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Chemical analysis of Ti/Al/Ni/Au ohmic contacts to AlGaN/GaN heterostructures

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Ohmic contacts to AlGaN/GaN heterostructures, which have low contact resistance and a good surface morphology, are required for the development of high temperature, high power and high frequency electronic devices. The paper presents the investigation of a Ti/Al based Ti/Al/Ni/Au ohmic contact to AlGaN/GaN heterostructures. Multilayer metallization of Ti/Al/Ni/Au was evaporated by an electron gun (titanium and nickel layers) and a resistance heater (aluminum and gold layers). The contacts were annealed by rapid thermal annealing (RTA) system in a nitrogen ambient atmosphere over the temperature range from 715 to 865 °C. The time of the annealing process was 60 seconds. The chemical analysis, formation and deterioration mechanisms of Ti/Al/Ni/Au ohmic contacts to AlGaN/GaN heterostructures were studied as a function of the annealing process conditions by a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS).

Keywords: ohmic contact, AlGaN/GaN heterostructures, surface morphology.

1. Introduction

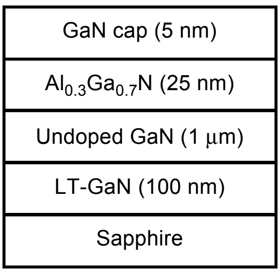
AlGaN/GaN heterostructure sensors and field-effect transistors have been an area of intense interest for high temperature, high power and high frequency electronic devices applications [1, 2]. Many efforts have been dedicated to the development of fabrication processes of nitrides devices. Wide bandgap semiconductors are able to withstand a harsh environment and high temperature, thus AlGaN/GaN devices can find many applications in such fields as the military, aerospace, automotive and petroleum industry, engine monitoring, as well as flame and solar UV detection [3, 4]. Low resistance ohmic contacts to AlGaN/GaN are of great importance, because improvement of their electrical properties would lead to the enhancement of device performance. Fabrication of low resistance ohmic contacts is difficult because of the relatively high work functions of large amounts of various metals in comparison with the electron affinity of $Al_xGa_{1-x}N$ materials [5]. Aside from the low resistance requirement, ohmic contacts to AlGaN/GaN heterostructures have to fulfill additional demands – like thermal and chemical stability – when they are dedicated to operate in extremely harsh conditions. What is more, the chemical composition of the ohmic contact surface should be known and defined very well because of the possible further technological stage – electrical connection in microelectronic package made by wire in ultrasonic or thermosonic bonding processes. This means that the surface of the ohmic contact should often be ready to make an electrical connection by wire in the bonding process. Aluminum (Al) and gold (Au) wires are most frequently and commonly used in the bonding process. The knowledge about the chemical composition of an ohmic contact will be very useful to predict the metallurgical behavior of bond interface between the wire and the surface of the ohmic contact.

The Ti/Al based Ti/Al/Ni/Au ohmic contact is one of the most prevalent metallization schemes of ohmic contact in AlGaN/GaN heterostructures. A titanium (Ti) layer is essential as, at elevated temperatures, the Ti participates in the reaction with nitrides at the interface and forms TiN [6–8]. This reaction extracts N from GaN and generates N-vacancies in the GaN layer. N-vacancies act as *n*-type dopants and create a highly doped layer underneath metallization, leading to low ohmic Ti/Al/Ni/Au contact resistance. The aluminum (Al) layer is the layer which is responsible for the formation of the ohmic contact to AlGaN/GaN heterostructures. A gold (Au) layer is commonly adopted as the outer layer to minimize oxidation of Ti/Al metals during the rapid thermal annealing (RTA) process. This metal layer should also ensure a good electrical connection for test probe measurements (*e.g.*, four-point probe or *I–V* measurement) and often should enable the bonding process. In addition, a nickel (Ni) layer is employed to minimize the diffusion of the upper Au layer downward.

2. Experimental details

The GaN(cap)/AlGaN/GaN heterostructure applied in this study consisted of GaN(cap 50 Å)/$Al_{0.3}Ga_{0.7}N$(250 Å)/*i*-GaN(1 μm) grown by metalorganic vapour phase epitaxy (MOVPE) on a sapphire substrate (Fig. 1).

