Optica Applicata, Vol. XXXIX, No. 4, 2009

Effect of annealing temperature on the morphology of ohmic contact Ti/Al/Ni/Au to *n*-AlGaN/GaN heterostructures

WOJCIECH MACHERZYŃSKI*, ANDRZEJ STAFINIAK, ADAM SZYSZKA, JACEK GRYGLEWICZ, BOGDAN PASZKIEWICZ, REGINA PASZKIEWICZ, MAREK TŁACZAŁA

Faculty of Microsystem Electronics and Photonics, Wrocław University of Technology, ul. Janiszewskiego 11/17, 50-372 Wrocław, Poland

*Corresponding author: wojciech.macherzynski@pwr.wroc.pl

Ohmic contacts to AlGaN/GaN heterostructures which have low contact resistance and good surface morphology are required for the development of high temperature, high power and high frequency electronic devices. One of the keys to the advancement of such devices is the understanding of ohmic contacts formation to epitaxial aluminium gallium nitride layers. The paper presents the investigation of Ti/Al/Ni/Au based ohmic contact to *n*-AlGaN/GaN heterostructures grown by LP-MOVPE technique. Multilayer metallization of Ti/Al/Ni/Au with thicknesses of 10/100/40/150 nm, respectively, was evaporated by an electron gun (Ti, Ni) and resistance heater (Al, Au). The contacts were annealed at RTA (rapid thermal annealing) system in nitrogen ambient atmosphere over the temperature range from 775 °C to 850 °C. The time of annealing process was 60 seconds. The morphology of Ti/Al/Ni/Au ohmic contacts to *n*-AlGaN/GaN heterostructures was studied as a function of the annealing process conditions by an optical microscope and AFM (atomic force microscope). Simultaneously, the electrical parameters of Ti/Al/Ni/Au ohmic contacts were studied as a function of the annealing process conditions by the current–voltage ($I-V$) method on dedicated test structures. The characteristic resistances of the Ti/Al/Ni/Au/*n*-AlGaN/GaN ohmic contacts were evaluated from the circular transmission line method (CTLM). The formation and deterioration mechanisms of the ohmic contacts to *n*-AlGaN/GaN hesterostructures were studied. One of the mechanisms of agglomerates enlargement during the thermal annealing of Ti/Al/Ni/Au metallization has been proposed.

Keywords: ohmic contacts, heterostructure, AlGaN/GaN heterostructure, Ti/Al/Ni/Au.

1. Introduction

The wide-bandgap GaN and related materials are thermally stable and have been extensively studied for sensors and high-temperature/high power/high frequency electronic devices applications. GaN and its alloys are also very promising semiconductor materials for ultraviolet lasers and photodetectors, light emitting diodes and field effect transistors [1]. Many efforts have been dedicated to the development of fabrication processes of nitrides devices. Wide-bandgap semiconductors could withstand the harsh environment and high temperature. GaN devices could find many applications, such as: military, aerospace, automotive, petroleum, engine monitoring, flame detection and solar UV detection [2, 3]. In developing devices for such applications, low-resistance ohmic contacts with good surface morphologies are essential. Ti/Al based metallization is commonly used for ohmic contacts to *n*-GaN and related compouds. One of disadvantages of these ohmic contacts is that they often have rough surface morphologies after their annealing. Neverthless, not much work has been performed to improve the surface morphology of the Ti/Al based ohmic contacts.

In the present study, we investigated the effect of the temperature of thermal annealing on the contact resistivity and surface morphology.

2. Experimental details

Ohmic contacts of Ti/Al/Ni/Au were fabricated to un-doped $Al_{0.25}Ga_{0.75}N$/GaN heterostructures grown on sapphire substrates (in the configuration as shown in Fig. 1). The heterostructure was grown by the low-pressure metalorganic vapour phase epitaxy (LP-MOVPE) technique.

The thicknesses of Ti/Al/Ni/Au multilayer metallization were 10/100/40/150 nm, respectively. Metals stack and layers thicknesses of the multilayer metallizations were selected on the basis of our previous study [4]. Prior to the ohmic contact deposition,

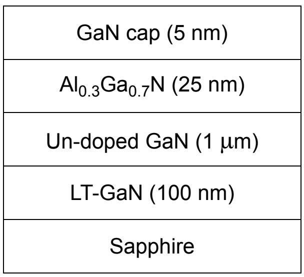

Fig. 1. AlGaN/GaN heterostructure used in this study.

