General Process Change Qualification framework for Wafer Fabrication

IOP Conf. Series: Materials Science and Engineering **530** (2019) 012035 doi:10.1088/1757-899X/530/1/012035

General Process Change Qualification framework for Wafer Fabrication

D S Nair and J F Chin*

School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

Corresponding author *: chinjengfeng@usm.my

Abstract. Wafer fabrication is the most value-added processes of semiconductor and electronics industries. The involved processes are state-of-the-art, most expensive, most complicated and highly sensitive. Any process changes require qualification dictated by different industry standards and also internal production performance specifications. The way a semiconductor industry performs qualification is often little known outside the industry and in contemporary literature. The paper offers insights into qualification process for wafer fabrication. Literature is reviewed on qualification in terms of reasons, stages and considerations. A general qualification framework currently employed in a foundry is shared as a valuable example.

Keywords : *Qualification, Semiconductor manufacturing, Framework*

1. Introduction

Wafer fabrication is the most expensive stage semiconductor manufacturing phase [1] and also the most complex manufacturing processes in existence [2]. It is the first basic stage of semiconductor manufacturing, preceding Sort (or Probe), Packaging (or Assembly) and finally Test [3-5]. Wafer fabrication builds integrated circuits (IC) such as electrical, photonic, or MEMS (Microelectromechanical Systems) circuits [6] in layers on silicon wafers normally 200mm or 300mm in diameter. Only some of these fabs, a common term for the factories that manufactures these products are considered to be pure play foundries. Foundries are wafer fabrication companies that produce custom made wafers for the different customers based on their product requirements, applications and specifications. They are the so called 'contract manufacturers' of semiconductor wafers.

Typically, steps ranging anywhere between 300 and 500 are involved [7], using high-tech machines, various gasses and chemicals. Wafer fabrication processes are done in (or a combination of various requirements) vacuum chambers or highly clean enclosed environment with tight control of particulate, ions, minerals, moisture, pressure, temperature, lighting and other forms of molecular level contaminants. Six main common modules of a fab are Diffusion, Implantation, Thin Films Deposition (Dielectric or Metal deposition processes), Chemical Mechanical Planarization (CMP), Photolithography and Etch [8]. In some process flows, wafers also undergo Epitaxial Growth and wafer backside grinding, also refereed as Thinning process. In each module, similar machines or tools sets (term used in fabs for machines or equipment) and processes are grouped together called tool group.

In wafer fabrication, tools and processes are closely monitored and maintained to ensure consistency of the output of every step. Any changes to any portion of process flows or tools cannot be arbitrarily done as it may affect final yield, electrical parameters and reliability of the devices. In technology

development stage of a particular device, experimental changes in the process parameters and suitable tools are studied to optimize yields that suit the customers' electrical output parameters and reliability requirements. The running of confirmation pilots lots and engineering lots verify the stability of the entire flow and yield as per required. Next, the processes and the tools sets are fixed and monitored to be within agreed specifications and control limits.

The way a semiconductor industry performs qualification is often little known outside the industry and in contemporary literature. The paper offers insights into qualification process for wafer fabrication. The next two sections present literature review on qualification in terms of reasons, stages and considerations. In section 5, a general qualification framework currently employed in a foundry is shared as a valuable example. The framework is discussed in section 6 before a conclusion is given.

2. Qualification

Formally, qualification is a set of procedures of assurance for a specific system, premises or equipment to demonstrate the ability to achieve and fulfill specified requirements [14]. In addition, it provides documented evidence that a specific equipment, facility or system is fit or ready for the intended use [15]. If the manufacturer's specification offers a bigger range compared to the intended use or if a new process is developed to run beyond the current intended use, the equipment has to be qualified for the new range [16].

Graham et al. [15] identifies four stages of equipment qualification: design qualification, installation qualification, operational qualification and performance qualification. Design qualification (DQ) defines the functional and operational quality parameters requirements of the equipment and systems. The objective is to provide documented evidence that quality has been built into the design of the application. As a minimum this should include a listing of the manufacturer's instrument specification. The manufacturer also needs to demonstrate compliance with an appropriate quality system, during development and manufacture, and that the software source code is lodged with a secure third party. Installation qualification (IQ) intends to provide guarantee that the intended equipment is received as designed and specified. At this stage, the equipment is unpacked and checked against the order, ensuring that any pre-delivery qualification checks were made and recorded. Operational qualification (OQ) provides confirmation that the equipment functions as specified and operates correctly within the committed operation and functional limits. The equipment has to be calibrated before commencing this stage of qualification. Then appropriate qualification tests have to be done based on the intended use.

