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TaN Resistor Process Development and Integration

M.J. Martinez, F.H. Austin[†], J.B. Clevenger, A.J. Griñe, G.A. Patrizi, K. Romero[†], P.S. Vigil[†], S. Wolfley, C.T. Sullivan

Sandia National Laboratories, Albuquerque, NM 87185
mmarti8@sandia.gov, 505-844-0113
[†]LMATA, Albuquerque, NM 87185

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Abstract

This paper describes the development and implementation of an integrated resistor process based on reactively sputtered tantalum nitride. Image reversal lithography was shown to be a superior method for lift-off patterning of these films. The results of a response surface DOE for the sputter deposition of the films are discussed. Several approaches to stabilization baking were examined and the advantages of the hot plate method are shown.

INTRODUCTION

In support of a new capability to produce special-purpose HBT-based Small-Scale Integrated Circuits (SSICs), we developed our existing TaN resistor process, designed for research prototyping, into one with greater maturity and robustness. Included in this work was the migration of our TaN deposition process from a research-oriented tool to a tool more suitable for production. Also included was implementation and optimization of a liftoff process for the sputtered TaN to avoid the complicating effects of subtractive etching over potentially sensitive surfaces. Finally, the method and conditions for stabilization baking of the resistors was experimentally determined to complete the full implementation of the resistor module.

Much of the work to be described involves the migration between sputter deposition tools – from a Kurt J. Lesker CMS-18 to a Denton Discovery 550. Though they use nominally the same deposition technique (reactive sputtering of Ta with N^+ in a RF-excited Ar plasma), they differ substantially in their design and produce clearly different results in terms of resistivity, conformality of the film and the difference between as-deposited and stabilized films. We will describe the design of and results from the design of experiments (DOE)-based method of process optimization on the new tool and compare this to what had been used on the old tool.

RESISTOR PATTERNING

An important aspect of this process module was to lift off the sputtered TaN film to avoid having to change other process modules to protect sensitive device layers from damage during overetch. Getting clean liftoff of a sputtered film is something of a challenge, particularly with a system that is designed for a high degree of conformality of the sputtered film (such as the one used here). This conformality makes any bilayer resist approach troublesome, at best, since the film will readily coat within the recess formed by the bottom layer. An optimized retrograde, single-layer resist profile is much better suited to this task, since it tapers much more sharply near the substrate leaving a small gap in the film that facilitates liftoff and gives a smother edge. This is illustrated in Figure 1.

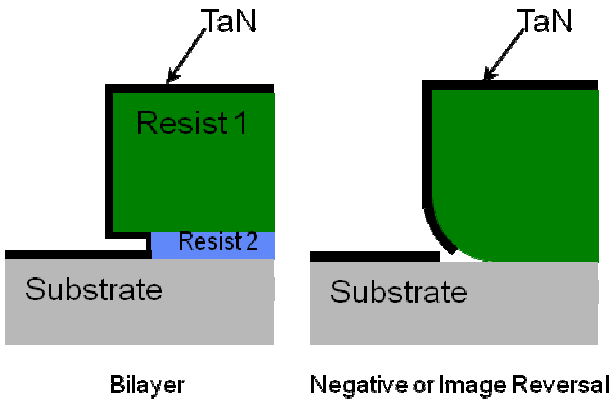
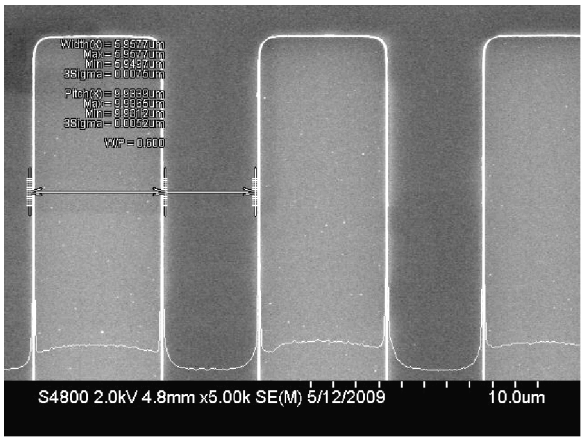


Figure 1. Comparing suitability of bilayer versus negative or image reversal lithography for sputtered film liftoff.

