AGENT-BASED CHEMICAL MECHANICAL PLANARIZATION QUALIFICATION FOR SEMICONDUCTOR WAFER FABRICATION

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ABSTRACT: Semiconductor wafer fabrication is one of the critical segments in overall integrated circuit (IC) production flow. There are number of processes involved in the wafer fabrication facility which are diffusion, ion implantation, lithography, etching and Chemical Mechanical Planarization (CMP). Process equipment is required to be in optimized condition. In order to achieve this, qualification is done on equipment prior to process production wafers. In CMP, qualification is to monitor pad performance. Pad performance depends on few critical parameters which are monitored by wafer thickness measurement. Measurement taken is based on Statistical Process Control (SPC) rules. Currently, the qualification activities are carried out manually based on Standard Operating Procedures (SOP) of wafer fab and Manufacturing Execution System (MES). For this purpose, agent based framework is applied to enhance qualification activity. The measurement results are computed by agent to manage selected data points on the wafer and to derive specific parameters. The results show that the proposed method is capable to produce consistent results.

KEYWORDS: *Semiconductor Manufacturing Fabrication Facilities; CMP; MES; Oxide Removal Rate; Wafer Uniformity*

1.0 INTRODUCTION

Integrated Circuit (IC) is one of the vital components in electronic devices, empowering advances in communications, computing, health care, transportation and other applications [1]. It is a catalyst and main component to innovate variety of modern electronics products. There are many stages in IC industry, which are involving IC designing, wafers producer, IC fabrication and assembly line. IC design is forming the circuit layout with millions of transistors, resistors and capacitors with its own functional [2]. Then, there is a wafer producer that is responsible to provide wafers to IC fabrication facilities. It involves of forming of ingot and cutting ingot into wafers. The third stage is the fabrication. In wafer fabrication, IC is fabricated on blank wafers to be functional as intended through its design. There are number of iterative processes involved in semiconductor manufacturing which are photolithography, diffusion, thin film deposition, ion implantation, etching, chemical mechanical planarization (CMP) and cleaning process.

CMP in particular, is a process of chemical and mechanical actions. CMP is able to produce planar surfaces to the wafer by micro, nano or atomic level. The process is vital in IC manufacturing due to its effectiveness of flattening thin films. In addition, it also enables the interconnect materials to be stacked throughout the layers. Material removal in CMP happens due to one or more chemical steps that change the wafer surface and eventually removes the changed surface via mechanical step. The main component in the process is pad. Material Removal Rate (MRR) falls over time if the pad is not conditioned during the CMP process. After the installation of new pad, a series of pre-polishing processes is performed to break in the pad. The purpose of the break-in process is to open up the pores on the pad surface [3]. The change of pad is inevitable. Pad is changed after number of wafers run and pad performance is monitored within that period of run. The equipment qualification is to monitor processing pad performance on daily basis. This acts as the basis of this paper to propose a new technique of pad performance qualification for semiconductor fabrication process.

Additionally, process recipe optimization is essential at the qualification stage in order to run the process recipe that optimizing equipment performance in the presence of noise that happens from batch to batch [4]. By actively planning and conducting qualifications of product recipes on tools, machine efficiency and operations in the fab can be improved [5-6]. There are two main concerns in the CMP polishing pad for optimum performance, which are consumable (pad, brush and buff) qualification and pad daily qualification. In particular, pad change is performed after number of wafers have been processed, which is estimated to be around 300 wafers on each head (this is about 2 times per week), this is when pad is estimated to wear off and eventually required to change. In addition, pad daily qualification is done to monitor solely on pad performance rather on pad wearing off within 2 times per week. Daily pad performance qualification is performed in ± 1.5 days. In order to improve the system performance, this study proposes an agent-based setup application for CMP Qualification Process. To the best of our knowledge, this is the first research that proposed an agent-based control for CMP qualification process.

The discussion is arranged into several sections. Section 2 consists of literature review on the importance of equipment qualification, MES, and agent based setup. Meanwhile, Section 3 is on methodology of CMP qualification process, measurement points on wafer, the integration with MES and the application of agent based setup. Section 4 is the results which is on parameter derived from the measurement points and check upon the control limit of statistical process control (SPC). Finally, Section 5 is the conclusion part.

