The Art of Holistic Metrology (in Memory of Alok Vaid)

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ABSTRACT

As device dimensions continued to shrink and semiconductor architectures evolved into increasingly complex 3D structures, single-tool metrology approaches began to encounter fundamental limitations in accuracy and precision. This challenge led to the development of holistic metrology, which enhanced scatterometry performance by incorporating multiple information channels, azimuth angles, and measurement targets. The concept of holistic metrology later expanded into hybrid metrology, enabling complementary use of OCD, CD-SEM, AFM, XPS, and other metrology techniques to further strengthen measurement robustness. More recently, AI-enabled hybrid approaches have extended these capabilities. Alok Vaid played a central role in pioneering all these innovations, and this article serves both as a technical review of these developments and as a tribute to his lasting contributions to the metrology community.

Keywords: Holistic metrology, Hybrid metrology, Scatterometry, OCD, CD-SEM, AFM, XPS, XRF, Machine Learning, Virtual Metrology, AI, TMU

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1. INTRODUCTION

The Art of Holistic Metrology is the Art of innovation, collaboration, and the remarkable impact of our colleague and friend, Alok Vaid, who shaped much of our industry's thinking about holistic and hybrid metrology.

The paper will primarily be based on papers published by Alok's teams (Alok has published more than 80 papers and patents with more than 240 co-authors!). The first part of this article reviews the development of holistic metrology between 2011 and 2016, highlighting the key milestones and technical breakthroughs as illustrated in Figure 1.
The second part covers the introduction and evolution of hybrid metrology, followed by the emergence of ML-driven approaches. The final section examines how Alok's ideas continue to influence both hardware and algorithm development and provides a perspective on the future of semiconductor metrology.

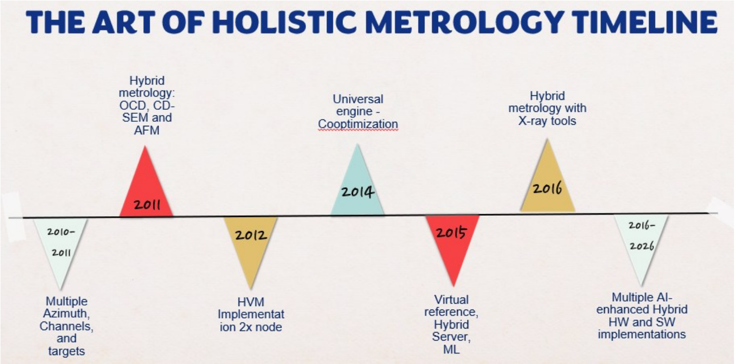


Figure 1. The timeline of the Art of Holistic Metrology

2. THE HISTORY OF THE ART OF HOLISTIC METROLOGY

The need for holistic metrology emerged from the pressures imposed by Moore's Law and the continuous reduction of device dimensions. Historically, semiconductor manufacturers relied on single-tool metrology solutions such as CD-SEM, CD-AFM, and OCD, each capable of addressing specific aspects of dimensional control [1]. However, these tools increasingly struggled to achieve the required accuracy as device architectures became more complex. As technology scaled below the 28 nm node, traditional stand-alone metrology tools reached their performance limits. The adoption of multi-patterning techniques and the transition from planar devices to 3D architectures, such as FinFET, introduced new profile parameters and process interactions that required more advanced, integrated metrology approaches.

Scatterometry limitations.

The first metrology technique to encounter significant constraints was scatterometry, which had long served as the primary method for profile characterization. Early Alok's works [2-4] explored how to address these limitations by expanding the spectral information available to OCD modeling. These studies examined the use of varied azimuth angles, multiple target types, and additional measurement channels to improve parameter sensitivity and reduce correlation.

In paper [2], Alok's team demonstrated that using variable and multiple azimuth (AZ) angles in spectroscopic ellipsometry significantly enhances performance by increasing parameter sensitivity (see Figure 2, as an example), and reducing parameter correlation, thus improving metrology performance. Results of 32 nm high-K metal gate (HKMG) applications demonstrated notable improvements in precision, tool matching, and accuracy, establishing multi-azimuth as a key component of holistic metrology.

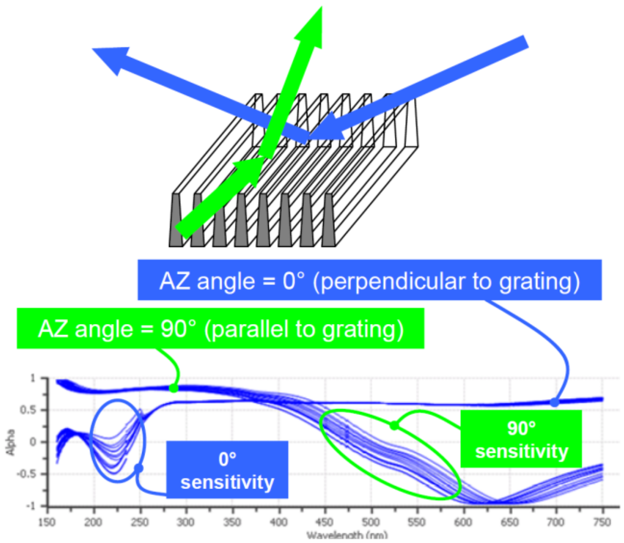


Figure 2. Schematic showing the varying spectral difference between azimuth (AZ) angles of 0 and 90 degrees [2].

A further limitation of scatterometry appears when fixed optical constants (n and k) are assumed, even though these parameters can vary across wafers and process conditions—particularly in photoresist metrology. In paper [3], Alok and co-authors investigated this issue using a 32 nm back-end of line (BEOL) lithography stack with intentionally varied optical planarization layer (OPL) bake conditions. Three modeling strategies were evaluated: a conventional fixed n&k model, a floating n&k model, and a multi-stack floating n&k approach that incorporates spectra from multiple adjacent targets (Figure 3).