the native oxide was removed by etching of samples in HCl:H_2O (1:1) solution for 30 seconds. Finally, samples were rinsed in DI water, dried with nitrogen and immediately transferred into the vacuum system for metal deposition. The metallic contact was deposited in sequence on the substrate under vacuum conditions with a base pressure lower than 10^{-6} mbar. Electron-beam evaporation was used to deposit titanium and nickel metal layers, while aluminium and gold layers were deposited by the conventional resistance evaporation. A lift-off technique was used to form circular shaped metallic systems in order to use the circular transfer length method (CTLM) [5]. The inner contact had a radius of 50 μm. On-wafer current-voltage four probes measurements were performed for CTLMs to eliminate the effects of resistance between the probe and metal contacts. The current-voltage curves were investigated to ensure that fabricated contacts had an ohmic character. The circularly patterned contact systems were formed using rapid thermal annealing (RTA) in nitrogen with the flow rate of 4000 sccm/min. The temperature of the annealing was altered in the range from 775 to 850 °C. The duration of annealing step was 60 seconds. A Ti/Au layers with thicknesses of 5/150 nm, respectively, were deposited on top of the ohmic contacts. That approach was applied in order to reduce the contact metal sheet resistance and to permit an accurate determination of the appropriate contact resistivity. The influence of annealing process of the contact on the properties of investigated metallization stacks was evaluated. The contact resistivity measurements and morphology images at different annealing temperatures were performed for all contacts to find the optimal conditions of formation (minimal resistivity and good morphology). Morphology images were performed with a Veeco Multimode atomic force microscope and optical microscope.

3. Results and discussion

Electrical characteristics of the fabricated ohmic contact systems were performed using the above mentioned CTLM method. Figure 2 shows the variation of contact resistivities of Ti/Al/Ni/Au contacts as a function of annealing temperature. Temperature of annealing was initially maintained at 775 °C. This value was selected based on our previous investigation, which revealed that annealing temperature lower than 775 °C caused non-linearity of *I-V* characteristics.

Contact resistivities strongly increased with increasing annealing temperature from 775 to 805 °C, from 4.5×10^{-5} to 1.3×10^{-3} Ωcm^2, respectively. A further increase in annealing temperature resulted in obtaining the resistivity of the order of 10^{-3} Ωcm^2. Figure 2 shows that the minimum resistivities of the Ti/Al/Ni/Au contact were obtained for thermal annealing at 775 °C.

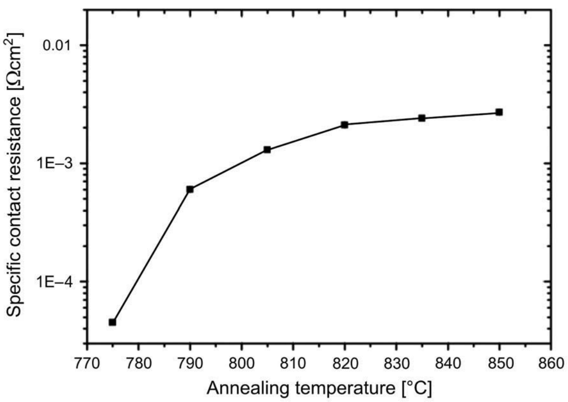

Fig. 2. Contact resistivity as a function of annealing temperature for Ti/Al/Ni/Au contacts for *n*-type AlGaN/GaN hesterostructure.

The metal sheet resistance of the Ti(10 nm)/Al(100 nm)/Ni(40 nm)/Au(150 nm) contacts increased significantly from 0.03 Ω/square for non-annealed contacts to 2.1 Ω/square for contacts anneal at 850 °C (Fig. 3).

To eliminate this effect, for measurement purposes, Ti/Au multilayers with thicknesses of 5/150 nm, respectively, were patterned and deposited on the Ti/Al/Ni/Au contacts what caused the metal sheet resistance decreased down to 0.03 Ω/square.

To help in understanding of the significant difference in the surface morphology for Ti/Al/Ni/Au contacts after annealing, AFM and optical images were performed.

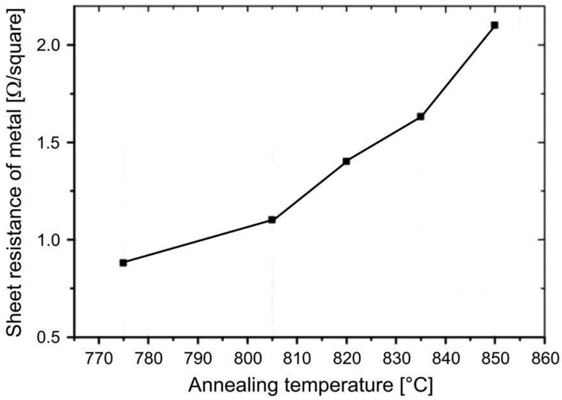

Fig. 3. Metal sheet resistance of Ti(10 nm)/Al(100 nm)/Ni(40 nm)/Au(150 nm) contacts as a function of annealing temperature (60 s of RTA in flowing nitrogen).

