ENHANCING QUALITY AND EFFICIENCY: SCADA-RTC-SPC ENGINE, UNLOCKING THE POTENTIAL OF FACILITIES SCADA AUTOMATED DATA ANALYSIS IN MANUFACTURING OPERATIONS QUALITY CONTROL AND MONITORING

Mary Irene T. Reyes
Louie Roy C. Esguerra
Christian Ivan V. Tiglao

Bump Automation / Quality
Texas Instruments Inc.
TI Clark, Clark Freeport Zone, Angeles City, Pampanga
m-reyes@ti.com, l-esguerra@ti.com, ivantiglao@ti.com

ABSTRACT

Semiconductor manufacturing operations are intrinsically reliant on facilities systems that support critical environmental and utility parameters. Disruptions in these systems pose substantial risks to product quality, particularly manifesting as oxidation and shear failures—two predominant failure modes in semiconductor metal layers.

This paper presents a novel approach to eliminating facilities-related disruptions by leveraging an automation solution through the integration of SCADA (Supervisory Control and Data Acquisition), RTC (Real Time Control and Monitoring System Architecture) a TI developed software, and SPC (Statistical Process Control) systems via the OPCUA (Open Platform Communications Unified Architecture) protocol. A predictive equation was developed to determine the allowable exposure time and moisture absorption threshold for each metal layer, enabling real-time risk assessment and interdiction. The implemented system enhances operational reliability, supports lean and lights-out manufacturing objectives, and significantly reduces dependence on external facility notifications that are susceptible to delay and failure.

1. 0 INTRODUCTION

In the highly controlled environment of semiconductor fabrication, precision and consistency are critical to ensuring yield and product reliability. Among the numerous environmental factors monitored during manufacturing, humidity and moisture control play a pivotal role in preventing oxidation and shear failure of metal layers. Traditionally, these controls are managed through facility-wide systems that are not fully integrated into the real-time automation of the manufacturing floor.

The emergence of Industry 4.0 has introduced new paradigms in manufacturing, particularly through the application of smart systems and automation. This paper explores the implementation of a SCADA-RTC-SPC Engine, designed to interface directly with facilities systems and internal automation layers, creating a feedback loop capable of active monitoring, interdiction, and notification to prevent quality excursions due to environmental factors.

1.1 Oxidation and Failed Shear

Oxidation, a chemical process where a substance loses electrons or gains oxygen, or loses hydrogen. Natural oxidation can occur within hours days weeks or even months however we can speed it up through aggressive oxidation. Aggressive oxidation happens when there is an oxidizing environment like high temperature, high moisture or high oxygen content. Studies like ‘Effect of oxidation and surface roughness on the shear strength of single-lap-joint adhesively bonded metal specimens by tension loading’ have shown that oxidation can lead to a decrease in adhesive strength or shear failure which frequently occurs at the interface of two metals stacked together where the molecular bond is weaker than the materials themselves causing them to separate. Refer to Fig 1 for the sample failed shear modes images.

Fig.1. Failed Shear Mode Images

1.2 Temperature and relative humidity

The resistance of materials decreases with increasing temperature and humidity. In contrast, surface resistance (rate) is sensitive to ambient humidity, while bulk resistance (rate) is more sensitive to temperature.[1]

We can see that in semiconductor wafers affected by uncontrolled environmental conditions like high temperature, high relative humidity or high oxygen content since it shows failure in electrical performance related to high contact resistance due to oxidation as shown in Fig. 2.

