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Salicide Residues Defects Characterization and Reduction in Front-End Pre-Metal Cleaning Process Wafer Fabrication

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ABSTRACT: High yield with minimal defect is always a key focus in semiconductor wafer fabrication process. Salicide residue defect is one of the major killer defect in pre-metal front end wet cleaning process in wafer fabrication process. The defect is contributing a total of 1% loss in overall wafer fab sort yield, that is an equivalent to USD$ 5 million loss per year. The objective for this research is to characterise the residue defect element and to identify the root cause of the residue defect in the wafer substrate. Investigation of one factor at the time has been conducted with various experiments including screening all the hardware resources available by using ANOVA studies. The finding has concluded that the salicide residue consists of carbon defect is observed after Salicide Pre-Clean step when the standard diluted hydrofluoric acid (dHF) is used by the wet station equipment to clean the product wafers

KEYWORDS: Wafer fabrication; pre-metal layer cleaning; salicide residue; diluted Hydrofluoric acid.

INTRODUCTION

Semiconductor wafer fabrication is the most complex manufacturing processes compared with any other industries. As shown in Figure 1, the fabrication of semiconductor wafer requires just in time and not too late scheduling. Too early job completion leads to inventory costs and a delay job completion may decrease customer satisfaction. With such characteristics as the large production scale, the diversity of machine types, the complex process route and highly dynamic environment of manufacturing system (Wang et al, 2018). The semiconductor wafer fab manufacturing integrated circuits also known as chips. They are manufactured on thin silicon disks called wafers, processed in semiconductor wafer fabrication facilities (wafer fabs).

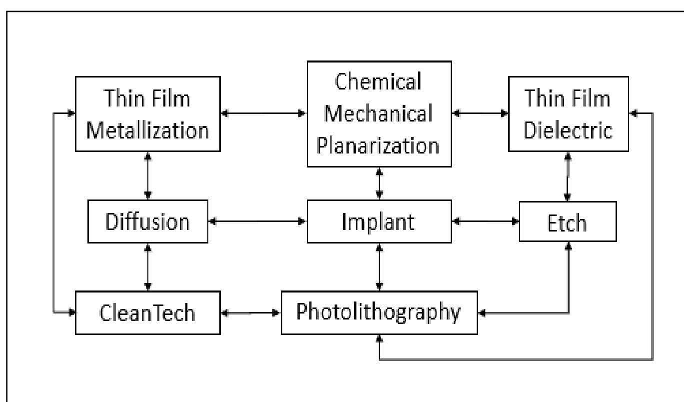

Figure 1. An illustration of a complex Semiconductor wafer fabrication process flow (Fatah, 2019; SilTerra Industrial Engineering, 2017; Kacar et al., 2016)

To stay competitive in today's wafer fab business, companies must make efforts to ensure many aspects to meet with stringent specifications (Conner, 2011). Apart from meeting the shortest product cycle time, producing high quality wafer helps to reduce the number of rejects and the need for replacement to the customer (Even et al, 2017). The wafer cleaning process contributes a large portion of the total process and plays major roles for any new technology introduction which includes new recipes development for new material removal and verification of current process capabilities. Wafer cleaning processes in general are divided into a single wafer cleaning and batch wafer cleaning. In most cases, a single wafer cleaning process provides an overall 2% to 5% better yield (Liang, 2016).

In this study, the focus is to address the problem of a new product introduction that causes the existing wafer process recipes although able to remove the respective material efficiently but produces defects on the salicide residue remaining count on the wafer surface. This will then interrupt the salicide growth of the next process and

subsequently has an impact on the electrical functionality which will eventually lead to a rejection of the wafer at the customer side. This can potentially cause millions of dollars of loss due to the die failures. As illustrated in Figure 2, salicide residue defect is found after the cleaning process and it has been identified as one of the key factors that directly contributes to loss.

