MODEL OF RULE PARAMETER CREATION FOR WAFER SCRAP PREVENTION IN THE APPLIED MATERIALS CENTURA 5200 METAL ETCHER PROCESS

M.Z. Deraman[1*], Z. Ebrahim[2], G. Omar[2], W.F. Hassan[1], A. Chik[1] and Z. Darmawan[3]

[1]SilTerra Malaysia Sdn Bhd, Phase 3, Kulim High Technology Park,
09000, Kedah, Malaysia

[2]Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

[3]Faculty of Engineering, Universitas Brawijaya, MT Haryono 167, 65145,
Malang, Indonesia

*Corresponding Author's Email: mohd_zamlitajudin@silterra.com

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ABSTRACT: Products with Integrated Circuits (IC) becomes necessity in daily life such as mobile phones, computers, televisions etc. In this regard, Etching stands out as the predominant procedure in the field of semiconductor manufacturing. This process involves a number of parameters and steps that requires close monitoring in order to be efficient and competitive by minimising the premature equipment failures. This study focuses on minimisation the number of wafers at risk during wafer fabrication at metal etch process. Design of Experiment approach was applied in identifying the key parameters with a significant relationship with equipment failures and root causes of wafer scraps. The key parameters were developed into smart decision matrix that integrates with SilTerra equipment monitoring systems. Then, the key parameters were optimised for Statistical Process Control (SPC) at the Metal Etching equipment named as Applied Material Centura 5200. This implementation enables the equipment to detect potential failures and stop the relevant process parameters. In this approach, the wafers can be secured from becoming scrap, resulting in a reduction in the cycle time required for additional testing. Accordingly, wafer scrap has been significantly reduced, resulting in a 56% decrease in the total wafer scraps from the equipment.

KEYWORDS: *Metal Etch; Wafer Scrap; Fault Detection System; Parameter; Integrated Circuit.*

1.0 INTRODUCTION

The Metal Etch in wafer fabrication involves the selective removal of aluminium layers up to a specific thickness. These layers have been coated with a resist during the lithography for creating certain patterns corresponding to the design of an Integrated Circuit (IC). IC manufacturers currently take extensive measures to ensure that manufacturing processes adhere to specified standards. Monitoring wafers and Statistical Process Control (SPC) techniques have been used as monitoring tools in wafer fabrication [1]. Table 1 shows the comparison between two types of monitoring processes in wafer fabrication.

Table 1: Monitoring Methods in Wafer Fabrication

Type of control	Method	Pro	Cons
SPC	Ex-situ	Uses a test wafer for testing	Detection of defect after manufacturing can potentially affect numerous product wafers
Fault detection (FD) control	In-situ	Real-time during processing	Affects a single product wafer before the process is halted

Monitoring wafers are processed alongside Product wafers but will be taken out from production line for testing purpose especially at critical stages such at Etching. The utilisation of a large number of monitoring wafers comes at a significant costs including additional human resources that use to conduct ex-situ measurements. Also, Monitoring wafers result in reduction of product throughput as it consume space along the processes. In this regard, defect wafers would remain in production lines until electrical testing of finished product wafers for several weeks if faults were not detected. At this stage, determining which process step caused the defect wafers is highly complicated. Normally, the process must be restarted to fill the gaps, resulting in additional cost to the company. Furthermore, the fabrication of advanced ICs may require several weeks and involve more than 100 process steps [2].

Although SPC techniques can detect undesirable process shifts [3], they are typically applied off-line, resulting in their incapability of detecting shifts. This type of delay causes the fabricated wafers could not be confirmed to the required standards. Hence, it is necessary for IC industry to enhance performance and minimise manufacturing costs by focusing on process improvements for reducing production of scrap especially with critical equipment [4]. Hence, this paper presents the improvement made on equipment productivity through new approach at in-situ monitoring process. On this basis, the study involved in metal etch process especially the dry etch area that focused on; (i) the improvement of detection level through Failure Detection (FD) system and (ii) the integration system between manufacturing execution system and quality management system. The study aimed to establish an effective control on significant parameter limits by using in-line preventive control software for FD control at SilTerra Manufacturing Semiconductor in Malaysia. Thus, the study has to investigate the factors contributing to metal etch scrap due to equipment issues in order to achieve the aim.

