Advanced Process Monitoring through Fault Detection and Classification for Robust Statistical Process Control of Tantalum Nitride Reactive Sputtering

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***Abstract*—This paper discusses Fault Detection and Classification (FDC) deployed in high-volume manufacturing for the Tantalum Nitride (TaN) reactive sputtering process. TaN thin film resistors (TFR) with an average sheet resistance (R_s) of 50 ohms/sq with high uniformity and negative temperature coefficient of resistance (TCR) were achieved. Optimizing interdiction capabilities for real-time prevention and detection of parameter excursions strengthened statistical process control (SPC) and improved yield.**

Keywords— TaN, TFR, SPC, PCM, FDC, Machine Learning

I. Introduction

TaN thin film resistors have favorable properties, such as physiochemical inertness, linear TCR, mechanical hardness, and self-passivation. Under optimized process manufacturing, high stability and accuracy can be achieved [1]. Ensuring a robust process control over the TaN thin film R_s and uniformity is increasingly pertinent for microwave integrated circuits (MMIC) in applications of both Gallium Arsenide (GaAs) and Gallium Nitride (GaN) devices [2].

Reactive processes, such as sputtering TaN, are especially sensitive to the chamber and shielding conditions. For a stable process and to minimize tantalum (Ta) cathode poisoning, the process chamber must be adequately conditioned through a combination of "burn" and deposition sequences especially after the chamber is vented and the target is exposed to atmospheric conditions [3]. Optimization of the procedures for tool requalification after preventative maintenance (PM) activities has been addressed in a previous study [4].

Data-driven diagnosis of detected faults as well as effective analysis of historical data sets for trends and anomalies have emerged as powerful tools to improve quality and process control in a fast-paced manufacturing environment [5]. Instantaneous feedback through automated detection and classification of process parameters is a critical procedure that allowed further analysis of both the strengths and weaknesses within the TaN sputtering process. Solutions to several of the challenges encountered will be discussed in this work. Successful optimization and implementation of a third-party software's capabilities and features into the production environment substantially enhanced process visibility in the device fabrication flow.

II. TaN Reactive Sputtering

A. Inherent Challenges

The reactive deposition process in this single wafer sputtering system involves bombardment of argon (Ar) atoms against a Ta target, knocking off Ta atoms that subsequently react with nitrogen ions and form a deposited thin metal-nitride film on the wafer over time. As shown in Figure 1(a), the magnet behind the target intensifies the plasma discharge. The ratio and flow rates of these process gases directly affect the thin film quality and properties, which impact the resistor performance.

Thorough conditioning of the chamber is necessary to optimize both the process stability and intra-wafer, across-cassette, and run-to-run uniformity. Variation for the intra-wafer uniformity can be attributed to multiple factors, such as the plasma, magnetic field, atom bombardment, Ta target's wear pattern, etc. The deterioration of the Ta target's uniformity is most apparent at the end of its life cycle. Resembling that of a "sombrero," the degraded uniformity signature results in sputtered TaN thin films with alternating regions of high and low R_s as shown in Figure 1(b). Therefore, it becomes increasingly pertinent for real-time process monitoring of both process trends and maintenance schedules to ensure consistent quality of all process runs.

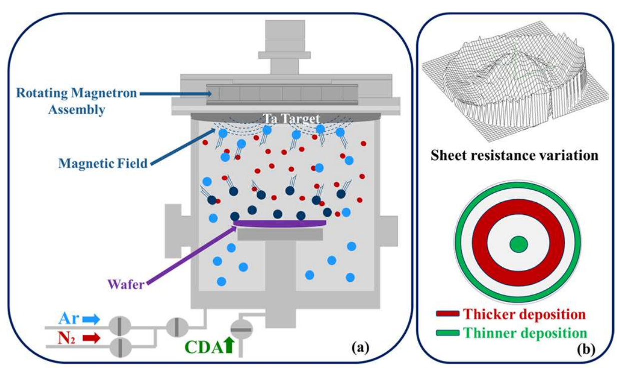

Fig. 1. (a) Reactive TaN sputtering has process gases, argon (Ar) and nitrogen (N_2), and platen cooling maintained by compressed dry air (CDA). (b) Target's wear pattern resulted in poor intra-wafer thin film uniformity.

