



## Importance of layer distribution in Ni and Au based ohmic contacts to p-type GaN

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### ► To cite this version:

Clément Mauduit, Taoufik Slimani Tlemcani, Meiling Zhang, Arnaud Yvon, Nicolas Vivet, et al.. Importance of layer distribution in Ni and Au based ohmic contacts to p-type GaN. Microelectronic Engineering, 2023, 277, pp.112020. 10.1016/j.mee.2023.112020 . hal-04097297

**HAL Id: hal-04097297**

**<https://hal.science/hal-04097297>**

Submitted on 3 Jun 2023

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# Microelectronic Engineering

## Importance of layer distribution in Ni and Au based ohmic contacts to p-type GaN --Manuscript Draft--

Manuscript Number:	
Article Type:	VSI:WBG materials: Research Paper
Section/Category:	Micro/Nanoelectronics processing & materials
Keywords:	p-GaN; metal deposition; ohmic contact; specific contact resistance; power diode; HEMT
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Abstract:	<p>In this work, we report on the importance of layer distribution after annealing to form a high quality ohmic contact on p-type GaN, using nickel (Ni) and gold (Au) thin layer association. Both the standard GaN/Ni/Au and its reverse, GaN/Au/Ni on p-type GaN were studied. The Au/Ni stack exhibits the most promising results in this study. While the standard Ni/Au contact exhibits a quasi-linear current-voltage (I-V) characteristic, its counterpart, Au/Ni, shows pure ohmic behavior, with a specific contact resistance (<math>\rho_c</math>) as low as <math>2.0 \times 10^{-4} \Omega \cdot \text{cm}^2</math> after rapid thermal annealing (RTA) at <math>500^\circ\text{C}</math> for 5 minutes under air ambient, equivalent to the best literature results. X-ray diffraction (XRD) and transmission electron microscopy (TEM) analyses demonstrate the incomplete inversion of layers during annealing leading to a GaN/Ni/Au/NiO stack that explains why Ni/Au contact shows inferior electrical performance. On the other hand, for the Au/Ni contact annealed in the same conditions, the excellent results can be attributed to both (i) the presence of the gold layer at the interface with GaN, allowing the formation of gallide solid solution (Ga-Au) and (ii) the formation of NiO directly contacted with the p-GaN. Those two mechanisms are known to lead to the formation of good ohmic contact on p-type GaN. These results demonstrate that although Ni/Au is a standard contact for p-GaN layers, the opposite stack (Au/Ni) gives the best Ohmic behavior. This is important for achieving the best performance of GaN power diodes or transistors including a p-gate structure.</p>
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# Importance of layer distribution in Ni and Au based ohmic contacts to p-type GaN

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## Abstract

In this work, we report on the importance of layer distribution after annealing to form a high quality ohmic contact on p-type GaN, using nickel (Ni) and gold (Au) thin layer association. Both the standard GaN/Ni/Au and its reverse, GaN/Au/Ni on p-type GaN were studied. The Au/Ni stack exhibits the most promising results in this study. While the standard Ni/Au contact exhibits a quasi-linear current-voltage (I-V) characteristic, its counterpart, Au/Ni, shows pure ohmic behavior, with a specific contact resistance ( $\rho_c$ ) as low as  $2.0 \times 10^{-4} \Omega \cdot \text{cm}^2$  after rapid thermal annealing (RTA) at 500°C for 5 minutes under air ambient, equivalent to the best literature results. X-ray diffraction (XRD) and transmission electron microscopy (TEM) analyses demonstrate the incomplete inversion of layers during annealing leading to a GaN/Ni/Au/NiO stack that explains why Ni/Au contact shows inferior electrical performance. On the other hand, for the Au/Ni contact annealed in the same conditions, the excellent results can be attributed to both (i) the presence of the gold layer at the interface with GaN, allowing the formation of gallide solid solution (Ga-Au) and (ii) the formation of NiO directly contacted with the p-GaN. Those two mechanisms are known to lead to the formation of good ohmic contact on p-type GaN. These results demonstrate that although Ni/Au is a standard contact for p-GaN layers, the opposite stack (Au/Ni) gives the best Ohmic behavior. This is important for achieving the best performance of GaN power diodes or transistors including a p-gate structure.