Prior to metal deposition, native oxide (Ga_2O_3) was removed from all samples surfaces by etching in HCl:H_2O (1:1) solution, which was followed by a deionized water rinsing and drying in N_2 flow. Then samples were immediately loaded into the vacuum chamber of an evaporation system. The metal stuck and the layers thicknesses of the Ti/Al/Ni/Au multilayer of the ohmic contact were selected on the basis



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

of the authors' previous study. The metallic contact consisting of Ti/Al/Ni/Au (20/100/40/150 nm) metal layers was deposited on the substrate under vacuum conditions with a base pressure lower than 10^{-6} mbar. In contrast to the Al and Au metallic layers, which were deposited by a resistance evaporator, the Ti and Ni layers were deposited by using an electron beam evaporator. The influence of the annealing process on the contact properties was studied by *I–V* characterization. The Ti/Al/Ni/Au multilayer ohmic metallizations were annealed at various temperatures by RTA system. The temperature of each annealing process was changed over the range from 715 to 865 °C and the annealing time of 60 seconds was kept for all samples.

To help in understanding the significant difference in the surface morphology for ohmic contacts after annealing, scanning electron microscopy (SEM) images and atomic force microscopy (AFM) images were included. The chemical analysis of Ti/Al/Ni/Au ohmic contacts to AlGaN/GaN heterostructures was examined with the use of a scanning electron microscope equipped with an energy dispersive spectrometer.

3. Results and discussion

Figure 2 shows SEM images of the surface of an alloyed Ti/Al/Ni/Au ohmic contact at various temperatures from 715 up to 865 °C.

In our case, the temperature of the thermal annealing process which linearized and decreased the resistance of the ohmic contact to an acceptable level was 805 °C. We observed the chemical composition and surface topography of ohmic contacts for lower temperatures from 715 up to 865 °C. In our previous work [9], we explained the mechanism of agglomerates enlargement during the sequential thermal annealing treatment of Ti/Al/Ni/Au metallization. The reason for the agglomerates' enlargement

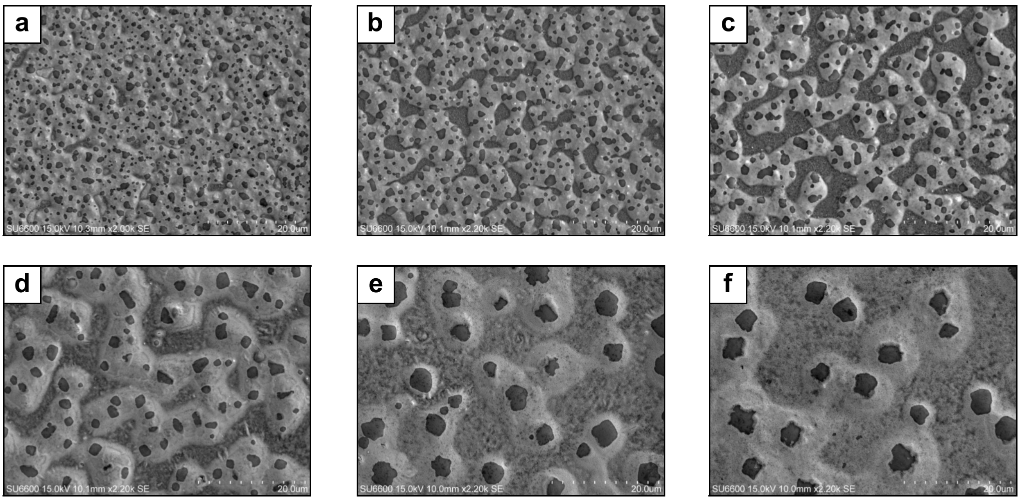


Fig. 2. SEM images of the surface of an alloyed Ti/Al/Ni/Au ohmic contact after thermal annealing at the temperature of 715 °C (**a**), 745 °C (**b**), 775 °C (**c**), 805 °C (**d**), 835 °C (**e**), 865 °C (**f**).

