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P-Gallium Nitride (GaN) Ohmic Contact Process Development

by Guifu (Jason) Sun, Ryan Enck, Kim Olver, and Randy Tompkins

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14. ABSTRACT
Low-resistance ohmic contacts to magnesium-doped p-type gallium nitride (GaN) grown by both metal–organic chemical vapor deposition and molecular beam epitaxy with carrier concentrations of 10^{15} and 10^{18} cm^{-3} were studied and their measured p-type specific contact resistivities were as low as 5.3×10^{-3} (Ω cm^2) and 1.8×10^{-3} (Ω cm^2), respectively. The optimized process included electron beam deposited palladium (Pd)/nickel/gold (Au) or Pd/Au contacts annealed at 500 to 550 °C for 10 min in a flowing N_2 and O_2 ambient. Prior to deposition, the GaN surface was treated to remove the native oxide by buffer oxide etching and hydrochloride etching at 100 °C for 10 min.

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1. Introduction

Low-resistance ohmic contacts are critical for power and optoelectronic device technologies as the contribution of contact resistance to the overall series resistance of a device should be minimal. However, low-resistance ohmic contacts to p-type gallium nitride (GaN) are quite challenging. Such challenges arise due to the low activation efficiency of magnesium (Mg) dopants and the tendency of the GaN surface to preferentially lose nitrogen (N) during processing, resulting in a donor-rich surface. Various combinations of metallization schemes, surface preparation methods, metal deposition techniques, and annealing treatments have been investigated to achieve a low contact resistance.

Multilayer metallic films with high work function, such as nickel (Ni)/gold (Au),[1–3] platinum (Pt)/Au,[4] palladium (Pd)/Au,[5] Pt/Ni/Au,[6] Pd/Pt/Au,[7] Ni/Pd/Au,[8] and Pd/Ni/Au[9,10] have been previously used as contacts to p-type GaN. A brief survey of these results is shown in Table 1. The lowest specific contact resistivity is 2.4×10^{-5} (Ω cm^2) according to this survey. However, for devices of interest to the Army, a reasonable specific contact resistivity should be less than 10^{-3} Ω cm^2 and is the overall goal of this effort.

Table 1 Literature survey of p-type GaN ohmic contacts

Metallization	Metal stack thickness (nm)	Carrier density $(cm)^{-3}$	Resistivity (Ω cm^2)	Anneal temperature (°C)	Reference
Ni/Au	50/100	6×10^{16}	3.3×10^{-2}	750	4
Ni/Au (NiO)	10/5	2×10^{17}	1.1×10^{-4}	500	2
Pt/Au	50/100	6×10^{16}	1.5×10^{-3}	750	4
Pd/Au	20/500	3×10^{17}	4.3×10^{-4}	500	5
Pt/Ni/Au	N/A	3×10^{17}	5.1×10^{-4}	350	6
Pd/Pt/Au	N/A	2×10^{16}	5.5×10^{-4}	600	7
Ni/Pd/Au	20/30/100	4.1×10^{17}	1.0×10^{-4}	550	8
Pd/Ni/Au	20/30/2000	1×10^{18}	5.03×10^{-4}	450	9
Pd/Ni/Au	10/20/30	2×10^{17}	2.4×10^{-5}	500	10

In this technical report, we outline our current in-house p-type GaN ohmic contact processes that give comparable specific contact resistivities to those found in literature for material of similar doping. We examine both commercial p-type metal–organic chemical vapor deposition (MOCVD)-grown GaN as well as in-house molecular beam epitaxy (MBE) p-GaN material to develop our p-type ohmic contact process schemes. Our results show specific contact resistivities as low as

$1.8 \times 10^{-3}\ \Omega\ cm^2$ and $5.3 \times 10^{-3}\ \Omega\ cm^2$ for MBE and MOCVD GaN material, respectively. Moving forward, this document will serve as a reference for p-GaN ohmic contact processes for future device development.