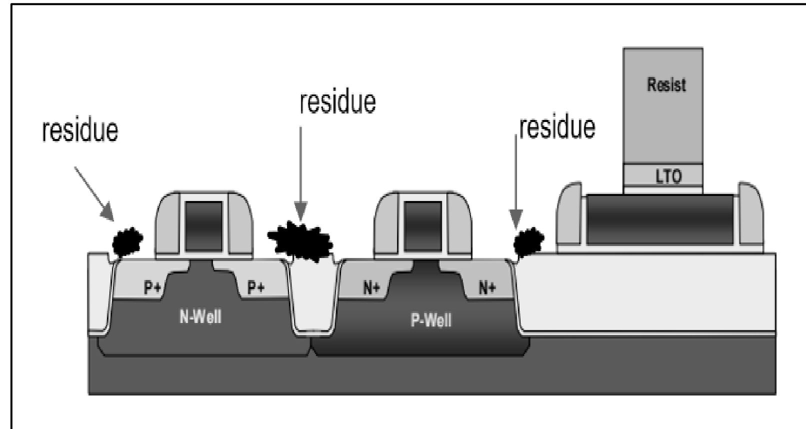

Figure 2. Residue deposited after salicide cleaning process (SilTerra Yield, 2018)

The defect is contributing a total of 1% loss in overall fab yield (SilTerra ILM, 2016). A salicide residue is a carbon defect that is observed after Salicide Pre-Clean step in the wafer process flow. The defect will usually cause an induced leakage current which will directly impact the electrical performance of the semiconductor device (SilTerra Fab Integration, 2019).

NOVELTY OF STUDY

Thispaper discusses the significance of the study both in the process and hardware engineering in the area of the semiconductor wafer fab industry. To benefit the engineers from semiconductor wafer fab and any other manufacturing industries, this study shall provide good reference in utilizing the systematic approach methodology used as a tool in resolving process, quality and manufacturing related problems.

METHODOLOGY

The concept of contaminant is investigated primarily within the boundaries of cleaning module. The investigation shall limit within the pre-diffusion Salicide Pre-Metal layer cleaning process steps. The field of study is also limited to the access within the cleaning module. Due to this, the process tuning parameters studies will also be limited within the cleaning process. The access into other module process is not possible during the study as all the engineering runs and experiments conducted were only allowed to be conducted within the cleaning module with very close monitoring from the module process team.

This research consists of experiments conducted to characterize the residue element and to identify the root cause of the residue defect in the wafer substrate at Salicide Pre-Clean wafer fabrication process. The complete experiments are summarized as shown in Figure 3. The screening experiments covers the process recipe, the equipment hardware as well as scrutinize if the residue is already embedded before the wafer reached the salicide pre-clean step. The experiments to determine the residue defect solution cover the extensive equipment types testing and modifications of recipe flows that are discussed.

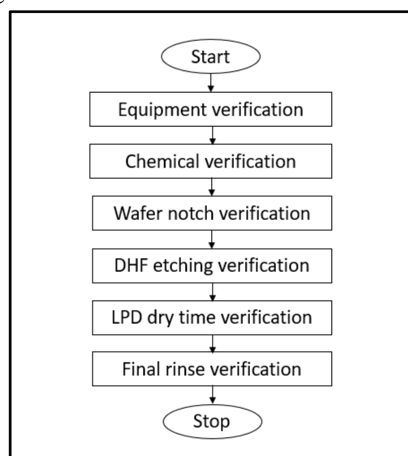

Figure 3. Salicide residue defect troubleshooting flow chart

PREPARATION

Test wafers are allowed to undergo the “short loop” process flows whereby the processing sequences and steps ultimately similar to actual complete production process steps except that several noncritical measurement steps that are omitted in order to “express” and rush the wafers into the desired steps, which is “Block Etch Resist Strip”. A typical standard production wafers take months to get into this step from the Wafer Start stage. But in the short loop flow, the test wafers could reach the desired step within 2 weeks. A short loop that is a created for the experimental wafer run through only some of the key process steps as shown in Figure 4.

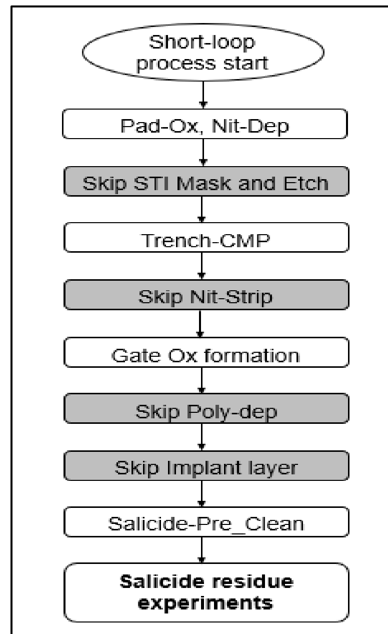

Figure 4. C18 CMOS process flow (Lee and Goh, 2017)

SAMPLING SIZE

There are 280 random selected pods that are sent for residue scan and inspection. Among the 280 lots, 178 lots are from CXX device. A total of 266 lots are found with salicide residues. And among the 266 lots, 176 lots belonged to the CXX device as shown in Table 1.

