JMP CASE STUDY: VARIATION IN SEMICONDUCTOR ETCHING PROCESS

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EXECUTIVE SUMMARY

This report presents a comprehensive analysis of the current state of statistical process control (SPC) for semiconductor manufacturing processes. Histograms, two-tailed tests and control charts were generated for process stability and capability analysis with JMP software. The findings of this case study prove that all processes from the data set are not in statistical control due to the presence of special cause variation and led to the infeasibility of process capability study due to instability.

Nevertheless, this case study showcased the application of real-world statistical process control and data analysis techniques such as histogram, control chart interpretation and optimisation via simulation. This case study serves to determine area of process instability and potential root causes for data-driven decision making, quality control and improvement.

Key observations include:

- Inconsistent mean shifts and wide data spread in multiple process lines.
- Processes falling outside control limits, signalling non-random variations.
- Lack of historical robustness to support generalisation beyond the current sampling period.

Several recommendations have been outlined in this case study for process improvement and increasing production readiness. Recommendations include additional data collection, root cause studies, and real-time monitoring implementations to enhance decision-making. This report showcases technical proficiency and analytic skills, laying a solid foundation for industry-scale production readiness and optimisation.

CONTENTS

INTRODUCTION

Etch rate is a crucial metric in oxide layer formation on silicon wafer. It is defined as the amount of oxide etched from the wafer area per unit time (unit: Angstroms/min). The **target Etch Rate for this study is 620** with **lower and upper specifications of 545 and 695** Å/min, respectively (i.e., 620 +/- 75 Å/min).

For this study, 20 wafers were etched for each calibration. 5 wafers will be randomly sampled across 40 runs per etching line, leading to 200 wafers sampled for each line. Moreover, the etch rate will be measured at 4 separate locations on each wafer. This results in 5 x 40 x 4 = 800 Etch Rate values per etching line.

Based upon this sampling strategy, three sources of variation can be examined for each line:

1) within wafer

2) between wafers within run

3) between run within calibration stages.

4) between calibration stages

In this case study, three etching lines, which are B, C and D, were analysed. Note that this case study is an exercise titled **"*JMP064: Variation in Semiconductor Etching Process*" provided by SAS, the developer of JMP software. (**Remarks, the original tutorial contains six lines, only **THREE** lines are chosen for the sake of simplicity in this case study**)**

OBJECTIVE

The primary objectives of this study are:

1. To evaluate the performance of each etching line relative to the target etch rate of 620 ± 75 Å/min.
2. To investigate the major sources of variation in etch rate for each line:

- Within-wafer
- Between wafers within a run
- Between runs within a calibration stage
- Between calibration stages

NUMERICAL AND GRAPHICAL SUMMARIES OF OVERALL ETCH RATE

This section will explore on numerical and graphical summary of Etch Rate data for Line B,C and D. Diagram 1 includes a histogram, boxplot, and summary statistics for the 800 Etch Rate values with reference lines indicating the target and specification limits.

Diagram 1 Histogram, Boxplot, Summary Statistics (*Red Box indicates out of spec)

From Diagram 1a, it is evident that **the data of Etch Rate B are within the LSL and USL**, indicating a stable and well-controlled variation. However, **Etch Rate C and D exhibit overall process variation that extends beyond the specification limits** as shown in Diagram 1b and 1c, respectively, which indicates undesirable variation as variation should be well within the defined specification ideally.

The mean and 95% confidence interval for Etch Rate B, C and D are tabulated below.

Table 1: Mean and 95% confidence interval of Etch Rate

Etch Rate	Lower 95%	Mean	Upper 95%
B	610.6884	611.7535	612.8186
C	585.8646	587.2547	588.6449
D	606.7888	609.1247	611.4606

The sample mean for Etch Rate B, C and D are **below the target of 620**, **especially Etch Rate C being the lowest**. The use of 95% Confidence Interval provides a formal inferential statistical technique to check for a possible variation of the mean. For instance, we can be 95% confident that the mean Etch Rate for line B is between 610.6884 as minimum and 612.8186 as maximum. Even at 95% confidence interval, all the etch rate is still below the target 620. Thus, we have statistical evidence to conclude that all etch rate is off target on average.

COMPARING ETCH RATE ACROSS CALIBRATION STAGES AND RUNS

Recall that the engineers recalibrated the equipment after 20 runs. It is important to compare the performance of the process within and between these calibration stages.

Diagram 2: (2a): Comparative Histogram of Etch Rate B at both calibration rate, (2b): Comparative Dot Plot of Etch Rate B at both calibration rate. (2c): 2 Tailed Test for Mean of Etch Rate B at Calibration 1 with Respect to Calibration 2.

The graphical analysis in Diagram 2 shows that the variation in etch rate during both calibration stages is not excessive, with no evident difference in either the variation or the average. A two-sample t-test comparing the process means between these two stages yielded a probability of 0.7915 (> 0.05) which indicates no significant difference between both means.

