Leveraging Smart Factory Principles for Chemical Usage and Cost Reductions

Mark J. Miller[1], Joaquin Currier Cubero[1], M. Arif Zeeshan[1]

[1]Skyworks Solutions Inc., 20 Sylvan Road, Woburn, MA 01801, USA

Email: Mark.Miller@skyworksinc.com, Phone: 781-491-6630

Keywords: FDC, Sustainability, Semiconductor Manufacturing, Sensors and Feedback

Abstract

Manufacturers across industries face myriad challenges such as complex supply chains, environmental health and safety challenges, cost headwinds due to complex market dynamics, and much more. With these considerations in mind, it is critically important to leverage "smart factory" principles (interconnected machinery and production systems with meaningful feedback) for maximum efficiency and value creation. Moreover, wet chemicals are an ideal candidate for efficiency improvements as they comprise a $7B global market, which is projected to grow to $11B by 2029 [1]. In this study, smart factory goals are achieved for solvent processes (metal liftoff and photoresist strips) by installing external flow sensors and integrating the feedback into a fault detection and classification system. The new system revealed opportunities for chemical usage and cost reductions, such as unnecessary wet station top-offs, end-of-life valves, and more. These chemical loss mechanisms were diagnosed, characterized, and eliminated. The results show desirable reductions in wet station temperature variability, chemical usage, and cost on both absolute and normalized per-wafer bases. The approach used in this study is broadly applicable in multiple process areas and industries.

INTRODUCTION

Manufacturers constantly face uncertainty due to numerous dynamic macroeconomic factors [2]. For example consumers shifted spending from services to durable goods during the COVID-19 pandemic, which led to a rapid increase in demand at a time when global supply chains were strained [3]. In addition to macroeconomic factors, customers are expecting increasing levels of environmental stewardship and sustainability [4]. Simultaneously, investors require exceptional gross margins and returns on investment [5]. Few solutions can address each of these challenges, however, factory automation coupled with FDC (fault detection and classification) can improve efficiency without compromising quality [6].

FDC can be utilized to add value in many ways, but it is primarily used to maximize production quality and prevent or minimize defectivity [7-11]. Some past studies have also shown how smart factory principles can be used to improve energy efficiency [12], predict chemical consumption [13], and reduce cost [6]. It should be noted that additional sensors may need to be installed to identify and control a process signal [14]. Clearly factory automation offers a powerful suite of techniques to produce the highest quality products at the lowest possible cost.

In the current study, chemical usage and cost goals are achieved by installing flow sensors and leveraging FDC to control solvent usage during photoresist strip and metal liftoff processes [15]. The results show how seemingly conflicting objectives can be accomplished simultaneously using smart factory principles, and the insights can be applied in many different industries.

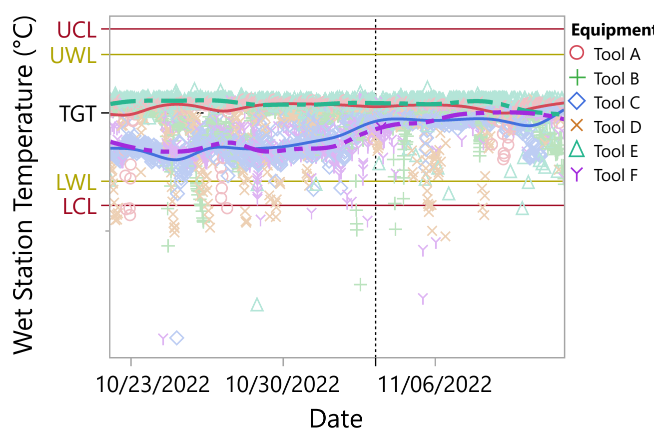

Fig. 1. Bivariate fit of wet station temperature by date. *Tools C* and *F* desirably trend up after the dashed line due to the elimination of unnecessary wet station top-offs, which were injecting fresh (cold) solvent into the heated immersion tank.