Table.1. Residue hit-rate

	All	*CXX*
Total scanned	280	178
Affected with residue	266	176
Hit rate	95%	99%

Referring to Table 2, the number of the affected wafers clearly showed that CXX device yielded the highest percentage of lot impact list from the scanned results. The CXX device occupied 95% wafer hit rate from the total scanned wafers, and among a total of 4094 wafers that are scanned, and 3872 wafers are reported to have carbon residues.

Table.2. Scanned wafer hit-rate

	All	*CXX*
Number of wafer scanned	6440	4094
Number of wafer affected	5852	3872
Hit rate	91%	95%

As the data suggested, a list of test wafers is allowed to start and be processed through the standard CXX process flow and all the wafers are then kept on hold after Block Etch Resist Strip (BLRS). Based on the number of wafers affected, it is listed at 65%, the design of experiment therefore required 2

Pods with 25 wafers from each pod to validate the result for all experiments that are carried out.

EXPERIMENTS

There are total of 6 main experiments to be conducted. The objective is to determine the root cause and streamline the focus to locate the source of the residue defect. As illustrated in Figure 5, a step-by-step verification is carried out to review if only a specific production tool within the CleanTech module is contributing to the residue. A study is done to determine if there are any correlation between the machine chemical life, process bath, the notch orientation from the wafers and the cleaning process recipe that contributed to the effect on the residue defect. The pre-verification also studied the drying recipe from the low-pressure dryer and final rinsing duration. The experiments are conducted in one of a time (OFAT). There is no interaction study between the experiments due to the lack of flexibility and opportunity in getting the set up done, while obtaining access to the production equipment from the manufacturing always remained a challenge.

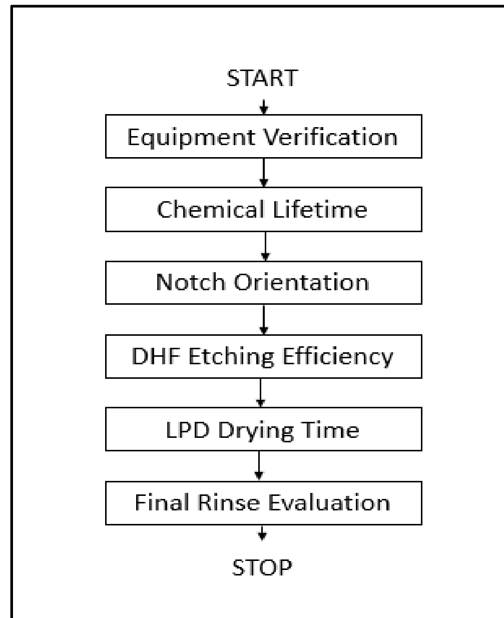

Figure 5. Phase 1 defect identification flowchart

RESULTS AND DISCUSSIONS

As shown in the defect images in Figure 6, the images show the scanned result that consists of the defect on the wafer. The energy-dispersive X-ray (EDX) analysed and found two major elements from the scanned wafers, carbon (C) and silicon (Si). Silicon is detected as the scanning electron microscope (SEM) picks up the bare wafer surface which is a silicon base as comparison.

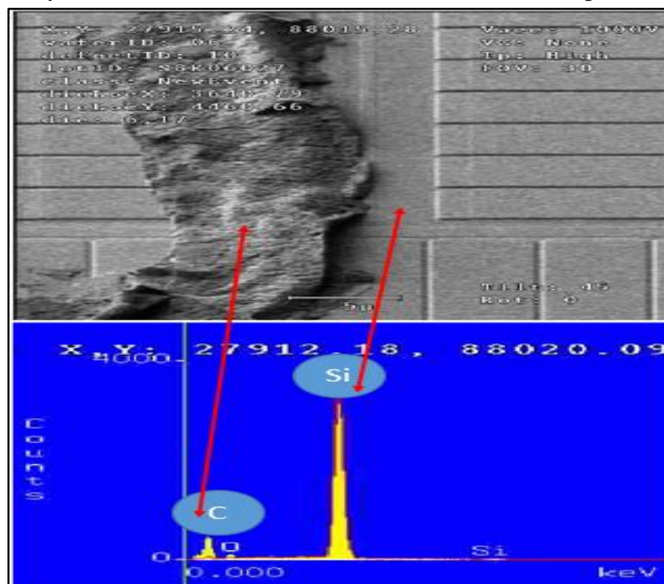

Figure 6. Actual SEM images and EDX from failure analysis results (SilTerra Failure Analysis, 2019)

The EDX scan showed a consistency in detecting carbon as major elements from the residues that resided on the post experimental wafers. As such the primary first objective which is to characterize the residue material in salicide residue is met.