Performance qualification (PQ) is carried out to ensure the equipment consistently perform as required. Repeatability and reproducibility checking procedure including some tests applied during OQ is commonly involved. The checking may be carried out before use or included in a regular program, or combination of the two, as appropriate. Performance checks must be performed after maintenance and must be scheduled. The results must be fully documented.

Qualification begins with first identifying the reasons that warrant for changes. Once that is agreed upon, experiments and Designs of Experiment (DOE) are carried out using non-production wafers called Test Wafers (TW). Various measurements and cross-sections of structures that are of interest are done in the fab and Failure Analysis (FA) lab. Once the required criteria are met, engineering wafers (which are also non-production wafers) may then be processed through to confirm the electrical parameters. Finally test and control runs on actual production wafers are done to statistically verify that the changes do not alter the output and yield requirement of the current process. In each stage of the qualification, the results of DOEs and experiments have to be presented to a board of decision makers who review the data and allow or disallow the changes or request for more data to make decision. It is clear that senior representatives from each area of expertise and interest have to be present in reviewing the proposed qualifications and giving their relevant approval for the qualification proposal to allow the intended changes to take place. The review board members, at minimum, should consist of representatives from the Quality, Manufacturing, Technology, Yield and Process Engineering departments as each of them are important stakeholders to ensure the changes made are truly beneficial to the company without

jeopardizing the customers' interest. The collection of these representatives, make up the Change Review Board (CRB) or can be also called by various different names in different companies.

3. Reasons of change

Policy makers and top management alter and steer the direction of the original heading of the company to new placements to best satisfy future market demand. It is vital for operation management and is a strategic investment for the future (of a company). The cause for these changes can be termed as *Strategic Forecasting* and changes towards the new heading may require qualifications.

Further, continuous improvements are always needed for an organization to be competitive and successful. It is nearly impossible to maintain permanent condition over a long period of time as market conditions and technology evolves and forces changes to take place [9]. Improvements should be as a continuous process instead of being done when a crisis occurs.

Second, Capacity Improvement causes can bring about changes by the direct addition of new tools or process modules of an existing tool or cluster tool [10] and will increase the capacity. The new addition must statistically perform comparable, if not better than the existing unit. Third, when improvements are done on the existing process or tools to improve productivity using any known methods of lean manufacturing, changes occur. It is basically done by eliminating waste [11]. One of the key methods of gauging the improved productivity of a fab is by analyzing the fab's Cycle Time [12] which can be used to indicate shorter development time, faster time to market the products, lower WIP and thus better customer satisfaction. Productivity Improvement causes such changes to occur by means of improvement of the productivity

Fourth, the prospects to improve yields are constantly present at all times [13] in fabs due to the nature of relatively short life of devices, processes and equipment. Thus Quality Improvement changes are done to improve the quality and/or robustness of the current process or tools.

External forces also cause a huge need for changes. Cost Reduction is one of the most common and popular causes for changes too. These activities are done to improve the cost competitiveness and profitability of the current process or tools. Finding alternative source of supply to replace Original Equipment Manufacturer's (OEM's) parts and consumables have a huge impact to operational cost and profitability. However it is also one of the most risky changes and has to be dealt with caution. Common actions include proper statistical analysis and controlled release to production upon approval to mitigate risks. This lead yet to another cause of change called Risk Reduction. Since wafer fabrication is the highest contributor to the overall cost of semiconductor manufacturing, huge risks are at stake due to the high investment costs. Examples of these changes include reducing or eliminating risk to humans, profitability and loss of production time, tools or product. Changes caused by fulfillment of Environmental, Health and Safety (EHS) are done to improve environmental friendly manufacturing practices and methods of waste management of the current process or tools.