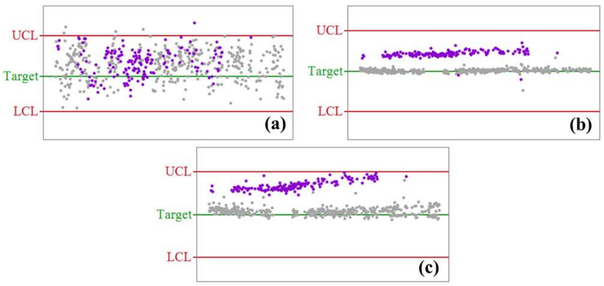

Fig. 2. A sputtering chamber with a high utilization percentage (nearing a target PM) has a relatively stable (a) inline average R_s but shows poorer intra-wafer uniformity as indicated by higher (b) %sigma and (c) range values.

III. Fault Detection and Classification

A. Process Parameter Excursions

A major advantage of run-to-run monitoring of process parameters (e.g., cryogenic and platen temperatures, deposition power, voltage, chamber pressure, gas flow rates) is the ability to establish correlations between data of specific runs to wafers with yield issues (e.g., failed electrical parameters, poor uniformity). To prevent wafer scrap, the FDC system's interdicting capabilities halt the tool so that detected parameter excursions, which the tool may not alarm for, can be immediately troubleshot. FDC monitoring of process trends provided instantaneous insight into sources that contributed to erratic inline R_s or a poorer intra-wafer uniformity signature. For instance, higher variability in Ar gas flow rates was attributed to a specific sputtering chamber's mass flow controller in Figure 3.

Wafers that were detected with out-of-control (OOC) process parameters were automatically flagged through FDC. These wafer runs were then collectively sorted into a list and reviewed for dispositioning and evaluated for risk assessment. Implementing a robust automated inline monitor of trending process parameters for all technologies and devices had significantly streamlined the down-selection of wafers that demonstrated higher process variation.

These selected wafers were then sent to a routine short loop sampling plan as shown in Figure 4 for earlier electrical characterization of critical resistor parameters. This reduced the average turnaround time by 4X, enabling faster feedback for earlier inline detection of shifts in TaN parameters as discussed in our previous work [6]. This short feedback loop was implemented after the discovery of the oxidative and thermal post lift-off ash treatment's stabilizing effects on the resistor parameters as shown in Figure 5. This step occurs downstream from the resistor layer stage.

As such, optimizing the FDC system and shortening the feedback loop for early electrical testing of TaN related parameters reduced process variation and tightened the distribution of the critical Process Control Monitor (PCM) resistor value for a specific resistor dimension by 25% as depicted in Figure 6.

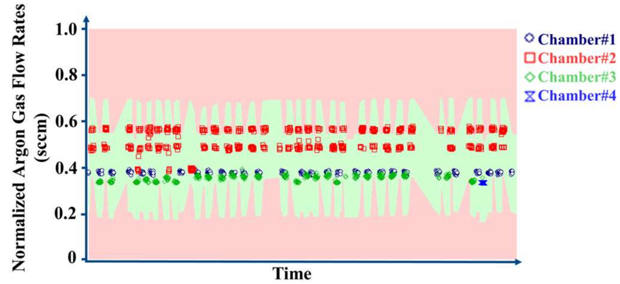

Fig. 3. Dynamic target hold x-bar set report tracked the standard deviation of charted residuals and revealed greater variability in Ar gas flow rates during TaN sputtering deposition for Chamber#2.