The data result is then verified using Shapiro-Wilk (SW) test for null hypothesis from the normally distributed samples collected. Shapiro-Wilk (SW) was chosen to use as an analysis tool due to process dynamics. The test statistic is derived as Equation (1).

$$shapiro\ wilk = \frac{(\sum_{i=1}^{n} a_i\, x_{(i)})^2}{\sum_{i=1}^{n}(x_i - x)^2} \qquad 1.$$

Where the abbreviation of the equation defined as; $x(i)$ is the order statistic, x is $(x_1 + \ldots + x_{50})$ from the sample means, and the coefficient alpha (a) is set at 95% and is used to extrapolate in JMP 5.2.1 statistical analysis software.

The overall summary is collected and tabulated as shown in Table 3. The data collection consumed a large portion from the project development time. The goodness of fit p-value obtained from all results are more than 0.05 hence therefore the data are concluded as independent of equal variance and normally distributed. Given a very limited equipment available time, each experiment is executed very carefully to mitigate potential error that will lead to wastage. Analysis must also be conducted carefully. Data must be validated to assure the integrity result is obtained

Table.3. Experiment summary with data integrity test

Experiment	Condition	Lot	Goodness of fit	Independent	Equal Variance
Standard	standard	SSMK*.1	0.474	Yes	Yes
		SSMK*.3	0.096	Yes	Yes
	Fresh	SFMK*.2	0.372	Yes	Yes
		SFMK*.3	0.125	Yes	Yes
	End	SEMK*.2	0.18	Yes	Yes
		SEMK*.4	0.83	Yes	Yes
Notch orientation	Std	NSMK*.2	0.634	Yes	Yes
		NSMK*.3	0.331	Yes	Yes
	Air dry	NAMK*.3	0.168	Yes	Yes
		NAMK*.4	0.055	Yes	Yes
	Rotate before LPD	NRMK*.2	0.672	Yes	Yes
		NRMK*.4	0.361	Yes	Yes
LPD Drying	30s	LPD3*.2	0.778	Yes	Yes
		LPD3*.3	0.088	Yes	Yes
	60s (std)	LPD6*.4	0.658	Yes	Yes
		LPD6*.5	0.07	Yes	Yes
	90s	LPD9*.8	0.13	Yes	Yes
		LPD9*.9	0.213	Yes	Yes
	Nozzle Adjust	LPDN*.10	0.095	Yes	Yes
		LPDN*.11	0.119	Yes	Yes
Final Rinse	120s (std)	FR12*.2	0.53	Yes	Yes
		FR12*.4	0.156	Yes	Yes
	300s	FR30*.5	0.237	Yes	Yes
		FR30*.6	0.122	Yes	Yes
	600s	FR60*.8	0.208	Yes	Yes
		FR60*.9	0.646	Yes	Yes
DHF Etching	90s	DE90*.10	0.459	Yes	Yes
		DE90*.11	0.138	Yes	Yes
	150s	DE15*.12	0.068	Yes	Yes
		DE15*.13	0.167	Yes	Yes
	300s	DE300*.14	0.122	Yes	Yes
		DE300*.15	0.514	Yes	Yes
	120s (std)	DE120*.16	0.08	Yes	Yes
		DE120*.17	0.141	Yes	Yes

The next phase of the data analysis review is to feed the experiment results into a variability chart by using the JMP 5.1.2. to screen for the significant factors that are supporting the hypothesis as shown in Figure 7.