EXPERIMENTAL PROCEDURE

FDC has been implemented at Skyworks Solutions and efforts have been made to maximize its utilization and effectiveness. An example report, wet station temperature, is provided in Fig. 1 for reference. For certain processes, insights were desired beyond the capabilities of the available hardware, therefore, additional instrumentation was installed.

Specifically, clamp-on flow sensors were added to solvent processing tools to measure and ultimately control their chemical usage. These sensors utilize a robust delta time-of-flight technique for flow detection, as indicated in Fig. 2 [16]. Feedback from the flow sensors was integrated into FDC, and a report was generated which integrates the flow rate over time to calculate daily volumetric consumption (Fig. 3).

Opportunities for chemical usage reductions were identified, and subsequent hardware diagnostic and maintenance activities were performed (Fig. 4). Lastly, FDC-calculated volumes were compared against actual fleet-level solvent usage and cost data. Solvent cost was analyzed on both absolute and normalized per-wafer bases to reveal the impact of improvements that were made.

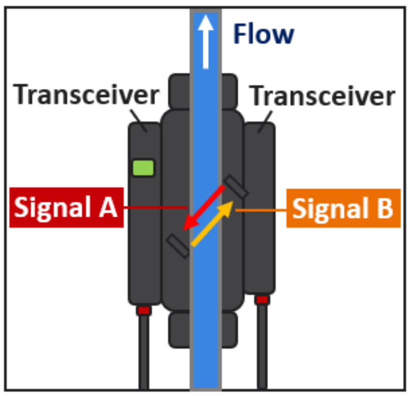

Fig. 2. Clamp-on flow sensor utilizing delta time-of-flight method for volumetric flow rate monitoring. A flow sensor was installed on each solvent tool in this study, which enabled more precise chemical tracking than was previously possible on this toolset.

Results and Discussion

Applying "smart factory" principles (interconnected systems and processes) has added value in myriad ways throughout industry and at Skyworks Solutions in particular. For example solvent wet station temperature, provided in Fig. 1, shows that *Tools C* and *F* had temperatures consistently below target despite being programmed to run at the same setpoint as the other tools in the fleet. The root cause for the temperature mismatch was determined through the course of this work and will be provided in the subsequent paragraphs.

Wet processing tools in this study receive fresh solvent from bulk-fill units which are supplied with large totes of chemicals. While the number of totes is carefully tracked, usage at each individual tool could not be measured prior to this work. Therefore, clamp-on flow sensors were installed on each tool-specific supply line as indicated in Fig. 2. Output from the flow sensors is sent to FDC, which integrates the rate over time to calculate daily chemical usage (Fig. 3). The usage report revealed that some tools had higher than average solvent consumption. Diagnostic equipment investigations were performed based on these findings.

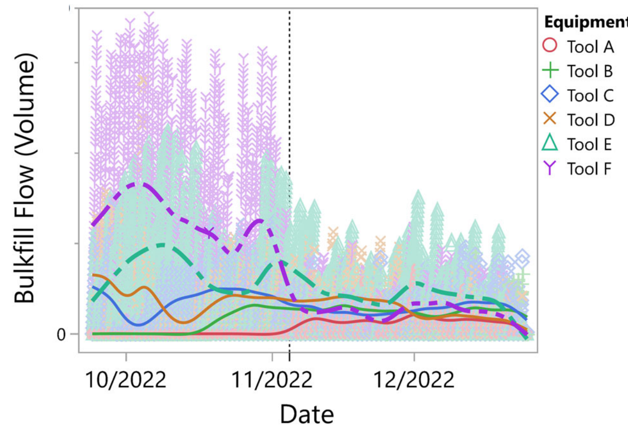

Fig. 3. Bivariate fit of bulk-fill flow (volume) by date. Solvent consumption was reduced after the dashed line by eliminating unnecessary top-offs, replacing end-of-life valves, and performing other maintenance activities.

By combining insights gained from the wet station temperature and bulk-fill flow reports, subsequent equipment investigations led to enhanced scrutiny of the solvent immersion tanks where wafers are soaked prior to receiving solvent spray. It was found that *Tools C* and *F* were receiving unnecessary "top-offs," as indicated in Fig. 4. This chemical loss mechanism was eliminated by increasing a delay parameter, which enables the cassette to immerse prior to the tool attempting a wet station top-off. Not only did wet station temperatures trend to target after this change, but more importantly solvent usage and cost was reduced.

