Design and Engineering of AlGaN Channel-Based Transistors

DISSERTATION

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By

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Abstract

This thesis presents theoretical and experimental investigation of wider bandgap AlGaN channels to achieve superior gain linearity and output power density in III-Nitride transistors.

GaN high electron mobility transistors (HEMTs) exhibit high saturation velocity and large breakdown field, resulting in unprecedented power densities at microwave frequencies. However, their cutoff frequency and gain reduce significantly as the gate bias or current density increase, causing non-linear behavior and soft gain compression at peak efficiencies. This phenomenon is shown to be related to the sheet density dependence of velocity in HEMTs. Velocity-field measurements are carried out on unique test structures as a function of sheet charge density, which revealed strong density dependence of saturation velocity. To realize constant velocity profile as a function of gate bias, polarization graded field-effect transistors (PolFETs) with engineered charge and capacitance profiles are discussed. Constant cutoff frequency and maximum oscillation frequency over wide gate-bias and output current range are achieved in highly-scaled PolFETs, indicative of enhanced gain linearity.

AlN with extremely large bandgap of 6.2 eV can withstand significantly higher breakdown field than GaN channels, which could enable higher voltage, as well as higher
charge density for the same device dimensions. To realize superior breakdown voltage and current density, AlGaN channels with high Al-content are investigated. Theoretical calculation of the low-field electron mobility in AlGaN channel HEMTs, as well as its implication on the high-field transport are discussed. A major limiting factor in the development of AlGaN channel transistors, thus far, has been high-resistance ohmic contacts. Contact layers with compositional grading (i.e. electron affinity grading) are shown to mitigate this issue significantly. Specific contact resistance of $2 \times 10^{-6} \, \Omega \cdot \text{cm}^2$, and average lateral breakdown field of 2 MV/cm are attained by 1st generation $\text{Al}_{0.75}\text{Ga}_{0.25}\text{N}$ MOSFETs grown by molecular beam epitaxy (MBE). Considerable improvement in channel mobility and current density is obtained in 2nd generation $\text{Al}_{0.7}\text{Ga}_{0.3}\text{N}$ MOSFETs grown by metal-organic chemical vapor deposition (MOCVD). Field-plated structures are demonstrated with current density of 0.5 A/mm and an average lateral breakdown field up to 3.6 MV/cm. The advantages of the two growth techniques are analyzed and compared, leading to a hybrid device design with MBE-grown graded contact layer and MOCVD-grown channel layer. Finally, the 3rd generation of high Al-content AlGaN PolFET is presented, which could potentially enable superior linearity and output power performance in III-Nitrides for advanced applications.
Dedication

Dedicated to my family
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There are many people who contributed to this work and made my journey truly gratifying.

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Chapter 1

Introduction

III-Nitride family of semiconductors (InN, GaN, AlN and their alloys)\(^1\) offers a broad spectrum of direct bandgaps from 0.6 eV (InN) to 6.2 eV (AlN), and has various device applications ranging from optoelectronics to RF amplification to power electronics. The developmental work on InGaN-based light-emitting diodes and GaN growth on Sapphire/SiC substrates in the 1980s [1] [2], along with the advent of the AlGaN/GaN high electron mobility transistors (HEMTs) in the early 1990s [3] led the path to worldwide research on GaN-based electronic devices. As of today, it would be safe to say that GaN has the potential to be the next mass semiconductor after Silicon. Figure 1 summarizes the major applications of III-Nitride semiconductors.

The material properties of GaN, such as the large bandgap \((E_g = 3.4 \text{ eV})\), strong polarization which can induce high carrier densities, high electron mobility \((\mu_n)\) and saturated velocity \((v_{sat})\) have enabled state-of-art high-frequency transistors ideal for microwave and mm-wave applications, producing unprecedented output power density over 40 W/mm in X-band [4], 6.5 W/mm in W-band [5], and excellent current/power cutoff frequencies \((f_{\text{r}}/f_{\text{max}})\) of 454/444 GHz, respectively [6].

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\(^1\) BN is another interesting part of the family which is relatively new, as discussed briefly in Chapter 5.
The remarkable progress made over the past three decades has also brought new research challenge/opportunity to further extend the frontiers of III-Nitride transistors. The aim of the work described in this thesis is to understand the high-power high-frequency limitations of III-Nitride transistors, and investigate methods to overcome those by means of bandgap engineering.

1.1. Motivation: improving microwave linearity

GaN-based HEMTs produce RF power densities that benefit several military (radar, electronic warfare) and communication applications, however they are known to have soft/premature gain compression as well as significant non-linearity, especially at higher operation frequencies. Figure 2 shows the contours for the transconductance and maximum
available gain for a standard AlGaN/GaN HEMT, both of which reduce significantly as the gate bias (or current density) is increased, resulting in the non-linear behavior.

Figure 2. Experimental contours for (a) the transconductance ($g_m$), and (b) maximum available gain (MAG)/maximum stable gain (MSG) for an AlGaN/GaN HEMT (Figure courtesy of Dr. David Meyer, NRL).

Future military and commercial communication applications require high linearity sources and receivers at high frequencies. Power amplifier linearity improvements can be achieved either at the circuit level, or through improvements in intrinsic device design. While circuit level methods for linearity improvement exist, direct improvement of the linearity by device level design to reduce distortion is gaining increased attention [7].
1.1.1. Engineering electron velocity by polarization grading

The power gain is proportional to cutoff frequency of a transistor, which is a strong function of saturated velocity. Theoretical study by Fang et al. on two-dimensional electron gas (2DEG) velocity in HEMT predicted a decrease in velocity with increasing charge density, due to the optical phonon emission [8]. Further investigation, both theoretical and experimental, could provide better understanding of the density-dependent velocity in GaN HEMTs, and a tool kit to design and simulate structures for improved velocity profiles as a function of gate bias for superior gain linearity. Characterization of velocity-charge-field relationships in GaN HEMTs in this work also revealed strong density dependence of velocity, suggesting that a more constant velocity versus gate bias profile is critical for improved linearity.

Polarization graded channels offer a viable approach to engineer the charge/velocity profiles, for example in this case, to make the velocity versus gate voltage dependence constant. The continuous grading of the Al composition in such channels has been shown to induce bulk electron concentrations [9] [10], creating MESFET-like bulk channels and allowing more flexibility in device design. This spatial distribution of the charge density allows for channel width modulation rather than charge density modulation in a 2DEG, hence resulting in a modified velocity versus gate bias profile. Moreover, the spatial distribution leads to a reduction in 3D density as compared to that in a 2D degenerate electron gases, leading to a higher effective velocity. A more detailed discussion is presented in chapter 3.
1.2. Motivation: enhancing output power density

1.2.1. AlGaN channels with high Al composition

The wider bandgap (> 5eV) achievable in the AlGaN system can enable much superior breakdown fields (12-15 MV/cm) than possible for GaN-channel transistors. The larger breakdown field can enable higher voltage, as well as charge/current density for the same device dimensions. Therefore, at mm-wave frequency, AlGaN-based devices can have significantly higher power density than achievable in current technology [11]. Furthermore, the intrinsic polar nature of III-Nitrides and the availability of high thermal conductivity AlN substrates [12] [13] make high Al composition AlGaN very attractive for ultra-wide bandgap (UWBG) semiconductor device development. The following figure of merit calculations estimate the quantitative advantage of replacing GaN channel with high Al-content AlGaN channels.

The product of breakdown voltage ($V_{br}$) and cutoff frequency ($f_T$), also known as the Johnson’s figure of merit ($JFOM$) [14], is dependent on material parameters and given by

$$JFOM = V_{br} f_T = \frac{F_{br} v_{sat}}{2\pi};$$  \hspace{1cm} (1)

where $F_{br}$ is the breakdown field. Figure 3 shows the estimated breakdown field [15] for some of the emerging UWBG semiconductors, and the $JFOM$ relative to GaN, plotted as a function of Al composition in AlGaN channels.
Figure 3. (a) Breakdown field of emerging UWBG semiconductors estimated using $E_g^{2.5}$ dependence, as a function of energy bandgap [15]; and (b) Johnson’s figure of merit [14] relative to GaN, plotted as a function of Al composition in AlGaN channels.

For the $JFOM$ calculation, as well as the analysis presented as follows, a constant saturated velocity is assumed for all Al compositions in AlGaN. Although theoretical studies based on Monte Carlo method have also predicted similar or higher saturated velocities in AlGaN as compared to GaN channels [16] [17], there has not been any experimental evidence yet. Therefore, these assumptions could lead to quantitative inaccuracies, but the analysis presented, nevertheless, provides a useful tool for comparing different material systems, and predicting trends.

Another means to compare $JFOM$ is by plotting the breakdown voltage as a function of cutoff frequency (Figure 4).
Figure 4. Theoretical breakdown voltage versus cutoff frequency for GaN, Al$_{0.7}$Ga$_{0.3}$N and AlN channels, plotted in the logarithmic scale.

Theoretical breakdown voltage versus cutoff frequency (Figure 4) illustrates the advantage in both parameters by replacing conventional GaN channels with high Al-content AlGaN channels. To estimate the transit time limited power density ($P_{out}$), Class-A amplifier approximation can be used as

$$P_{out} = \frac{I_{\text{max}} V_{\text{br}}}{8} \ (W/mm) ; \quad (2)$$

where $I_{\text{max}}$ is the maximum current density (A/mm). For a given dimension (gate length, $L_{GD}$), using AlGaN instead of GaN as the channel and barrier materials can impact this curve in two ways. First, if the breakdown field of AlGaN is ‘K’ times higher than GaN, then the larger bandgap channel will have breakdown voltage that is ‘K’ times higher than in GaN. The second impact is on the charge scaling in the channel. The electric fields within a lateral device depend linearly on the total channel charge density. Thus, for an
AlGaN channel with ‘K’ times higher breakdown field than GaN, we can estimate that for the same device structure (device dimensions, passivation etc.), a total charge density, $n_s$ that is ‘K’ times higher can be supported before breakdown. Now the $I_{\text{max}}$ dependence on $n_s$ is complex, since the saturated velocity is also a function of $n_s$. Theory predicts the $I_{\text{max}}$ dependence to be proportional to $n_s^{1/2}$ in a 2D electron gas [8], whereas in graded channels this can be engineered (as discussed in the previous section), such that the dependence is simply $n_s$. Therefore, the enhancement of current density of an AlGaN channel over a GaN channel can be predicted to be given by $K^{1/2}$. Combining the effects of the dependence of the breakdown voltage and the current density, the power density for an AlGaN channel can be estimated to be higher than GaN channel by a factor of $K^{3/2}$, or $(\frac{F_{\text{br,AlGaN}}}{F_{\text{br,GaN}}})^{3/2}$.

