Optimizing Process Conditions for High Uniformity and Stability of Tantalum Nitride Films

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Abstract

This paper describes a design of experiment (DOE) to study the effects of process drifts on the electrical properties and composition of the Tantalum Nitride (TaN) thin films. The effects of reactively sputtered deposition itself and downstream fabrication processes are analyzed. TaN film properties were characterized through sheet resistance (R_s) and temperature coefficient of resistance (TCR) to assess the change in resistivity in response to heat treatment. Greater TaN film stability was achieved through M1 post lift-off ash treatment. This finding shortened the feedback loop for implementing earlier inline detection of shifts of TaN related parameters, thus enhancing the statistical process control (SPC).

INTRODUCTION

Various properties of TaN, such as its high temperature stability and melting point, chemical inertness, and corrosion resistance render this transition metal nitride desirable for thin film resistor (TFR) applications. However, limited literature exists on optimizing process conditions at TaN deposition and downstream in the fabrication flow to achieve high uniformity and stability with optimum TCR, which are increasingly pertinent concerns for both reliability and integrated circuit (IC) processing performance for Gallium Arsenide (GaAs) and Gallium Nitride (GaN) devices [1]. Greater process control over R_s, uniformity, and stability are crucial for power amplifier (PA) IC in mobile devices; hence enhancing detectability and understanding the sources of drifts in process parameters within the fabrication flow are imperative [2].

In this study, various DOE conditions were performed throughout the fabrication flow using 150mm GaAs substrates to analyze the effects of process variation on the TaN thin film resistivity, uniformity, and reliability. In particular, the effects of varying nitrogen composition of the TaN film and subjecting the film to several forms of oxidative and thermal treatments are explored. Due to experimental assessments for high temperature processes, this study may also be relevant for GaN devices which have high thermal conductivity. This feature enables operation at higher temperatures and voltages to deliver greater power [3].

METHODOLOGY AND PROCESS CHARACTERIZATION

Sheet resistance of the TaN thin film was measured using the four-probe method with a 49-point map. The %sigma was calculated using the following equation to assess the uniformity of the TaN film for each wafer:

$$\%sigma = \frac{\sqrt{\frac{\sum(x - \bar{x})^2}{(n-1)}}}{\bar{x}} * 100\%$$

where x, $\bar{x}$, and n represent a R_s point measurement, the average R_s across the wafer, and the total number of point measurements respectively. A higher %sigma suggests a poorer uniformity of the TaN film.

TCR was obtained through the transmission line model (TLM), in which resistances were measured at Process Control Monitor (PCM) resistor structures on seven sites across each wafer at 25°C and 75°C to calculate the average slope of the resistance values over the change in temperature using the following equation:

$$TCR = \frac{R_1 - R_0}{R_1(T_1 - T_0)}$$

Process conditions were optimized for high uniformity of <1.5 %sigma and TCR interval of -100 to -125 ppm/°C.

TaN DEPOSITION

For the reactive magnetron TaN sputtering process, the chamber and shielding conditions, platen temperature, nitrogen to argon gas flow ratio (N_2:Ar), process time, and power can all influence the physical and electrical properties of the deposited TaN film [4]. The sputtering platform used in this experiment allows the process gases to flow through a single inlet in the chamber and controls the platen temperature through compressed dry air (CDA) cooling. The magnets of the magnetron had been adjusted prior to deposition to allow for optimal uniformity.

The deposition time and power were adjusted to target an average TaN R_s of 50 ohms/sq by the end of frontside fabrication processing. As shown in Figure 1, N_2 flow rate was varied from 4 to 10 sccm at a fixed Ar flow rate and platen temperature to study the influence on TaN R_s, TCR, and thin film uniformity.