The comparative histogram, dot plot and 2 tailed test for Etch Rate C and D are provided in **Appendix A (Figure A1 & A2)**.

For **Etch Rate C**, the distribution appears approximately normal with most data points concentrated around 585.25 at Calibration 1 and shifted to 589.26 at Calibration 2, with numerous points exceeding the LSL for both calibrations. This is accompanied by an increase in standard deviation from 19.62 to 20.26. The dot plot suggests that the recalibration led to the Etch Rate C being closer to the target mean, but led to wider spread and more outliers. A two-sample t-test confirmed a significant difference between means of both calibrations for Etch Rate C with a probability of 0.0048 (< 0.05).

In contrast, **Etch Rate D** exhibits a broader spread and larger standard deviation, suggesting higher variability in the process. The two-sample t-test confirmed a non-significant difference between the means of both calibration 1 and 2 for Etch Rate D with a probability of 0.5648 (> 0.05).

Table 2: Mean, Standard Deviation and 2 Tailed Rest Result

Etch Rate	Calibration 1		Calibration 2		2 Tailed Test (Calibration 1 relative to Calibration 2) (Prob >|t|)	Significant Difference Between the Mean of Calibration 1 and 2
	Mean	STD	Mean	STD		
B	611.61	15.68	611.90	15.03	0.7915	No
C	585.25	19.62	589.26	20.26	0.0048	Yes
D	608.44	32.57	609.81	34.74	0.5648	No

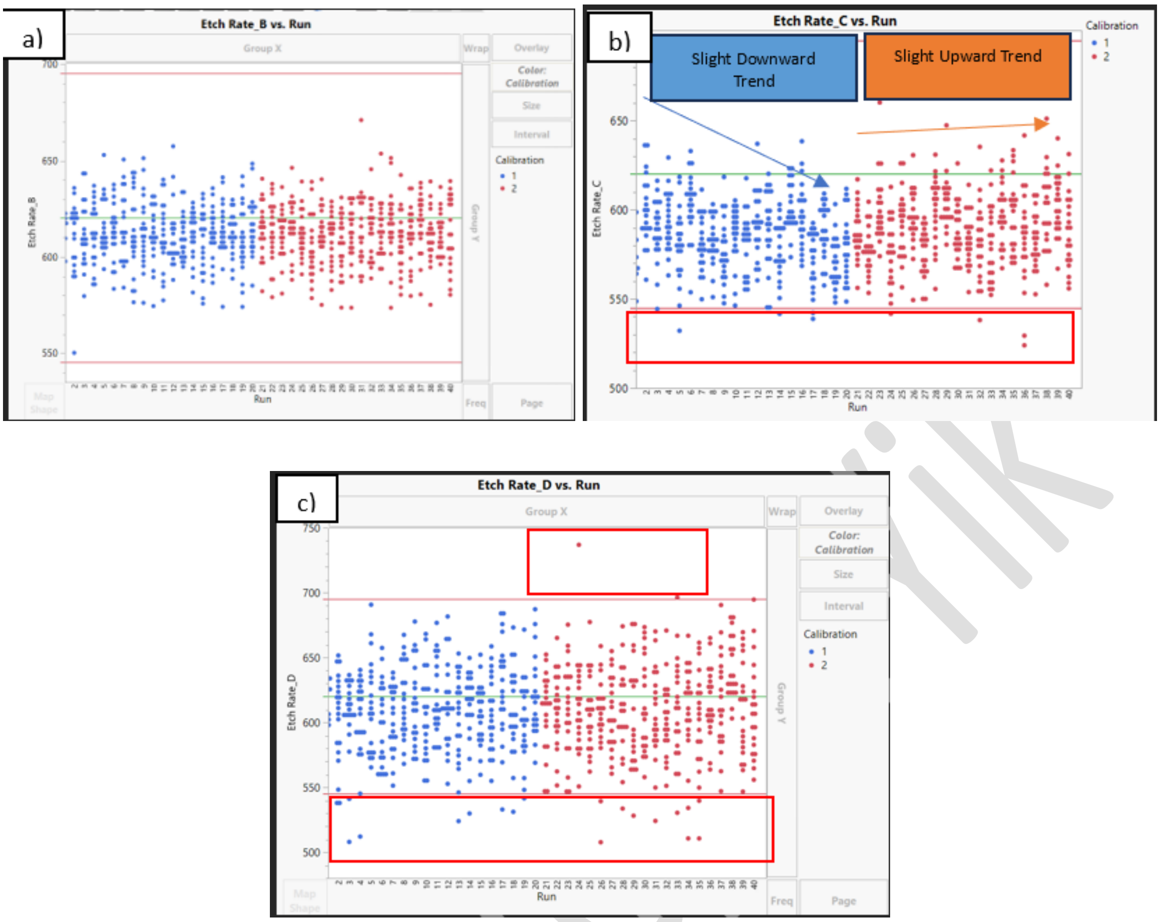

Diagram 3: Dot plot of (a)Etch Rate B (b) Etch Rate C (c) Etch Rate D vs Run for both calibration (*Red box indicates out of specs)

