FABRICATION AND CHARACTERIZATION OF THIN FILM RESISTORS FOR GaAs-BASED POWER AMPLIFIERS

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Abstract

This paper presents a comprehensive study of sputtered TaN thin film resistor with a low resistivity of only 150 μΩ-cm, its comparison with thin film resistors fabricated by evaporated NiCr and sputtered NiV. Sheet resistance (Rs), temperature coefficient of resistance (TCR), and voltage coefficient of resistance (VCR) were measured using a standard Van Der Pauw (VDP) structure. Thickness was measured by a profilometer as well as cross-section SEM. Biased-drift tests and thermal tests were performed to check the reliability of the thin film resistors.

INTRODUCTION

Tantalum nitride (TaN) and nickel chromium (NiCr) are widely used in the fabrication of resistors for passive-array technologies and other thin film based multichip module technologies. More recently, TaN has been chosen for resistor fabrication because of its good resistivity uniformity, low TCR, low VCR, good thermal stability, and the fact that it can be tuned to achieve a wide range of electrical properties by varying the film stoichiometry [1-4]. TaN resistors with a sheet resistance of 50 Ω/sq., fabricated by reactive sputtering, have been widely used for GaAs power amplifiers. Reported resistivity values of TaN resistors range from 200 μΩ-cm to 1000 μΩ-cm [5]. However, to support the wide range of ballasting resistor requirements, the 50 Ω/sq. sheet resistance would be too large and the development of a thin film resistor with lower sheet resistance is needed. The resistor must also have a film thickness that is compatible with the traditional or dielectric assisted lift-off process if a dry etch process is not practical. To fulfill these requirements, the bulk resistivity of the film has to be lowered below 200 μΩ-cm.

Evaporated NiCr films have been used historically due to their low TCR and low bulk resistivity [6]. However, the difference in vapor pressure between nickel and chromium makes it challenging to consistently reach the target sheet resistance in a high-volume manufacturing environment.

EXPERIMENTAL

TaN resistors were fabricated using reactive DC sputtering, followed by a dielectric assisted metal liftoff process. NiV resistors were DC sputtered from an alloyed target. Due to the sputtering process, the NiV thin film may have a different composition and structure compared to the bulk NiV target. NiCr resistors were fabricated using a conventional evaporation and liftoff process, in which the R_s was controlled using a chart recorder to monitor the sheet resistance value in real time. The NiCr thin film resistor (TFR) was built on passivation nitride while the TaN and NiV resistors had to be built directly on GaAs to facilitate the dielectric assisted liftoff process.

R_s values were also measured on a 4-point probe station using a monitor wafer. CD was measured using a scanning electron microscope (SEM). Final DC parametric tests were done on an automated probe station. R_s, TCR, and VCR were measured using standard Van der Pauw structures. A 10-μm long resistor was used to measure current limits as well as carry out biased drift tests on the resistors. Comb structures were used to obtain breakdown voltage and leakage current at an elevated temperature.

RESULTS AND DISCUSSIONS

Resistivity: By changing process parameters such as pressure and Ar/N_2 ratio, thus the composition of the TaN thin film resistor, its bulk resistivity can be lowered to 150 μΩ-cm, compared to 100μΩ-cm for NiCr thin film resistors and 60 μΩ-cm for NiV thin film resistors, which will satisfy the low sheet resistance requirement, which is 20 Ω/sq. Contact resistance from TLM measurements is also 50% lower than the 50 Ω/sq. (260 μΩ-cm) TaN peer because of the lowered bulk resistivity.

The changes in the crystal orientation and grain boundary of the TaN film are responsible for the lowered resistivity. Figure 1 shows the low angle x-ray analysis (XRD) of the low resistivity TaN film. Compared to the 50 Ω/sq. TaN film, which XRD is also shown in Figure 1, the intensity of the peak at 37° of the 20 Ω/sq. TaN film, which composition includes TaN0.1(110) and Hex TaN(101), is much higher than that of the 50 Ω/sq. TaN film. The 50 Ω/sq. TaN film also has one more crystal, Cube TaN(111), than the 20 Ω/sq. TaN film.

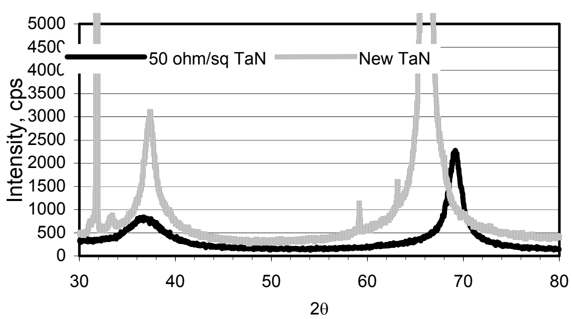

Figure 1 XRD comparison between the new TaN film and the 50 Ω/sq. TaN film, both on silicon substrates.