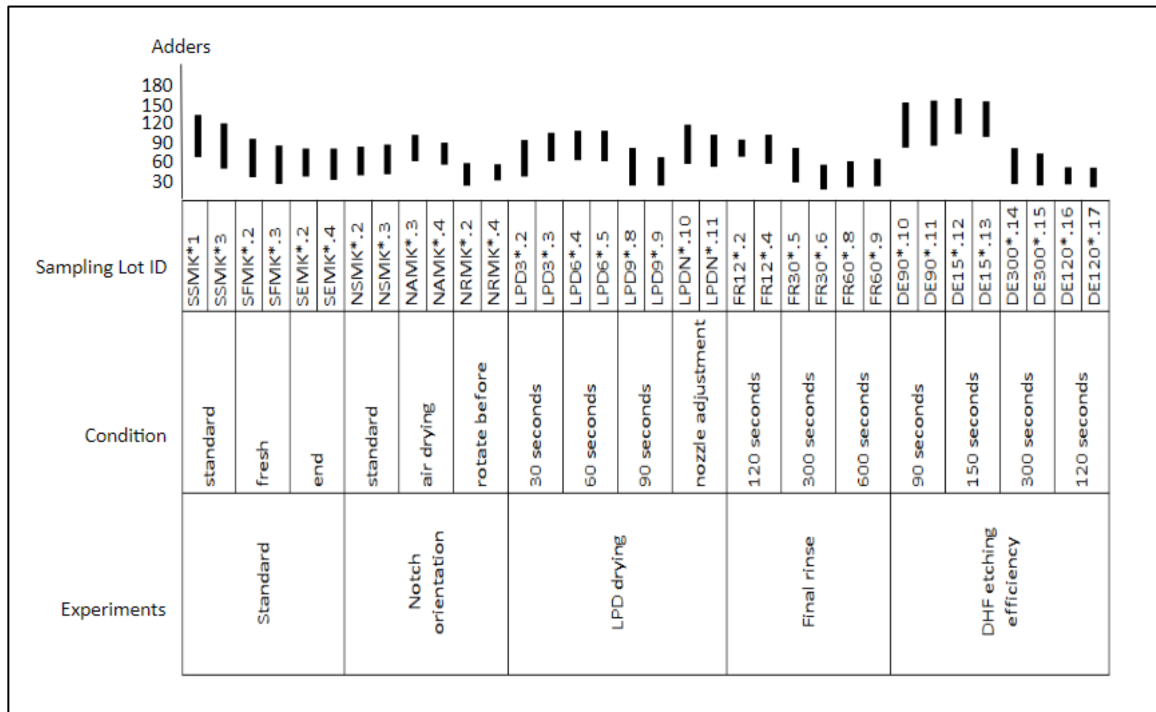

Figure 7. Actual image taken from JMP Variability chart from Phase 1 experiment

As seen from the variability chart above, all experiments carried indeed showed that the particle adders count is surpassing the salicide residue screening specifications, that is 20 adders counted. All experiments yield the adders result in the range of 40 adders to 80 adders. This is indicating overall root cause screening experiments over the chemical life, dHF efficiency test, LPD drying time and notch orientation check indeed return with null significant result. The salicide residue particle adders is still seen on the wafer surface at the 6 o’clock to 9 o’clock region. However, the experiments from notch orientation to screen dHF process bath show particle adder results are observed higher with particle adder counts. Wafer samples from Lot NRMK*.2 and NRMK*.4 are detected at the range from 120 adders to 160 adders for the condition rotate before LPD. Furthermore, the residue location from this experiment shifted 180° to a new location spotted at 12 o’clock to 2 o’clock region as illustrated in Figure 8.

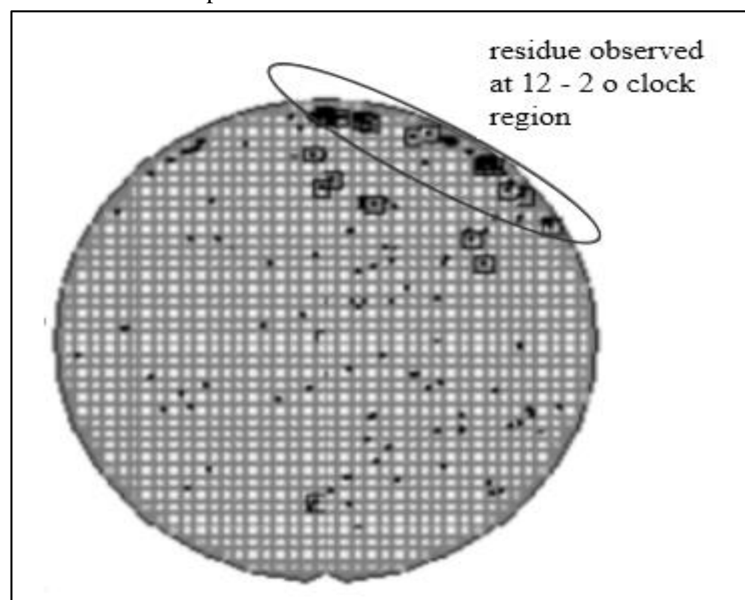

Figure 8. Stack map showing residue result has shifted by 180o to a new location at 12 o’clock to 2 o’clock on the wafer

The new residue location observed from this result correlates with the manual rotational angle from the experimental wafers after Salicide Pre-Clean process in dHF bath, and before processing inside the LPD. The residue must have stayed on the wafers from any potential process baths before the LPD process. Likewise if the results obtained remain unchanged, therefore it is then that it can stated confidently that the residue could be contributed from the LPD.