This paper consist of four main sections. The first section introduces systems involved in monitoring quality at wafer fabrication process including its problems. The second section explains the methodology used for the new approach of monitoring process. Section 3.0 discussed the results of the experiments and the final section presents the conclusions of the study.

1.1 Wafer Scrap Monitoring Technique

As has been shown in Table 1, there are two types of monitoring approach in wafer fabrication process. Figure 1 shows the linkage between ex-situ monitoring and in-situ monitoring which supported by Failure Detection (FD) system. The interaction between the FD and the SPC monitor is depicted in Figure 1.

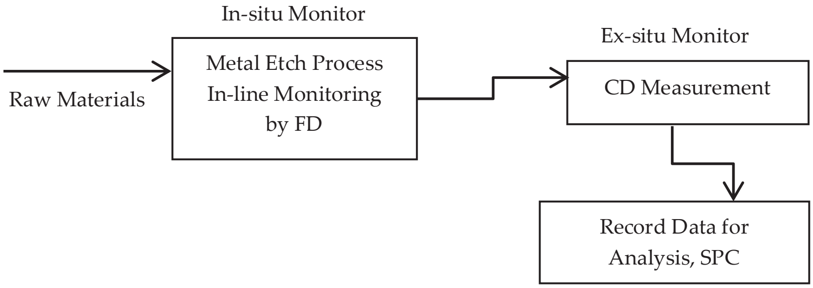


Figure 1: Linkage between ex-situ and in-situ monitoring

In-situ monitoring involves real-time monitoring of the manufacturing process, allowing for the immediate detection of any shift or deviations in the process [5]. In-situ monitoring and control are essential to minimise wafer scrap, thereby reducing the cost of using monitoring wafers and improving the conventional SPC methods. This process can also play a significant role in scheduling equipment downtime, and in the long run, predicting an out-of-control state before it actually occurs [6]. In wafer fabrication, in-situ monitoring has been applied as a cost-effective technique for enabling real-time control and decision-making in the operation of a reactive ion etcher.

1.2 Fault Detection (FD) System

In semiconductor manufacturing, detection of process and tool faults in the shortest possible time is critical for minimising scrap wafers. In metal etching, the Fault Detection (FD) system has been applied to detect early equipment parameters and minimise wafer scrap [7]. FD can capture real-time data during wafer processing and analyse the data in real-time [8]. This method is designed to minimise costly misprocessing and wafer scrap by using control charts to monitor fluctuations in critical process variables [9-11]. This technique is capable of monitoring key process parameters, including gas flow rates, RF power, temperature, and chamber pressure. Real-time data capture during wafer processing is carried out [12-13], and in-situ analysis is performed by the FD system [5].

Here, the process parameters will be captured by equipment interface through State Variable Identification (SVID) [14-15] on every second processing interval. Then, the captured process parameters will be automatically transferred to a remote work-station for further in-situ decision that uses statistical interquartile range (IQR) analysis [16]. This method can be used to compare the results with a specified target and control limits through SPC. Given that majority of these measurements are done off-line and less frequently than every wafer, this method could lead to a large number of scrapped wafers before a fault is detected. In this regard, some other faults, such as device damage during plasma etching, could pass through this limited number of wafer-state measurements undetected.

At SilTerra Wafer Fabrication, The FD system has been developed by Lodestone Inc. This system has been used as storage to perform a real-time analysis based on a process parameter model. The processing parameter data are collected on a real-time basis during wafer processing by FD. Once the data are collected, they are stored in the FD server for real-time analysis and decision-making. Figure 2 shows an example of a data collection flow by the FD system