There are also other causes that contribute for changes to occur such as Customers' Request. Customers make certain changes for reasons known to them or their customers. These changes include alteration to certain parameters to suit their product requirements. Normally it involves recipe or process changes. The next drive for changes is caused by suppliers. Supply Issues causes changes triggered due to the unavailability or discontinuation of current supplies of process/production/spares or other materials which requires an alternative. There is no intend to bring about changes and it does not bring about any benefit to neither the fab nor the customers. However, due to unavailability or discontinuity of direct or indirect materials or parts, alternative source has to be used. Finally there are changes brought about by Governmental Policies. In order to abide to Governmental or other formal Global Policies, Rules and Regulations, forced changes have to be made in order for the company to continue supplying their customers who may be affected by such policy changes.

4. Factors affecting qualification

4.1. Industrial Standards

A qualification has to fulfill the requirements of accreditations, imposed by customers and the respective industry. To date, a number of accreditations are generally applied in wafer fabrication. These include MS ISO 9001:2008 [17], MS ISO 14001, OHSAS18001 [18], Sony Green Certificate, IECQ QC 080000 HSPM [19], SEMI standards [20] and JADEC [21].

MS ISO 9001:2008 [17] is a set of standards set by International Organization for Standardization which defines and specifies the requirements for an overall Quality Management System (QMS) of an organization. The focus is on effectively implementing QMS to meet customer requirements, it encompasses five major areas: QMS, Management responsibility, resource management, product realization, and measurement, analysis and improvement.

MS ISO 14001 and IECQ QC8000 HSPM [19] more focus on environment and hazardous material management. MS ISO 14001 governs and details the requirements for an overall Environment Management System (EMS) of an organization. The items stated here are specific to minimize the impact of the organizations' activities, products and services to the environment and strive for continuous improvement of an organization for its environmental performance. IECQ QC 080000 HSPM [20] lists the requirements for an electrical or electronic components manufacturer or supplier to exhibit to the international market place that the organization has developed, documented, and implemented processes for managing the production, selection and use of electronic components, assemblies, processes and related materials in accordance with customer, local, national and international HSF requirements. Sony Green has the similar intent of the previous two mentioned. Sony Green Certificate is a qualifications arrangement which is specific to Sony Corporation. In 2002, Sony established a set of "Management regulations for environment-related substances to be controlled which are included in parts and materials." Environment-related substances which are deemed harmful were immediately banned or reduced, as well as their applications. Since 2003, the corporation only purchases parts or materials for its products exclusively from suppliers that are certified as their Green Partners. To ensure that suppliers observe these regulations, the "Green Partner Environmental Quality Approval Program" was introduced. This qualification is a requirement for the suppliers and Green Partner approval needs to be renewed every two years.

OHSAS 18001:2007 is an international Occupation Health and Safety Assessment Series (OHSAS) for occupational health and safety (OH&S) management systems. It aims to help an organization to control OH&S risks for its employees and to improve their performance. The main aim of implementing the OHSAS standard is reducing and preventing accidents (including accidents related loss of live, equipment and time). It does not include product and service safety requirement nonetheless.

Apart from the general industrial standards, fabs are also governed by Semiconductor Equipment and Materials International (SEMI) standards [20]. There are many SEMI standards but the two most commonly used by fabs are the SEMIE10 and the SEMIE79. The former is the standards for specification for definition and measurement of equipment reliability, availability, and maintainability (RAM) and utilization, whereas the latter are standards for specification for definition and measurement of equipment productivity used in Overall Equipment Effectiveness (OEE) calculations for fab equipment.

The Joint Electron Device Engineering Council (JEDEC), was originally establishment in 1924 and after undergoing a few stages of revamps, was names as JEDEC in1958 [21]. As of current time, JEDEC emerges as one of the most dominant technical documentation reference in semiconductor industry.

4.2. Production Stability

The second aspect is to provide assurance to the production stability. The major indices commonly used to gauge the success of the manufacturing processes in the fab are done by the observant of other more general output parameters which are defined in the SEMI standards. Here are some of the indices:-

1. Moves - The number of wafers that successfully passes through a series of process steps clustered together as a stage. A fab which has the capacity to produce 24 thousand wafers a month may typically have to make 145,000 moves per day.