**Keywords:** p-GaN; metal deposition; ohmic contact; specific contact resistance; power diode; HEMT

## 1. Introduction

In recent past, III-N semiconductors have gained traction for power electronic applications [1]. Due to their excellent properties such as wide band gap and high electrical breakdown field, III-N materials are promising for replacing traditional silicon-based devices used for operations at high voltages, high frequencies and/or high temperatures. One particularly useful property is their ability to create heterojunctions. In particular, the AlGaN/GaN heterostructure results in a two-dimensional electron gas (2DEG) at its interface, thanks to the intrinsic polarization properties of gallium nitride. As a result, High Electron Mobility Transistors (HEMTs) based on AlGaN/GaN can be fabricated with outstanding performances such as, for example, an extremely low resistance channel. Among the various devices that may be obtained [2–7], by modifying the gate contact, lateral Schottky diodes, using this 2DEG channel, can also be fabricated on HEMT fabrication lines.

In general, GaN-based power Schottky diodes suffer from reliability purposes, especially in IFSM (Intensity Forward Surge Maximum) conditions. Indeed, Schottky diodes may face high

surge current up to 5 times its nominal current “outside safe operation area”. To overcome this problem, hole injection is necessary, which is made possible by locally adding a p-GaN region on top of the AlGaN layer [8]. In the case of devices using such p-GaN regions, a good ohmic contact, with a low resistance, stable across a wide range of temperatures, is still quite difficult to obtain due to the high Schottky barrier height at the metal/p-GaN interface [9]. Another obstacle to high quality ohmic contacts is the high ionization energy ( $\approx 170$  meV) of the Mg acceptor in the bandgap, leading to a low free hole concentration [10].

The most popular solution to these challenges in the literature is the p-GaN/Ni/Au metallization, annealed in air at around  $500^{\circ}\text{C}$  for a few minutes using a Rapid Thermal Annealing (RTA) process [11]. The formation of a low resistance ohmic contact can be explained by two different effects. First, the oxidation of the nickel layer during the annealing leads to the inversion of Ni and Au layers, which induces a final p-GaN/Au/NiO stack [12]. The second explanation is the creation of gallium vacancies at the top of the p-GaN, caused by the formation of gallide solid solutions, increasing the free hole concentration at the contact interface [13–15].

In this work, we investigated the formation of ohmic contacts to p-GaN using the standard configuration, i.e. Ni/Au contact, as well as Au/Ni, since according to the literature a p-GaN/Au/NiO stack is necessary after annealing.

Based on electrical and physical analyses presented here, the importance of the Ni and Au layers distribution to form good ohmic contacts to p-GaN will be discussed.

## 2. Experimental procedure

A  $0.5\ \mu\text{m}$  thick Mg-doped GaN layer was grown on a standard GaN/AlGaN buffer on Si substrate by metal organic vapor phase epitaxy (MOVPE). In order to activate the acceptors, a standard annealing sequence was performed using RTA, and the hole concentration of p-GaN was determined to be  $4 \times 10^{17}\ \text{cm}^{-3}$  from Hall measurements at room temperature. Several samples were then fabricated, starting with surface cleaning. This consisted of immersion in Caro’s acid for 10 min, hydrofluoric acid (1% HF concentration) for 30 sec and hydrochloric acid for 10 min before being rinsed in deionized water. Next, Circular Transfer Length Method (c-TLM) patterns, with an inner radius of  $100\ \mu\text{m}$ , were defined using a negative photoresist. The spacing between the metal electrodes varied from 12 to  $48\ \mu\text{m}$ . Then, 20 nm of Ni followed by 20 nm of Au were deposited on the p-GaN by electron beam evaporation to form the Ni/Au contact. For the Au/Ni contact, the deposition sequence was inverted. After deposition, the photoresist was removed using lift-off and the samples were subsequently annealed at  $500^{\circ}\text{C}$  in air using RTA for 5 min. Alternative anneal sequences were also tried, but this gave the best electrical results.

For electrical characterization of the contacts, Current-Voltage (I-V) characteristics were extracted at room temperature using a 2636 Sourcemeter Keithley with the four-point probe method.

