Ultrathin all-binary AlN/GaN based high-performance RF HEMT Technology

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Abstract

AlN/GaN HEMTs offer a number of performance improvements over traditional AlGaN/GaN structures. In this work, the epitaxial growth and characterization of of AlN/GaN heterostructures by MBE is shown to lead to record low channel sheet resistances, lower than 150 Ohms/square. The DC performance of the resulting HEMTs on sapphire substrates shows that current densities in excess of 2 A/mm and transconductances larger than 400 mS/mm can be routinely obtained in such HEMTs. Preliminary high-frequency characterization of the binary HEMTs shows that by virtue of the reduction of access resistances, very high frequency performance is achievable. Alloy-free AlN/GaN heterostructure technology offers a number of critical advantages over competing AlGaN/GaN and AlInN/GaN technologies for vertical and lateral scaling to push the high-frequency limits of nitride HEMTs.

INTRODUCTION

III-V nitride semiconductors are being actively pursued by various academic institutions and industrial laboratories alike for high-power, high-frequency RF power amplification. The primary advantages of the nitrides over other semiconductor materials stem from the large bandgap (and corresponding large breakdown electric fields), the respectable thermal conductivity, good electron transport properties, and the freedom of heterostructure design. A point of departure for nitride heterostructures compared to other III-V zinc-blende semiconductors and even SiC is the extremely high 2DEG densities that can be achieved in these heterstructures. As opposed to all other HEMT technologies, the 2DEG in nitride heterostructures orignates from the difference in spontaneous and piezoelectric polarization between the barrier (typically AlGaN) and the underlying GaN layer – i.e., there is no need for modulation doping. The 2DEG densities for a ~30% AlGaN barrier is limited to roughly 10^{13}/cm^2, which indeed is the charge density in current AlGaN/GaN HEMTs. The electrostatics dictates that the 2DEG density scales with two parameters of the barrier – the Al composition, and the thickness. The maximum achievable 2DEG density depends on the thickness – a) strain relaxation occurs if the AlGaN barrier exceeds a critical thickness, and b) the 2DEG density saturates beyond another critical thickness if the barrier does not relax.

The physics of polarization dictates that the highest possible 2DEG density possible in Al(Ga)N/GaN heterostructures is achieved when the barrier layer is AlN. 2DEG densities ranging from 2 – 6 x 10^{13}/cm^2 are possible due to the maximum difference in polarization between a coherently AlN barrier and the underlying GaN. Within this high 2DEG density window, it is also possible, with controlled growth, to achieve high electron mobilities (> 1000 cm^2/V.s), which leads to a drastic reduction of the 2DEG sheet resistance. Since reduction of the access resistances is crucial for the enhancement of high-frequency characteristics of HEMTs, this is very desirable. Since the room-temperature electron mobilities are fundamentally limited to 1000 - 2000 cm^2/V.s in nitride 2DEGs due to optical phonon scattering, increasing the carrier density is the key to achieving low sheet resistances, and paves the way towards frequencies of operation in excess of 200 GHz. This paper is a progress report on the development of next-generation AlN/GaN HEMT technology for RF applications.

EPITAXIAL GROWTH OF ALN/GAN HETEROJUNCTIONS

The growth of the AlN/GaN heterojunctions was performed in a RF-plasma assisted Veeco Gen 930 MBE system that has an idle background pressure lower than 10^{-10} Torr. The Ga and Al fluxes were provided from heated effusion cells, and values in the range of 10^{-7} Torr were used to maintain metal-rich growth conditions. A Veeco N_2 plasma source equipped with an auto-tuner was used to supply active nitrogen atoms at 275 Watt with a background N_2 pressure of ~2x10^{-5} Torr. The resulting growth rates were measured to be ~ 210 nm/hr by high-resolution XRD characterization of Al(Ga)N/GaN multiple quantum well samples grown specifically for that purpose. The growths were performed on commercially available semi-insulating (Fe-doped) GaN templates on sapphire (vendor: LumiLog). During the growth of the ultrathin AlN barrier layer, the Ga flux was not turned off to improve the adatom mobility. After growth, small Ga metal droplets were typically observed on the surface for high Ga fluxes, which were removed by HCl treatment (see [1] for further details).

STRUCTURAL CHARACTERIZATION

The structural properties of AlN/GaN samples with varying AlN thicknesses were characterized by AFM, high-resolution XRD, and TEM (see [1]). Figure 1 shows the evolution of the surface of the single AlN layer surfaces with increasing AlN thickness. The elastic strain in the AlN layer due to a 2.4% lattice mismatch with GaN restricts the AlN layer thickness to ~ 6 nm before strain relaxation and cracking occurs. For AlN thicknesses less than 6 nm, very smooth surface morphologies are observed, with atomic steps clearly discernible. As the AFM images show, the cracking of the AlN surface occurs along hexagonal axes of the underlying wurtzite crystal, and cracks nucleate and propagate away from the parts of AlN with larger thickness.