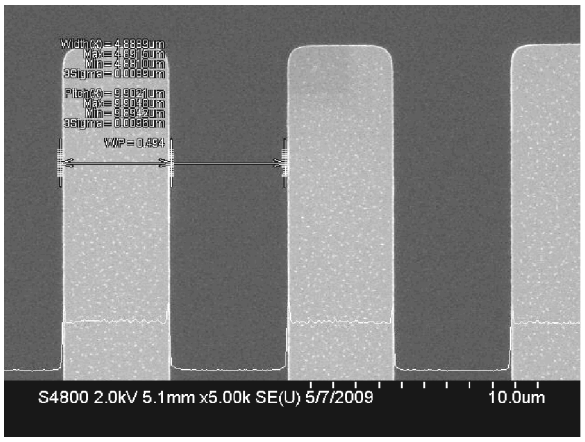
To meet this requirement, a negative resist process using Clariant AZ NLOF 2020 was compared to an image reversal process using Clariant AZ 5214E. All lithography work was done using a Suss Microtec ACS200 for photoresist coating and developing and an ASML PAS5000/55 *i*-line projection stepper.

The negative process was initially favored, as it offered the advantages of being shorter and simpler. This, however, had to be balanced with the need for good dimensional control of the finished resistors. While initial results were promising for the negative resist, it quickly became apparent that it was not possible to achieve the desired linewidth of the resistor pattern with any combination exposure, focus or bake temperature. The best that was demonstrated was about 20% larger than the smallest target dimension of 5 µm, which was unacceptable.

In contrast, the image reversal process, while more cumbersome, gave better quality results and more consistency in the results. This process gave linewidths within 2% of the target, with better resolution in general. Results of the two approaches are compared in Figure 2.



a. Clariant AZ NLOF 2020, mean width ~ 6 µm.



b. Clariant AZ 5214E Image Reversal, mean width 4.94 µm.

Figure 2. Liftoff results for TaN showing best linewidth and edge quality results. Image *a* shows lines formed with AZ NLOF 2020 negative photoresist and image *b* shows lines formed with AZ 5214E positive photoresist using an image reversal process. Note the brightness of edges for *a*, which is the result of increased roughness at these edges.

REACTIVE SPUTTERING OF TAN

In migrating our resistor process from a Kurt J. Lesker CMS-18 to a Denton Discovery 550, we had little information on which to base a process – only the results of a screening DOE that had been run a year earlier. The chamber design of the two tools is very different, with the Denton tool featuring a cathode angled down towards the platen from the side with a rotating platen, intended to enhance conformal coverage while give good thickness uniformity across the platen. This angled configuration complicates the situation for reactively sputtered films since ions ejected from Ta target can have a longer or shorter path to the platen, depending on where they began, which affects the likelihood of combining with nitrogen, ultimately affecting the uniformity of film resistivity. For the targeted resistivity, this required some adjustment of the cathode angle to provide a better trade-off between thickness uniformity and resistivity uniformity.

As a result of these adjustments, the prior DOE results were not directly applicable, since this shifted the resistivity of the film produced by a given set of conditions. Thickness uniformity was confirmed first to decide if placement of a thickness monitor piece was critical. This was done by measuring step height across a patterned 3" wafer, which showed a total range of only 1 nm, which is less than the typical capability of the step height tool, a KLA/Tencor P-15 profilometer.

After a few confirming runs based on that DOE, to gauge the amount of process shift there had been, a response surface DOE was executed from those results. This was an orthogonal central composite design having three factors: Ar flow, N_2 flow and RF power. The DOE comprised 15 conditions with a repeat for the center point, giving a total of 16 runs. To avoid having to adjust to different deposition rates to achieve the targeted thickness of 100 nm, all runs were done with a fixed time, with thickness measured on lift-off monitor samples and resistivity calculated as the primary output of the experiment, along with deposition rate and uniformity. All runs were done on unpatterned 3" semi-insulating GaAs wafers, and sheet resistance was measured with a Lehighton Electronics 1510B contactless resistivity tool, measuring 25 points per wafer. A separate sheet resistance monitor sample was also measured using a Prometrix Versaprobe VP10e four-point probe for comparison. Four-point probe and contactless measurements gave the same average results. Resistivity results ranges from 240 µΩ-cm to 1140 µΩ-cm with a median value of 400 µΩ-cm. Deposition rates ranged from 0.096 nm/s to 0.18 nm/s with a median value of 0.14 nm/s. Across-wafer uniformity (range/mean) ranged from 0.57% to 5.4%, with a median value of 2.4%.

