Subtractive WSiN thin film resistors for RF GaN and InP MMICs

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In this study, WSiN-based thin film resistors are implemented and characterized as an alternative to NiCr-based resistors in GaN and InP MMICs. This approach simplifies the fabrication process by utilizing an etch-back technique instead of a lift-off method. Additionally, electrical evaluations have demonstrated promising stability (less than ~1%) of WSiN over 100 hours of stress, along with an absolute resistance temperature coefficient (200-300 ppm/K) which is comparable to NiCr resistors.

INTRODUCTION

Thin film resistors are essential components in GaN and InP microwave monolithic integrated circuits (MMICs). They are commonly made of sputtered NiCr due to its high stability and low Temperature Coefficient of Resistance (TCR) [1]. Additionally, NiCr's high resistivity enables the attainment of desired resistance with smaller structures. These characteristics make NiCr a suitable material for thin film resistors in GaN-based MMICs, especially under elevated operating temperatures. While NiCr can be deposited by e-beam evaporation, the differing melting points of Ni and Cr can lead to unstable alloying compositions. This requires the sputtering of pre-alloyed NiCr targets, which leads to significant challenges when combined with the lift-off technique. A higher deposition angle and back-scattered species during sputtering lead to metal coverage across nearly the entire resist profile. This necessitates a trade-off between needed photoresist undercut and accepted deviation from the targeted metallization dimensions.

An alternative approach for patterning a sputtered metal is the subtractive method. However, in this case, back etching of the NiCr layer requires Cl-based dry etching with a high plasma bias. This conflicts with our baseline technology, as it would also etch already existing Au-based interconnections. On the other hand, WSiN has been reported as an alternative material for thin film resistors in GaN [2-3] and InP [4] MMICs. One of the significant advantages of WSiN over NiCr lies in the back-etching process. WSiN can be etched with low-bias SF_6 plasma, simplifying the patterning of resistors without causing damage to other structures. Furthermore, NiCr is vulnerable to fast oxidation, and, therefore, passivation of thin film resistors in a short time span after metallization is required. In contrast, there is no concern for oxidation of WSiN. These factors indicate that the use of WSiN could lead to a more robust solution. In this study, the fabrication technology and performance for WSiN thin film resistors are investigated. The fabricated resistors are electrically characterized and then compared to corresponding NiCr structures produced by using lift-off technology.

FABRICATION OF THIN-FILM RESISTORS

Two wafers (W1 and W2) using WSiN and one wafer (W3) using NiCr thin film resistors (as a reference) were fabricated on 4-inch Si wafers with pre-fabricated interconnect metallization. In both cases, the thin-film resistor thickness was adjusted to achieve a sheet resistance of 50 ± 5 Ω/□, as needed for our MMICs technology. For wafers W1 and W2, WSiN was sputtered onto the entire wafer using a tungsten silicon target with a ratio of 5:3, with 50 sccm argon and 2 sccm nitrogen at 200 W RF power. The deposition rate is 24 nm/min. This means that to attain 50 Ω/□, a duration of 200 seconds (equivalent to 80 nm thick WSiN) is required. Following these steps, WSiN was patterned with i-line lithography using SPR 955c positive tone photoresist. Subsequently, WSiN outside the resistor areas was etched by means of SF_6-based RIE with a rate of 45 nm/min.

For reference wafer W3, NiCr resistors were fabricated according to FBH technology with employing the same layout and reticle, using AZ 5214 as negative tone resist. The NiCr was sputtered to a thickness of 25-30 nm with an 8:2 nickel chromium sputter target, maintaining the same argon gas ratio (50 sccm) and RF power as in the WSiN case. The deposition rate is approximately 2-2.5 nm/min. Afterwards, 40 nm PECVD-based SiN_x was deposited on the NiCr resistors as protection layer.

Microscope images of the fabricated resistors using the subtractive method (W1) and lift-off technique (W3) are shown in Fig. 1. Accordingly, the patterning of sputtered metal by this approach demonstrates similar or superior results when compared to the lift-off technique in wafer 3. Specifically, the subtractive approach does not suffer from formation of metal fences which is a typical liftoff issue when metal sputtering and lift-off technique are combined (Fig.1c).

