Integration of Nichrome Process as a Competitive Alternative to Tantalum Nitride for Thin Film Resistors in Compound Semiconductors

Stephanie Y. Chang, Shiban Tiku, Tom Brown, Lam Luu, Manohar Krishnappa, Randy Bryie, Nercy Ebrahimi

Skyworks Solutions, Inc., 2427 W. Hillcrest Drive, Newbury Park, CA 91320
Stephanie.Chang@skyworksinc.com, (805) 871-6801

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Abstract

This paper describes a development study of sputtered nichrome (NiCr) thin film resistors (TFR) with resistivity of 50 ohms/sq and high uniformity in order to thoroughly assess an alternative to a well-established tantalum nitride (TaN) fabrication process. Characterization studies were evaluated for various critical process steps and components at the resistor layer including dielectric assisted lift-off (DAL) etch, insulating substrates, pre-cleans prior to sputter deposition, and natural oxidation of the thin film surface. Technical challenges for each thin film material were evaluated within the context of feasible integration for high volume manufacturing of compound semiconductor integrated circuits.

INTRODUCTION

Some studies have suggested that reactively sputtered TaN thin films may have poorer temperature coefficient of resistance (TCR) and stability properties than those of NiCr but can be advantageous for its corrosion resistance when placed in a humid environment [1]. While TaN has been optimized for high uniformity and stability with low TCR, our previous studies have shown that other downstream process variables, such as oxidative and thermal treatments have considerable influence over its stability and film characteristics [2]. In addition to how process recipes are set up, post-preventative maintenance activities and qualification procedures play a critical role in improving both the process stability and repeatability for TaN TFR development [3]. Yet, limited literature provides a comprehensive, comparative study between TaN and NiCr at multiple critical fabrication steps within the resistor layer stage to evaluate these sputtered materials for TFR applications.

Moreover, the degradation of the tantalum (Ta) target's uniformity over time, along with the intrinsic nature of reactive sputtering, results in poorer uniformity of the TaN thin films toward the end of the Ta target's life cycle. Since NiCr sputtering is a non-reactive process, it is anticipated that the uniformity should be comparable if not superior to TaN. Optimization of NiCr thin films could offer substantial benefits for GaAs monolithic microwave integrated circuits (MMIC) due to its corrosion resistance properties and low noise [4].

In this study, the NiCr sputtering process was dialed in to achieve a thin film resistor with high intra-wafer uniformity and process control monitor (PCM) sheet resistance (R_s) of 50 ohms/sq at the end of the frontside process in the fabrication flow. Various components, including the DAL etch, pre-cleans prior to DC magnetron sputter deposition, substrate material, and natural oxidation of the thin film surface over time, were assessed to determine the feasibility of integrating NiCr in the fabrication process flow.

DIELECTRIC ASSISTED LIFT-OFF (DAL) ETCH

It is common for various compound semiconductor circuits to have the sputtered thin film resistors patterned by lift-off. The DAL etch process can be used by which a dielectric film is etched, and the sputtered resistor thin film remains on the GaAs substrate. However, the DAL process results in electrically narrower resistors. This applies a high bias to the mask and limits the design's minimum spacing between the resistors. Having the sputtered resistor layer's thin film placed on a dielectric film could also help to reduce the leakage current through the GaAs [5]. Furthermore, challenges in preventing rounded corners of resist can result in poor lift-off, particularly for the DAL etch process, and can lead to raised metal flaps and redeposition of lifted material [6].

As shown in Figure 1, a prominent undercut is visible for both TaN and NiCr films that received DAL etch. It has been a common practice to perform lift-off patterning with DAL etch for TaN. However, with NiCr, which is very thin compared to the few microns of photoresist used and about half as thin as TaN, it became of interest to assess the feasibility of cleanly lifting off the NiCr thin film without performing a DAL etch. Performing automated optical inspection to survey the resistor layer structures shown in Figure 2 after sputter deposition and lift-off steps did not detect any defects or jagged edges that would indicate unlifted metal.

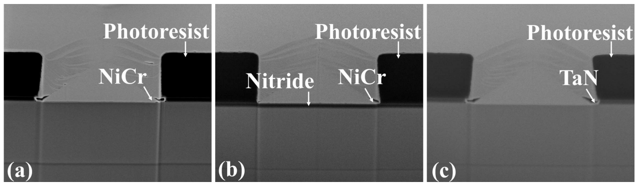

Fig. 1. FIB cross section of resistor layer's negative resist profile after sputter deposition for (a) NiCr with DAL etch, (b) NiCr without DAL etch, and (c) TaN with DAL etch.