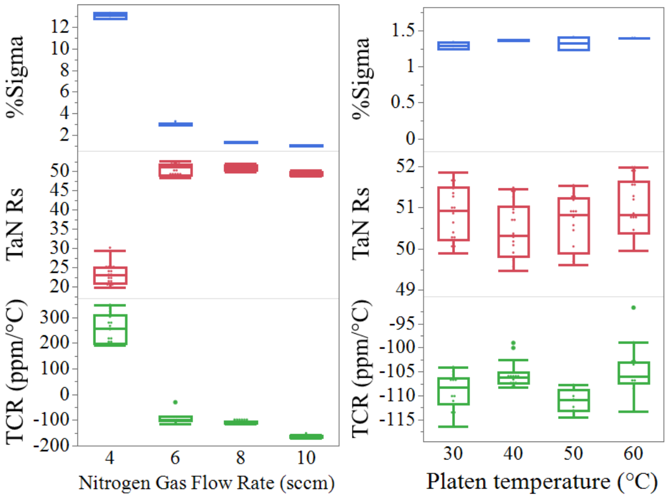

Fig. 1. Dependence of TaN resistivity and TCR on (left) N_2 flow and (right) platen temperature during thin film deposition

Increasing the N_2 flow rate to 10 sccm resulted in the most negative TCR (-162.9 ± 4.5 ppm/°C), thereby suggesting greater sensitivity to resistivity shifts arising from changes in temperature. Flowing N_2 at 8 and 10 sccm resulted in similar TaN R_s distributions of 50.9 ± 0.7 and 49.4 ± 0.5 ohms/sq respectively as well as high uniformity of the TaN thin films, as suggested by averages of <1.3 %sigma. However, decreasing the N_2 flow rate further to 6 and 4 sccm had an increasingly larger impact on the distribution of TaN R_s, film thickness uniformity, and TCR. Flowing N_2 at 6 sccm led to a wider distribution of TaN R_s values resulting in an average %sigma of 3.0 ohms/sq, indicating about two to three times worse thin film uniformity than at 8 and 10 sccm. Decreasing the N_2 flow rate further to 4 sccm resulted in a positive TCR of 255.3 ± 55.8 ppm/°C (thus metallic phase) and had the poorest thin film uniformity with an average %sigma of 13.1 ohms/sq.

In another experiment, the temperature of the platen which each wafer is laid upon during the reactive sputtering process was varied from 30 to 60°C at fixed Ar and N_2 flow rates. As platen temperature increased from 40 to 50 to 60°C, the TaN R_s distribution shifted from 50.4 ± 0.7 to 50.6 ± 0.7 to 51.0 ± 0.7 ohms/sq respectively.

Overall, among all platen temperature variations, minimal to no effect was observed for thin film uniformity (<1.4 %sigma), TaN R_s distributions averaged between 50.4 to 51.0 ohms/sq, and TCR distributions were negative. Such suggests that even with process drifts in platen temperature during reactive TaN sputtering, the TaN thin films are still likely to achieve high uniformity and optimal TaN R_s and TCR distributions.

OPTIMIZING DOWNSTREAM PROCESSES

Oxidative Descum

Prior to deposition of M1 metal onto the TaN film, a descum step was performed to clean the wafer of residues and increase the stability of the interfaces. To study its oxidative effect on the TaN resistor, this descum step was either skipped, performed once, or repeated. Descum was conducted at a chuck temperature of 100°C with oxygen gas flow rate of 180 sccm at 30 seconds.

As shown in Figure 2, processing the wafers through two iterations of oxidative descum slightly shifted the TaN R_s distribution downward from 50.9 ± 0.7 ohms/sq for a single iteration to 50.7 ± 0.6 ohms/sq for a second iteration. It also tightened the TCR distribution from -109.0 ± 3.6 ppm/°C for a single iteration of descum to -111.2 ± 1.9 ppm/°C for a second iteration of descum. Skipping the descum step resulted in the TaN R_s distribution of 50.9 ± 0.6 ohms/sq and TCR distribution of -105.7 ± 2.7 ppm/°C. Regardless of receiving none or additional descum treatment, the TaN thin film uniformity remained high with <1.3 %sigma for all three conditions.