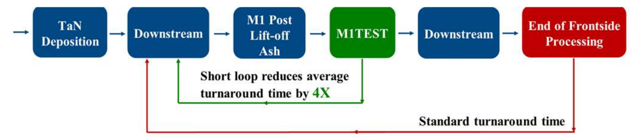

Fig. 4. A short loop (M1TEST) for earlier electrical characterization of TaN parameters was implemented to closely monitor for process drifts.

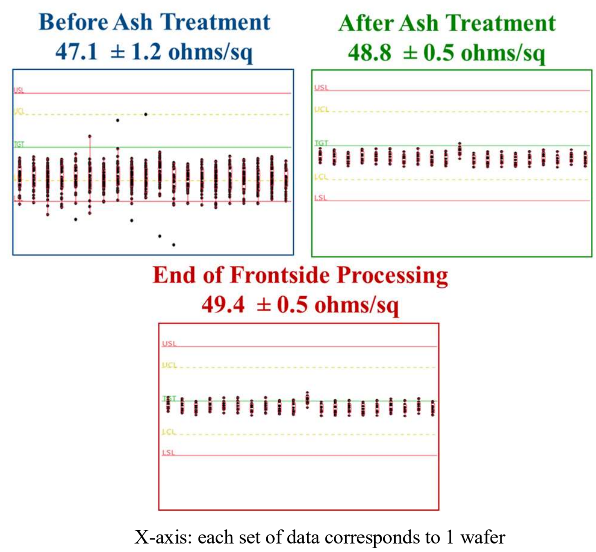

Fig. 5. Oxidative and highly thermal ash treatment tightened the TaN R_s distribution by 58% and promoted greater stability.

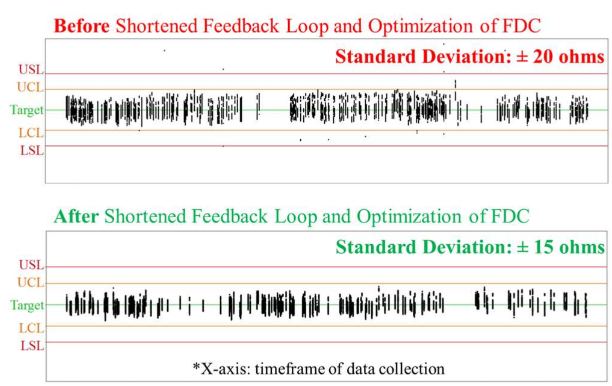

Fig. 6. Tightened SPC chart of several months' PCM resistor data for a specific resistor dimension to check the integrity of the resistor process. This was measured at the end of frontside processing for both before and after deployment of FDC monitoring and implementation of the early feedback testing of electrical parameters.

B. Automated Tracker and Scheduler for Preventative Maintenance

While some cases of detected parameter excursions were due to process variation, other cases aligned with approaching maintenance timelines. Performing PMs at a regulated basis is crucial not only for extending the Ta target life cycle but also serving as cost savings since Ta is a semi-precious metal. The online maintenance indicator in Figure 7 was implemented to schedule PMs by tracking the kWh-based target utilization percentages for every wafer run.

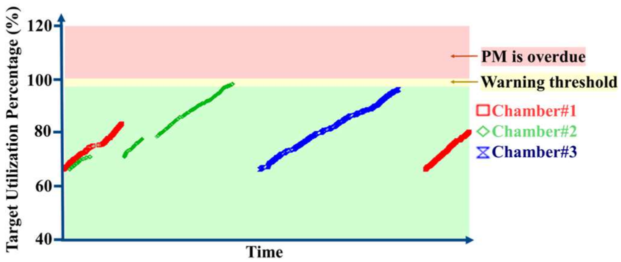

Fig. 7. Maintenance management tracks kWh-based target utilization percentages for scheduling routine preventative maintenance of each TaN sputtering chamber. Once the target utilization percentages enter the warning threshold, an alarm notification will signify the approaching PM.