The results from the rotational experiment with air drying condition also obtained with additional adders in the range of 120 adders to 160 adders. This observation of salicide residue remains at the same original location as shown in Figure 9, which is the 6 o’clock to 9 o’clock region despite skipping the LPD process.

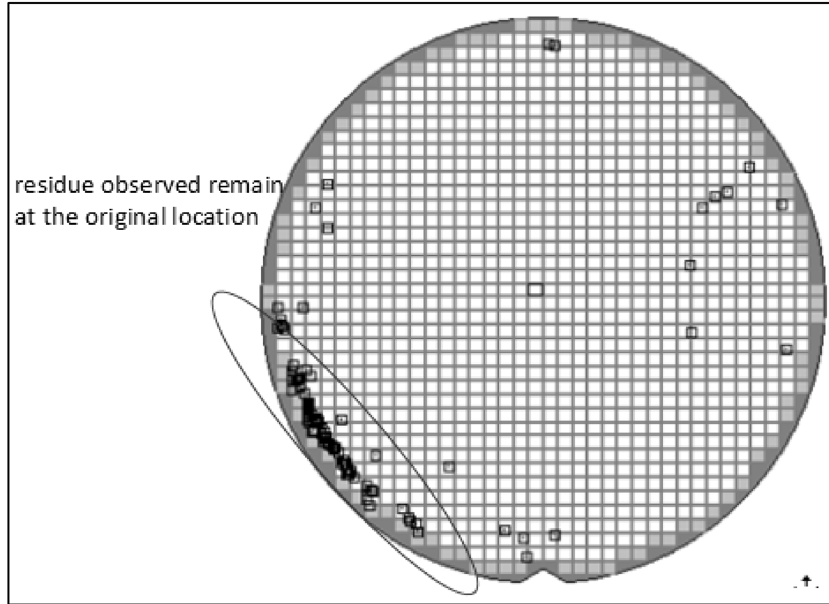

Figure 9. Stack map from Lot RMK15314.3 and Lot RMK15314.4 showing residue result remains at 6 o’clock to 9 o’clock region on the wafer

Since the residue is still observed even though without the LPD process, the LPD process cannot be considered as one of the factors. Having said that, the possible root cause that contributed to the residue left with the remaining process baths before the LPD process bath, which are dHF and the EDR process baths that require focus. The summary of rotational and air-drying experiments can be summarized as shown in Table 4.

Table. 4. Rotation and Air Drying experiments hypothesis summary

Scan result	*Observation*	*Hypothesis*	*Suspected bath*
Residue detected	Location remained at 7 o'clock region	possible root cause - after rotation done on the wafer	LPD, output unloader
Residue detected	Location changed and followed experimental rotation shift angle	possible root cause - before rotation done on the wafer	input loader, dHF, EDR

DOE carried a total of 24 runs inclusive of 1 repetition is to find out any correlation within the main factors residing in dHF and EDR process baths. dHF etching efficiency is determined by several key factors namely the etching time, chemical temperature and the HF mixing ratio. The supporting factors are the fluid flowrate from the chemical bath and the EDR bath as high chemical and DIW flowrate enhanced the etching efficiency in the process. ThePhase 1 DOE performed on dHF and EDR process parameters therefore is valid after ruling out the LPD as the main contributor.

The experiment continues to utilize the design of experiment by the JMP 5.1.2 to construct the experiment run table as shown in Table 5.