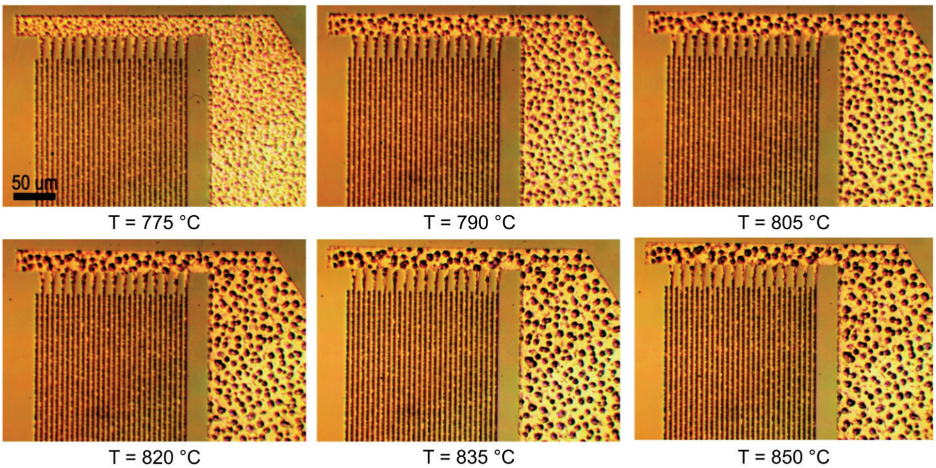

Fig. 4. Optical images of surface morphology of the ohmic contact systems Ti/Al/Ni/Au after sequence thermal annealing at various temperatures for 60 s. The remarkable variation in agglomerates density can be seen.

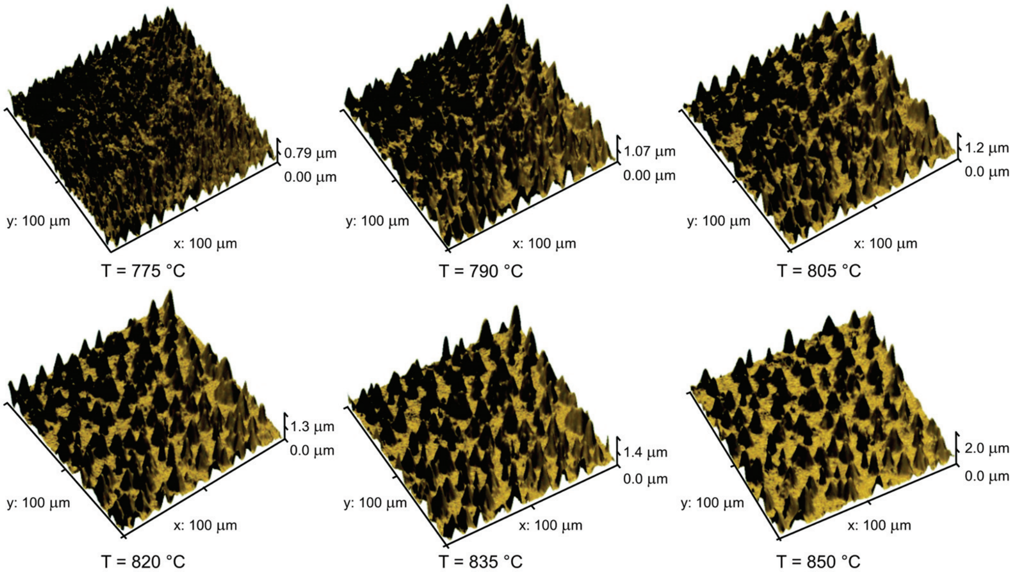

Fig. 5. AFM images of surface morphology of the ohmic contact after sequence thermal annealing at various temperatures for 60 s. The height of agglomerates increased from 0.79 μm for 775 °C to 2 μm for 850 °C. Also the variation in agglomerates density was observed.

Figures 4 and 5 show the optical and AFM images for deposited ohmic contact annealed at the temperature range from 775 to 850 °C, respectively.

The first temperature of annealing was 775 °C. The thermal annealing strongly affected the surface morphology. A further increase in annealing temperature resulted in the decrease in the density of agglomerates. AFM images of surface morphology (Fig. 5) of the ohmic contacts after annealing in various temperatures showed the increase in the height of agglomerates. To show the modification of surface morphology during the thermal annealing at various temperatures, the same sample and the same part of ohmic contact were observed (Fig. 6). The thermal annealings in this case were performed in sequence.

