Novel Nichrome Thin Film Resistor Fabrication Approach in E-Beam Evaporation for High Volume Semiconductor Manufacturing

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Abstract

E-beam evaporated nichrome (NiCr) thin film resistors (TFR) are a category of resistors produced in the compound semiconductor industry for use in GaAs and GaN monolithic microwave integrated circuits (MMICs). NiCr TFR fabrication via e-beam evaporation generally exhibits great process variability due to run-to-run variable film composition (Ni:Cr) as a result of the difference in Ni and Cr vapor pressures. We developed a novel NiCr fabrication approach utilizing a homogeneous e-beam scan algorithm during the deposition step to overcome this intrinsic challenge. This novel approach resulted in homogeneous and isotropic collimated NiCr metal vapor flux in the evaporator chamber, leading to the reduced intra-wafer and run-to-run film composition variability. Nonetheless, this novel NiCr TFR fabrication approach also exhibits some degree of intermittent process variability due to incoming NiCr pellet material quality variability. However, the mechanism of the incoming NiCr material quality variability is poorly understood. In this report, we investigate how incoming NiCr material quality could impact the TFR fabrication process variability and explore ways to mitigate its negative effects on high-volume semiconductor manufacturing. Further, inline Process Control Monitoring (PCM) and long-term reliability data are presented for the new NiCr TFR fabrication approach.

INTRODUCTION

NiCr is widely used in the fabrication of resistors for passive-array technologies and other thin film based multichip module technologies due to its wide range of resistivities, low temperature coefficient of resistance and highly stable electrical properties.[1,2,3] Electrical properties of an evaporated TFR mainly depend on its spatial geometry (film thickness), microstructure of the film (film composition) and the deposition parameters of the evaporator. Although film thickness and deposition parameters can be controlled well in evaporation, consistent achievement of target sheet resistance in a high-volume manufacturing environment can prove challenging. Thermal evaporation of NiCr from a finite mass of molten alloy causes a film composition to change away from the composition of the source. Additionally, run-to-run changes in film composition are often observed owing to the difference in vapor pressure between nickel and chromium. In this report, we discuss a novel approach to addressing this challenge where a homogeneous e-beam scan algorithm is utilized during the deposition step.

NiCr TFR fabrication has been running with occasional process excursions since this novel fabrication approach was adopted into production, which was attributed to the incoming NiCr material quality variability. However, the mechanism of the incoming NiCr material quality variability is poorly understood. In this paper, we also report the relevant measures to mitigate the effects of compromised incoming material quality towards the process repeatability. Further, we report the inline PCM electrical and long-term reliability data on GaAs MMICs with the NiCr TFRs fabricated from the newly improved approach to warrant there are no negative effects to the device performance.

RESULTS AND DISCUSSION

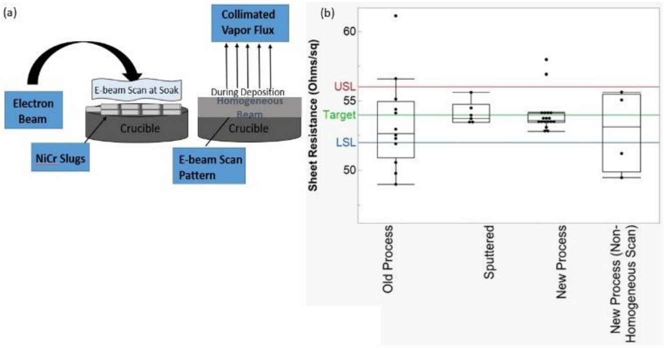
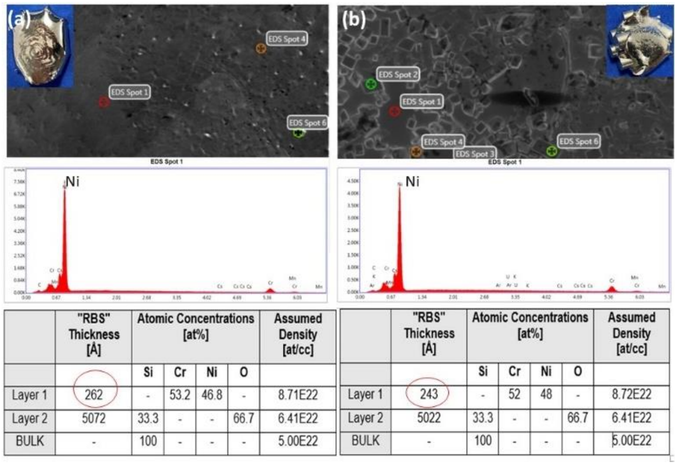


Fig 1. (a) Nichrome TFR fabrication using a homogeneous e-beam scan algorithm during the deposition step. (b) Sheet resistance data for 54 Ω /sq resistor.