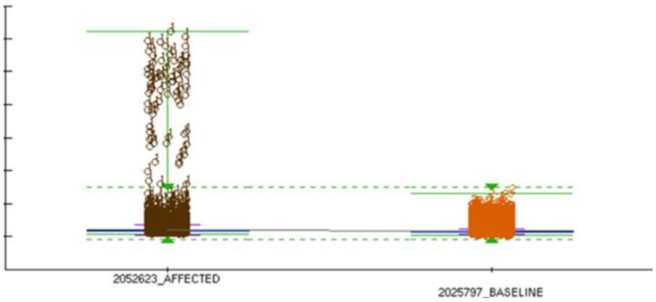

Fig.2. Contact resistance comparison

When the contact surface is oxidized, the contact resistance will increase sharply.[2]

1.3 Facilities Systems

Manufacturing plant is supported by the facilities systems. The facilities system refers to the combination of various systems within a building or facility that ensure its functionality, comfort, safety, and efficiency which includes everything from basic utilities like plumbing and electrical to more complex systems like fire protection, HVAC (heating, ventilation, and air conditioning), and security.

Environmental and process conditions inside the manufacturing line need to be monitored and maintained with extreme precision as semiconductor components like chips are extremely vulnerable to moisture. Water is, in fact, the most significant contaminant in semiconductor manufacturing, with estimates indicating that non-optimal moisture conditions account for as much as 25% of lost revenue.[3]

One known method for monitoring and control of facilities systems critical parameters, ensuring they remain within acceptable limits is automation through systems like SCADA. SCADA is highly vulnerable to cyberattack thus traditionally the system is not connected to the internet. This limited the accessibility of SCADA data to Manufacturing Operations thus created a data flow impairment and reduction in reaction time once facilities related disruption occurs. This always leads to high scrap cost and critical quality issues.

1.4 Real Time Control and Monitoring System Architecture (RTC)

To continuously gathers data such as temperature, pressure, flow rates, and other key indicators that reflect the performance and health of the tools, RTC, a TI developed software, is a real-time monitoring platform designed to track and collect critical tool parameters from manufacturing equipment through modelling. The model can also alert automation systems for any abnormalities on the tool thus avoiding its operation for production.

1.5 Manufacturing System

An MES is a software-based solution used in manufacturing to monitor and control production processes on the shop floor. In manufacturing operations, an MES serves as a bridge between the planning and control systems of an enterprise and the actual manufacturing operations.[4]

1.6 Quality System

Statistical Process Control (SPC) is a method of quality control that uses statistical techniques to monitor and control a process. Statistical Process Control is a data-driven approach to quality management that allows the user to understand, monitor, and improve processes over time. It’s like a health check-up for manufacturing processes, providing real-time insights into their performance and stability.[5] This provides a real time containment for any product processed on out of control conditions.

Citing the effect of uncontrolled facilities system and its quality risk and effect, oxidation, shear failure and high contact resistance, this study discloses the process of attaining improved reliability and reducing dependence on external facility notifications—which are prone to delays and failures—a SCADA-RTC-SPC Engine has been developed to interface directly with the SCADA system using the OPC UA protocol. This local solution enhances operational awareness, facilitates real-time monitoring, and enables proactive machine and lot interdiction and user notifications through integration with internal automation systems.

2. 0 REVIEW OF RELATED WORK

In the paper SCADA WebView: A State-of-the-Art Enterprise Transmission SCADA Engine, the authors described an architectural overview of indigenously developed WebView, a distributed, scalable, and fault-tolerant web-based transmission SCADA Engine. Kafka-based data acquisition from Power System telemetries, person-centric HMI, reporting and trending for BI, SVG-based Power system graphics editor, diagnostic tools, protocol-agnostic implementation, seamless integration with underlying protocols, support for legacy systems are the prime features of the designed system.[6]

Similar approach was used in this study further enhancing it by integrating it to automation systems.

3.0 METHODOLOGY

3.1 Environmental Conditions

This study involved using wafers with different metal layers were processed in varied conditions and exposed to different Temperature and Relative humidity setting inside an oven at a certain period of time. The critical input parameters were identified through accomplishing the input variable matrix related to processing of each metal layer. Refer to table 1.

