# Reactive Sputtering: TaN Process Characterization and Post PM Qualification Improvements

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**Abstract**

**The purpose of this paper is to contribute to the limited reactive sputtering process literature with specific focus on the importance of gas ratios and the effect those ratios have on process output parameters. Particular emphasis is focused on the role of Nitrogen as the reactive process gas. $N_2$ is shown to be positively correlated with $R_s$ (sheet resistance) and negatively correlated to uniformity – to a point. TCR (Temperature Coefficient of Resistance) values are demonstrated to be dependent upon the gas ratios as well. Also presented in this paper are the results from post-preventative maintenance improvements and the optimization of the subsequent qualification procedures. Furthermore, as part of the process improvements, calculators were created to facilitate $R_s$ targeting during recoveries and for TCR computations.**

## INTRODUCTION

A great deal of literature exists discussing sputtering thin films such as Au, Cu, NiCr and NiV. However, limited work has been published on processes utilizing reactive gases. Whereas non-reactive sputtering is essentially a function of power and time in determining film properties (thickness and stress), reactive sputtering requires stringent control of additional process parameters. Output parameters are particularly sensitive to gas ratios and changes to operating powers will require further optimization of partial pressures. In systems lacking active throttling, precision control of constituent gas flows is imperative for repeatable outputs. Reactive processes are also particularly sensitive to chamber and shielding conditions.

To avoid some of the more significant processing complications and subsequent shifts in resistor performance inherent in Nichrome passives, Tantalum nitride (TaN) has been a popular choice for a thin film resistor (TFR) material, due to its unique film properties and numerous phases that make it ideal for wireless applications [1]. TaN is comparable to NiCr in electrical properties, has low TCR values, and is thermally stable. With dielectric assisted lift-off processing, this material is suitable for III-V circuit fabrication. The following sections will detail the reasoning behind a process revision and the related output shifts noted during evaluation, as well as measures taken to improve repeatability and process stability wafer to wafer, run to run, and after maintenance activities.

## METHODOLOGY

Sputter processing was performed on a single horizontal platen wafer module, mounted as part of a cluster configuration, utilizing a rotating magnet pack for uniformity control. DC magnetron sputtering of pure Tantalum was performed in all instances using Argon (Ar), with Nitrogen as the reactive gas. Incidentally, there is no active throttle valve on this particular system, and gas distribution was limited to a single inlet opposite the cryo on the chamber. Platen temperature was controlled to 30 °C via Compressed Dry Air (CDA) cooling.

We prepared 150 mm Si substrates with 2000 Angstroms of SiN as a dielectric film and used these for monitor wafers in the TaN deposition. SiN films were prepared in-house and used in place of oxide films to avoid resistivity shifts from the formation of TaO [2]. The dielectric isolation from the Si substrate provides a better representation of actual device performance; although, unrelated oxygen plasma steps and thermal treatments do cause a predictable nominal shift in resistance from inline measurement to parametric test on product wafers.

A CDE ResMap 4 point probe was used to measure sheet resistance utilizing a 49 point map for uniformity validation. All $R_s$ and % standard deviation plots are based on within-wafer values from the 49 point measurement on the prepared monitor wafers. TCR was derived from the following formula using PCM resistor structures through the transmission line method (TLM) at seven sites across the wafer collected on an Electroglas 2001X prober, with increasing chuck temperature on subsequent iterations.

$$TCR = (R2 - R1) / R1\,(T2 - T1) \times 10^6 \text{ ppm/°C}$$

R1 and R2 are the measured resistances at temperatures T1 and T2, 30 °C and 70 °C respectively.

## PROCESS CHARACTERIZATION

A single wafer process TFR recipe was originally developed to move beyond throughput limitations of the previous 100 mm substrate generation batch tools, which ran at a 1 kW power setting. An acceptable power of 2 kW was initially determined to be ideal when targeting a comparable process window while considering plasma stability, gas ratios, and heating effects at the substrate [3]. Some of the $R_s$ targeting resolution was lost, however, compared to the batch process in which the number of passes before the target determined thickness. In the new chambers at 2 kW power, one second changes in deposition times resulted in ~1.4 ohm/sq shifts in $R_s$; similarly, 0.01 kW changes in power resulted in ~0.7 ohm/sq shifts. Additionally, any micro-excursion such as arcing would have a greater effect with shorter deposition times. A 1 kW process would be less sensitive to arcing and was thought to provide greater resolution in targeting sheet resistance.

