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COMMUNICATIONS

IMPROVING THE OHMIC PROPERTIES OF Au/Ni–Mg/p–GaN CONTACTS BY ADDING SWCNT METALLIZATION INTERLAYER BETWEEN METAL AND p–GaN LAYERS

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We have examined electrical properties and concentration depth profiles of contact structures Au/Ni-Mg-(O)/SWCNT/p-GaN and Au/Ni-Mg-O/p-GaN, thus with and without an interlaying layer of single-walled carbon nanotubes (SWCNT). The metallization layers were deposited on p-GaN by DC reactive magnetron sputtering in an atmosphere with and without a low concentration of oxygen (cca 0.2 at%). The contacts were annealed in N_2. We have found that the structure containing the SWCNT interlayer exhibits lower values of contact resistivity in comparison with an otherwise identical contact without the SWCNT interlayer.

Keywords: p-GaN, Au/Ni-Mg-O/p-GaN, Au/Ni-Mg-(O)/SWCNT/p-GaN, single-walled carbon nanotubes (SWCNT), ohmic contact, specific contact resistance, circular transmission line method (CTLM)

1 INTRODUCTION

Gallium nitride has lately attracted significant attention for various optoelectronic applications such as light emitting diodes, laser diodes, etc. One of the factors limiting the reliability and performance of these devices is the possibility to create a low-resistance ohmic contact to p-type GaN. These contacts still present a big problem, mainly because of difficult achieving of high charge carrier concentrations ($> 10^{18} cm^{-3}$) [1]. For improving the ohmic properties of the p-GaN contact, a number of metallization layouts 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 resistance and in the case of very thin layers also thanks to its optical transparency. It was found that annealing of such a thin Ni/Au bilayer in air 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 [2-7].

By examining the effect of a NiO_x layer with a low concentration of oxygen deposited by reactive magnetron sputtering upon the electrical properties of ohmic contacts Au/NiO_x/p-GaN [8] it was found that a low-resistance ohmic contact was provided by annealing not only in oxygen but also in nitrogen. Both annealing modes lead to reconstruction of the contact into a metal/p-NiO/p-GaN structure. The ohmic nature of these contacts is predetermined by formation of a thin oxide layer (NiO) at the metal/p-GaN interface. Promising results were reached by incorporating group II dopants into the metallization layer intended to increase the charge carrier concentration in the surface region of p-GaN [9, 10]. Contact structures Au/Ni-Mg-O/p-GaN and Au/Ni-Zn-O/p-GaN exhibited lower values of specific contact resistance than the same structures without Mg and Zn dopants [11].

In [12], low-resistance ohmic contacts to p-GaN were presented based on a layer of single-walled carbon nanotubes. Thanks to its specific properties, this material is highly promising for creating ohmic contacts to p-GaN. It has both semiconducting and metallic properties, whereas the semiconductor exhibits p-type conductivity, and unlike metallic layers it also has excellent thermal and optical properties [13, 14].

The objective of this work is to improve the ohmic properties of the contact to p-type GaN by modifying the original Au/Ni/p-GaN structure to a Au/Ni-Mg-(O)/SWCNT/p-GaN structure. Between the Ni layer containing Mg p-dopant deposited by reactive magnetron sputtering at low concentration of oxygen (approx. 0.2 at%) and the layer of p-GaN a layer of single-walled carbon nanotubes (SWCNT) was deposited by spraying a solution of carbon nanotubes (CNT) with optimized density and homogeneity. The specific contact resistance was determined by the circular transmission line method (CTLM). The effects of the contact structure annealing temperature and time were investigated.