2. Experimental

The MBE-grown p-GaN was deposited using a plasma-assisted Varian Gen II MBE reactor. The gallium (Ga) effusion cell was an E-Science Titan source with a graphite crucible. The Mg source was a 50-cc valved Titan source, also containing a graphite crucible and manufactured by E-Science. The plasma source was a Veeco-built Uni-Bulb design. The p-GaN films were grown at a growth rate of 180 nm/h at a substrate temperature of 730 °C as measured using a backside thermocouple to the substrate heater with a Ga beam equivalent pressure (BEP) of 1.5 E^{-7} Torr, which corresponded to a Ga arrival rate of approximately 200 nm/h. The Mg BEP was $2.0E^{-8}$ Torr, with the bulk zone temperature set at 525 °C, while the valve temperature was 700 °C. The p-GaN fluxes were varied periodically, modeled after a technique called metal modulation epitaxy (MME), which was pioneered by Dr Alan Doolittle's group at Georgia Tech.[11] The modulation scheme was as follows: Ga, Mg, and N shutters were opened for 27.8 s, followed by closing of only the Ga shutter for 12.2 s, followed by the closing of the Mg shutter for 13.9 s. By allowing the Mg flux to impinge on the surface of the epitaxial material without a competing Ga flux, more Mg can be incorporated. The amount of Mg incorporation was strongly and nonlinearly dependent on this exposure time. Also, by maintaining the Mg valve temperature at 700 °C, the hot Mg atoms arriving on the GaN surface appear less likely to re-evaporate or coalesce, possibly in conjunction with the MME approach, helping to reduce the polarity inversion problems that plagues most highly doped p-GaN growth efforts. While acceptor concentrations in the range of 2E19 cm^{-3} are possible, the surface morphology suffers; therefore, for these contact studies, we chose an acceptor concentration of 3E18 cm^{-3}, resulting in a mobility of approximately 2 $cm^2\ V^{-1}\ s^{-1}$.

For MOCVD-grown GaN p-type contact studies, a 2-inch commercial MOCVD GaN wafer consisted of 1-µm p-type GaN grown on sapphire substrates. The vendor performed a proprietary Mg activation anneal to get measureable p-type conductivity. The wafer was diced into 11 mm × 10.5 mm pieces for ohmic contact analysis. Although the vendor did the carrier activation annealing, an additional activation annealing was performed in a N_2 ambient at 700 °C for some MOCVD samples. After annealing, a carrier concentration of $2 \times 10^{15}\ cm^{-3}$ was determined by Hall measurements. Prior to metal evaporation, the surface of p-GaN was cleaned using a two-step process, buffered oxide etching (BOE) and 40% hydrochloride (HCl). Both etches were done at 100 °C for 10 min. A standard contact photolithography and negative photoresist liftoff process was used to pattern the samples. Pd (10 nm)/Ni (20 nm)/Au (200 nm) or Pd (10 nm)/ Au (200 nm) layers were deposited on the MOCVD and MBE p-type GaN, respectively, by electron beam evaporation. Before loading the samples into electron-beam chamber, they were dipped in BOE for 10 s. Samples were annealed under N_2 (90%)+O_2(10%) atmosphere for 10 min at temperatures of 500 to 550 °C using a rapid thermal annealer. Circular transmission line models (CTLMs) were employed to extract sheet resistance, transfer length, and specific contact resistivity.