2.0 SEMICONDUCTOR MANUFACTURING

2.1 MES for Semiconductor Manufacturing

The nature of semiconductor manufacturing involves multiple re-entrant of specific processes to build up the IC layers. The process and measurement steps involved come up to hundreds of steps. In process, this is repeated standard activities such as of deposition, polishing, masking, etching and cleaning steps. Since this involves multiple steps and re-entry steps thus, Computer Integrated Manufacturing (CIM) is applied to help out floor operator running the lot with minimum mistakes and to assist operation team plans lot work in progress.

CIM system is divided furthermore into MES and equipment integration (EI). There are standard components defined in both systems. In MES, there are work in progress (WIP), process flow, equipment, factory model, data collection, and carrier. Meanwhile EI is the medium of communication between physical equipment and MES system via SECS-GEM standard. Events from equipment are translated into sequence of actions the moment operator placing the lot for processing till operator moving the lot for the next action [7]. Furthermore, this is also customized to include business rules (BR) in MES to fit in the fab operation needs. BR is added to standardize the operating procedures for operators handling the lot upon arrival at equipment, lot proceed to be processed, process completed and lastly removing the lot for next step. BR is also capable to customize the operating procedures for particular processing step for cycle time improvement.

2.2 Employing Autonomous Control Using Multi Agent System

A multi agent system (MAS) consists of a few agents that exist concurrently, share common resources, as well as communicate to each other concurrently or differently. Problem solving is facilitated by splitting the necessary knowledge into subunits to which an independent intelligent agent is associated and by organizing the agents' activity [8]. An agent is characterized as an autonomous problem-solving entity. In order to execute its role, it is capable to sense, communicate and react continuously to fulfil the stated goal within an operating environment. There are number of type of agents and shared as the follows [9-10]:

i. Purely reactive agent:
   A type of agent fitted with sensor to detect changes and react appropriately by using an actuator. The work of the agent is based on the rule of condition-action.
ii. Agent with perception:
   Compared to a reactive agent, this agent is equipped with higher level of internal architecture. There are three main subsystems- agent's decision-making function, perception and action subsystems.
iii. Agent with state:
   The most advanced agent with an internal data structure. This will enable the agent to have greater decision-making ability. The examples of an agent with state are route recommender or behaviour profiling robots.

MAS has been widely used to solve numerous problems in manufacturing industry. Among them include supply chain management [11-12], warehouse automation and optimization [13-14], scheduling optimization [15-16] and production with remanufacturing process [17]. It is also applied to MES for smart-factory within lab environment [18]. Therefore, MAS could play a major role in enhancing the performance of various manufacturing aspects.

3.0 METHODOLOGY

3.1 Qualification Procedures

Qualification activity inside the fab is extensive since it involves all processes including CMP. It requires standard activity for operator to avoid error and to ensure it is straightforward. Hence, manufacturing operator (MO) activity follows standard operating procedures as in fab facility. In short, MO brings the qualification wafer to the measurement and process equipment. It starts with pre-particle check, pre-measurement wafer thickness. It goes to polishing process, then post-particle check, and lastly post-measurement wafer thickness. MO is required to dispatch in/out of the equipment through CIM system [7]. 90 mm refers to the radius of wafer. It is related to wafer edge performance as it is hard to obtain consistent result further to the edge. Agent-based approach is used to manage the calculation of removal, average and standard deviation.

3.2 Proposed Agent-based Setup Application for CMP Qualification Process

The monitored component is pad performance. The process equipment qualification is done on four dummy wafers, which representing the heads. The environment setup is inside wafer fabrication facilities using FactoryWorks version 2x MES system and utilizing CMP process and measurement equipment running with SEMI standard. CMP process equipment has four polishing heads and a pad. Figure 1 illustrates the agent based setup on CMP qualification process:

i. Pre-measure the wafer to obtain the initial thickness of 53 sites.
ii. Execute polishing process on the wafers.
iii. Post-measure the wafer thickness of 53 sites.
iv. Execute Calculation Agent.