Table 1. Input Variable Matrix for Environmental Conditions

		10	10		
#	KPIV / Input	Moisture Absorption	Shear Strength	Total	% Rank
1	Temperature	10	10	200	1
2	Relative Humidity	10	10	200	1
3	Dew Point	8	8	160	2
4	Pressure	5	5	100	3
5	Peripheral Integrity	4	4	80	4
6	Staging Time	8	8	160	2

Responses were measured through resistivity shift and shear mode results. Refer to Table 2 for the phase 1 DOE employing the input variable matrix.

Table 2. Phase 1 DOE Matrix for Environmental Conditions

	BASELINE RH and Temp		USL RH and Temp		OOS RH and Temp	
Peripheral Condition	GOOD	BAD	GOOD	BAD	GOOD	BAD
Metal A	1	2	3	4	5	6
Metal B	7	8	9	10	11	12
Metal C	13	14	15	16	17	18
Metal C + PR	19	20	21	22	23	24
PI + Metal C	25	26	27	28	29	30

In the phase 2 DOE as seen in Table 3, the study on different suppliers for sputter processing was included in the evaluation.

Table 3. Phase 2 DOE Matrix for Environmental Conditions

BUMP LAYER	**Supplier**	BASELINE RH and Temp	USL RH and Temp	OOS RH and Temp
Metal B	A	31	32	33
	B	34	35	36
Metal C + PR	A	37	38	39
	B	40	41	42
PI + Metal C	A	43	44	45
	B	46	47	48

Peripheral integrity was checked through the use of Humidity Indicator Card (HIC). Refer to table 4. Adobe Photoshop ® was used to quantify changes in gradient color-correlating to quantity of moisture present during HIC simulation.

Table 4. HIC Paper Testing Conditions

	Location	Conditions														
HIC Paper Test	Slot 1, 12, 25	Good		Bad		Good		Bad		Good			Bad			
TIME (HRS)		0.5	1	2	4	8	0.5	1	2	4	8	0.5	1	2	4	8

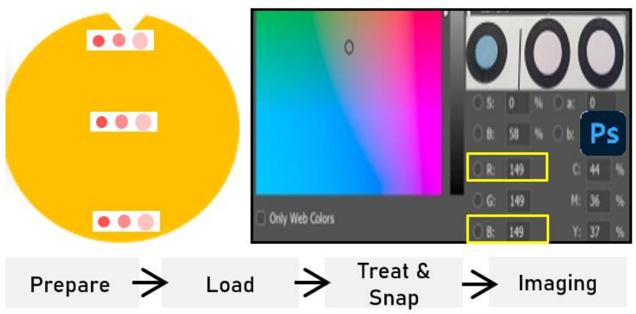

Fig. 3. Adobe Photoshop procedure for quantifying moisture Absorption

3.2 Process Gas Monitoring

The results from Section 3.1 was used in this study and applied into the determination of the best signal for detection of Process Gas Moisture Contamination. Samples taken were from baseline process and from those that were exposed to contaminated process gas. The critical input parameters were identified through accomplishing the input variable matrix related to processing of each metal layer. Refer to table 5.

Table 5. Input Variable Matrix for Process Gas Monitoring

		10	9	8		
#	KPIV / Input	Moisture content	O2 Content	Other contaminants	Total	% Rank
1	Filter Efficiency	10	10	1	198	2
2	Sensor Stability	10	10	1	198	2
3	Process Gas Concentration Purity from supplier	10	10	10	270	1
4	Hookup Procedure	10	5	5	185	3

Metal Resistivity, shear data and electrical data were measured for each wafer condition and plotted with reference to specification limits.

3.3 SCADA to RTC to SPC controls

A SCADA-RTC-SPC Engine was developed to bridge the communication between the SCADA system and internal factory automation. Using the OPC UA protocol, the engine collects real-time environmental data (temperature, humidity, pressure, etc.) and correlates it with MES for machine and Work-In-Progress (WIP) data tracked by RTC and SPC (Statistical Process Control) metrics.

