Molecular Beam Epitaxy Regrowth of Ohmics in Metal-face AlN/GaN Transistors

Chuanxin Lian, Yu Cao, Ronghua Wang, Guowang Li, Tom Zimmermann, Debdeep Jena, and Huili Xing

Department of Electrical Engineering, University of Notre Dame, Indiana 46556, USA
Email: clian@nd.edu; Phone: 1-574-6310755

Keywords: AlN, GaN, Transistor, Ohmic, Regrowth

Abstract

Selective-area regrowth of source/drain was studied for metal-face AlN/GaN high electron mobility transistors (HEMTs) using molecular beam epitaxy. Heavily doped graded n-type InN/InGaN/GaN was regrown to reduce the source/drain contact resistance. For the 70 nm regrown material, a sheet resistance of ~ 100 Ω/sq and a contact resistance of ~ 0.2 Ω.mm were extracted using non-alloyed Ti-based metal contacts. But the ohmic contact resistance and sheet resistance of the HEMTs with regrown source and drain were found to be yet high using the current processes.

INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs) have established themselves in high speed high power electronic applications. The primary advantages of AlGaN/GaN systems stem from such material properties as large energy bandgap and therefore large breakdown field, heterostructure design freedom, unique polarization-induced two dimensional electron gas (2DEG) with both high electron density and mobility, and excellent stability at harsh thermal and chemical environment. AlGaN/GaN HEMTs with extracted f_t/f_{max} values in the 100 – 300 GHz regime have been reported by scaling down the gate length to sub-100 nm and gate recess techniques [1, 2]. To further improve the device performance, AlN/GaN heterostructures has been touted as a suitable candidate. Compared with AlGaN/GaN, AlN/GaN structures allow very small gate-2DEG distance (~ 1-4 nm) for the ease of vertical scaling while maintaining decent 2DEG properties: large 2DEG density, high mobility and good charge confinement. Very low sheet resistance of ~ 150 Ω/sq has been reported in AlN/GaN with a 4.0 nm thick AlN film [3]. Maximum dc output current density of ~ 2.3 A/mm and peak extrinsic transconductance (g_m) of ~ 480 mS/mm have been demonstrated in ultra-thin AlN/GaN HEMTs [4]. Besides downscaling of the device dimension, low source/drain contact resistance is also required for high frequency performance. By far, the ohmic contact resistance on AlN/GaN heterostructures is usually above 0.4 Ω·mm due to the large energy barrier height of AlN [5]. Although Si implantation could be an approach to reduce the ohmic contact resistance [6], the high temperature annealing (> 1200 °C) following the implantation can degrade the AlN/GaN material properties given the material growth temperature is normally below 700 °C by molecular beam epitaxy (MBE). Source/drain regrowth has been successfully demonstrated on nitrogen-face GaN HEMTs and a contact resistance as low as ~ 0.06 Ω.mm was reported recently [7]. In this work, we explored the source/drain regrowth with heavily-doped (In)GaN materials on metal-face AlN/GaN heterostructures and present the preliminary results.

EXPERIMENTS

The AlN/GaN heterostructure sample used in this work has a 4 nm AlN layer with 2DEG density of 3.1×10^{13} cm^{-2} and mobility of 1193 cm^2/V.s resulting in sheet resistance of 170 Ω/sq. The sample was grown by MBE in a Veeco Gen 930 system. More growth details can be found in Ref [3]. Selective-area growth was done by using tungsten as regrowth mask. The detailed process flow is illustrated in Fig. 1. Tungsten film (~ 30 nm thick) was first deposited by e-beam deposition on top of AlN/GaN. Source/drain regions were exposed by removing W in SF_6 plasma followed by BCl_3/Cl_2 plasma etching of AlN/GaN in the same RIE system. The etched AlN/GaN thickness in total is ~ 50 nm. Smooth GaN surface after plasma etching with local RMS ~ 6 Å was achievable. Regrowth was performed in the same MBE system as used for the HEMT structure growth. The growth was in the metal-rich regime and the thermocouple temperature (T_c) was 660 °C. A 20 nm Si doped GaN layer was first grown on the patterned HEMT sample, followed by a 30 nm-thick graded GaN→InN layer with T_c decreasing to 400 °C. Finally, a ~ 20 nm Si doped InN cap layer was grown at 400 °C. The Si doping concentration, in the order of 10^{20} cm^{-3}, was kept the same during the whole growth. The same materials were also regrown on a bare SI-GaN substrate as the control sample. After the regrowth, some amorphous material was observed on the tungsten mask. Molten KOH was used to remove the amorphous material while the crystalline InN/InGaN/GaN material was protected by patterned PECVD SiN_x. Finally, tungsten and SiN_x were removed by wet etching in H_2O_2 and BHF, respectively. The regrown structures were characterized by atomic force microscope (AFM) and secondary electron microscope (SEM). Transfer Length Method (TLM) device structures with non-alloyed Ti-based contacts were measured to extract the sheet resistance and the contact resistance.