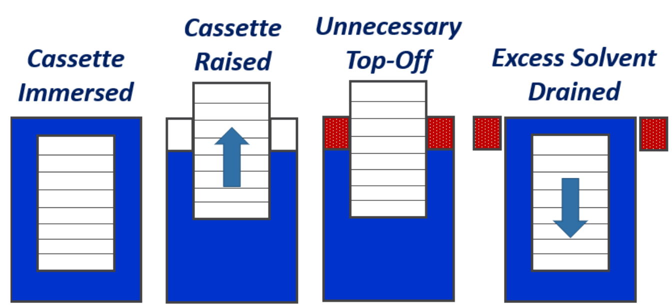

Fig. 4. Schematic showing solvent loss mechanism in wet station. Unnecessary top-offs (fresh solvent additions) were eliminated by increasing a delay parameter, which allows the cassette to re-immerse before an attempted top-off.

Monthly solvent costs were calculated on both absolute and normalized per-wafer-start bases, as shown in Fig. 5. Note that solid lines and circles represent absolute solvent cost, while dash-dotted lines and pluses represent normalized cost. The results show that after equipment maintenance activities were performed, both traces trended down as desired. Moreover, an uptick in absolute cost in early 2023 did not correspond to an increase in cost per wafer start, also as desired. In addition to the financial impacts of this work, sustainability goals were achieved as the rate of industrial chemical usage and waste handling was concurrently reduced.

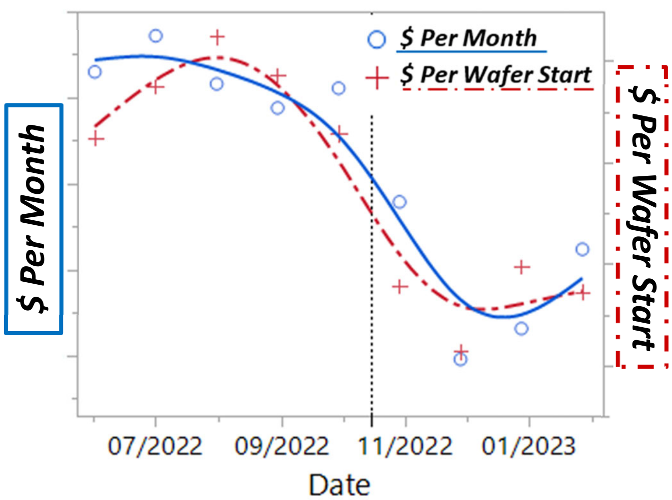

Fig. 5. Solvent cost reduction on both absolute and normalized (per wafer start) bases.

CONCLUSIONS

In this study, smart factory goals were achieved for solvent processes (metal liftoff and photoresist strips) by installing external flow sensors and integrating the feedback into a fault detection and classification system. The new system revealed opportunities for chemical usage and cost reductions, such as unnecessary wet station top-offs, end-of-life valves, and more. These chemical loss mechanisms were diagnosed, characterized, and eliminated. The results show desirable reductions in wet station temperature variability, chemical usage, and cost on both absolute and normalized per-wafer bases. The approach used in this study is broadly applicable in multiple process areas and industries.

ACKNOWLEDGEMENTS

The authors would like to thank Aida Castro for support on FDC implementation, Les Roach for equipment troubleshooting, Dan Lyons and Ed Williams for material cost details, and Ravi Ramanathan, Eric Finchem, and Ed Burke for helpful feedback on the manuscript.

REFERENCES

[1] Maximize Market Research, "Wet Chemicals Market: Recycling of Semiconductors & E-Waste Trends to Create Growth Opportunities," https://www.maximizemarketresearch.com/market-report/wet-chemicals-market/167848/, 2023.

[2] J. Mullin, "Supply Chain Disruptions, Inflation, and the Fed," *Econ Focus,* vol. 22, no. 3Q, pp. 14-17, 2022.