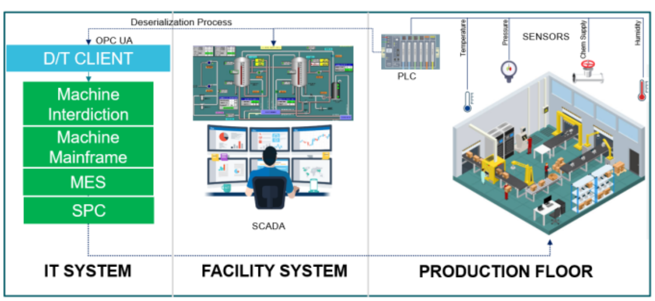

Fig. 4. SCADA to RTC to SPC controls Process Flow

4.0 RESULTS AND DISCUSSION

4.1 Environmental Conditions

Phase 1 DOE results showed Metal B, Metal C + PR, evaluations have highest response in moisture absorption as seen on Fig. 5. These metal layers and the combination with resist are most susceptible to oxidation. Using bad peripheral is also showing a significant response to moisture absorption with p-value< 0.05. Refer to Fig. 6.

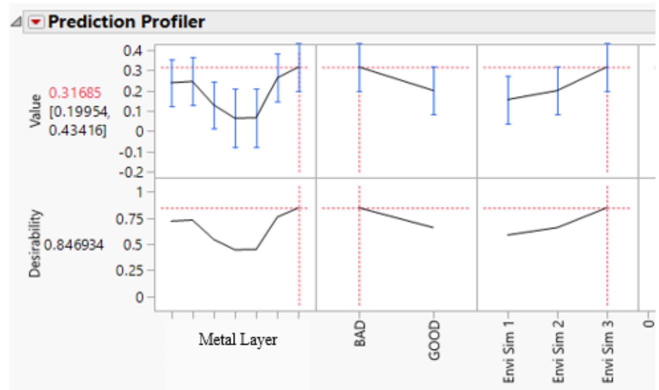

Fig. 5. Prediction Profiler results for Phase 1 DOE data

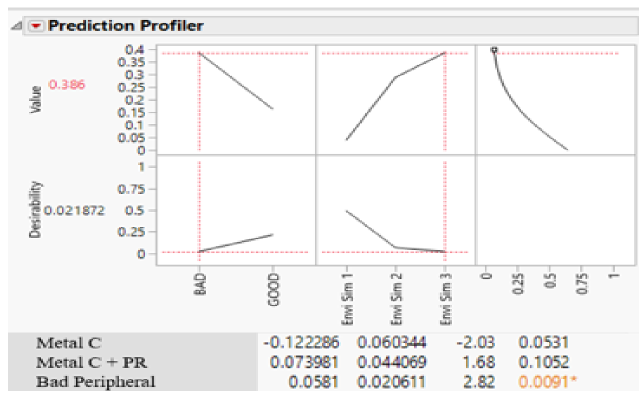

Fig. 6. Prediction Profiler results for Phase 1 DOE data

HIC testing of Bad Peripheral is showing more evident moisture absorption than Good peripheral as shown on Fig. 7-8.

