AIP Applied Physics Letters

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Citation: Applied Physics Letters **103**, 152104 (2013); doi: 10.1063/1.4824894
View online: http://dx.doi.org/10.1063/1.4824894
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/103/15?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS **103**, 152104 (2013)

Low resistance copper-based ohmic contact for AlGaN/GaN high electron mobility transistors

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(Received 11 July 2013; accepted 4 September 2013; published online 8 October 2013)

Ti/Al/Ni/Cu ohmic contact for AlGaN/GaN structure has been fabricated. The Ni layer played an important role in achieving low specific contact resistance (r_c), smooth morphology, and excellent edge acuity. With a 50-Å Ni layer, a r_c of 1.35×10^{-6} Ω-cm^2 and a root-mean-square roughness of 7.65 nm have been realized. The characterization results indicated that no evidence of Cu diffusion into the semiconductor layers. The formation of Al-Cu and Ti-Cu alloys might have confined the Cu within the ohmic metal. In the absence of gold, the surface roughening caused by Au-Al alloy in conventional Ti/Al/Ni/Au structure was also prevented. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4824894]

Due to their high energy bandgap and high electron saturated velocity, the AlGaN/GaN high electron mobility transistor (HEMT) has become an ideal device for high frequency and high power applications.[1] In order to realize the potential of GaN devices, a good metallization, especially for ohmic contact, is essential. The ohmic contact must fulfill the requirements of low contact resistance, smooth surface morphology, and good edge acuity. The most widely used ohmic contact for AlGaN/GaN HEMT devices is the alloy of a multilayer metal structure that consists of Ti/Al metal layers. These layers will form a low resistance alloy upon annealing at high temperature (750–950 °C) and the mechanism is well documented.[2,3] Since Ti/Al is prone to oxidation, an oxidation prevention layer such as gold (Au) is deposited on Ti/Al to protect the ohmic contact for long-term device operation. Finally, a barrier layer (such as Ni, Pt, Cr, or Mo) is also needed to prevent Au from diffusing into GaN during thermal annealing process. By optimizing the ohmic contact formation parameters, specific contact resistances (r_c) as low as 7.3×10^{-7} (Ref. 4) and 4.7×10^{-7} Ω-cm^2 (Ref. 5) have been demonstrated using Ti/Al/Ni/Au and Ti/Al/Mo/Au ohmic structure, respectively.

However, the ever rising gold cost on a long-term basis has fuelled the search for an alternative material to replace the Au layer for GaN device metallization. In this context, the copper (Cu) is a potential candidate. Besides the cost issue, Cu also has lower resistivity and higher thermal conductivity as compared with Au. Therefore, the Cu has been widely used for multi-level interconnects in the silicon VLSI technology.[6,7] These advantages will certainly generate much interest in using Cu metallization on GaN devices as well. In fact, Cu has been demonstrated to perform well as gate contacts[8,9] and as interconnects[10] on the GaN HEMTs. Nevertheless, the diffusion of Cu into GaN at elevated temperatures can be detrimental to the GaN devices.[11–13] An effective diffusion barrier to Cu is thus required, especially for the ohmic contact. A few ohmic contact structures for GaN devices, such as Si/Ti/Al/Cu/Au,[14] Ge/Cu/Ge,[15] and Ti/Cu/Ge,[16] have been investigated. Although ohmic contacts could be achieved at relatively lower temperatures (<800 °C) for these structures, they all suffer from having high contact resistance ($r_c > \times 10^{-5}$ ohm cm^2). In this study, we investigate the feasibility of using Ti/Al/Ni/Cu as the ohmic contact material for AlGaN/GaN structures. This metal stack differs from the conventional Ti/Al/Ni/Au in that the top metal Au is replaced by Cu. The Ti/Al layers were adopted to achieve good ohmic. The role of Ni as an adhesion and diffusion barrier layer will also be examined. We will show that, with an optimized Ni layer thickness, a low contact resistance and smooth surface morphology can be achieved with the Ti/Al/Ni/Cu ohmic contact. The mechanism for the formation of ohmic contact will also be discussed.

