Investigation of Contact Metal Stacks for Submicron GaN HEMT

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Abstract

Encapsulated Ti/Al/Ni/Au metal stack for Ohmic contacts and TaN *vs.* Ni for Schottky contacts for submicron GaN HEMTs have been investigated.
The results show that the composition of the SiN_x encapsulation layer is a dominant factor, affecting metal morphology, edge definition and e-beam lithography alignment mark detection. The results show that TaN can be used as a Schottky gate at very high temperature applications, but Ni has superior barrier height and it is stable at 300°C.

INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMT) are excellent candidates for high power applications at microwave frequencies [1]. One critical demand for high power application is materials with high temperature stability [2]. High quality, low resistance Ohmic contacts are a vital part of AlGaN/GaN HEMT technology [3]. Low contact resistance for high electrical performance is achieved by rapid thermal alloying at extremely high temperatures that may damage surface morphology. Good morphology and smooth edge definition are essential for e-beam lithography alignment, which defines the submicron gate, and for device reliability.

For an AlGaN/GaN power HEMT a Schottky gate contact with a large barrier height is always desirable to achieve low gate leakage currents, high breakdown voltages and high turn-on voltages [4]. The gate material is one of the factors that determine the above parameters.

We investigated the effect of alloying Ti/Al/Ni/Au Ohmic contact encapsulated with SiN_x and SiO_2 cap layers to achieve low ohmic contact, good morphology and smooth edge definition.

The second subject of the article is focusing on the investigation of TaN and Ni as Schottky gate materials for AlGaN/GaN HEMT. We investigated the thermal stability of TaN as a Schottky gate material and we used Ni Schottky contacts as a reference.

ENCAPSULATED OHMIC CONTACTS

EXPERIMENTAL:

Unintentionally doped $Al_{0.25}Ga_{0.75}N$/GaN layers grown by MOCVD on sapphire substrates have been used. The wafer was sawed into rectangle samples. The samples were dry etched using ICP to form mesa isolation, followed by a patterned Ti/Al/Ni/Au metal stack. Before annealing at 930°C for 30 s the samples encapsulated by different stoichiometry SiN_x and also by SiO_2. Stoichiometry of SiN_x was determined by refractive index (R.I.). R.I. 2.2 for Si-rich SiN_x, R.I. 2 for Si_3N_4 and R.I. 1.8 for N-rich SiN_x.
Wet etching at HF solution and dry etching at the ICP were evaluated for the purpose of removing the cap layer.

RESULTS & DISCUSSION:

Both the SiN_x encapsulation layers with R.I. 1.79 and 2 are cracked, but the metal morphology and edge definition are improved relative to non-encapsulated Ohmic contacts (figure 1). AFM characterization of e-beam alignment mark (EBAM) encapsulated by SiN_x with R.I. 2 reveals RMS (Root Mean Square) roughness of 174 Å and Rp-v (maximum peak to valley height) of 1260 Å. The non-encapsulated EBAM on the same sample reveals RMS roughness of 269 Å and Rp-v of 2500 Å.

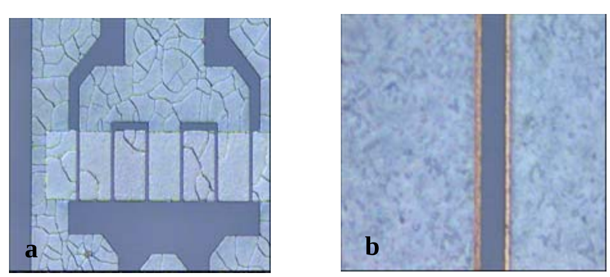


Figure 1 –R.I. 1.79 SiN encapsulation: - (a) HEMT micrograph showing crack pattern (x100); (b) metal morphology and edge definition (x1000).

The SiN_x capping with R.I. 2.2 shows cracking patterns and "clouds" around the edge definition (figure 2), but the metal morphology is improved relative to non-encapsulated samples.

EDX analysis reveals that those “cloudy” areas are composed of Au/Al/Si phases. Phase diagrams indicate that Si-Au has a eutectic at 363^{o}C [5] and Si-Al has a eutectic at 577^{o}C [6]. One explanation for this phenomenon is that the excess Si from the Si-rich SiN may react with the Au and Al to form a liquid phase and diffuse through the surface while alloying at 930^{o}C.