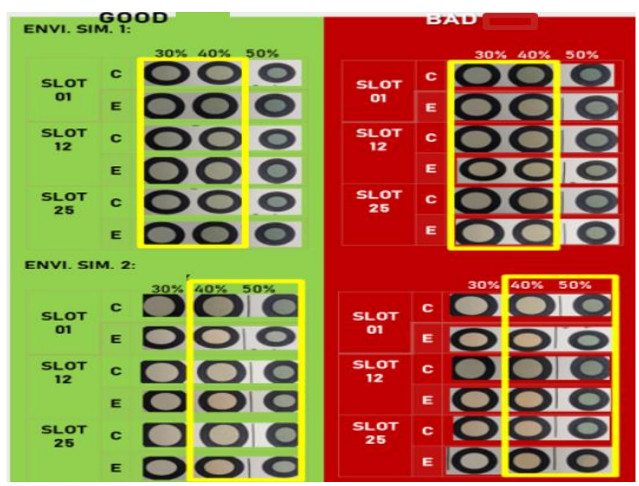

Fig. 7. HIC visual results and moisture content thru gradient color scoring

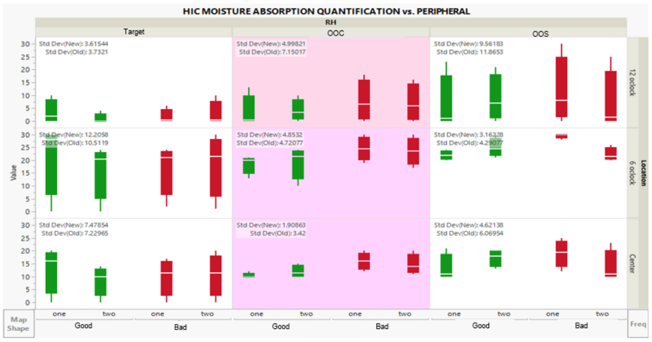

Fig. 8. HIC Moisture Absorption Quantification vs Peripheral

Predicted equation revealed that maximum moisture content of occurs at 8 hours exposure time. Above 8 hours exposure time, there is no additional absorption of moisture. Supplier B splits shows steepest slope at USL RH and Temperature thus is more susceptible to oxidation as shown on to Figure 9.

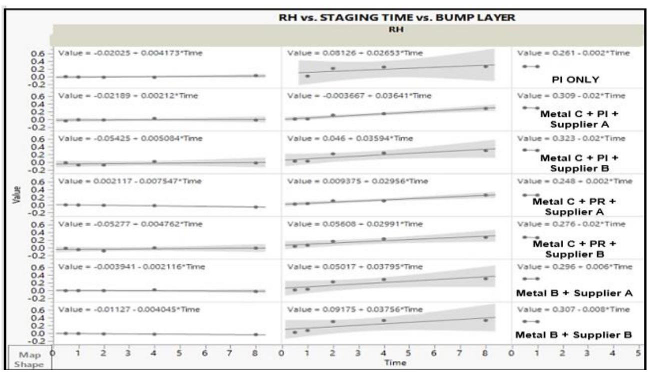

Fig. 9. Predicted Equation for each Metal and resist combination

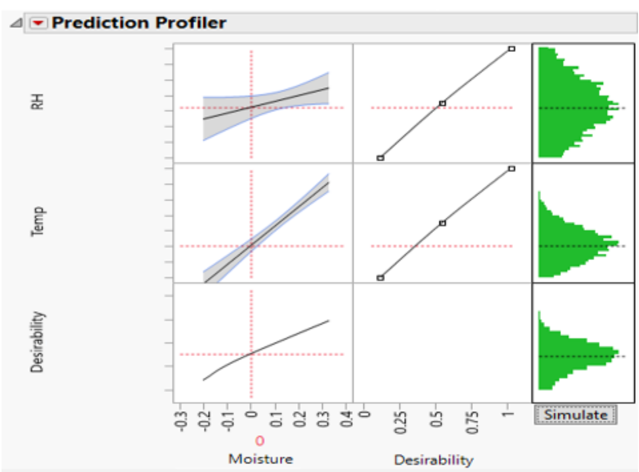

Fig. 10. Prediction profiler data for maximum relative humidity and temperature identification at zero moisture absorption

From the combined RH-TEMP simulation data, maximum RH and temperature when moisture absorption will start was identified in a prediction profiler where desirability is maximum at 1 and value of moisture is zero as shown in Figure 11-12. This calculated data is set as the control limit in the Tool Information control model