The results of the experiments showed a mostly negligible effect of Ar flow on TaN resistivity and deposition rate and no effect on uniformity for the fairly small range used in the design. As expected, N_2 flow and RF power were the dominant factors for all modeled outputs. Because of small variations in measured conditions versus those set in the recipe, the best fidelity of models was achieved when using the measured conditions. Very good model fits were achieved for both resistivity and deposition rate, but not for uniformity, mostly because uniformity did not vary significantly within this design. It was possible, however, to identify gross trends for uniformity that were useful.

While there were interactions between some of these factors in the generated models, in general increases in N_2 flow increased resistivity, decreased deposition rate and worsened uniformity. Increases in delivered RF power decreased resistivity, increased deposition rate and improved uniformity. In broad terms, these results meant that there was no unique solution for a given target result. N_2 flow and RF power could be traded off to keep resistivity constant. Unfortunately, since uniformity was subject to roughly the same trade-offs, it was not possible to affect uniformity to any significant degree once the target resistivity was established. Since across-wafer uniformity was generally better than 2 % for films of interest, this was acceptable.

Stabilization Bake

With the proposed process space mapped out and response surface models generated, the next step was to determine what the as-deposited sheet resistance target should be. This required knowing how much the sheet resistance would change after stabilization so that the target value is selected to give a stabilized value of nominally 50 Ω/□. This is a bit of an iterative process since the degree of change after stabilization was found to be dependent on particulars of the film involved. Not only did the degree of change depend on the starting resistivity, but even films with nominally equal resistivities produced by different combinations of N_2 flow and RF power behaved differently.

The stabilization bake of TaN resistor films can be a time-consuming process, but is essential for both stabilizing the resistor values and for sintering the contacts to them (Ti/Au overlaid on ends of resistors) to assure they are of good quality. The existing process for stabilizing TaN films used a 16 hour oven bake with a resistivity increase of 18 %. Early results showed the films produced in our Denton sputter tool stabilized much more quickly than those from the prior tool along with a much smaller shift in sheet resistance, presenting an opportunity to use bake methods that were more practical than the typical oven-based bake.

Stabilization of TaN is based on accelerating the natural formation of a durable oxidized layer (primarily Ta_2O_5) on the surface [1] which raises the resistivity of that part of the film, and raises the effective resistivity of the entire film. For all stabilization trials, 3" wafers with blanket TaN films were used and sheet resistance was measured at each step with the Lehighton tool. To determine the extent of stabilization, baking was done in increments and the response was fit to a model of the form $a(1 - b * e^{-c*t})$, where a, b and c are constants and t is time.

Because the original oven used had a N_2 atmosphere, we elected to use a convection oven using atmospheric gas to determine if this would speed the oxygen incorporation into the film, but we could not reach the same temperature with ovens of this type. In addition to ovens, we tested bakes on standard bench hot plates and with RTA. The RTA approach was quickly discarded because stabilization reach a plateau very quickly that was far short of what was seen with other methods, indicating the system was starved of oxygen (no oxygen-bearing gas was available for use on this tool).

All films from the Denton system stabilized much more rapidly and changed much less than films from the Kurt J. Lesker system. The Kurt J. Lesker film's sheet resistance shifted more than twice as much as the Denton film. The Denton film shifts much more rapidly than the Lesker film, even at lower temperature, after 24 hours, the Lesker film is still only at 92% of its projected end value of 18% above the initial value. It is known that TaN film properties are sensitive to details of microstructure [2] which are certainly affected by the differences between the two systems, but nothing more specific is known about the cause of the difference. Oven stabilization of TaN from the Kurt J. Lesker tool and oven and contact hot plate baking for the Denton tool are compared in Figure 3.