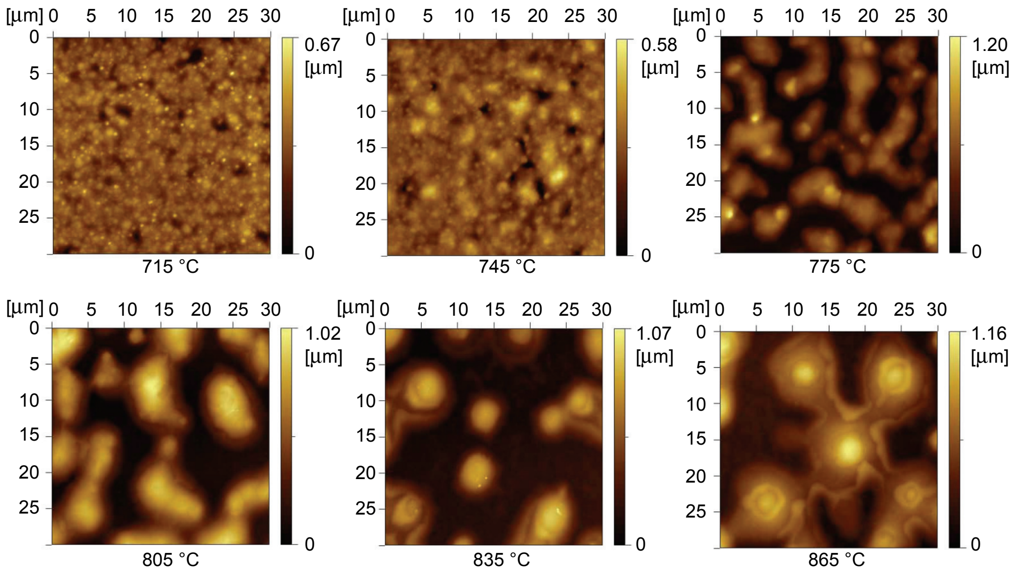


Fig. 3. AFM images of surface morphology of the ohmic contact after thermal annealing at various temperatures for 60 s. A variation of agglomerates density was also observed.

was their migration and subsequent coalescence. We assumed that when the temperature of thermal annealing is higher, this process is faster and as a result we observed the significant changes in surface morphology showed in Figs. 2 and 3.

The total thickness of the deposited ohmic Ti/Al/Ni/Au multilayer was 310 nm but the height of the agglomerates is above 1 μm for the ohmic contact annealed above 775 °C (Fig. 3). This means that the thermal annealing process significantly changes the morphology of the ohmic contact and influences not only the surface topography but also the chemical composition of the surface of ohmic Ti/Al/Ni/Au contacts.

Figure 4**a** shows SEM images of a 58 μm×43 μm area of the surface of the alloyed Ti/Al/Ni/Au ohmic contact annealed at 835 °C. Figures 4**b**–4**e** show the corresponding EDX chemical analysis. In the SEM image (Fig. 4**a**) we observed three characteristic regions: A, B and C (marked in Fig. 4**a**). The A region area is a few square micrometers. According to the EDX analysis, the A region consists of a large amount of Al (Fig. 4**c**) and Ni (Fig. 4**d**). We assumed that the A region represents the chemical composition of the agglomerate's body. The A region mainly consists of Ni–Al alloy. The B region consists mainly of Au (Fig. 4**e**) and Al (Fig. 4**c**). The C region represents the part of the ohmic Ti/Al/Ni/Au contact without agglomerates. There is a much smaller amount of Al and Ni in the C region than in the A region.

We believed that the reason we did not observe Au in the A region was that, in the time of thermal annealing, the Al became liquid (660 °C) and started to make droplets. We further assumed that this process caused cracking and next the displacement of the top Au layer. The Ti signal (Fig. 4**b**) was difficult to interpret because the Ti is the lowest layer in Ti/Al/Ni/Au multilayer stack. We observed that the A region