The study showed that fixed n&k models produce substantial bias, especially in sidewall angles (SWA), when material properties drift. Floating n&k models correct this bias but suffer from reduced precision due to the introduction of additional floating parameters. The multi-stack approach addresses both challenges by increasing the spectral information content available to the model, enabling simultaneous improvements in accuracy and precision. This methodology demonstrated robust extraction of key profile parameters—including CD, SWA, dose, and defocus, highlighting the value of multi-target data for process-tolerant OCD metrology [3].

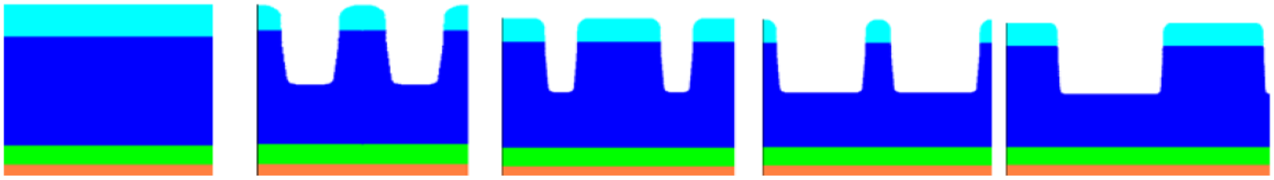


Figure 3. Different nearby measurement targets are used to solve for the common set of parameters (materials) and the geometry of each target (product-driven methodology) [3].

Introduction of Holistic Metrology.

The ideas from these foundation papers were combined in the groundbreaking paper by Alok et al [4], where the term Holistic Metrology was formally introduced.

Figure 4. The Holistic Metrology Approach: a combination of all possible information sources (internal and external) into a single simultaneous optimization [4].

The Holistic Metrology Approach was defined as a combination of all possible information sources (internal and external) into a single simultaneous (concurrent) optimization (Figure 4). The study [4] focused on internal spectral information within scatterometry tools, demonstrating the value of combining multiple optical channels, including normal- and oblique-incidence measurements and multi-azimuth measurements. By jointly interpreting the spectra from all these channels, the authors showed that the combined dataset provides greater spectral diversity and reduces parameter correlation compared to any individual channel. Applications at the 32 nm node, including shallow trench isolation (STI) and Gate Etch structures, confirmed that multi-channel fitting enhances sensitivity to weak parameters, improves dynamic repeatability, and maintains accuracy even when low sensitivity channels are included. These results established multi-channel analysis as a core principle of holistic metrology for advanced 3D structures [4].

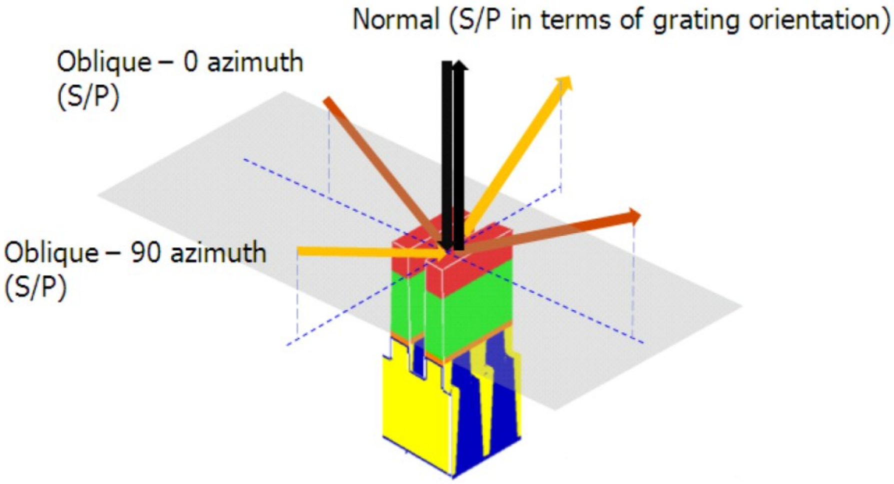
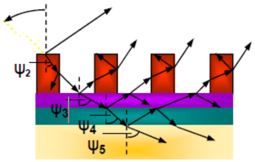


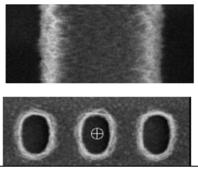
Figure 5. Optical configuration of a multi-channel system [4].

Alok and co-authors extended the holistic metrology concept in 2011 by introducing Hybrid Metrology, which incorporates external metrology sources into the interpretation of scatterometry or CD SEM data [5,6]. In this approach, two or more metrology techniques are used either sequentially or simultaneously on the same dataset, enabling parameter hybridization that decreases model correlation, increases sensitivity, and improves both precision and accuracy. Importantly, Hybrid Metrology differs from traditional "injection" approaches: while injection generally propagates (upstream) metrology results into a model as is, hybridization "fuses" measurement outputs from multiple tools, improving metrology robustness.

Hybrid Metrology strategies

The first practical implementation of Hybrid Metrology demonstrated the benefits of combining multiple CD measurement platforms—including OCD, CD SEM, and CD AFM—to address the inherent limitations of each individual technique. By merging complementary sensitivities and leveraging the strengths of each tool, hybridization improved accuracy, precision, and model robustness for both 2D and 3D device structures, as summarized in Table 1 [5,6].





