**A Study of Low-Annealing-Temperature Ohmic Contact on n-Type GaN Layers**

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## **Abstract**

**Typical *n*-type ohmic contact formation for GaN material systems requires high-temperature thermal processes. The high-temperature process often leads to a rough surface after the annealing step. Low-annealing-ohmic contact is advantageous to prevent undesired surface roughening on the metal stack during this thermal process. We report an approach to achieve low contact resistance on *n*-type GaN layers using a nitrogen plasma and a conventional Ti/Al-based metal stacks. We observed an as-deposit ohmic contact behavior on the *n*-type contact with a specific contact resistance (**c,sp) in the mid-E-6 Ω∙cm2 range. The c,sp was further reduced to 6.8E-7 Ω∙cm2 after an annealing step at 600 oC.**

## Introduction

Gallium Nitride (GaN) materials systems are widely used for optoelectronics and electronic applications. Many efforts were made to improve the GaN device and related integrated circuit performance through substrate quality improvement, material growth refinement, and device processing optimization. In device processing development, low-resistivity ohmic contact is one of the key steps for achieving high-performance III-nitride (III-N)-based devices, among many other critical fabrication processing developments.

The techniques to form *n*-type ohmic contact in III-N materials systems were extensively studied. For examples, Ti/Al/Ni/Au metal stacks are known for issues with surface roughening due to a Ti-Al aggregation during high temperature annealing. Such surface roughening on the contact metal is not desirable in device manufacturing [1]. Efforts to achieve low-temperature annealing processes to retain smooth post-annealing metal surface were actively sought. In the context of achieving good ohmic contact on III-N materials with lower thermal budget, several methods were introduced such as varying metal stacks [2-4], co-doped metal stack [5]. These approaches have been effectively reduced the annealing temperature below 800oC for GaN and AlGaN. It was also known that a surface treatment using wet chemical or plasma treatment prior to the metal deposition could help the ohmic contact formation for *n*-type III-N layers [6-8] .

In this paper, we report a procedure to achieve low ohmic contact resistance at the annealing temperature of 600 oC or less. The approach involved a pre-deposition surface treatment in wet-chemicals and nitrogen plasma, along with digital Ti/Al metal stacks. The as-deposit metal stacks showed an ohmic contact property on an *n*-GaN layer with a specific contact resistance (**c,sp) < 10-5 -cm2. When the contact metal was annealed at 600 C, a temperature below the melting temperature of aluminum, c,sp of 6.8×10-7 -cm2 was achieved on a MOCVD-grown *n*-GaN layer on a sapphire template. Smooth surface morphology on the post-annealed ohmic contact region with an RMS roughness of less than 25 nm was achieved for annealing temperature up to 600 oC. An x-ray photoelectron spectroscopy (XPS) analysis showed that a formation of N vacancies after low-energy N2 plasma treatment, which could promote the ohmic contact properties for *n*-type GaN layers at these low-temperature annealing conditions.

## Experiment setup

The ohmic contact study was performed on a silicon-doped GaN layer ([*n*] = 4E18 cm-3) that was grown on a sapphire substrate using a Thomas-Swan close-coupled showerhead (CCS) metalorganic chemical vapor deposition (MOCVD) reactor. After the material growth, coupon samples were cleaved from the same wafer. Lithographically defined patterns for circular transmission line method (CTLM) was created using a two-layer photoresist for a metal lift-off process. The CTLM patterns consist of a set of circular patterns with the diameter of 160 µm were and various gaps of 4, 8 12, 16, 20 and 24 µm, respectively. After the photoresist patterning, the sample was treated with diluted HCl and BOE followed by low-power N2 plasma at 15 W, 0.5 Torr, and 1 sccm of N2 in a March Jupiter III RIE system. After the surface treatment, a digitally switched metal stack consists of Ti/Al/Ti/Al/Ni/Au using an electron-beam evaporator. The deposited metal stacks were subsequently annealed in an AnnealSys rapid-thermal annealing (RTA) tool under the nitrogen ambient. The CTLM patterns measured with a four-probe method on a D.C. on-wafer probe station and a semiconductor parameter analyzer (Agilent 4156C). The contact resistance and the sheet resistance were assessed using a linear fitting from the resistance vs. gap relationship [9].

