Continual Improvement of Cumulative Yield in GaAs Wafer Fabrication

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ABSTRACT

Improvement of corporate level profit margin is a continual theme within all production operations. Those operations commonly target high quality and reliability while reducing manufacturing costs through management of wafers processed, cycle time, process yield and product yield. Implementation and acceleration (12 months) of continual improvement in these metrics are accomplished through benchmarking and implementation of best process engineering practices. This paper discusses improvements accomplished in process yield, quality process control, and product yield made during a recent joint project between MAX I.E.G. LLC and a GaAs Wafer manufacturer client.

INTRODUCTION

"If left to themselves, machines do not stay adjusted … a stable stationary state is an unnatural one and its approximate achievement requires a hard and continuous fight." [1]

The arduous effort of continual improvement requires measuring what is to improve, and trending what is measured. Establishing aggressive but achievable goals for each measured characteristic is equally as important as the quality skills and tools available to the engineering teams. An upward trend is the obvious desired effect however long term reduction in variation and stabilization at newly improved levels are the ultimate proof that the "fight" is won.

This paper showcases the method and result of a structured implementation of the MAX Precision Engineering (MPE^{TM}) business process. Wafer fab operational gains were achieved through immersive implementation of best practices in continual improvement and statistical process control methods. Quantitative gains are achieved in both in-line production quality and end-of-line test yield.

METHODOLOGY

A MAX lead-in assessment identified the following MPE business process components for which the client agreed to engage for an accelerated implementation:

- Client to internally revisit/refresh product based process FMEA's (results not included here-in)
- Engineering SPC best practices; assess, teach and mentor 31 topics in 10 categories
- Critical chart classification for reliability, function and process; ensure alignment of in-line charts to cumulative yield without impairing client customer quality
- In-line SPC chart set-up maturity; assess and ensure five basic aspects of chart set-up
- Continually improve critical in-line SPC process capabilities; Cpk's to ≥ 1.33, for implied later yield gain
- Implement SPC practices for end-of-line electronic test characteristics and correlate to in-line variation

The immersive application of these quality skills and tools resulted in a more cohesive process control system, reducing in-line excursions/escapes and enabling more highly correlated feedback from end-of-line test to enable interactive continual improvement in production. MAX Precision Engineering defines a path to best-in-class objectives and measures progress of team execution to goal. (Table 1)

Key Performance Objective	KPI Measure / Goal
▪ Product based PFMEA	Performed by client, excluded here
▪ Engineering Best Practices	Qualitative best-in-class behaviors
▪ Critical chart classifications	Align In-line to End-of-line yield
▪ SPC Chart Set-up Maturity	Score ≥ 8 of 10 for all critical charts
▪ Continually Improve Cp/Cpk	100% of critical charts ≥ 1.33 Cpk
▪ OE Test Monitor Chart Set-up	Identify Fab & Tester instabilities
▪ Continually Improve Test Yield	Yield goal varies by product

Table. 1: Key aspects and goal setting for teaming success

RESULTS

Engineering Best Practices

One major aspect of the joint project is to teach, mentor and transform the engineering mind set to use documented best practices (quality skills and tools) as the new default. Client engineering practices were assessed on a quarterly basis throughout the implementation and, in most cases, improved to industry benchmarked levels. (Fig. 1)

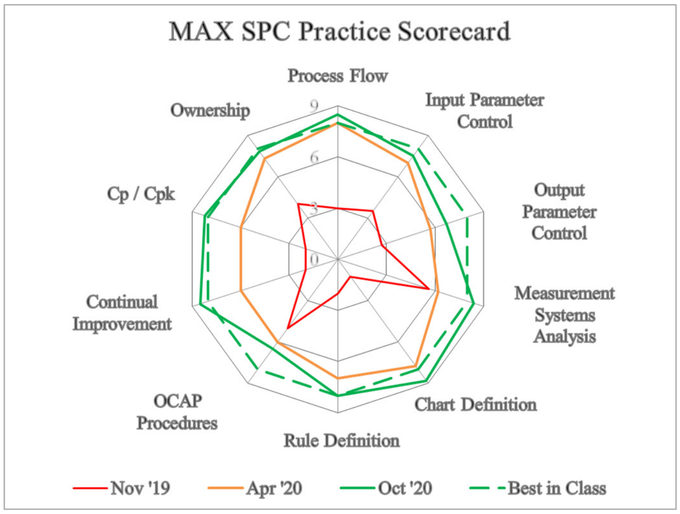

Fig. 1: Measured qualitative improvements in 10 categories of engineering best practices in statistical process control

The criteria supporting each of the 10 practice categories are well defined in many quality control publications, however some pragmatic assumptions were made in order accelerate implementation. For instance, the initial application of WECO rules was limited to alert at an "appropriate level" and gradually increased to allow focus on the most significant concerns as we simultaneously tightened control limits. Also, the Input and Output Parameter categories were defined from a product-lot-perspective in order to emphasize a feedback network between in-line and end-of-line performance.