The 20 Ω/sq. TaN film is more organized and orientated. Using Sherrer's equation one can calculate that the grain size of the 20 Ω/sq. TaN film is 60 Å, compared to 20 Å for the 50 Ω/sq. TaN film. The bigger grain size, thus the lower grain boundary density, and higher degree of orientation of the 20 Ω/sq. TaN film contribute to its lower bulk resistivity.

Temperature Coefficient of Resistance: The Rs of each resistor film was measured incrementally from room temperature up to 120 °C. The TCR can be calculated based on the following equation:

$$R_s = R_0[\alpha(T - T_0) + \beta(T - T_0)^2] \qquad (1)$$

where R_s is the sheet resistance at higher temperature T, R_0 is the resistance at temperature T_0, α represents the linear portion of TCR, and β represents the non-linear portion of TCR. Since the TCR of the studied materials is presumably small, the second power term was not used in the calculation. Therefore, the above equation was simplified to:

$$R_s = R_0\alpha(T - T_0) \qquad (2)$$

A linear regression was performed using all the data points, and the slope was used to calculate the TCR, as shown in Figure 2. The exclusion of the higher order term was justified, since the regression coefficient was above 0.99.

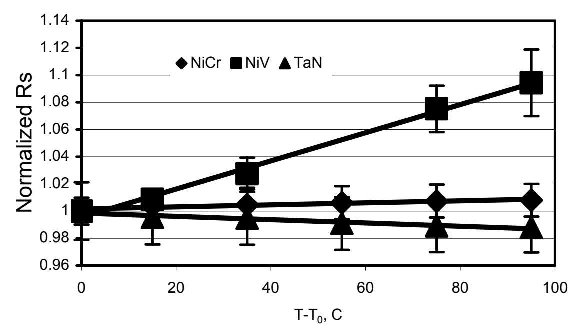

Figure 2 Temperature coefficient of resistance comparison for different TFR materials.

The TaN resistor shows a decrease in resistance value as a function of temperature. Its calculated TCR is –100 ppm/°C, which is comparable to the 50 Ω/sq. TaN resistors. The calculated TCR for the NiCr resistor is +80 ppm/°C. At elevated temperatures the NiCr resistor value does not change dramatically, indicating its excellent temperature merits as a resistor material. However, on the other hand, the TCR for NiV is +1004 ppm/°C, which is significantly larger than that of TaN and NiCr. At a normal power amplifier junction temperature during operation, which is over 100 °C, the NiV resistor value will increase more than 10%. It's worth noting that the TCR value is often dependent on the process parameters. Considering NiV's low stress and high current carrying capability, it would still be a good candidate for a TFR if its TCR can be lowered by process changes.

Leakage Current: A TaN resistor typically has a resistor to active area (RL-AA) leakage current about 4 orders of magnitude higher than that of a NiCr resistor, measured with comb structures where the distance between the resistor and the active area is kept at 1.9 μm. As described previously, with the current sputtering/dielectric assisted liftoff process it is not feasible to fabricate TaN resistors on passivation nitride because the sputtered material will coat on the sidewall of the photoresist trench, making subsequent liftoff extremely difficult, if not impossible. However, using the evaporation process, NiCr resistors can be fabricated on dense PECVD Si_xN_y, which results in a much lower leakage current between the resistor and active area.

The advantage of building resistors on Si_xN_y is also shown in the leakage current between resistor lines (RL-RL), which are separated by 3.0 μm. The leakage current of NiCr resistors is also about 4 orders of magnitude lower than that of TaN resistors.

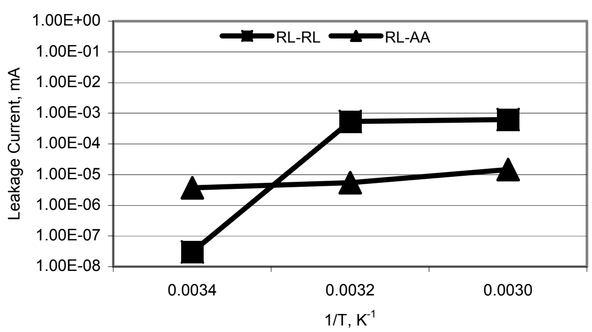

Figure 3 Temperature effect on TaN TFR leakage currents at 7 V.