Assuming conservatively a breakdown field of 10 MV/cm for Al$_{0.75}$Ga$_{0.25}$N channel, and 3 MV/cm for GaN channel, a significant enhancement of $\sim$ 5X can be predicted over existing GaN technology.

Finally, to estimate the frequency dependence of the power density, $P_{\text{out}}$ can be represented in terms of the operating frequency, $f = \frac{f_{\text{max}}}{G_P}$, where $f_{\text{max}}$ is the maximum oscillation frequency ($\approx f_T \sqrt{R_L/R_{\text{in}}}$, where $R_L$ and $R_{\text{in}}$ are real parts of the output and input impedance, respectively) and $G_P$ is the power-gain. Using the expression for cutoff frequency, $f_T = \frac{v_{\text{sat}}}{2\pi L_G}$, $P_{\text{out}}$ can be expressed as

$$P_{\text{out}} = \frac{I_{\text{max}} F_{\text{br}}}{8 L_G} \cdot f = \frac{I_{\text{max}} F_{\text{br}} v_{\text{sat}}}{16\pi L_G G_P f} \sqrt{\frac{R_L}{R_{\text{in}}}}$$ (3)
This equation shows that the output power density is inversely proportional to the gain-frequency product. Additionally, the $I_{\text{max}}F_{br}V_{\text{sat}}$ product leads to a superlinear dependence on the breakdown field, and therefore for a given gain-frequency product, a superior power density can be expected by increasing the breakdown field. Figure 5 shows a comparison of $P_{\text{out}}$ as a function of operating frequency estimated for GaN, $\text{Al}_{0.7}\text{Ga}_{0.3}\text{N}$ and AlN channels at gain of 10 dB, and illustrates the advantage of AlGaN channels over GaN channel for high-power high-frequency performance enhancement.

![Graph showing output power density as a function of operating frequency for GaN, $\text{Al}_{0.7}\text{Ga}_{0.3}\text{N}$, and AlN channels at $G_p = 10\,\text{dB}$]  

Figure 5. Output power density as a function of operating frequency estimated for GaN, $\text{Al}_{0.7}\text{Ga}_{0.3}\text{N}$ and AlN channels using equation 3, at $G_p = 10\,\text{dB}$.

For example, at 30 GHz ($Ka$ band), the output power for GaN is limited to $< 10\,\text{W/mm}$, whereas the limit for $\text{Al}_{0.7}\text{Ga}_{0.3}\text{N}$ is significantly higher. Above $\sim 40\,\text{W/mm}$, highlighted as the thermal limit, devices can be restricted by the heat dissipation/thermal cooling [18].
1.3. Overview of the thesis

Chapter 2 of the thesis presents the theoretical and experimental study of electron transport in GaN and AlGaN channels. Low-field and high-field transport, both are discussed in GaN and AlGaN channel transistors. The first section of the chapter investigates 2DEG density-dependent velocity in GaN channel HEMTs. Experimental velocity-field-density curves are characterized in ungated test structures designed to achieve fairly uniform electric field profile. The results are compared to a theoretical model based on optical phonon emission (developed by Professor J. B. Khurgin, John Hopkins University). TCAD simulation of GaN HEMTs using the experimental density-dependent velocity are carried out. The second section presents the theoretical calculation of 2DEG mobility in AlGaN channels based on two most critical mechanisms: optical phonon scattering and alloy scattering. The implications of lower mobility in AlGaN channels are studied on high-field velocity, as well as on cutoff frequency in AlGaN channel transistors. The mobility values are also used to evaluate AlGaN channels for power switching, where on-resistance and breakdown voltage are key parameters.

Chapter 3 aims at engineering the velocity dependence on gate bias measured in GaN HEMTs through the use of polarization grading. The advantage of achieving constant velocity profile with gate bias is discussed for improved linearity performance. TCAD simulations using experimental density-dependent velocity are carried out to compare HEMT and polarization-graded transistors. Finally, highly-scaled polarization-graded field
effect transistors (PolFETs) with constant $g_m/f_{rl}/f_{max}$ profiles over wide range of bias range are demonstrated, in good agreement with the simulation results.

Chapter 4 presents an elaborate study on wider bandgap AlGaN channel transistors with high-Al-content. It explains the key challenges in AlGaN channel transistor development, and the approaches that are taken to overcome those. The first section describes low-resistance ohmic contact formation to high Al-content AlGaN channels through the use of composition (or electron affinity) grading. The 1st generation devices are designed using Al$_{0.75}$Ga$_{0.25}$N channel layer and composition graded contact layer, both grown by plasma-assisted molecular beam epitaxy (MBE). The low channel mobility in MBE-grown films is recognized as the main limiting factor in the devices. In the second section, AlGaN films grown by metal-organic chemical vapor deposition (MOCVD) are investigated and compared to MBE-grown films. The 2nd generation devices employing MOCVD-grown Al$_{0.7}$Ga$_{0.3}$N channel and graded contact layers are developed, demonstrating the highest current density/breakdown field among any reported literature on AlGaN channel transistors with Al composition > 0.25. However, the higher contact resistance in MOCVD-grown structures and the challenge in realizing highly-doped conductive films is analyzed. The 3rd generation devices are designed and fabricated with hybrid MOCVD/MBE approach, utilizing high mobility channel layer and low-resistance contact layer, respectively. The last section presents a unique AlGaN transistor design that uses all-refractory metal process, and is suitable for extreme temperature applications.

The thesis concludes with high Al-content transistor design approaches for future research in III-Nitrides based on the work presented, followed by the Appendix that
summarizes process steps for regrowth process, which could be useful in contact/channel epitaxial regrowth in MBE for Nitrides, as well as some other material systems.
Chapter 2

Transport in GaN and AlGaN channel transistors

A discontinuity in polarization at the AlGaN/GaN heterointerface results in a polarization sheet charge, which in turn leads to a two-dimensional electron gas (2DEG) at that heterointerface without the use of modulation doping [19]. It forms the channel of GaN HEMTs, and exhibits excellent properties such as high density (>10^{13} \text{ cm}^{-2}), high mobility (~ 2000 \text{ cm}^{2}/\text{V}s) and capacity for vertical scaling. To further improve the HEMT performance, it is critical to understand the transport of the 2DEG, and the factors which limit the low-field mobility, or the high field saturated velocity. For RF amplification, the high-field saturated velocity ($v_{\text{sat}}$) is of primary interest, since the electrons transit in high fields especially in scaled devices. The saturated velocity is key in determining the transit delay and gain of a transistor. For power switching, the low-field 2DEG mobility ($\mu$) is of interest, which determines the intrinsic on-resistance of the device, and hence switching losses.

In this chapter, high-field 2DEG velocity in GaN HEMTs, and its dependence on sheet density are investigated. Experimental velocity-field-density curves are characterized in ungated test structures designed to achieve fairly uniform electric field profile. The results are compared to a theoretical model based on optical phonon emission (developed
by Professor J. B. Khurgin, John Hopkins University). Two-dimensional (2D) technology computer aided design (TCAD) simulations of GaN HEMTs using the experimental density-dependent velocity are presented.

In the second part, theoretical 2DEG mobility in AlGaN channels is estimated, and found to be mainly limited by alloy scattering mechanism. The implications of lower mobility in AlGaN channels are studied on high-field velocity, as well as on cutoff frequency in AlGaN channel transistors. The mobility values are also used to evaluate AlGaN channels for power switching, where on-resistance and breakdown voltage are key parameters.

2.1. GaN channel: high-field transport in 2DEG

The low-field mobility in GaN HEMT has been studied and characterized extensively in literature [20] [21] [22]. The dependence on sheet density (at room temperature) is known to first increase with decreasing density, and then decrease after reaching a saturation value (figure 6).
Figure 6. Measured Hall mobility ($\mu_{\text{Hall}}$) as a function of sheet density ($n_s$) in an AlGaN/GaN HEMT structure.

As the 2DEG density is lowered, the wavefunction moves marginally away from the heterointerface, resulting in reduced effects of interface roughness and alloy scattering from AlGaN barrier [23]. With further reduction in 2DEG density, coulombic scattering from charged cores in AlGaN (ex. positively charged acceptor states from defects) and dislocation scattering from strain fields of dislocations can come into play [20].

The literature on high-field transport in GaN HEMTs mostly comprised of Monte Carlo simulations, and velocity estimations based on transistor time delay analysis. Monte Carlo simulations in GaN predicted peak electron drift velocities as high as $3 \times 10^7$ cm/s, with comparatively lower saturated velocities up to $\sim 2 \times 10^7$ cm/s, limited mainly by longitudinal optical (LO) phonon scattering [24] [16] [25] [26]. From the total time delay
analysis in recent ultra-scaled GaN HEMT results, the average electron velocity, $v_{\text{ave}}$, of the devices was found to be in the range from $1 \times 10^7$ to $2.8 \times 10^7$ cm/s [4] [27] [28] [6]. However, few experimental reports investigated the sheet density-dependence of saturated velocity, $v_{\text{sat}}$ [29]. Furthermore, transistors were used for the previous studies, which have significantly non-uniform electric field profiles with peaks near the gate edge, leading to non-uniform charge profiles. Hence, they give an average estimation of velocity and are not the ideal structures to characterize true velocity and its dependence on density.

2.1.1. $n_s$-dependent velocity, and its effect on $g_m / f_T$

Most reports of GaN HEMT RF performance report the peak cutoff frequency, $f_T$, which is typically observed at 10-20% of the highest saturated current density. The transconductance and current gain, however, are found to drop significantly as the current density is increased. For applications of GaN HEMTs in power amplifiers, where large signal gain and linearity are critical, the current and power gain values over the entire operating range are important. The intrinsic current unity gain cutoff frequency ($f_{T, \text{intrinsic}}$) is directly proportional to the electron velocity in the channel, and is given by

$$f_{T, \text{intrinsic}} = \frac{g_m}{2\pi C_{GS}} = \frac{v_{\text{sat}}}{2\pi L_G};$$

(4)

where $g_m (= C_{GS}.v_{\text{sat}})$ is the transconductance, $C_{GS}$ is the gate-source capacitance, and $L_G$ is the gate-length. Hence, both $g_m$ and $f_T$ directly depend on the velocity. While parasitics do play an important role in the frequency performance, recent advances in ohmic contact
technology have achieved ultra-low resistance (< 0.1 Ω.mm) [27] [30] [31], thereby making the channel transit delay the main component of the overall delay in GaN HEMTs.

