Optimization of Ohmic Contact Metallization Process for AlGaN/GaN High Electron Mobility Transistor

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Received May 18 2012, Accepted December 14 2012

In this paper, a manufacturing process was developed for fabricating high-quality AlGaN/GaN high electron mobility transistors (HEMTs) on silicon carbide (SiC) substrates. Various conditions and processing methods regarding the ohmic contact and pre-metal-deposition BCl3 etching processes were evaluated in terms of the device performance. In order to obtain a good ohmic contact performance, we tested a Ti/Al/Ta/Au ohmic contact metallization scheme under different rapid thermal annealing (RTA) temperature and time. A BCl3-based reactive-ion etching (RIE) method was performed before the ohmic metallization, since this approach was shown to produce a better ohmic contact compared to the as-fabricated HEMTs. A HEMT with a 0.5 μm gate length was fabricated using this novel manufacturing process, which exhibits a maximum drain current density of 720 mA/mm and a peak transconductance of 235 mS/mm. The X-band output power density was 6.4 W/mm with a 53% power added efficiency (PAE).

Keywords: AlGaN/GaN, High electron mobility transistor (HEMT), Ohmic contact, SiC substrate, Reactive-ion etching (RIE)

1. INTRODUCTION

Due to their high frequency power handling capability, wideband gap, high-breakdown voltage, high current density, and high saturation velocity, AlGaN/GaN HEMTs have emerged as a promising candidate for next generation commercial wireless communication systems [1-3]. Most HEMTs are grown on sapphire [4-6], silicon [7-9], or SiC [10-12] substrates. SiC substrates are presently the best choice for epitaxial growth because of their excellent crystal quality and have been used in devices with the highest output power densities.

Low-resistance ohmic contacts are essential parts of HEMTs and are needed to achieve high current densities and high extrinsic gains, which are required to obtain high thermal stability and a smooth surface morphology [13,14]. In this study, we consider a SiC-based AlGaN/GaN HEMT fabrication process, which is highly competitive in terms of device performances. Several optimized processes were presented with the goal of improving the device characteristics. The formation of low resistance ohm contacts to HEMTs is a key issue in the fabrication process of AlGaN/GaN HEMTs. These ohmic contacts are required to produce a smooth surface morphology and well-defined edge acuity [15]. Pre-metal-deposition ion etching is also a widely used technique for improving metal to semiconductor contact resistivity in HEMT [16].

In this paper, we present a Ti/Al/Ta/Au-based metallic system that forms ohmic contacts under different annealing conditions, which can provide a reliable solution for AlGaN/GaN HEMT applications with superior electrical, morphological, and microstructural properties. Furthermore, a BCl3 pre-metal-deposition RIE was used to fabricate an AlGaN/GaN heterostructure for improving metal contact resistance. Standard transmission line model (TLM) and atomic force microscopy (AFM) measurements were used to investigate the Ti/Al/Ta/Au-based ohmic contact structure. When this device was analyzed, a record power density of 6.4 W/mm for a 0.5 μm gate-length AlGaN/GaN HEMT on SiC was achieved which is needed for X-band applications (Fig. 6). This device also exhibited a maximum PAE of 53%, a power gain of 9.0 dB, a current density of 720 mA/mm, and a peak transcon-
ductance of 235 mS/mm.

2. EXPERIMENTS

The AlGaN/GaN epi-layers were grown using metal organic chemical vapour deposition (MOCVD) on a 4-in SiC substrate. The device fabrication started with an initial passivation layer consisting of SiO₂ deposited by plasma-enhanced chemical vapour deposition (PECVD). The mesa isolation process was then performed using the RIE. Before the ohmic contact was established, BCl₃ RIE treatment was carried out for 10, 20, and 30 s etches. The source and drain ohmic contacts, with a source-drain spacing Lsd of 6 μm, were achieved by the evaporation of Ti/Al/Ta/Au (20/80/40/100 nm) followed by an RTA at 850, 900, and 950 ℃ for 30 and 60 s, respectively. The specific contact resistances ($\rho_c$) were recorded based on TLM measurements; the contact metals were separated by 2, 4, 8, 16, and 32 μm. The circular TLM data indicated a $\rho_c$ of below $10^{-5}$ ohm·cm² with a sheet resistance of around 350 ohm·cm². After that, a Ni/Au (40/400 nm) gamma gate with a length of 0.5 μm, was formed between the source and drain ohmic contacts. The passivation process was performed after all of the aforementioned steps, followed by the forming of vias to open the metal contacts. DC current-voltage (I-V) and RF performance was measured to characterize the electrical properties of the device. The DC I-V measurements employed a $V_{DS} = 0$ to 15 V and a $V_{GS} = 2$ to -5 V. The load-pull measurements were performed at 10 GHz using an active load-pull setup under probes, permitting one to get the optimum load impedance, particularly for the smaller transistors. The cross-sectional schematic and the layout diagram of an AlGaN/GaN HEMT on a SiC substrate is shown in Fig. 1.