3. Results and Discussion

3.1 Transmission Line Models (TLMs) and CTLMs

The specific contact resistivity (ρ_C) cannot be measured directly and must be computed from a linear fit to a series of current-voltage (I-V) curves taken as a function of distance between ohmic contacts. So far, several TLMs have been developed to test the I-V characteristics of a metal–semiconductor ohmic contact. The most widely used rectangular TLM pattern must be fabricated by a mesa isolation etch step to eliminate current spreading. This step is not only a complicated procedure but also reduces the accuracy of measurement.[12] Another commonly used test pattern is CTLM, consisting of an inner central pad and outer contact separated by a ring without metal.[13–16] With this advanced model, the related parameters, such as the sheet resistivity (R_S) and the transfer length (L_T), are easily extracted from the correlation between the total resistance and the pattern size to calculate the value of ρ_C. This study focuses on processing the CTLM test pattern for resistance measurements. The geometry of the CTLM patterns included an inner circle radius r = 200 µm and the gap sizes d between inner and outer concentric rings were designed to be 50, 40, 30, 20, 10, and 5 µm. Therefore, there are six outer circle radii R (R_i=r+d_i). Both two- and four-point-probe arrangements were used to measure total resistances at room temperature. Figure 1 shows an optical microscopy image of the processed test patterns for CTLM.

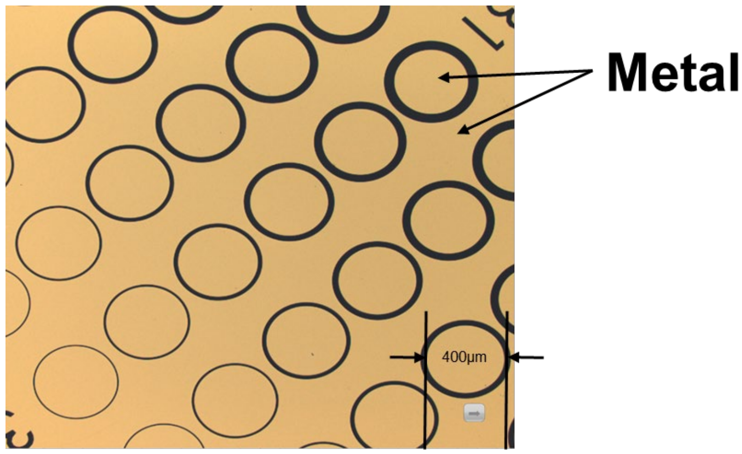

Fig. 1 **Optical microscopy image of the CTLM test structures**

3.2 The Fitting Function for CTLM

In the frame of CTLM, the total resistance (R_{tot}) between the inner metal pad and outer area can be given by the expression

$$R_{tot} = \frac{R_S}{2\pi}\left[ln\left(\frac{R}{r}\right) + \frac{L_T I_0(r/L_T)}{r I_1(r/L_T)} + \frac{L_T K_0(R/L_T)}{R K_1(R/L_T)}\right] \qquad (1)$$

where I_0 (I_1), K_0 (K_1) are the modified Bessel functions of zero order (first order); R_S is the sheet resistivity (ohms per square) of the GaN; and L_T is the transfer length, which represents the distance required for the current to transfer from metal to semiconductor. The specific contact resistance ρ_C can be expressed as

$$\rho_C = R_S \cdot L_T \qquad (2)$$

However, due to the complexity of the Bessel function, it is not easy to obtain R_S and L_T from Eq. 1 using the measured parameters: R_{tot}, r, and R. Therefore, in the conventional method, Eq. 1 is generally reduced when r and R are greater than L_T by at least a factor of 4; both I_0/I_1 and K_0/K_1 are approximate to unity. Here, Eq. 1 could be simplified to the following form:

$$R_{tot} = \frac{R_S}{2\pi}\left[ln\left(\frac{R}{r}\right) + L_T\left(\frac{1}{r} + \frac{1}{R}\right)\right] \qquad (3)$$

Therefore, from the measured R_{tot}, we can plot the correlation between R_{tot} and ln (R/r). The conventional method is applying linear least-squares fitting to eliminate the complex mathematics, and extract R_S and L_T from the slope of the straight line and the intercept with R_{tot}-axis, respectively. In this study, we use Matlab to analyze the measured R_{tot}, R, and r. Both the Bessel function and linear least-squares fitting were utilized to calculate the ρ_C, R_S, and L_T and compare the results.