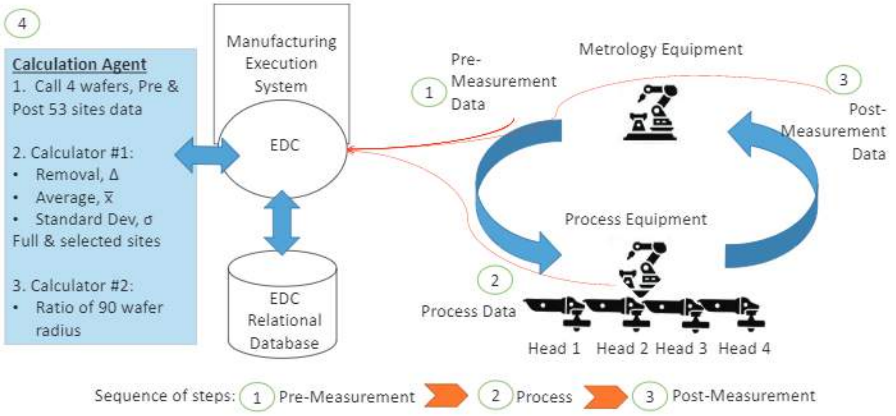

Figure 1: Agent based setup application in CMP qualification process

Calculation Agent is to recall pre and post measurement data of four wafers and further obtaining the removal, average and standard deviation of maximum full and selected sites. Number of sites are covering the full sites of 53 and selected sites out of the 53 sites.

Monitoring is essential to validate the pad condition before and after polishing process. In addition, after processing wafer thickness is targeted to achieve the specified thickness. Therefore, pre and post measurement data is collected via Electronics Data Collection (EDC). EDC is the main component in MES when measurement and data collection are involved. Thickness data is obtained from metrology equipment and then stored through EDC components. 53 sites are captured during pre-measurement as well as post-measurement via measurement specification. Measurement specification is one of the components in EDC that is to keep the parameter and data. EDC components help to gather pre, post and head information in one data collection. The 53 sites represent the whole surface area of 200 mm wafers as shown in Figure 2. The data will be further calculated to obtain:

i. Removal, Δ is pre-measurement – post-measurement data
ii. Average, $\bar{x}$
iii. Standard Deviation, δ

Details of removal, average and standard deviation of the selected sites is referring to Table 1. Meanwhile, Table 2 shows the full and selected measurement sites out of the 53 sites.

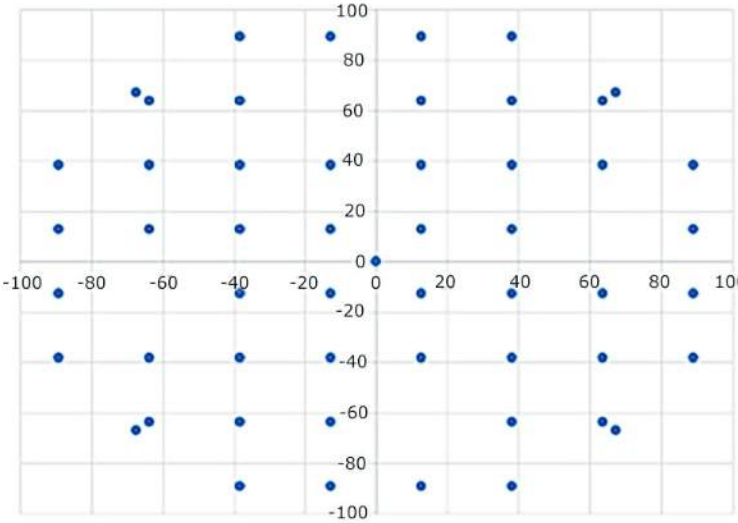

Figure 2: 53-site map on the wafer

Table 1: List of parameter derived from raw thickness data, calculator #1

Measurement Specification	Calculated Parameter	Descriptions	No. of Sites
1	97 Rate = Measurement Spec #1/2.5	97 mm radius rate calculation	Not applicable
2	97 NU = (Measurement Spec #2 x 100)/	97 mm radius non-uniformity calculation	Not applicable
3	97 CTE = Measurement Spec #5/	97 mm radius center-to-edge calculation	Not applicable
4	90 Rate = Measurement Spec #3/2.5	90 mm radius rate calculation	Not applicable
5	90 NU = (Measurement Spec #4 x 100)/	90 mm radius non-uniformity calculation	Not applicable
6	90 CTE = Measurement Spec #5 /	90 mm radius center-to-edge calculation	Not applicable

Table 2: Sample of selected sites applied in calculator#1

Measurement Specification	Calculated Parameter	All/Selected Sites
1	Measurement Spec #1	1-53
2	Measurement Spec #3	2,3,5,6,8,9,10,12,13,14,15,16,17,19,20,21,22, 23,24,26,27,28,29,30, 31,32,34,36,37,38,39, 40,41,43,44,46,47,48,50,51,53
3	Measurement Spec #5	22,23,30,31,53
4	Measurement Spec #6	1,4,11,18,35,42,49,52
5	Measurement Spec #7	2,3,5,10,19,26,27,34,43,48,50,51

The purpose of this architecture is to manage data on each of the equipment. Purely reactive agents were deployed to gather particular data, to manage and to provide the response based on the calculation.