The Ti/Al/Ni/Cu ohmic contact was formed on the AlGaN/GaN heterostructure grown on 6-in. Si (111) substrates. The epi-structure, from the Si substrate to the top, consisted of AlN and AlGaN buffer layers, a 1.6-μm GaN channel layer, a 25-nm $Al_{0.25}Ga_{0.75}N$ barrier layer, and a 2-nm GaN cap layer. Prior to the metallization, the wafers were first rinsed in acetone and isopropanol to remove organic contaminants. The wafers were then dipped into buffered hydrofluoric acid (BHF) solution to etch away native oxide from the wafer surface. Standard optical I-line lithography process was used to define patterns for the ohmic metal deposition. Four samples, designated as samples A, B, C, and D, were prepared. Cu instead of Au was deposited on samples A, B, and C as the top layer of the ohmic metal stack while sample D followed the standard ohmic contact Ti/Al/Ni/Au process and thus acted as a control sample. The Ti and Al layers were fixed at 200 Å and 1200 Å for all

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samples. Both Au and Cu layers have the same thickness of 1000 Å. However, Ni layers with thicknesses 0, 50, and 250 Å were deposited on samples A, B, and C, respectively, for the investigation of its influence on the Cu-based ohmic contacts. The Ni layer thickness for sample D was 250 Å. All the ohmic metals were deposited using an electron beam evaporator except the copper layer which was deposited using a sputtering machine. The annealing process was performed in a rapid-thermal-annealing (RTA) system at 900 °C for 30 s under pressure of 5×10^{-6} Torr in N_2 ambient. Mesa isolation was performed using an inductively coupled plasma etcher with Cl_2/Ar gases. The specific contact resistances of the ohmic contact were measured with an Agilent E5270 system at room temperature using transmission line model (TLM) method. The contact pads on the TLM pattern are separated by increasing distances from 3 to 36 μm. A set of samples without the ohmic pattern was also prepared for material characterizations. An atomic force microscope (AFM, Digital Instrument, D3100) and a scanning electron microscope (SEM, Hitachi S-4700) were employed to examine the surface morphology and edge acuity of the ohmic metals. Depth profiling Auger electron spectroscopy (AES, Microlab 350) were performed to study the intermixing of metal layers upon annealing. Finally, X-ray diffraction (XRD, Bede D1) was used to investigate the compositional change in the Cu-metallization. In this study, a grazing incident angle XRD method was adopted to exclude diffraction signals from the epitaxial layers and substrate.

The r_c of different ohmic contacts are shown in Figure 1. Among the Cu metallized samples, the sample B with a 50 Å Ni shows the lowes r_c of 1.35×10^{-6} Ω-cm^2. This value is comparable to that of the conventional ohmic contact scheme (sample D, $r_c = 1.19 \times 10^{-6}$ Ω-cm^2). On the other hand, for sample A (without Ni layer) and sample C (250 Å Ni), their r_c, when compared with the control sample, are higher by approximately 1 and 2 orders of magnitudes, respectively. Furthermore, the sample A shows the worst surface morphology among all samples. There seemed to be a serious metal peeling problem as revealed in an optical microscope image (inset of Figure 1). It has been shown that when the Cu was in direct contact with Al, intermetallic compound and cavities would form.[17] Since the residual stress between the metals was asymmetric and relatively larger at the contact periphery than at the center, cavities or voids would start to form at the edge and propagate towards the center area of contact. This reduced the contact area between the ohmic metal and semiconductor and thus increased the contact resistance. As for the sample C, a 250 Å thick Ni layer also increased the contact resistance. The same result was observed by Jacobs *et al.* in the Ti/Al/Ni/Au metallization case.[4] This may be due to the increased metal resistance of a thicker metal layer.