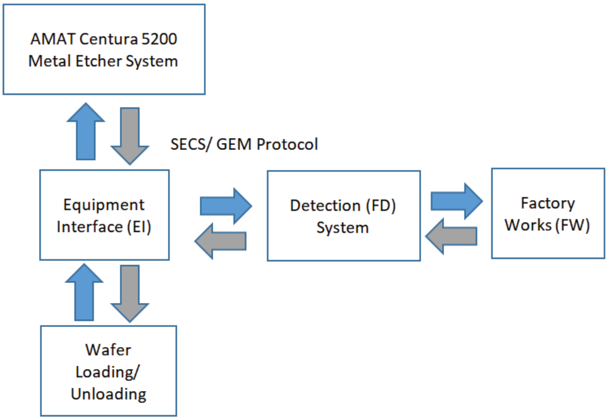


Figure 2: Example of equipment data collection flow by FD

As shown in Figure 2, the metal etch equipment represented by AMAT Centura DPS 5200 which FD communicates through the EI using the SECS/GEM interface for the machine-to-machine M2M communication protocol [17]. In this regard, the FD system will use the SVID [15] and M2M protocol to communicate with the wafer manufacturing equipment. The equipment will then determine the availability of the necessary State Variable parameters referred to as SVIDs. FD communicates with the Factory Works Intelligent Client (FWIC) in terms of what parameter has drifted, indicating whether it has deviated below the control limit or exceeded the control limit.

Accordingly, the equipment will be stopped from accepting any new production lot. This pause enables technicians or engineers to address the problem or make some adjustments on the equipment side. These SVIDs must be pre-programmed into the FD system to collect data related to the process parameters, such as pressure, temperature and gas flow information. Another important task during the FD implementation is acquiring these SVIDs by using the latest software version in which the process equipment is running on and converting them to a format compatible to the data collection software.

1.3 Problem Statement

The variations brought about by changes in mixed product runs can result in a shorter lifespan for critical input parameters of the equipment, potentially leading to equipment failures and wafer scraps [18]. Wafer scraps in SilTerra Wafer Fabrication is the main concern in this study. Table 2 provides the data on the total cumulative wafer scraps at SilTerra from 2015 to 2018, wherein 55% of SilTerra's overall wafer scraps is due to equipment-related issues which resulting in loss of 30,000 wafers, approximately.

Table 2: Overall wafer scraps by reason in three years (2015 until 2018)

No	Category/ Reason	Baseline (%)	Excursion (%)	Near-Miss (%)	Total (%)
1	Equipment	3,121 (42.54)	1,844 (25.13)	262 (3.57)	5,227 (71.24)
2	Out of Specification	110 (1.50)	1,131 (15.42)	132 (1.80)	1,373 (18.71)
3	Line Yield	39 (0.53)	232 (3.16)	85 (1.16)	356 (4.85)
4	Miss-Process	26 (0.35)	146 (1.99)	56 (0.76)	141 (1.92)
5	Failure Analysis	131 (1.79)	3 (0.04)	7 (0.10)	141 (1.92)
6	Thermal Broken	12 (0.16)	0	0	12 (0.16)
	Total (Qty)	**3,439**	**3,356**	**542**	**7,337**

SilTerra's management has provided a clear classification of wafer scrap reasons. These scrapped wafers directly result in missed delivery dates to customers, necessitating the production of additional wafers to compensate for the gaps. Hence, the company faces adverse consequences in the form of delivery delays and additional costs.

Hence, this study focuses on quantifiable improvements that can be achieved through the deployment of an in-line prevention technology and carefully designed with controlled experiments. Furthermore, such studies are rarely reported in the literature [19]. The complicated setting in the manufacturing environment further increases the difficulty of maintaining process stability and controlling quality [17].

2.0 METHODOLOGY

Integration of manufacturing execution system and quality management system is the new approach applied in Fault Detection (FD) system in this study. Hence, this study creates rules for each of the critical process parameters, which lead to frequent equipment failures based on the previous analysis. In this case, the FD control system has been used to create a rule mode for the critical process parameter. Figure 3 illustrates how the FD system has been setup.

