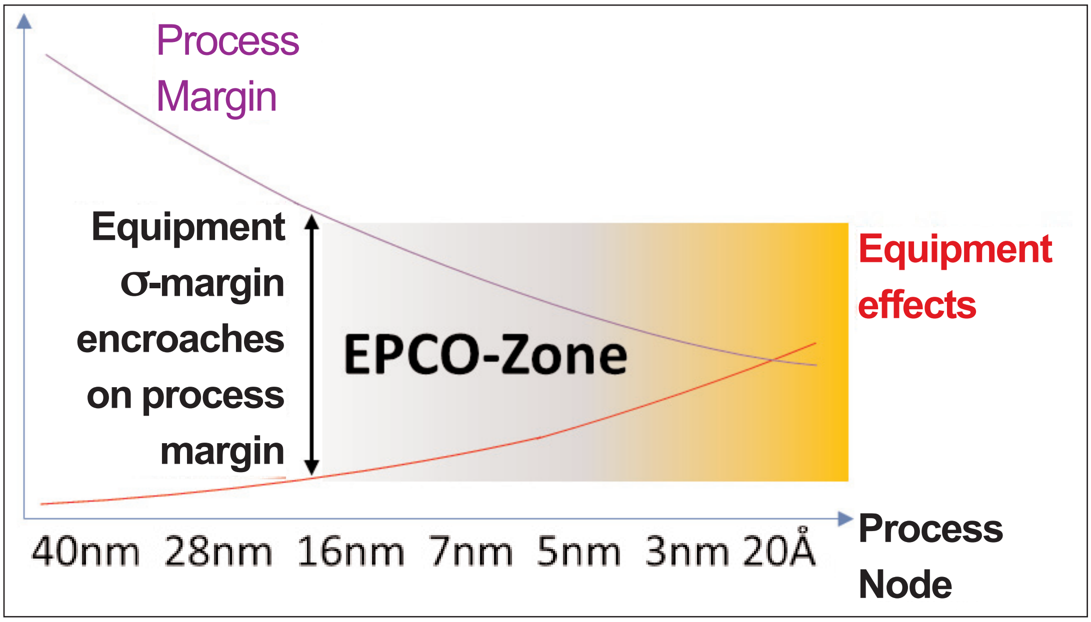

**Figure 2. As process geometries shrink, the effects of equipment variation on process margins drive the need for equipment process co-optimization within the EPCO Zone.**

## The solution

We can improve semiconductor metrology in two ways: either by capturing better data with more sensitive metrology tools or by extracting more value from existing data with new ML algorithms. Of course, if we can do both, we may well see the biggest improvements.

Either way, for successful AI/ML deployment, it's vital to have truly actionable real-time data. This enables appropriate models to be created and tested with data correlation between real-world and ML model inputs and outputs.

For example, statistical process controls can look at the real effects of chamber-to-chamber, machine-to-machine and run-to-run performance variances, even on the exact same equipment with the same recipe. Chamber cleaning and seasoning have material effects on chamber performance and drift in process results (process margins) between cleans, and PM (performance management) cycles are common. The difference is that, at mature nodes like 40nm, the differences run-to-run are small compared with the process control limits. However, as process geometries shrink, so do process control margins and the chamber and equipment effects (sigma variation) become increasingly critical (see Figure 2).

Process control has become a lot more complicated as critical dimensions have shrunk, along with the margin for error. This means that individual chamber management is becoming fundamental to ensuring high line-yield, with tight statistical process control.

This is what EPCO is all about: leveraging ML to jointly optimize equipment, chambers and processes in unison.

## In-situ, real-time data

There are three main types of data in the semiconductor process control environment:

1. in-situ data taken real-time on the process tool;
2. in-line data to measure results (usually immediately) after a processing step;
3. parametric or post-fab data (used for wafer line-yield and wafer ship acceptance criteria).

One of the fundamental changes needed to optimize fab management is the switch from in-line to in-situ metrology. Measurements taken after processing is completed are sequential in nature, costing throughput and cycle time, and lack the immediacy to affect meaningful real-time process change and optimization.

Measuring in-situ, real-time data at the molecular level gives true insight to how the process is set up and proceeding, offering rich, actionable and impactful data. Reactants, by-products and partial products can be identified and quantified, allowing for dynamic process control to ensure tight mean and standard deviation control for a given process module across run-to-run, chamber-to-chamber, tool-to-tool and even site-to-site.

Managing overall complex semiconductor process control and line-yield starts with having tight control on individual process steps and ensuring low variability and precise statistical process control (SPC). In-situ data from processing chambers can be used with machine learning to improve linearity and accuracy, and to achieve the control required.

## Molecular sensor

Atonarp has spent a lot of time understanding the fab and equipment manufacturers' problems and challenges. The result of those efforts is the Aston, a robust molecular sensor.

Aston provides the accurate, actionable, real-time data that's critical for effective EPCO. This data enables

**Figure 3. Atonarp ASTON metrology instrument.**

suitable ML models to be built and tested. In fact, Aston was designed from the ground up to meet the needs of in-situ molecular analysis to enable EPCO.

Importantly, Aston is more robust than existing in-situ metrology solutions, meaning it can provide dependable, consistent data in the harsh environment of a fab — including corrosive gases and particles. For example, Aston's self-contained ionization source enables a scheduled maintenance period that is up to 100 times longer than regular residual gas analysis (RGA) solutions.

## EPCO examples: plasma impedance and process end-point detection

Let's look at a couple of examples where real-time in-situ data is essential for an EPCO approach to achieve the best results in semiconductor manufacturing.

Every time you clean a process chamber you change its characteristics. Unnecessary time (and lost throughput) is spent in fabs over-cleaning and then re-seasoning process chambers. Optimized end-point-based cleaning and chemically specific chamber fingerprinting and characterization can reduce the time to get a chamber back to production and minimize process variations and process margin risk.

Secondly, end-point detection (EPD) is used in many semiconductor processes and is difficult to get right. A common use of EPD is in etch, where it is vital to avoid the etching process from stopping too soon (under-etch) or continuing too long (over-etch), as both scenarios can decrease yield. The etch process can be optimized by monitoring the quantity of etch by-products and looking for a clear flattening of the etch rate curve. This will provide optimum throughput and a consistent etch profile, reducing risk in subsequent processing steps and providing more consistent electrical performance.

Additionally, Aston works with 'lights out' or non-plasma processes such as atomic layer deposition (ALD) to give insight where legacy optical emission spectroscopy (OES) does not work.

## Conclusion

For today's semiconductor manufacturing fabs, optimizing processes can achieve significant improvements in yield and other metrics, while helping to reduce costs. Equipment and Process Co-Optimization (EPCO) provides a way to do this effectively — but requires highly accurate real-time data, obtained in-situ.

Existing metrology solutions are unable to provide this data in a practical manner, and lack the necessary durability to deliver under harsh chamber conditions. We believe that advanced metrology solutions, such as our Aston platform, will help further digital transformation within fabs and unlock the many benefits of EPCO for semiconductor manufacturers. ■

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