Various benefits were achieved through ensuring a timely reassessment of the sputtering chamber condition (e.g., outgas, leak rates, cryogenic regeneration, bake-out) and equipment components (e.g., anode ring, shielding, shutter blade). As a result, unscheduled equipment downtime was significantly reduced, and risk was minimized for overloaded shielding or burning through the target into the backing plate which would result in product contamination and thus wafer scrap. After scheduled maintenance activities were completed, vigilant tracking of process parameters during requalification runs through FDC and inline SPC was necessary to ensure process stability and repeatability for consecutive wafer processing.

C. Report and Model Types

Automated detection of these process parameters with immediate feedback provided the opportunity to identify areas of both strengths and weaknesses for optimizing tool capabilities. The high customization of the filtered model type enables tracking of statistical calculations most suited to the defined process parameter's trends.

While some reports have user-defined control limits, others determine limits from evaluating historical trending data for each unique sputtering chamber or process recipe. For instance, to remove the Ta target's surface contamination or oxidation, recipes used for conditioning the target after PMs reach higher platen temperatures than standard production recipes. The software's history splitting feature by recipe allows each process recipe to have its own historical target for tracking the platen temperature. After implementation of tool interdiction during conditioning runs with OOC platen temperatures caught by FDC, there was a considerable reduction in burnt or warped monitoring wafers that are shown in Figure 8. This is especially crucial since warped wafers can result in handling issues during wafer processing.

The robustness of automated detectability for fluctuations in platen temperature was further enhanced by setting up FDC reports that captured both the calculated range and average for the platen temperature during the duration of each wafer run. This improved the platen temperature monitoring for both conditioning and standard production runs since additional data points were being accounted for rather than using a single point readout.

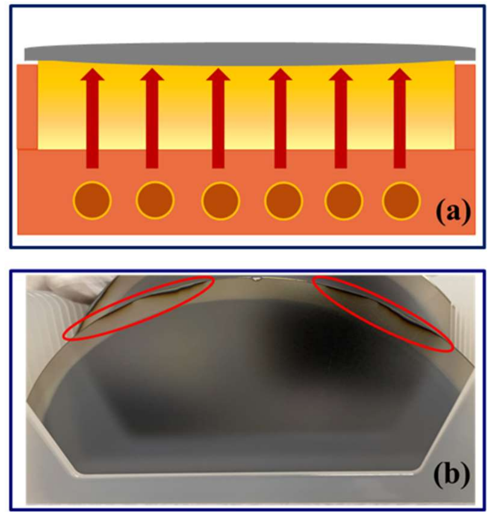

Fig. 8. (a) Wafer placed on the platen is heated during the sputtering process by radiation. (b) Extensively used silicon monitoring wafers for inline SPC were subjected to high thermal stress induced from burn-in conditioning of the Ta target.

D. Tool Recipe Management and Interdiction

The system's central management of tool process recipes and revision control compares the current recipes against their respective golden recipes to ensure that recipe files remain uncorrupted and no unauthorized changes have been made. Mismatches for any parameters detected at a set time interval would interdict, thus preventing subsequent lots from running a nonstandard deposition recipe that would adversely affect TaN thin film composition and properties.

E. Process Capability Timers

A capability timer was implemented to automatically switch off process capabilities that were no longer qualified or in usage for production. For instance, reload recipes, which contain different values for certain process parameters in comparison to the standard production recipe, are used for consecutive run-to-run processing in the same sputtering chamber. While this is favorable in the events of high work-in-progress (WIP), in which many wafers are queued at the resistor layer deposition step, it is crucial for vigilant monitoring of potentially erratic inline TaN R_s. OOC inline TaN data would disqualify the reload recipe to allow for recipe adjustments to retarget R_s.

Certain devices with nonstandard process specifications require a different targeted inline R_s. The FDC system would track when these nonstandard recipes were processed in the sputtering chamber and initiate a timer. If these nonstandard recipes were not run within a specified time interval, their corresponding process capabilities would be automatically switched off by the system's capability timers. This prevents accidental selection of unqualified process capabilities and signals that requalification is necessary to reenable those specific process capabilities.