The reason for this reduction in current gain and transconductance as a function of charge density was previously investigated theoretically for bulk GaN [32], as well as 2DEG [8]. Fang et al. developed a model based on optical phonon scattering to predict the 2DEG density-dependence of velocity [8]. A simplified explanation of the model can be given by considering the energy-band profile of GaN and comparing two sheet density values under equilibrium and under applied electric field (Figure 7). Here, a simplified parabolic $E-k$ dispersion relationship is used for illustration of the concept. The 2DEG, represented as Fermi-circle in the momentum space, has no effective momentum and the centroid is at the origin for both values of $n_s$. As the electric field is applied, the electron gas gains energy and the centroid of the Fermi-circle moves in the opposite direction of the applied field, causing an effective momentum, $\hbar k_o$. The electron gas gains momentum until the highest energy approaches the optical phonon energy, $\hbar \omega_{op}$, resulting in the onset of phonon emission. This leads to a difference in the effective momentum, $\hbar k_o$, for the two $n_s$ values, where the higher $n_s$ has a lower effective momentum than that of the lower $n_s$. 

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Figure 7. A simplified illustration of the optical phonon model developed by Fang et al. [8] to predict the 2DEG density-dependence of velocity.
2.1.2. Experimental velocity-field-density characteristics

20 nm Al$_{0.23}$Ga$_{0.77}$N/GaN HEMT structures grown on SiC substrates by plasma-assisted molecular beam epitaxy (PAMBE) [33] were used for this study (Figure 8).

![Figure 8. Structure schematic and equilibrium energy-band profile of the AlGaN/GaN HEMT used for the experimental characterization of $n_s$-dependent velocity field curves.](image)

The equilibrium energy-band diagram was calculated using a Schrodinger-Poisson solver, *BandEng* [34]. Instead of gated transistors, ungated I-shaped test structures were used to characterize velocity-field characteristics, consisting of contact/access regions much wider (up to 20X) than thin channel constriction defined by mesa isolation (of depth 100 nm) (Figure 9).
Figure 9. I-shaped test structure used for velocity measurement using 2-terminal RF probe; (a) isometric view; (b) micrograph and schematic; (c) SEM images of 2 μm x 2 μm and (d) a 5 μm x 5 μm constriction structures.

Due to this geometry, the resistance from the ohmic/access regions is significantly lower than that from the thin channel constriction [35] [36]. Therefore it is assumed that the entire potential drop and current limiting mechanisms must be related to the constriction. To verify this assumption, 2D TCAD simulations of this geometry was performed using n+−GaN (N_D = 5x10^{19} \text{ cm}^{-3}) in Silvaco ATLAS. A cutline of the thin channel constriction
indicated a linearly rising potential profile, and a nearly constant electric field profile (Figure 10).

Figure 10. TCAD simulation of (a) potential profile; and (b) electric field profile in a cutline across the channel constriction.
To measure velocity at varying electron concentrations, the constriction region was recess etched to different depths while the access regions were left unetched to further maintain a low access resistance. The velocity $v_e$ was estimated from the current density, $J$

$$v_e = \frac{J}{qn_s}$$

as a function of sheet charge density $n_s$, where $q$ is the electronic charge. The sheet charge density was estimated by Hall measurements made on Van der Pauw patterns. Since the resistance of the constriction is estimated to be significantly higher than the ohmic/access regions, the field $F$ across a constriction of length $d$ was assumed to be given by

$$F = \frac{V}{d},$$

where $V$ is the applied bias. All measurements were done at room temperature.

The fabrication of the test structures was done as follows. Ti/Al/Ni/Au ohmic contacts (100 μm wide) were deposited by e-beam evaporation and alloyed through rapid thermal annealing for 30 seconds at 850°C in N2 ambient. Cl₂/BCl₃ plasma-based dry etching (RIE power of ~ 10 Watts) was used to define isolation mesas. For velocity measurements, I-shaped test structures of width 2 μm, 5 μm and 10 μm, and length 0.7 μm, 1 μm and 2 μm were used. The constriction dimensions were inspected using scanning electron microscope to confirm an error of ~ 2% (Figure 9). To obtain different sheet charge densities, low-damage ICP-RIE etching was used (RIE power ~ 3 Watts). Ohmic contact resistance of 0.4 Ω.mm was extracted using transmission length method (TLM) measurements. The extracted values for electron sheet density and the corresponding Hall mobility across several dies with different recess depths are shown in Figure 6.
To measure the velocity-field curves, pulsed IV measurements were done using 2-terminal GS RF probes [37] and a commercial Dynamic IV Analyzer system [38]. A pulse duration of 500ns, a duty cycle of 0.01%, and quiescent bias of 0 V were used. The conditions were chosen to ensure that self-heating effects did not have significant impact on the measured data. To eliminate leakage currents from the buffer layers and the instrument, an adjacent mesa-isolated device was measured and subtracted from each active device I-V characteristic. Figure 11(a) shows an example of a series of pulsed measurements carried out at different sheet charge densities.

Figure 11. (a) Measured $n_s$-dependent velocity-field characteristics; and (b) $n_s$-dependent saturated velocity ($v_{sat}$) values extracted from measured velocity-field characteristics. The error bars include data from multiple devices. The data is also compared to the optical phonon-based model discussed in section 2.1.3.
The velocity profiles start to saturate above ~ 200 kV/cm, though the shape of the curves is different from different carrier density. There is negligible increase in the velocity beyond 500 kV/cm in all cases. At lower sheet charge density, the saturated velocity is significantly higher than that at higher sheet charge density. An increase in the noise level is also noticed with decreasing $n_s$ since the noise from the equipment is more evident as the device current density reduces. Using the velocity value at the maximum field (600 kV/cm) as the saturated velocity, the saturation velocity is plotted as a function of the 2DEG charge density (Figure 11(b)). For each charge density, multiple devices were measured to verify uniformity, and the spread in the velocity is indicated through error bars. The saturation velocity at low sheet charge density is $1.9 \times 10^7$ cm/s, which is similar to that estimated by previous work in GaN [16] [25] [39]. However, as the sheet charge density is increased above $10^{13} \text{ cm}^{-2}$, the electron saturation velocity decreases significantly (by approximately 50%). This velocity decrease plays a critical role in device characteristics, including the current density, transconductance profile and small-signal parameters. Engineering the sheet density (or gate-bias) dependence of velocity and making it constant is a key requirement to achieve improved gain linearity, and will be discussed in chapter 3.

2.1.3. Stimulated emission of longitudinal optical (LO) phonons

The theoretical model discussed in this section relates the density-dependent velocity saturation to stimulated emission of longitudinal optical (LO) phonons, and was developed
The strong dependence of saturation velocity on the sheet charge density measured (Figure 11) could not be explained by conventional mechanisms, such as band non-parabolicity and inter-valley transfer. The hot LO phonons are prevalent in wide gap nitride semiconductors (unlike Si and GaAs) due to their relatively long (few picoseconds) lifetimes $\tau_{LO}$ [42]. Previous works [32] [43] have shown that the presence of hot phonons increases momentum relaxation time while not affecting the energy relaxation time – a clear recipe for the velocity saturation. In case of standard Fermi-Dirac distribution function (Figure 12(a)), the electron population in the state with larger momentum $f_2$ is always less than population of the state with a smaller momentum $f_1$.

![Fermi-Dirac distribution](image)

Figure 12. Fermi-Dirac distribution (a) for low drift velocity $v_d$; and (b) for high $v_d$ shown for two states $k_1$ and $k_2$. 

by Prof. J. B. Khurgin (Johns Hopkins University, Baltimore MD). Further in depth discussions can be found in references [40] and [41].
Therefore, the probability of absorption of LO phonon (black, thin arrow) with momentum \( q = k_2 - k_1 \) (red, thick arrow) is always stronger than stimulated emission for small drift velocity \( v_d \). If, however one uses a more suitable model, with the so-called drifted Fermi-Dirac distribution [44] in which Fermi function is shifted by the amount of “average” drift momentum \( k_d = m_c v_d / \hbar \), then for large \( v_d \), the situation when \( f_2 > f_1 \) shown in Figure 12(b) arises. Now the higher energy state \( k_2 \) has larger population than the lower one \( k_1 \), and, with probability of stimulated LO emission exceeding that of LO absorption, phonons now experience gain \( g_{\text{LO}} \) (per unit of time) that is naturally proportional to the carrier density \( n_s \). At some value of \( k_2 \) gain reaches its maximum value \( g_{\text{LO}}^{\text{max}} \sim n_s v_d^{m(T_e)} \), where \( m(T_e) \) depends on the electron temperature \( T_e \), and modeling using Boltzmann distribution for \( f \) shows that for a wide range of electron temperatures, \( 2 < m < 4 \). This situation is entirely analogous to the photon gain in laser medium, and, just as in a laser, threshold condition

\[ g_{\text{LO}}^{\text{max}} r_{\text{LO}} > 1 \]

is reached when the phonon gain exceeds phonon decay. At this point the density of LO phonons starts growing exponentially and velocity saturates as all the additional power gets immediately transferred to LO generation, just as the upper level population in the laser gets clamped at threshold. Clearly, with higher carrier density, the threshold is reached earlier and velocity saturates at a lower value. The simple model outlined above predicts \( v_{\text{sat}} \sim n_s^{1/m} \), but it is only a qualitative approximation. The exact dependence of saturation velocity on sheet density is complicated as electron temperature also changes with increase in current density. Performing full self-consistent simulations
with drifted Fermi-Dirac distribution that included all the additional scattering mechanisms, we have obtained velocity saturation curves and then fitted the results into expression shown in Eq. (2.2), where \( n_{s,0} \) is \( 1.8 \times 10^{13} \text{ cm}^{-2} \).

\[
\nu_{sat}(n_s) = \frac{10^7}{0.38 + \left(\frac{n_s}{n_{s,0}}\right)^{0.45}}
\]  

(5)

The theoretical curve is displayed in Figure 11(b) and shows good agreement with the measured results, suggesting that the model explains strong dependence of saturation velocity on carrier concentration, and captures the physics of 2DEG transport in GaN rather well. A general expression for 3D carrier density dependent saturation velocity was also obtained as Eq. (2.3), where \( n_{v,0} \) is \( 6 \times 10^{18} \text{ cm}^{-3} \).

\[
\nu_{sat}(n_v) = \frac{10^7}{0.38 + \left(\frac{n_v}{n_{v,0}}\right)^{0.5}}
\]  

(6)