Formulas are computed in the calculation agent. Calculation agent is to determine Δ, $\bar{x}$ and δ values for all sites, as well as average and standard deviation of selected sites. The calculated parameter then is stored to EDC. Upon recalculation, it is then re-structured to comply with the EDC format structure in order for the data to be stored and eventually able to be validated by spec limit and control limit automatically via the SPC tool. The flow is depicted in Figure 3.

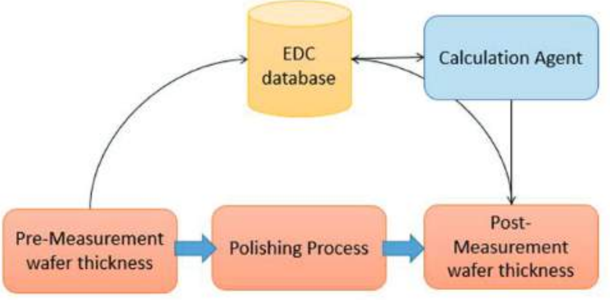

Figure 3: CMP process qualification via calculation agent

Additionally, the following three performance measurements will be used to measure the effectiveness of this proposal:

i. 90 mm radius of removal rate (90-Rate)
ii. 90 mm radius of Non-uniformity (90-NU)
iii. 90 mm radius of Center-to Edge (90-CTE Rate)

4.0 RESULTS AND DISCUSSION

Measurement data from the metrology equipment is further derived through Calculation Agent to obtain the removal, average, as well as standard deviation on full and selected sites. Then, with the EDC component in MES, pre and post thickness are stored and then recalled after post-measurement to execute recalculation process.

LineWorks Statistical Process Analysis & Control Environment (SPACE) software is used for continuous monitoring of SPC. Figures 4 until 6 represent the 90-rate, 90-NU and 90-CTE rate data, respectively. Based on the charts, process engineer (PE) is able to monitor those critical parameters and eventually the process equipment performance. By using the process, PE is able to plan and to react quickly on the equipment either to optimize further the process recipe or even shutdown the equipment to continue processing.

EDC data is captured on four heads and are represented by four wafers. Data is taken for every ± 1.5 days. 90-rate is conducted based on the 90 mm radius on wafer with the removal rate on the four heads as shown in Figure 4. The x-axis is representing the measurement Lot ID for each wafer at specified time. Meanwhile y-axis is representing the mean value of the 90-rate for each wafer (unit in Å/min). Blue line depicted as upper and lower target limit. The four successive data points are considered as one data collection. Next is the non-uniformity (NU) data.

The x-axis represents the measurement Lot ID for each wafer at specified time. Meanwhile y-axis represents the mean value of the 90-NU for each wafer as shown in Figure 5. Furthermore, the last chart is 90-CTE ratio, which is the centre to wafer edge ratio is shown in Figure 6. There will be a time where the process is started to drift away from the targeted limit and there will be a time where the process stays within the limit. x-axis is representing the measurement lot Id for each wafer at specified time. Meanwhile y-axis is representing the mean value of the 90-CTE rate for each wafer.

In particular, results for 90-rate are comparable to an experiment conducted with variations in experimental setup as Kenchappa et al. [19] utilized 3 different type of polishing pads. The range of result from the experiments of different pad types are between 1200 – 3250 Å/min and this demonstrates similarity to our results that fall within range of 2840 – 3050 Å/min. As this experiment only applied a single type of pad for manufacturing purpose, it is sensible that smaller range of rates were obtained.

On the other hand, the result for 90-CTE rate, which is if compared to another experiment [20] that is for longer pad life time improvement, the key characteristic is also focusing on the center and edge area where the pad is in contact for longer time on both areas compared to in between them. The criticality of both areas mentioned in [20] supports the findings of this study.