The dot plot in Diagram 3 illustrates that **the variation in Etch Rate B remains stable throughout 20 runs for each calibration**. This suggests that the recalibration of the equipment's has no significant effect on the consistency or the average of the Etch Rates B within each run. In contrast, **the Etch Rate C appears to be approaching the LCL with a downward trend throughout the run in Calibration 1**, the downward trend is eliminated at Calibration 2, suggesting that recalibration improved the performance of Etch Rate C. The increase in the mean in Calibration 2 of Etch Rate C further supports this observation. Both Etch Rate **C and D have several points falling beyond the specification limit**, evident that both processes **of C and D are out of specification**. **Etch Rate C shows a notable change in mean**, while Etch Rate B and D remain relatively unchanged across calibration. However, it's not clear if those changes indicate true run-to-run variation. We will explore this in more detail via control charts.

CONTROL CHARTS

Control charts are crucial for determine multiple variation source in a process. The X-bar chart plots the mean of etch rate value within every run while the S-chart displays the standard deviation. The red control limits line in the X-bar chart is obtained from the variation estimation in S Chart, thus as a rule of thumb **it is recommended to check the S chart first**, then the X-bar Chart. For the S Chart, the green lines represent average standard deviation across 20 runs within each calibration stage. The red lines denote the lower and upper control limits (LCL and UCL) which are based upon the variation in the standard deviation values, set at +/- 3 standard deviation of the statistic being plotted. The X-bar chart uses the average of 20 runs means as the centre line with control limit set as +/- 3 standard deviation of the sample mean which derived from the S chart. Thus, if the S chart exhibit inconsistent variation, the standard deviation and control limit might be overestimated leading inaccurate control limit in X-bar chart as well. This is why the S chart is evaluated first.

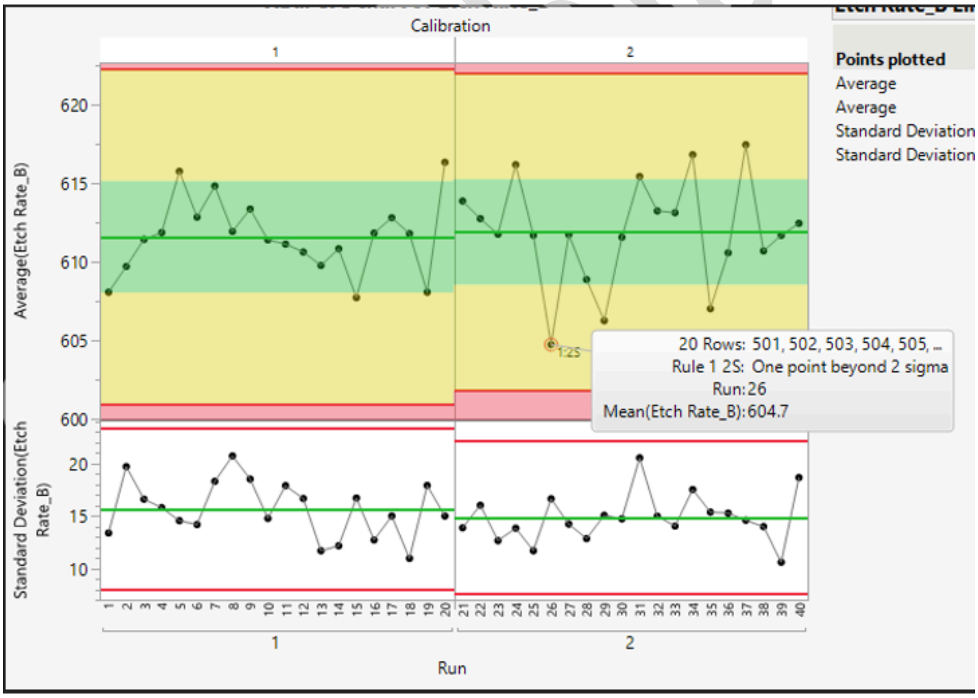

Diagram 4: X Bar and S chart for Etch Rate B between Runs

From Diagram 4, the **S chart for Etch Rate B** shows that both **Calibration 1 and Calibration 2 are in statistical control**, with all points falling within the control limits. Notably, the control limits for **Calibration 2 are slightly narrower**, indicating **reduced variation** compared to Calibration 1.

On the **X-bar chart**, the average etch rate for **Calibration 1 remains stable and well within control limits**. However, during **Calibration 2**, the process shows **greater fluctuation**, with **six points falling within the warning (yellow) region** and 1 point [Run 26] significantly outside beyond the 2 sigma which violated the Rule 1 2S of Westgard Rule. While these points are not out of control, their clustering may suggest **a potential shift or increased variability** that warrants monitoring. Another control chart is required to examine the within-wafer variation as further investigation.