2.1.4. TCAD simulation using experimental results

To further verify the presented measurement results, the experimental sheet density-dependent saturation velocity characteristics were used in 2D TCAD simulator Silvaco ATLAS to simulate DC and RF characteristics of a reported GaN HEMT for comparison [45]. The simulated device was a standard sub-100 nm GaN HEMT structure on SiC substrate, with 20 nm of AlGaN barrier layer and 1 nm of AlN interlayer. The source-to-drain distance, \( L_{SD} \), and the gate length, \( L_G \), were 1.1 \( \mu \text{m} \), and 60 nm, respectively, and the heights of gate, \( h_{gate} \), was set to be 560 nm. The gate resistance, \( R_g \), was 0.15 \( \Omega \cdot \text{mm} \), and contact resistance, \( R_c \), was 0.23 \( \Omega \cdot \text{mm} \), as described in [45]. Figure 13 shows the
comparison between the simulated and the experimental transfer characteristics, current gain profile, and the output characteristics. The simulated characteristics matched well with the experimental results, in particular the drop in transconductance as the gate bias increases. This behavior could not be captured without the use of density-dependent velocity model, validating the measurement results presented, and also suggesting that using a density dependent velocity model is critical for predictive models of AlGaN/GaN HEMTs. Other reported devices with varying gate lengths were also simulated, and good agreement was observed between simulated and experimental results (not included here).
Figure 13. Comparison between the simulated and the experimental device characteristics (Results from J. W. Chung, W. E. Hoke, E. M. Chumbes, and T. Palacios, IEEE Electron Device Lett. 31(3), 195-197, 2010) [45]; (a) transfer characteristics; (b) current gain profile; and (c) output characteristics.
2.2. AlGaN channels: low-field transport in 2DEG

As discussed in chapter 1, the significantly larger estimated breakdown field of AlN (12-16 MV/cm) as compared to GaN (3 MV/cm) makes AlGaN channel transistors attractive for next-generation devices. It is critical to investigate the low-field mobility in AlGaN channel transistors, as it is a key parameter in transistor operation. In a power electronic switch, the mobility dictates the on-resistance, which causes potential drop and hence conduction losses in the device. In an RF amplifier or emitter, however, the mobility (sheet resistance) plays a more subtle, nevertheless very crucial role. Although the carriers experience high electric fields, low channel mobility or high sheet resistance could significantly impact the carrier velocity, and have serious implications on gain of the transistor. This is discussed in more detail in the section 2.3.

2.2.1. Theoretical 2DEG mobility

Electron mobility calculations for AlGaN channels were done using the dominant scattering mechanisms - alloy scattering and optical phonon scattering [46] [47]. The total mobility was approximated using Mattheisen’s rule,

\[ \frac{1}{\mu_{\text{Total}}} = \frac{1}{\mu_{\text{alloy}}} + \frac{1}{\mu_{\text{op}}} \]

(7).

The alloy scattering-limited mobility was calculated using a previously derived expression [48]:

\[ \mu_{\text{alloy}} = \frac{\mu_{\text{free}}}{1 + \frac{1}{N_c \lambda^2}} \]

where \( N_c \) is the carrier density and \( \lambda \) is the mean free path.
\[ \mu_{\text{alloy}} = \left( \frac{q \hbar^3}{m_{\text{eff}}[x]^2 V_0^2 \Omega_o [x](1-x)x} \right) \left( \frac{16}{3b[x]} \right), \]

(8)

where \( m_{\text{eff}} \) is the electron effective mass, \( V_0 \) is the alloy scattering potential for AlGaN alloys reported earlier to be 1.8 eV [49], \( \Omega_0 \) is the unit cell volume calculated using lattice and elastic constants varied linearly between AlN and GaN, \( x \) is the Al mole fraction, and \( b \sim n_s^{1/3} \) is the variational parameter for Fang-Howard wavefunction, chosen at the minimum energy. Here the alloy scattering in the channel is considered, while the scattering component from the barrier alloy is ignored as the wavefunction penetration is small. An AlN barrier would give no alloy scattering component from the barrier layer.

The optical phonon scattering-limited mobility was calculated using [22]:

\[ \mu_{\text{op}} = \frac{2Q_0 \hbar^2 F(y)}{qm_{\text{eff}}[x]^2 \omega_0 N_B(T) G(k_0)}, \]

(9)

where \( Q_0 = \sqrt{2m_{\text{eff}}(\hbar \omega_0)/\hbar^2} \) is the polar optical phonon wave-vector,

\[ N_B(T) = \frac{1}{\exp(\hbar \omega_0/k_B T) - 1} \]

is the Bose-Einstein distribution function, \( F(y) \) is given by

\[ 1 + \frac{1 - \exp(-\pi \hbar^2 n_s/m_{\text{eff}} k_B T)}{\pi \hbar^2 n_s/m_{\text{eff}} k_B T} \]

, \( \omega_0 \) is the optical phonon frequency and \( G(k_0) \) is the screening form factor.

Figure 14(a) shows the calculated alloy-scattering limited mobility and optical-phonon limited mobility curves for \( n_s = 10^{13} \text{ cm}^{-2} \).
Figure 14. 2DEG mobility calculated as a function of Al mole fraction in AlGaN channel ($n_s = 10^{13} \text{ cm}^{-2}$); (a) alloy scattering limited and optical phonon limited mobility components; and (b) temperature-dependent total mobility at 300K (blue, dashed), 500K (purple, dot-dashed) and 700K (red, solid).

The alloy-scattering limited mobility (temperature independent) degrades as the AlGaN alloy composition increases, but again recovers at higher AlN compositions with reduced alloy. The optical-phonon limited mobility illustrates a severe degradation as the channel temperature rises from 300K to 700K. Figure 14(b) represents the total 2DEG mobility calculated at operating temperatures of 300K, 500K and 700K. The plots show that the effect of alloy scattering is reduced at very high compositions (closer to AlN composition...
of 1). More significantly, the reduction in total mobility in AlGaN with respect to GaN is less severe at the higher operating temperatures that are expected for typical power switching devices. For example at room temperature, for an 80% AlGaN channel, the reduction in mobility relative to GaN is ~ 92% at room temperature, but only ~ 78% at 500K, suggesting that the performance degradation at higher temperatures may not be as severe as at room temperature.

2.2.2. Evaluation of AlGaN for power switching

To compare the losses in high composition AlGaN channels with GaN channel, 2DEG mobility and breakdown field is estimated as a function of AlGaN composition and operating temperature. For vertical devices, Baliga’s figure of merit relates device performance to the fundamental material characteristics as [50]

\[ BFOM = \varepsilon_s \mu E_C^3, \tag{10} \]

where \( \varepsilon_s \) is the dielectric constant, \( \mu \) is the calculated electron mobility and \( E_C \) is the critical breakdown field. For lateral devices such as GaN HEMTs, the lateral device figure of merit can be estimated as [50] [51] [52]

\[ LFOM = n_s \mu E_C^2, \tag{11} \]

calculated for \( n_s = 10^{13} \) cm\(^{-2}\). Figure 15 shows the calculated power figures of merit for AlGaN channels normalized with GaN.
Figure 15. AlGaN channel power figures of merit (normalized with GaN) as a function of Al mole fraction at device operating temperatures of 300K (blue, dashed), 500K (purple, dot-dashed) and 700K (red, solid); (a) Baliga figure of merit; (b) Lateral figure of merit calculated for \( n_s = 10^{13} \text{ cm}^{-2} \). The vertical line (red, dotted) represents the Al composition of 80% in the AlGaN channel.

For breakdown field, a quadratic dependence on the AlGaN composition was assumed from GaN (3.3 MV/cm) to AlN (11 MV/cm), as expected from WKB tunneling theory. It was observed that the estimated performance of AlGaN channel exceeds that of GaN channel above a critical value of Al composition, especially at higher device operating temperatures. Assuming device temperature of 500K [53], AlGaN channel with Al composition of 65% would have similar performance to GaN channel. AlGaN channels
with even higher compositions than 65% could outperform GaN channels at 500K. Another advantage offered by high Al composition AlGaN channels is the larger positive threshold voltages for normally-off power switching operation than conventional GaN-channel HEMTs due to the low electron affinity of AlN [54].

2.3. AlGaN channels: high-field transport

2.3.1. Effect of mobility on velocity, $f_T$

Although there are no experimental reports on velocity-field characteristics in AlGaN channels, previous reports based on Monte-Carlo calculations have predicted higher saturation velocity than GaN [16] [17]. This suggests that in high electric fields, the carrier velocity in AlGaN channel should be comparable to that in GaN channel. However, since the mobility in AlGaN is much lower (< 10X) than GaN, the electrons may not experience sufficiently high fields to be able to transit at saturated velocity. In other words, if the slope of the velocity-field curve at low field (i.e. mobility) is gradual, then the electric field at which velocity saturation occurs would increase. Therefore the gate length, $L_G$ must be scaled to the point where critical field for velocity saturation is achieved. This is illustrated by TCAD simulations of a conventional AlGaN/GaN HEMT structure by varying the mobility and gate length parameters to study their effect on the velocity profile. A sheet charge density of $10^{13}$ cm$^{-2}$ and a saturated velocity of $10^7$ cm/s were used. Figure 16 compares the simulated electron velocity profiles as a function of channel mobility for two gate lengths, $L_G = 250$ nm and 100 nm, carried out at $V_{DS} = 10$ V, $V_{GS} = 1$ V.
Figure 16. Simulated electron velocity profiles in the channel as a function of channel mobility for a HEMT structure with (a) $L_G = 250$ nm; and (b) $L_G = 100$ nm (Figure courtesy of Zhanbo Xia, OSU).

When mobility is $> 500$ cm$^2$/Vs, both gate lengths show similar electron velocity profiles and the electrons transit at saturated velocity. As the mobility drops below $\sim 300$ cm$^2$/Vs, there is a severe degradation in the channel velocity profile in case of $L_G = 250$ nm (Figure 16(a)). Therefore, the performance of an AlGaN channel HEMT with mobility $< 200$ cm$^2$/Vs is expected to be lower than a GaN channel HEMT with mobility $> 1500$ cm$^2$/Vs. This phenomenon, however, subsides as the gate length is reduced and the fields are higher. The electron velocity even for low mobility channels approaches saturated velocity as the gate length is reduced from 250 nm to 100 nm (Figure 16(b)). This effect can also be seen
in the transistor cutoff frequency, $f_T$ simulated as a function of mobility for $L_G = 700$ nm, 250 nm and 100 nm (Figure 17).

![Graphs showing simulated $f_T$ profiles and normalized profiles](image)

Figure 17. (a) Simulated $f_T$ profiles and (b) $f_T$ profiles normalized with respect to the maximum value ($f_{T,\text{MAX}}$), both as a function of channel mobility and gate length.

As one would expect, the effect on $f_T$ is identical as discussed in the case of the electron velocity. For high mobility $> 500$ cm$^2$/Vs, $f_T$ approaches its maximum value, $f_{T,\text{MAX}}$, which is governed by the ratio of saturated velocity to gate length (Figure 17(a)). As the mobility reduces, the $f_T$ starts to drop due to the lower electron drift velocity in the channel. This reduction is less severe for shorter gate lengths, as can be seen from the ratio $f_T / f_{T,\text{MAX}}$ plotted for the three values of $L_G$ (Figure 17(b)).
Finally, the ratio \( f_T / f_{T,\text{MAX}} \) as a function of mobility can be translated to a function of Al-composition in AlGaN channel, which can then be used to predict the Johnson’s figure of merit \( \sim f_T F_{BR} \) (Figure 18).