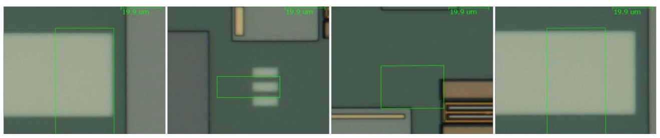

Fig. 2. Optical inspection of resistor layer structures revealed no unlifted sputtered NiCr thin film after lift-off.

As shown in Figure 3, wafers with TaN thin films that skipped the DAL etch resulted in an upward shift for both the average sheet resistance and resistivity of a resistor dimension with a few microns width. By comparison, wafers with NiCr thin films that skipped DAL etch had resulted in a downward shift for the R_s but an upward shift for the resistivity. Since the DAL etch's effect in shifting the average PCM R_s was three times the magnitude for TaN than for NiCr, adjustments to the inline targeting of the thin film R_s should account for achieving 50 ohms/sq by the end of the frontside process. The difference in surface conditions also decreased the contact resistance for both TaN and NiCr wafers that skipped the DAL etch.

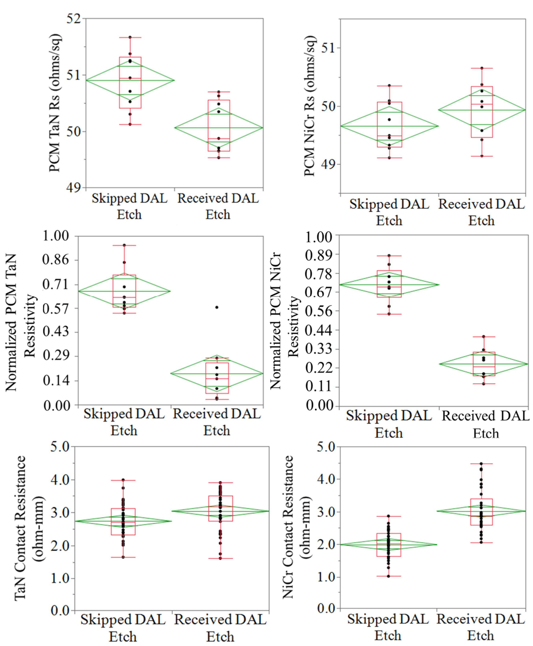

Fig. 3. The effect of DAL etch on R_s, resistivity, and contact resistance for TaN and NiCr.

As revealed by the FIB cross-sections in Figure 4, NiCr thin films were found to be approximately two times thinner than TaN thin films to achieve equivalent inline R_s measurements. Furthermore, inputting these thin film thicknesses into the film stress measurement system computed stress values of 285 and -1300 MPa for NiCr and TaN, indicating their respective natures of tensile and compressive stress. Notably, the NiCr thin film is about 4.5 times less stressful than TaN. This is a major benefit for NiCr since thin film stress can directly impact the reliability and durability of the device components. Highly stressful films can result in mechanical defects such as delamination for high tensile stress and buckling for high compressive stress [7].

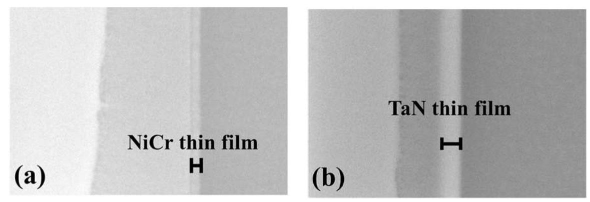

Fig. 4. Thickness measurements of (a) NiCr and (b) TaN thin films with identical inline sheet resistance on GaAs substrates.

Underlying Insulating Material

The design of experiment (DOE) in Table I was conducted to compare the thin film R_s measurements on monitoring wafers with an insulating layer of nitride versus resist coated nitride. There was <0.03 ohms/sq difference for the average TaN R_s measured on nitride versus resist coated nitride wafers. The distribution of average TaN R_s across all the DOE conditions was approximately 5 times tighter than that of NiCr. The thickest nitride layer in DOE conditions, 5 and 6, resulted in a minimal difference of <0.005 ohms/sq between measurements on nitride and resist coated nitride wafers for NiCr. This was found to be the most suitable insulating material for NiCr thin film measurements.

