Ultra-low ohmic contacts to N-polar GaN HEMTs by In(Ga)N based source-drain regrowth by Plasma MBE

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Abstract

For highly scaled submicron HEMTs, ultra-low ohmic contact resistances are required to reduce the drop in intrinsic g_m (transconductance) of the device to obtain higher f_t and f_{max}. Moreover, for self-aligned HEMT structures, reducing the ohmic contact resistance becomes the most pivotal issue in attaining better small signal performance and cutoff frequencies. N-face GaN HEMTs, growth direction $(000\bar{1})$, offer a natural advantage for this issue over Ga-face GaN HEMTs, since the ohmic contact to the 2DEG is made through GaN, with lesser band-gap, than AlGaN. In this work we extend the advantage of N-face HEMTs by making use of polarization induced charges through re-growth of graded InGaN ohmic contact regions, to obtain ultra-low and record ohmic contact resistances. An ohmic contact resistance of 27 Ω µm was obtained to a N-face GaN HEMT by regrowth of graded InGaN capped with a thin layer of InN by plasma MBE. To the best of our knowledge, these are the lowest ever reported ohmic contact resistances to a GaN 2DEG.

INTRODUCTION

In recent years Ga-face AlGaN/GaN HEMTs have demonstrated high RF output power[1] and small signal performance[2]. However, the small signal performance of these devices is limited due to parasitic resistances. As devices are scaled and gate lengths reduced, the parasitic delay τ_p due to high source and drain ohmic contact resistances, become a substantial part of the total delay ($\tau_{total} = \tau_p + \tau_{int} + \tau_{drain}$) and thus limit the values of f_t and f_{max} of the transistor[3]. Several efforts have been undertaken to reduce the ohmic contact resistance for Ga-face AlGaN/GaN HEMTs, by methods such as highly doped n+ cap GaN layer, selective implantation of Si near the source and drain contacts[4,5,6].

N-face HEMTs have recently demonstrated excellent RF performance and output power and efficiency[7,8,9]. Due to the reversal of polarization fields, N-face HEMTs offer several advantages over Ga-face HEMTs; such as a natural back barrier for stronger electron confinement, ohmic contact to a lower band-gap material (GaN in this case), and the possibility of InN channel HEMTs[10]. Since the metal to 2DEG does not have a high barrier material (like AlGaN) in between, N-polar HEMTs offer a possibility of drastic improvement of ohmic contact resistances. Recently, a n+ GaN cap layer for the source and drain contacts have yielded an ohmic contact resistance of 0.16 Ω mm to the N-face GaN 2DEG[11].

It has been experimentally shown that the conduction band in InN is pinned below the surface Fermi level, which results in a surface electron accumulation layer [12] with densities as high a $1 \times 10^{13} cm^{-2}$. Hence, a metal to InN contact would be an ideal ohmic contact, with very minimal barrier. However due to the high ΔE_c between GaN and InN, we need a thin graded layer in between the GaN 2DEG and InN-metal interface to form an ohmic contact. For N-face GaN, linearly graded InGaN (from GaN → $In_xGa_{1-x}N$) induces a 3DEG (3 dimensional electron gas) due to polarization induced charges[13]. (Figure 1b) Thus an ohmic contact through a surface accumulated electron layer at the InN and a 3DEG due to a graded InGaN layer should be a least resistance path for the flow of electrons to the 2DEG. In this work we hence combine a gate first process, for a self aligned HEMT, and regrowth of InN/graded-InGaN source-drain ohmic contact regions by plasma MBE to obtain ultra-low ohmic contact resistances to the 2DEG.