	Scatterometry	**CDSEM**	**AFM**	**TEM/XSEM**
What to measure	CD, profile, other	CD	CD, profile	CD, profile, other
Where to measure	Periodic grating	Any	Any	Any
Time-to-solution	Days to weeks	Minutes	Hours	Hours to days
Destructive	Negligible	Minor (resist)	No	Yes
Time to measure	Seconds	Seconds	Minutes	Days
Summary: Strengths	- Fast measure - Most profile info	- Quick setup & fast measure - Measure anywhere	- Most profile info - High accuracy	- Full profile info - High accuracy
Assumptions & limitations	- Model assumptions - Tradeoff b/w Accuracy-Precision - Requires grating	- Constant & uniform profile - No profile info - Diff. to measure true bottom	- Tip wear & characterization - Large space - Low thrpt	- Resolution is process dependent - Limited statistics
Typical Fab usage	- "Workhorse" for CD & profile	- "Workhorse" for CD	- Good RMS - Partial in-line	- Absolute reference
Issues alleviated via Hybrid Metrology in this work:	***- Parameter correlation & sensitivity*** ***- Long setup time***	***- Measurement error due to profile variation***	***- Restriction on structure (tight spaces)***	

Table 1: Summary comparison of various CD metrology techniques [5.6]

Hybrid Metrology demonstrated clear performance benefits by enabling parameter exchange between tools, for example, using CD-SEM critical dimensions to stabilize OCD model convergence or using OCD extracted sidewall angle (SWA) to refine CD SEM thresholding. This cross-tool interaction reduced parameter correlation, increased sensitivity to process variations, and enabled accurate characterization of complex 22 nm Gate photoresist (PR) stacks and 32 nm FinFET Gate Etch profiles. Across multiple evaluations, hybridization consistently lowered Total Measurement Uncertainty (TMU) and improved robustness to process variation. In addition, it expanded the capability of CD-AFM into narrow pitch regions through OCD assisted extrapolation. The authors also outlined practical deployment methods, from offline hybrid recipe optimization to real-time hybridization and universal hybridization engines (Figures 6 and 7), demonstrating the scalability of the approach for future nodes.

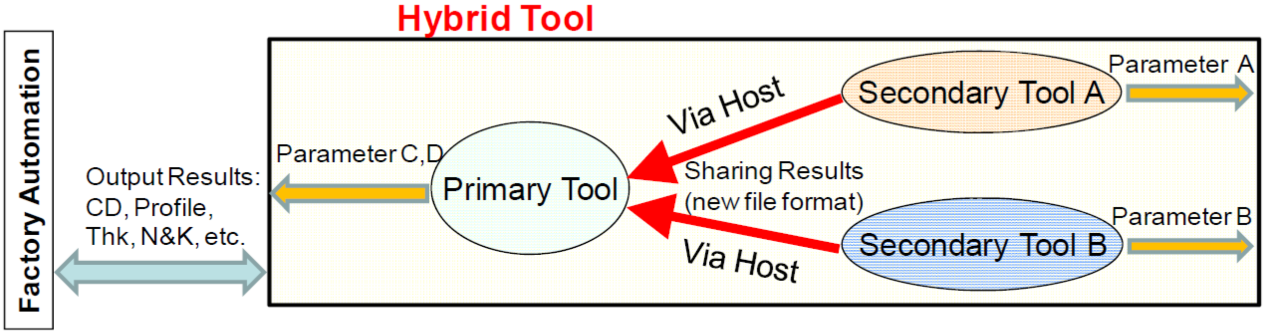


Figure 6. Simple hybrid metrology schematic [5].

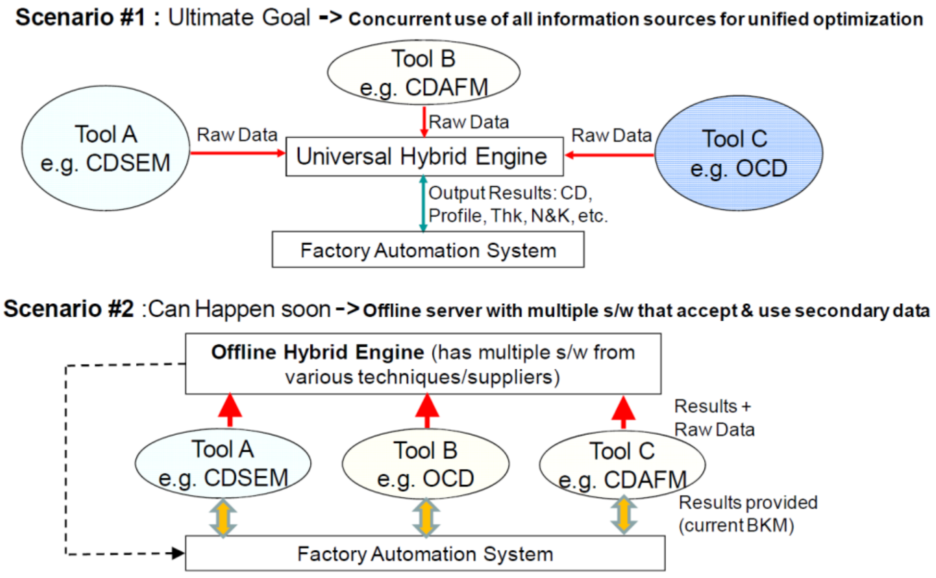


Figure 7. Alternate scenarios for Hybrid Metrology setup [5].

Following the introduction of Hybrid Metrology, it rapidly became one of the most powerful tools of holistic metrology strategies, particularly for HVM environments. One notable (non-OCD) early implementation was the development of a universal hybrid interface that combined CD SEM waveform data with 3D AFM profiles. This fusion compensated for limitations of individual tools, such as proximity effects, material-dependent shrinkage, and gaps in profile sensitivity. By aligning CD SEM intensity waveforms with AFM-derived geometry, hybridization enabled corrected SEM thresholds and significantly improved wafer-level CD maps. Subsequent work extended this approach to contour-based hybridization, in which AFM or TEM reference contours were used to recalibrate CD SEM image-processing thresholds. [7-8].

Golden years of Hybrid metrology and HVM implementations.

In 2012, Alok and a co-author team from GF, IBM, Nova, and Hitachi [9], validated a hybrid metrology (HM) solution for 1X-node technologies by combining Scatterometry/ and CD-SEM (using TEM/X-SEM and CD-AFM as references) to overcome the accuracy-precision tradeoff, and parameter-correlation limits of scatterometry. A major contribution of this work was the introduction of the Data Modification Parameter (DMP), which defines the extent to which the primary tool incorporates information from a secondary tool. DMP values were optimized to minimize TMU and maximize metrological stability across varying process conditions.