2. Utilization of tools – These manufacturing indices are derived based on the SEMI E10 and the SEMI E79. These standards among others show how many percent of the time the tool is being used for production activity with respect to the available of the tools.
3. Availability of tools – Also derived based on the SEMI standards for semiconductor manufacturing indicates how many percent of the time a tool is available for production regardless on whether or not there is material to process on that tool. This index is also commonly referred as the Uptime.
4. Turn Ratio – This index is common to reflect the number of moves generated compared to the ending of hand wip. It generally reveals how fast the production materials are moving through the various stages within the fab.
5. DPML – Days per mask layer. A normal industry standard for a 200mm fab running Aluminum metal layers can range anywhere from 1.6 to 2.0 DPML. It literally means from one mask layer to the immediate next mask layer it will take about 1.6 to 2.0 days. So for a 32 mask layer device, it will typically take about 64 days from start to complete if the declared mask layer is 2.0 DPML.

4.3. Process Stability

A process needs to be proven of its stability before release to production. To demonstrate process stability, all the response parameters of interest must display constant means and variances over a significant period. In-line product monitoring (ILM) systematically samples and scans production lots for defect levels based on individual rules for sampling as set and agreed by the customers' request, Technology department's and Quality department's respective representatives. The ILM is also done on tools that have recently undergone any form of maintenance that were scheduled or unscheduled, before being fully released back to production. Periodically performing qualification (qual) runs ensures the tools and their respective processing modules are kept into check for performance deterioration and stability monitoring. Quals are done using TW and the measurements are also monitored through sophisticated SPC systems as used for production wafers. It is also worth mentioning at this juncture that particulate contaminations and many physical forms of defects (such as scratches) are also monitored by performing particle quals using TW.

4.4. Customer Specifications

The control of quality, defect and yield supersedes all other priorities in any typical wafer fab. The reason being is, there is no point in producing defective wafers, which may fall below the acceptance yield or electrical test criteria of the customers. There are very strict acceptance criteria set by customers to ensure the chips in wafers are considered 100% good before they can be sawn into separate chips and be used in the semiconductor packaging process. Customers can easily reject a batch of wafers based on samples taken from the batch that fails to meet their criteria. These wafers will then have to be scrapped and thus a great loss of revenue to the company. So, sacrificing the speed of manufacturing to do inline monitoring and measurement as a measure of process stability monitoring and stopping the manufacturing line if certain tools fail their periodic qual runs or if the ILM fails the control limits or if the SPC charts for measurement parameters violates the Western Electric (WE) rules, is somewhat an acceptable practice and common in this industry.

5. A general framework for qualification in a foundry fab

Before the process of creating a generalized framework commence, a few factors need to be clearly defined and studied in order to make the step by step procedure optimal for the intended qualification. The first step is the establishment of a qualification review committee. As aforementioned the CRB members are formed and periodic congregations of such meetings are done to review the required changes. A facilitator from the quality department will arrange and document the proceeding of the meeting and follow up with the action items generated during the course of the change request.

The second step classifies the qualification based on the type of change required and further split it into the stages based on current organizational structure, urgency of the changes and risk mitigation. A set of guideline with standardized method of classifying the description of changes has to be devised. A typical example involving four classes based on the extent of changes required is given in Table 1.

Table 1: Class of changes

Class	Class 1	Class 2	Class 3	Class 4
Description	Major change	Minor change	Operational change	Unreleased technology change

Some very minimal Installation Qualifications (IQ) are being performed when new tools are brought into the fab during commissioning. However these works, mostly related to calibration, are done by equipment vendors to verify their tools' factory settings. These types of qualification works are normally go-no-go type or calibration whereby the tools must comply with the required calibration data before being handed over for further production qualifications. The majority of the qualifications that are performed on operational wafer fabs are the Operational Qualification (OQ) or the Performance Qualification (PQ). Other qualification, such as Design Qualification (DQ) is actually done by equipment manufacturers.