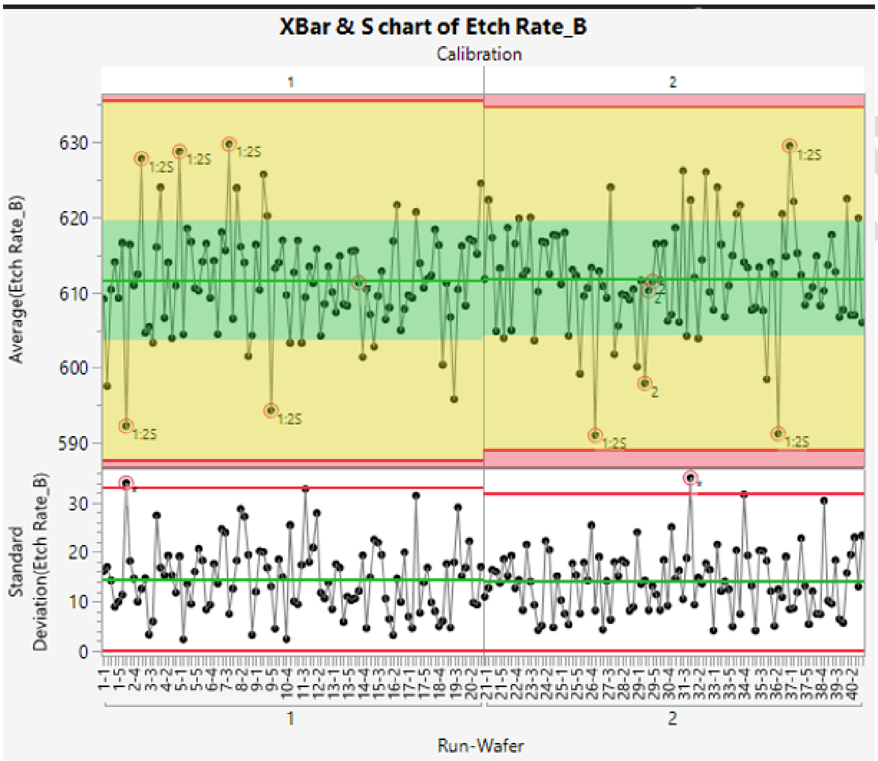

Diagram 5: X-Bar and S chart for Etch Rate B between Runs-Wafer

Diagram 5 presents the control chart for Etch Rate B, focusing on within-wafer variation. Recall that five wafers were sampled from each run of 20 wafers — hence, every five consecutive points in the chart represent wafers from the same run.

In the **S chart**, **Calibration 1 shows one out-of-control points** and several points approaching the control limits, while **Calibration 2 also shows two outliers and one point near the upper control limit**. These observations suggest that the **within-run variation is unstable**, indicating **inconsistency among wafers** within the same run.

The **X-bar chart** for both calibrations exhibits large fluctuations, with many points fallings within the 2-sigma region as indicated by red circles. This reflects **potential shifts or inherent variability** similar to those observed in Diagram 4. In conclusion, the variation in Etch Rate B appears to be primarily driven by **within-wafer inconsistency** rather than between-run differences. The control charts highlight that while the process may seem stable at the run level, it is **not fully under statistical control at the wafer level**, undermining process reliability.