F. *Process Tracking and Utilization for Maximizing Throughput*

Reports tracking production's process utilization of each sputtering chamber provided greater insight that allowed the engineering and production teams to maximize throughput while abiding by process constraints (e.g., minimum time for stabilization between process runs on the same sputtering chamber). For instance, evaluations were conducted to assess if simultaneous wafer processing on two separate sputtering chambers as shown in Figure 9 from the same tool platform would affect FDC process parameters or TaN thin film characterization. Figures 10 and 11 are examples of FDC reports used to identify wafer runs that were processed at varied overlapping intervals. A comprehensive study allowed for the qualified release of simultaneous processing for the standard production recipe, thereby doubling the throughput at the resistor layer deposition step.

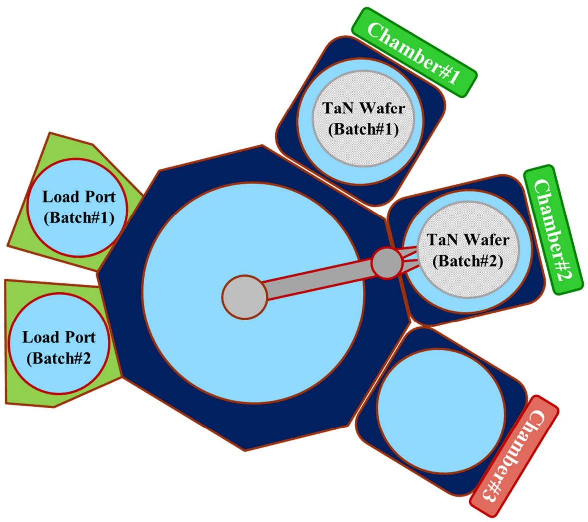

Fig. 9. Two chambers are actively in usage for simultaneously processed wafers from batch#1 and batch#2 for reactive TaN sputtering.

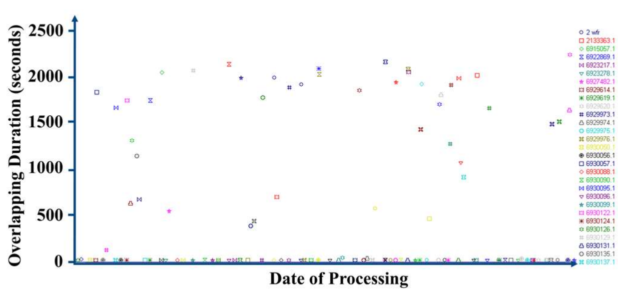

Fig. 10. Overlapping duration is shown for each pair of runs processed simultaneously on the same tool platform but in different sputtering chambers. Any data point with a non-zero overlapping value would indicate a simultaneously processed run.

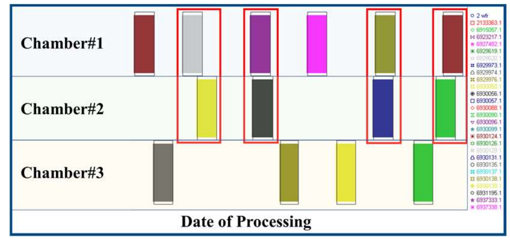

Fig. 11. Process tracking and utilization report allows for identification of simultaneously processed wafer runs. Each pair of simultaneously processed runs is boxed in red.

IV. Conclusion

Data visualization and automated statistical analysis enhanced the visibility of process trends and equipment behavior for reliable monitoring of PM schedules, identifying sources of process variation and drifts, diagnosing tool alarms, and establishing correlations between process data and TaN thin film characterization. Substantial improvements to process monitoring were reflected in tightened TaN PCM resistor values, resulting in yield improvement. Additional engineering analytical tools and machine learning can be integrated into further developing the current third-party FDC system to perform automated training, create models, and flag anomalies. Enhanced capabilities would reduce risks to product manufacturing, efficiently address tool issues in a production environment, and comprehensively detect and analyze semiconductor processes through simplified deployment.

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