Hybrid Metrology was evaluated across three representative high-volume manufacturing applications.

1. FinFET Gate Final Etch: Incorporating CD-SEM fin CD into OCD models reduced CD/SWA coupling and significantly improved TMU for gate CD and undercut.
2. Extreme ultraviolet (EUV) M1 Lithography: Introducing line edge roughness (LER) as a scatterometry parameter and hybridizing it with CD SEM LER measurements allowed substantial SWA accuracy gains compared to X SEM references.
3. Negative Tone Development (NTD) M1 Lithography: LER-based hybridization yielded near-perfect agreement with CD-AFM SWA measurements.

Across all applications, hybridization reduced parameter entanglement and enhanced model stability relative to standalone OCD. In addition, the authors demonstrated a hybrid calibration in which OCD-measured resist height is used to calibrate CD-SEM pattern-top roughness (PTR), to allow CD-SEM monitoring of the in-die line-height variations. This illustrates how HM extends each tool’s metrological capabilities and reach.

A first HVM implementation was demonstrated for the primary tool (OCD), getting input from the secondary tool (CD-SEM) via the host - “the low hanging fruit” or sequential implementation, as shown in Figure 8 [10].

Figure 8. Left: Generic data flow between the tools and the factory system; Right: Data flow between the tools and the factory system for the “low hanging fruit” or sequential implementation [10].

Two process steps (20 nm contact etch (CA/CB) and 14 nm FinFET gate etch) were used to demonstrate how combining CD-SEM and OCD measurements significantly improves accuracy and process control in HVM. Hybrid Metrology solution enabled critical dimensions by CD-SEM (CDx, CDy, fin CD, etc.) to hybridize into the OCD model with DMP, reducing model correlation and enabling accurate measurement of such profile features as sidewall angle, bottom CD, trench depth, and spacer variations. Validation against TEM shows substantially reduced TMU, confirming improved absolute accuracy after hybridization.

After qualification, hybrid metrology solutions were deployed using newly developed communication protocols that transfer CD-SEM data from the fab host to the OCD tool for real-time hybridization. Analysis of multiple production lots showed that HM produces tighter distributions, lower variance, and notably improved process capability (Cp) with some parameters showing up to 3× improvement compared to non-hybrid OCD.

While sequential hybrid metrology [10] used data from a secondary tool (typically CD-SEM) to refine the primary tool (typically OCD), it still treats each tool’s data stream independently, which limits its effectiveness for the most challenging structures. For complex 14 nm FinFET profiles after High-k/Interfacial Layer (HK/IL) deposition, CD-SEM and OCD measurements capture different aspects of the profile that cannot be addressed with DMP tuning. Alok’s team, which combined GF, OCD, and CD SEM experts, has proposed a novel approach, where the CD-SEM measurement threshold must be dynamically modulated based on the OCD-derived sidewall angle (SWA), allowing the CD-SEM to report a CD value corresponding to a consistent physical height along the fin profile—something not possible using fixed thresholds [1. As a result, co-optimization improved the accuracy and TMU of the High-k thickness and across-wafer variation for the Interfacial Layer thickness and finally enabled the implementation of server-based concurrent hybridization (Figure 9), where raw data from multiple toolsets are jointly optimized [11-12].

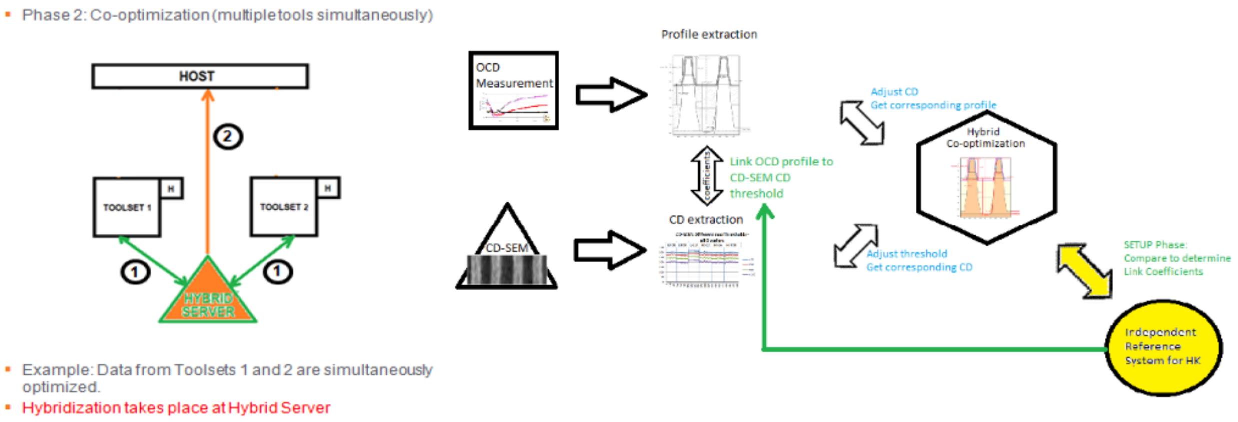

- Phase 2: Co-optimization (multiple tools simultaneously)
- Example: Data from Toolsets 1 and 2 are simultaneously optimized.
- Hybridization takes place at Hybrid Server

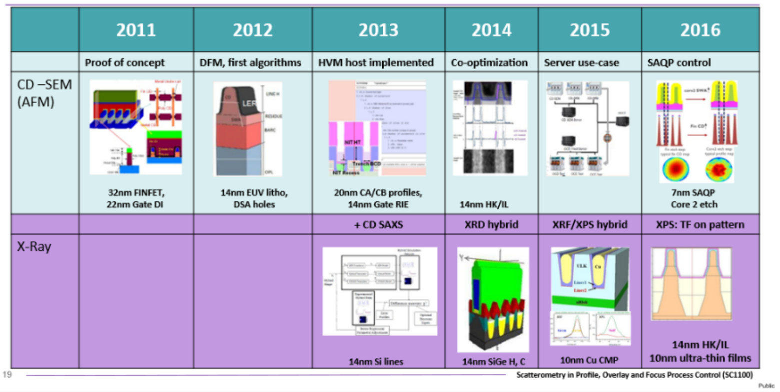
Figure 9. Left: Generic co-optimization data flow between the tools and the factory system; Right: Co-optimization implementation details. The independent reference system shown in yellow is used only during the setup of linking the OCD profile with the CD-SEM threshold [11-12].