RESULTS AND DISCUSSION

The fabricated thin-film resistors were characterized and compared in terms of sheet resistance, TCR, long-term stability (ΔR/R), and absolute resistance of a 5 µm width line. The mean value of resistance and sheet resistance were obtained by 4-probes measurements on 37 wafer shots. To obtain the TCR, resistors were measured at room temperature and 125 °C (Fig. 2). Also, WSiN resistors (wafer W1) were subjected to 0.24 mA/µm current density (upper MMIC design limit at FBH) at 125 °C for 100 hours to assess reliability and any resistance drift (Fig. 3). The obtained characteristics are summarized in Table 1. The sheet resistance and therefore the resistance of resistor lines are in the targeted range of 50 ± 5 Ω/□. Moreover, the mean value of TCR of ~ -249 ppm/K from W1 (Fig. 2) and W2 shows a similar absolute value of temperature sensitivity as expected from NiCr resistors in our baseline technology (~ + 200 ppm/K). One needs to notice that TCR for NiCr is highly dependent on the metal's ratio and + 200 ppm/K has been reported for 8:2 nickel-chromium ratio [1, 5]. The opposite TCR is the well-known phenomenon comparing metal versus nonmetallic materials [6]. This can be explained by the different temperature dependencies/mechanisms of conductivity in the pure metals (like NiCr) compared to the metal-insulator scheme (WSiN). Additionally, stability under the discussed accelerated life tests is ≤ 1.5 % for W1 (Fig. 3). This is comparable with the reported values for NiCr resistors [1] (in dissimilar conditions).

In an additional test, the stability of resistors was evaluated under extreme bias conditions, up to 10x the maximum specified resistor current density limit in FBH MMIC design (R-I or R-V characteristics in Fig. 4). This was carried out with 5 µm and 17.5 µm wide lines (~4.0-4.2 kΩ and 50 Ω, respectively). Fig. 4 shows the deviation from linear IV characteristics for applied bias up to 40 V and current densities up to 2.4 mA/µm. As shown in Fig. 4a, both NiCr and WSiN demonstrate less than 1 % resistance alternation. Note that resistance decreases with bias for WSiN while it increases for NiCr. This behavior follows the measured TCR values (Table 1) and suggests that the slight variation was caused by heating the resistors. In addition, the targeted 50 Ω resistors for both technologies (Fig. 4b) could survive up to 10x the maximum specified limit in FBH MMIC design for the current density of the thin film resistor.

TABLE I

MEASURED PROPERTIES OF NICR AND WSIN resistors.

Wafer	**Material**	**R [kΩ]**	**Sheet r. [Ω/□]**	**TCR [ppm/K]**	**ΔR/R [%]**
1	WSiN	4.2	53±1	- 207	≤ 1.5 %
2	WSiN	4.1	52±1	- 291	-
3	NiCr	4.0	48±2	~ +200 [1, 5]	≤ 1% [1]

CONCLUSIONS

The developed WSiN-based thin film resistors in this study have shown the targeted sheet resistance (~ 50 Ω/□), |TCR| down to 207 ppm/K, and stability (≤ 1.5 %) over 100 hours of stress at 125 °C. This qualifies WSiN as an alternative to NiCr-based resistors in GaN and InP MMICs. WSiN-based thin film resistors can be easily patterned in MMIC-technologies by SF_6-based dry etching and using a positive-tone resist mask. This is an advantage compared to NiCr-based resistors where a challenging combination of NiCr sputtering and lift-off technique is needed. Additionally, WSiN thin film resistors do not require a passivation layer to prevent oxidation, promising a more robust technology. Therefore, the developed WSiN resistors are to be used in the production of GaN and InP MMICs at the Ferdinand-Braun Institute.

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ACRONYMS

MMIC: Microwave Monolithic Integrated Circuits
HEMT: High-Electron-Mobility Transistor
HBT: Heterojunction Bipolar Transistor
TCR: Temperature Coefficient of Resistance
SEM: Scanning Electron Microscope

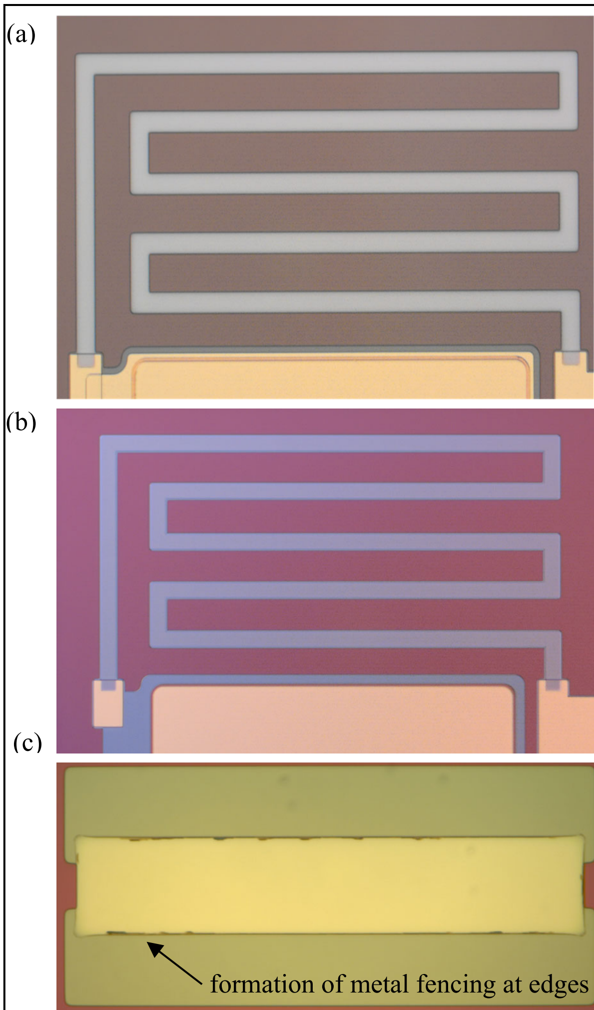

Fig. 1. Fabricated thin film resistors using a) NiCr and b) WSiN. c) liftoff issue for the sputtered NiCr resistors.

