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COMMUNICATIONS

OHMIC CONTACTS TO p–GaN USING Au/Ni–Mg–O METALLIZATION

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Electrical characteristics and elemental depth profiles of ohmic contacts to p-GaN using Au/Ni-Mg-O_x metallization have been investigated. The objective was to examine the possibilities of increasing the charge carrier concentration in the surface region of GaN by adding Mg, thus of a p-type dopant into the Au/NiO_x metallization structure. For this purpose, a Ni-Mg-O_x layer with a low concentration of Mg was deposited on p-GaN by dc reactive magnetron sputtering. The top Au layer was deposited in a similar way. The fabricated contact structures were annealed in N_2. When the Ni-Mg layer in the Au/Ni-Mg-O_x/p-GaN structure was deposited in an atmosphere with a low concentration of oxygen (0.2 at%), the structure exhibited a low resistance ohmic nature. The contact resistance was lower than in the case of a Au/Ni-O_x/p-GaN structure without the Mg dopant in the metallic layer. An increase in the concentration of oxygen in the working atmosphere resulted in higher values of the contact resistance of the Au/Ni-Mg-O_x/p-GaN structure. In our opinion the ohmic nature of the contact structure is related to the existence of a metal/p-NiO/p-GaN scheme. The measured values of the contact resistance in the Au/Ni-Mg-O_x/p-GaN structure in comparison with the Au/Ni-O_x/p-GaN structure are caused by an increased charge carrier concentration in the surface region of p-GaN, which is a consequence of Mg diffusion from the Ni-Mg-O_x layer.

K e y w o r d s: p-GaN, Au/Ni-Mg-O/p-GaN contact structure, AES depth profiling, low resistance ohmic contact

1 INTRODUCTION

The exploitation of novel materials for applications beyond the current electronics is closely connected with mastering the properties of the systems. To do that, it is necessary to assess the relation between the electrical and structural properties. Therefore, a possibly exhaustive characterization is required.

Gallium nitride has lately attracted significant attention for various electronic and optoelectronic applications like light emitting diodes, laser diodes, high power and high frequency devices. One of the factors limiting the reliability and performance of these devices is the possibility to create a low-resistance ohmic contact to GaN. Ohmic contacts with a low contact resistance on n-GaN can be manufactured relatively easily. However, contacts with p-GaN still present a big problem, mainly because of difficult achieving of high charge carrier concentrations (higher than $10^{18}\mathrm{cm}^{-3}$ [1]). For improving the ohmic properties of the p-GaN contact, a number of metallization layouts and diverse surface treatments have been used. However, the best contact structure to p-GaN seems to be the Au/Ni structure, namely because of the relatively good values of contact resistivities 10^{-4} to $10^{-6}\Omega\mathrm{cm}^2$ and its optical transparency. It was found that oxidation of such a thin Ni/Au bilayer in air or in water vapour brings about a change of Ni into NiO, diffusion of Au into the interface and at the same time an improvement in the transparency of the metallization layer [2–11].

Similar values of contact resistivity, but a better light transparency than that of the Ni-Au bilayer, were reported for Ni-Mg/Au ($10^{-6}\Omega\mathrm{cm}^2$) [12] and Ni-Zn/Au ($10^{-5}\Omega\mathrm{cm}^2$) [13] bilayers. The objective of adding p-dopants Mg and Zn into Ni was to increase the concentration of holes in GaN and to improve the optical transparency.

Lately [14] it has been found by studying the influence of the NiO_x layer on the electrical characteristics of the Au/NiO_x/p-GaN ohmic contacts that the Au/NiO_x/p-GaN structure with a low content of oxygen in NiO_x, deposited on p-GaN by reactive magnetron sputtering and annealed in the mixture of O_2+N_2 or N_2 ambient, provided a low resistance ohmic contact. Slightly higher contact resistances in samples annealed in O_2+N_2 can be explained by a smaller effective area of the contact at the layer/p-GaN interface due to created voids. While annealing in O_2+N_2 ambient leads to a transformation