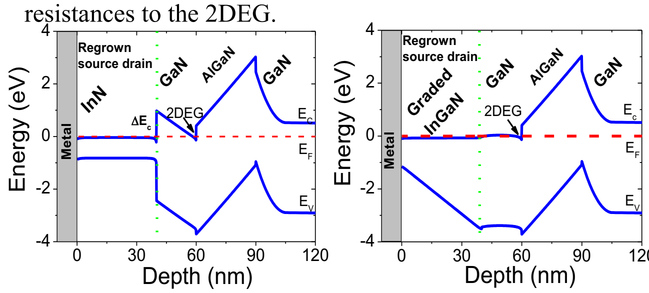


Fig. 1 (a) Simulated band diagram of InN regrown source drain to a N-polar GaN HEMT. The high ΔE_c at the InN and GaN interface is a barrier to the flow of electrons from the metal to the 2DEG.
(b) Simulated band diagram of InGaN graded from GaN → InN for source drain regions of a N-polar GaN HEMT.

EXPERIMENT

The N-face HEMT samples for this study were grown both on C-face SiC 4H by plasma MBE and on miscut sapphire (4° towards 'a') by MOCVD[14]. The 2DEG density for the samples (both by MBE and MOCVD) were measured to be $\sim 1 \times 10^{13} cm^{-2}$ and had room temperature Hall mobilities in the range of 1200 – 1400 cm^2/Vs. After the epitaxial growth of the N-face HEMT gate metal was deposited by a gate-first process for regrowth[15]. This process has been adapted from self-aligned InGaAs MOSFET technology[16]. Gate formation involved blanket deposition of sputtered W followed by e-beam evaporation of Cr and plasma-enhanced chemical-vapor-deposition of SiO_2. The gate was then defined by projection stepper lithography and the subsequent layers in the gate metal stack were then etched. To prevent conduction between gate metal and regrown layers, a SiN_x spacer was formed by blanket deposition of PECVD SiN_x followed by a vertical etch.

The N-face HEMTs with the gate metal deposited on them, were cleaned ultrasonically in acetone, methanol and iso-propanol and then loaded into the MBE chamber. They were outgassed at 450°C for one hour prior to loading in the main chamber. For all the regrowth experiments, high purity In and Ga effusion cells were used as the group III source. An AppliedEpi Unibulb rf-plasma source was used to supply active Nitrogen for growth. In all the regrowths described here a N_2 flow rate of 0.4 sccm, and a plasma power of 300 W was used.

For the first set of experiments, regrowth of 50nm InN on N-face HEMT structures were done at different growth temperatures, to study the surface morphology, surface coverage, and metal to InN contact resistance.

In the second set of experiments, the second layer of the proposed ohmic contact regrowth stack, the graded GaN → InGaN layer was optimized. Two schemes were used for the grading of InGaN. In the first scheme, three samples were grown at different growth temperatures, but the initial and final Ga-fluxes for all the three samples were kept the same. Both the In incorporation and the surface morphology of the regrown layers were studied. In the second grading scheme, we chose an optimum growth temperature, for best surface morphology, and grading to a higher composition of InGaN was achieved by changing the final Ga-flux.

In the final set, both these optimized layers were put together to regrow the source and drain regions, with graded InGaN and an InN cap layer.

X-ray diffraction (XRD) ω-2θ scans were done using a Philips Materials Research Diffractometer operated in triple-axis mode. Scanning electron microscopy was used to study the surface coverage and the morphology and also the sidewall coverage of the gate stripe. The microstructure of the samples was further evaluated by transmission electron microscopy (TEM) with a FEI Tecnai20 operated at 200 kV.

The fabrication of electrical test structures started by removal of polycrystalline InN/InGaN layers regrown on top of the gate. A 1 µm thick layer of positive resist (SPR 510-A) was spun on the sample followed by etch-back in O_2 plasma to a resist height of ~ 180 nm, thereby exposing the top of the gate stripes. The InN/InGaN layers were then etched in BCl_3/SF_6 based inductively-coupled plasma chemistry. Ti/Au-based non-alloyed source and drain contacts were deposited by e-beam evaporator. The isolation of test-patterns was done by chlorine-based reactive-ion etching. Transmission-line measurement (TLM) was done to calculate the ohmic contact resistance. The regrown layers between the TLM patterns had been etched in BCl_3/Cl_2 chemistry to force the current to flow through the 2-dimensional electron gas for accurate measurement of ohmic contact resistance to the 2DEG.