For structural observations, X-ray diffraction (XRD) analysis was performed using the Cu  $K\alpha$  radiation (AXS D8 Discover Bruker) in Bragg-Brentano configuration.

Transmission Electron Microscopy (TEM) and Scanning Transmission Electron Microscopy - Energy Dispersive X-Ray spectroscopy (STEM-EDX) measurements as well as Fast Fourier Transform (FFT) analyses were carried out using a JEOL ACCELARM 200 cold FEG microscope. This tool has double analytical correction of spherical aberrations (probe and image) and was used at 200kV giving a TEM resolution of  $1.2\ \text{\AA}$  and a STEM resolution of  $0.8\ \text{\AA}$ . The lamellae for TEM observations were prepared by focused ion beam (FIB) using a FEI Helios Nanolab 600i dual beam microscope and they had a thickness of  $t/\lambda \approx 0.4$  (ratio between the thickness  $t$  and the electron mean free path  $\lambda$ ).

### 3. Results and discussion

Figure 1 displays the I-V characteristics of the two different contacts, Ni/Au and Au/Ni, before and after annealing, for voltages varying from -5V to +5V. For the Ni/Au contact, the difference between the as-deposited and annealed samples is small and a quasi-linear I-V characteristic is observed in both cases. Even though the I-V characteristic is slightly better after annealing, it is still not completely ohmic. On the contrary, the Au/Ni contact of the as-deposited sample is rectifying while it exhibits pure ohmic behavior across the entire voltage range after annealing. This is crucial for a device operation under injection regime, as mentioned before.

Specific contact resistance ( $\rho_c$ ) was obtained using the c-TLM method, by plotting the measured total resistance versus the spacing of the c-TLM rings. The specific contact resistance was  $2.0 \times 10^{-4} \Omega \cdot \text{cm}^2$  for the Au/Ni contact after annealing. Despite not being completely ohmic, the specific contact resistance of the Ni/Au contacts was extrapolated, and was evaluated as  $2.6 \times 10^{-3} \Omega \cdot \text{cm}^2$  and  $1.2 \times 10^{-3} \Omega \cdot \text{cm}^2$  for the as deposited and after annealing contacts, respectively.

The hole concentration was  $4 \times 10^{17} \text{ cm}^{-3}$ , explaining why the maximum current values are not very high, at around 2.5 mA at 5V, despite the good quality of the ohmic contact.