Such a hybrid server with high bandwidth, direct data exchange between toolsets, support for both sequential and concurrent hybridization, enabling the simultaneous optimization of raw data such as spectra, images, and traces, was demonstrated in [12]. Validation on 20 nm contact and 14 nm M1 etch production applications showed that server-based co-optimization matches or exceeds host-based sequential performance, significantly reducing SWA/CD cross-correlation, improving accuracy and repeatability, and enabling tighter across-wafer distributions.

All these early efforts to implement OCD and CD-SEM hybridization demonstrated that co-optimization offers a robust approach to aligning different metrology methods and laid a crucial foundation for a future universal hybrid metrology engine, enabling simultaneous multi-tool optimization to meet next-generation Angstrom-level metrology requirements.

Hybrid metrology expansion

After implementing hybrid metrology on dimensional metrology tools, such as optical, E-beam, and probe metrology systems, the approach was extended to X-ray tools. Summary Table 2 presents the hybrid metrology papers published at SPIE from 2011 to 2016.



	2011	2012	2013	2014	2015	2016
	Proof of concept	DFM, first algorithms	HVM host implemented	Co-optimization	Server use-case	SAQP control
CD –SEM (AFM)	32nm FINFET, 22nm Gate DI	14nm EUV litho, DSA holes	20nm CA/CB profiles, 14nm Gate RIE	14nm HK/IL		7nm SAQP Core 2 etch
			+ CD SAXS	XRD hybrid	XRF/XPS hybrid	XPS: TF on pattern
X-Ray			14nm Si lines	14nm SiGe H, C	10nm Cu CMP	14nm HK/IL 10nm ultra-thin films

19 Scatterometry in Profile, Overlay and Focus Process Control (SC1100)

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Table 2. Hybrid metrology early implementations [13].

While all hybrid metrology HVM evaluations were a success, a widespread implementation of Hybrid metrology during these years was limited because of the cost (of ownership). Besides the cost of the Hybrid toolsets and the server(s), there is the cost of the day-to-day implementation, where each measurement location is always measured at least twice by hybrid metrology tools. So, compared to other holistic approaches, hybrid metrology proved more powerful but less cost-efficient.

Machine Learning (ML) addition to the Holistic toolset – the baton transfer.

In 2016, two papers pioneered the ML approach for directly extracting POIs from spectra. In these papers, in-line and EOL reference measurements were used to train the ML models.

Alok's paper [14] introduced a machine–learning–driven approach to lithography metrology to overcome the long-standing limitations of CD-SEM and traditional scatterometry at advanced nodes. Instead of relying on RCWA-based modeling, the new method directly correlates not only profile parameters (such as CD), but also lithography tool or process parameters (such as focus and dose) with the rich spectral response collected from multiple design-rule-compatible targets and/or on-device structures such as SRAM (Figure 10). Using principal component analysis and neural network parameter models trained on the focus-exposure (FEM) wafers, ML extracts critical lithography parameters with high accuracy while remaining robust to underlayer variation and reference noise and reducing recipe development time from weeks to hours.

A related study by Rana and co-workers [15], demonstrated that neural networks, multivariate regression, principal components analysis, and partial least squares modeling can extract hidden trends from raw metrology signals - including CD-SEM resist-shrinkage curves, CD-AFM profiles, and scatterometry spectra - to predict physical CDs accurately, forecast deep trench capacitance, and estimate metal line resistance well before electrical test becomes possible (Figure 10). Using only optical spectral data, neural networks significantly outperform linear models, achieving sub-nanometer CD prediction uncertainty, robust handling of nonlinearities and outliers, and accurate resistance predictions. These results established ML-driven predictive metrology as a natural extension - and in some cases a replacement — for conventional hybrid metrology, offering earlier decision points, reduced risk, and improved control, all at lower cost.

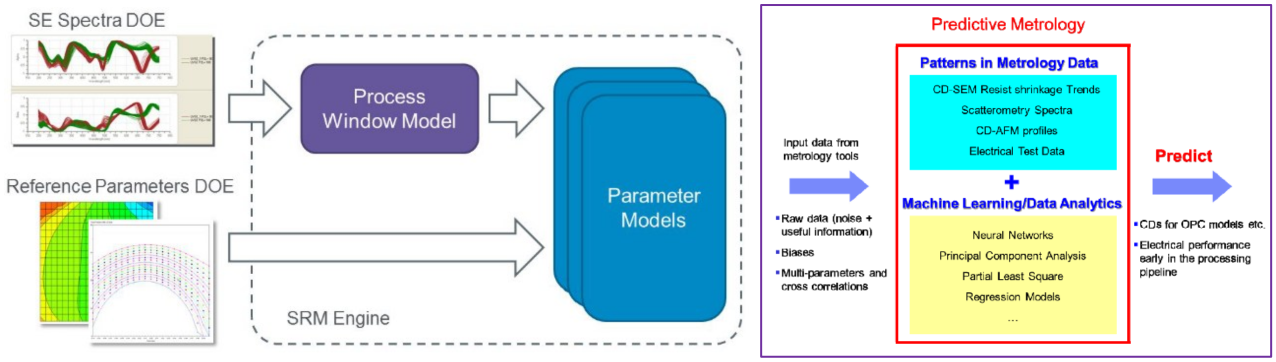


Figure 10. (Left) ML training for Lithography Process Window [14]. (Right) Predictive metrology concept [15].