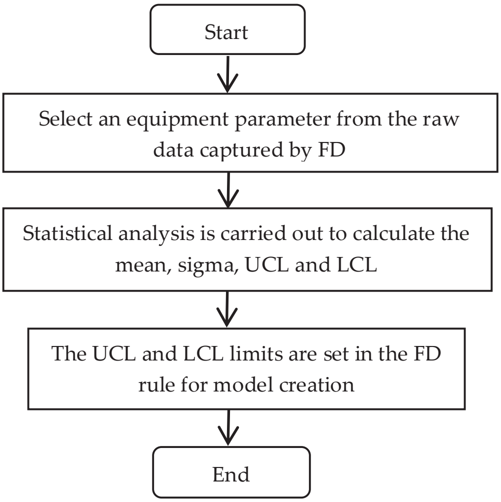


Figure 3: Flowchart of the equipment parameter FD setup

The processed raw data from the process equipment is transferred in real-time mode with an interval of every 2 seconds and stored in the FD server. Here, a parameter rule is established by extracting raw data from the FD system, followed by the calculation of the limits using statistical analysis. The data will be analysed by the FD system, and a decision will be made in real-time with feedback through the EI interface. The FWIC will record lot processing events. If the parameter limits are detected to be out of control, then the FD system will act to prevent the affected process chamber from running the next wafer. Accordingly, the chance of wafer scrap will be reduced.

Figure 4 shows the flow of creating the FD rule boundaries. In this case, a sample of 3 months of raw data was collected by using the FD server and was analysed by using the statistical analysis for sigma and mean values. In this regard, the determination of the Lower Control Limit (LCL) and Upper Control Limit (UCL) is the basis for creating a rule model for the critical process parameter (i.e. radio frequency [RF]). The rule model functions as a guideline for the process parameter, allowing for early detection before they reach the equipment hard limits. When the equipment hard limit is reached, it triggers Interrupted Lot Processing (ILP), resulting in the halt of wafer processing.

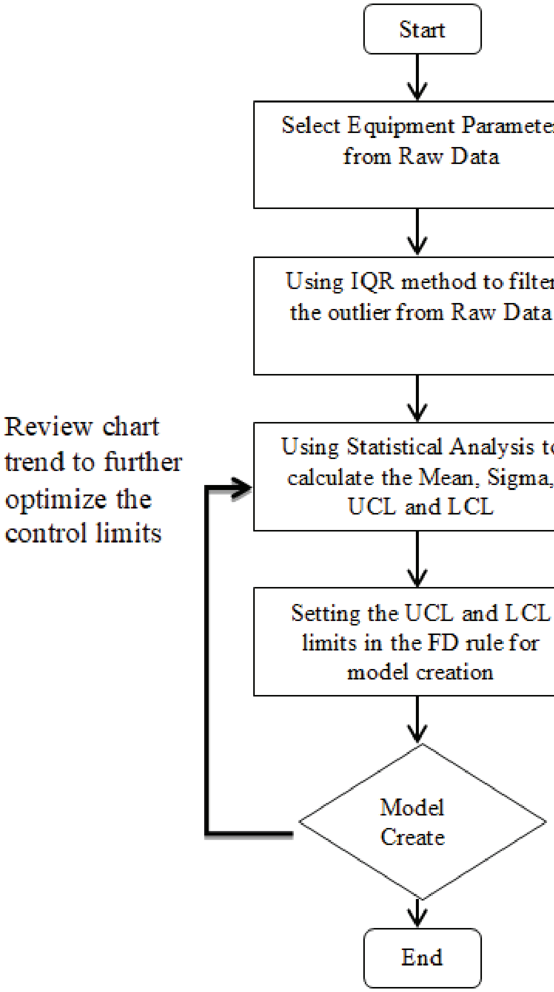


Figure 4: Flow of rule creation by the FD system

2.1 Method of Limit Calculation

The limits for creating the rule model to be used in the FD system will be calculated based on the high critical parameter raw data obtained from the analysis. The mean of the data can be determined by using Equation (1), whilst the standard deviation of the data is determined by utilising Equation (2), which will be used for setting up the limits [20].

$$\mathrm{Mean}(\bar{x}) = \sum_{i=1}^{n} (x_i)/n \tag{1}$$

$$\mathrm{STDEV} = \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 /(n-1)} \tag{2}$$

Where:
x_i = value of the i^{th} point in the data set;
$\bar{x}$ = mean value of the data set;
n = number of data points in the data set.