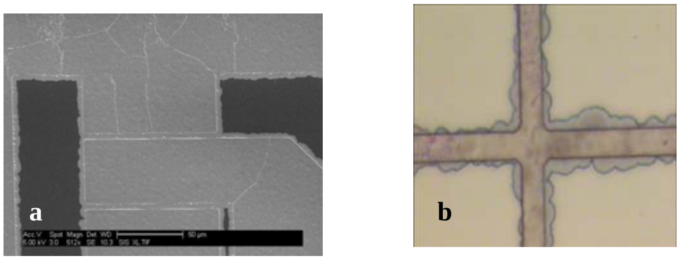


Figure 2 – R.I. 2.2 SiN encapsulation – (a) HEMT micrograph showing crack pattern (SEM); (b) EBAM surrounded by “clouds”.

Wet etching in HF solution and dry etching using ICP were used in order to remove the SiN_x cap layers.
The SiN_x with R.I. 1.79 has a higher etching rate than SiN_x with R.I. 2.2. The all SiN_x layers were easily removed by ICP dry etching.
The EBAM on a sample with SiN_x (R.I. 2) encapsulation was more easily detected by the e-beam machine as compared to a sample with the non-encapsulated EBAM.

The SiO_2 cap has no cracks but the contacts are surrounded by “clouds”, short-circuiting the source and drain (Figure 3).

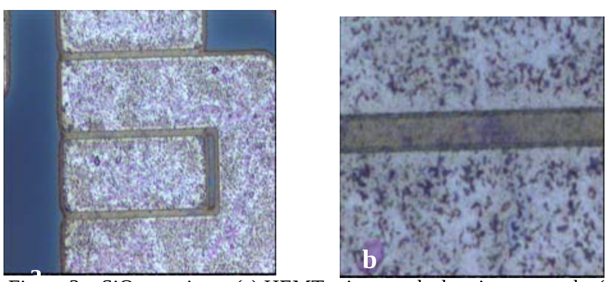


Figure 3 – SiO_2 capping – (a) HEMT micrograph showing no cracks (x200); (b) metal morphology and edge definition surrounded by “clouds” (x1000).

In summary, due to poor edge definition, SiO_2 and SiN_x with R.I. 2.2 are not good candidates as cap layers for Ohmic contacts. The different SiN_x cap layers have cracks in large area pads but the metal stack morphology improved relative to non-encapsulated Ohmic contacts. Good edge definition of the Ohmic metal stack encapsulated by SiN_x with R.I. 1.79 or 2 insures easier EBAM detection in comparison with the non-encapsulated sample.
The conclusions have been applied by using low temperature deposition of SiN_x with R.I. 2 only at the EBAM and the lift-off method before alloying, to gain easy detection and accurate alignment of the submicron gate.

SCHOTTKY GATE METAL STACKS

EXPERIMENTAL

Unintentionally doped $Al_{0.25}Ga_{0.75}N/GaN$ layers grown by MOCVD on sapphire substrates have been used. The wafer was sawed into rectangular samples. Ring patterns of Ti/Al/Ni/Au metal stacks followed by annealing at 900^{o}C for 30 s form Ohmic contacts to the samples. A circle pattern inside the Ohmic ring is defined as the area of the Schottky diode. The geometry of the inner Ohmic ring diameter is 35 um and the circle diode diameter is 20 um.
The first characterized diode metal stack is TaN(560 Å)/TiW(300 Å)/Au(1000 Å) and the second diode metal stack is Ni(500 Å)/ Au(4000 Å).
The Schottky diodes were subjected to different annealing treatments. The Schottky barrier height (V_b) and ideality factor (n) were determined from the diode I-V curve by plotting $\ln(J/A^{**}T^2)$ as a function of V, using $(\ln(J/A^{**}T^2)=-V_b/(KT)+V/(nKT))$ were J is the current flux through the diode, A** is the effective Richardson’s constant of GaN, T is the temperature in degrees Kelvin, K is the Boltzmann constant and V is the applied voltage.