[3] X. Wang, "Economic Crisis: Inflation in Post-COVID Time," *Economic and Social Development: Book of Proceedings*, pp. 148-153, 2022.

[4] C.-w. Shen, P. P. Tran, and P. T. Minh Ly, "Chemical Waste Management in the US Semiconductor Industry," *Sustainability,* vol. 10, no. 5, pp. 1545, 2018.

[5] M. Mahdi, and M. Khaddafi, "The Influence of Gross Profit Margin, Operating Profit Margin and Net Profit Margin on the Stock Price of Consumer Good Industry in the Indonesia Stock Exchange on 2012-2014," *International Journal of Business, Economics, and Social Development,* vol. 1, no. 3, pp. 153-163, 2020.

[6] C.-F. Chien, A. C. Diaz, and Y.-B. Lan, "A Data Mining Approach for Analyzing Semiconductor MES and FDC Data to Enhance Overall Usage Effectiveness (OUE)," *International Journal of Computational Intelligence Systems,* vol. 7, no. 2, pp. 52-65, 2014.

[7] S. Y. Chang, S. Tiku, and L. Luu-Henderson, "Advanced Process Monitoring Through Fault Detection and Classification for the Process Development of Tantalum Nitride Thin-Film Resistors," *IEEE Transactions on Semiconductor Manufacturing,* vol. 36, no. 4, pp. 520-526, 2023.

[8] C.-F. Chien, C.-Y. Hsu, and P.-N. Chen, "Semiconductor Fault Detection and Classification for Yield Enhancement and Manufacturing Intelligence," *Flexible Services and Manufacturing Journal,* vol. 25, pp. 367-388, 2013.

[9] F. Khatkhatay, C. C. Huang, L. Popova, J. Yoon, T. Zalocha, P. Tatti, K. Gopal, H. Shen, H. Y. Song, and A. Gupta, "Leveraging Focus Spot Monitoring Data in FEOL to Resolve a High Impact MOL Defect," *29th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC)*, pp. 249-254, 2018.

[10] M. J. Miller, M. L. Balandan, A. J. Castro, L. Ross, and M. A. Zeeshan, "Mechanisms and Control of Photolithography Hotspots in Compound

Semiconductor Manufacturing," *CS ManTech*, 2023.

[11] S. Yasuda, T. Tanaka, M. Kitabata, and Y. Jisaki, "Chamber and Recipe-Independent FDC Indicator in High-Mix Semiconductor Manufacturing," *IEEE Transactions on Semiconductor Manufacturing,* vol. 34, no. 3, pp. 301-306, 2021.

[12] K.-H. Chang, C.-C. Tsai, C.-H. Wang, C.-J. Chen, and C.-M. Lin, "Optimizing the Energy Efficiency of Chiller Systems in the Semiconductor Industry Through Big Data Analytics and an Empirical Study," *Journal of Manufacturing Systems,* vol. 60, pp. 652-661, 2021.

[13] H. Zisgen, R. Kleinhenz, H.-J. Eickelmann, M. Haubrich, and F. Marschollek, "Prediction of Chemical Consumption in Semiconductor Fabrication," *2009 IEEE/SEMI Advanced Semiconductor Manufacturing Conference*, pp. 119-123, 2009.

[14] S. J. Qin, G. Cherry, R. Good, J. Wang, and C. A. Harrison, "Semiconductor Manufacturing Process Control and Monitoring: a Fab-Wide Framework," *Journal of Process Control,* vol. 16, no. 3, pp. 179-191, 2006.

[15] S. K. Tiku, and D. Biswas, *III-V Integrated Circuit Fabrication Technology*, Boca Raton, FL: CRC Press, 2016.

[16] Keyence Corporation, " Clamp-On Micro Flow Sensor: FD-X Series," *FD-X Catalog-KA-C-US*, 2018.

ACRONYMS

FDC: Fault Detection and Classification
MLO: Metal Liftoff
NMP: *N*-Methyl-2-pyrrolidone
PR: Photoresist