Figure 1 (a) depicts the newly developed NiCr TFR fabrication approach and (b) compares the resulting sheet resistance of films deposited using the novel approach, where a homogeneous e-beam scan algorithm is utilized, to those deposited using the historically used non-homogeneous e-beam algorithm. This novel approach results in homogeneous and isotropic collimated NiCr metal vapor flux in the evaporator chamber, leading to the reduced intra-wafer and run-to-run film composition variability. As shown in Figure

1b, this state-of-the-art e-beam evaporated NiCr TFR fabrication approach yields outstanding process repeatability equivalent to sputter-deposited fabrication approach. Sputter deposition is the industry recommended technique for fabricating binary TFRs like NiCr. Additionally, this novel NiCr TFR fabrication approach resulted in 94% reduction in daily hold lots due to sheet resistance being out of specification limits and the elimination of the necessity for 7–9-hour worth of evaporator chamber pre-conditioning and qualification. Thus, this new NiCr TFR fabrication method dramatically improved the wafer fab cycle time and tool utilization in the metals area.



	"RBS" Thickness [Å]	Atomic Concentrations [at%]				Assumed Density [at/cc]
		Si	Cr	Ni	O	
Layer 1	262	-	53.2	46.8	-	8.71E22
Layer 2	5072	33.3	-	-	66.7	6.41E22
BULK	-	100	-	-	-	5.00E22

	"RBS" Thickness [Å]	Atomic Concentrations [at%]				Assumed Density [at/cc]
		Si	Cr	Ni	O	
Layer 1	243	-	52	48	-	8.72E22
Layer 2	5022	33.3	-	-	66.7	6.41E22
BULK	-	100	-	-	-	5.00E22

Fig 2. Incoming NiCr material quality. (a) SEM micrograph of a thin NiCr film evaporated from good NiCr slugs (*top left*). EDAX elemental map for the same film (*middle left*). NiCr composition of the same film derived from RBS (*bottom left*). (b) The same analyses as in (a) for a thin NiCr film evaporated from problematic NiCr slugs.

NiCr TFR fabrication has been running with occasional process deviations since the novel fabrication approach was adopted into production. These intermittent process hiccups were attributed to the incoming NiCr material quality variability. However, the mechanism of the incoming NiCr material quality variability has never been investigated and understood. Incomplete melting of NiCr slugs during the soak step (see *Fig. 2b*) caused the process to enter intermittently into a failure state. These failures resulted in sheet rho values above the upper specified limit for the process. Scanning electron micrograph (SEM) analysis revealed the presence of crystalline islands across the films resulting from these failed runs that were not present in those resulting from successful runs. Elemental analysis found that the crystalline islands were composed of nickel. We postulate that the nickel which composes these islands is in a different electronic state than that which composes the successfully deposited films. Rutherford Back Scattering (RBS) revealed that both “good” films (sourced from successful runs) and “bad” films (sourced from failed runs) have comparable film compositions with a 20 Å difference in thickness, which was postulated to be due to a difference in film density caused by NiCr material quality shift.

We studied the Certificate of Analysis (CoA) of the incoming NiCr materials to identify if there is a significant difference in Post-Transition Metals (PTM) concentration between “good” and “bad” materials. The presence of thermally conductive substances such as PTM can affect the solid-to-vapor phase transition of NiCr, leading to an evaporated film of atypical crystal structure from the process of record structure (see *Fig. 2b)*. Vendor provided CoAs did not show evidence of excessive PTM concentrations in NiCr (see *Table 1*). However, Glow Discharge Mass Spectroscopy (GDMS) done on NiCr metal sources and incoming NiCr slugs revealed that good NiCr slugs had 97% more PTM than in bad slugs: see Table 1.