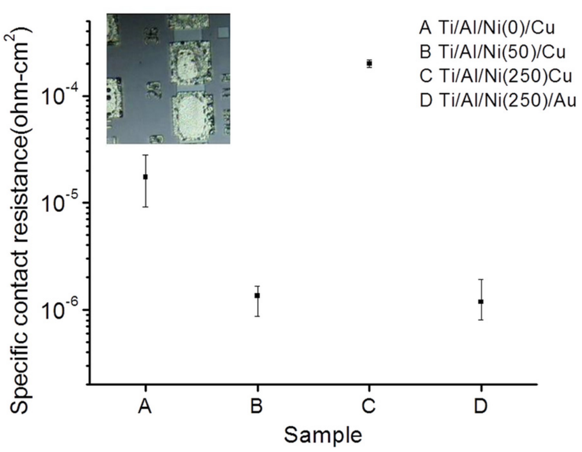

FIG. 1. Specific contact resistance of different ohmic metal structures. The numbers in the legend are the Ni layer thickness in angstrom. Inset is the optical microscope image of ohmic contact for sample A.

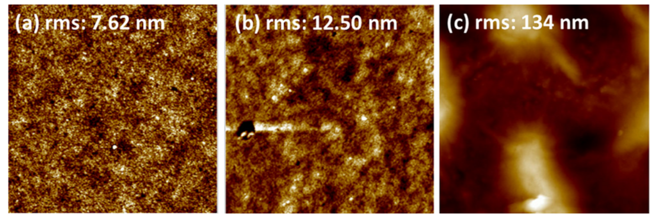

FIG. 2. AFM images of $10\,\mu m \times 10\,\mu m$ area for ohmic contact with (a) Ti/Al/Ni (50 Å)/Cu, (b) Ti/Al/Ni(250 Å)/Cu and (c) Ti/Al/Ni(250 Å)/Au structure. The vertical scales on the images are (a) 53.8 nm, (b) 84 nm, and (c) 830.8 nm, respectively.

Besides contact resistance, the surface roughness of the ohmic contact is another important issue. A rough surface may cause a poor edge acuity, which is undesirable for short-channel device fabrication. Figure 2 shows the AFM scans on a 10×10 μm^2 area of samples B, C, and D. Sample A had a serious peeling problem and was excluded from further analysis. Sample B with 50-Å Ni demonstrated the best surface morphology with a root-mean-square (rms) roughness of 7.62 nm. For sample C (250 Å-thick Ni), the rms roughness (12.50 nm) was slightly worse. Both samples show a much smoother surface compared to that of sample D (rms = 134 nm). The rough Ti/Al/Ni/Au surface is a common issue and the roughness might be induced by the Au-Al and NiAl alloys as proposed by Gong *et al.*[18] However, we believe that the Au-Al alloys played a much more significant role. This can be supported by comparing the samples B and C, both without the Au layer. The surface roughness of the latter was only slightly worsened even with a five-fold increase in the Ni layer thickness. In addition to the surface morphology improvement, the Cu-based ohmic contact also showed much better edge acuity (Figure 3).

In order to gain an insight into the composition change of the Cu-based ohmic metals, depth profiling AES analyses were performed on sample B. Figure 4 shows the AES spectra of sample B before and after RTA. Before annealing, all

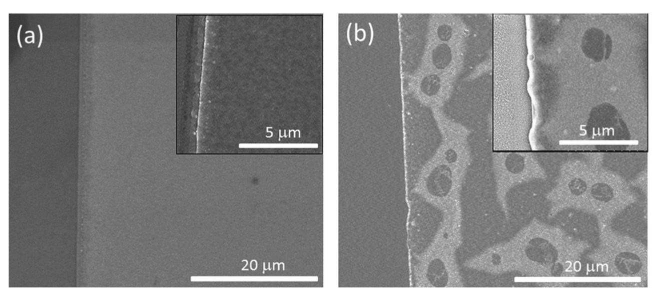

FIG. 3. Plan-view SEM images show the surface morphology of (a) Ti/Al/Ni (50 Å)/Cu and (b) Ti/Al/Ni(250 Å)/Au structure. Insets show the larger magnification images at the edge of the contacts.