TABLE I
Nitride and Resist DOE for Thin Film Sheet Resistance Measurements

		Standard Deviation (ohms/sq)	
DOE	**Insulating Material**	**NiCr R_s**	**TaN R_s**
1	630Å Nitride	0.310	0.001
2	630Å Nitride + Resist		
3	2000Å Nitride	0.110	0.002
4	2000Å Nitride + Resist		
5	6000Å Nitride	0.003	0.018
6	6000Å Nitride + Resist		

Varied nitride thicknesses and resist combinations as insulating layers for NiCr and TaN thin film R_s measurements

THIN FILM PRE-CLEANS

Due to the high reactivity of GaAs substrates, treating wafers with pre-cleans prior to sputter deposition at the resistor layer is necessary to remove native oxide and promote thin film metal adhesion. In this study, a series of pre-cleans using diluted hydrochloric acid (HCl) and ammonium hydroxide (NH_4OH) were carefully evaluated for effective removal of polymer and etch residues while avoiding galvanic corrosion of underlying and exposed metal-semiconductor interfaces.

As shown in Figure 5, adding an additional NH_4OH pre-clean following the HCl pre-clean resulted in a slight upward shift of <2 ohms/sq for the average PCM R_s on both thin films. The standard deviation of the R_s distributions for wafers processed with this two-step pre-clean was reduced by 14.1% for TaN and increased by 30.8% for NiCr, suggesting that intra-wafer uniformity was also affected by the method of surface preparation and chemical reactivity.

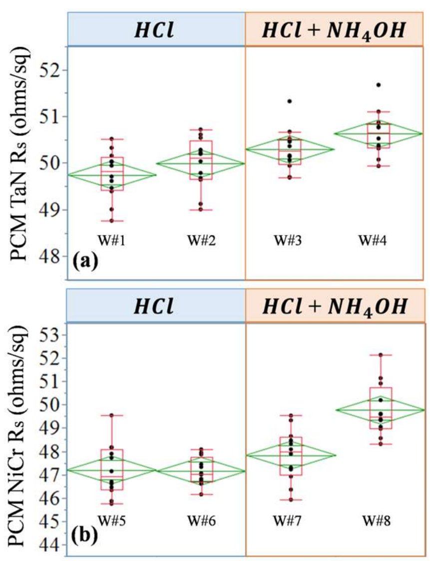

Fig. 5. DOE of pre-cleans using HCl and NH_4OH prior to the sputter deposition of (a) TaN or (b) NiCr.

NICR DEPOSITION

Dialing in the Process Recipe

As shown in Figure 6, the NiCr DOE matrix revealed that the targeted inline R_s could be achieved at about five to six times shorter deposition time than that for TaN sputtering without sacrificing uniformity (<1.5% sigma) at a comparable deposition power and platen temperature. As such, the effect of a shorter process time while retaining product quality would be magnified substantially in high-volume manufacturing. Once deposition power and time were dialed in, argon gas flow rate was varied and found to have a lesser effect on R_s but was a process parameter that could be advantageously tuned to optimize thin film uniformity. A positive correlation between improved intra-wafer uniformity and higher argon gas flow rate was established, in which %sigma and range improved by 14.5% and 91.4% respectively as argon gas flow rate was increased from 80 to 280 sccm.

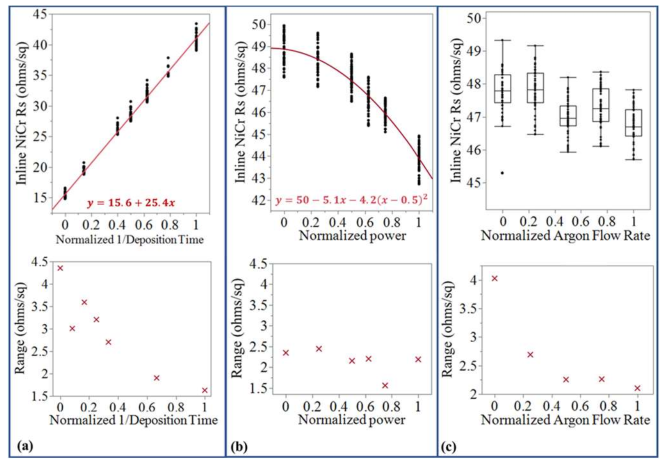

Fig. 6. Inline NiCr R_s has a (a) linear relationship with 1/deposition time, (b) quadratic relationship with power, and (c) negative correlation with argon gas flow rate.