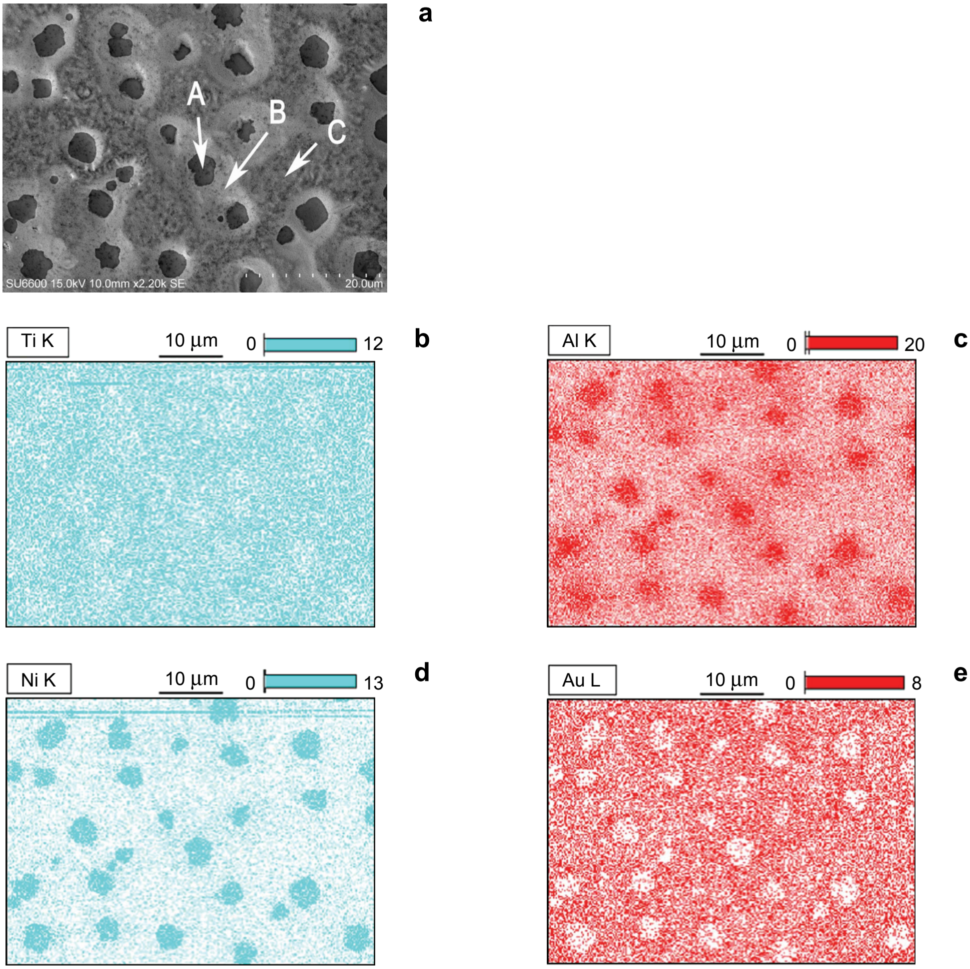


Fig. 4. SEM image of the surface of ohmic contact after thermal annealing at 835 °C (**a**) and corresponding EDX analysis (**b**–**e**).

consists of a smaller number of Ti measurement signal counts but this is probably caused by different thicknesses of the material covering the Ti layer in the A, B, and C regions. We deduced that the migration of the Ti layer does not play a significant role in the chemical composition of the surface of Ti/Al/Ni/Au ohmic contacts.

4. Conclusions

The chemical analysis of the agglomerates in Ti/Al/Ni/Au ohmic contacts to AlGaN/GaN heterostructures was studied with the use of a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). According to the analysis of EDS and SEM images, the agglomerates were found to consist mainly of Ni–Al alloy in the body and Au–Al alloy surrounding. Between agglomerates in the C region, we observed Au, Ni and Al. There is a much smaller amount of Al and Ni than in the A region. Based on SEM images and corresponding EDX analyses, we conclude that the primary mechanism responsible for the poor morphology and the heterogeneous chemical composition of the ohmic contact is the formation of Al droplets above 660 °C (melting point of Al). During the formation of droplets the top Au layer cracked and was displaced revealing the lower Ni layer and a Ni–Al alloy – the product of a reaction between the Al droplets and the Ni layer. This mechanism, together with the chemical reaction, caused significant changes in the chemical composition of the surface of ohmic Ti/Al/Ni/Au contacts to AlGaN/GaN heterostructures.

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References

[1] AMANO H., KITO M., HIRAMATSU K., AKASAKI I., *P-type conduction in Mg-doped GaN treated with low-energy electron beam irradiation (LEEBI)*, Japanese Journal of Applied Physics, Part 2: Letters **28**(12), 1989, pp. L2112–L2114.

[2] 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.

[3] 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.

[4] 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.

[5] SCHMITZ A.C., PING A.T., ASIF KHAN M., CHEN Q., YANG J.W., ADESIDA I., *Metal contacts to* n-*type GaN*, Journal of Electronic Materials **27**(4), 1998, pp. 255–260.

[6] RUVIMOV S., LILIENTAL-WEBER Z., WASHBURN J., DUXSTAD K.J., HALLER E.E., FAN Z.F., MOHAMMAD S.N., KIM W., BOTCHKAREV A.E., MORKOÇ H., *Microstructure of Ti/Al and Ti/Al/Ni/Au ohmic contacts for* n-*GaN*, Applied Physics Letters **69**(11), 1996, pp. 1556–1558.

[7] LIANG WANG, MOHAMMED F.M., ADESIDA I., *Dislocation-induced nonuniform interfacial reactions of Ti/Al/Mo/Au ohmic contacts on AlGaN/GaN heterostructure*, Applied Physics Letters **87**(14), 2005, article 141915.

[8] LIANG WANG, MOHAMMED F.M., ADESIDA I., *Formation mechanism of ohmic contacts on AlGaN/GaN heterostructure: Electrical and microstructural characterizations*, Journal of Applied Physics **103**(9), 2008, article 093516.

[9] MACHERZYNSKI W., STAFINIAK A., SZYSZKA A., GRYGLEWICZ J., PASZKIEWICZ B., PASZKIEWICZ R., TŁACZAŁA M., *Effect of annealing temperature on the morphology of ohmic contact Ti/Al/Ni/Au to* n-*AlGaN/GaN heterostructures*, Optica Applicata **39**(4), 2009, pp. 673–679.

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