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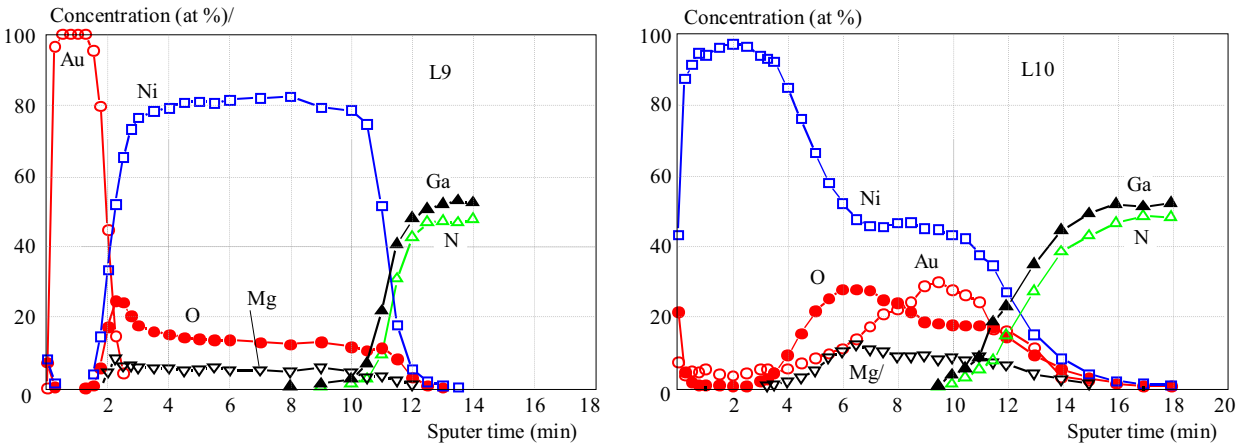

Fig. 1. AES depth profiles of Au/Ni-Mg-O_x/p-GaN contact structures (sample L10) in which Ni-Mg-O_x was deposited at the highest content of oxygen in the working atmosphere (3 at%): (a) – as deposited, (b) – after annealing in N_2 at 500 °C for 2 minutes

of the deposited Au/NiO_x/p-GaN contact structure into Au/p-NiO/p-GaN, annealing in N_2 leads to reconstruction of the deposited structure into Au/p-NiO/p-GaN and Ni/p-NiO/p-GaN. Thus in both cases, annealing in N_2 as well as in $O_2 + N_2$ ambient, the ohmic properties of the contacts are predetermined by creating a thin NiO oxide layer on the metal/p-GaN interface. The arising contact structure metal/p-NiOx/p-GaN created after annealing the Au/NiO_x/p-GaN structure in either N_2 or O_2+N_2 is the main mechanism responsible for the ohmic nature of the system.

The topic of this work is to examine the possibilities of increasing the charge carrier concentration in the surface region of GaN by addition of Mg, thus of a p-type dopant into the metallization structure Au/NiO_x. For this purpose, a Ni-Mg-O_x layer with a low concentration of Mg was deposited on p-GaN by dc reactive magnetron sputtering. The top Au layer was deposited in a similar way. The contact resistance measured using the CTLM method was correlated with the depth distribution of elements in the contact structures measured by Auger electron spectroscopy.

2 EXPERIMENTAL

GaN films were grown in AIXTRON 200 RF-S horizontal flow MOCVD reactor on (0001) sapphire substrates using the procedure of substrate nitridation, deposition of a low-temperature GaN nucleation layer at 540 °C with subsequent annealing and, finally, growing a 1μm thick GaN buffer at 1050 °C. Doping was achieved using Cp_2Mg during the growth at 950 °C. After annealing in N_2 atmosphere at 780 °C for 15 minutes to activate Mg, p-GaN layers were obtained with typical carrier concentrations around $7 \times 10^{17}\mathrm{cm}^{-3}$ and mobility around $10\mathrm{cm}^2/\mathrm{Vs}$.