Within the new toolset power, time, and gas flows were all adjustable to target desired film properties. At 1 kW, gas flow changes were necessary to achieve desired film qualities due to the change in delivered target power. Specifically, to target end of line PCM resistance, longer deposition times were necessary but not double the time required at 2 kW. Deposition rates remained fairly comparable; primarily due to the fact the required gas concentrations were very close in relative percentage. Argon was not seen to be a significant contributing factor in any of the shifts in output parameters; however, very small changes in Nitrogen flow (1 sccm) had significant effects on all measured values (see Figures 1 & 2).

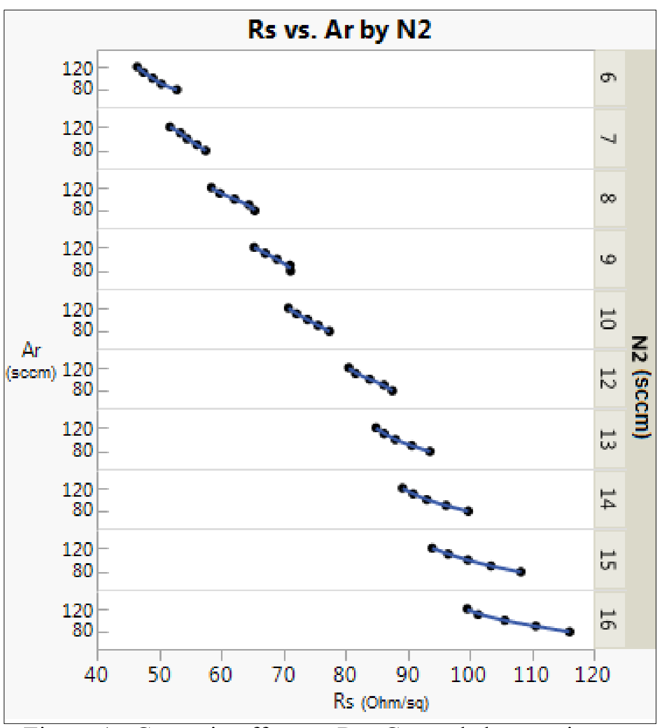


Figure 1. Gas ratio effect on $R_s$. General sheet resistance spread as a function of gas ratios across the entire process window. Note the distribution of points and general positive/negative trends.

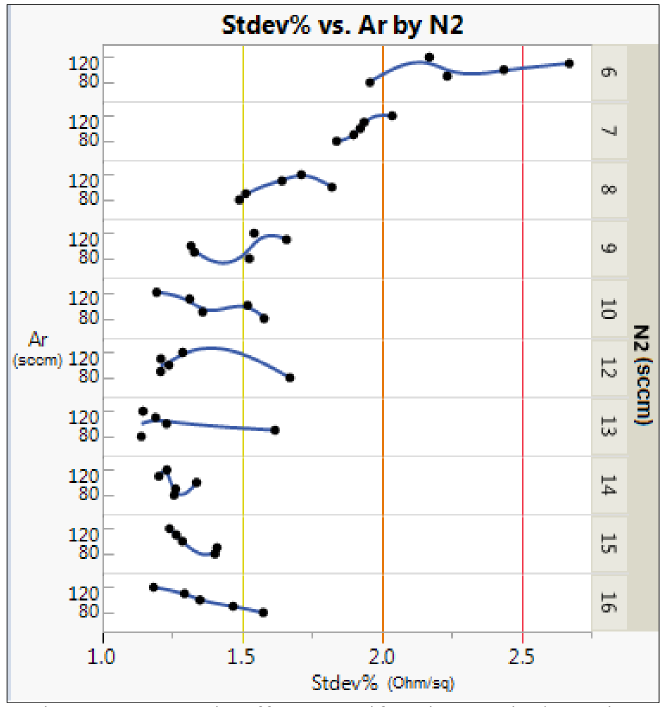


Figure 2. Gas ratio effect on uniformity. $N_2$ is the main driver of uniformity. Time was held constant at 1 kW for all runs.

In addition to increases in deposition times at the lower power, a significant reduction in the $N_2$ was necessary to meet TCR requirements. Unfortunately, this had a negative effect on across-wafer uniformity. Figures 3 and 4 demonstrate the gas ratio effects further validating the reactive component ($N_2$) as the main driver of the output parameters.