## Result and Discussion

The main objective of the study was to explore the low-temperature annealing characteristics of n-contact on III-N materials and high-temperature annealing conditions were omitted in this study. In this study, a study of the specific contact resistance, the sheet resistance, and the corresponding surface roughness and surface bonding characteristics were evaluated after the RTA annealing at the temperature from 300 to 600 oC. The annealing time, N2 plasma treatment time, pressure and flow rate remained identical for all test samples to understand the ohmic contact characteristics at different annealing temperature, although the annealing time also plays a role in the ohimic contact optimization. A summary of the annealing temperatures and the N2 plasmatreatment times are listed in Table 1.

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| Table . A summary of annealing and N2 plasma treatment condition variations used in this study.   |  |  |  |  |  | | --- | --- | --- | --- | --- | | **Sample** | **n**  **(cm-3)** | **Temp.**  **(oC)** | **Annealing Time in N2 (s)** | **N2 Plasma Treatment time (s)** | | A | 4E18 | n.a | n.a | 120 | | B | 4E18 | 300 | 300 | 120 | | C | 4E18 | 450 | 300 | 120 | | D | 4E18 | 600 | 300 | 120 | |

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| Figure . Current-voltage (I-V) characteristics of measured CTLM with various distances for *n*-GaN sample before annealing |

As shown in Figure 1, the current-voltage (I-V) characteristics of the as-deposited *n*-type metal contact. The data indicated that the ohmic behaviors can be achieved without any annealing process. The corresponding **c,sp of 6.8E-6 Ω∙cm2 and a sheet resistance (*R*s) of 179.1 Ω /sq. were obtained on the as-deposit *n*-type metal contact. The as-deposit ohmic contact behavior could arise from increased nitrogen vacancies on the GaN surface with the additional plasma treatment step that enhanced the formation of TiN [6, 7].

Figure 2 shows collective plots of optical microscope images and two-dimensional (2D) surface profiles for samples annealed in the four conditions: As-deposited (sample A), 300 oC (Sample B), 450 oC (Sample C), and 600 oC (Sample D), respectively. The microscope images showed that a change of color for the metal contact area was observed for samples with an annealing temperature of greater than 450 oC. To assess the change in the surface roughness at different annealing conditions, wide-area 2D images was measured in an optical interferometer surface profiler (Veeco Wyko NT3300). The surface roughness changes from 18.31 nm for the as-deposit metal to 21.7 nm for sample annealed at 600oC. A summary of the measured RMS surface roughness (*R*q) and the related electrical properties for each annealing condition is summarized in Table 2. The measurement shows that the surface roughness of the contact metal was not significantly changed up to 600oC annealing in the RTA

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| Figure 2. Optical microscope images (top images for each quadrant) and optical 2D surface profile images (bottom images for each quadrant) for CTLM samples with different annealing temperature: (a) as-deposit, (b) 300 oC, (c) 450 oC, and (d) 600 oC. |

The CTLM patterns were characterized using a 4-probe measurement method. Figure 3(a) shows the resistance versus gap of the TLM pattern for a sample annealed at 600 oC with a **c,sp of 4.95E-7 Ω∙cm2 and *R*s of 162 Ω/sq. was obtained. Figure 3(b) shows a trend of *ρ*c as a function of the annealing temperature. We observed the samples presented highly resistive non-ohmic properties for annealing temperature between 300 and 400 oC. However, the samples restored its ohmic contact properties for annealing temperatures greater than 450 oC. The highly resistive contact for annealing temperature between 300 and 400oC could be due a combination of reduced N-vacancy during the annealing and incomplete formation of TiN or AlN at the metal/GaN interface.