As many other Fabs, the client's team already had good SPC practices in several categories including; measurement systems, a control plan from design timeframe, placement of control plan charts within product routings and out-of-control action plans. Categories to improve included; chart ownership, chart definition, rule definition and continual improvement of process capabilities. So the implementation focused first to drive SPC chart set-up maturity, then continual improvement of process capability.

SPC Chart Setup Maturity

Maturity of existing charts was assessed against five basic set-up criteria. A metric was devised with a goal to accelerate completion of four aspects and to initiate a continual improvement process for the fifth aspect. A score card was established and pressed for completion. Early setup issues where identified and systematically addressed, including:

- Chart type gaps
- Control limit calculation method
- Inadequate application of WECO Rules
- MES chart setup gaps

Scoring criteria and final result histogram are shown in Fig 2.

M-score Criteria for chart maturity (48 charts)	Value
1. Is SPC chart in use in real time?	2 pts
2. Is OCAP in place for OOC / OOS?	2 pts
3. Are Control Limits statistically determined?	2 pts
4. Are adequate WECO rules turned on?	2 pts
5. Is CPk ≥ 1.33? (Goal = 100%	2 pts
M-score maximum per chart	10 pts

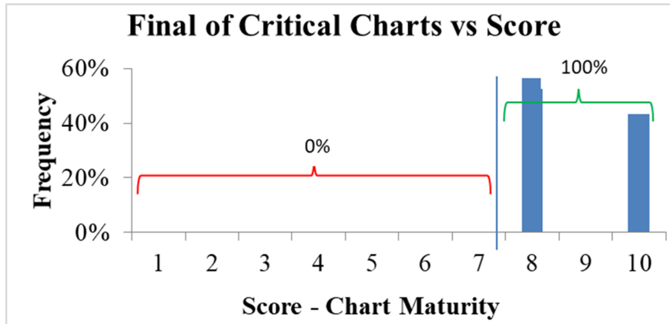

Figure 2. Chart set-up criteria and final score card

Process Capability Maturity

The fifth aspect of chart maturity is process capability which is normally addressed longer term with continual improvement teaming strategy. The client process engineering team once again committed to an aggressive goal and schedule. A continuous improvement team involving all process area section managers was kicked off as soon as the chart setup goals were achieved. Membership successfully ensured priority and acceleration of implementation.

MAX also joined by-area engineering chart reviews which were occurring prior to the start of the project. All SPC meetings and follow up discussions became opportunities to teach, mentor and demonstrate the best practices described above.

Deeper dive actions were needed after resolving the early limitations. A bulk listing of individual factors limiting process capabilities was provided to create a high-level view of the increasingly difficult improvement opportunities. Cpk is a function of distribution shape, centering and control limit settings. The later and more difficult phase of process capability improvement was made more navigable by mapping each factor for each chart needing attention. A final wave of Cpk issues was prioritized by potential gain and degree of difficulty and driven to the goal through team actions. The final and most difficult opportunities involved slightly misshapen distributions as shown using Skew in the map in Table 2.

MSA gauge capability / fitness did not require much attention during the joint implementation. P/T Ratios are included in Table 2, showing minimal negative contribution in the last wave of chart improvements.

Process Group		GRR/SPEC Tolerance		Sep 2020 Skew	# STDs off target	Calculated Control Range Vs Fixed Range
1						
1						
1						
1						
1						
2						
2						
2						
2						
3						
3						
3						

Table 2. Map of Cpk issues in the last layer of improvement (Numbers are removed to protect client's data)

The process capability score card in Figure 3 reflects monthly results throughout the continuous improvement teaming activity. The changes in slope of the data trend clearly show the initial easier gains, the tapering off of easy gains, and the more difficult period (staying linear in final phase) aided by revelations from the monthly opportunity maps.

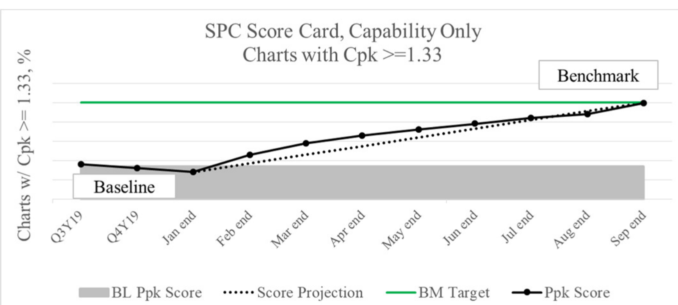

Fig. 3: Percentage of Critical Charts with Cpk >=1.33

The process capability gains above were thought to be a huge challenge by management and team members, especially within the set one year time period. Introduction of best practices, concise performance metrics, and drill-down continual improvement tools allowed the team to exceed expectations and in several cases to reset the MAX best-in-class engineering behavior levels. (Refer back to the spider chart in Figure 1 above.)

Wafer Process Yield

MAX joined existing client activities in the area of process yield loss reduction. As many other GaAs wafer manufacturers, wafer scrap is identified as a top cause of process yield loss and a key detractor from cumulative yield goals. The existing effort was reconstituted with the introduction of benchmark best practices for teaming and continual improvement which were practiced over time. Better analysis tools were provided to help accelerate results.