Table 1**.** PTM concentration in incoming NiCr slugs and NiCr metal sources made from good and problematic NiCr materials.

NiCr Sample	**PTM Content from CoA (ppm wt)**	**PTM Content from GDMS (ppm wt)**
Bad Pellets	20	4.7
Bad Metal Source	N/A	4.6
Good Pellets	16	220
Good Metal Source	N/A	220

NiCr deposition rate can be used to gauge the PTM concentration in NiCr slugs: variability in deposition rate correlated negatively with the PTM concentration of the NiCr as measured by external GDMS analysis (see *Fig. 3a)*. Higher variability in NiCr deposition rate results in a shift in film density from the desired range, causing a shift in sheet resistance from customer specification limits. The film density shift could be compensated for by a change in thickness via tooling adjustment in the evaporator to bring the resultant sheet RHO within the desired specification limits (see *Fig. 3a*). NiCr materials from various vendors have been evaluated in terms of ability to melt within the desired e-beam power range with respect to the PTM concentration (verified via external GDMS analysis) to further validate the proposed NiCr material quality model. As postulated above, incoming NiCr slugs with less than 90 PPM of PTM failed to fully melt during the soak process in the e-beam evaporator within the desired e-beam power range. GDMS analysis showed high shipment-to-shipment variability in the PTM concentration of incoming NiCr slugs sourced from the same vendor. Figure 3b summarizes the effectiveness of externally adding PTM into NiCr source in the e-beam evaporator to its phase transition. Addition of external PTM to the NiCr metal source reduced the e-beam power needed to melt the very low PTM (4-6 ppm) NiCr slugs by 60%. As depicted in Figure 3b, NiCr deposition rate variability was studied as a function of added PTM in to the NiCr metal source. Note that the PTM concentration was only 4 PPM in the incoming NiCr slugs used for this investigation.

