TiWN Thin Film Resistor Process Control

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ABSTRACT

Thin film properties and temperature stability of titanium-tungsten nitride (TiWN) sputter-deposited films have been investigated as they apply to the manufacture of both thin film resistors (TFR) and Schottky contacts to GaAs for MSAG^{TM} MMICs [1,2]. The TiWN film is reactively sputtered [3] from a $Ti_{10}W_{90}$ (by weight) target in a nitrogen atmosphere with argon as a diluent gas. The partial pressure of nitrogen, the deposition time and the deposition power are used as the key control parameters to maintain the target sheet resistance (R_{sh}) and other film characteristics. One critical aspect of the process is that the final TFR R_{sh} value is not obtained until after a high temperature implant-activation anneal that occurs with the TiWN in place.

This paper examines difficulties experienced with process control as a consequence of the process constraints and the equipment set in use. Of particular note, throttle-valve control in the sputter system was found to be deficient and therefore it was upgraded to achieve the desired process control. The paper includes data relating the partial pressure of nitrogen to both the as-deposited and the post-annealed TFR R_{sh} values. A discussion of the influence of deposition pressure on film stress and a summary of process control methods and considerations relating to process targeting and film stability is also presented.

INTRODUCTION

Although TFR's have been a standard element of MSAG^{TM} MMIC manufacture for many years, our ability to control this process has at times been problematic. Two deposition systems have been in use in our facility for TFR film formation; one system is a sputter-down system and the other is a sputter-up system. Historically, the sputter-down system has had better work-cycle stability for the resulting film characteristics, but it was prone to on-wafer particulate contamination problems – thus the preventive maintenance (PM) schedule was based on minimizing particulate contamination, and not related to stability of the TFR characteristics. The sputter-up system had a longer time period between PMs, but during the work cycle it suffered from a propensity to exhibit drift in post-annealed TFR Rsh when TiWN particulates from shields, etc. "rained" onto the TiW target, causing the sputtered film to become influenced by sputter deposition of the TiWN particulate contaminants.

The gas flow and pressure controls on the two sputter systems were also set up differently. One tool utilized pressure control via feedback to the throttle valve controller while Mass Flow Controllers (MFCs) directly controlled the individual gas flows of nitrogen and argon to present flow values. The other tool was set up with a fixed-position throttle valve and pressure control was achieved by feedback control to the MFCs, continuously adjusting gas flow as needed; furthermore, proportional gas controlling was used such that one gas slaved to the other and total flow was limited to a maximum value. One consequence of the second approach for process control was that the system gas flows changed as a function of cryo pumping speed or, more importantly, the gas flow was a function of the stop position of the throttle valve as set by the equipment maintenance group.

The sheet resistance of the deposited film typically shows a linear positive slope with R_{sh} increasing as more nitrogen is added to the process gas mix and nitrogen content in the TiWN film increases. In Figure 1 note that even though the N_2 gas percentage is being modified over the normal control range, the as-deposited R_{sh} is not changing. This is in contradiction to past experience with this sputter tool, and all experience with the alternative tool. Nevertheless, the post-annealed R_{sh} is responding strongly to the changes in N_2 gas percentage, indicating that important characteristics of the film, not apparent from as-deposited R_{sh} values, are being influenced by the N_2 gas-flow set point.

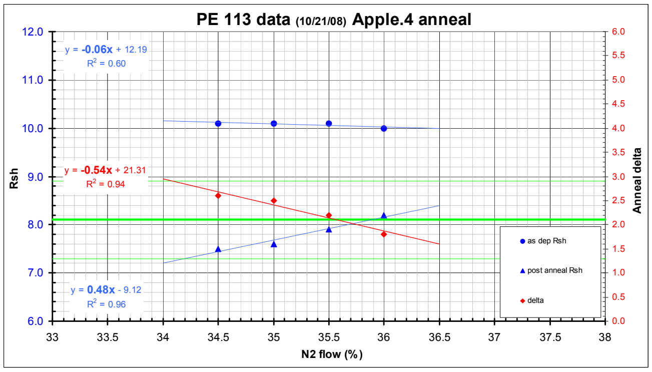


Figure 1: Poor response for As-Deposited R_{sh} as N_2 flow is adjusted. But nevertheless, Post-Annealed R_{sh} shows response to changes in N_2 flow as expected.

In Figure 2, one of the difficulties regarding process control is clear: Even though the value of as-deposited R_{sh} for the film is in accord with control limits for the process, the value of real importance, the post-annealed R_{sh} measured at process-control-monitor (PCM) test, is not as well controlled as required, resulting in PCM failures for some wafers. The process has been established to allow variation in as-deposited R_{sh} of ±0.2 ohm/sq; values outside of this range require either a rework or engineering disposition. The upper portion of Figure 2 demonstrates regular conformance to the control limits. At PCM test the allowed range is ~±1.0 ohm/sq and the lower portion of Figure 2 shows the scatter of values around the target. Some of the scatter is a consequence of variation of other processing factors such as may occur at etch steps and anneal. But compared with the other sputter tool used for this process, the system under investigation shows much wider dispersion of results and much poorer process control.