RESULTS and DISCUSSION

Regrown InN layers

InN regrowth on N-face HEMT structure with the gate stripe was done at 4 different growth temperatures (475 °C, 500 °C, 525 °C and 575 °C). Figure 2 shows the cross section scanning electron microscope (CSSEM) images of the regrown layers. As shown in Fig.2 (a), for a growth temperature of 575 °C, there was no regrowth observed, but with decreasing temperature, a uniform film of InN was regrown (Fig.2(d)). In droplets were observed which are indicative of a group-III rich growth regime. Subsequently the III/V flux ratios were adjusted to ensure the growth of InN in the intermediate regime, and minimize In droplet accumulation. As shown in Fig. 2(e), a uniform InN film was grown with very less shadowing next to the gate stripe. Since selective area regrowth cannot be achieved by MBE, there is polycrystalline InN deposited on the gate and the sidewall. By subsequent processing steps, these are removed in the final device.

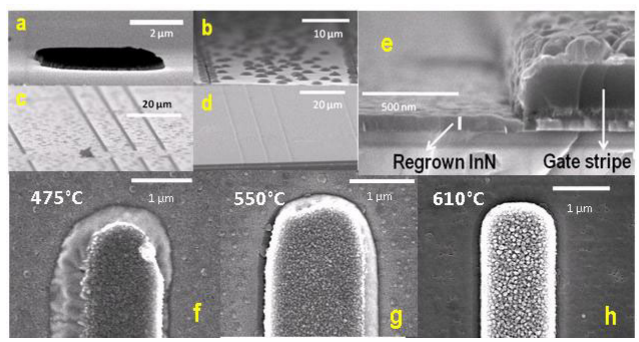


Fig. 2(a-e) Top view scanning electron micrographs of InN source-drain regions regrown at growth temperatures of (a) 575°C, (b) 525°C, (c) 500°C and (d) 475°C. (e) Cross-section SEM image of regrown InN source-drain region next to the gate stripe **(f-h)** Top view scanning electron micrographs of regrown graded InGaN layers grown at (f) 475°C (g) 550°C (h) 610°C

An ohmic contact resistance of 5 Ω-µm and a sheet resistance of 80 Ω/□ were obtained by TLM measurements of metal to regrown InN. This is attributed to the high surface electron density of InN, and the low sheet resistance could be explained by the nominally high background electron concentration of as-grown InN. However due to a high ΔE_c of ~1.5 eV between InN and GaN (Fig.1(a)), we could not make an ohmic contact to the GaN 2DEG through the regrown InN layer.

Regrown N-face Graded InGaN

Due to the reversal of polarization fields in N-polar nitrides, a linearly graded GaN → $In_xGa_{1-x}N$ epilayer results in the formation of a three dimensional electron gas (3DEG). The polarization induced 3DEG is used here to act as an intermediate layer for the conduction of electrons from the metal → InN → GaN 2DEG. With increasing In composition, the ΔE_c between the final InN cap layer and the graded InGaN layer decreases. Also all the graded InGaN films are grown with Si dopant, as a source of electrons for the 3DEG.

To maximize the In incorporation, which would result in a higher final InGaN composition, we tried one set of experiments in which the InGaN was graded by decreasing the Ga-flux from a initial Ga-flux (used for GaN growth) to a fixed final Ga-flux. Using this grading scheme, three different 40 nm graded InGaN films were regrown on N-face HEMT structures at three different growth temperatures (475 °C, 550 °C, and 610 °C). The In flux was adjusted to maintain a slightly group III growth rich regime for each growth temperature and minimize the formation of In droplets on the surface. Table 1a summarizes the grading obtained by this method, and with lowering the growth temperature, we observed an increase in the In incorporation in the InGaN film. Using this grading scheme we were able to obtain a linear grade from 1% InGaN to 43% InGaN at 475°C.