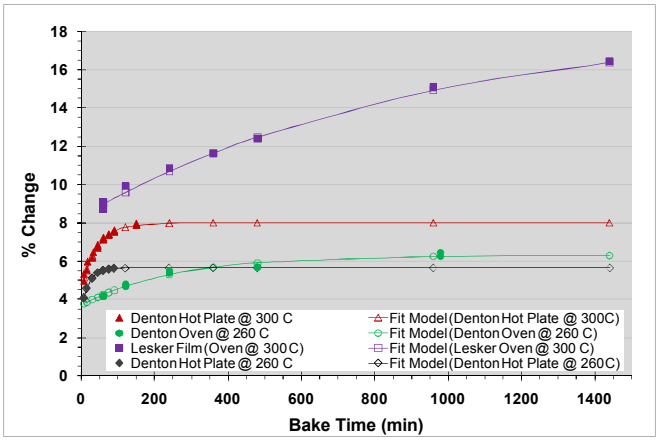


Figure 3. Comparison of stabilization methods for film from two sputtering tools with nominally the same starting resistivity and thickness (1000 Å).

For the same temperature, hot plate baking stabilized films much faster than did ovens, showing very stable films after less than an hour compared to requiring about 8 hours

in ovens. This is due at least partly to the much more rapid heating from contact with a hot plate and also to the greater availability of oxygen from the exhaust hood containing the hot plate.

This type of difference is precisely what we had hoped to see, but the difference between wafers done at different hot plate temperatures was a surprise. The oxidation of TaN is a self-limiting reaction much like the oxidation of Si, so it was expected that for small changes in temperature (15 % in this case), there would be little difference between the end states of films. The only expected difference was the speed with which that state was reached. However, there was a distinct difference between those baked at 260 °C and 300 °C on hot plates. Their sheet resistances changed by about 6% and 8%, respectively, and the lower temperature trials reached their end state more quickly. Given the mechanism involved, we believe the larger change seen at higher temperatures implies that oxygen is able to diffuse more deeply. This implies that, to a small degree, the amount of change in sheet resistance from stabilization can be adjusted by changing the bake temperature, which could be important for fine adjustment of a high-precision resistor process.

Though the lower temperature bake could be somewhat shorter, the majority of our data was taken at 300 °C, so we chose to stay with that temperature for a hot plate bake of 60 min., which meant a change of 8 % in sheet resistance. This, in turn, meant that the as-deposited film would need to be targeted at 46.3 Ω/□ to achieve a final value of 50 Ω/□.

INTEGRATION

Using the models from the DOE, we chose the following conditions: Ar flow = 19.9 sccm, N_2 flow = 3.7 sccm, delivered RF power = 294 W and time = 640 s. These process conditions were run on a series of test wafers to gauge the overall process control, and some wafers were processed through to produce discrete, testable resistors, which validated the process integration design. A control chart of the test runs is shown in Figure 4. The full electrical test results of discrete resistors across wafer are beyond the scope of this paper, but they showed no difference from measurements on blanket wafers.

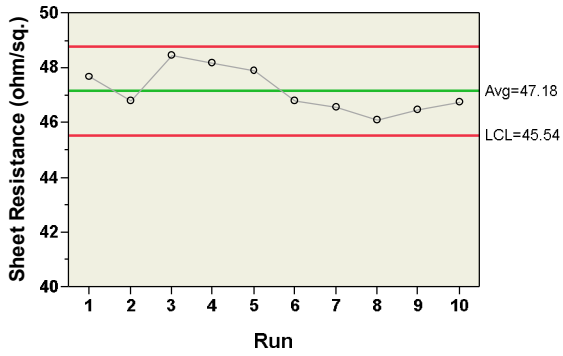


Figure 4. Control chart of resistor wafer test runs with a target sheet resistance of 46.3 Ω/□, showing control limits no more than 5.4 % off target.

CONCLUSIONS

In summary, we have described the development and implementation of an integrated resistor process based on reactively sputtered tantalum nitride. Image reversal lithography was shown to be a superior method for lift-off patterning of these films. The results of a response surface DOE for the sputter deposition of the films were discussed, describing how the process factors affected resistivity, deposition rate and across-wafer uniformity. Several approaches to stabilization baking were examined and the advantages of the hot plate method were shown.

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ACRONYMS

DOE: Design of Experiments
HBT: Heterojunction Bipolar Transistor
RF: Radio Frequency
RTA: Rapid Thermal Anneal