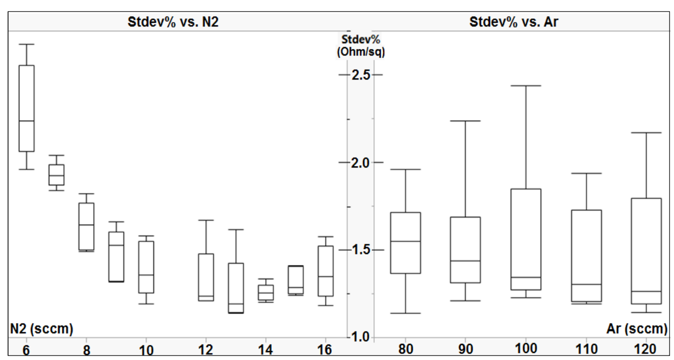


Figure 3. Uniformity distribution by gas flow. Variation in uniformity driven by $N_2$, not Ar.

It is yet to be determined if the uniformity distribution as a function of $N_2$/Ar ratio is consistent with the microstructure growth and surface morphologies seen in other studies [4]. However, TCR is an excellent indicator of film composition and low TCR is necessary to adequately target reliable thin film resistor performance through a broad range of operating demands. As with sheet resistance and uniformity outputs, Nitrogen is shown to have a greater effect on TCR values.

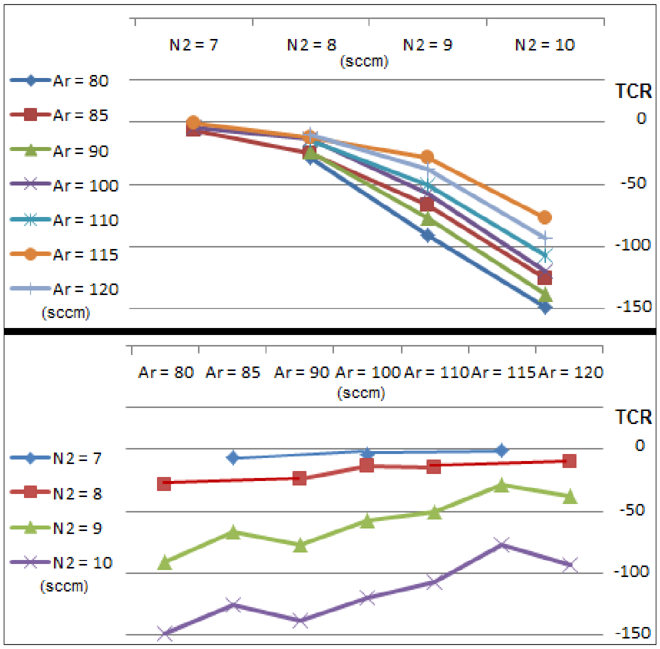


Figure 4. Gas flow effect on TCR. $N_2$ seen as primary contributor on resistor performance as TCR is an indicator of Ta: $N_2$ ratio, and therefore the particular phase of TaN.

TaN has smaller deviations in biased TCR values, similar to NiCr, with both films performing much better at higher temperatures compared to NiV resistors [5]. TaN is still preferred in the discussed applications due to its benefits as a barrier layer, higher Nichrome defectivity, and the physical characteristics of TaN previously mentioned.

## TOOL REQUALIFICATION OPTIMIZATION

Chamber conditioning is an essential aspect of process stability between maintenance events and run-to-run. Any time the chamber is vented to atmosphere contamination will bond to the target and shielding surfaces. Bake outs are used to reach base pressure in these instances. However, due to the reactive nature of the process it is important to condition the chamber by sputtering Tantalum, without the Nitrogen component. Ta cathode poisoning is a known byproduct in reactive sputtering that not only decreases deposition rates through target life, but also requires adequate chamber conditioning for a stable process [6]. These "burn" sequences not only stabilize the shielding surface states, but are also imperative to removing the $N_2$ poisoning on the target. The added heat from the plasma and bombardment of the Ta molecules will aid in releasing the additional moisture, as well as acting to coat the shielding, creating a stable condition for subsequent processing within the chamber. Several iterations in post-PM conditioning procedures were evaluated to remove unnecessary qualification steps and reduce the number of necessary process targeting iterations.

Previously, numerous iterations of Ta burns were run with one hour in between to allow the platen to cool, followed by a conditioning TaN run to reincorporate the reactive constituent for desired film properties. It was determined that a reduction in the number of burn runs was still adequate to clean the target and condition the chamber. This also alleviates the load on the cryo pump and eliminates handling errors of wafers warped by thermal stress from platen heating under aggressive sputtering. Furthermore, it was discovered that the full cassette conditioning TaN run was not necessary as the pre-existing shutter steps in the production recipe were sufficient to equalize the partial pressures to adequate processing levels once the chamber was cleared of moisture and previous $N_2$ poisoning.