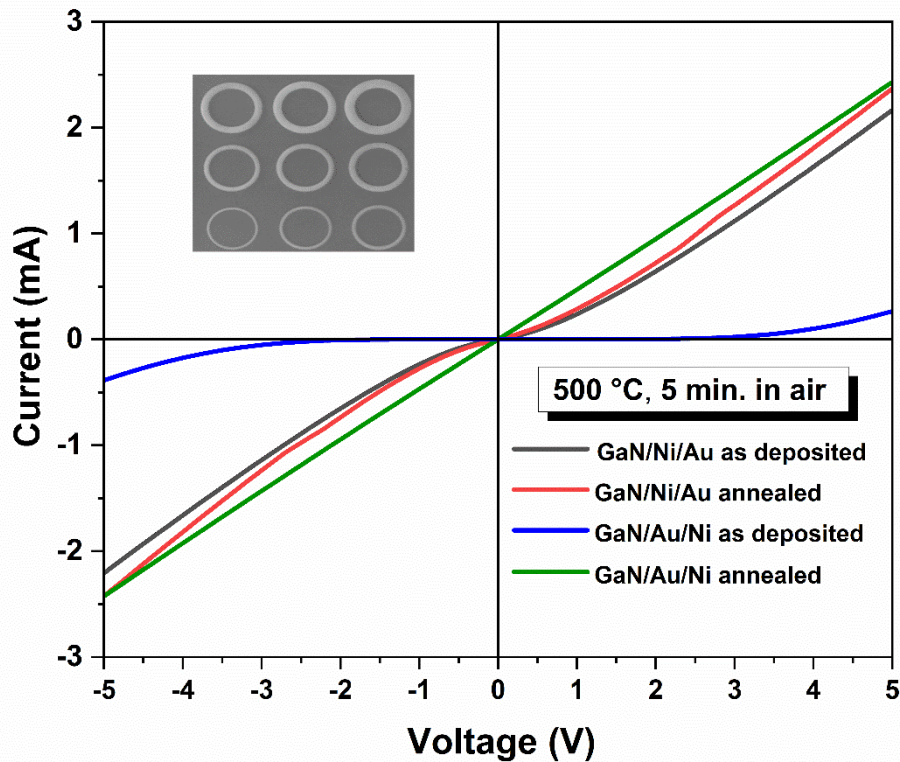


Figure 1. I-V characteristics of a TLM structure (48  $\mu\text{m}$  spacing) for Ni/Au and Au/Ni contacts, both before and after annealing at 500°C for 5 min in air.

In order to explain this quasi-ohmic behavior of the standard Ni/Au contact TEM analyses were performed. The behavior can be explained by an incomplete inversion of layers during the annealing. Indeed, we can clearly see on figure 2, showing a TEM micrograph of the annealed Ni/Au contact, that the final stack is p-GaN/Ni/Au/NiO and not the p-GaN/Au/NiO expected from the literature. Thus, the layer in contact with the p-GaN is Ni, which is known to form a poor contact on p-GaN. Greco et al. [12], showed that during the annealing under air, the entire Ni layer should diffuse through the Au layer and react with oxygen to form the surface NiO layer. However, we did not observe this full inversion in our case, whatever the annealing. Hence, the inversion of metal deposition sequence (Au then Ni) to form the required p-GaN/Au/NiO stack after annealing, which exhibits the lowest resistance contacts in the literature [11], was an interesting case to better understand the contact formation.

Figure 3 shows TEM, STEM-EDX and FFT analyses of the p-GaN/Au/Ni sample after annealing. The stack is completely different from that obtained for the Ni/Au sample. Firstly, the Au layer is discontinuous on the surface of the p-GaN with some voids, as seen in figures 3(a) and 3(c). However, the Au remains in contact with the p-GaN, and the NiO is also in contact with the p-GaN surface as shown by the STEM-EDX and FFT analyses on figure 3(b) and figure 3(d), respectively. This behavior is crucial to understanding the mechanisms of ohmic contact formation to p-GaN according to the literature [16,17]. Indeed, crystalline NiO is known to be a p-type semiconductor and to act as an intermediate layer reducing contact resistivity. It also prevents the outdiffusion of N atoms from the decomposed GaN during annealing [18,19], avoiding the creation of N vacancies near the GaN surface which are well-known to cause poor ohmic contacts to p-GaN [20,21].

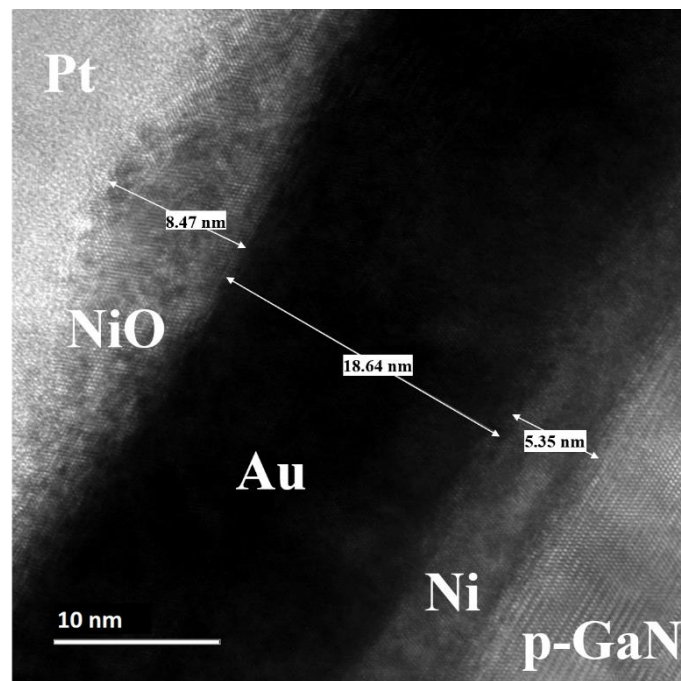


Figure 2. Cross-sectional micrograph for the annealed Ni/Au contact of high-resolution TEM viewed from the  $[1\bar{1}00]$  direction of p-GaN. Platinum (Pt) comes from the FIB preparation.