Table. 5. Actual table taken from JMP 5.1.2 DOE full factorial table with one repetition

Run	Pattern	Process Time	DHF Flow	EDR Flow	Particle Count
1	Process time = 170s, DHF flow = On, EDR flow = Off	170	On	Off	354
2	Process time = 170s, DHF flow = Off, EDR flow = On	170	Off	On	589
3	Process time = 300s, DHF flow = Off, EDR flow = Off	300	Off	Off	699
4	Process time = 430s, DHF flow = Off, EDR flow = On	430	Off	On	354
5	Process time = 170s, DHF flow = On, EDR flow = On	170	On	On	239
6	Process time = 300s, DHF flow = Off, EDR flow = On	300	Off	On	989
7	Process time = 430s, DHF flow = Off, EDR flow = On	430	Off	On	330
8	Process time = 430s, DHF flow = On, EDR flow = Off	430	On	Off	590
9	Process time = 170s, DHF flow = On, EDR flow = On	170	On	On	208
10	Process time = 300s, DHF flow = On, EDR flow = Off	300	On	Off	343
11	Process time = 300s, DHF flow = On, EDR flow = Off	300	On	Off	322
12	Process time = 430s, DHF flow = Off, EDR flow = Off	430	Off	Off	744
13	Process time = 430s, DHF flow = On, EDR flow = On	430	On	On	405
14	Process time = 170s, DHF flow = Off, EDR flow = Off	170	Off	Off	1652
15	Process time = 430s, DHF flow = On, EDR flow = Off	430	On	Off	226
16	Process time = 430s, DHF flow = On, EDR flow = On	430	On	On	429
17	Process time = 170s, DHF flow = Off, EDR flow = On	170	Off	On	369
18	Process time = 300s, DHF flow = Off, EDR flow = On	300	Off	On	802
19	Process time = 430s, DHF flow = Off, EDR flow = Off	430	Off	Off	452
20	Process time = 300s, DHF flow = Off, EDR flow = Off	300	Off	Off	220
21	Process time = 300s, DHF flow = On, EDR flow = On	300	On	On	128
22	Process time = 300s, DHF flow = On, EDR flow = On	300	On	On	169
23	Process time = 170s, DHF flow = Off, EDR flow = Off	170	Off	Off	781
24	Process time = 170s, DHF flow = On, EDR flow = Off	170	On	Off	292

The DOE Full Factorial experiments are conducted based on 1 repetition and 2 wafers are used to conduct each experiment instead of 2 pods x 25 wafers. This is meeting the requirement of confidence interval of 95% data analysis and goodness of fit in a normal distribution. Since the analysis are based productions data sample the analysis of variance (ANOVA) statistic for F test and T test are being used to avoid complication of Type I error as shown in Table 6, ANOVA table with the equation explain in (2) (SilTerra Continuous Improvement Competition, 2013) and (3) (SilTerra Continuous Improvement Competition, 2015) as the following. The data is re-validated with JMP 5.1.2 to eliminate manual calculation error.

Table. 6. ANOVA table for Phase 1 DOE

Source	*Degree of Freedom(DF)*	*Sum of Squares(SS)*	*Mean Square(MS)*	*F*	*P value*
Model	9	1243604.2	171658	2.085	0.106
Error	14	1363301.7	85206		
Total	23	2606905.8			

The P value provided from ANOVA table is greater than 0.005 hence further analyse on the parameters estimate is required to identify the outliers. Table 7 shown the first regression analysis perform on DOE. After identifying the p-value that are exceeding the significant value, the regression analysis is re-run in order to acquire samples to provide enough evidence to reject the null hypothesis for the entire population .

Table 7. Parameters estimate table for Phase 1 DOE run

Term	*Estimate*	*Standard Error*	*T ratio*	*Probability*
Process time(170)	73.58	79.66	3.15	0.3713
Process time(300)	-27.91	79.66	-0.35	0.7312
dHF flow(Off)	178.16	56.32	3.16	0.0069
EDR flow(Off)	69.33	56.32	1.23	0.2387
Process time(170)*dHF flow(Off)	109.08	79.66	1.37	0.1925
Process time(300)*dHF flow(Off)	40.33	79.66	0.51	0.6205
Process time(170)*dHF flow(On)	139.9	79.66	1.76	0.1009
Process time(300)*dHF flow(On)	-132.3	79.66	-1.66	0.1189
dHF flow(Off)*EDR flow(Off)	23.58	56.32	0.42	0.6818

The factors and interactions between factors with high p-value are removed in order to re-run the regression analysis as indicated from the table above. The result from the regression analysis provided the ANOVA table as shown in Table 8 below with significant p-value improved to 0.0135 in which is below 0.05 hence the evaluated factors and the results obtained provides evidence to reject the null hypothesis.

Table.8. ANOVA table after removing the outlier factors

Source	*Degree of Freedom(DF)*	*Sum of Squares(SS)*	*Mean Square(MS)*	*F*	*P value*
Model	1	877211.3	13348.2	0.1555	0.0135
Error	20	1729694.5	82366		
Total	21	2806905.8			

The simplify F ratio is illustared as in Equation (2):

$$F = \frac{MSbg}{MSwg} \quad 2.$$

Where the abbreviation of the equation defined as: MS, Mean Square, which derive from sum of square with degree of freedom. Bg is data between group. Wg is data within group.