The third step of the framework relates to project-management and development of ownership. By looking into the overall qualification as a project that has clear sets of problem statement, goals, timeline and ownership, the entire qualification can be executed into few major stages as shown in the model framework of process change qualification in Figure 1 - first, the Pre-Change Qualification (PCQ) stage, where, non-destructive (to production wafers) tests and preliminary data are obtained to convince stake holders and CRB members to give approval to test the changes onto the production line using actual saleable wafers; Second, the Change Qualification (CQ) process being done on the production line in the fab using actual production wafers to obtain life data to make comparison of the required output parameters between wafers that have undergone the changes and wafers that are processed in standard conditions. Here, after reviewing the outcome of the production wafers' output parameters, the CRB members shall perform approval to the manner of which the changes are to be released to the fab based on the proposal of the change requestor. Some qualifications can be directly implemented some will have some form of amendments before being given approval for the third stage of Full Release (FR).

In these individual stages a cluster of activities have to be carried out in order to proceed to the next stage. At the PCQ stage, the requester defines the problem statement and conducts the tests and proposes the changes based on the results of the tests to the CRB member by preparing the PCQ presentation material, the CRB then makes decision to proceed as requested, proceed with the change request but the proposal need to be amended or the last option, reject the change request. They also review and in some case, when one or some of the CRB members deem fit, challenge the class of changes suggested by the requester based on the reasoning given and the individual fab's internal criteria requirements. If the CRB members approve the PCQ, then the evaluation with production lots are carried out at the CQ stage.

At the CQ stage, the requester who proposes the changes presents the results of the changes done on production units called split lots to the CRB members. Again at this stage, the CRB members can decide to either proceed with the proposal, proceed with the change with further changes to the proposal or they can also opt to reject the request. However, since at the PCQ stage, the CRB members already agreed to proceed to the CQ stage, rejecting the change request in this juncture is extremely rare. If the Class decision was not made in the PCQ session, then the CRB members can also decide what class of changes it is now and further decide if there is a need to update the customers of this change. If it is a class 1 or 2 change request, then customer approval is required before the changes can be actually implemented or tested on their wafers.