Fig. 2(f-h) shows the top view SEM images of the surface morphology of the graded InGaN films. We observe a sharp change in surface morphology with temperature, with lower growth temperatures the regrown layer becomes rougher and In metal droplets start accumulating near the gate sidewall. However for high growth temperatures, we obtain a very smooth uniform regrown InGaN layer with minimal In droplet accumulation near the sidewall. The rougher surface morphology and clustering of In metal near the gate could be attributed to the lower In adatom mobility as the growth temperature is reduced.

Growth Temperature (°C)	*Ga-flux variation (Torr)*	*$In_xGa_{1-x}N$ grade measured by HRXRD*
610	$3\times10^{-7} - 1.5\times10^{-7}$	1% to 26%
550	$2.8\times10^{-7} - 1.5\times10^{-7}$	1% to 35%
475	$2.4\times10^{-7} - 1.5\times10^{-7}$	1% to 43%

(a)

Growth Temperature (°C)	*Ga-flux variation (Torr)*	*$In_xGa_{1-x}N$ grade measured by HRXRD*
575	$3\times10^{-7} - 1.5\times10^{-7}$	1% to 30%
575	$3\times10^{-7} - 1\times10^{-7}$	1% to 54%
575	$3\times10^{-7} - 7.5\times10^{-8}$	1% to 63%

(b)

Table 1 (a) Different graded InGaN composition obtained by varying the growth temperature, and keeping the end Ga-flux constant. The In flux is adjusted to ensure III/V flux ratio ~ 1
(b) Second grading scheme in which the growth temperature was kept constant but the final Ga-flux was decreased to obtain higher In incorporation and steeper grading profile

TLM measurements of the ohmic contact resistance to the GaN 2DEG through the graded InGaN layers were done. The results are shown in Figure 5(a) (filled circles). With higher In incorporation the ohmic contact values increase which could be due to alloy fluctuations due to lower growth temperatures, or different surface pinning positions for the InGaN graded films. This phenomenon is not clearly understood at present, and the causes are being investigated. The best results were obtained for the 1 → 26% graded InGaN film grown at 610 °C.

A different grading scheme was investigated next to maximize In incorporation, while keeping the growth temperature high (~ 590°C - 600°C) to obtain both high In composition and maintain a good surface morphology. In this scheme, three samples were grown with a different final Ga-flux but keeping the grading thickness constant at 40 nm. We obtain a higher final InGaN composition by decreasing the final Ga-flux, and hence changing the linear grade, while maintaining a III/V ratio ~ 1 by careful adjustment of the impinging In flux. The results are summarized in Table 1(b) and we obtain a steeper linearly graded InGaN. The surface morphology of these films were also investigated by SEM and we did not observe considerable roughening even for the highest graded InGaN epilayer.

Thin InN cap and graded InGaN layer regrowth

In the final set of experiments, the results of the two previous experiments were combined to yield ultra-low ohmic contact resistances to a GaN 2DEG. Three different structures were regrown on the same N-face GaN HEMT structure and the ohmic contact resistances were measured. The 3 different structures (A,B,C) are summarized in Figure 3a and in Fig. 3b we show an ω-2θ HRXRD scan of the (0002) reflection of a graded InGaN layer and InN cap regrown epilayer (sample C). SIMS of the regrown source drain region (Fig.4a) shows the presence of an InN cap layer and linearly graded InGaN. Fig. 4(b) is a HRTEM image of the regrown interface, showing a sharp crystalline interface and minimal shadowing next to the gate region.

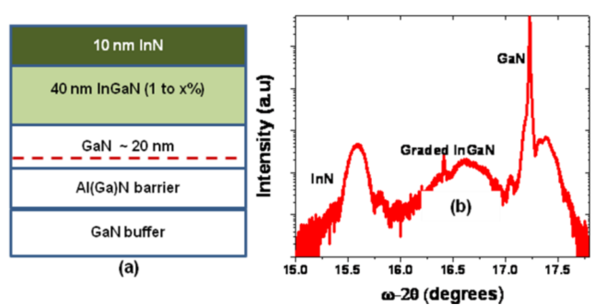


Fig. 3 (Color online) (a) Epitaxial structure of the samples with 40 nm InGaN graded from 1% to A (30%), B (54%) and C (63%) and 10 nm InN cap (b) HRXRD (ω-2θ) for sample C with peaks corresponding to regrown InN and graded InGaN indicated.