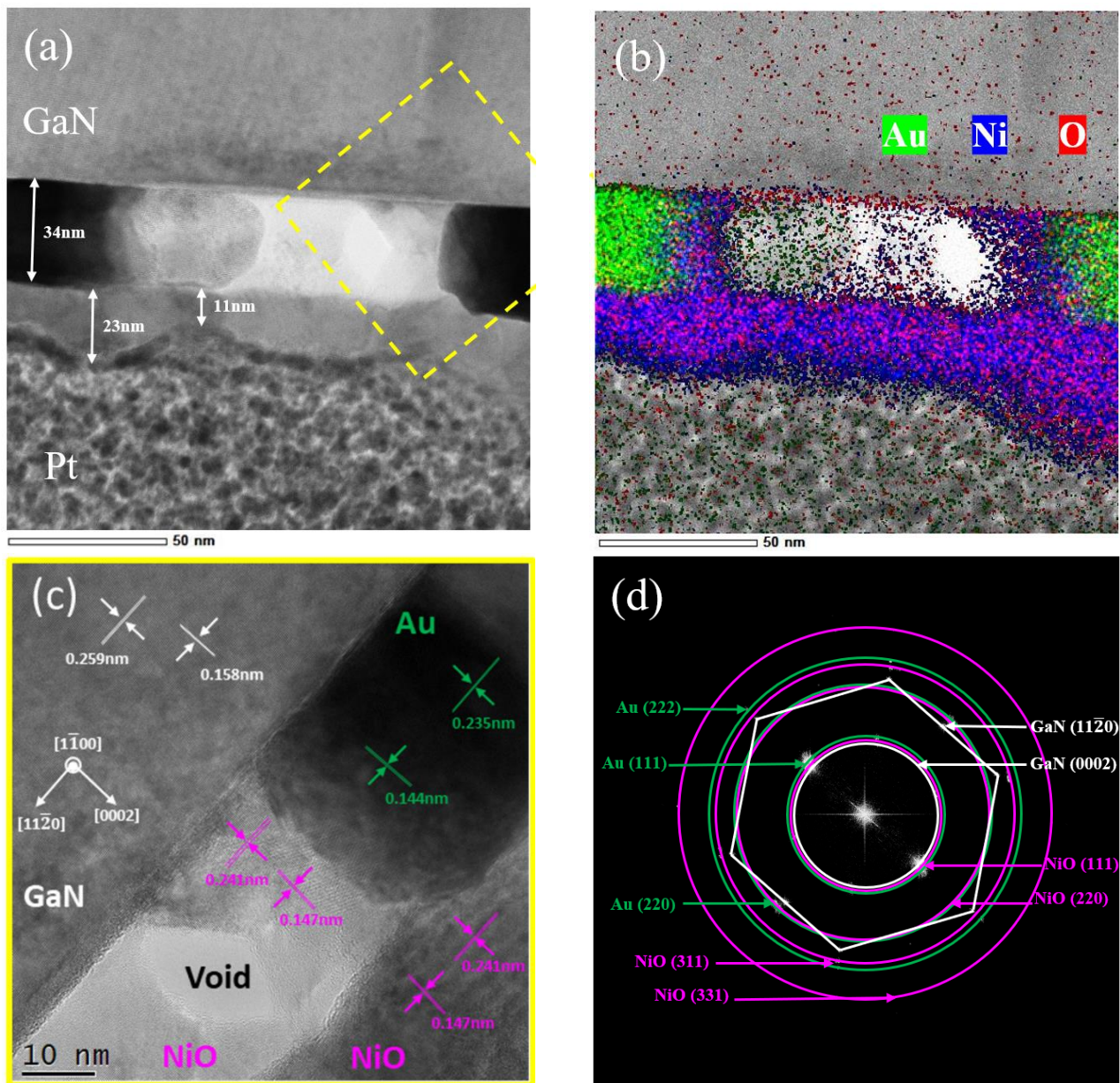


Figure 3. Cross-sectional images for the annealed Au/Ni contact of (a) Bright Field (BF)-STEM and (b) corresponding STEM-EDX elemental overlay mapping of Au (green), Ni (blue), and O (red); (c) high-resolution TEM of the boxed area in (a); (d) Fast Fourier Transform (FFT) pattern of (c). These images were viewed from the  $[1\bar{1}00]$  direction of p-GaN. Platinum (Pt) comes from the FIB preparation.