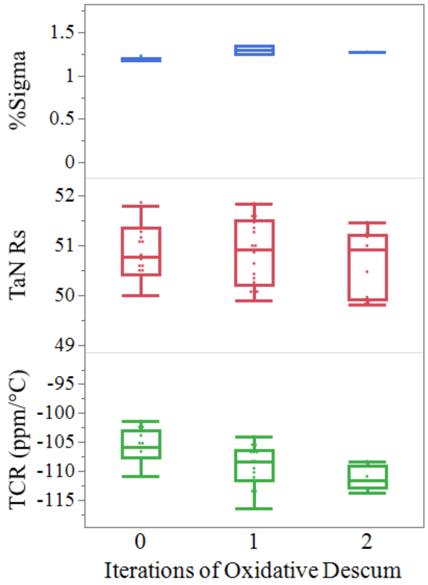

Fig. 2. Dependence of TaN resistivity and TCR on oxidative descum treatment

M1 Post Lift-off Ash Treatment

After M1 metal was deposited on the TaN film, a post lift-off ash treatment was conducted to remove resist residues. As shown in Figure 3, experiments were conducted during the ash treatment to vary the chuck temperature between 200 to 240°C at 10°C intervals, process time between 10 to 25 seconds at 5 second intervals, and at powers of 900 and 1800W.

A slight upward shift in average TaN R_s (<0.5 ohms/sq) was observed after increasing the chuck temperature from 200 to 240°C, process time from 10 to 25 seconds, or power from 900 to 1800W, suggesting that to an extent, enhancing the oxidative and thermal ash treatment correlates to an increase in TaN R_s. Halving the power to 900W tightened the TCR distribution from -111.6 ± 3.1 to -111.1 ± 1.9 ppm/°C and shifted the TaN R_s distribution from 50.9 ± 0.7 to 50.6 ± 0.7 ohms/sq. Overall, varying these process conditions for the ash treatment had little effect on the uniformity of the TaN film (<1.4 %sigma) and resulted in negative TCR distributions within the optimal range.

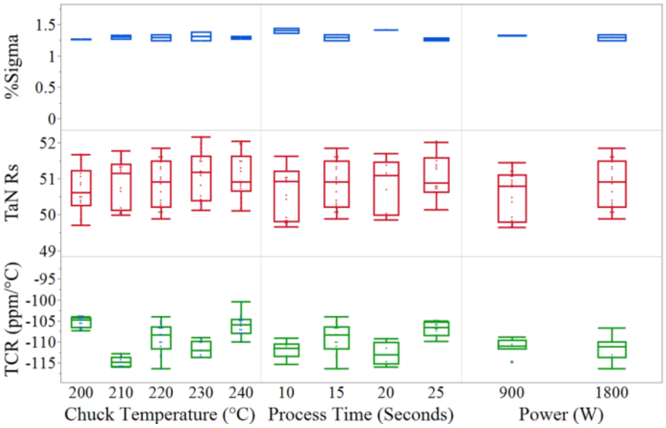

Fig. 3. Dependence of TaN resistivity and TCR on chuck temperature, process time, and power of post lift-off ash treatment

Inline testing for TaN parameters before and after the ash treatment revealed that this oxidative high thermal process tightens the distribution of TaN R_s and promotes greater stability. In fact, at the optimized operating conditions, there is <1 ohms/sq shift in the TaN R_s distribution between values after receiving M1 ash treatment and after completing full frontside processing for PCM testing. Taking advantage of the opportunity for greater detectability of process shifts earlier in the fabrication flow, a routine sampling plan to test TaN related parameters following ash treatment was established.

Anneal

Prior to Metal-Insulator-Metal (MIM) nitride deposition, annealing at 300°C was introduced for further thermal cycling. Shown in Figure 4 are the effects of annealing on the TaN R_s and TCR distributions. The TaN R_s distributions at PCM averaged at 50.9 ± 0.7 ohms/sq regardless of whether the wafers were annealed. However, the TCR distribution was significantly tighter for annealed wafers (-113.1 ± 1.7 ppm/°C) in comparison to unannealed control wafers (-109.0 ± 3.6 ppm/°C). Uniformity remained high for both conditions with <1.4 %sigma.

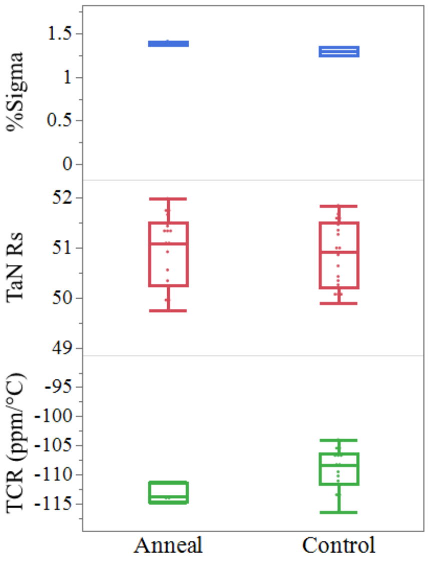

Fig. 4. Dependence of TaN resistivity and TCR on thermal cycling treatment through annealing

Curing Polyimide

Further downstream of the fabrication flow, wafers were coated with polyimide and cured to become an insulating layer between the interconnect layers with minimal capacitance. In the event of an aborted process, re-curing the wafers subjects the TaN resistors to a second iteration of high temperature processing.