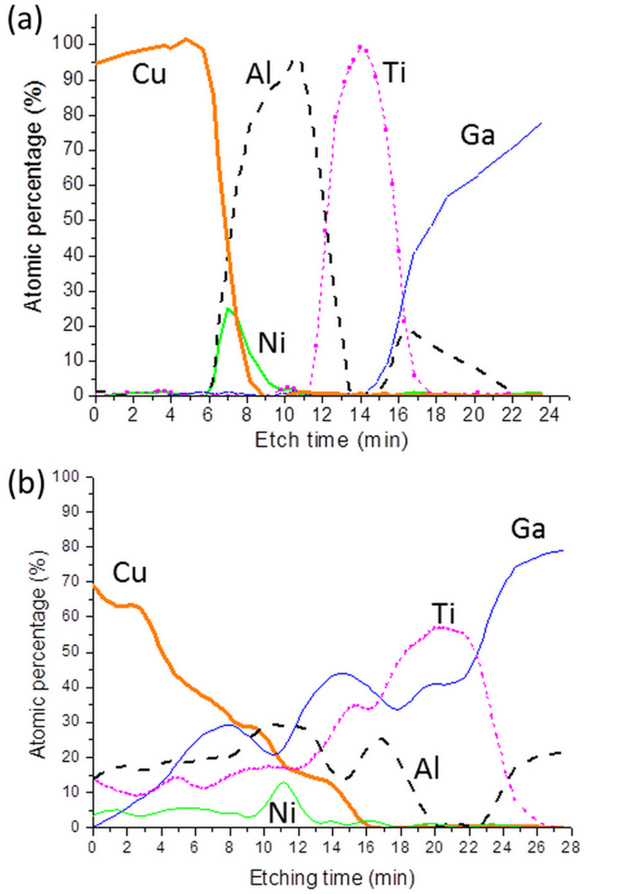

FIG. 4. Depth profiling Auger results of Ti/Al/Ni (50 Å)/Cu ohmic contact (a) before and (b) after high temperature annealing.

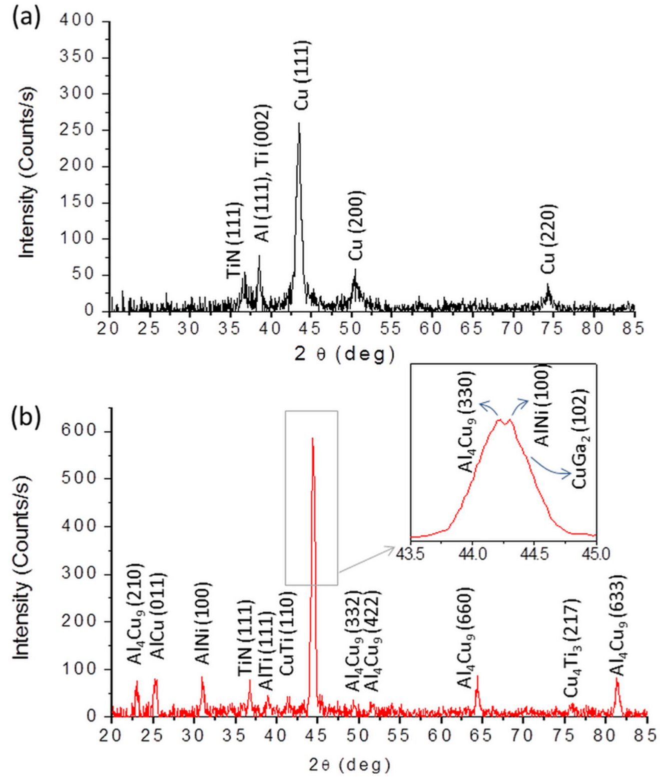

FIG. 5. XRD results of Ti/Al/Ni(50 Å)/Cu ohmic contact (a) before and (b) after high temperature annealing.

the metal layers had a clear boundary with minimum inter-diffusion. The small Ni spectrum is seen embedded in that of Al. This is because the Ni layer was very thin (5 nm) and the Auger electrons could be detected from a depth of a few nanometers below the material surface depending on the material investigated.[19] Furthermore, the thin Ni deposited using the evaporator might not develop into a continuous film and locally exposed Al-layer underneath would have caused the coincidence of Ni and Al profile in the Auger spectrum. On the other hand, for sample after annealing, intermixing of metals was clearly observed (Figure 4(b)). All elements out-diffused towards the surface except Cu. The result shows that Cu could easily diffuse into various metals but the diffusion was seen stopped at a depth corresponding to the initial Ti thickness. Although the thin Ni layer might not be an effective diffusion barrier to Cu, but the intermixing of these metals could have led to the formation of compounds that prevented the Cu from diffusing into the semiconductor layers.