RESULTS & DISCUSSION

TaN/TiW/Au metal stack

Three diodes were measured after the lift-off step; each diode was measured 7 times. Figure 4 shows ln $[J/A^{**}T^2]$ as a function of V. The slope changes from measurement to measurement on all diodes, which indicates an improvement of V_b from 0.57 V to 0.65 V as a function of the measurement number.

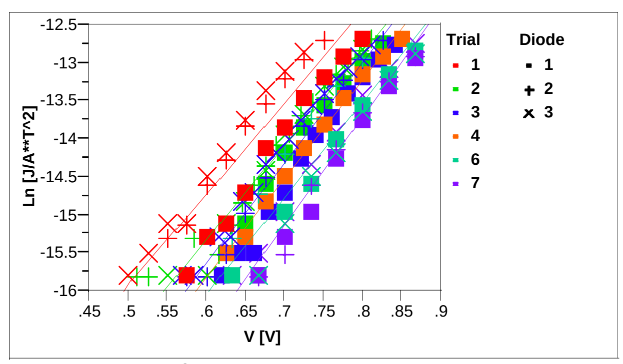


Figure 4 - ln $[J/A^{**}T^2]$ as a function of V immediately after diode lift-off.

We estimated that an annealing treatment would stabilize the Schottky contact. Figure 5 shows ln $[J/A^{**}T^2]$ as a function of V after annealing at 300^{o}C for 24 h in nitrogen environment. This time the slope for all the diodes did not change from measurement to measurement. The V_b stabilized at 0.66 V and n improved to 2.

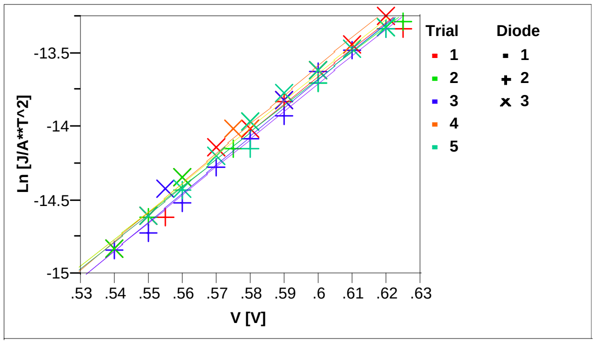
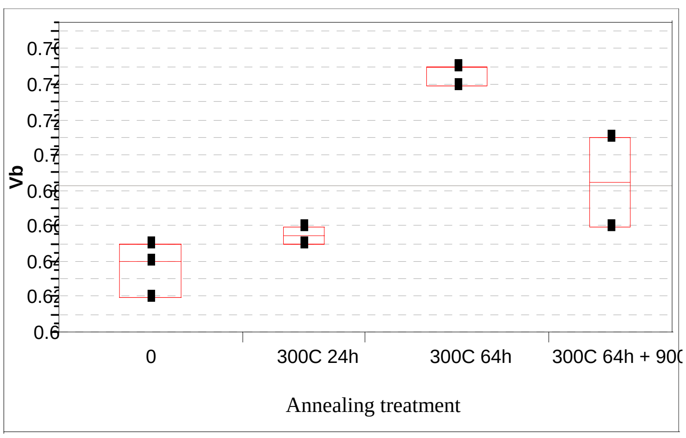


Figure 5 - ln [J/A**T^2] as a function of V after annealing at 300°C for 24 h.

After annealing at 300°C for 64 h in nitrogen environment the slope for all the diodes did not change from measurement to measurement. The results indicate that V_b ~ 0.75 V and n improved to 1.4.

After annealing at 300°C for 64 h followed by 900°C for 30 s in nitrogen environment V_b ~ 0.68 V and n is 1.5.

Figure 6 summarizes the V_b results for the different annealing treatments. The analysis shows that after annealing the ideality factor n improved and the best V_b is 0.75 V, which is achieved after 64 h at 300°C.



Annealing treatment	Median V_b [V]	Median n
0	0.64	2.8
300C for 24h	0.655	1.95
300C for 64h	0.75	1.4
300C for 64h + 900C for 30s	0.685	1.5

Figure 6 - summary of V_b for the different annealing treatments.