The FD setups a rule model for each of the process parameters in the raw data by using the values obtained from Equations 1 and 2. The UCL and LCL are calculated using Equations 3 and 4 [20].

$$\mathrm{UCL} = (\mathrm{Mean} + 3 * \mathrm{STDEV}) \tag{3}$$

$$\mathrm{LCL} = (\mathrm{Mean} - 3 * \mathrm{STDEV}) \tag{4}$$

3.0 RESULTS AND DISUSSION

Table 3 displays a sample of the approximately 4000 data examined for these RF power parameters recorded by the FD system in 2020. However, once the outlier was removed using the IQR analysis at the Main Etch (ME) process, the final count for the statistical analysis was 334 data. For instance, Table 4 shows 140 data of equipment parameters for the RF power. The FD system determines the mean, standard deviation, UCL and LCL for the equipment parameters based on the 334 data.

Table 5 shows the results obtained from the statistical analysis. The limits will be used to develop the rule model. In the FD system, the UCL and LCL values are incorporated in the SEC tool for rule creation. Both limit values are known as boundary high (UCL) and boundary low (LCL) values at the boundary field.

Figure 5 presents the FD model for the RF parameter detection after applying the limit setting, as shown in the red box limit boundary setting.

Figure 6 shows the data plotter with control limits for the equipment parameter data captured during the wafer processing. The data were divided on a weekly basis for the analysis.

Table 3: Sample of the RF parameter raw data captured by the FD system

No	Date Time	EqID	Lot ID	Recipe ID	Slot ID	Step ID	RF Value
1	18Nov20 12:04	E1MEAM04	GZY39195.1	M4K-REV1	16	ME	101
2	18Nov20 13:01	E1MEAM04	GZY39195.1	M4K-REV1	17	ME	101
3	18Nov20 14:06	E1MEAM04	GZY39195.1	M4K-REV1	18	ME	101
4	18Nov20 12:08	E1MEAM04	GZY39195.1	M4K-REV1	19	ME	101
5	18Nov20 12:10	E1MEAM04	GZY39195.1	M4K-REV1	20	ME	101
6	18Nov20 12:15	E1MEAM04	GZY39195.1	M4K-REV1	21	ME	101
7	18Nov20 12:22	E1MEAM04	GZY39195.1	M4K-REV1	22	ME	101
8	18Nov20 12:30	E1MEAM04	GZY39195.1	M4K-REV1	23	ME	101
9	18Nov20 12:35	E1MEAM04	GZY39195.1	M4K-REV1	24	ME	101
10	18Nov20 12:45	E1MEAM04	GZY39195.1	M4K-REV1	25	ME	101
11	18Nov20 12:55	E1MEAM04	GZY39196.1	M4K-REV1	16	ME	101
12	18Nov20 13:12	E1MEAM04	GZY39196.1	M4K-REV1	17	ME	101
13	18Nov20 13:18	E1MEAM04	GZY39196.1	M4K-REV1	18	ME	101
14	18Nov20 13:40	E1MEAM04	GZY39196.1	M4K-REV1	19	ME	101
15	20Nov20 12:10	E1MEAM04	GZY39197.1	M4K-REV1	16	ME	101
16	20Nov20 12:15	E1MEAM04	GZY39197.1	M4K-REV1	17	ME	101
17	20Nov20 12:20	E1MEAM04	GZY39197.1	M4K-REV1	18	ME	101
18	20Nov20 12:25	E1MEAM04	GZY39197.1	M4K-REV1	19	ME	101