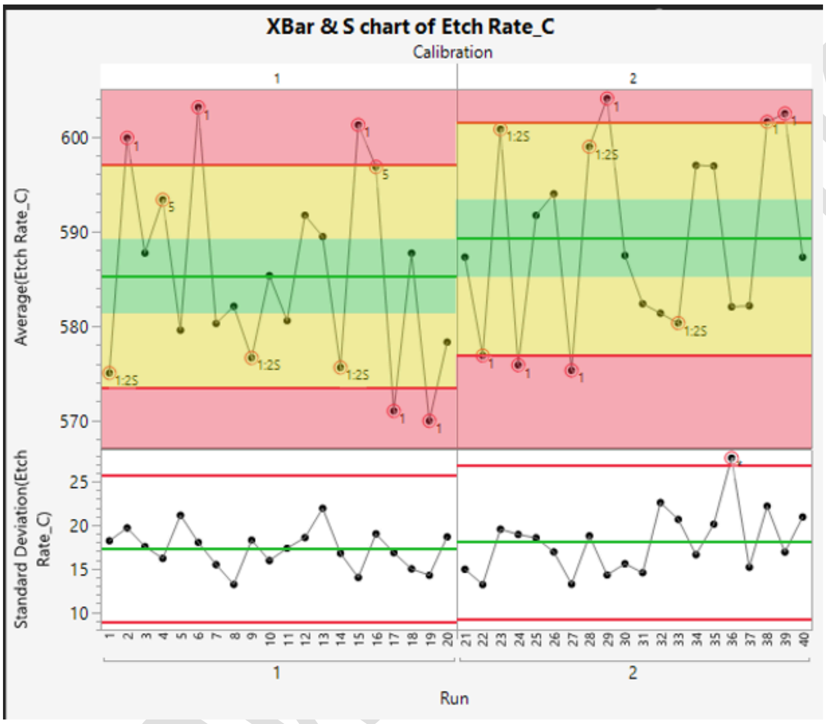

Diagram 6: X-Bar and S chart for Etch Rate C between Runs

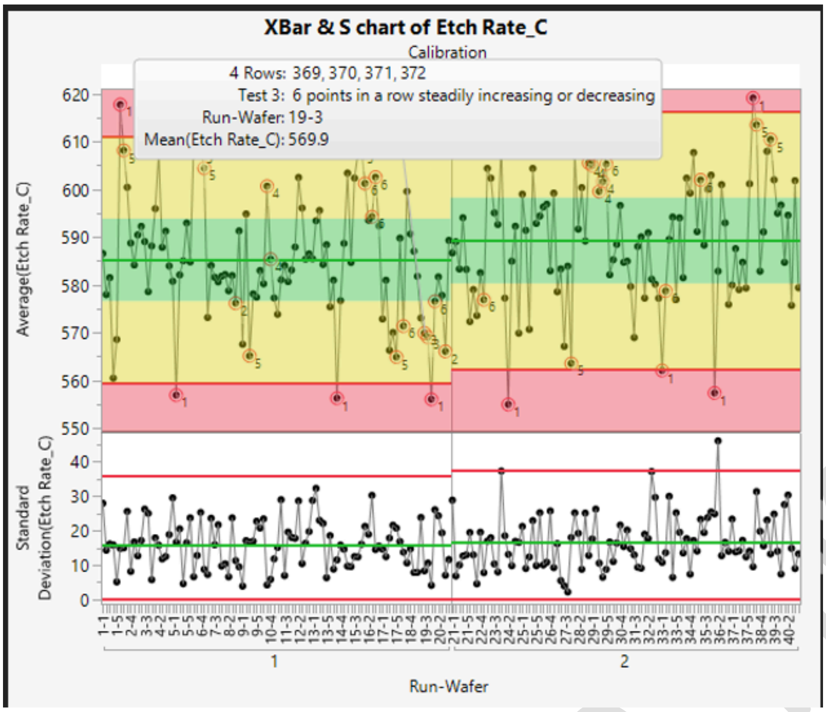

Diagram 7: X-Bar and S chart for Etch Rate C between Runs-Wafer

The X-bar & S charts for Etch Rate C in both Diagrams 6 and 7 **indicate a lack of statistical control in both calibration phases**. While the standard deviation remains largely within acceptable limits, the average etch rate frequently extends beyond 2 sigma and even breaches control zones, suggesting persistent process instability. **This instability worsens when the dataset is expanded to the Run-Wafer level**, where both mean and variability exhibit chaotic behaviour. In Calibration 1, the process exhibits a downward trend, which shown by the warning bar. The issue appears to be systemic rather than isolated.

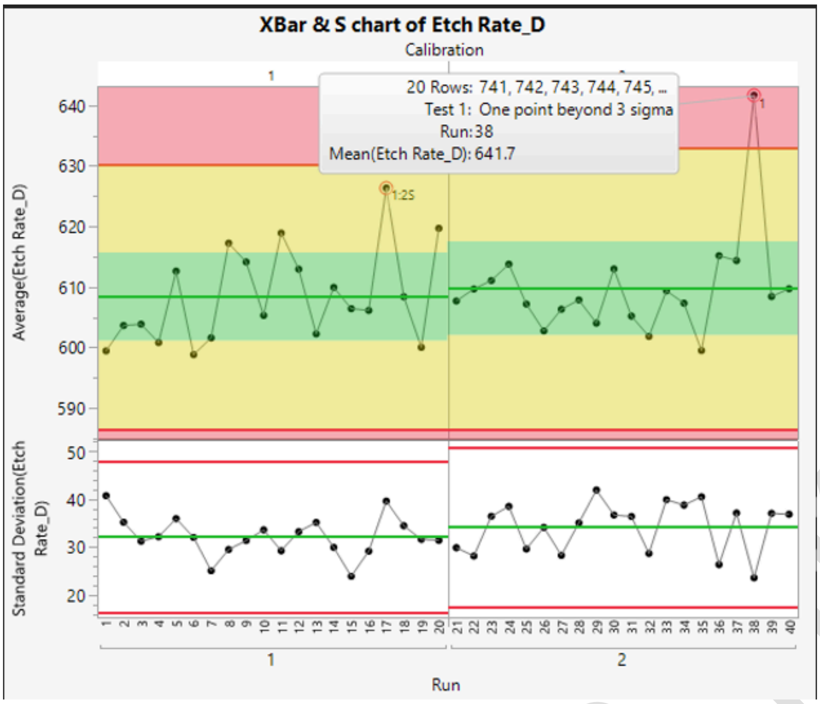

Diagram 8: X-Bar and S chart for Etch Rate D between Runs

From Diagram 8, the **S chart for Etch Rate D** shows that both **Calibration 1 and Calibration 2 are in statistical control**, with all points falling within the control limits. Notably, the control limits for **Calibration 2 are slightly wider**, indicating **increased variation** compared to Calibration 1.