In addition, structural characterizations of the samples were performed by XRD as shown in figure 4. For the Ni/Au contact, prior to annealing both Ni (111) and Au (111) peaks are observed. After annealing at 500°C, both peaks increase in intensity and broaden, likely related to strain modifications. The existence of a NiO (200) peak at  $2\theta=43.3^\circ$  confirms the presence of both Ni and NiO after annealing, as seen on the TEM analysis (see Fig.2). The Au/Ni contact before annealing is similar to the Ni/Au contact, but after annealing, the XRD spectrum has a NiO (111) peak but no peak for pure Ni. This demonstrates that the oxidation of Ni is complete. Moreover, we observe the presence of Au (200) at  $2\theta=44.3^\circ$  and a broadened peak for the Au (111), which suggests that the Au structure is different to the Ni/Au contact. It could also be linked to the reaction between Au and GaN during the annealing which indicates the formation of a Au-Ga solid solution. In this case, the outdiffusion of Ga is assisted by the annealing in air since Ga reacts strongly with oxygen [15].

This outdiffusion of Ga causes the creation of Ga vacancies in the p-GaN near surface, vacancies that as mentioned above act as acceptors, increasing the net hole concentration near the interface with the contact. As a consequence, the Schottky barrier height between the GaN and the metal is lowered which results in a reduction of the contact resistance.

The excellent electrical results of the Au/Ni contact can therefore be attributed to the formation of Ga vacancies but also to the presence of NiO directly in contact with the p-GaN. This indicates that both phenomena may occur at the same time increasing contact efficiency.

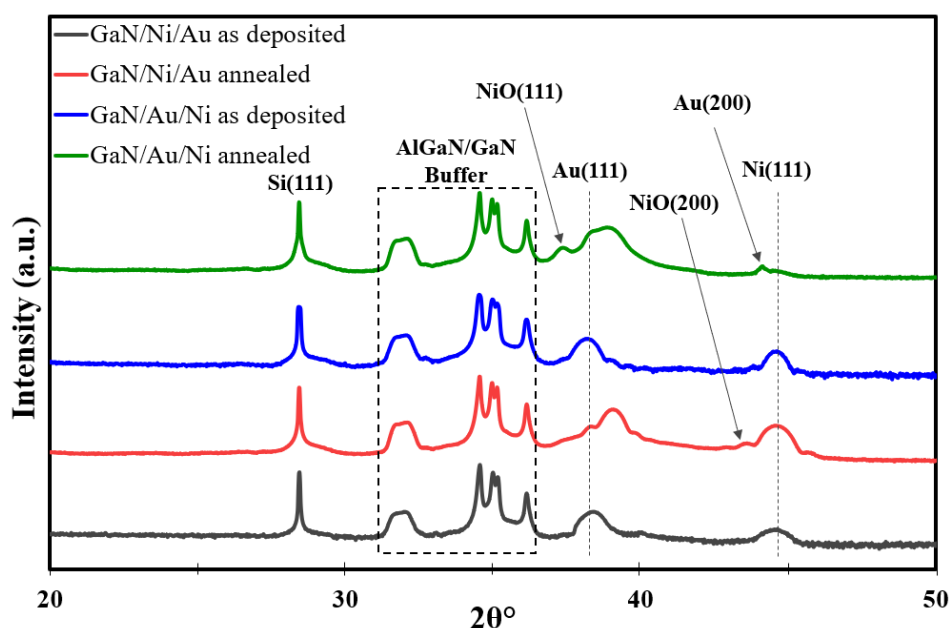


Figure 4. XRD spectra for the Ni/Au and Au/Ni contacts, both before and after annealing.