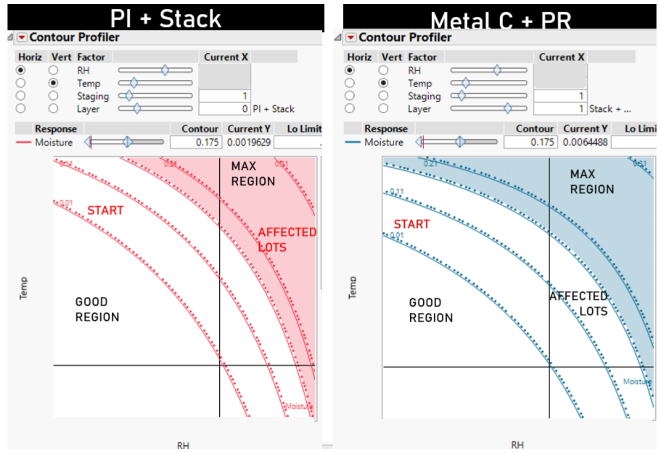

Fig. 11. Contour Profiler data for maximum relative humidity and temperature identification at zero moisture absorption

Data from process runs were analyzed to derive an empirical model predicting the critical exposure limits of metal layers. The equation calculates the rate of absorption, maximum time and moisture which we can expose our metal layers as basis of risk assessment for similar issues. This equation will help immediately plot moisture absorbed by each metal layer. Refer to Fig. 13.

Prediction Expression

-2.185307358

+0.0221269831 • RH

+0.0603116271 • Temp

+0.0037946243 • Staging

Fig. 13. Predicted Equation for Moisture Absorption

This model was validated against actual process excursions and demonstrated high predictive accuracy. The overall breakdown of % Contribution of factors causing moisture absorption test are as shown in Table 6.

Table 6. % Contribution of Factors affecting Moisture Absorption

Factor	Temperature	Relative humidity	BUMP Layer	Peripheral	Staging time	Peripheral Locks
Contribution (%)	33.7	24.3	14.6	13.76	8.33	5.31

4.2 Process Gas Monitoring

Based on the Metal A Sheet Resistance versus Moisture study, strong correlation in the increase of resistivity together with the moisture content of Process Gas which shows 89% coefficient of determination (r^2) as shown in Figure 14.

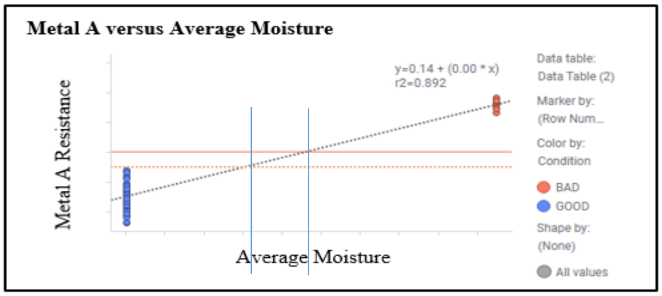

Fig. 14. Metal A resistance versus average moisture exposure.

Metal B Sheet Resistance which also manifested out of control and out of specification conditions shows only 48% coefficient of determination (r^2) as shown in Figure 15.

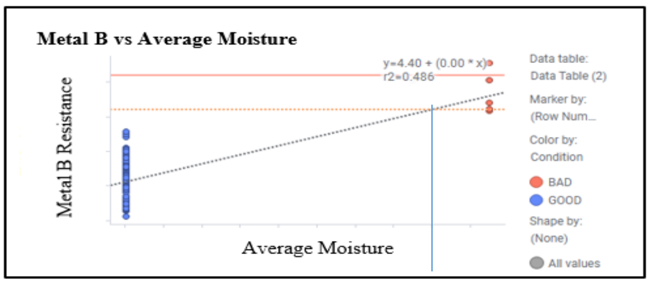

Fig. 15. Metal B resistance versus average moisture exposure.

Metal A sheet resistance can have a higher chance in detecting high moisture level when Process Gas contamination occur. With the identification of Metal A resistance as the more effective small signal for gas contamination detection, OOC and OOS moisture level are defined for the process gas and is set as limits in the Machine Interdiction model.