On the **X-bar chart**, the average etch rate for **Calibration 1 exhibits consistent oscillation except for 1 point [Run 17] beyond the 2-sigma region while within the control limits**. It's likely **just normal process noise**. Calibration 2 shows a stable and consistent trend overall, except for **a spike beyond the control limit in Run 38**. This spike indicates a **special cause variation as S chart is stable**, excluding the possibility of increased variation.

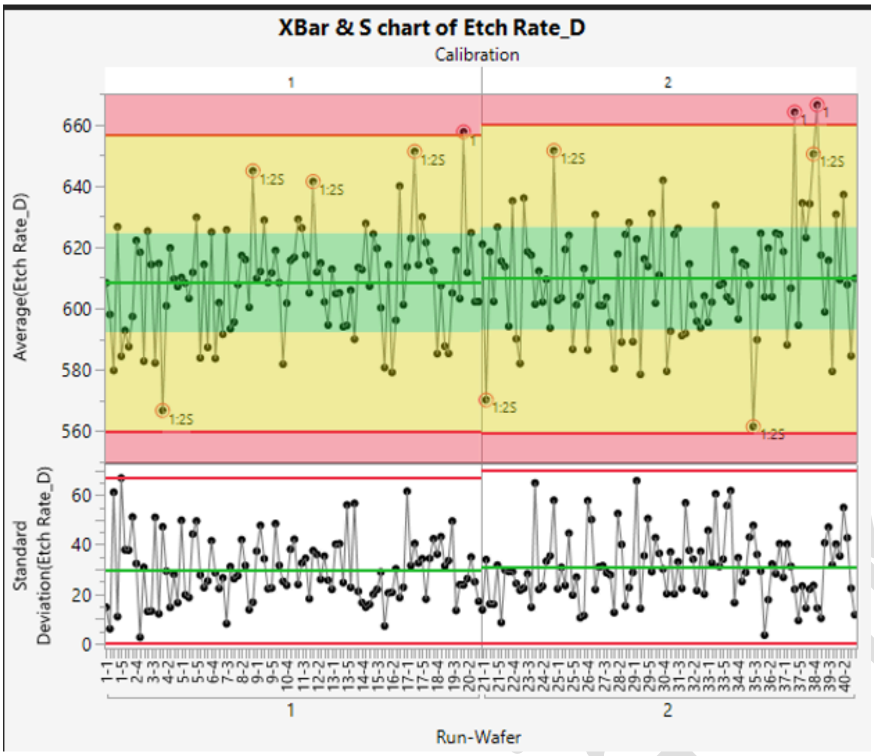

Diagram 9: X-Bar and S chart for Etch Rate D between Runs-Wafer

Diagram 9 illustrates the control chart for Etch Rate D, examining within-wafer variation across different runs. In the **S chart**, one point touches the upper control limit, indicating borderline variation. The **X-bar chart** reveals **one outlier in Calibration 1 and two outliers which contribute to the spike in Calibration 2.** Moreover, **numerous points in the yellow region have been observed in both calibrations**, suggesting potential process shifts or instability. This implies that although the variability may appear somewhat consistent, the **mean etch rate per wafer fluctuates significantly across runs**, pointing to a **lack of control at the wafer level**. Overall, this reinforces the presence of **within-wafer inconsistency**, making the process statistically unstable. Table 3 below shows the summary of finding for each etch rate.

Table 3: Stability Finding of Etch Rate B, C and D

Etch Rate	Status	Common/Special Cause
B	Not fully stable	Special Cause (stable within run, but unstable within wafer, between runs)
C	Not stable	Special (1 outlier in S chart in Cal 2 shows unusual variability and frequent violation of control limit throughout each calibration)
D	Not stable	Special (sudden spike in Run 38 within run, numerous point beyond 2 sigma and out of control limit within wafers)

JUSTIFICATION FOR ABSENCE OF PROCESS CAPABILITY

Process capability is infeasible for this case study. Generally speaking, process capability should be proceeded only if the sample passed the control chart test as process capability assumes the process is already stable and Cpk and Ppk will be misleading for unstable case.

RECOMMENDATIONS

Based on the methods conducted above, we can conclude that all three etch rate are not stable due to special cause effect such as tool drift as observed in the X bar chart within wafer between run of each etch rate. Hence, several recommendations or corrective action should be taken to rectify this issue.