Since the resistor temperature increases during operation, it is of interest to know the temperature dependence of the leakage current. Figure 3 shows the leakage currents of a TaN resistor as a function of temperature. In the tested temperature range both the RL-AA leakage current and the RL-RL leakage current increase at elevated temperatures. Conversely, the leakage currents for NiCr decrease at higher temperature, as shown in Figure 4.

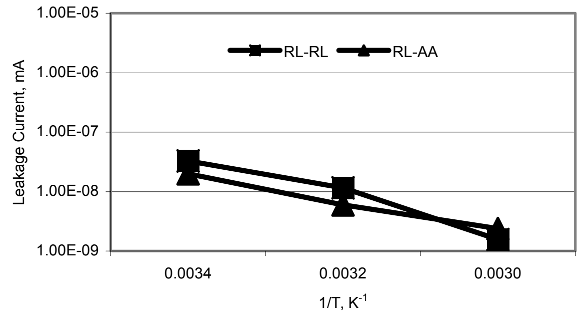

Figure 4 Temperature effect on NiCr TFR leakage currents at 7 V.

Breakdown Voltage: Using a comb structure, the TFR breakdown voltage can be measured by applying high voltage across the resistor, at 150 °C. At a high enough voltage the leakage current from resistor to resistor will rise sharply when the substrate in between the resistors breaks down. As shown in Figure 5, the resistor to resistor breakdown voltage of TaN is found to be 62 V. Using the same structure, the TaN resistor to active area breakdown voltage was determined to be 31 V, also shown in Figure 5. It is expected that both RL-RL breakdown voltage and RL-AA breakdown voltage for a NiV TFR should be the same as those of TaN as they are built on the same GaAs substrate. Both RL-RL and RL-AA breakdown voltages for a NiCr TFR are expected to be higher because there is an insulating PECVD silicon nitride underneath the resistor.

Current Limits: Current limit, or current carrying capability, is defined as the highest current that can be passed through a resistor before its I-V curve deviates from the Ohm's Law, at 125 °C. Both NiV and TaN resistors have superior current limits compared to NiCr resistors. The tested current limit for the NiV resistor is 11.9 mA/μm, and for TaN resistor is 11 mA/μm, compared to only 4 mA/μm for the NiCr resistor. The major reason for the high current limits of NiV and TaN TFRs is that they are fabricated on GaAs, instead of Si_xN_y. Since the thermal conductivity of GaAs is four times higher than Si_xN_y, the surface temperature of NiV and TaN resistors will stay lower than that of NiCr resistors, and will result in higher current carrying capability. In addition, the current limit is also a function of resistor length. The longer the resistor, the more heat will be generated, and the lower the maximum current carrying capability of the resistor.

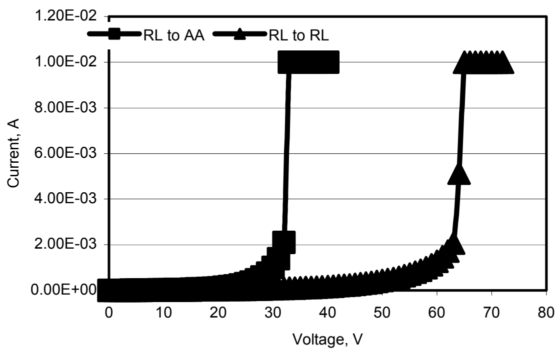

Figure 5 Breakdown voltage of both resistor to resistor and resistor to active area for TaN resistors, at 150 °C.

CONCLUSIONS

Intensive comparisons are made among different PVD films for thin film resistors used in the GaAs power amplifier. These films, reactive sputtered TaN, sputtered NiV, and evaporated NiCr, each have advantages and disadvantages. TaN and NiV have higher current limits and higher breakdown voltages, but poor leakage currents. NiV has the highest TCR and VCR among these three and is not suitable if the applications require a low TCR. NiCr has the best TCR and VCR and its overall process integration is easier compared to TaN and NiV. However, Ni content control in the film as well as the NiCr reactivity when exposed to solutions at later processing steps, remain a challenge. In addition, NiCr has the lowest current carrying capability due to the poor heat dissipation nature of underneath Si_xN_y, which the NiCr TFR is built on. All three films show good stability for high temperature operation.

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ACRONYMS

TaN: Tantalum nitride
NiCr: nickel chromium
NiV: nickel vanadium
TFR: thin film resistor
TCR: temperature coefficient of resistance
VCR: voltage coefficient of resistance
RL: resistor line
AA: active area
R_s: sheet resistance
XRD: x-ray diffraction analysis