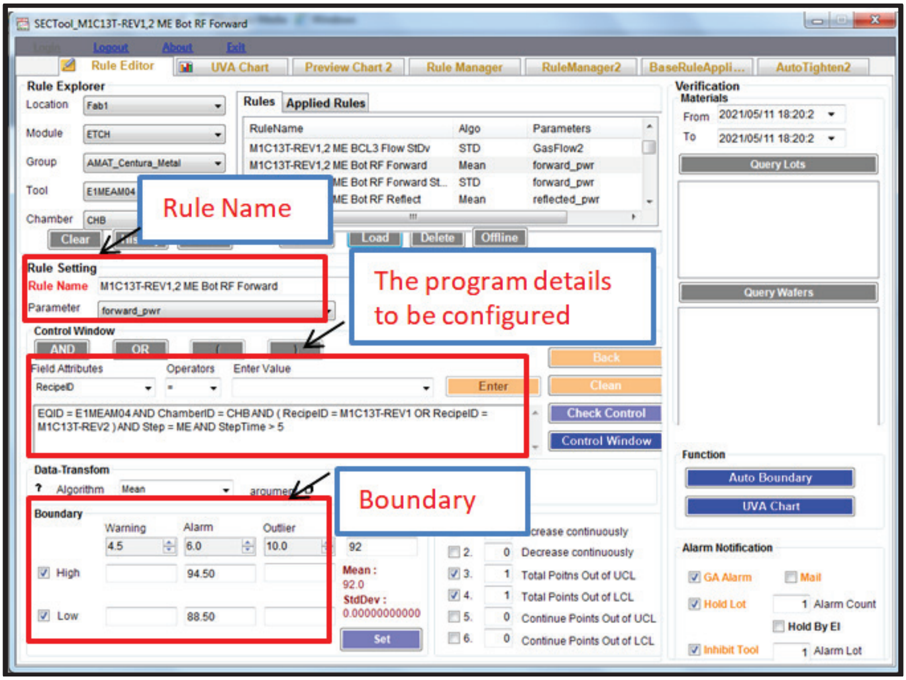
19	20Nov20 12:30	E1MEA M04	GZY391 97.1	M4K-REV1	20	ME	101
20	20Nov20 12:35	E1MEA M04	GZY391 97.1	M4K-REV1	21	ME	101
21	20Nov20 15:20	E1MEA M04	GZY391 97.1	M4K-REV1	22	ME	101
22	20Nov20 15:25	E1MEA M04	GZY391 97.1	M4K-REV1	23	ME	101
23	20Nov20 15:30	E1MEA M04	GZY391 97.1	M4K-REV1	24	ME	101
24	20Nov20 15:35	E1MEA M04	GZY391 97.1	M4K-REV1	25	ME	101
25	22Nov20 12:04	E1MEA M04	GZY391 98.1	M4K-REV1	16	ME	101
26	22Nov20 17:01	E1MEA M04	GZY391 98.1	M4K-REV1	17	ME	101
27	22Nov20 17:01	E1MEA M04	GZY391 98.1	M4K-REV1	18	ME	101
28	22Nov20 17:10	E1MEA M04	GZY391 98.1	M4K-REV1	19	ME	101
29	22Nov20 17:15	E1MEA M04	GZY391 98.1	M4K-REV1	20	ME	101
30	22Nov20 17:20	E1MEA M04	GZY391 98.1	M4K-REV1	21	ME	101
31	22Nov20 17:25	E1MEA M04	GZY391 98.1	M4K-REV1	22	ME	101
32	22Nov20 17:30	E1MEA M04	GZY391 98.1	M4K-REV1	23	ME	101
33	22Nov20 17:35	E1MEA M04	GZY391 98.1	M4K-REV1	24	ME	101
34	22Nov20 17:40	E1MEA M04	GZY391 98.1	M4K-REV1	25	ME	101
35	22Nov20 17:45	E1MEA M04	GZY391 98.1	M4K-REV1	9	ME	101
36	22Nov20 17:5	E1MEA M04	GZY391 98.1	M4K-REV1	12	ME	101