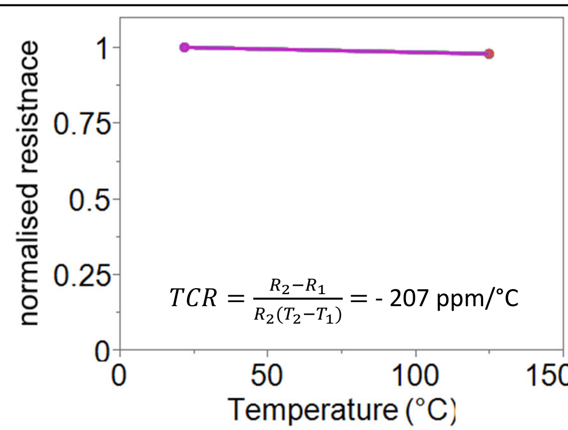

Fig. 2. Normalized resistance of WSiN thin film from 5 measured shots at room temperature (22 °C) and at 125°C for wafer W1. TCR was calculated from ~ 2 % reduction of resistance over 103-degree temperature variation.

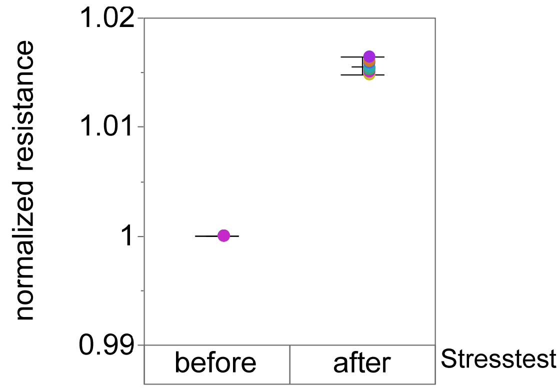

Fig. 3. Normalized resistance of WSiN thin film from 9 measured shots at room temperature (22 °C) after and before 100 h stress test of 0.24 mA/µm at 125°C.

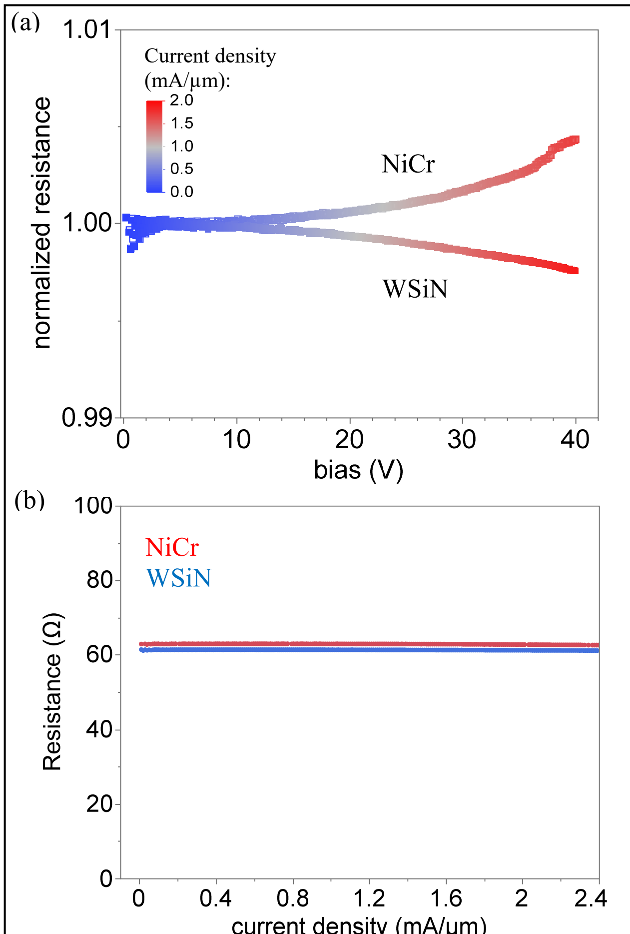

Fig. 4. Stability estimation. a) normalized resistance of 5 µm width lines (4.0-4.2 kΩ) of NiCr or WSiN thin films up to 40 V. In this figure, the current density during measurements is presented in the color of the lines. b) resistance of 17.5 µm width lines (targeted 50 Ω) of NiCr or WSiN up to 2.4 mA/µm. (This is 10x higher than the allowed current density at FBH technology for the thin film resistors).