Publications over the subsequent years reflected a clear shift from hybrid metrology toward AI-driven solutions. Figure 11 [16] illustrates this trend using the example of SPIE publications. A cost-of-ownership consideration favored ML models, which avoided the need for multiple metrology platforms to measure each wafer. The scalability, speed, and reduced operational complexity of ML-based metrology (Figure 12 [16]) make these methods attractive for advanced nodes, where dimensional and material variations have become increasingly subtle and difficult to isolate using traditional approaches.

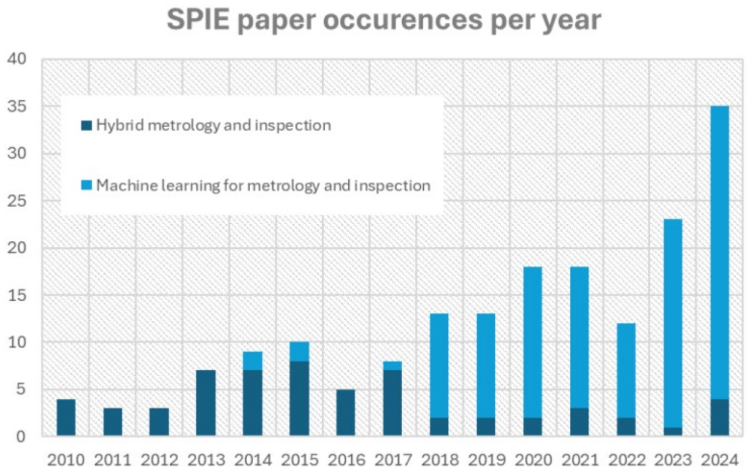


Figure 11. Number of Hybrid metrology and ML publications. Source: SPIE digital library, Proceedings Volume Metrology, Inspection, and Process Control for Microlithography [16].

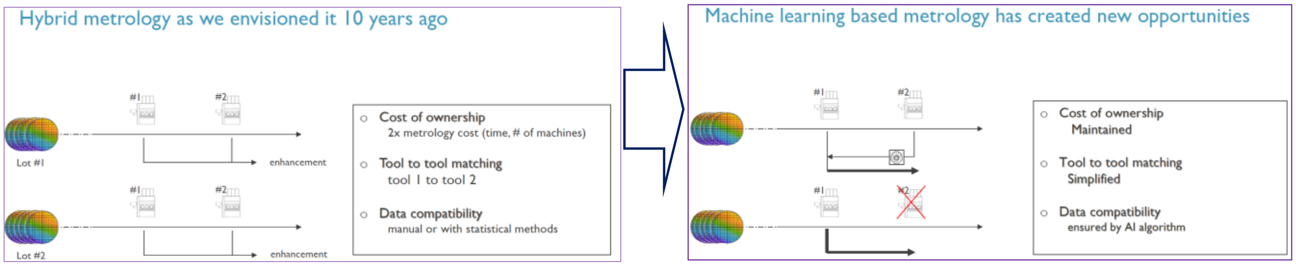


Figure 12. ML takes over Hybrid Metrology [16].

3. INSPIRATIONS OR THE CURRENT STATE OF THE ART

Many of Alok's concepts and ideas were later implemented, inspiring numerous novel developments in both HW and algorithms.

Holistic Ideas Driving New Hardware Architectures

Although hybridization had long been considered technically desirable, full hardware-level integration remained challenging due to cost and compatibility constraints. Eventually, however, a new generation of “hybrid tools” emerged.

In the e-beam domain, search for a unified high-resolution image-based platform materialized in systems that adopted a “Swiss Army Knife” approach [16], integrating profile, topography, buried features, and overlay measurements within a single instrument architecture. Additional innovations — including pump-probe electron-beam techniques - enabled nanoscale electrical property measurements, expanding the scope of e-beam metrology far beyond traditional (dimensional) imaging (Figure 11) [17].

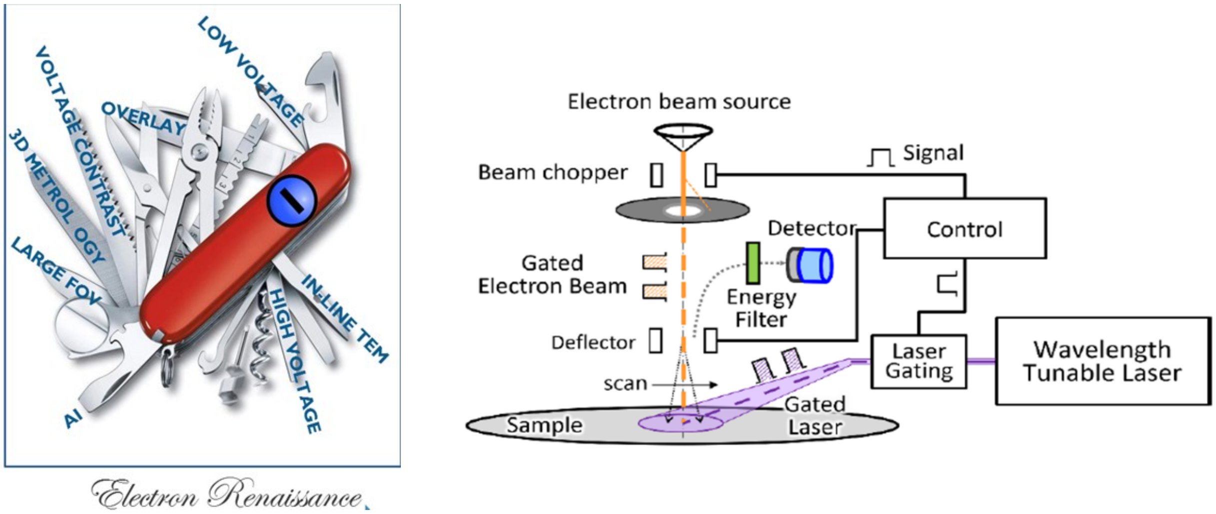
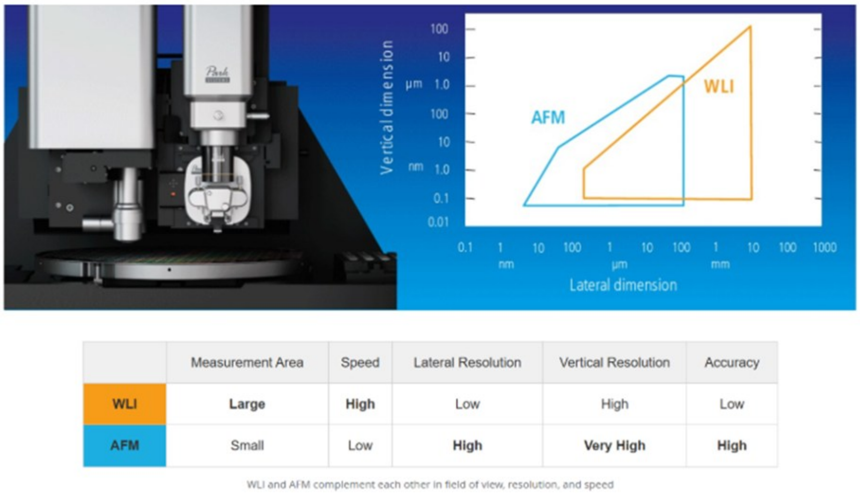