Table 4: RF power data 1 until 140

NO	RF Power	NO	RF Power	NO	RF Power	NO	RF Power	NO	RF Power
1	92	29	92	57	92	85	92	113	92
2	92	30	92	58	92	86	92	114	92
3	92	31	92	59	92	87	92	115	92
4	92	32	92	60	92	88	92	116	92
5	92	33	92	61	92	89	92	117	92
6	92	34	92	62	92	90	92	118	92
7	92	35	92	63	92	91	92	119	92
8	92	36	92	64	92	92	92	120	92
9	92	37	92	65	92	93	92	121	92
10	92	38	92	66	92	94	92	122	92
11	92	39	92	67	92	95	92	123	92
12	92	40	92	68	92	96	92	124	92
13	92	41	92	69	92	97	92	125	92
14	92	42	92	70	92	98	92	126	92
15	92	43	92	71	92	99	92	127	92
16	92	44	92	72	92	100	92	128	92
17	92	45	92	73	92	101	92	129	92
18	92	46	92	74	92	102	92	130	92
19	92	47	92	75	92	103	92	131	92
20	92	48	92	76	92	104	92	132	92
21	92	49	92	77	92	105	92	133	92
22	92	50	92	78	92	106	92	134	92
23	92	51	92	79	92	107	92	135	92
24	92	52	92	80	92	108	92	136	92
25	92	53	92	81	92	109	92	137	92
26	92	54	92	82	92	110	92	138	92
27	92	55	92	83	92	111	92	139	92
28	92	56	92	84	92	112	92	140	92

Table 5: RF power data statistical analytical results (SilTerra, 2020)

No	Statistical Analysis	Value
1	Mean	91.0
2	sigma	1.1
3	3-sigma	3.3
4	LCL	88.5
5	UCL	94.5



Rule Name

The program details to be configured

Boundary

Rule Explorer

Location: Fab1
Module: ETCH
Group: AMAT_Centura_Metal
Tool: E1MEAM04
Chamber: CHB

Rules | **Applied Rules**

RuleName	Algo	Parameters
M1C13T-REV1,2 ME BCL3 Flow StDv	STD	GasFlow2
M1C13T-REV1,2 ME Bot RF Forward	Mean	forward_pwr
ME Bot RF Forward St...	STD	forward_pwr
ME Bot RF Reflect	Mean	reflected_pwr

Verification
Materials
From: 2021/05/11 18:20:2
To: 2021/05/11 18:20:2

Rule Setting
Rule Name: M1C13T-REV1,2 ME Bot RF Forward
Parameter: forward_pwr

Control Window
Field Attributes: RecipeID
Operators: =
Enter Value:

EQID = E1MEAM04 AND ChamberID = CHB AND (RecipeID = M1C13T-REV1 OR RecipeID = M1C13T-REV2) AND Step = ME AND StepTime > 5

Data-Transform
Algorithm: Mean
argumen

Boundary

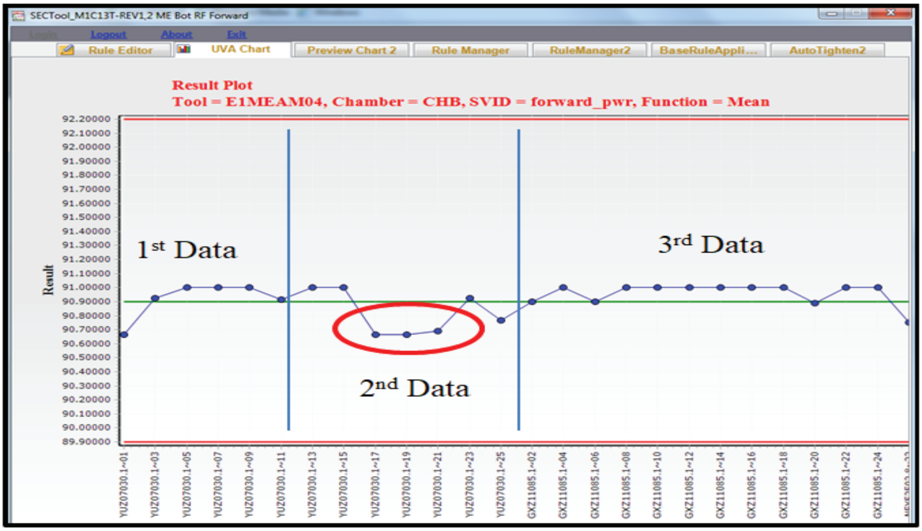
	Warning	Alarm	Outlier
	4.5	6.0	10.0
☑ High		94.50	
☑ Low		88.50	