![Graph showing simulated \( f_T \) profiles normalized with respect to the maximum value \( f_{T,\text{MAX}} \) and Johnson’s figure of merit \( \sim f_T F_{BR} \) normalized with respect to GaN, both as a function of Al-composition in the channel and gate length.](image)

Figure 18. (a) Simulated \( f_T \) profiles normalized with respect to the maximum value \( f_{T,\text{MAX}} \); and (b) Johnson’s figure of merit \( \sim f_T F_{BR} \) normalized with respect to GaN, both as a function of Al-composition in the channel and gate length.

Using total 2DEG mobility in Figure 14(b) at 300K, the ratio \( f_T / f_{T,\text{MAX}} \) is plotted as a function of Al-composition in the channel and varying gate length (Figure 18(a)). The product of this calculated ratio \( f_T / f_{T,\text{MAX}} \) with the estimated breakdown field as a function of Al-composition in the channel results in the Johnson’s figure of merit, as plotted in
Figure 18(b). The plot illustrates that the figure of merit increases with higher Al-composition in the channel, and improves further as the gate lengths are scaled.

In general, the channel sheet resistance dictates this phenomenon, where a high sheet resistance would cause an adverse effect on electron velocity and \( f_T \). Due to the larger breakdown field of AlGaN, the channel charge density can essentially be higher (~2-3X) than in GaN channel, making the case of \( n_s = 10^{13} \text{ cm}^{-2} \) discussed above an overestimation of the reduction in velocity and \( f_T \). Hence, an AlGaN channel transistor with mobility \( \sim 100 \text{ cm}^2/\text{Vs} \), \( n_s \sim 2\text{-}3\times10^{13} \text{ cm}^{-2} \), and an \( L_G \) of 100 nm, the \( f_T \) would be reduced by only \( \sim 10\% \) than in a conventional GaN transistor, as seen from Figure 17(b). It is again noted that the calculations are done assuming a constant saturated velocity of \( 10^7 \text{ cm/s} \), and may differ if a modified saturated velocity (for example as a function of Al composition in the channel) is used.

2.4. Conclusions

In this chapter, transport in GaN and AlGaN channels and its implications on device properties were studied. Electron velocity as a function of sheet charge density was characterized in AlGaN/GaN HEMTs by means of pulsed I-V measurements on I-shaped test structures. It was found that the saturated velocity is a strong function of charge density, where the velocity decreased significantly as the charge density increased. A physical model based on optical phonon emission was described, and TCAD simulations were carried out using the measured \( n_s \)-dependent saturated velocity. The model and the
simulations, both showed good agreement with the experimental observation. Theoretical 2DEG mobility in AlGaN ternary channels was calculated, which was mainly limited by alloy scattering mechanism. Calculations of power switching figures of merit for AlGaN channels suggested an improvement in switching losses with respect to GaN channel, especially at higher Al compositions and operating temperatures. To understand the effect of lower mobility on electron velocity and $f_r$, TCAD simulations were performed with varying the channel mobility. The results showed a reduction in electron velocity for low mobility channels below $\sim 500 \text{ cm}^2/\text{Vs}$, which was less severe for shorter channel (scaled) devices.
Chapter 3

Graded AlGaN channels for improved current/power gain linearity

GaN high electron mobility transistors (HEMTs) have, thus far, enabled high power and current gain capability that is suitable for mm-wave and THz amplifiers [55] [56] [45] [57] [58] [6]. However, however they are known to have soft/premature gain compression as well as significant non-linearity, especially at higher operation frequencies. The transconductance, current gain and power gain at a given drain bias reach a peak value and drop off with gate bias [59]. Reduction in power gain with gate voltage is detrimental for linearity under large signal operation, and translates into intermodulation distortion and gain compression. Circuit level techniques such as pre-distortion and amplifier back-off are currently used to overcome these issues, but often have costly trade-offs in terms of complexity, bandwidth, efficiency and performance. Methods to overcome inherent device non-linearity using device epitaxial design can therefore be valuable, especially at higher frequency where circuit level techniques may cause unacceptable loss.

While the large-signal linearity itself is a relatively complex function of various device properties, small-signal parameters – power gain and current gain – can provide insight into the performance over the bias plane of the device. The small-signal power gain
of a device, $\mathcal{G}_p$, is given by

$$
\mathcal{G}_p = \left(\frac{f_T}{f}\right)^2 \frac{R_L}{R_{in}} ;
$$

(12)

where $f_T$ is the current gain cutoff frequency, and $R_L(R_{in})$ is the real part of the output (input) impedance. If the parasitic resistances and the gate-drain capacitance are ignored, the cutoff frequency can be expressed as $f_T = \frac{v_{sat}}{2\pi L_G}$, where $L_G$ is the gate length, and $v_{sat}$ is the saturated velocity of electrons. The cutoff frequency and power gain, therefore both depend directly on the electron saturated velocity. This chapter discusses the advantages of graded PolFETs over HEMTs in terms of electron velocity and gain linearity, and presents TCAD simulations and experimental demonstration of constant $g_m$, $f_T$ and $f_{max}$ profiles as a function of gate bias or current density.

### 3.1. PolFET versus HEMT

#### 3.1.1. Velocity dependence on gate bias

As discussed in chapter 2, the saturated electron velocity is an extrinsic property that depends on the electron density. It was shown experimentally that the 2DEG velocity in GaN HEMTs decreased with increasing sheet charge density. Since current and power gain are functions of velocity, they are expected to decrease with increasing the 2D electron gas (2DEG) or current density in an AlGaN/GaN HEMT, leading to a “droop” in the transconductance, current gain/cutoff frequency, and power gain/maximum oscillation frequency as a function of gate bias.
Metal semiconductor field effect transistors (MESFETs) and related devices, on the other hand, do not rely on electron density variation, but *channel width modulation* to vary the output current. In such devices, the local electron density throughout the channel is constant, and therefore, the *effective* channel velocity is expected to be constant as a function of gate bias [60] [61] [62] [63] [64]. Polarization (spontaneous and piezoelectric) in III-Nitride materials provides a way to realize MESFET-like electron channels without impurity doping through the use of compositionally graded layers [9] [10]. Grading the Al composition in the channel leads to a polarization gradient in the graded region which in turn induces a 3D bulk charge. Such a polarization-graded field-effect-transistor (PolFET) has a distributed electron density with lower peak value compared to a 2DEG [65]. Thus, a higher and constant *effective* velocity versus gate bias is expected in PolFET in contrast to a high density 2DEG. Polarization or composition grading, however, is not limited to linear or step grade, and can be varied, hence providing a powerful tool to engineer the charge and velocity profiles as a function of gate bias or current density, and consequently $g_m / f_T / f_{\text{max}}$ profiles [66].

The main trade-off in using a graded channel is the increase in the gate-channel spacing and the decrease in gate-source capacitance. The graded channels can however be designed (scaled) for W-band operation such that their gate length to barrier thickness aspect ratios can still be maintained above ~10, allowing suitable electrostatic control. Furthermore, the increased velocity when moving to a lower charge density could help to overcome some of the effects of reduced aspect ratio.
3.1.2. TCAD device simulations

Graded channels were further investigated by simulating the DC and small-signal characteristics using 2D simulator Silvaco ATLAS. A PolFET structure was simulated with total channel thickness of 25 nm, with Al composition graded linearly from GaN to Al$_{0.25}$Ga$_{0.75}$N over 15 nm. For comparison, a similar HEMT structure with 25 nm Al$_{0.25}$Ga$_{0.75}$N barrier / GaN channel was also simulated (Figure 19).

![Figure 19](image1.png)

Figure 19. Structure schematic, and vertical energy-band profile for the simulated structures; (a) AlGaN/GaN HEMT; and (b) Graded PolFET (Figure courtesy of Omor F. Shoron, OSU).
The equilibrium energy-band diagrams and charge profiles shown in Figure 19 were calculated using Schrodinger-Poisson solver [34]. Both structures had a total integrated density of \( \sim 9 \times 10^{12} \text{ cm}^{-2} \). For the simulations, the 3D density dependent-velocity model discussed in chapter 2 was used. The channel mobility of 1500 (1200) \text{ cm}^2/\text{Vs} was used in HEMT (PolFET) structure, respectively. A contact resistance, \( R_C = 0.2 \ \Omega \text{mm} \), source-gate spacing, \( L_{SG} = 0.5 \mu\text{m} \), gate length, \( L_G = 0.25 \mu\text{m} \), and a gate-drain spacing, \( L_{GD} = 1.0 \mu\text{m} \) were used in both simulated structures. The simulated \( g_m / f_T \) profiles of the two structures are shown in Figure 20.
Figure 20. Simulated $g_m$ (transfer characteristics) at $V_D = 10$ V, and $f_T$ as a function of $V_{GS}$ and $V_{DS}$ for (a) AlGaN/GaN HEMT; and (b) Graded PolFET (Figure courtesy of Omor F. Shoron, OSU).

In the case of HEMT, the simulated $g_m$ and $f_T$ reduce as the gate bias or current density is increased. However, in the case of the PolFET, the simulated $g_m$ and $f_T$ stay nearly constant as the gate bias or current density is increased. Rather, the $g_m$ increases as the current density is increased. This is expected as the gate-source capacitance for a graded channel increases with increasing gate bias.
3.2. Demonstration of constant $g_m/f_{T}/f_{\text{max}}$ in scaled PolFETs

3.2.1. Device design/fabrication

The device design used for experimental demonstration consists of an upward composition graded AlGaN channel to induce a 3D channel, and a reverse composition graded n$^{++}$ AlGaN layer to eliminate abrupt conduction band offsets and facilitate low resistance non-alloyed ohmic contact formation [31]. More details on the composition graded contact layers are presented in the section 4.1 of the next chapter. The structure was grown on 4H-SiC substrates using N$_2$ plasma-assisted molecular beam epitaxy (Figure 21(a)). The buffer layer consists of a 50 nm AlN nucleation layer (N-rich regime with Al/N ~ 0.6), followed by a 700 nm thick two-step GaN buffer [33]. Above the GaN buffer layer, an AlGaN channel layer with AlN mole fraction graded from 0% (bottom) to 33% (top) over 30 nm was grown, followed by 20 nm reverse composition-graded (33→0%) n$^{++}$ AlGaN contact layer. The equilibrium energy-band and charge profiles for the device under the gate region (recessed) were calculated using Schrodinger-Poisson solver [34] (Figure 21(b)). For the energy-band diagram calculation, surface Fermi-pinning of $E_C-E_F$ = 0.9 eV and 1.8 eV were used at the GaN and Al$_{0.33}$Ga$_{0.67}$N surfaces, respectively. In addition, a low unintentional n-type doping ($10^{14}$ cm$^{-3}$) was used in the channel and buffer layers for faster solver convergence.
Figure 21. Graded PolFET: (a) structure schematic; (b) calculated energy-band diagram under the ohmic region (as-grown) and gate region (recessed) with charge profile; (c) XRD scan; and (d) AFM scan.