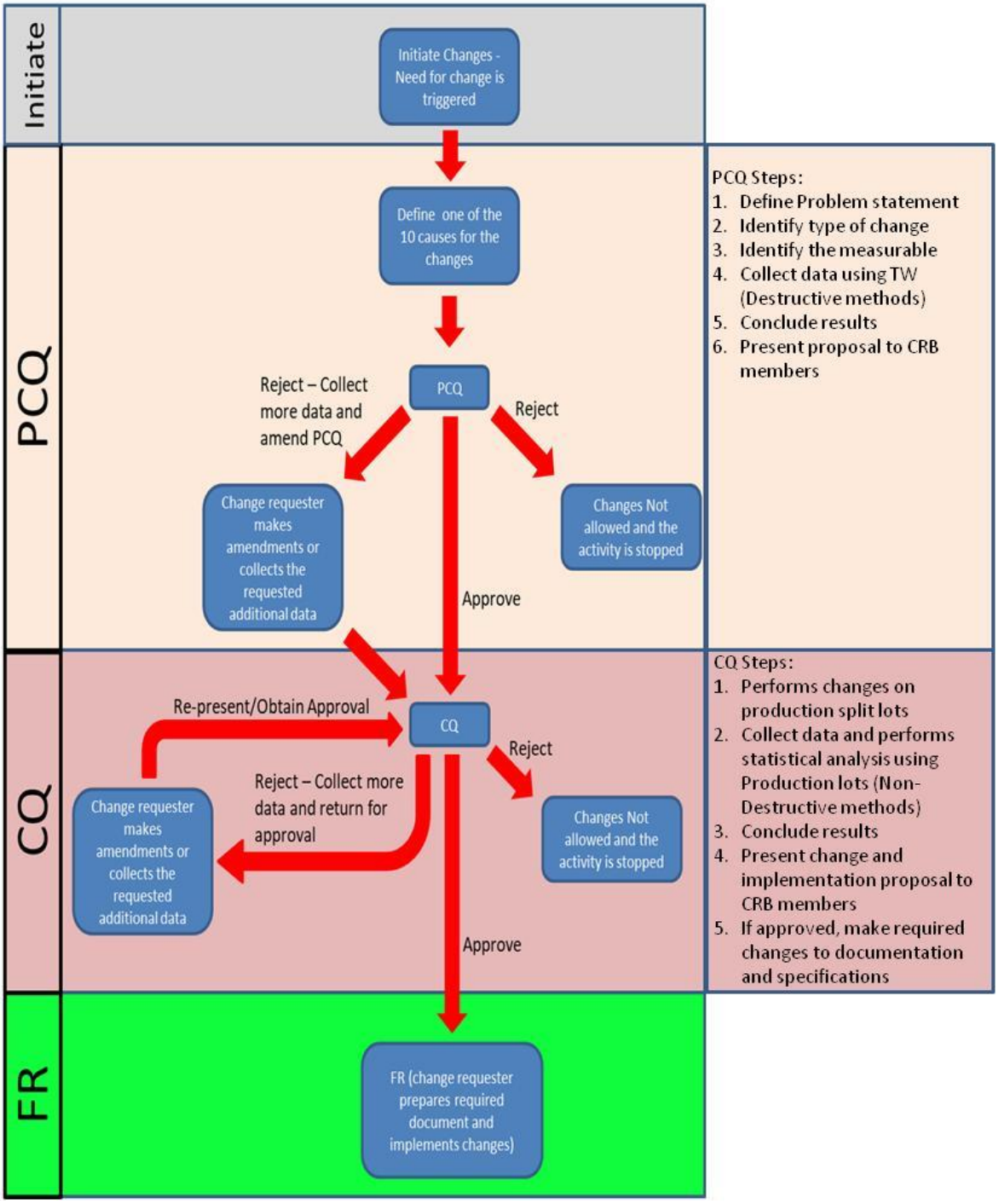

Figure 1: Model of a process qualification framework

The change requestor also proposes the manner in which the change will be implemented to the fab once the CQ is approved. In some the cases, CR may need some amendments before the FR is granted. The CQ data is usually reviewed for changes that may impact product quality and alignment with the relevant Technology or Yield Engineering department's person in charge is done and mentioned in the CQ presentation. Finally when FR is obtained, it also involves the amendments of all documentations and specification prior to execution of the qualified changes in the fab.

6. A case study of a process qualification in a foundry fab

The case study (Table 2) is for a change request for qualifying a new additional tool for Contact Etch Process. It is a repeat tool qualification, meaning that there already exists a similar tool of the same make and model that is qualified and running in the fab in stable mode. Thus this new tool is for a Capacity Improvement causes.

The case study shows the step by step action done by the change requester in order to release the new repeat too to the line. As can be seen, at the PCR stage, a lot of data from TW and engineering wafers are obtained and presented to the CRB members to convince the board that the tools is indeed reliable and qualified to proceed to the next step, CQ. Qualification runs are repeated to obtain as many as 10 separate data points at different intervals and timing to monitor the repeatability and reproducibility of the required results. The requester has to have enough data to statistically provide these evidences to the CRB. This is because, at the CQ stage, customer production lots are being used, thus if the tool is not able to perform as intended, it may cause deviations or defects on the production split lots and may cause scraps and yield loss. This will cause loss of money, man hours and delay in the tool being qualified to increase the fab capacity which is crucially required.

In the CQ stage, the actions are very straight forward, the requester runs the splits, collect the required monitoring data and statistically proof that the new tools performs the same as the POR tool by ensuring that there is not significant difference between the two sets of data. The results of electrical and yield parameters are also verified by the technology department's person in charge of Contact Etch process.

Finally the requester proposes the condition of release to the CRB and once the condition is accepted and met, the FR is granted.

7. Discussion on the framework

The framework clearly provides a strong visible guideline for change requesters. As the need to achieve manufacturing excellence and continuous improvements to move forward is ever demanding, it is important that such guidelines are available for change requester to ensure that they can perform their tasks in a predetermined step by step sequential procedure. It is self-explanatory and reduces time wasting to gather the methods from others who know the procedure due to past experiences.

Although passed all relevant product testing evaluations, changes frequently may not be feasible to be implemented throughout the production floor as FR. The reason being, different customers' devices have different aspect of sensitivity towards changes although they are built upon the same technology platform of fabrication. Thus, by cleverly adding a CR stage, where controlled production releases based on specific devices and customers that are often required to minimize risk both for the company and to the customers, can be done safely in a win-win manner.