92
Mean : 92.0
StdDev : 0.00000000000

crease continuously
☐ 2. 0 Decrease continuously
☑ 3. 1 Total Poitns Out of UCL
☑ 4. 1 Total Points Out of LCL
☐ 5. 0 Continue Points Out of UCL
☐ 6. 0 Continue Points Out of LCL

Alarm Notification
☑ GA Alarm ☐ Mail
☑ Hold Lot 1 Alarm Count
☐ Hold By EI
☑ Inhibit Tool 1 Alarm Lot

Figure 5: RF parameter FD model setting



1st Data

2nd Data

3rd Data

Figure 6: RF power plotter results

In Figure 6, the upper and lower control limits are indicated by the setting marks with red lines. All values entered into the plotter for each sample are significantly within the control limits. However, the second data are somewhat below the target value but is still entirely within the range of control. Accordingly, the applied power has an effect on the electron energy distribution and causes greater collisional processes. The etch rates often monotonically increased with the increase in the applied power [21]. The result obtained is similar with {21]. Table 6(a) and Table 7 shows the comparison between before and after the implementation of the FD system.

Table 6(a): Data of equipment scrap cost before implementation (2015–2018)

Equipment Scrap Cost (Before)	2015	2016	2017	2018	Total (USD)
Gas Failure	2,847.20	269.25	354.90	746.50	4,217.85
Pressure	8,595.60	2,421.30	3,924.60	2,704.40	17,645.90
RF Alarm	53,714.20	18,819.35	15,933.00	93,388.45	181,855.00
Temperature	1,962.65	1,818.50	1,582.90	1,405.75	6,769.80
Overall (USD)	67,119.65	23,328.40	21,795.40	98,245.10	210,488.55

Table 7: Data of equipment scrap cost after the implementation (2019 until 2022)

Equipment Scrap Cost (After)	2019	2020	2021	2022	Total (USD)
Gas Failure	1,315.00	192.20	277.60	304.60	2,089.40
Pressure	1,361.05	1,469.00	1,563.35	1,622.65	6,016.05
RF Alarm	45,102.40	12,876.35	14,323.45	13,714.30	86,016.50
Temperature	197.80	776.30	1,035.00	388.15	2,397.25
Overall (USD)	47,976.25	15,313.85	17,199.40	16,029.70	96,519.20

Figure 7 shows the trend of wafer scrap starting from 2015 to 2022. The FD model of rule has been implemented since 2019. Figure 7 clearly shows that the reduction in wafer scrap since then.

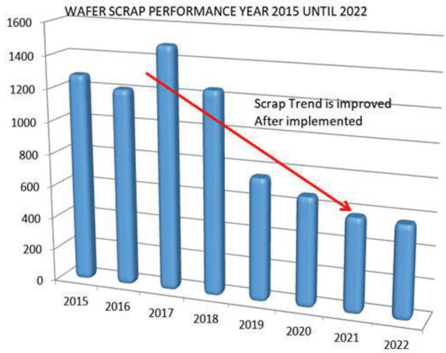


Figure 7: Etch wafer scrap trend from 2015 to 2022

4.0 CONCLUSION

Development of a rule model for the equipment parameters, using limits from the integration between the FD system and the IQR, has significant effect on the wafer scrap reduction. The novelty lies in establishing a real-time process parameter model that is integrated in the data during wafer processing, enabling the machine to be promptly halted upon detecting any out-of-control data. In this regard, the FD plotter chart is monitored to trigger the alarm based on the model setup. This proactive response acts as an early detection mechanism, providing real-time feedback before the machine's hard alarm triggers and leads to wafer scrap. The ultimate result of this study is the development of a rule-based model for equipment parameters, which had led to a significant reduction in wafer scraps at the Dry Etch equipment, achieving a remarkable 56% reduction in wafer scraps during the same period before the implementation.

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AUTHOR CONTRIBUTIONS

M.Z. Deraman: Conceptualisation, methodology, writing—original draft and preparation; Z. Ebrahim: Data structure, data validation, and editing; G. Omar: data structure; W.F. Hasan: Data collection and validation; A. Chik and Z. Darmawan: Validation, writing–reviewing and editing.

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