To confirm the layer compositions and thicknesses, X-ray diffraction (XRD) scan was carried out (Figure 21(c)) showing good agreement between simulation and experimental
data. Atomic force microscopy (AFM) image of the as-grown surface showed smooth surface with rms roughness ~ 0.7 nm (Figure 21(d)).

Device fabrication was carried out as follows. Non-alloyed Ti/Al/Ni/Au ohmic contacts were formed, followed by 100 nm mesa isolation using Cl$_2$-based plasma etching. Device access and intrinsic regions, or source drain spacing were defined by removing the 20 nm contact layer using a calibrated low power (3W) Cl$_2$-based plasma etch. In this device design, incomplete recessing of the n$^{++}$ contact layer can deteriorate Schottky gate characteristics. Therefore a carefully calibrated recipe with low etch rate is desirable. The device may also be designed to create some recess tolerance, such as a thicker channel graded up to a marginally higher Al composition, or an undoped AlGaN inserted below the contact layer although it might lead to an increase in contact resistance. A T-shaped gate profile with gate length, $L_{foot}$, of 250 nm and head length, $L_{head}$, of 500 nm was defined by a bilayer PMMA/MMA photoresist process using a Vistec EBPG-5000 e-beam lithography system. Ni (20 nm)/ Au (100 nm)/Ni (30 nm) Schottky contact for the gates was deposited using e-beam evaporation, followed by 150 nm plasma-enhanced chemical vapor deposited (PECVD) silicon nitride passivation. The process flow is illustrated in Figure 22.
Figure 22. Process flow illustration of the scaled graded PolFETs: non-alloyed Ti/Al/Ni/Au ohmic contacts deposited using e-beam evaporation; contact layer recess in the gate/access regions using Cl₂-based ICP-RIE; Ni/Au/Ni T-gates written using e-beam lithography; and Si₃N₄ passivation layer deposited using PECVD.
Figure 23 shows cross-sectional scanning electron microscope (SEM) images of the T-gate profiles taken before and after nitride passivation.

![Cross-sectional SEM image of the PolFET device showing T-gate profile with gate length, $L_G = 250$ nm (a) before passivation; and (b) after passivation.](image)

3.2.2. Experimental results

Transfer length measurement (TLM) gave sheet resistance, $R_{SH}$ of 1816 Ω/□, and an effective ohmic contact resistance, $R_C$ of ~ 0.1 Ω.mm. Hall measurement gave total integrated charge density, $n_{Hall}$ of 6x10^{12} cm^{-2}, and Hall mobility, $\mu_{Hall}$ of 574 cm^{2}/Vs. The measured integrated charge density was found to be lower than the calculated value (~7x10^{12} cm^{-3}) (calculated charge profile shown in Figure 21(b)). This could be attributed to dislocation effects in MBE-grown films that introduce an effective compensation charge [67], and were previously observed in AlGaN/GaN HEMTs. The electron mobility in
random AlGaN alloys is limited by alloy scattering, as discussed in chapter 2, and therefore the effective mobility in such graded channels is lower than that obtained in AlGaN/GaN HEMTs [47]. The measured effective Hall mobility was also found to be even lower than the theoretical value (~ 1000 cm²/Vs) calculated based on optical phonon scattering and random alloy scattering mechanisms [47]. Again this could be attributed to the dislocation effects in MBE-grown AlGaN films and may be improved with growth optimization [20].

Capacitance-voltage profiling was done with gate metal on the recessed regions on circular diodes with radius = 100 μm (Figure 24(a)).

![Capacitance-voltage characteristics of the graded PolFET (frequency = 1 MHz); and (b) the measured charge profile from CV measurement.](image)

The charge density was estimated to be approximately 4x10¹⁸ cm⁻³, which is ~20% lower than the modeled charge profile (Figure 24(b)) as in the case of measured integrated density.
described earlier. The CV measurement gave a threshold voltage, $V_{TH}$, of -3 V, which is also lower than the calculated threshold (approximately -3.5 V), and is consistent with the lower charge density measured.

Figure 25. DC characteristics of the graded PolFET with $L_{GD}$ of 0.3 μm, $L_{SD}$ of 0.9 μm, $L_G$ of 250 nm: (a) 2-terminal gate-drain characteristic; (b) experimental transfer characteristics at $V_{DS} = 9$ V; (c) output characteristics comparing DC and pulsed curves.
DC characteristics of the device were measured using an Agilent B1500 parameter analyzer (Figure 25). 2-terminal gate-drain characteristics (Figure 25(a)) show rectifying Schottky behavior of the gate contact. The measured transconductance, $g_{m,ext}$, profile for $V_{DS} = 9$ V (Figure 25(b)) is different from that of a conventional AlGaN/GaN HEMT. The transconductance increases as the gate bias is increased, as is expected for a MESFET-like device where the capacitance increases with gate bias [68]. However the increase of the transconductance does not follow the trend expected from CV profiling. The transconductance is (to first order) given by $g_{m,int} = C_{gs}v_{sat}$. While the capacitance $C_{gs}$ increases by almost 100% over the operating voltage range, i.e. from 0.25 μF/cm$^2$ to 0.5 μF/cm$^2$ (Figure 24(a)), the transconductance is almost constant as a function of $V_{GS}$. We attribute this to a combination of two factors. Firstly, with increasing gate bias, electrons spread more into the higher composition AlGaN which has lower mobility, and this could be reducing the effective velocity. Secondly, there could be non-linear source resistance due to source region pinch-off as the current density is increased [69] [58] [70].

The device pinch-off voltage for the 250 nm gate length devices was measured to be ~ -4.5 V, which is more negative than that on large-area diodes. We attribute this to the low aspect ratio (~ 8) of the channel leading to drain-induced barrier lowering. The maximum drain current density at $V_{GS} = 1$ V was measured to be 0.95 A/mm (Figure 25(c)), for transistors with $L_{GD}$ of 0.3 μm, $L_{SD}$ of 0.9 μm, $L_{G}$ of 250 nm. The output characteristics also showed output conductance (short-channel effect), again due to the low aspect ratio. PolFETs with larger gate-length, $L_{G} = 0.7$ μm (hence improved aspect ratio) were also measured, which showed well-behaved device characteristics and no output conductance.
Pulsed IV curves (500 ns pulse width, duty cycle = 0.1%) from quiescent condition of $V_{GS} = -6 \text{ V}$, $V_{DS} = 9 \text{ V}$ showed significant current dispersion that may be due to non-optimal surface passivation, and can be mitigated by further optimization of the deposition conditions, or adopting passivation-first process flow which allows for strong acid/base surface treatments.

The PolFET structure described was also simulated using 2-D TCAD simulator Silvaco ATLAS. The measured channel mobility and contact resistance values were used. Since the channel velocity in AlGaN is not known, the saturated velocity was varied to match the measured current. It was found that a saturated velocity of $1.18 \times 10^7 \text{ cm/s}$ provides good agreement with the data. The results showed maximum $I_{DS}$ and $g_{m,\text{ext}}$ in good agreement with the measurement (Figure 26).

![Figure 26. Comparison of simulated and measured DC characteristics of the graded PolFETs: (a) transfer characteristics at $V_{DS} = 9 \text{ V}$; and (b) output characteristics.](image)
More significantly, in agreement with experiment, a constant $g_{m_{\text{ext}}}$ profile was obtained from simulation. In addition, output conductance of similar magnitude to the experimental device characteristics in Figure 26(b) was observed, confirming our previous assertion that low gate-to-channel aspect ratio was causing a degradation of output resistance.

The small-signal RF performance of this transistor was measured using an Agilent E8361 network analyzer. On-wafer calibration was carried out using short-open-load-through (SOLT) off-wafer impedance standards in the frequency range from 100 MHz to 67 GHz. S-parameters were measured as a function of the drain bias (1 to 9 V), and gate bias (-4 to 0 V). Peak extrinsic $f_T$ of 52 GHz and $f_{\text{max}}$ of 67 GHz were measured at $V_{GS} = -1.5$ V and $V_{DS} = 9$ V (Figure 27).

![Figure 27. Extrinsic RF gain characteristics at $V_{GS} = -1.5$ V, $V_{DS} = 9$ V.](image)
The $f_T L_g$ product for the device (13 GHz-μm) is comparable to AlGaN/GaN HEMTs at these gate lengths, suggesting that the saturated velocity in AlGaN channels is comparable to those in GaN channels. Contours of $f_T$ profiles and the $f_{MAX}$ profiles were measured as a function of both $V_{GS}$ and $V_{DS}$ (Figure 28).

![Figure 28](image)

Figure 28. (a) Contour plot of the $f_T$ profiles as a function of both $V_{GS}$ and $V_{DS}$; (b) contour plot of the $f_{MAX}$ profiles as a function of both $V_{GS}$ and $V_{DS}$.

These contour plots show that both $f_T$ and $f_{max}$ remain constant over a large bias range. $f_T$ and $f_{max}$ values extracted at $V_{DS} = 9$ V are also plotted as a function of current density, $I_{DS}$ (Figure 29).
Figure 29. $f_T$ and $f_{MAX}$ plotted as a function of current density, $I_{DS}$ showing a reduction <
5% and 10%, respectively, at $V_{GS} = 0$ V from their peak values.

Unlike conventional AlGaN/GaN HEMTs, the current and power gain do not show a droop at high drain current density values. Compared to the peak values, there is less than 5% reduction in $f_T$ and less than 10% reduction in $f_{MAX}$ at $V_{GS} = 0$ V. This shows that the use of graded AlGaN channels can help to realize constant $f_T$ and $f_{MAX}$ profiles over a large region of the device IV plane, and can enable highly linear current and power gain profiles at high frequencies.