2.1 Ohmic contact process

The metallization scheme uses Ti/Al/Ta/Au with a thickness of 20/80/40/100 nm. A deoxidation process using HCl/H₂O (1:10) for 20 s and distilled water cleaning for 480 s, and smooth O₂/H₂ plasma-etching was performed using a UHVAC microwave ash with a gas mixing rate of 9,000/450 sccm, a working pressure of 2 Torr, a chuck temperature of 80 ℃, and an RF power of 550 W for 20 s in order to remove the native oxides in the ohmic contact area. The metals were deposited by e-beam evaporation, followed by a lift-off process. After lift-off, the samples were sequentially annealed under an N₂ flow at annealing temperatures ranging from 850 ℃ to 950 ℃ over 30 or 60 s. Figure 2 shows the behavior of the $\rho_c$ as a function of the annealing temperature and the annealing time for all of the samples. A better ohmic contact was observed when the annealing time increased from 30 s to 60 s. In addition, the contact resistance decreased as the annealing temperature increased from 850 ℃ to 900 ℃; the lowest value of $3.25 \times 10^{-5}$ ohm·cm² was obtained at an annealing temperature of 900 ℃ and an annealing time of 60 s. In the fabricated ohmic contact metallization structure, Ti is essential because it participates in the reaction at the interface with nitrides to form TiN or AlTi₂N layers by high-temperature RTA, and nitride vacancies are
simultaneously formed at the AlGaN/GaN surface. At the same time, the diffused Ti and Al reduce the native gallium oxide on the AlGaN/GaN surface. Au is applied as an outer layer to prevent the oxidation of the Ti/Al metals during the RTA process. In addition, a diffusion barrier layer Ta is applied to prevent or minimize the Au upper layer from diffusing downward. The ohmic contact is formed by the reaction between the Ti and the AlGaN, which produces TiN. In addition, there is a high potential barrier between the Ti and the AlGaN. The Al atoms diffuse through the Ti layer to enable a low work function for the Al-Ti with an intermetallic phase to relieve the barrier. When the annealing temperature is low and the annealing time is insufficient, the ohmic contact property is poor due to the limited amount of Al and Ti. With an increase in the annealing temperature and annealing time, a great deal of Al diffuses into the AlGaN surface and reacts with the Ti, resulting in a reduction in the resistance. Significant intermetallic diffusions - an in-diffusion of Au towards the AlGaN interface and an out-diffusion of Al towards the contact surface occur when the temperature increases beyond 900 °C, which causes a degradation in the contact characteristics. The surface morphologies of the ohmic contact metallization at different annealing temperatures are shown in Fig. 3. In addition, considerable differences were observed in their surface morphology. The surface morphology was smooth after annealing at 850 °C or 900 °C. But after annealing at 950 °C, the ohmic contact surface morphology was degraded. Various sized semispherical bulges were found to be randomly distributed on the surface, including some that cracked and broke apart. The smoother surface was probably due to the reaction between the different metals and no excessive Al remained. Therefore, a temperature as high as 900 °C was deemed to be the best, since the lowest contact resistance and a relatively smooth surface morphology was obtained under these conditions.

2.2 Pre-metal-deposition BCl\textsubscript{3} etching process

The pre-metal-deposition BCl\textsubscript{3} process was implemented before the ohmic contact formation using an inductively coupled plasma (ICP) etching system. The ICP etching conditions were as follows: 100 W input power, 5 sccm BCl\textsubscript{3} flow, and 10 mTorr pressure. Three different etching times (10, 20, and 30 s) were used and the results were compared to the un-etched samples. An initial decrease in \(\rho\) was observed with an increase in the etching time. As shown in Fig. 4, the \(\rho\) decreased from 3.25 × 10\textsuperscript{-5} ohm-cm\textsuperscript{2} for un-etched ohmics to about 7.74 × 10\textsuperscript{-5} ohm-cm\textsuperscript{2} for 20 s etch. A slight increase in \(\rho\) was observed when the etch time was 30 s, which was most likely due to the non-uniformities in AlGaN thickness and composition. Thus, a RIE time of around 20 s was determined to be optimal.