Figure 7 shows the diode leakage current after annealing at 300°C for 64 h and after annealing at 300°C for 64 h followed by 900°C for 30 s. The diode leakage current after annealing at 900°C for 30 s increased by more than twice.

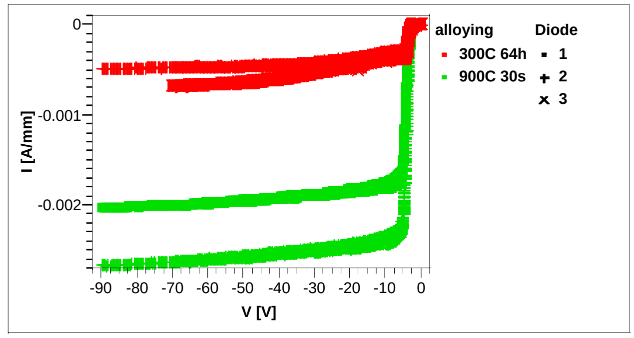


Figure 7 - diode leakage current as a function of the reverse bias after annealing by different treatments.

Ni/Au metal stack

Three diodes were measured after the lift-off step; each diode was measured 8 times. Figure 8 shows ln [J/A**T^2] as a function of V. Again, for all the diodes the slope moved from measurement to measurement from 0.87 V to 0.94 V as a function of the measurement number.

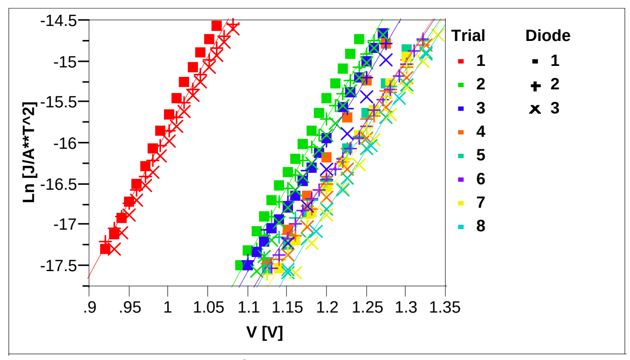


Figure 8 - ln [J/A**T^2] as a function of V after diode lift-off.

Figure 9 shows ln [J/A**T^2] as a function of V after annealing at 300°C for 24 h in nitrogen. The slope for all the diodes stabilized at V_b =1.2 V and n is 1.4.

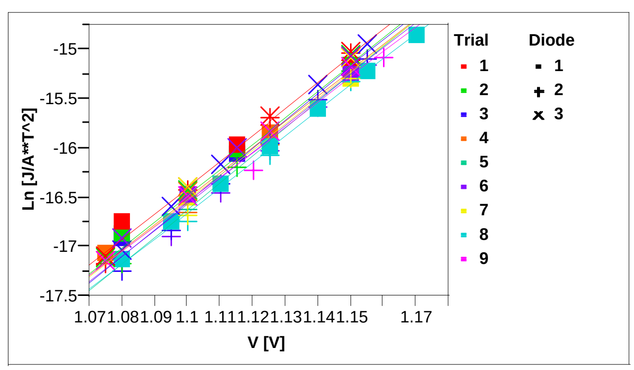


Figure 9 - ln [J/A**T^2] as a function of V after annealing at 300°C for 24h.

After annealing at 300ºC for 72 h in nitrogen V_b ~ 1.15 V and n is 1.6, and stay fixed after additional 48 h at 300ºC.
After annealing at 300ºC for 72 h followed by 900°C for 30 s in nitrogen V_b drops to ~ 0.48 V. Visual inspection by

optical microscopy reveals major changes in the diode metal stack morphology.
In summary, V_b improved by ~0.3 V by annealing at 300°C and did not change after additional 48 h at 300°C but collapsed to 0.5 V after the 900°C treatment. The Ni gate cannot withstand such high temperatures (900°C) as TaN.