3.3. Conclusions

In the previous chapter, the implications of decreasing velocity versus gate bias (or charge density) profile in GaN HEMTs were discussed. This chapter described the engineering of
electron velocity dependence on gate bias through the use of polarization grading. TCAD simulations using the experimental density dependent velocity (chapter 2) were carried out to compare small-signal characteristics in PolFET and HEMT. Constant $g_m$ and $f_T$ profiles were predicted in PolFET with linearly graded AlGaN channel. Experiments were performed on MBE-grown structures consisting of graded AlGaN channel and reverse graded and heavily doped contact layers. Highly-scaled PolFET structures were fabricated with T-gate profiles using e-beam lithography, and Nitride passivation. Constant $g_m$ and $f_T$ profiles were experimentally verified in PolFETs with linearly graded channels, as predicted by device simulations, suggesting that these devices could enable highly linear transistors.
Chapter 4
High Al-content AlGaN channel transistors

The potential advantages of high-Al content AlGaN channel-based transistors were analyzed in chapter 1. It was discussed that the large bandgap of ultra-wide bandgap (UWBG) AlN (6.2 eV) results in a theoretical breakdown field (~ 12-16 MV/cm) that is almost 4-5 times higher than that of GaN [15]. This in combination with high estimated electron saturated velocity makes AlGaN a promising material for advanced high frequency applications [16] [17]. Also, for power electronic application, analytical calculations in chapter 2 suggested that replacing conventional GaN channel with high Al composition AlGaN channel in high electron mobility transistors (HEMTs) could result in reduced switching losses and enhanced normally-off operation [54]. In this chapter, experimental results on UWBG AlGaN transistors grown by different growth techniques – molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) – are presented. The key challenges related to AlGaN transistors, and some plausible solutions are investigated.

In the first section, formation of low-resistance ohmic contacts to UWBG AlGaN channels is discussed. A heterostructure engineering approach is described in which the Al alloy composition in the AlGaN channel is graded from wider bandgap to narrower
bandgap under the ohmic contacts. The first demonstration of graded contact layers is presented, followed by 1st generation MOSFETs grown by MBE in the second section. The main limitations of MBE grown channels, and the advantage of MOCVD-grown channels are then discussed. 2nd generation MOCVD-grown transistors are achieved with significantly superior performance than the 1st generation devices. To combine the advantages of the previous generations, the 3rd generation devices were designed with a hybrid MOCVD/MBE approach. The last section presents a proof of concept demonstration of an AlGaN transistor with all-refractory metal process, suitable for extreme temperature device operation.

4.1. Heterostructure graded ohmic contacts

Previous reports on AlGaN channel HEMTs, with channel Al composition up to 60%, focused on power electronic application, and showed encouraging on-state and off-state device characteristics [52] [71] [72] [73] [74]. However, a critical challenge which prevented further advancement in ultra-wide bandgap (UWBG) AlGaN-based devices was high-resistance ohmic contacts. The low electron affinity of AlN, and lower doping efficiency together result in large tunneling barrier for electrons. Figure 30 shows the specific contact resistance as a function of channel Al composition in these previously reported results [30] [75] [76] [71] [73] [74].
A severe degradation in ohmic contact resistance was observed as the channel compositions were higher than 20-30%, rendering them impractical for any application since such contact resistances would overwhelm the device. These AlGaN HEMT results employed conventional alloyed ohmic contacts to form contacts through the AlGaN barrier layers. More studies on alloyed contacts using metals such as Titanium, Vanadium and Zirconium [77] [78] [79] [80] [76] [81] reported low specific contact resistance values below $10^{-5} \ \Omega \cdot \text{cm}^2$ on n-AlGaN channels with Al compositions up to 66% [79]. However, they were challenging to reproduce reliably due to extremely high temperature processes and typically showed non-uniformity in current-voltage characteristics. Alternate heterostructure engineering approaches were therefore needed to realize low contact resistance to high composition AlGaN.
A low-resistance ohmic contact is formed by reducing the potential barrier between a metal and semiconductor. The ideal n-type ohmic contact would have a zero or low Schottky barrier height at the metal-semiconductor interface, which can be achieved by matching the semiconductor electron affinity and metal work function. However, the intrinsic low electron affinity of AlN (0.6 eV) leads to larger metal-AlGaN Schottky barriers, resulting in a poor tunneling probability for electrons (probability $\sim e^{-\sqrt{\varphi_b W}}$, where $\varphi_b$ is the barrier height and $W$ is the tunneling width), and therefore highly resistive ohmic contacts (Figure 31(a)).
In this approach, the Al alloy composition in the AlGaN channel is graded from wider bandgap to narrower bandgap under the ohmic contacts, hence grading up electron affinity and presenting a higher electron affinity at the metal-semiconductor interface (GaN electron affinity, $\chi_{\text{GaN}} = 4.1$ eV). AlGaN layers with compositional grading from GaN to AlGaN have been studied extensively, and shown to induce bulk three-dimensional electron distributions due to positive polarization (spontaneous+piezoelectric) charge [9].
The polarization-induced fixed charge, $\rho_\pi$, can be given by $\rho_\pi = -\nabla \cdot \mathbf{P}$, where $\mathbf{P}$ is the sum of spontaneous and piezoelectric polarization in AlGaN alloy. In case of layers with reverse Al compositional grading from wider to narrower bandgap AlGaN, a negative polarization charge is formed, causing a positive curvature in the energy band profile, and thereby creating a barrier to electron flow (Figure 31(b)). To ensure that the conduction band stays flat, it is necessary to compensate for the negative polarization charge using donors. This is shown in Figure 31(c), where donors in the graded region compensate for the negative charges, leading to an effectively n-type region. The entire energy band gap offset is supported in the valence band, as shown in the energy band diagram, and there are no heterojunction or electrostatic barriers to transport between the channel and the surface of the semiconductor.

4.1.1. Experimental results on MBE-grown structures

Experimental demonstration was carried out on AlGaN structures (Figure 32) grown on Al-face AlN on Sapphire templates [82] using plasma-assisted molecular beam epitaxy (PAMBE).
Figure 32. (a) Schematic of AlGaN structures used for the study; (b) the associated energy-band diagram under the ohmic contact region (as-grown) showing upward grading of electron affinity towards the surface.

The 100 nm n-Al_{0.75}Ga_{0.25}N channel (Si=3x10^{19} \text{ cm}^{-3}) was grown at 720°C on a 30 nm undoped Al_{0.75}Ga_{0.25}N buffer layer, followed by 50 nm n^{++} contact layer formed by linearly grading down the Al content from 75% to ~0% (actual 6%). Figure 32(b) shows the energy-band diagram in the contact region (as-grown), simulated using 1D Schrodinger-Poisson solver [34]. It can be seen that the conduction band (E_C) profile under the contacts does not have any abrupt or electrostatic barriers to block the flow of electrons. Figure 33(a) shows the X-ray diffraction scan measured with AlN as the reference to confirm the Al composition and thickness of the epi layers. Atomic force microscopy (AFM) on the as-grown surface (Figure 33(b)) indicated a fairly smooth surface morphology with rms roughness of 1.1 nm and a step-flow growth mechanism.
Figure 33. (a) Measured X-ray diffraction scan confirming AlGaN compositions and thicknesses; and (b) Atomic force microscopy on as-grown surface showing fairly smooth surface morphology and step-flow growth mechanism.

Device structures were fabricated using standard processing techniques. Non-alloyed Ti/Al/Ni/Au ohmics were evaporated on as grown structures, followed by device mesa isolation of 200 nm using Cl$_2$-based inductive plasma etching. To achieve active Al$_{0.75}$Ga$_{0.25}$N channel and characterize the ohmic contact, the compositional graded contact layer was recessed between the source and the drain of the device using low-power (6 Watts) Cl$_2$-based inductive plasma etching.

Hall measurement on as-grown structures with both channel and contact layers gave a sheet resistance ($R_{Si}$) of 160 $\Omega/\square$, and net effective mobility of 35 cm$^2$/Vs. Figure 34(a) illustrates the transport and resistance components in the as-grown structures.
Figure 34. (a) As-grown n-Al_{0.75}Ga_{0.25}N MESFET structure depicting current flow, contact resistance, $R_{C1}$, and net sheet resistance, $R_{SH}$ in the device; and (b) Transfer length measurement on the structure in (a) with measured values of $R_{C1}$ and $R_{SH}$.

Transfer length measurement (TLM) gave an $R_{C1}$ of 0.15 $\Omega$.mm, which is the contact resistance at the metal-n$^{++}$ Al$_{0.06}$Ga$_{0.94}$N junction (Figure 34(b)). To test the contact to Al$_{0.75}$Ga$_{0.25}$N channel, the measurements were repeated after recessing the graded contact layer and leaving 90 nm thick channel. Hall measurement on the recessed structure gave a sheet resistance ($R_{SH}$) of 726 $\Omega$/□, and a low channel mobility of 16 cm$^2$/Vs, feasibly limited by impurity scattering effect due to high Si donor concentration and native defects in the channel layer. Further discussion of low channel mobility/material quality in MBE-grown channels is presented in section 4.2.1.

To measure the effective contact resistance to n-Al$_{0.75}$Ga$_{0.25}$N channel, TLM was performed and plotted against varying recess spacing (Figure 35).
Figure 35. (a) Gate-recessed n-Al$_{0.75}$Ga$_{0.25}$N MESFET structure with 90 nm channel layer between the ohmic contacts, depicting current flow, effective contact resistance, $R_C = R_{C1} + R_{SH1}$, and channel sheet resistance, $R_{SH2}$; and (b) Transfer length measurement on the structure in (a) with measured values of $R_C$ and $R_{SH2}$.

The effective contact resistance in the recessed device geometry is given by the summation of $R_{C1}$ (Figure 34(b)), and $R_{SH1}$ which consists of the sheet resistance components of the graded contact layer and the channel layer (Figure 35(a)). TLM gave $R_{SH}$ values of 725 Ω/□, and $R_C$ of 0.32 Ω.mm (Figure 35(b)). The specific contact resistance ($\rho_{sp} = R_C^2/R_{SH}$) was extracted to be $1.9 \times 10^{-6}$ Ω.cm$^2$, which is the lowest value reported to AlGaN with such high bandgap of 5.3 eV using non-alloyed ohmic contacts, and is comparable to typical values achieved on lower band gap GaN channels [75] [30] (Figure 36).
4.2. 1st generation: AlGaN transistors grown by MBE

To demonstrate transistors, identical structures with thinner (20 nm) n-Al$_{0.75}$Ga$_{0.25}$N channels were grown for better recess control and to achieve a lower channel charge suitable for transistor operation, mainly device pinch-off and high breakdown voltage. The graded contact layer was recessed between source/drain pads to form active channel with thickness ~ 12 nm confirmed using AFM. Schottky-gate devices fabricated on the recessed channel showed high reverse gate leakage due to high Si dopant concentration. Other growths with lower dopant concentrations below $10^{19}$ cm$^{-3}$ had resulted in highly resistive channels, as discussed in section 4.2.1. Atomic layer deposited (ALD) Al$_2$O$_3$ gate-dielectric layer was employed to suppress gate leakage. The device process was concluded with a 20 nm ALD Al$_2$O$_3$ deposited at a substrate temperature of 300°C, followed by post-deposition anneal at 700°C to minimize the Al$_2$O$_3$/AlGaN interface defect states or hysteresis [83].
and deposition of Ni/Au/Ni gate metal. Figure 37 shows the final MOSFET device structure schematic and experimental characteristics for gate-length, $L_G = 0.7 \, \mu m$ and gate-drain spacing, $L_{GD} = 1.1 \, \mu m$.