## 4. Conclusion

This work investigated ohmic contacts to p-GaN, comparing the standard Ni/Au contact and an Au/Ni stack. The Ni/Au samples, as deposited and annealed did not exhibit ohmic behavior. However, the Au/Ni contact exhibited pure ohmic behavior, after annealing at 500°C in air, with an excellent specific contact resistance of  $2.0 \times 10^{-4} \Omega \cdot \text{cm}^2$ . TEM, STEM-EDX, FFT and XRD analyses have been conducted to understand the mechanisms of ohmic contact formation to p-GaN. The relatively poor performance of the Ni/Au contact was attributed to incomplete inversion of the layers, and an intact Ni layer at the p-GaN surface. The excellent electrical performance of the Au/Ni was attributed to the presence of the NiO layer at the interface of the p-GaN reducing the contact resistivity. Also, the formation of a Au-Ga solid solution during the annealing may lead to the creation of Ga vacancies near the GaN surface, reducing the Schottky barrier height of the metal/p-GaN interface. This shows that the layer distribution after annealing is crucial to obtain good ohmic contacts to p-GaN. Hence, the Au/Ni deposition sequence may be an easier and better solution to obtain low resistance ohmic contacts to p-GaN.

## Acknowledgment

This work has been carried out in the framework of the European Project GaN4AP (Gallium Nitride for Advanced Power Applications). The project has received funding from the Electronic Component Systems for European Leadership Joint Undertaking (ECSEL JU), under grant agreement No.101007310. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation program, and Italy, Germany, France, Poland, Czech Republic, Netherlands. One of the authors (CM) want to thank the ANRT association for its support. This work is also part of the IPCEI Nano 2022 and ARD+ CERTeM project (supported by Region Centre Val de Loire and Tours Metropole).

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## **Highlights:**

- The influence of layer distribution in Ni and Au based ohmic contacts on p-GaN is studied.
- Standard GaN/Ni/Au contact to p-GaN did not show pure ohmic behaviour.
- Low resistance ohmic contact is obtained after inversion of the metal deposition sequence.
- Presence of NiO and formation of gallide phases are keys to the formation of good ohmic contacts.



January 17th, 2023

Dear Editor,

Please find enclosed our original manuscript entitled “**Importance of layer distribution in Ni and Au based ohmic contacts to p-type GaN**” by Clément Mauduit, Taoufik Slimani Tlemcani, Meiling Zhang, Arnaud Yvon, Nicolas Vivet, Matthew Charles, Romain Gwoziecki & Daniel Alquier which we would like to submit for publication in the Special Issue entitled "New frontiers in wide-band-gap semiconductors and heterostructures for electronics, optoelectronics and sensing" in the Microelectronic Engineering.

In this work, we report on the importance of layer distribution after annealing to form a high quality ohmic contact on p-type GaN, using nickel (Ni) and gold (Au) thin layer association. Both the standard GaN/Ni/Au and its reverse, GaN/Au/Ni on p-type GaN were studied. While the standard Ni/Au contact exhibits a quasi-linear current-voltage (I-V) characteristic, its counterpart, Au/Ni, shows pure ohmic behavior, with a specific contact resistance ( $\rho_c$ ) as low as  $2.0 \times 10^{-4} \Omega \cdot \text{cm}^2$ . Physical analyses demonstrate the incomplete inversion of layers for the Ni/Au contact during annealing leading to inferior electrical performance. On the other hand, for the Au/Ni contact, the excellent results can be attributed to both the presence of the gold layer at the interface with GaN and the formation of NiO directly contacted with the p-GaN. These results are important for achieving the best performance of GaN power diodes or transistors including a p-gate structure.

The proposed manuscript is original and of high interest. It has not been previously submitted and is not currently under consideration by any other journal. Due to the significant implications of our results, the expected strong outreach, the multidisciplinary approach, and the importance of the field, we believe that Microelectronic Engineering is particularly relevant to publish these results.

Yours sincerely,

Mr. Clément Mauduit, Université de Tours, [clement.mauduit@univ-tours.fr](mailto:clement.mauduit@univ-tours.fr)  
Pr. Daniel Alquier, CNRS/Université de Tours, [daniel.alquier@univ-tours.fr](mailto:daniel.alquier@univ-tours.fr)



**Declaration of interests**

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Daniel Alquier reports financial support was provided by European Commission.
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