2 EXPERIMENTAL

Metalorganic vapour phase epitaxy (MOVPE) p-GaN layers with a thickness of 800 nm, carrier concentration $2\times10^{17}\,cm^{-3}$ and mobility around 5 cm^2/Vs produced in the Magnetic Spin Materials Group at Johannes Kepler University in Linz were used for preparation of Au/Ni-Mg-(O)/SWCNT/p-GaN structures. The p-GaN layers

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were first sequentially ultrasonically treated for 5 minutes in each step in acetone, isopropanol, DI water, dried with compressed N_2 and then chemically etched in HCl:H2O (1:1) etchant to remove the surface native oxide. On such p-GaN layers, SWCNTs prepared by the standard laser ablation method followed by a purification process were deposited. High-quality SWCNTs prepared in this way were deposited on p-GaN by spray coating using an off-the-shelf airbrush. As a solution, 2mg of SWCNTs diluted with 20 ml of N-methyl-2-pyrrolidine were tip-sonicated for 10 min. In order to accelerate the evaporation of the solvent and prevent formation of bigger droplets the substrate was heated to 165 °C. The thickness of the SWCNT layer was approx. 75 nm. This thickness guarantees a sufficient (more than 60%) optical transmittance of the SWCNT layer [12].

After processing in HCl:H2O (1:1) etchant, patterns were created on the SWCNT layer by lift-off technique needed for measuring the specific contact resistance by the circular transmission line method. In the end, the metal thin films were deposited by DC magnetron sputtering. The $Ni_{92}Mg_8$ (10 nm) thin film was prepared by DC reactive magnetron sputtering from a Ni target containing 8 at% of Mg in an atmosphere of argon with and without a low concentration of oxygen (approx 0.2 at%). The upper Au layer (50 nm) was also prepared by DC magnetron sputtering. The distance between the target and the substrate was approximately 75 mm. A sputtering power of 600 W was used. Both the argon inert flow and oxygen reactive flow were controlled by mass flow controllers. The total gas pressure was kept at 0.5 Pa.

After rinsing out the photoresist from the patterns for CTLM measurement, the SWCNT layer was denuded by etching in RF oxygen plasma using Plasma Etch PE-200 equipment.

After deposition the samples were subsequently annealed in N_2 in a rapid thermal annealing furnace at a temperature of 700 °C for 1 minute. $I-V$ measurements were performed on a Keithley 2400 SourceMeter equipped with MDC micropositioners by applying a voltage ramp from 10 V to +10 V and measuring the respective current. From the slope of the $I-V$ curves, the total resistance was determined. The specific contact resistance was determined using the model of Marlow and Das.

To study the effects of the annealing temperature and time upon the specific contact resistance of Au/Ni-Mg(-O)/SWCNT/p-GaN contact, identically prepared samples were annealed, immediately after deposition, in a rapid thermal annealing furnace at temperatures from 400 °C to 800 °C C for 1 to 3 minutes.

3 RESULTS

Figure 1 shows the contact structure Au/Ni-Mg/SWCNT/p-GaN for ohmic contact characterization by the circular transmission line method. The outer radius of the test patterns is 155 μm with gap length from 5 to 45 μm. Measurements of the influence of the annealing temperature and time upon the specific contact resistance of Au/Ni-Mg (-O)/SWCNT/p-GaN and Au/Ni-Mg-O/ p-GaN contacts on identically prepared samples revealed that the lowest value of specific contact resistance of the contacts both with and without the SWCNT was achieved after annealing in N_2, in the former case at 700 °C for 1 minute, in the latter case at 500 °C for 2 minutes and these parameters were further used in the presented study.

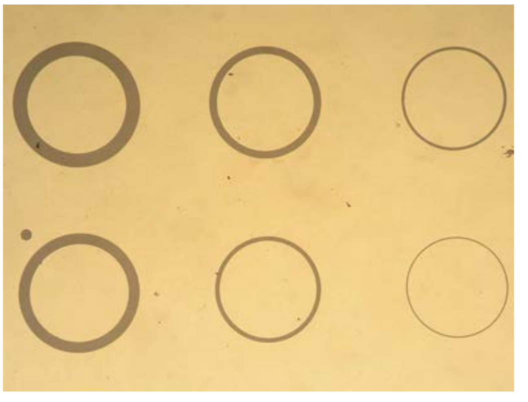

Fig. 1. Au/Ni-Mg /SWCNT/p-GaN contact structure for CTLM ohmic contact characterization. The outer radius of the test patterns is 155 μm with gap length from 5 to 45 μm.