5.0 CONCLUSION

The SCADA-RTC-SPC Engine presents a scalable and efficient solution to a longstanding challenge in semiconductor manufacturing. By integrating facility systems directly with factory automation and embedding predictive intelligence into process monitoring, manufacturers can significantly reduce quality risks associated with environmental disruptions. This system contributes directly to operational excellence and sets the foundation for fully autonomous, lights-out semiconductor fabs.

The new % RH and Temperature set-point for BUMP must be enforced to minimize moisture absorption that is impacting die quality and reliability. In thus study, the following information was collected, maximum moisture content and absorption rate that each BUMP layers can take or absorb, derived equations providing the percentage of moisture absorbed as a function of Temperature, RH, Time of staging, to which can be used as reference for future risk assessment of similar Facilities system issue or any qualification of new chemistries or machine which may impact moisture absorption on material.

The MAD (moisture absorption desorption) analysis retrofitted to be used for samples in wafer form can be used by BUMP for any defect or issue simulation from which Environment and process moisture abnormality is the potential root cause.

The New Real Time SCADA Data Analyzer for facilities systems which monitored critical input parameters through connectivity to RTC and SPC thus enabling Auto-STATE CHANGE of machine or equipment and Auto-LOT HOLD in the manufacturing systems. The predictive equation enabled proactive quality assurance by visualizing real-time risk levels across all monitored metal layers, thereby significantly improving operational awareness.

With this program, the following benefits were achieved, Reduced Scrap Rate and Cost by > 95%, Reduced affected lots by facilities Issue by 99%, Reduced Machine downtime by 98%, Real Time Issue detection, control and immediate reaction employed at Manufacturing Operations Area.

6.0 RECOMMENDATIONS

The integration of the SCADA and manufacturing operations to react during facilities disruption events without human intervention is highly important to the execution of Lights Out Strategy. It is highly recommended to employ neural networks or machine learning for more complex and advance algorithms.

To achieve its ultimate universal applications, future enhancements will focus on expanding predictive models to other failure modes (e.g., corrosion, ESD), applying machine learning for dynamic threshold adjustments, and integrating with AI-driven decision support systems for full closed-loop control.

7.0 ACKNOWLEDGMENT

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8.0 REFERENCES

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9.0 ABOUT THE AUTHORS

Mary Irene Reyes is a graduate of Saint Louis University, College of Engineering and Architecture, Chemical Engineering Department. She joined Texas Instruments Incorporated Baguio as a New Product Development apprentice of the Flip Chip Area from June to November 2006. She continued working for TI Baguio as subcon at New Product Development Flip Chip in the Special Work Request Team from February 2008 to June 2009. She joined Texas Instruments Incorporated Clark as a Process Engineer for TI Clark Bump Area in 2009. In her 5th year of service, she became the Process team lead of Wet Clean and AVI Module until November 2022. She has then transferred to Quality and Reliability Engineering handling TI Clark Bump Area until Nov 2024 and is now handling Quality and Reliability Engineering for TI Clark WCSP and QFN Front of Line (FOL) Area.

Louie Roy C. Esguerra is an Electrical Engineering graduate from Holy Angel University. Part of the Bump Processing Engineering Team under Thin Film and Backgrind process. Also handling Bump Automations focused on Real-time process data monitoring and control systems.

Christian Ivan V. Tiglao, a Bachelor of Science in Computer Science graduate in 2010, has built a remarkable career in technology and automation. Starting as an On-the-Job Trainee at Texas Instruments in 2009, he quickly secured a role as an Applications Developer the following year. In 2015, Ivan took on a pivotal role in automation becoming the Automation Lead for the Clark site. His expertise extended globally as he supported Chengdu automation startup in 2014 and played a significant role in the TI Melaka automation startup in 2023.Beyond his professional accomplishments, Ivan channels his passion for innovation into hobbies like working on IoT projects and microcontrollers. His journey reflects commitment to advancing technology and creating impactful solutions.

10.0 APPENDIX

"Not Applicable"