Strategies were implemented to ensure the new teams were setup to succeed:

- Priority was established and vertically aligned throughout the organization, from Fab manager to front line operator
- Clear trending indicator was devised to track improvements in wafer-loss count and to translate the losses into a more relatable loss-value metric
- All loss categories were redefined within the MES to enable use of multi-level Pareto analyses
- A stand-alone data display tool was extended to show the MES extracted process yield loss data in real-time in a multi-level Pareto, drill-down, format
- Owners were identified and empowered to work with cross functional resources in each major category using the improved drill-down analysis tool
- Periodic management reviews were modified to emphasize and expect improving trends in multiple Pareto drill-down categories, (enabling 12 total simultaneous continual improvement activities within the top 4 loss categories.

Wafer scrap during fabrication of not only GaAs-based manufacturing but many other Compound Semiconductors is very much aggravated by substrate brittleness. As such it was a top loss category and the first demonstration of success in continual improvement of process yield. Real root causes and solutions were contributed exactly as the vertically aligned priorities intended. Process, equipment and operations personnel came together on the factory floor and in working sessions to identify and implement lasting solutions. Internal data continues to verify permanence of each solution.

There were two cycles of improvement and stabilization effected by continual improvement efforts:

- Manual data analyses; non-standard across user base and shallow dives, drove a 60% reduction in lost value to the Fab
- Best practices in place; Real-time three-level Pareto analyses standardized for all users enabling structured deep dives, drove an additional 71% or 89% cumulative reduction in lost value to the Fab

Both periods were effective in reducing mean and variation due to good team effort however it is clear that aggressive priorities, expectations, and better continual improvement tools empower the teams to effect and maintain more dramatic gains.

Electronic Product Yield

G. Box et.al. [1] describe two types of variation as permanent and transitory and how the former may corrupt correlations and attempts to predict end-of-line yield using the transitory manufacturing data.

"(An example of a permanent component is) when any procedure in manufacturing is slightly changed in a manner not regarded as important, or perhaps not even consciously realized or remembered. The accumulation of undetected permanent components of the noise produces "nonstationarity". … "Nonstationarity reflects the steady increase of entropy (disorganization) that occurs in any uncontrolled (portion of a) system. … The aggregated permanent components produce a continuous increase in entropy. The purpose of quality control is to reduce or possibly nullify th(is) effect…" [2]

Pyzdek (1990) was credited for this concept in the Box publication. "… every deviation must be caused by something and what is called a special cause and what is called a common cause entirely depend on the level of what we choose to call residual noise. If this can be reduced, more "special causes" will become evident."

The author takes poetic licence to alter the intent of Box's original focus. The client found that attempts to model the impact of in-line variation on electronic device performance were mostly inconclusive due to the aggregation of noise from other known unavoidable causes of variation within the production line. A prime example is the impact from known minor variations of incoming substrate characteristics on electronic performance.

Another critical activity in this project was the set up of sequential Least Squares Regression models to quantify and filter out the aggregated permanent noise from the Fab database and identify new transitory causes. These models were owned and sustained by the client. Secondary SPC treatments of the normalized scaled estimates provided a time-based trending of the model's individual term coefficients. These secondary control charts clearly indicated new transitory variations in electronic performance that could then be correlated back to specific in-line process steps. As claimed by Box and Pyzdek, reducing aggregated permanent noise within the predictive yield model made it easier to discover other assignable in-line causes.

The early efforts did connect several process control issues to product yield losses and contribute to achievement of the cumulative yield goal, see Table 3. However, as of the end of the joint effort we were unable to fully translate the in-line process capability gains to the end-of-line product yield gains.

Product	Metric	% Improvement
High Runner 1	Cumulative Yield	17.6%
High Runner 2	Cumulative Yield	5.7%
Development 1	Parametric Test Yield	11.4%
Development 2	Cumulative Yield	180%

Table 3: Quantitative gains in cumulative yield

The client has committed post project resources to continue refinement of the critical feed-forward / feed-back of predictive yield information

CONCLUSION

The MAX Group was chartered to drive process and product yield objectives in a GaAs-based wafer fabrication facility. The charter was fulfilled through joint implementation of a MAX business process which teaches, mentors and practices excellence in precision engineering through industry benchmarking of process engineering and quality process control best practices. Qualitative best practice categories were committed to the client including; continual improvement, process and equipment sustaining (especially long down events), process and yield management, and SPC for process and product. All best practices were addressed through immersion to coach existing engineering efforts. The SPC and cumulative yield categories were addressed with a much more quantitative program, throughout the duration of the project.

The project resulted in improvements in cumulative yield of 6%, 11%, 18% and 180% for four respective product lines. Guided continual improvement activities achieved significant improvements in process yield, quality process control, and product final test yields.

REFERENCES

[1]Box, G., Luceño, A., Paniagua-Quiñones, C. M. d. *Statistical Control by Monitoring and Adjustment.* Wiley 2009.

ABBREVIATIONS

I.E.G.: International Engineering Group
SPC: Statistical Process Control
MES: Manufacturing Execution System