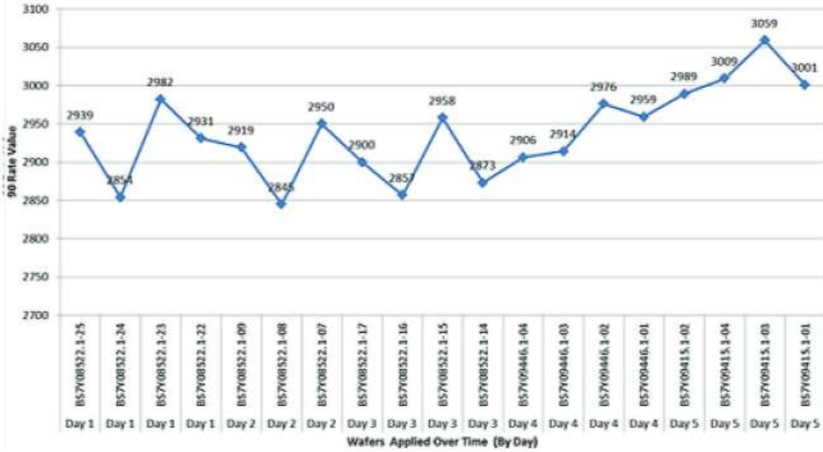

Figure 4: 90-rate monitoring chart

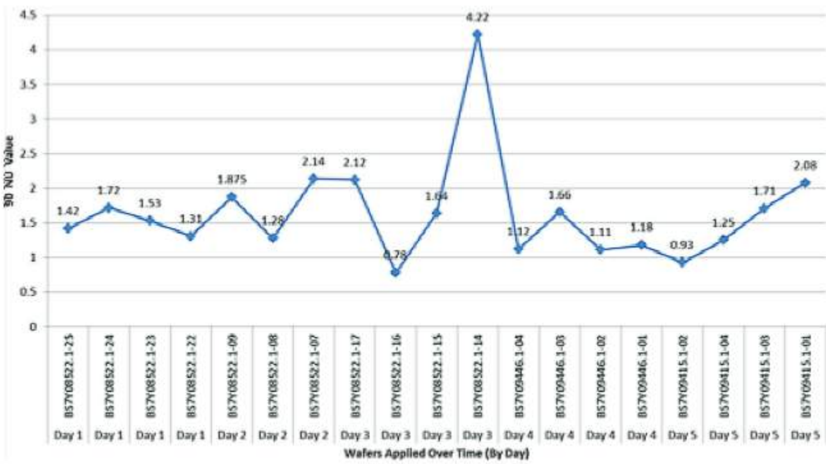

Figure 5: 90-NU monitoring chart

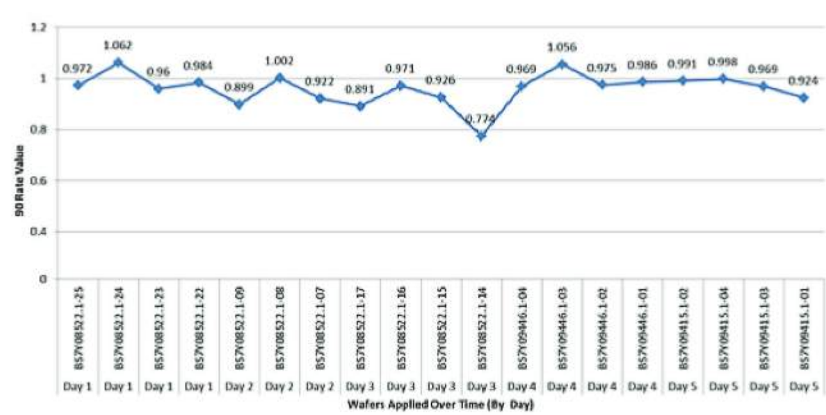

Figure 6: 90-CTE rate monitoring chart

5.0 CONCLUSION

Processing good wafer is critical for CMP and other processes in semiconductor manufacturing, yet it would not be achieved without the equipment readiness to support this activity. This is where the equipment qualification is vital in the whole process. Besides replacing the consumable parts because of wear and tear reason, CMP module is also required to monitor pad performance and to ensure the equipment is at optimum state. At optimum state, the process equipment is always on ready state to polish saleable wafer and minimize wafer from under-polished or over-polished. Under-polished will cause the wafer to be reworked, which requires additional processing time.

Meanwhile, over-polished is causing wafers to be scrapped. Both bring economic disadvantage to fab facility and eventually making a loss. The calculation module is made as an agent to the EDC component. The calculation agent is able to handle the required pre and post measurement data with 53 sites and selected sites out of this. The challenge is to manage the four heads requirement with four wafers data. In addition, at any of the qualification time, one or more heads will be unavailable because of maintenance as well as the need to perform re-qualification because of initial qualification results out of specification limit. Calculation agent is one of the agents based concept that was implemented in wafer fab due to process complexity while maintaining the existing system and existing standard operating procedures.

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