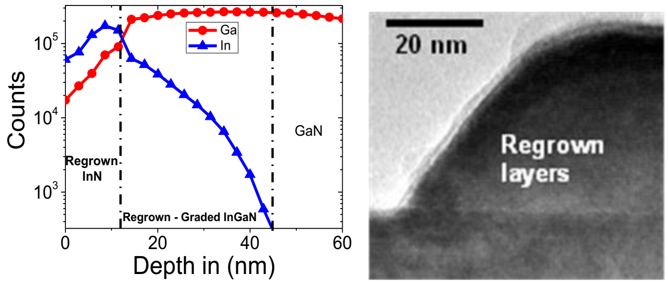


Fig.4(a) SIMS measurements showing graded InGaN and InN cap
(b) HRTEM of the regrown region indicating a sharp regrowth interface

Fig. 5a (filled squares) demonstrates the different ohmic contact resistances obtained for the three different samples. As shown in Fig. 5a, with higher final In composition in the graded alloy, the Δ E_c between the InN cap and the graded alloy is reduced and this is directly reflected in the lowering of the ohmic contact values. Fig. 5b shows the TLM measurement for sample C for which a record ohmic contact resistance of 27 Ω-µm was obtained. Thus we have combined the advantages of a low metal to InN ohmic contact resistance, a minimal resistance conduction path for electrons through a graded InGaN layer to form an ohmic contact to a N-polar GaN HEMT. To the best of our knowledge this is the lowest ever ohmic contact value to a GaN HEMT (both Ga-face and N-polar HEMTs). Fig.6 shows the current-voltage characteristics of a N-polar HEMT with regrown InN-graded InGaN source drain regions with a gate length of 1µm. Further device details, DC and RF performance will be reported elsewhere.

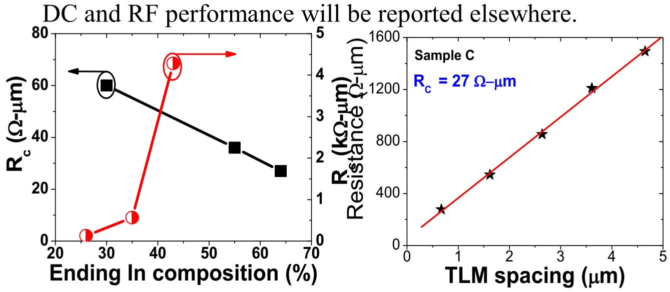
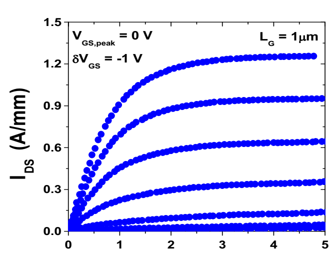


Fig.5(a) (filled squares) Variation of ohmic contact resistance with final composition of graded InGaN (samples A,B,C) (filled circles) Variation of ohmic contact resistance to the GaN 2DEG with graded InGaN composition Fig. 5(b) TLM measurements of sample C from which an ohmic contact resistance of 27Ω-µm was extracted by linear fit (red line).

Fig.6 I-V characteristics of a self aligned regrown ohmic contact N-polar HEMT, with gate length = 1 µm.



CONCLUSIONS

In summary, a unique process of self aligned gate first N-polar GaN HEMT with regrown source drain regions by PAMBE has been demonstrated. The optimized regrown source drain regions consist of 10 nm InN cap and a 40 nm Si-doped graded InGaN layer. Non alloyed ohmic contacts to this self-aligned N-polar GaN HEMT yielded a contact resistance of 27 Ω µm and are the lowest ever reported ohmic contact resistances to a nitride 2DEG. N-face heterostructure HEMTs have a clear advantage over Ga-face heterostructure HEMTs in the development of low ohmic contact resistances and this has been demonstrated in this work. Large and small signal characterization of the source drain regrown self aligned N-polar HEMTs are currently in progress.