In this experiment, curing the polyimide layer at 300°C with a soak time of 60 minutes resulted in similar TCR and TaN R_s distributions of -106.4 ± 1.6 ppm/°C and 50.7 ± 0.6 ohms/sq for a single iteration and -105.6 ± 1.7 ppm/°C and 50.8 ± 0.6 ohms/sq for a second iteration.

Alternatively, wafers with polyimide cured at a higher temperature of 350°C with a soak time of 60 minutes widened the TCR distribution to -104.1 ± 4.5 ppm/°C and TaN R_s distribution to 50.8 ± 0.7 ohms/sq.

As shown in Figure 5, despite processing the wafers at a higher soak temperature or with additional iterations of curing the polyimide, overall, the average TaN R_s and TCR distributions were comparable to one another and remained within the optimal range with high uniformity (<1.4 %sigma). Such is indicative of the high stability of the TaN resistor even when the device is subjected to high thermal conditions downstream from the resistor layer stage.

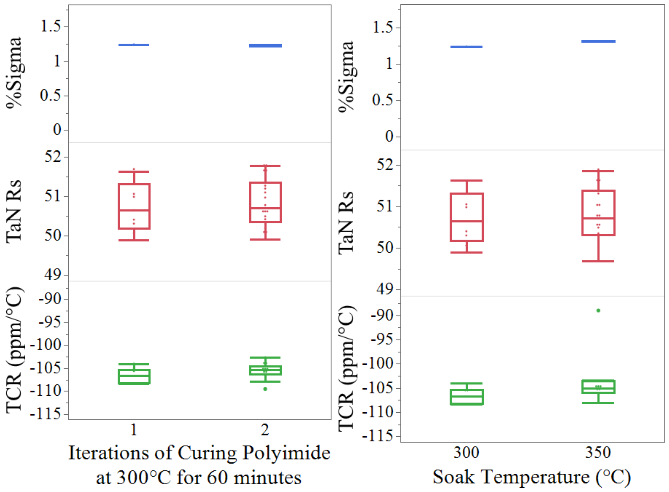

Fig. 5. Dependence of TaN resistivity and TCR on processing conditions during the curing of polyimide

CONCLUSIONS

The efforts of this study provided valuable insight into how various process knobs at TaN deposition and downstream can influence the film characteristics and PCM parameters.

During TaN deposition, nitrogen gas flow particularly at low flow rates had the largest influence on uniformity and distributions of TaN R_s and TCR. Regarding downstream processes influencing the TaN resistor, introducing additional iterations of oxidative descum treatment resulted in a slight downward shift in the TaN R_s distribution and tightened a more negative TCR distribution that remained within the optimal range. Enhancing the ash oxidative thermal treatment through increased temperature, process time, and power resulted in a slight upward shift in the TaN R_s distribution. Adding an annealing step prior to MIM deposition tightened the TCR distribution. Meanwhile, minimal effects on TaN resistivity and TCR were observed at varying conditions during the process of curing the polyimide layer.

Understanding the device characteristics and behavior throughout the fabrication process flow facilitates a more robust prevention and detection system to enhance SPC in production. Furthermore, earlier inline detectability measures became feasible due to the greater stability of TaN R_s achieved through the addition of the ash oxidative thermal treatment.

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ACRONYMS

DOE: Design of Experiment
TaN: Tantalum Nitride
R_s: Electrical Sheet Resistance
TCR: Temperature Coefficient of Resistance
SPC: Statistical Process Control
TFR: Thin Film Resistor
IC: Integrated circuit
GaAs: Gallium Arsenide
GaN: Gallium Nitride
PA: Power Amplifier
TLM: Transmission Line Model
PCM: Process Control Monitor
CDA: Compressed Dry Air
MIM: Metal-Insulator-Metal