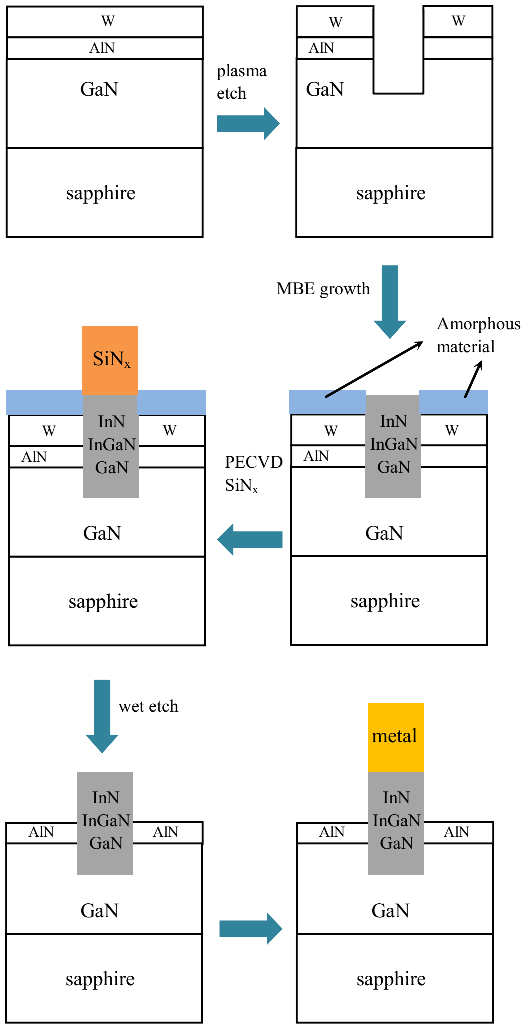

Fig. 1 Process flow of source/drain selective-area regrowth.

RESULTS AND DISCUSSIONS

TLM measurements on the control sample indicated that the regrown Si-doped InN/InGaN/GaN had a sheet resistance of ~ 100 Ω/sq, and a contact resistance as low as 0.2 Ω·mm with non-alloyed Ti-based ohmic contacts, as shown in Fig. 2. The challenge of source/drain regrowth on the AlN/GaN HEMTs, however, is to make zero-barrier intimate contact between the regrown region and 2DEG while keeping the 2DEG properties intact during the whole process. In the first regrowth experiment, a gap was observed between the regrown material and the transistor channel, revealed by both AFM and SEM, as shown in Fig. 3. This gap prevents low-resistance contact between the regrown structure and 2DEG, causing unacceptably large access resistance. It can also be seen that the top InN film is

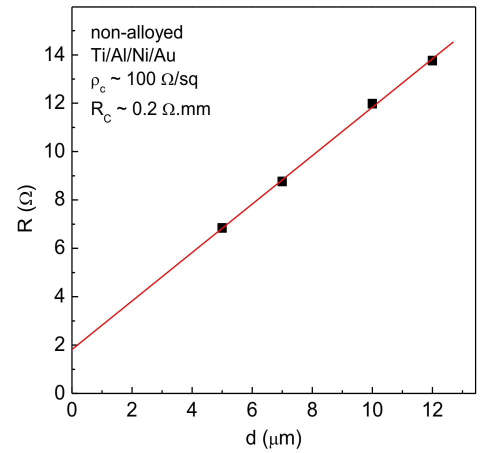

Fig. 2 TLM results on regrown Si-doped InN/InGaN/GaN.

not continuous although the surface looks smooth on individual islands. The thickness of InN is only ~ 20 nm, while the gap depth is ~ 70 nm, almost the total thickness of the entire regrown InN/InGaN/GaN structure. So the gap

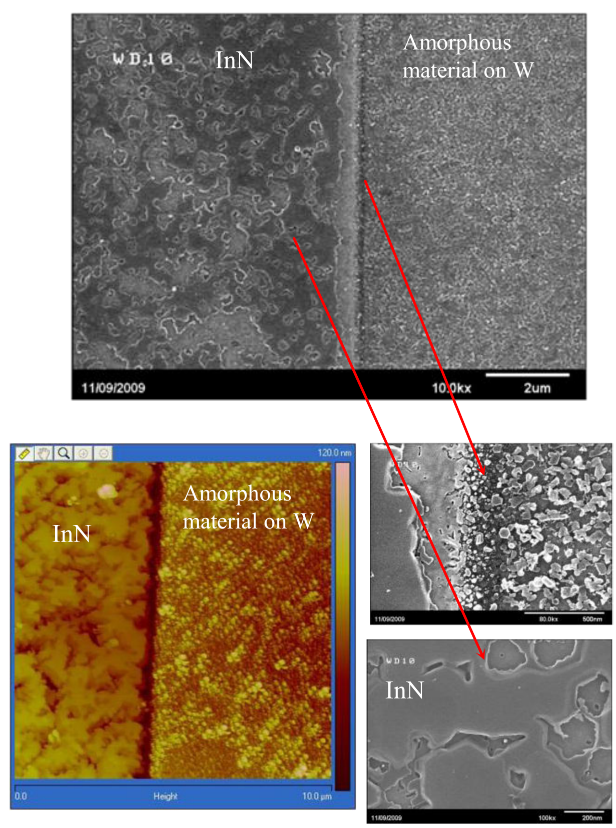

Fig. 3 AFM and SEM images show a gap between the regrown region and 2DEG.