3. RESULTS AND DISCUSSION

In this study, optimal RTA conditions and a pre-metal-deposition etching method was identified to minimize the contact resistance. To achieve this, the properties of Au/Ta/Al/Ti/AlGaN/GaN/AlN/SiC under different annealing conditions were investigated. In these experiments, the annealing process was shown to affect Al diffusion to the AlGaN surface to create N vacancies and were found to simultaneously react with the Ti and Au resulting in the formation of TiAl and AuAl phases. The concentration of N vacancies led to heavy doping and, hence, a reduction in the contact resistance. An initial decrease in the contact resistance with etching time was observed due to the removal of an oxide surface layer and/or to an increase in tunneling transport with a decrease in the AlGaN thickness. The presence of a dissimilar surface layer was confirmed by an initial non-uniform behavior in etch depth as a function of etch time. In order to obtain an efficient large signal operation, it is critical to fabricate HEMTs with a low parasitic gate and drain currents as well as minimized carrier trapping. The high voltage stability of the HEMTs was investigated in three-terminal configuration with the breakdown voltage defined at a current density of 1 mA/mm. Figure 5 shows the gate-drain breakdown voltage of the AlGaN/GaN HEMTs. The gate-drain breakdown voltage was better than 140 V and even at 100 V drain bias the parasitic drain currents under the pinch-off conditions were well below 1 mA/mm. This result demonstrates the excellent high-voltage stability of the HEMT.
The SiC substrate with the high-quality MOCVD-deposited epi-layers and the optimized ohmic contact process enabled us to develop high-performance AlGaN/GaN HEMTs. The DC and RF properties were determined to evaluate the device performance. The DC transfer characteristics of the $2 \times 0.5 \mu m^2$ HEMT recorded at a drain source voltage of 10 V are shown in Fig. 6 (a). A maximum drain-source current of 720 mA, a peak transconductance of 235 mS/mm, and a threshold voltage of 3.6 V were achieved. Large signal measurements were performed using a load-pull system at 10 GHz. The device was biased at a drain bias of 25 V. The measured input power ($P_{in}$) versus the output power ($P_{out}$) responses of the device are illustrated in Fig. 6 (b), which indicate an output power density of 6.4 W/mm, PAE of 53.2%, and a gain of 9.0 dB.

The summary of the published X-band AlGaN/GaN HEMTs on different substrates is shown in Table 1. Based on these results, this ohmic contact process holds great promise for use in fabricating HEMTs for X-band high-power applications.

<table>
<thead>
<tr>
<th>Works</th>
<th>Substrate</th>
<th>Power density</th>
<th>PAE</th>
<th>Gain</th>
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<tr>
<td>[17]</td>
<td>Si (001)</td>
<td>2.9 W/mm</td>
<td>20%</td>
<td>7.0 dB</td>
</tr>
<tr>
<td>[18]</td>
<td>Si (111)</td>
<td>1.9 W/mm</td>
<td>18%</td>
<td>10.0 dB</td>
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<td>[19]</td>
<td>Diamond</td>
<td>2.08 W/mm</td>
<td>44.1%</td>
<td>14.6 dB</td>
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<td>[20]</td>
<td>Sapphire</td>
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<tr>
<td>[21]</td>
<td>SiC</td>
<td>4.1 W/mm</td>
<td>33.6%</td>
<td>6.13 dB</td>
</tr>
<tr>
<td>[22]</td>
<td>SiC</td>
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<td>25%</td>
<td>15 dB</td>
</tr>
<tr>
<td>[23]</td>
<td>SiC</td>
<td>5.06 W/mm</td>
<td>34.7%</td>
<td>11.8 dB</td>
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</table>

This work SiC 6.4 W/mm 53.2% 9.0 dB

4. CONCLUSIONS
In this study, a 0.5 μm gamma-gate AlGaN/GaN HEMTs fabricated on SiC substrates was evaluated. In order to meet the performance improvement requirements needed for high power applications in microwave systems, we proposed using an optimized ohmic contact process that minimizes the specific contact resistance. The DC and RF performances of this device were shown to be excellent. Based on these results, this ohmic contact manufacturing process holds great promise for use in fabricating HEMTs for X-band high-power applications.

ACKNOWLEDGMENTS
This research was supported by the National Research Foundation of Korea (NRF) and a Grant supported from the Korean government (MEST) No. 2012R1A1A2004366 and No. 2012-0009224. This work was also supported by a Research Grant of Kwangwoon University in 2012.

REFERENCES