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REFERENCES

[1] T. Palacios, A. Chakraborty, S. Rajan, C. Poblenz, S. Keller, S. P. Denbaars, J. S. Speck, and U. K. Mishra, IEEE Electron Device Lett. **26**, 781 (2005).
[2] M Higashiwaki, T. Matsui, and T. Mimura, Conference Digest of the 64th Device Research Conference, IEEE pp.151 (2006).
[3] P. J. Tasker and B. Hughes, IEEE Electron Device Lett **10**, 291 (1989).
[4] J. C. Zolper, R. J. Shul, A. G. Baca, R. G. Wilson, S. J. Pearton, and R. A. Stall, App. Phys. Lett. **68**, 2273 (1996).
[5] C. H. Chen, S. Keller, G. Parish, R. Vetury, P. Kojodoy, E. Hu, S. P. Denbaars, and U. K. Mishra, App. Phys. Lett **73**, 3147 (1998).
[6] F. Recht, L. McCarthy, L. Shen, C. Poblenz, A. Corrion, J. S. Speck, and U. K. Mishra, Conference Digest of the 65th Device Research Conference, SouthBend, IN, 37, (2007). IEEE, New York, (2007).
[7] S. Rajan, A. Chini, M. H. Wong, J.S. Speck, and U.K. Mishra,J.Appl.Phys. **102**, 044501 (2007).
[8] Nidhi, S. Dasgupta, Y. Pei, B. Swenson, D. Brown, S. Keller, J.S. Speck, and U.K. Mishra, IEEE, Electron Device Lett **30**, 599 (2009).
[9] M. H. Wong, Y. Pei, D. Brown, J.S. Speck, and U.K. Mishra, IEEE, Electron Device Lett. **30**, 802 (2009).
[10] K. Xu and A. Yoshikawa, Appl. Phys. Lett **83**, 251 (2003).
[11] M. H. Wong, Y. Pei, T. Palacios, L. Shen, A. Chakraborty, L. McCarthy, S. Keller, S.P. Denbaars, J.S. Speck, and U.K. Mishra, App. Phys. Lett **91**, 232103 (2007).
[12] I. Mahboob, T.D. Veal, C.F. McConville, H. Lu, and W.J. Schaff, Phys. Rev. Lett **92**, 036804 (2004).
[13] O. Ambacher, J. Smart, J.R. Shealy, N.G. Weimann, K. Chu, M. Murphy, W.J. Schaff, L.F. Eastman, R. Dimitrov, M. Stutzmann, W. Rieger, and J. Hilsenbeck, J.Appl. Phys. **85**, 3222 (1999).
[14] S. Keller, N. Fichtenbaum, F. Wu, D. Brown, A. Rosales, S.P. Denbaars, J.S. Speck, and U.K. Mishra, J.Appl. Phys. **102**, 083546 (2007).
[15] U. Singisetti, M. Wistey, G. Burek, E. Arkun, A. Baraskar, B. Thibeault, A. Gossard, C. Palmstrom, and M Rodwell, Physica Stat. Sol (C) **6**, 1394 (2009).
[16] M. J. W. Rodwell, U. Singisetti, M. Wistey, G. Burek, A. Gossard, C. Palmstrøm, E. Arkun, P. Simmonds, S. Stemmer, R. Engel-Herbert, Y. Hwang, Y. Zheng, P. Asbeck, Y. Taur, M. V. Fischetti, B. Yu, D. Wang, Y. Yuan, C. Sachs, A. Kummel, P. McIntyre, C. Van de Walle, and J. Harris, IEEE Indium Phosphide and Related Materials Conference, Versailles, France, (2008).

ACRONYMS

HEMT: High Electron Mobility Transistor
HRTEM: High Resolution Transmission Electron Microscopy