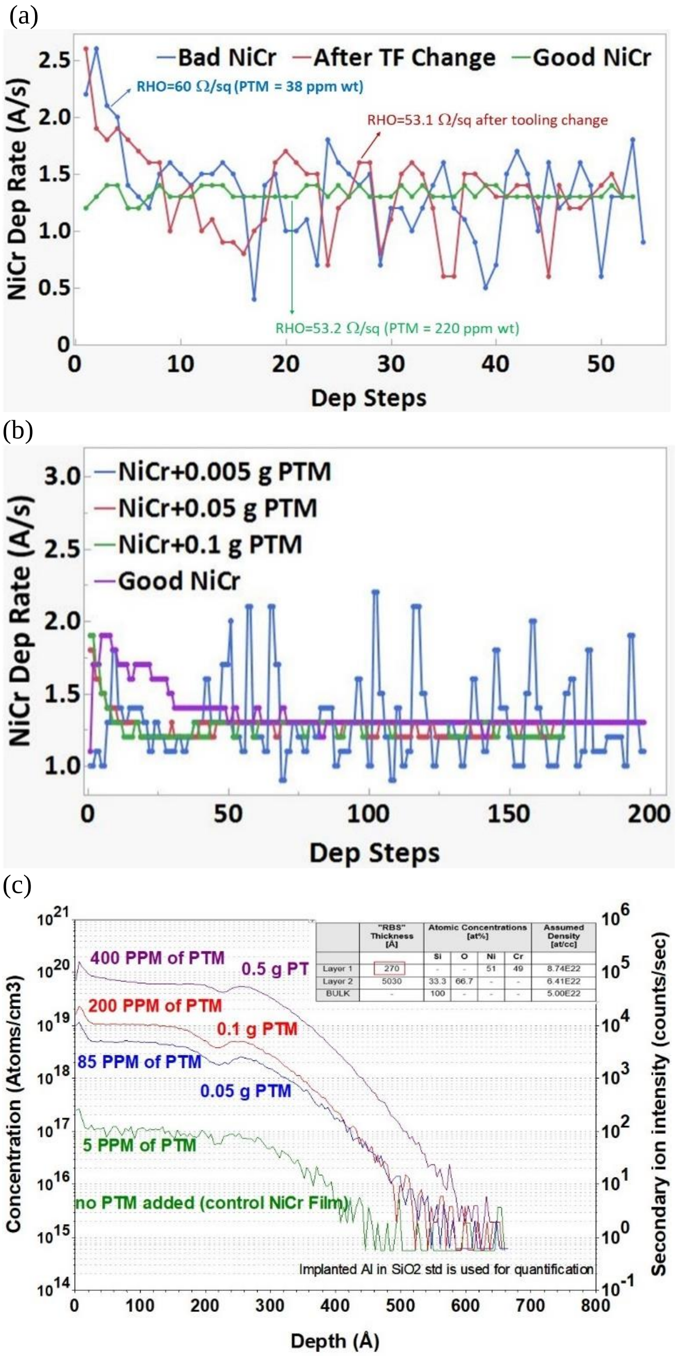


Fig 3. (a) Significance of the presence of PTM in NiCr slugs for achieving improved deposition rate profile. Target sheet RHO is 53 Ω /sq. (b) Achieving stable NiCr deposition rate profile via PTM addition to the metal source. (e) SIMS of the NiCr thin films evaporated from NiCr metal sources with and without PTM doping.

NiCr phase transition approaches a self-limited steady equilibrium state with sequential PTM doping (see *Fig. 3b*). Figure 3c shows the PTM concentration in the evaporated NiCr film as a function of added PTM concentration to the NiCr metal source as measured using Secondary Ion Mass Spectroscopy (SIMS). 85 PPM of PTM was detected in the NiCr film when 0.05 g of PTM was added to the NiCr metal source of 34 g in the e-beam evaporator. RBS analysis of the same NiCr film confirmed the process of record film composition along with the film thickness that is commensurate with the nominal (target) thickness.

We reviewed the end of line PCM electrical data to confirm that the novel NiCr TFR fabrication approach introduces no detrimental effects on device performance. For PCM data evaluation, GaAs MMIC engineering lot was split at the NiCr TFR fabrication step, and selected wafers through the anneal process at 350 ^{O}C for 15 min at post gate metal deposition. The change in NiCr sheet RHO from NiCr evaporation process step to the final PCM for annealed wafers was independent of the PTM addition (see *Fig. 4a)*. However, the sheet RHO delta from the process level to the final PCM for non-annealed wafers shrinks upon PTM addition. Additionally, NiCr sheet resistance dispersion at the final PCM test is improved by 33% and 50% upon 0.05 g of PTM addition as compared to the process of record process for annealed and non-annealed wafers, respectively (see *Fig. 4b*).

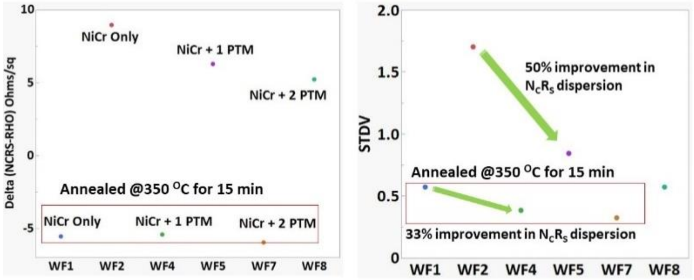


Fig 4. Design of Experiment (DOE) to probe the effect of PTM doping on NiCr metallic source for end of line E-test data. (a) Delta in sheet RHO from process level to the final PCM step with and without PTM doping in the NiCr metal source for annealed and non-annealed wafers. (b) Standard deviation of the NC_RS at the final PCM for the same DOE wafers as described in (a).

NiCr has been tailored as a ternary mixture, for example by doping with Au[4] or Si[5], in semiconductor integrated circuits manufacturing to lower the Temperature Coefficient of Resistance (TCR) of the evaporated NiCr film. Therefore, we performed the biased stress bake test using Transmission Line Measurement (TLM) and Van der Pauw (VDP) structures in the GaAs MMIC engineering lot used for above PCM investigation to determine/identify any long-term reliability concerns, such as degradation of sheet or contact resistance in conjunction with TCR (see *Fig. 5)*. Figure 5 shows the degradation of NiCr sheet resistance and contact resistance (between NiCr and Overlay metal layers) at 220 ^{O}C and 40 mA biased stress conditions over 600 hours using TLM test structure.