Figure 11. Hybrid E-beam tools. Left: Swiss Army knife approach [16]. Right: material properties by pump-probe E-beam [17].



	Measurement Area	Speed	Lateral Resolution	Vertical Resolution	Accuracy
WLI	**Large**	**High**	Low	High	Low
AFM	Small	Low	**High**	**Very High**	**High**

WLI and AFM complement each other in field of view, resolution, and speed

Figure 12. Hybrid AFM and WLI [18].

Atomic force microscopy (AFM) systems also became hybridized. One example is the integration of AFM with white-light interferometry (WLI), pairing AFM's high resolution and small-area sampling with WLI's fast, large-area imaging. Together, these techniques achieved efficient measurement of sub-nanometer topographic variations over multi-millimeter-scale fields of view, a need that no single system could meet (Figure 12) [18].

On the optical side, scatterometry systems were enhanced through hybridization with spectral interferometry (SI). This innovation addressed a long-standing challenge in scatterometry: difficulty isolating spectral contributions from specific vertical regions within complex stacks. Vertical Traveling Scatterometry enabled selective extraction of information from top layers and enabled complete Z-direction profiling of deep 3D structures, such as 3D NAND, something previously inaccessible with OCD alone (Figure 13) [19-20].

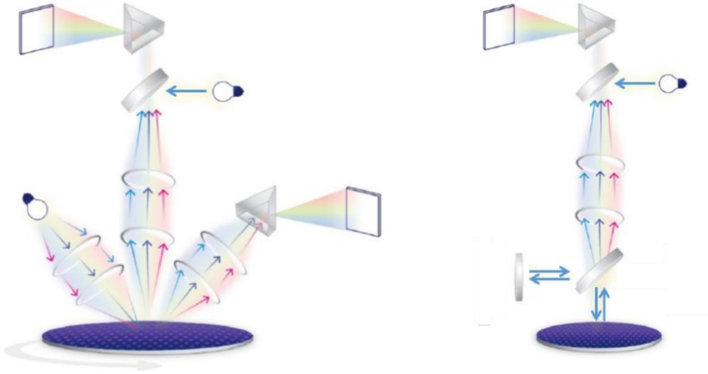


Figure 13. Hybridization of scatterometry and Spectral Interferometry (SI) [19-20].

AI-Enabled Hybrid Metrology

AI-enabled hybrid approaches leverage the strengths of multiple metrology methods, enabling the fusion of information streams without the high operational cost of physical hybridization.

A notable example — awarded the Vladimir Ukraintsev Prize at SPIE Metrology. Inspection and Process Control conference in 2024 — demonstrated a hybrid solution for measuring the thickness of the SOM (Selector Only Memory) layer (Figure 14 [21]). Sparse TEM cross sections were used to calibrate Raman spectroscopy signals, which were in turn used to train ML models that interpret SI (spectral interferometry) data. This workflow dramatically reduced the need for expensive and destructive TEM measurements, enabling rapid recalibration in response to process drift while maintaining HVM-level robustness and cost efficiency.

Other studies also show that AI-enabled hybridization of material-sensitive techniques, such as XRF [22], can contribute to dimensional metrology despite their traditional use only for compositional analysis.

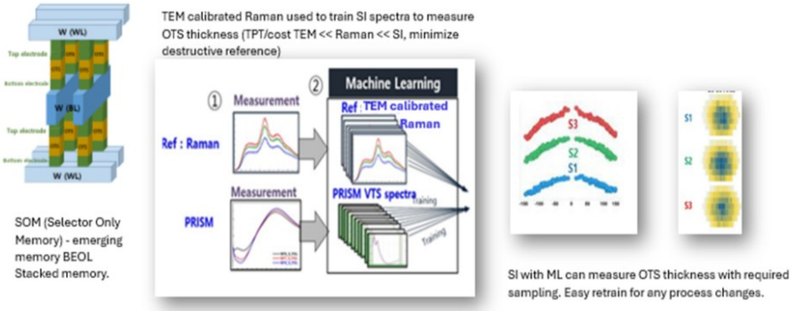


Figure 14. Usage of AI-enabled Hybrid metrology in HVM [21].