Figure 2 shows the fitting results for MOCVD sample (left) and MBE sample (right). Both the linear least-squares and the original Bessel function are used to fit the experimental measured R_{tot} versus *ln* (*R/r*). Both samples have high values of R^2 suggesting correlation between values of *R* and distance between contacts. Those values were 0.9774 for MOCVD films and 0.9984 for MBE.

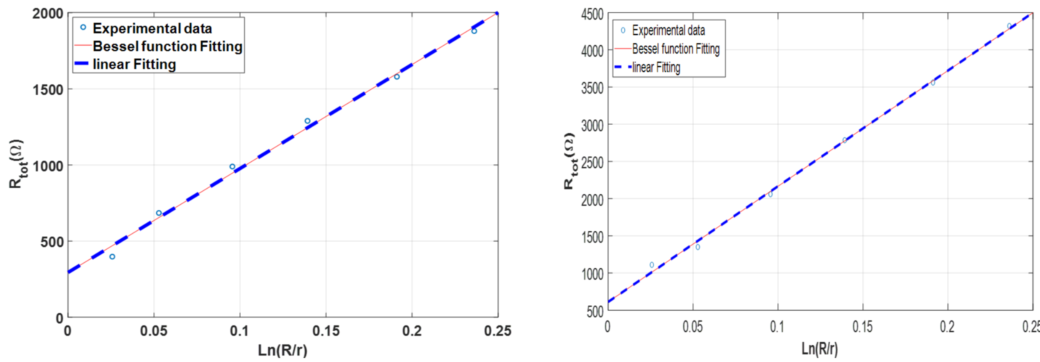

Fig. 2 Comparison of the fitting results between linear least-squares and the original Bessel function for two lowest resistivity samples (Piece 8 and Q197)

4. Contact Resistivity and Process

Table 2 shows the process parameters and the Bessel functions fitting results of the MOCVD p-GaN samples. From Table 2, we find that carrier activation annealing, surface treatment, and contact stack annealing are important process parameters for achieving a low contact resistivity of MOCVD and MBE p-GaN. The comparison between piece1 and piece2 indicates that adding 10% O_2 in the annealing gases improved the resistivity by 1 order of magnitude. If we compare two as-deposited samples, surface treatment decreases the resistivity by 2 orders of magnitude. The oxide on p-GaN surface acts as a barrier for hole injection from metal to p-type GaN, which reduces contact resistivity by 2 orders of magnitude.[5]

Table 2 Resistivity of commercial MOCVD-grown p-GaN and their process parameters

Sample #	Carrier Activate Annealing	Surface treatment	Transfer Length (µm)	GaN sheet Resistance (Ω)	Contact Resistivity (Ωcm²)	Anneal temperature (°C)	Carrier Density (cm⁻³)	Metal
Piece 1	Vendor	No	7.88	55735	3.46×10^{-2}	500C, N_2+O_2	E15	Pd/Ni/Au
Piece 2	Vendor	No	39.69	67871	9.75×10^{-1}	500C, N_2	E15	Pd/Ni/Au
Piece 3	Vendor+home	No	11.67	51728	$7.04\mathrm{x}10^{-2}$	350C, N_2+O_2	E15	Pd/Ni/Au
Piece 3	Vendor+home	No	94	18790	1.66	550C, N_2+O_2	E15	Pd/Ni/Au
Piece 7	Vendor+home	No	62.18	49141	1.9	No	E15	Pd/Ni/Au
Piece 7	Vendor+home	No	34.47	43445	5.2×10^{-1}	550C, N_2+O_2	E15	Pd/Ni/Au
Piece 8	Vendor+home	Yes	8.221	41618	2.81 x 10^{-2}	No	E15	Pd/Ni/Au
Piece 8	Vendor+home	Yes	6.144	42101	1.59 x 10^{-2}	400C, N_2+O_2	E15	Pd/Ni/Au
Piece 8	Vendor+home	Yes	3.445	44908	5.33 x 10^{-3}	500C, N_2+O_2	E15	Pd/Ni/Au

Table 3 shows the Bessel functions fitting results of in-house-grown MBE p-GaN samples and their process parameters. For in-house-grown MBE samples, the specific contact resistivity reached 10^{-2} Ω-cm^2 without annealing. However, the resistivities increased unexpectedly after annealing in N_2 ambient at 350 or 550 °C and we do not have an explanation for that so far. The specific contact resistivity was 1.83×10^{-3} Ω-cm^2 at 550 °C in an N_2+O_2 annealing environment for sample Q197.