Optical images of the surface of the ohmic contact annealed at various temperatures (Fig. 6) showed the mechanism of the decrease in agglomerates density with increasing the temperature of thermal annealing. The reason of the increase was migration followed by coalescence of agglomerates, what is marked by the line on the optical images of the ohmic contact annealed at various temperatures. First, grains agglomeration appeared during thermal annealing at 775 °C (Fig. 6). Next, with increasing the annealing temperature, the agglomerates migrated on the surface and coalescence into larger agglomerates (Fig. 6). This is the reason why after sequential annealing in the range from 775 to 850 °C the height of agglomerates increased

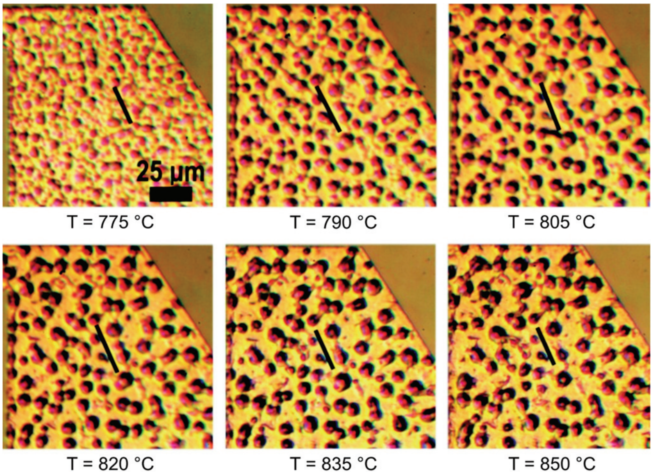

Fig. 6. Optical images of surface morphology of the ohmic contact Ti/Al/Ni/Au after sequence thermal annealing at various temperatures for 60 s. To show the modification in surface morphology, the same sample and the same part of ohmic contact were observed.

from 0.79 to 2 μm (Fig. 5). The 775 °C thermal annealing temperature was optimal in the case of both surfaces morphology as well as contact resistivity. The specific contact resistance was equal to 4.5×10^{-5} Ωcm^2.

4. Conclusions

In conclusion, we studied Ti/Al/Ni/Au ohmic contacts formation to *n*-AlGaN/GaN heterostructure. We have demonstrated an influence of thermal annealing at various temperatures on surface morphology and characteristic resistance of ohmic contacts of Ti/Al/Ni/Au with the thicknesses 10/100/40/150 nm, respectively. The results showed one of the mechanisms of agglomerates heights increase during thermal annealing at various temperatures. We have explained the enlargement of agglomerates with increasing the temperature of thermal annealing process.

We have shown that 775 °C thermal annealing temperature was optimal in the case of surface morphology as well as contact resistivity evaluated for Ti/Al/Ni/Au ohmic contact. The lowest contact resistance of 4.5×10^{-5} Ωcm^2 was obtained.

The annealing temperature of ohmic contact was very important because the surface morphology and resistivity strongly depend on temperature. However, further detailed structural studies are necessary for better understanding of these ohmic contacts formation.

Acknowledgements – This work has been supported in a part by the Ministry of Science and Higher Education under the grants no. R0201802, PBZ-MEiN-6/2/2006, NN 515360436, NN 515053535, by the European Union within European Reg. Develop. Fund Grant Innovative Economy (POIG.01.01.02-00-008/08), by the Ministry of Regional Development PO KL 2007-2013, European Union European Social Fund and by Wrocław University of Technology statutory grant.

References

[1] NAKAMURA S., MUKAI T., SENOH M., *Candela-class high-brightness InGaN/AlGaN double--heterostructure blue-light-emitting diodes*, Applied Physics Letters **64**(13), 1994, pp. 1687–1689.

[2] FERGUSON I., TRAN C.A., KARLICEK R.F., FENG Z.C., STALL R., LIANG S., LU Y., JOSEPH C., *GaN and AlGaN metal–semiconductor–metal photodetectors*, Materials Science and Engineering B **50**(1–3), 1997, pp. 311–314.

[3] WALKER D., ZHANG X., KUNG P., SAXLER A., JAVADPOUR S., XU J., RAZEGHI M., *AlGaN ultraviolet photoconductors grown on sapphire*, Applied Physics Letters **68**(15), 1996, pp. 2100–2101.

[4] MACHERZYŃSKI W., *Fabrication of ohmic contacts to n-type GaN*, Proceedings of the 8th International Electronics and Telecommunication Conference of Students and Young Scientists, November 7–8, 2007, Warsaw, Poland, pp. 20–21.

[5] REEVES G.K., *Specific contact resistance using a circular transmission line model*, Solid-State Electronics **23**(5), 1980, pp. 487–490.

Received June 23, 2009