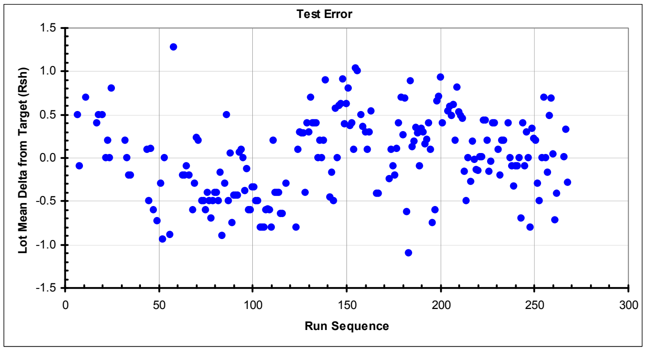


Figure 2a: As-Deposited error-vs-target for TiWN R_{sh}
Figure 2b: Post-Anneal error-vs-target for TiWN R_{sh} at the PCM test point.

Having previously found this sputter-down tool to give *better* process control than the sputter-up tool, the irregular behavior for as-deposited TiWN R_{sh} was especially puzzling. Early attempts to correct the performance took several tacks. In an effort to improve across-wafer uniformity, a modification to the gas distribution inlet was tried. This modification produced no substantial improvement. Because it is known that the TiW sputter targets used for the film deposition change characteristics somewhat with usage, they also came under scrutiny, but it was found that changing to a new target had no effect on the observed behavior of the process as shown in Figure 1. Other maintenance history for the tool was also evaluated and, aside from problems reported with a "sticking throttle valve", no major difficulties were revealed. At that point, the problematic system was relegated to secondary status and used for deposition of films where control of post-annealed R_{sh} was less critical.

INVESTIGATION

Upon reaching the poor control condition illustrated in Figure 1 and after repeated unsuccessful attempts to qualify the system for producing normally-responding post-annealed R_{sh} results, an investigation was undertaken with focus on the throttle valve stop position. In particular, there was evidence to suggest that the gas flows were being constrained by the throttle-valve-pressure-seeking mode of operation and that the bulk portion of the deposited film was nitrogen-starved once the plasma ignited and reactive gas was consumed. This condition may have been exacerbated by the higher pumping speed for nitrogen gas compared to argon gas in this cryo pumped system.

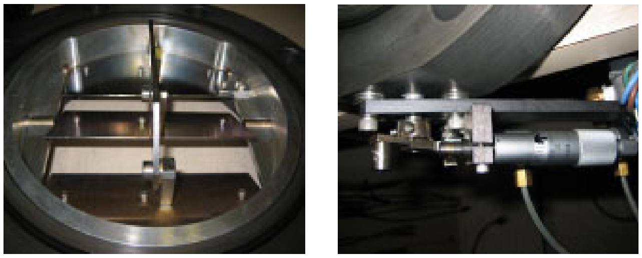


Figure 3: Old throttle valve and mechanical stop linkage. Stop position determines capability of the system to achieve pressure set point.

The mechanical stop nature of the old throttle valve meant that it was utilized in only two modes: either fully open, or closed to the stop position. As described earlier, during a deposition run, set point pressure control in this system is achieved via feedback control on gas flow, with pre-set proportionalized gas flows and the total flow set to a maximum. Thus, depending on cryo pump health (which can affect pumping speed), or as a consequence of throttle-valve stop position adjustments, the absolute gas flows would sometimes be one value and other times a different value. Once the throttle valve was adjusted to a more open position a series of runs were performed. Sheet resistance response to nitrogen adjustment is shown in Figure 4. This is in-line with previous performance.

Again referring to errant performance demonstrated in Figure 1, we conclude that the bulk film characteristics of the film were a consequence of a throttle position that was too far closed and that this resulted in the flat response to nitrogen adjustments. Because of the pressure seeking setup for the system, reactant gas flows were too low to achieve a sustained nitrogen environment. Conditions at plasma ignition were adequate to influence the early film and thus the post anneal sheet resistance. But the majority of the film was being deposited in a nitrogen depleted atmosphere and thus adjustments to nitrogen set point were not evident in the bulk film sheet resistance determination.

While a greater understanding of the influence of throttle stop position is now in hand, the consequence of the adjustment has pushed the process to a regime where conditions are not suitable for producing acceptable product. Because, in a finished IC, this film is used for making both thin film resistors and the Schottky gate metal in FETs and diodes, multiple film characteristics are important. In our applications it is necessary to have an as-deposited film with an R_{sh} ~ 11.0 ohm/sq , a post-annealed R_{sh} of ~8.0 ohms/sq and an as-deposited film stress on the order of ~400 MPa compressive. Past experience has shown a strong inverse relationship for stress with changes in deposition pressure: as the pressure is decreased, the film stress would be expected to increase. In order to achieve higher total gas flows, we would have to sacrifice operating pressure and this could not be tolerated because of the stress response.