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| Table . Surface roughness of the contact metals and specific-contact resistivity with different annealing conditions measured by optical profiler   |  |  |  |  | | --- | --- | --- | --- | | **Sample** | **Rq (nm)** | **c,sp **(Ω∙cm2)** | **Rs (Ω/☐)** | | A | 18.32 | (6.8 ± 2.5)E-6 | 179.1 ± 8.3 | | B | 17.64 | Non-ohmic | n.a | | C | 19.41 | (5.6 ± 2.5)E-5 | 253.9 ± 15.7 | | D | 21.7 | (6.8 ± 2.0)E-7 | 162.0 ± 0.7 |  |  | | --- | | Figure 3. (a) A plot of the resistance versus the gap between two contacting pads in a CTLM sample annealed at 600oC and (b) a cumulative plot of *ρ*c,sp as a function of the annealing temperature with a fixed annealing time of 300s. | |

To understand the surface properties of the plasma-treated GaN, X-ray photoelectron spectroscopy (XPS) was used. Table 3 shows the surface contents spectra using XPS survey scan for both untreated and plasma-treated samples. The atomic percentages of Ga, N, O and C elements were analyzed based on Ga3d, N1s, O1s and C1s peaks. The XPS survey scan clearly shows the increased percentage of oxygen, from 4.05 to 14.46% after the plasma treatment while Ga and N are reduced from 34.35 to 30.81% and from 57.45 to 50.31%.

Figure 4 shows the fine scan of Ga3d peaks for both untreated and N2 plasma-treated samples by XPS. The Ga3d peaks were deconvoluted into three peaks: Ga-N, Ga-O and Ga-Ga. After N2 plasma treatment, a weak positive shift of Ga-N peak ~ 0.1eV was observed, and this could be due to the increased N vacancies or the formation of Ga oxide.

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| Figure 4. The X-ray photoelectron microscopy (XPS) spectra of Ga3d for both untreated and N2 plasma-treated samples. Ga3d peaks were de-convoluted into three binding energy peaks: Ga-N, Ga-O, and Ga-Ga bonds |

To investigate the formation of N vacancies, N/Ga ratio and Ga-O/Ga-N ratio of the sample before and after the N2 plasma treatment as shown in Table IV. The N/Ga ratio was calculated based on N-Ga in N1s and Ga-N in Ga3d. After the plasma treatment, N/Ga ratio was reduced from 1 (normalized) to 0.96 indicating the presence of increased N-vacancies [10]. Figure 5 shows more pronounced O1s peak for the plasma-treated sample while the O1s peak is very weak for the untreated sample. This indicates O-related bonding

was formed on the surface after the plasma treatment. However, Ga-O to Ga-N ratio was also reduced from 1 (normalized) to 0.93 after the plasma.

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| Table 3. Atomic percentages of the major elements for both untreated and nitrogen plasma-treated GaN samples by XPS survey scan | | | | |
| ***Sample*** | ***Ga (%)*** | ***N (%)*** | ***O (%)*** | ***C (%)*** |
| *Untreated* | *34.35* | *57.45* | *4.05* | *4.16* |
| *Plasma-treated* | *30.81* | *50.31* | *14.46* | *4.42* |

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| Table . N-Ga and Ga-O/Ga-N ratios for both untreated and nitrogen plasma-treated samples   |  |  |  | | --- | --- | --- | | **Sample** | **N/Ga** | **Ga-O/Ga-N** | | Untreated | 1 | 1 | | Plasma-treated | 0.96 | 0.93 | |

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| Figure . A comparison of O1s *x*-ray photoelectron microscopy (XPS) spectra for untreated and N2 plasma-treated samples |

## Conclusions

Low-annealing-temperature n-GaN ohmic contact was established using low energy N2 plasma pre-treatment and Ti/Au/Ti/Al/Ni/Au metal stacks. The CTLM measurement result showed **c,sp of 6.8E-6 Ω∙cm2 for as-deposited sample and 6.8E-7 Ω∙cm2 for samples annealed at 600 oC. The specific contact resistivity versus the annealing temperature revealed non-ohmic characteristics between 300 oC and 400 oC, possibly due to incomplete TiN formation at low temperature and surface reconstruction of the N vacancies formed during the N2 plasma treatment.

A study of the surface roughness revealed slight change of the RMS roughness on the metal surface up to an annealing temperature of 600 oC. An XPS study showed the N/Ga ratio was reduced after the N2 plasma treatment and suggested an increased N vacancies on the GaN surface. The surface O content was also increased after the plasma treatment, suggesting additional oxide removal step after the N2 plasma treatment may be beneficial to help further enhance the ohmic contact properties.

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## Acronyms

CTLM: Circular Transmission Line Measurement

XPS: X-ray Photoelectron Spectroscopy

RMS: Root-Mean-Square

BOE: Buffered Oxide Etch

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