The T value in this analysis is generated from the Equation (3) as shown:

$$T = mean1 - mean2var1^{2n1} + mean2var2^{2n2} \ldots mean2var50^{2n50} \quad 3.$$

Theresponse from DOE is obtained as shown in Table 9. From the analysis result, dHF Flow obtained a Probability >(t) of 0.058 which is > target P value of 0.05 that is indicating the effect from dHF Flow is indeed justified as a main factor in contributing high residue defects.

Table. 9. DOE analysis result for main factor

Term	*Estimate*	*Standard Error*	*T ratio*	*Probability*
dHF flow(Off)	178.17	56.55	3.15	0.058

The DOE profiler diagram as shown in Figure 10 also illustrates the rational relationship between the chemical flows and the minimization of the particle count. From DOE Profiler obtained, particle counts disproportionate with the increased of process time, EDR flow time as well as dHF flow rate

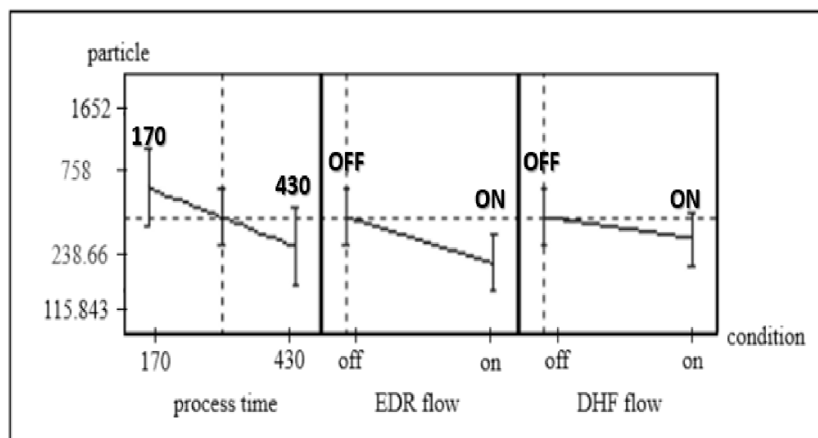

Figure 10. DOE analysis result showing main profilers that contributed to the residue

It is is therefore convincing that dHF process bath chemical flow has a strong correlation with the salicide residue formation. The second objective is therefore met by identifying the root cause to the salicide residue issue.

There are limitations in the current hardware facilities set up in wafer fab. The process equipment configurations do not render further availability to improve for the increase of the chemical flow efficiency. Due to the current wet bench process equipment configuration limitations, as the product wafers are sitting and resting on the quartz wafer guide while the process is taking place, any chemical flow that is more than 16 litres per minute will result in a wafer cross-slot incident. The chemical flow that is

purged out from the quartz bath nozzle will potentially lift the product wafers out from the wafer guide slot, and eventually cause the wafer to jump slot and stick with another wafer. Such incident causes wafers being missed pick and will lead to a wafer drop during the wafers transfer process. In addition to such limitation, the current bellow pump that is set up with the DNS WS820L wet bench equipment is by far the largest type available in the category that could be fit into the equipment plumbing compartment. The CDA that is supplying the driving energy force within the equipment piping does not permit any further upgrade beyond the current pump configuration. As such, the motivation to into experiments to determine a solution is very desirable.

CONCLUSION

The aim of this research had successfully characterized and identified the persistent residue that is a carbon base element. All experiments conducted in this study also yield a consistent finding. Even though the residue defect is considered as common defect that is found in the similar process step from other fab foundries, but there has never been a similar report stated carbon element was detected. The conclusion also supports that the residue defect is caused by the diluted hydrofluoric acid interacts with the wafer surface for all the wafers processing with pre-salicidation cleaning. There is no commonality found in equipment hardware nor any associated process factors. The aim of this study is to identify the silicide residue root cause and to provide a platform to the next project research to identify the solution to reduce, or to eliminate the residue defects, hence increase profitability by regaining the 1% line yield that is lost due to the residue defects. The cost avoidance achieved by regaining the yield improvement is estimated to benefit the company USD$5 million per year. The objective in this study which is to screen through the process in order to ascertain the root cause of the salicide residue defect is completed successfully.

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