Table 3 Resistivity of in-house MBE-grown p-GaN and their process parameters

Sample #	Substrate	Transfer Length (µm)	GaN sheet resistance (Ω)	Contact Resistivity (Ωcm²)	Anneal temperature (°C)	Carrier Density (cm⁻³)	Metal and Thickness (nm)
Q195	Commercial template	N/A	N/A	Not Ohmic	550C, N2	Test unsuccessful	Pd/Ni/Au (10/20/200)
Q195	Commercial template	51.37	279010	7.17 × 10^{-2}	550C, N2 (tube furnace)	Test unsuccessful	Pd/Ni/Au (10/20/200)
Q196	Free Stand	17.5	59495.43	1.82 x 10^{-1}	750,N2 (tube furnace)	3E18	Pd/Ni/Au (10/20/200)
Q197	Free Stand	17.35	121832	3.67×10^{-1}	350C, N2	3E18	Pd/Au (10/200)
Q197	Free Stand	10.74	80509.6	9.29 x 10^{-2}	No Annealing	3E18	Pd/Au (10/200)
Q211	Free Stand	4.02	76780	7.8 x 10^{-2}	No Annealing	3E18	Pd/Au (10/200)
Q211	Free Stand	7.17	85010	2.7 x 10^{-1}	550C, N2	3E18	Pd/Au (10/200)
Q197	Free Stand	1.45	13850	1.83 x 10^{-3}	550C, O_2+N_2	3E18	Pd/Au (10/200)

The mechanism of ohmic contact formation to p-type GaN, and the role of oxygen have been widely debated in the GaN community. Several authors attributed the formation of an ohmic contact to the presence of nickel oxide (NiO) at the interface formed in an oxidizing atmosphere and suggested that the thin p-type semiconducting NiO layer at the interface is responsible of a low Schottky barrier height (0.19 eV).[17,18] However, a later work from Yu and Qiao[19] reported a significantly higher calculated value of the barrier height (2.28 eV) for the p-NiO/p-GaN interface. Basing on these controversial findings, it remains unclear what the correlation between the formation of NiO and the reduction of contact resistivity is.

5. Conclusions

We have investigated Pd/Au and Pd/Ni/Au ohmic contacts to high- and low-doped p-type GaN. Using 500 and 550 °C annealing in 90%N_2+10%O_2 ambient, the lowest specific contact resistivities were 5.33×10^{-3} and 1.83×10^{-3} Ω-cm^2 for MOCVD and MBE p-GaN material, respectively. The three most important process parameters for the formation of a low contact resistivity are surface treatment to remove the native oxides, contact anneal, and carrier activation annealing for MOCVD p-GaN materials. A prerequisite for ohmic contacts to GaN is a metal selection based on having a high work function, which can be accomplished by a variety of metals. However, our results show that the subsequent contact anneal process is crucial. While these results are encouraging, further optimization of the process parameters discussed in this report is needed to reach a specific contact resistivity of less than 10^{-3} Ω-cm^2.

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List of Symbols, Abbreviations, and Acronyms

Au	gold
BEP	beam equivalent pressure
BOE	buffered oxide etching
CTLM	circular transmission line model
Ga	gallium
GaN	gallium nitride
HCl	hydrochloride
I-V	current-voltage
MBE	molecular beam epitaxy
Mg	magnesium
MME	metal modulation epitaxy
MOCVD	metal–organic chemical vapor deposition
N	nitrogen
Ni	nickel
NiO	nickel oxide
O	oxygen
Pd	palladium
Pt	platinum
TLM	transmission line model

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