most likely had started to form at the beginning of the regrowth. After exploring several regrowth conditions, encouraging results have been achieved. The images in Fig. 4 show a HEMT sample with regrown source/drain areas after removing the tungsten mask. As shown by both AFM and SEM images, no gap is seen between the regrown structure and the active HEMT region. The InN film also looks more continuous than before. Non-alloyed Ti-based was deposited on the regrown source/drain areas sandwiching HEMT channels and TLM patterns were measured. Unfortunately, the sample was found to suffer from very large resistances. There are a couple of possible reasons. First, although both AFM and SEM images show intimate contact between the regrown material and the HEMT region, it is possible that there is a very small disconnection which cannot be detected by either AFM or SEM. TEM investigation is currently under way to zoom into the regrowth-sidewall interface. Second, the 2DEG transport properties could be damaged under the current process flow or regrowth conditions such as plasma etching, high temperature, and surface treatment, etc. Detailed studies are being carried out to find the cause of the high resistances observed after regrowth.

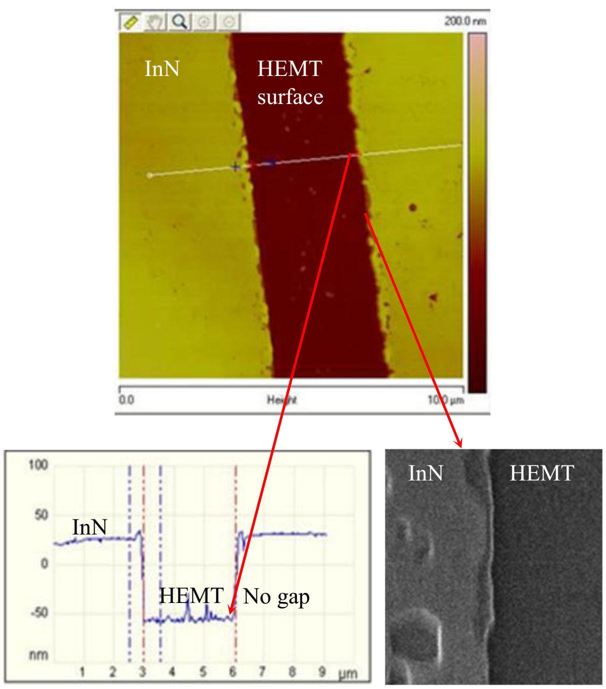

Fig. 4 AFM and SEM images show intimate contact between the regrown material and the sidewall.

CONCLUSIONS

Heavily doped InN/InGaN/GaN layers were regrown in the source/drain areas of ultrathin barrier metal-face AlN/GaN HEMTs using MBE. The regrown materials have decently low sheet resistances and non-alloyed contact resistances. Intimate contact between the regrown materials and the active HEMT region has been confirmed by AFM and SEM. Given the 2DEG-surface distance is only a couple of nanometers, it is more challenging to perform regrowth on AlN/GaN than on AlGaN/GaN structures with a thicker barrie (> 20 nm) [8]. Further studies will focus on achieving low contact resistance between the regrown souce/drain and the HEMT channel.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support from: John Albrecht, Harry Dietrich, and Mark Rosker from the Defense Advanced Research Projects Agency (DARPA NEXT program HR0011-10-C-0015), Kitt Reinhardt from the Air Force Office of Scientific Research (AFOSR-FA9550-09-1-0198), and Paul Maki from the Office of Naval Research.

References

[1] M. Yan, et al., IEEE Electron Device Lett. **30**, 913 (2009)
[2] J. Chung, et al., ICNS Y1, Jeju Island, Korea, 2009
[3] Y. Cao, et al., Appl. Phys. Lett. **92**, 152112 (2008)
[4] T. Zimmermann, et al., IEEE Electron Device Lett. **29**, 661 (2008)
[5] T. Zimmermann, et al., Phys. Stat. Sol. (c) **5**, 2030 (2008)
[6] F. Recht, et al., IEEE Electron Device Lett. **27**, 205 (2006)
[7] Nidhi, et al., EMC F5, PSU, USA, 2009
[8] H. Seo, et al., Appl. Phys. Lett. **93**, 102102 (2008)

ACRONYMS

HEMT: High Electron Mobility Transistor
2DEG: Two Dimensional Electron Gas
MBE: Molecular Beam Epitaxy
PECVD: Plasma Enhanced Chemical Vapor Deposition
BHF: Buffered Hydrofluoric Acid
RIE: Reactive Ion Etching
TLM: Transfer Length Method
AFM: Atomic Force Microscopy
SEM: Scanning Electron Microscopy
TEM: Transmission Electron Microscopy
RMS: Root Mean Square