Figure 5 depicts relative chamber condition after an open chamber event. Each point represents results of the standard production recipe with each separated by a conditioning TaN run. The initial data has very high sheet resistance due to significant poisoning and continual outgassing of exposed shielding immediately upon pumping back to high vacuum. The next data point is very low as the $N_2$ has effectively been removed from the target, resulting in a greater Tantalum film concentration. The subsequent points stabilize as the partial pressures and chamber condition reach equilibrium.

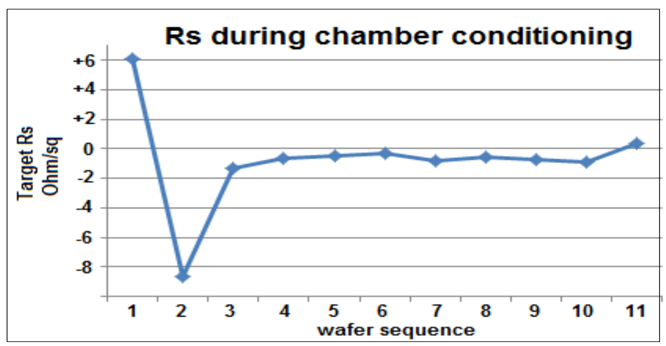


Figure 5. TaN run post chamber opening; no conditioning or target burn-in. (5 kW TaN process for 3 minutes in between wafers.)

Once steady state conditions were reached, further characterization was possible of sheet resistance which remained quite stable over time (Figure 6).

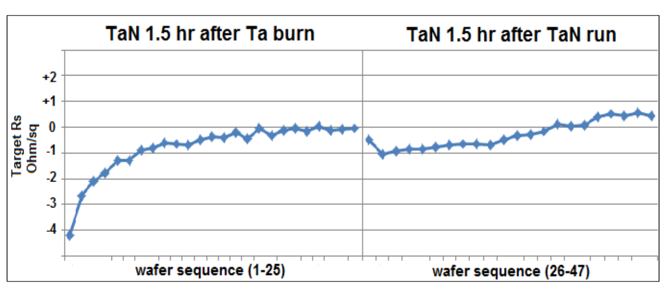


Figure 6. $R_s$ over time following a Ta "burn" sequence.

Further review of the PM procedures revealed additional opportunities to improve the toolset performance. Incorporating a Mega Ohm R Measurement test once the system was closed (prior to any other processing) eliminated instances where shorts were detected hours or days later, which would require the system to be vented again. Additionally, a two-hour increase in bake out time following maintenance allowed the chambers to reach base pressure in less time overall compared to the previous procedure. Under the aggregate optimized qualification procedure the process was shown to be more stable, resulting in a 39% decrease in the number of required sheet resistance re-targetings between PM cycles.

## CONCLUSIONS

Although the per-lot processing time was increased slightly under the 1 kW process, the overall impact to throughput was not significant given the improvements to the qualification procedures, resulting in fewer necessary re-targetings. Comparable film properties were obtained through reductions in gas flows requiring improved hardware capabilities. Because lower Nitrogen flows ($N_2$ ratio of 5-6%) were required at the reduced deposition rates, new Mass Flow Controllers (MFC) were installed for flow rates below the accuracy threshold of the previous units.

Extensive data collection activities provided additional insights into target utilization rates for future consumption calculations. We are now able to accurately forecast how many days the systems can safely run until the next PM event, and can quickly determine at what durations maintenance events can be postponed. A recovery (top-up) calculator was also created for completing depositions after chamber aborts. Furthermore, the efforts also provided the initial characterization of magnet alteration effects in tilt and radial adjustments to facilitate uniformity optimization on new targets. Future work is planned on uniformity improvements for inline monitor and end-of-line device structures across wafer and run-to-run.

As a quick reference tool (holding other input parameters constant) the overall effects of gas ratio changes can be seen in Table I for sheet resistance, uniformity, and TCR values.

TABLE I
GENERAL GAS FLOW EFFECT ON SHEET RESISTANCE, UNIFORMITY, AND TCR.

| | | Rs | stdev% | TCR |
|---|---|---|---|---|
| N2 | increase | higher | better | more negative |
| | decrease | lower | worse | more positive |
| Ar | increase | lower | undefined | undefined |
| | decrease | higher | undefined | undefined |

## ACKNOWLEDGEMENTS

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## ACRONYMS

CDA: Compressed Dry Air
MFC: Mass Flow Controller, controls gas flow.
$R_s$: electrical Sheet Resistance
TCR: Temperature Coefficient of Resistance
TFR: Thin Film Resistor