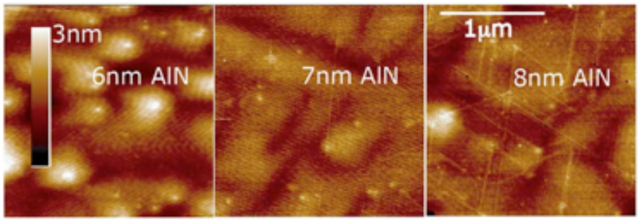

Fig. 1: AFM images of the AlN surface as the thickness increases. Below 6 nm, smooth surfaces with atomic steps are observed [1]. Beyond ~7 nm, cracks along the hexagonal axes appear, causing degradation of 2DEG transport properties.

Figure 2 shows a TEM image of a buried AlN/GaN heterojunction from a AlN/GaN superlattice structure grown under the same conditions as the HEMTs. Sharp heterojunctions are observed, but not without a degree of interface roughness. We have observed that by increasing the MBE growth rate, the roughness can be reduced, resulting in an improvement of electron mobility.

Fig. 2: TEM image of a buried AlN/GaN heterojunction showing a smooth heterojunction interface.

High-resolution XRD measurements of AlN/GaN superlattices grown under similar conditions as the HEMT structures showed that the AlN layers are coherently strained for thickness in the 2-5 nm range. No peaks for the AlN layers in the single AlN layer HEMT structures were observed, indicating that they are pseudomorphic.

TRANSPORT CHARACTERIZATION

Good charge transport properties are crucial to the performance of RF HEMTs. Figure 3 shows the Hall-effect 2DEG sheet densities and electron mobilities at room temperature and 77 K in these AlN/GaN heterojunctions as the epitaxial AlN layer thickness is changed from 2-7 nm. The polarization-induced 2DEG densities achieved are the highest in all known semiconductor heterostructures, and for AlN thicknesses between 3-5 nm, the RT mobility is in excess of 1000 cm^2/V.s – yielding sheet resistances below 150 Ohms/sq.

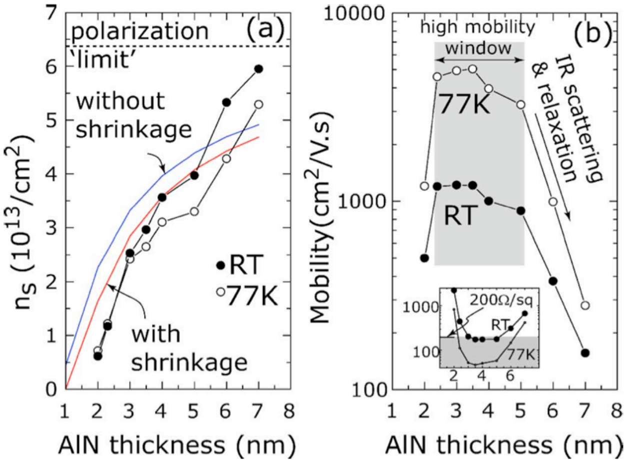

Fig. 3: Transport properties of the 2DEG at the AlN/GaN heterojunction showing that there exists a high-mobility window where the sheet resistance is greatly reduced [1].

Samples from the high-mobility window are chosen for HEMT fabrication, as explained later. A point of interest at this juncture is to understand whether the mobilities as shown in Figure 3 are optimized. By comparing data from a temperature-dependent Hall-effect measurement of the electron mobility from room temperature to 10 K to a theoretical model of various scattering rates, it was found that interface roughness scattering has a measurable impact on the room-temperature 2DEG mobility [1].

Therefore, reduction of the AlN/GaN interface roughness is expected to result in an improvement in the electron mobility. Temperature-dependent measurement of the 2DEG mobilities of AlN/GaN HEMT structures grown at two different growth rates showed that this is indeed true, and the resulting sheet resistances have thus been lowered to below 130 Ohms/sq. From the transport measurements and theoretical modeling, we have found that a faster growth rate leads to higher RT mobilities, directly translating to low sheet resistances. With further optimization of the growth conditions and layer structures, sheet resistances in the range of 100 Ohms/sq should be achievable, which will compare very favorably to other III-V HEMT technologies.

LOW RESISTANCE OHMIC CONTACTS

The ultrathin AlN barrier in these heterostructure poses two major challenges for fabricating high-performance HEMTs. Both challenges are intricately linked to the electronic properties of the AlN barrier. The thin (2-5 nm) barrier enables a very high transconductance due to the high gate capacitance. However, at the same time, it poses problems with gate leakage through tunneling and defects. Due to the very high bandgap of AlN, low-resistance ohmic contact formation for the source and drain contacts is also challenging.