1. **Root Cause Analysis**
   - Root cause analysis with the aid of tool such as Fishbone Diagram should be carried out to determine and eliminate the special causes.
2. **Improve Process Monitoring**
   - Real**-time Statistical Process Control (SPC)** should be implemented to for earlier issue identification.
   - Use **subgrouping** by shift, machine, or operator to identify potential hidden patterns of variation.
3. **Collect Additional Data**
   - Environmental **variables** such as temperature, humidity, or other setup conditions that may affect the variation should be recorded.
   - Comparative study and observation of process behaviours **before and after maintenance** to see any improvements made.
4. **Assess Measurement System**
   - **Gage R&R study** should be performed to ensure reliable measurement system.
5. **Conduct Designed Experiments (DOE)**
   - If root causes remain unclear, use **DOE techniques** to study the effects of several key variables for a more comprehensive understanding and allow optimisation.

CONCLUSION

Based on this case study, the processes for **Etch Rate B, C and D are not in statistical control** as observed from the out-of-control point in the control chart. The process performance cannot be generalised for now due to the instability of the processes. Moreover, **the process capability study cannot be interpreted** as well. This is because of the **presence of special cause variation,** which leads to **inaccuracy of results and misinterpretation of true performance**. This analysis emphasises that process stabilisation should be prioritised before the process can be validated for production.

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REFERENCE

Potcner, K, (2025) "***JMP064: Variation in Semiconductor Etching Process***", **SAS**. Available at: https://www.jmp.com/en/academic/case-study-library/variation-in-semiconductor-etching-process