Another subtle factor complicating control of the deposition process is the wafer vendor. Whether from surface preparation, crystal growth conditions, defect density or other cause, the film stress and final sheet resistance are influenced by the actual wafer itself. Split lots have time and again shown that the delta between as deposited film and post anneal R_{sh} is dependant on the substrate in use. Stress similarly changes, not only from deposition conditions, but also as a direct result of the wafer starting material.

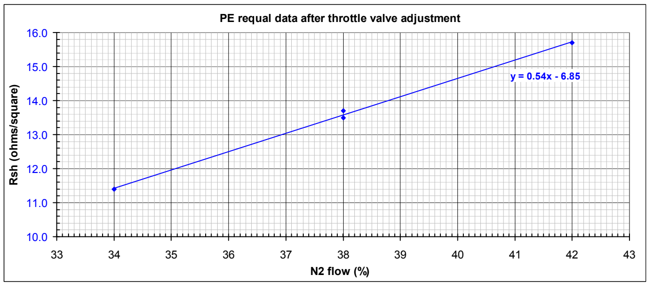


Figure 4: As Deposited R_{sh} after throttle valve adjust to a more open position and showing improved deposition control.

The difficulty with process control, and the strong influence of throttle valve stop position, along with subordinate concerns about future variations in cryo pumping speed and system performance, ultimately led to a decision to replace the mechanical stop valve with an alternative style. Figure 5 shows the new-style throttle valve which produces a continuum of throttle conditions by rotating it's 12 vanes from fully closed to one hundred percent fully open. After installation, the system setup was changed to be nearly identical to the other sputter deposition system: the system now flows gases to preset flow values via MFC control for each gas and the throttle valve closes as much as necessary to maintain the desired operating pressure.

Figure 5: New throttle valve with vane openings set by pressure feedback controller.

With the new throttle valve installed, new operating conditions were established for the process, beginning with an Ar gas flow appropriate to allow the throttle valve to operate at ~20% open. The N_2 gas flow was then set to produce a TiWN film with the desired post-annealed R_{sh} value. The graph in Figure 6 shows the new as-deposited and post-annealed curves for TFR R_{sh}. At the top of Figure 6 are two sequences of experimental runs where deposition was performed several days apart. Note that response for as-deposited TFR R_{sh} (as evidenced in the fitted line slope) and the reproducibility of runs are dramatically improved compared to the results shown in Figure 1 using the old throttle valve. The post-annealed curves for TFR R_{sh} are also well aligned, although not as tightly overlapping one another as the as-deposited curves. This curve separation or offset is related to other aspects of the TFR manufacturing sequence, as previously discussed.

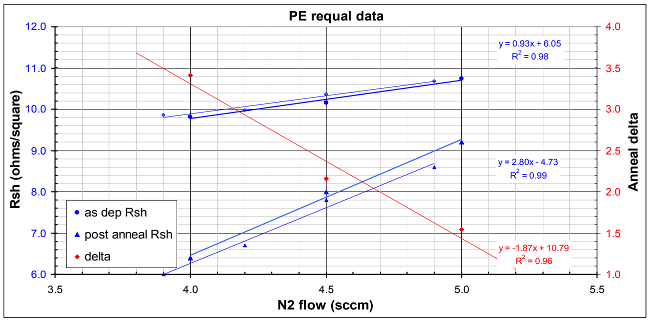
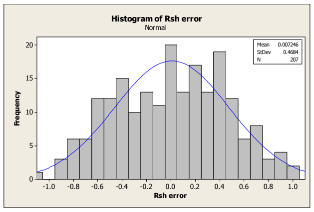


Figure 6: New throttle valve and improved response and control of TiWN film for As-Deposited and Post-Annealed R_{sh} as a function of the N_2 set point.

Figure 7 shows promise of significant improvement achieved with the new throttle valve. Although the number of runs performed so far is small, in comparison with those for the old throttle valve, the runs have a tighter grouping both for the as-deposited film and post-annealed R_{sh} results.



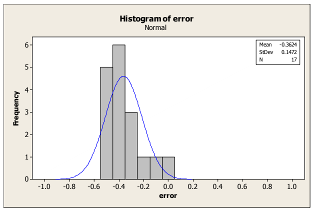


Figure 7a: Histogram of runs during errant period and old throttle valve.

Figure 7b: Histogram of runs after throttle valve replacement

SUMMARY

Numerous factors influence the deposition process for thin film TiWN resistors. In particular, accurate control of the flows of the reactant gases and control of the system operating pressure are important for determination of sheet resistance and film stress. Improved process control was achieved after upgrading the throttle valve to a type capable of direct pressure control. In conjunction with this change, the process was converted from a proportioning control of gas flows to direct MFC control.

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