Stability Factors

Natural oxidation of the thin film due to environmental factors was assessed. While intra-wafer uniformity showed little variability over time, there was a minimal but apparent upward shift in R_s for both NiCr and TaN thin films. As shown in Figure 7, sputtered thin films deposited on resist coated nitride monitoring wafers were remeasured over the course of two days. There was a shift in average R_s of 0.29 ohms/sq and 0.17 ohms/sq for NiCr and TaN respectively. This suggests that both NiCr and TaN thin films are susceptible to oxidation.

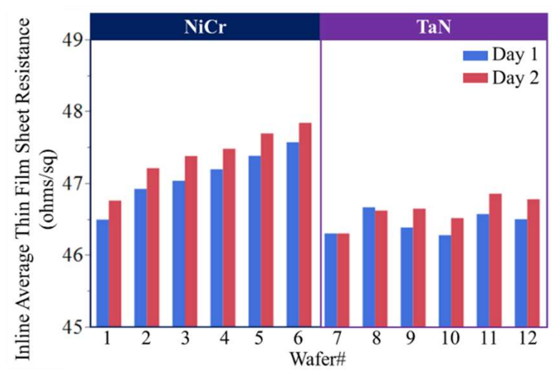

Fig. 7. Oxidation effect on R_s in the ambient environment

After additional thermal and oxidative processes in downstream steps within the fabrication flow, product wafers were electrically characterized for resistor related parameters. While TaN product wafers had a tight R_s distribution with all data in control, some NiCr product wafers had several sites flagged for outlying values as shown in Figure 8. Optical inspection revealed discoloration indicative of oxidation on the NiCr transmission line model (TLM) structures for sites with abnormally high R_s values. Future studies will pursue additional developments for safeguarding NiCr's resistivity against over-oxidation, such as drybox storage and chemical removal of the oxide growth.

At the end of the frontside process, the thin film's change in resistance as a function of temperature was determined through TCR. This parameter is important to both the resistor's reliability and performance. The absence of the DAL etch resulted in a positive TCR and wider distribution for NiCr wafers. By comparison, the average TCR for TaN wafers of all DOEs were negative and comparable within a few ppm/°C. The two-step pre-clean of HCl and NH_4OH resulted in a slight upward shift for the average TCR of both NiCr and TaN.

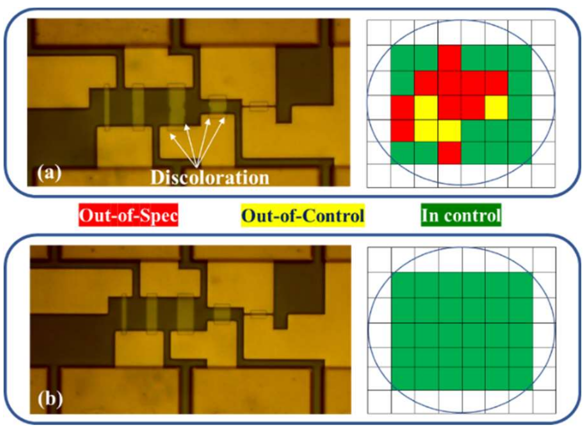

Fig. 8. Optical inspection of resistor TLM structures for (a) NiCr and (b) TaN product wafers. Sites affected by discoloration had Out-of-Spec (OOS) or Out-of-Control (OOC) R_s as indicated by the color-coded wafer maps.

Conclusions

In pursuit of capability advancement, this process investigation provided valuable insight for the evaluation of sputtered NiCr as a less expensive and process competitive alternative to TaN for TFR applications. This feasibility study explored the removal of DAL etch for metal lift-off, evaluated different pre-cleans prior to the resistor layer's thin film sputter deposition, assessed downstream effects on thin film R_s and intra-wafer uniformity, and electrically characterized resistors through PCM test.

Performing the DAL etch had a significant effect on the TCR for NiCr but not for TaN. Using the two-step pre-clean with HCl and NH_4OH for thin film surface preparation resulted in a slight positive shift in TCR for both thin films. Further studies are being conducted on NiCr to explore alternative photo processes to define resistor features smaller than what is practical with TaN. In particular, new photoresist coat recipes, tones of photoresists, reticles, as well as different conditions for exposure, develop, and post exposure bake are being evaluated within the resistor layer's photo process scheme.

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Acronyms

TFR: Thin Film Resistor
DAL: Dielectric Assisted Lift-off
TCR: Temperature Coefficient of Resistance
MMIC: Monolithic Microwave Integrate Circuits
PCM: Process Control Monitor
DOE: Design of Experiment
TLM: Transmission Line Model
OOS: Out-of-Spec
OOC: Out-of-Control