TLM (transmission line method) patterns were fabricated using chlorine-based reactive-ion etching for mesa isolation. Ti/Al/Ni/Au source and drain contacts were finally deposited by electron-beam evaporation. Rapid thermal annealing was used to obtain alloyed ohmic contacts. The I-V characteristics were tested on TLMs using an Agilent 4156C semiconductor parameter analyzer.

Shown in Figure 4 are the I-Vs taken across two TLM pads separated by 3 μm with as-deposited metal stacks for 2.3, 3, 3.5 and 5 nm AlN barrier samples [2]. For samples with very thin barriers of 2.3 nm, the as-deposited contacts are ohmic owing to the strong tunnelling current as well as the large number of leakage paths (dislocations) under the large area contacts. With increasing AlN thickness, the as-deposited contacts become more Schottky-like, this is because of the suppressed tunnelling current in the thicker barrier structures.

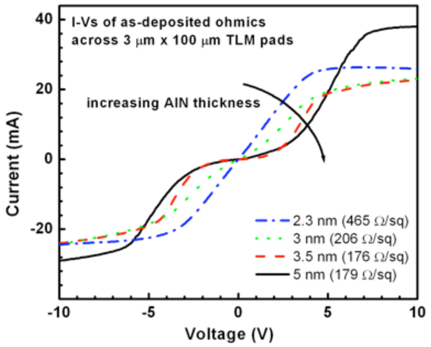

Fig. 4: I-Vs of as-deposited ohmic contacts measured across TLM pads, indicating a strong tunneling transport in thin AlN barrier samples [2].

Upon annealing, ohmic contacts were obtained on all AlN thickness samples and contact resistance is in the range of 0.8 - 2 Ohm-mm. A separate annealing study revealed that the contacts degraded at high annealing temperatures while the channel resistances remained unchanged for all the AlN thicknesses studied here. The optimal temperature was determined for a range of AlN barrier thicknesses – the contact resistance increased almost linearly from 400 ^{0}C to 860 ^{0}C as the AlN thickness increases from 3 nm to 5 nm.

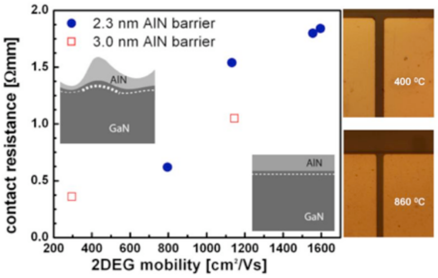

Fig. 5: (Left) The dependence of contact resistances on the AlN/GaN heterostructure quality (an AlN barrier thickness results in rather consistent 2DEG densities in the channel independent of mobility.). Ohmic contacts are increasingly more challenging to obtain on higher quality AlN/GaN heterostructures. (Inset) Schematic of low and high mobility AlN/GaN structure cross-sections. (Right) Optical images of annealed contacts at 400 ^{0}C (2.3 nm AlN) and 860 ^{0}C (5 nm AlN) – extremely smooth ohmic contacts.

Interestingly, it was observed there exists a strong dependence of the annealing temperature window as well as the resultant contact resistance on the 2DEG carrier mobility. For samples with low mobilities (< 600 cm^2/Vs), a wide range of annealing temperatures was found to result in comparable contact resistances, ~ 0.3 - 0.6 Ohm-mm. For example, a contact resistance of 0.36 Ohm-mm was obtained on a 3 nm AlN/GaN sample with mobility of 300 cm^2/Vs at an annealing temperature as high as 860 ^{0}C. On the other hand, an annealing at 860 ^{0}C of a 3 nm AlN/GaN sample with mobility of 1000 cm^2/Vs resulted in an open circuit. Using the optimal annealing temperatures, the contact resistance was observed to increase with increasing carrier mobilities. This trend is presented in Figure 5. We postulate this is largely due to the fact the 2DEG density in an AlN/GaN heterostructure is highly sensitive to the AlN thickness, and to the reaction between the metals and the AlN barrier during annealing.

HEMT FABRICATION

HEMTs were fabricated from very low sheet resistance AlN/GaN heterostructures (~ 165 ohm/sq) [3]. The structure (see Figure 6) consists a 3.5 nm AlN, a 2DEG density of 2.75 x 10^{13} /cm^2 and a RT mobility of 1367 cm^2/Vs, leading to a sheet resistance of ~ 166 Ω/sq at RT. A 3 nm aluminum oxide gate dielectric was deposited using electron-beam evaporation. The devices were not passivated. An insulating gate dielectric was used to prevent gate leakage. The reverse bias current density of metal Schottky diodes decreased with decreasing diode area, indicating that a large portion of the gate leakage current on these untreated heterostructures stems from leakage through a high density of dislocations (~ 10^9 /cm^2). The contact resistance was high compared to traditional AlGaN/GaN HEMTs (~ 1.1 Ω-mm) and provides room for further improvement.