APPENDIX

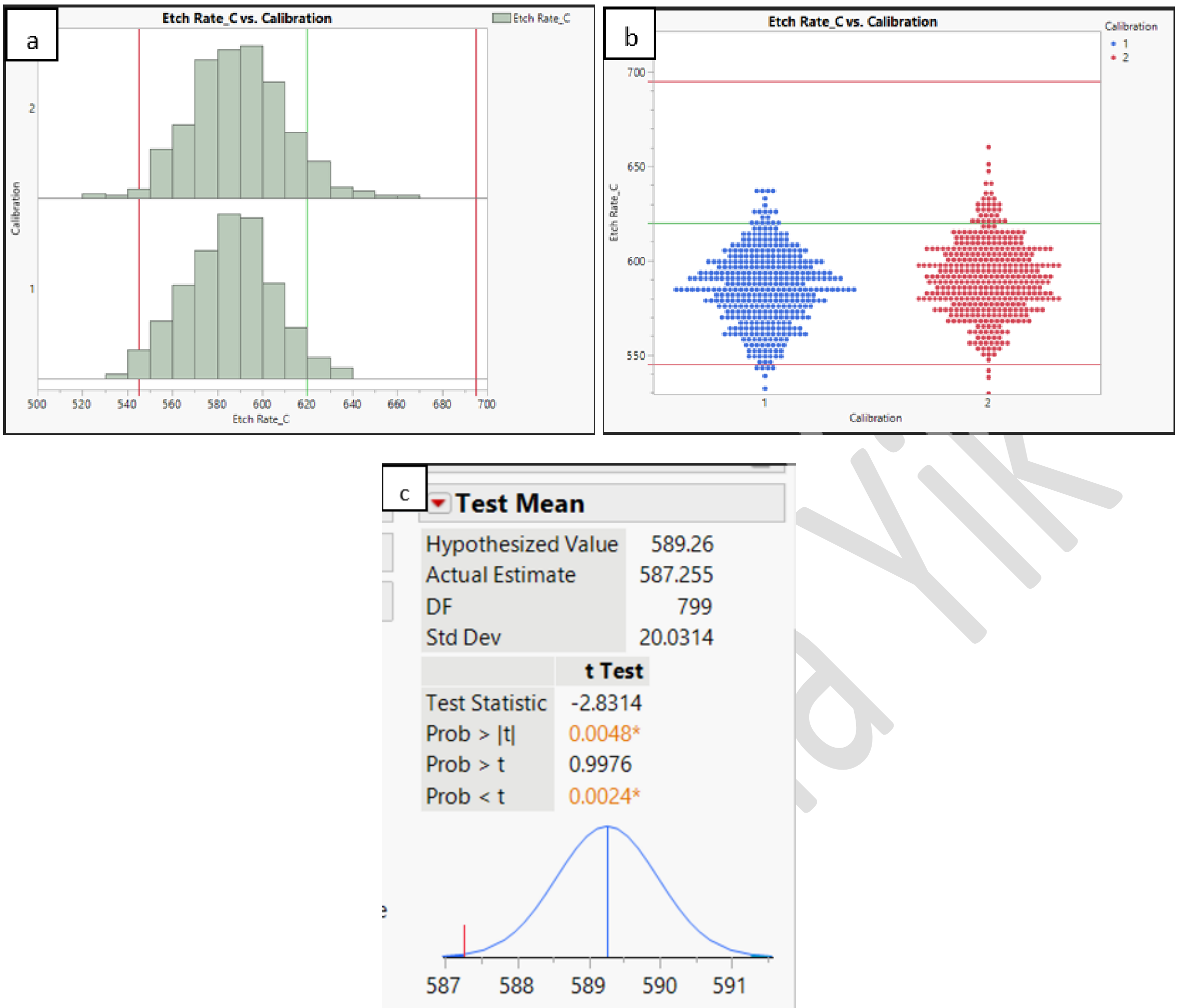

Diagram A1: (a): Comparative Histogram of Etch Rate C at both calibration rate, (b): Comparative Dot Plot of Etch Rate C at both calibration rate. (c): 2 Tailed Test for Mean of Etch Rate C at Calibration 1 with Respect to Calibration 2.

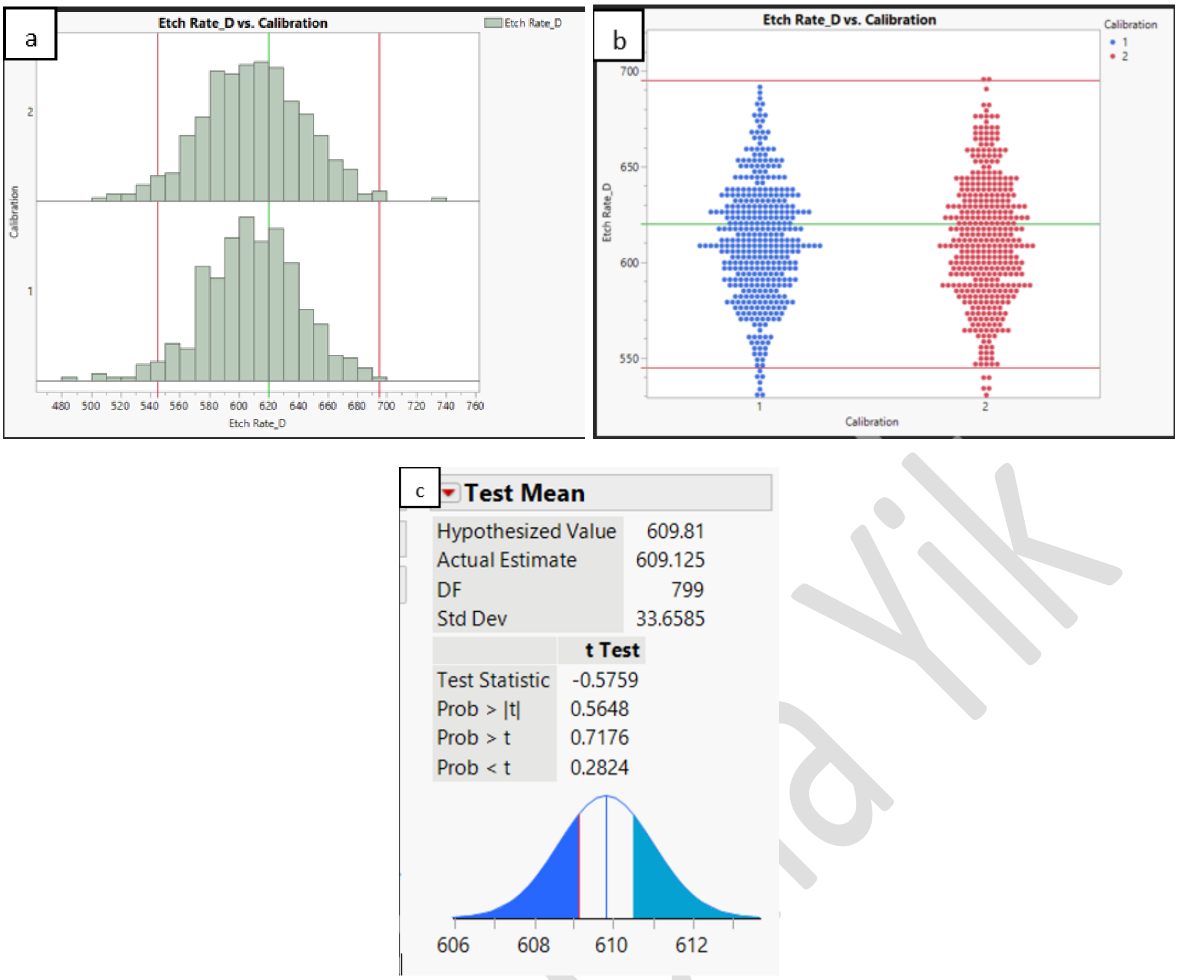

Diagram A2: (a): Comparative Histogram of Etch Rate D at both calibration rate, (b): Comparative Dot Plot of Etch Rate D at both calibration rate. (c): 2 Tailed Test for Mean of Etch Rate D at Calibration 1 with Respect to Calibration 2.