The p-GaN layers were first sequentially ultrasonically treated for 5 minutes in each step in acetone, isopropanol, DI water, and then they were dried with compressed N_2. Prior to lithography they were chemically etched to remove the surface native oxide. Circular transmission line method (CTLM) patterns to characterize the ohmic contacts were photolithographically defined for the measurement of the contact resistivity. Metal thin films were deposited by dc magnetron sputtering. The Ni92Mg8 (20 nm) thin film with a small content of oxygen was prepared by dc reactive magnetron sputtering in a mixture of oxygen and argon from a Ni target containing 8 at% of Mg. The distance between the target and the substrate was approximately 75 mm. A sputtering power of 600 W was used. Both argon inert flow and oxygen reactive flow were controlled by mass flow controllers. The total gas pressure was kept at 0.5 Pa.

After deposition, the samples were subsequently annealed in a rapid thermal annealing furnace at a temperature of 500 °C for 2 minutes. For each deposition sequence, one sample was left as deposited and one annealed in N_2. I-V measurements were performed on an HP 4155A semiconductor parameter analyzer by applying a voltage ramp from $-10,\mathrm{V}$ to $+10$ V and measuring the respective current. From the slope of the I-V curves, the total resistance was determined. The contact resistivity was determined using the model of Marlow and Das.

AES depth profiling was carried out in a Varian Auger electron spectrometer equipped with a cylindrical mirror analyzer (CMA) and EX 05 VG ion gun. A primary electron beam was used with energy 3 keV and angle of incidence 0° with respect to the surface normal. Sputtering was achieved by a scanned Ar^+ ion beam with energy 1 keV and angle of incidence 80° with respect to the surface normal. The energy resolution of the CMA was $\Delta E/E = 0.3\,\%$. Auger depth profiling employed the Auger peaks of Au (239 eV), Ni (848 eV), Mg (1186), Ga (1070 eV), N (385 eV), O (510 eV) and C (270 eV).

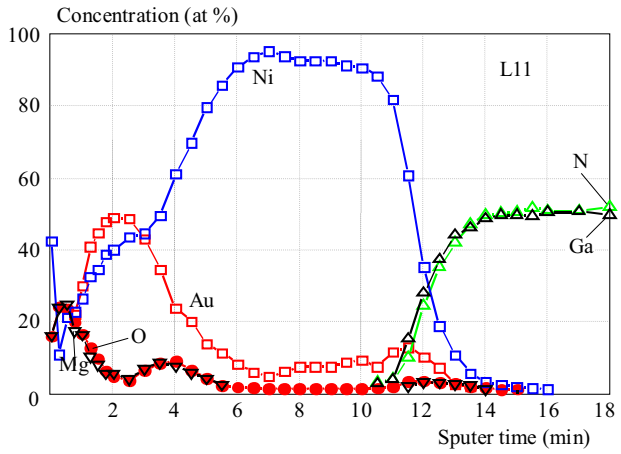

Fig. 2. AES depth profiles of Au/Ni-Mg-O_x/p-GaN contact structures (sample L11) in which Ni-Mg-O_x was deposited at 0.2 at% of oxygen in the working atmosphere after annealing in N_2 at 500 °C for 2 minutes

Table 1. Samples, their preparation and contact resistivities

Sample	Oxygen content in the atmosphere during deposition of Ni-Mg-O_x (at%)	Oxygen content in the atmosphere during deposition of Ni-O_x (at%)	Contact resistivity on annealing in N_2 (Ωcm^2)
L8	no oxygen		4.7×10^{-2}
L11	0.2		9.0×10^{-4}
L7		0.2	3.9×10^{-3}
L10	3.0		2.1×10^{-2}

3 RESULTS

The contact resistivities of the Au/Ni-Mg-O_x/p-GaN, Au/Ni-Mg/p-GaN and Au/Ni-O_x/p-GaN samples annealed in N_2 are summarized in Table 1. Whereas the Au/Ni-Mg/p-GaN contact structure, thus when the Ni-Mg layer was deposited without any oxygen in the ambient atmosphere, does not show good ohmic properties, the Au/Ni-Mg-O_x/p-GaN structure in which the Ni-Mg was deposited in the presence of a low concentration of oxygen in the ambient atmosphere (0.2 at%) had an ohmic nature. The value of the contact resistivity is lower than in the case of the Au/Ni-O_x/p-GaN contact. Increasing the oxygen concentration in the ambient atmosphere during depositing the Ni-Mg layer struct brought about a rise of the contact resistivity of the Au/Ni-Mg-O_x/p-GaN structure, similarly like in the case of Au/Ni-O_x/p-GaN contacts [14].