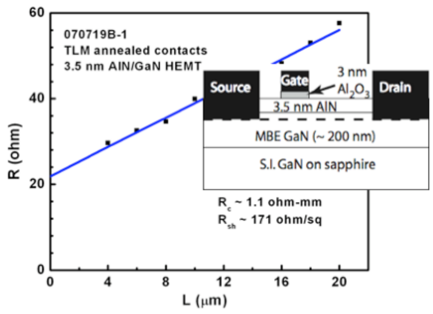

Fig. 6: TLM measurement of the annealed ohmic contacts shows a contact resistance of ~ 1.1 ohm-mm & a sheet resistance of ~ 171 ohm/sq, in good agreement with Hall-effect measurements. (Inset) Schematic of the AlN/GaN HEMT structure.

HEMT CHARACTERIZATION

These HEMTs attain very high DC current densities (~ 2.3 A/mm) and extrinsic transconductances (~ 480 mS/mm), providing a glimpse into the performance limits of III-V nitride HEMT technology. A maximum current density of 2.3 A/mm was measured for a 12.5 μm gate width device (Fig. 7).

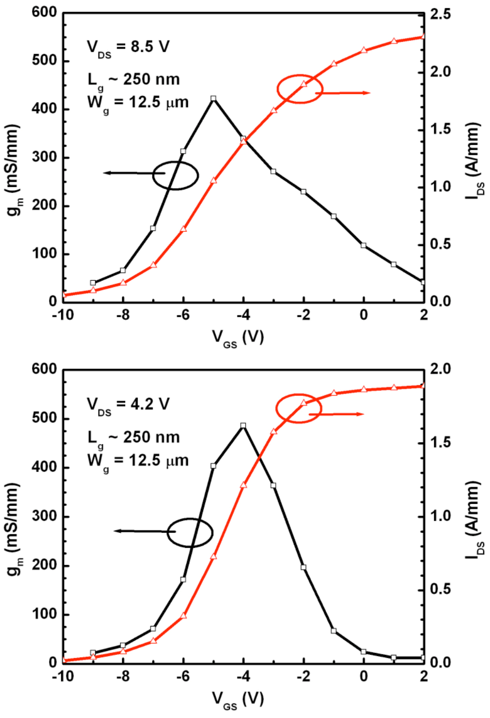

Fig. 7: DC I-V transfer curves showing a record high maximum drain-source current ~ 2.3 A/mm (top) and peak extrinsic transconductance ~ 480 mS/mm (bottom) measured on a 12.5 μm gate width device.

From the same measurement, a peak extrinsic transconductance of ~ 480 mS/mm can also be extracted. Using the contact resistance of 1.1 Ω-mm, the calculated intrinsic transconductance is as high as ~ 1 S/mm. This performance shows that both high current density and transconductance can be achieved in a single AlN/GaN HEMT with insulated gates. Further characterization of the HEMTs show that the channel charge is influenced by slow traps, possibly in the gate dielectric, at the Al_2O_3/AlN interface, or at the unpassivated AlN surface. Since the 2DEG is situated very close to the surface states that are considered to be its source, the virtual gate effect is also a valid concern owing to charging and discharging these surface states, which is observed in almost all nitride HEMTs but satisfactorily solved employing SiN_x passivation. The hard breakdown of these HEMTs were also tested to be > 20 V.

High-frequency characterization yielded the unity current gain cutoff frequency and power gain cutoff frequency f_T/f_{max} to be 52/60 GHz for a 0.25 x 60 μm^2 gate HEMT. These values are lower than expected given the observed high output current and transconductance, limited by the contact resistance, leaky buffer and traps.

CONCLUSIONS

Based on the encouraging results demonstrated by AlN/GaN HEMTs, there is reason to believe that they can carry current densities approaching, and perhaps exceeding 3 A/mm in the near future. The transconductances can exceed 500 mS/mm, and reduction of contact resistances and gate leakage is expected to propel these heterostructures into highly attractive candidates for very high-frequency RF power amplifiers operating at lower drain voltages than traditional AlGaN/GaN HEMTs.

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REFERENCES

[1] Y. Cao and D. Jena, Appl. Phys. Lett., **90**, 182112 (2007).
[2] T. Zimmermann, D. Deen, Y. Cao, D. Jena, & H. Xing.,Physica Status Solidi, (accepted, to appear, 2008).
[3] T. Zimmermann, D. Deen, Y. Cao, D. Jena, & H. Xing.,IEEE Electron Device Letters, (accepted, to appear, 2008).

ACRONYMS

HEMT: High Electron Mobility Transistor
2DEG: Two Dimensional Electron Gas
MBE: Molecular Beam Epitaxy
XRD: X-Ray Diffraction
AFM: Atomic Force Microscopy
TEM: Transmission Electron Microscopy