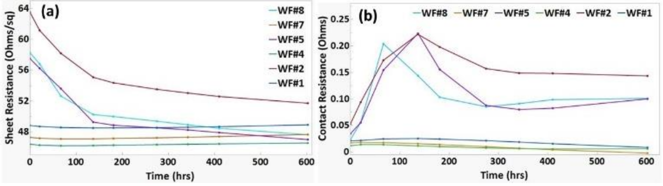


Fig 5. Long-term reliability study using biased stress bake test upon PTM addition to NiCr metal source as outlined in Figure 4a above. (a) Change in sheet resistance (b) Change in contact resistance over time under 220 ^{O}C and 40 mA stress conditions.

Degradation of sheet resistance is negligible for annealed NiCr TFRs irrespective of PTM addition whereas non-annealed parts degrade over time, indicating they have not yet reached their thermal steady state. Activation energy of the degradation is calculated to further understand the effect of PTM addition on the rate of sheet resistance degradation. Contact resistance degradation of annealed NiCr parts is also negligible over time. However, non-annealed NiCr parts show some degree of variation in contact resistance over time, where PTM added parts follow similar trend as of process of record parts.

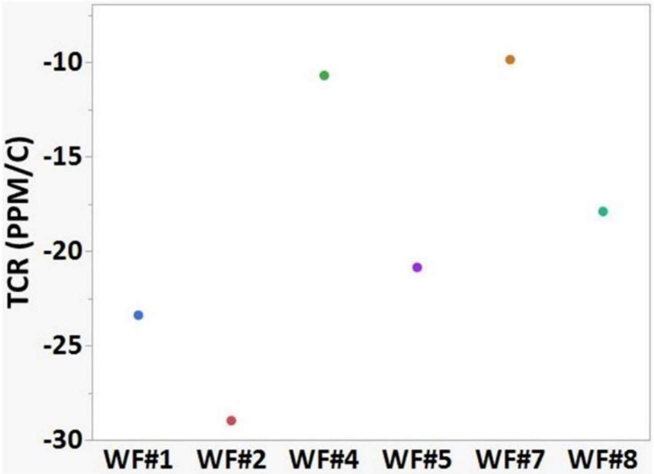


Fig 6. TCR for NiCr with and without PTM addition to the metal source in the e-beam evaporator as outlined in Figure 4a above. Resistance measurements were made from 24 ^{O}C to 130 ^{O}C using VDP test structures in the GaAs MMIC devices.

NiCr thin film resistors with more than 40% of Cr should have slightly negative TCR as the crystal structure is amorphous.[6,7] Annealing such a NiCr TFR should bring about amorphous to semi or polycrystalline phase transition, resulting a decrease in resistivity (i.e., nearly zero TCR). The tertiary alloy matrix of NiCr, for example Ni/Cr/PTM, promotes amorphous to crystalline phase transition, thereby resulting in a further reduction in TCR. Figure 6 summarizes the TCR measurements from 30-130 ^{O}C for the wafer split matrix as shown in Figure 4a. By alloying NiCr with PTM, near zero TCR can be achieved, as confirmed by our TCR measurements in agreement with existing literature reports.

CONCLUSIONS

NiCr TFR fabrication utilizing a homogeneous electron beam scan algorithm during the deposition step in e-beam evaporation guarantees a highly robust process with improved repeatability. Moreover, this work reveals the correlation between the incoming NiCr material quality and NiCr phase transition in the e-beam evaporator Knudsen cell, thereby further improving the repeatability of e-beam evaporated NiCr TFR fabrication process. Collectively, utilization of homogeneous e-beam algorithm at the deposition step and addition of PTM into the NiCr metal source offer a robust method for fabricating NiCr TFRs with enhanced process repeatability. This innovative e-beam evaporation fabrication method has the same repeatability and robustness as the industry-recommended sputter-fabrication approach for a binary metallic thin film resistor.

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ACRONYMS

TFR: Thin Film Resistor, MMIC: Monolithic Microwave Integrated Circuit, PCM: Process Control Monitoring, RBS: Rutherford Back Scattering, SEM: Scanning Electron Microscope, CoA: Certificate of Analysis, PTM: Post Transition Metal, GDMS: Glow Discharge Mass Spectroscopy, SIMS: Secondary Ion Mass Spectroscopy, TLM: Transmission Line measurement, VDP: Van der Pauw, TCR: Temperature Coefficient of Resistance.