Since the needs of data to be presented to the CRB can vary significantly depending on a variety of reasons and factors that have to be considered, it is difficult to actually lay out a specific requirement guideline for each type and category of qualifications. These requirements may be diverse based on different customers, devices, technology and applications. As such, the requirements are very subjective and are often discussed in the CRB forum to get consensus from attending members before the CQ split lots are run. Thus these prerequisites are not mentioned in qualification framework and are maintained as a subjective matter that are finally determined and agreed upon during the proposal is presented by the requestor. However a general guide as to what are normally required based on past experiences and feedback from the customers and device owners help the requesters to provide near accurate proposals for their change qualifications

An opportunity to further enhance the framework is identified by defining each step of the PCQ and the CQ in detailed sequential steps instead of being stated in a summarized manner. We also see that if each step can be additionally broken down, anyone following the guideline would know exactly what needs to be done at each stage within the step. The framework can be further be detailed out in a working step by step flowchart with decision making steps inserted to help the requester to make decisive decision at each juncture of the flow. In real practice, certain situations warrant conditional approval which requires minor modification or adjustment on the initial proposal, thus the usage of decision steps

as options should be explicit into the flowchart to further improve choice making with multiple plausible alternatives as accurate guidance for the requester.

In view of evolving nature of the qualification framework, a good documentation practice is vital such as adding clearer labels or identification tag numbers for each individual steps and further sub dividing them into groups of similar tasks. It also offers quick identification when search is required to be done in reference to a particular step of stage of qualification.

8. Conclusion

Qualification frameworks in fabs, till today, still remain a trade secret of each company. Different fabs in the world have their own methods of performing change qualifications but in general they all have the same considerations factors and requirements for similar processes, tools and application. Qualification methodologies are also some of the closely guarded knowhow of wafer fabrication industry alongside technical knowhow. The above qualification framework is the results of years of continuous improvements to enhance change qualification methods in a more efficient, manufacturing friendly and cost effective manner. It has worked out very well for the company. However, as steps are taken to move forward towards being competitive and positioning the company successfully ahead of other competitors, qualification framework remains a living document, open for multitudes of enhancement to add to our current best known methods of wafer fabrication change qualifications.

Table 2: Summary of the running of the case study

Stage	*Step*	*Action description*	*Day*
Initiate	1.0	A new additional tool for Contact Etch Process is brought in and has to be qualified to run production. It is a repeat tool qualification, meaning that there already exists a similar tool of the same make and model that is qualified	Day 1
PCR	2.1	Define the problem statement and what warrens the qualification, in this case, it is to support manufacturing capacity	Day 5
	2.2	Define the changes from the current condition to the proposed condition	Day 5
	2.3	Classify Changes to be undertaken based on DQ or OQ	Day 5
	2.4	Alignment check statement with other stakeholders (such as IE or Technology) and impact of changes to manufacturing indices (such as cycle time, capacity increase)	Day 10
	2.5	Define the methods and qualification matrix that was used to evaluate the new tool in comparison with the required specification and performance of an already existing tool. Qualification parameters are oxide etch rate, nitride etch rate, particle qual data, engineering wafers' contact diameter measurement also called Critical Dimension (CD) and engineering wafers' contact holes cross section view to measure and observe the profile of the hole	Day 10
	2.6	Present the evaluation and DOE results (preliminary results) of the TW and Engineering wafers' compared to the specification and current process of release (POR) tool to the CRB	Day 45
	2.7	Propose for some production split lots and request permission to proceed to the CQ stage where the declared the output parameters that will be checked on the split lots based on the relevant qualification matrix for the Contact Etch process	Day 45
CQ	3.0	Performs changes on production split lots the collect data and perform statistical analysis (using Non-Destructive methods)	Day 52
	3.1	Conclude results and prepare proposal including implementation strategies and timeline	Day 89
	3.2	Present the summary of the PCR and what was agreed upon and consented earlier (to refresh memory of the CRB members)	Day 92
	3.3	Present the split lots data of the parameters and statistically compare the data to the specification and current process of release (POR) tool to the CRB	Day 92
	3.4	Requester proposes the conditions for FR	Day 92
FR	4.0	FR Granted once the all condition meets the agreed criteria of the CQ proposal and requester updates all required documentations for the change to be implemented in the fab	Day 96

Acknowledgement
This work was supported by Research University Grant (RUI), Universiti Sains Malaysia [grant number 8014069].

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