Figure 10 shows the leakage current as a function of reverse bias on the diodes, as deposited and after different annealing steps; the lowest leakage current is without any ageing treatment. After thermal aging at 300°C for 24 h, the leakage current is higher. Additional 48 h at 300°C do not affect the leakage current relative to the treatment at 300°C for 24 h, but after 900°C for 30 s the leakage current becomes extremely high relative to the as-deposited case.
Figure 11 is a summary of the leakage current at 50 V reverse bias as function of the thermal treatments. This plot is across section from Fig. 10 at 50 V bias. After 300°C the leakage current is higher by a factor of two compared to the as deposited case, while after 900°C treatment the leakage current is higher by two orders of magnitude than the leakage current after 300°C for 72 h.

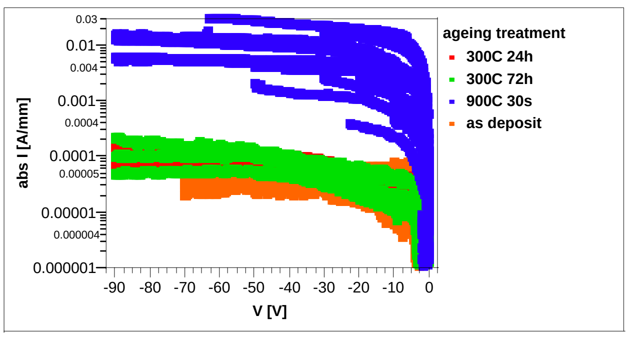


Figure 11. Leakage current as a function of reverse bias after annealing by different treatments.

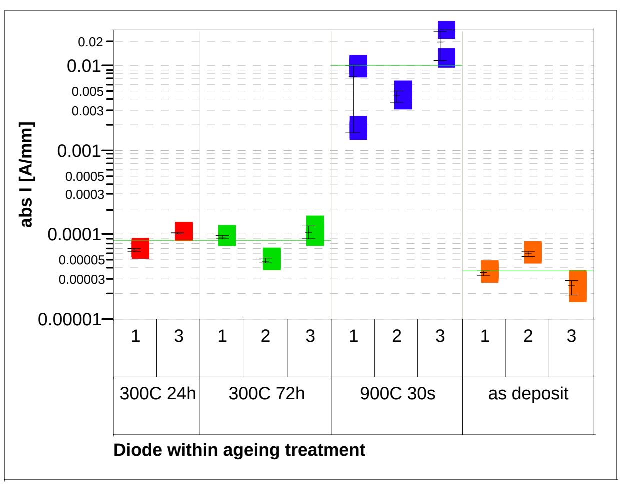


Figure 12. Leakage current at reverse 50V bias after annealing by different treatments.

In summary, TaN and Ni can be used as gate materials for GaN HEMT. Annealing is recommended in the process flow after the gate module (stabilization step). This step improves and stabilizes V_b and n; the best achieved V_b is 0.75 V and 1.2 V for TaN and Ni, respectively.
Ni is durable at 300°C and no significant change was noticed after 72 h of aging. After 900°C for 30 s, a critical change was noticed in the electrical performance and the diode morphology stack. TaN is durable at 300°C. Even after 900°C for 30 s, no critical change was noticed in the electrical performance and the diode morphology stack. This information enables a change in the process flow by fabricating the gate module before the Ohmic contacts alloying. This may provide better identification of the EBAM, which allows accurate alignment of the gate between the source and drain of the transistor.
Ni is a better candidate than TaN for GaN HEMT as a gate material, due to higher V_b and good stabilization at 300°C.

CONCLUSIONS

The composition of the SiN_x encapsulation layer is a dominant factor, affecting metal morphology, edge definition and EBAM detection. By using low temperature deposition of SiN_x with R.I. 2 only at the EBAM before alloying, easy detection of the EBAM and accurate alignment of the submicron gate have been obtained.

TaN may be used as a Schottky gate metal for very high temperature applications, but Ni has superior barrier height and it is stable at 300°C. Therefore Ni is a better candidate than TaN for GaN HEMTs as a gate material. Both for TaN and Ni, annealing is recommended in order to achieve higher V_b.

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ACRONYMS

SiN: silicon nitride
TaN: tantalum nitride
EBAM: e-beam alignment mark
n: Schottky contact ideality factor.
Vb: Schottky contact barrier height
R.I.: Refractive Index
RMS: Root Mean Square