Figure 1(a) shows AES depth profiles of the as-deposited Au/Ni-Mg-O_x/p-GaN structure. The content of oxygen in the working atmosphere was 3 at%. The content of oxygen in the deposited Ni-Mg-O_x layer was around 15 at%. The depth profiles of Mg and O show a slight pile-up at the interface with the Au layer and decrease towards the interface with GaN. Annealing in N_2 resulted in out-diffusion of part of Ni, Mg and O through the Au layer (Figure 1(b)), and conversely, diffusion of Au up to the interface of the metallization layer with p-GaN. The depth distributions of Mg and O reveal that due to out- diffusion these elements were partially piled-up in the vicinity of the Au/Ni-Mg-O_x interface.

Figure 2 shows AES depth profiles of the Au/Ni-Mg-O_x/p-GaN structure in which Ni-Mg-O_x was deposited at a lower content of oxygen in the working atmosphere (0.2 at%). The content of oxygen in the deposited Ni-Mg-O_x layer was below 5 at%. Annealing in N_2 had a similar effect as in the contact structures with a higher content of oxygen, however in-diffusion of Au and out-diffusion of Ni were less intense and substantial amounts of these elements remained at their initial places. On the contrary, diffusion of Mg and O were stronger. The almost identical concentrations and gradients of Mg and O in the contact structure point at creation of MgO that precipitates mainly in the region of the initial interfaces and on the surface. Based on our previous work [14] we believe that oxygen interacts with Ni giving rise to NiO and, due to annealing, the initial Ni-Mg-O_x layer is transformed to a mixture of Ni, NiO and MgO crystals. The observed distribution of the components in the contact, being a consequence of annealing, can be explained by a polycrystalline structure of the contact layer composed of Au, Ni, MgO and NiO crystallites.

Our study of the Au/NiO_x/p-GaN contact [14] revealed that annealing in N_2 caused reconstruction of the contact into Au/p-NiO/p-GaN and Ni/p-NiO/p-GaN and ohmic properties of the contacts were predetermined by creating a thin NiO oxide layer on the metal/p-GaN interface. In our view the ohmic nature of the Au/Ni-Mg-O_x/p-GaN contact structure may be similarly like in the previous case related to the existence of a metal/p-NiO/p-GaN contact scheme. The lower measured contact resistivities in the Au/Ni-Mg-O_x/p-GaN structure as compared with Au/Ni-O_x/p-GaN (Tab. 1) are caused by an enhanced concentration of charge carriers in the surface region of p-GaN, which is a consequence of Mg diffusion from the Ni-Mg-O_x layer.

4 CONCLUSIONS

We have examined the possibility of increasing the charge carrier density in the surface region of GaN by adding Mg, thus a p-type dopant into the Au/NiO_x metallization structure. The layers of Au and Ni-Mg-O_x containing Mg as a p-dopant were deposited on p-GaN by dc reactive magnetron sputtering. The contact structures were annealed in N_2. When the Ni-Mg layer was deposited in the presence of a small concentration (0.2 at%) of oxygen in the ambient atmosphere, the contact structure had an ohmic nature. The contact resistivity was lower than in the case of the Au/Ni-O_x/p-GaN contact. Increasing the oxygen concentration in the ambient during deposition of the Ni-Mg layer resulted in a rise of the contact resistivity of the Au/Ni-Mg-O_x/p-GaN contact structure similarly like in the case of Au/Ni-O_x/p-GaN contacts. The Au/Ni-Mg/p-GaN structure, thus when the Ni-Mg layer was deposited without any oxygen

in the working atmosphere, does no exhibit good ohmic properties.

In our opinion the ohmic nature of the Au/Ni-Mg-O_x/p-GaN contact structure with a low concentration of oxygen is related to the existence of a metal/p-NiO/p-GaN contact scheme. The lower measured values of the contact resiststivity in the Au/Ni-Mg-O_x/p-GaN in comparison with the Au/Ni-O_x/p-GaN structure are caused by an increased charge carrier density in the surface region of p-GaN due to diffusion of Mg from the Ni-Mg-O_x layer.

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