4. METROLOGY FUTURE

Looking ahead, semiconductor metrology is expected to continue advancing along paths shaped by holistic principles. One important direction is virtual metrology, where AI models infer post-process outcomes using signals collected by sensors that never directly observe the wafer. When trained on sufficient process and metrology data, virtual metrology models can significantly reduce reliance on expensive inline measurements, improving throughput and further reducing the cost of ownership. However, to build such models, extensive baseline characterization is required - an effort that depends critically on holistic metrology, hybrid data fusion, and AI-assisted modeling. These needs will intensify with emerging device architectures, including CFETs [23,24], 3D memory structures, and advanced packaging technologies.

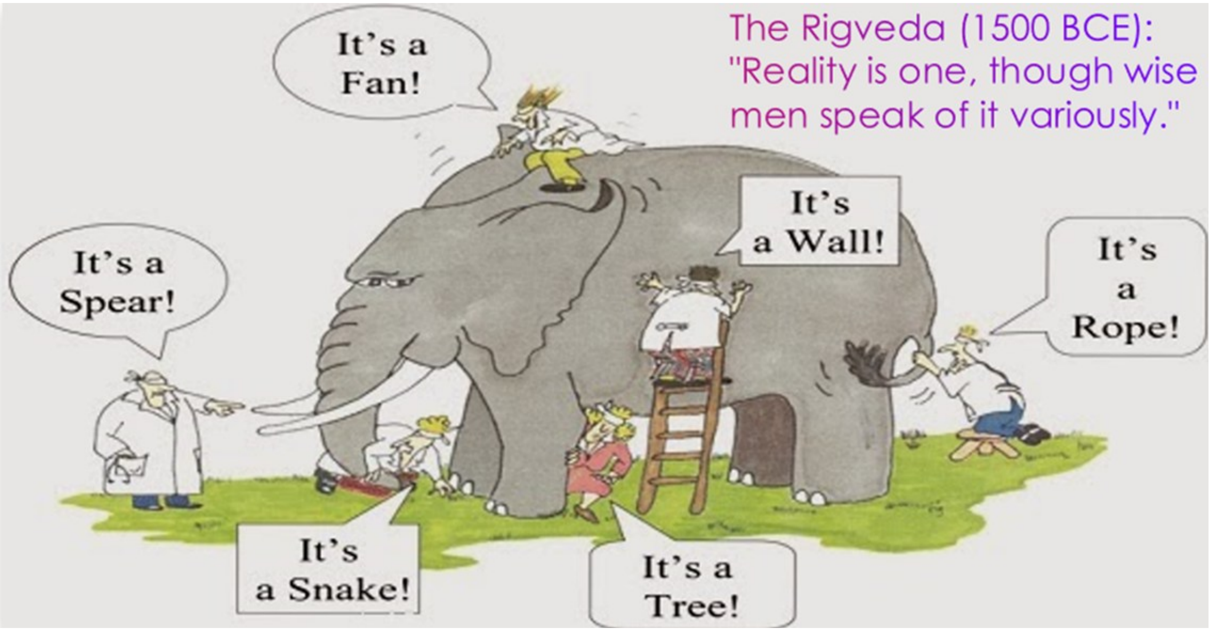


Figure 15. Future of holistic metrology [25].

A fitting metaphor for the future of metrology can be found in the familiar “Blind Men and the Elephant” parable (Figure 15) [25]. Each blind man (or sensor, metrology technique, etc.) captures only a partial view of reality, and only by combining all available data, as holistic, hybrid, and AI-based approaches do, can a complete understanding be formed. As device complexity grows, the “elephant” grows as well, requiring more sophisticated sensing and metrology tools, more intelligent algorithms, and more integrated approaches to achieve precise and accurate process control.

ACKNOWLEDGEMENTS

The author would like to thank Cornel Bozdog (Micron), Padraig Timoney (IBM), Eric Solecky (GF), Michael Sendler, Avron Ger, and Hadar Peled Vaissman (Nova) for their help.
The author would like to thank Nitii Garg for providing additional information about her husband: her eulogy and a few pictures of Alok are included in the Appendix below.

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APPENDIX 1.

Eulogy by Nitii Garg.

I found it difficult to write anything when I was first asked to share a few words about Alok.

But with time, and in a calmer frame of mind, I felt I owed it to him to try to do justice to the life he lived and the love he gave.

Alok was a devoted husband—and an even more devoted father to our two daughters.

He often said he was the luckiest man in the world, surrounded by the love of his girls.

But in truth, we were the fortunate ones. He had a remarkable way of giving that love back to us—always in his own unique and heartfelt way.

He believed deeply that life was meant to be lived fully and joyfully—and he embodied that belief every single day, right until the very end.

He loved the outdoors and cherished every opportunity to be out in nature. Even on his final day, he wanted to go for a walk.

He found joy in the simple and the adventurous alike—biking, boating, kayaking, hiking, playing tennis, and traveling.

In fact, he loved traveling so much that often, before we had even unpacked from one trip, he would already be planning the next.

At times, it felt exhausting, especially with young children—but he would always say, "This is just the beginning. One day, the kids will grow into it, and everything will fall into place."

And in many ways, it did.

While he was extraordinary within our family, he was equally remarkable in his professional life.

He truly loved his work and treated everyone around him with respect and kindness. His team meant a great deal to him - they were, in many ways, an extension of his family.

He took immense pride in solving problems and supporting those around him, always offering encouragement, guidance, and a listening ear.

To honor him, our daughters and I have made a quiet promise—to carry forward his spirit.

To live fully, to embrace each day, and to find joy even in the smallest moments.

The path ahead will not be easy without him, but we will do our best to walk it with the strength and optimism he showed us every day.

Alok will always live on in our hearts, in our memories, and in the countless ways he shaped our lives.

And I know, in his own way, he is still watching over us—guiding us, and perhaps even making sure that everything is done just right 😊

His life was a beautiful reminder that love, when given fully, never truly leaves us!

Thank you, Alok!