The XRD results give clues about the formation of metallic alloys after the intermixing. Figure 5 shows the XRD analysis on sample B. There is a striking difference between the as-deposited and after high temperature annealing samples. As seen in Figure 5(a), the XRD peaks of the as-deposited sample indicate mainly the pure metals. This is in agreement with the Auger analysis. On the other hand, the result of the annealed sample shows that various alloys, especially Al-Cu and Ti-Cu based alloys were formed. A strong peak observed at around 44.25° could probably be attributed to the Al_4Cu_9 ($2\theta = 44.22°$), AlNi ($2\theta = 44.31°$), and $CuGa_2$ ($2\theta = 44.39°$) (inset of Figure 5(b)). The $CuGa_2$ compound was associated with the out-diffusion of Ga as shown in the Auger results. Other Cu-based alloys formed included CuTi ($2\theta = 41.11°$) and Cu_4Ti_3 ($2\theta = 75.64°$). Besides the Cu-based alloys, solid solutions that normally occurred in a Ti/Al-based ohmic contact such as AlTi ($2\theta = 38.72°$) and TiN ($2\theta = 36.62°$)[20] were also detected. Generally, the TiN signal represents the existence of a thin polycrystalline TiN layer formed at the Ti-GaN interface when Ti was first deposited on the GaN materials.[3,20,21] This TiN layer played an important role in achieving low contact resistance because the formation of TiN could lead to the supersaturation of nitrogen vacancies at the semiconductor surface to generate a highly N-doped layer.[22,23] On the other hand, the partial decomposition of GaN material near the interface might have promoted the out-diffusion of Ga atoms.[14] The TiN signal was also detected on the as-deposited sample (Figure 5(a), $2\theta = 36.66°$). This observation was also reported by Ruvimov and co-workers[3] but the reason was left unexplained. In short, it should be noted that no pure metallic peak was detected on the annealed sample, indicating that all the deposited pure metals had been transformed into different alloys. The formation of large amounts of Ti-Al-Cu alloy as observed in both Auger and XRD is the result of high diffusivity of Cu and strong interaction between Al and other metals. Such Ti-Al-Cu alloys were thermally more stable than the pure Cu and thus forms stable ohmic contact for GaN devices. The fact that a good ohmic behavior was obtained implied that Cu was completed consumed and no trace was left to contact with or diffuse into the semiconductor.[15] This is consistent with the Auger result that the Cu signal was stopped at Ti layer. Nevertheless, further study of the reliability of Cu-based ohmic contacts is needed for future device applications.

An ohmic contact of Ti/Al/Ni/Cu with AlGaN/GaN has been fabricated with low specific contact resistance, smooth surface morphology, and excellent edge acuity. The Ni layer thickness was found critical to the contact resistance and surface morphology. With a 50-Å Ni layer, a low r_c of 1.35×10^{-6} Ω-cm^2 was achieved. Similar to the Au-based ohmic contact, the formation of TiN alloy might have contributed to the low contact resistance of the Cu-based ohmic contact. The results also suggested that no Cu diffused into the semiconductor layers, and it rather interacted with Ti and Al to form more stable Ti-Al-Cu alloys. Furthermore, due to the absence of Au-Al alloys of the Au-based ohmic contact system, the surface morphology and edge acuity of the Ti/Al/Ni/Cu ohmic contact was also significantly improved. The current study suggests that the Ti/Al/Ni/Cu metallization has a great potential to be used as the ohmic contact for AlGaN/GaN devices.

This work was supported in part by the Ministry of Economic Affairs and in part by National Science Council of Taiwan under research Grant Nos. 101-EC-17-A-05-S1-154 and NSC 101-2221-E-009-173-MY2.

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