Measurements of the specific contact resistance Au/Ni-Mg(-O)/SWCNT/p-GaN contacts by CTLM have shown that even annealing in N_2 at 400 °C for 1 minute resulted in ohmic properties of contacts. Figure 2 displays the $I-V$ curves for gap length 5, 10 and 25 μm from CTLM measurements of Au/Ni-Mg (-O)/SWCNT/p-GaN contacts annealed in N_2 at 700 °C for 1 minute and of Au/Ni-Mg-O/p-GaN contacts annealed in N_2 at 500 °C for 2 minutes. These results clearly demonstrate that ohmic contacts with the SWCNT intermediate layer exhibit better ohmic properties. The obtained results of the specific contact resistances are summarized in Table 1.

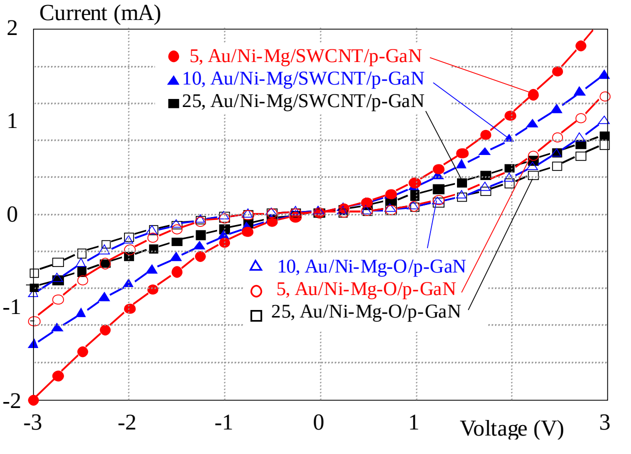

Fig. 2. $I-V$ curves for gap length 5, 10 and 25 μm from CTLM measurements of Au/Ni-Mg/SWCNT/p-GaN contacts annealed in N_2 at 700 °C for 1 minute and of Au/Ni-Mg-O/p-GaN contacts annealed in N_2 at 500 °C for 2 minutes

Table 1. Specific contact resistances of annealed Au/Ni-Mg(-O)/SWCNT/p-GaN contacts (in N_2 at 400 °C and 700 °C for 1 minute) and Au/Ni-Mg-O/p-GaN contact (in N_2 at 500 °C for 2 minutes)

contact structure	specific contact resistance (Ωcm^2)		
annealed in N_2	400 °C, 1min	500 °C, 2min	700 °C, 1min
Au/Ni-Mg/SWCNT/p-GaN	2.8×10^{-3}		7.3×10^{-4}
Au/Ni-Mg-O/SWCNT/p-GaN	4.3×10^{-2}		3.0×10^{-3}
Au/Ni-Mg-O/p-GaN		7.5×10^{-3}	

In the study of the Au/Ni-O/p-GaN structure [8] it was found that RTA annealing in nitrogen or in a mixture of oxygen and nitrogen caused reconstruction of the system into a metal/p-NiO/p-GaN sequence and that its ohmic properties were predetermined by creating a thin NiO oxide layer on the metal/p-GaN interface. In [11] it was reported that by adding p-type dopants (Mg or Zn) into the Ni-O layer brought about an increase in the density of free charge carriers in the sub-surface region of p-GaN resulting in lower values of contact resistivity in comparison with otherwise identical contacts without dopants. In our opinion the further improvement of the ohmic properties of the Au/Ni-Mg-O/p-GaN contact by adding the SWCNT interlayer between the metal Au/Ni-Mg(-O) and p-GaN layers is related to the existence of a contact scheme metal/p-SWCT/p-GaN.

4 CONCLUSION

With intention to improve the ohmic properties of the Au/Ni-Mg-O/p-GaN contact to p-type GaN we have studied a modified contact structure Au/Ni-Mg(-O)/SWCNT/p-GaN in which a layer of SWCNT was deposited between the Ni layer containing Mg p-dopant and the layer of p-GaN. It has been found that the contact created by a layer of carbon nanotubes deposited on p-GaN by spray coating and covered by Ni-Mg and Au deposited by reactive magnetron sputtering in an atmosphere with and without a low concentration of oxygen (approx. 0.2 at%) provides a lower resistivity ohmic contact in comparison with an identical contact structure without the SWCNT interlayer. It is believed that the ohmic nature is related to the existence of a contact scheme metal/p-SWCT/p-GaN.

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