Figure 37. (a) Structure schematic of the Al$_{0.74}$Ga$_{0.26}$N channel MOSFET; (b) measured capacitance-voltage characteristics (10 kHz frequency) on circular diode structures (radius = 100 μm) and the integrated charge density as a function of gate-bias; (c) measured family output I-V characteristics; and (d) measured transfer characteristics at $V_{DS} = 20 \, V$. 

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Figure 37(b) shows the capacitance-voltage measurement (10 kHz frequency) on a circular (100μm radius) diode structure, with MESFET-like behavior in accumulation region and a pinch-off voltage of -8 V. Capacitance-voltage characteristics at higher frequencies showed dispersion, which could be related to trap states at the AlGaN/AlN interface under the channel. Proper designing of the buffer layers could mitigate these effects, for example making the undoped AlGaN buffer thicker, as done in the case of 2nd generation devices (section 4.3). The measured family output I-V characteristics (Figure 37(c)), showed maximum drain current, $I_{DS,MAX}$ of ~ 60 mA/mm at $V_{GS} = 2$ V. The transfer characteristics at $V_{DS} = 20$ V (Figure 37(d)), with peak transconductance, $g_{m,peak}$ of 14 mS/mm. The $I_{DS,MAX}$ and $g_{m,peak}$ values are largely limited by the low channel mobility, and expected to improve with enhanced material quality (lower native defect/Si dopant concentrations).

Breakdown performance was evaluated by measuring 3-terminal off-state breakdown at 1 V below pinch-off voltage. At $V_{GS} = -9$ V for a gate-drain spacing, $L_{GD} = 1.1$ μm (confirmed using scanning electron microscope), a 3-terminal breakdown voltage, $V_{br}$, of 224 V was measured (Figure 38). Using $L_{GD}$ and $V_{br}$ values, an average lateral breakdown field, $F_{br}$ of ~ 2 MV/cm can be computed.
Although the measured breakdown voltage of approximately 200 V/μm is significantly lower than theoretically predicted values, it was nevertheless among the highest for AlGaN channel devices. These measurements were done in presence of Fluorinert solution, and without any field plates or edge termination techniques. Engineering the peak electric field in the channel (eg. field plates) and superior material quality are expected to enhance the $F_{br}$ in these devices.

### 4.2.1. Limitation of MBE-grown AlGaN channels

Evidently, the low channel mobility was the main issue in the 1st generation MBE-grown devices and impeded their performance. In a high quality Al$_{0.75}$Ga$_{0.25}$N channel, i.e. with low defect density/impurities, the electron mobility dominated by alloy scattering (chapter...
2) is calculated to be approximately 100-150 cm$^2$/Vs [47]. With high dopant concentrations, as in the case of 1$^{st}$ generation devices (Si concentration of $3 \times 10^{19}$ cm$^{-3}$), impurities can become dominant scattering sites for electrons. Devices with high Si concentration were demonstrated since the channels grown with concentrations below $10^{19}$ cm$^{-3}$ were found to be insulating, suggesting an acceptor-like compensating defect with concentration of the same order. Therefore, the low electron mobility < 20 cm$^2$/Vs in 1$^{st}$ generation devices could be due to a combination of impurity scattering (ionized and unionized) [22] and dislocation scattering [84]. Another phenomenon which can severely limit the electron mobility is the phonon-assisted hopping transport [85]. Due to the difference in surface adatom mobility of Ga and Al at MBE growth temperatures (~ 600-800ºC), it is possible that AlGaN films have non-uniform AlGaN alloy and possible lateral alloy fluctuations, hence causing AlN/GaN energy barriers for lateral electron transport.

Growth of high Al-content AlGaN films has been extensively studied for optoelectronic devices, such as lasers and light emitting diodes (LEDs). Early AlGaN growth studies by MBE achieved high Si-doping ($>10^{20}$ cm$^{-3}$) in all Al compositions up to AlN [86] [87] [88] [89], and measured carrier concentrations $>10^{19}$ cm$^{-3}$ for Al compositions up to ~ 85%. A rapid decrease in ionization (increase in ionization energy of Si) was observed for Al compositions greater than ~ 85% (~ 250 meV for AlN) [87]. In all these results, however, the mobility values were lower than ~ 23 cm$^2$/V$s$, whereas MOCVD-grown AlGaN films reported considerably higher mobility values. For example, AlGaN films with Al compositions of 70% [90] and 100% [91] showed high room-temperature mobility of 100 cm$^2$/V$s$ (Si = $2 \times 10^{18}$ cm$^{-3}$ with ~100% ionization) and 426
75 cm²/Vs (Si concentration of 3x10¹⁷ cm⁻³ with <1% ionization), respectively. Understandably, most of the research work in the last decade studied MOCVD-grown films, rendering incomplete understanding of poor electron transport in MBE-grown films.

To investigate the electron transport in MBE-grown AlGaN films, multiple growth experiments were performed to study the effect of growth conditions on the material quality and electrical transport (courtesy of Dr. Fatih Akyol, OSU). At lower growth temperatures below 740°C (Ga-rich regime), secondary ion mass spectrometry (SIMS) revealed Carbon and Oxygen background concentrations below 3x10¹⁷ cm⁻³, which were much lower than the estimated compensating defect density ~ 10¹⁹ cm⁻³. At higher growth temperatures above 760°C (intermediate regime), however, Carbon and Oxygen background concentrations were measured to be higher than ~10¹⁹ cm⁻³. X-ray diffraction (XRD) scans on the other hand, indicated a reduction in edge/screw dislocations with increasing growth temperature up to 810°C. The highest dislocation density in AlGaN bulk films with Al compositions of 50-90% was estimated on the order ~ 10⁹ cm⁻³. AlN templates with extremely low dislocation densities (free standing AlN templates [92] and AlN on Sapphire templates [82]) were also studied. It was concluded that all growths resulted in very low mobility values (~ 5-20 cm²/Vs) at room temperature, and increased marginally with increasing temperature. This behavior was indicative of electron hopping transport through the films laterally due to alloy fluctuations.

To solve the lateral alloy fluctuations, another approach was tried where AlN/GaN periods were grown with monolayer (sub-nm) thickness to form a “digital” alloy. For example, a 75% AlGaN bulk layer was formed by 3 AlN / 1 GaN monolayers, such that
the average Al composition corresponded to 75%. Such n-type digital channels also resulted in poor mobility values ~ 5 cm$^2$/Vs, which could be due to inefficient AlN/GaN layer coverage resulting in Al-rich pockets rather than continuous “digital” films. Further research may be needed to investigate and improve transport in MBE-grown AlGaN films.

In contrast, AlGaN films grown by MOCVD use significantly higher growth temperatures (~ 1000-1300ºC) than in MBE. The n-type Al$_{0.7}$Ga$_{0.3}$N films grown with Si concentrations of 0.5-1 x 10$^{18}$ cm$^{-3}$ (Dr. Andy Allerman, Sandia National Laboratories, NM) were found to be highly conductive, with electron mobility of ~ 90 cm$^2$/Vs (used as channels in 2nd generation devices). A comparison of scanning transmission electron microscopy (STEM) images of high Al composition AlGaN films grown by MBE and MOCVD on AlN on Sapphire templates revealed a drastic contrast in the compositional uniformity (Figure 38). Here, AlGaN films with Al composition linearly graded from ~ 65% to 88% were studied in dark-field STEM. The streaky appearance of MBE-grown films was indicative of non-uniform alloy coverage and fluctuations in Al composition, where darker contrast is representative of higher Al composition. The MOCVD-films did not show such fluctuations, and showed highly uniform alloy graded vertically as expected. These high composition graded AlGaN channels are employed in the 3rd generation devices, and discussed later in this chapter.
Figure 39. A comparison of scanning transmission electron microscopy (STEM) images of high Al composition AlGaN films grown by MBE and MOCVD.

4.3. 2nd generation: AlGaN transistors grown by MOCVD

After the demonstration of 50 mA/mm current density with MBE-grown channels, other reports published current densities up to 0.25 A/mm in Al$_{0.65}$Ga$_{0.35}$N channels grown by MOCVD [93], but using standard ohmic contact alloying methods. The reported mobility values were significantly higher than those measured in MBE channels. For example, the measured mobility reported by Muhtadi et al. [93] for n-Al$_{0.65}$Ga$_{0.35}$N channels was ~ 90 cm$^2$/Vs. However, these current densities were still dominated by the high contact resistance. The objective of this experiment was to realize 2nd generation devices with
Al$_{0.7}$Ga$_{0.3}$N channels and reverse composition graded contact layers, all grown by metal-organic chemical vapor deposition (MOCVD).

The structures for the 2nd generation devices were grown on AlN on Sapphire templates by MOCVD. The epitaxial stack consisted of 200 nm insulating AlN buffer, 300 nm n-Al$_{0.7}$Ga$_{0.3}$N channel (Si: $10^{18}$ cm$^{-3}$), and a 30 nm n$^+$ (Si: $4.5x10^{19}$ cm$^{-3}$) reverse Al composition graded (70% to 0%) ohmic contact layer (Figure 40).

<image description>

Figure 40. Structure schematic of the MOCVD-grown Al$_{0.7}$Ga$_{0.3}$N channel MOSFET, illustrating gate-length, $L_G$, and the gate-connected field plate length, $L_{FP}$.

The X-ray rocking curve full widths at half maximum (FWHM) of the (0004) and (10-11) planes were 306 and 653 arcsec for AlN buffer layer, and 374 and 576 arcsec for AlGaN layer, respectively. These gave an estimated threading dislocation density (TDD) of 2-3x10$^9$ cm$^{-2}$, which is comparable to other AlN on sapphire reports [94] [95]. Device structures were fabricated using standard processing techniques. Non-alloyed Ti/Al/Ni/Au
ohmic contacts were evaporated on the n⁺ GaN as-grown surface, followed by device mesa isolation using Cl₂-based inductive plasma etching. To form the active region, the graded contact layer and 50 nm channel layer were removed between the contacts using low-power (6W) Cl₂-based inductive plasma etching, leaving 250 nm thick channel. A 20 nm thick Al₂O₃ gate-dielectric was deposited using atomic layer deposition (ALD) at 300°C, followed by e-beam evaporation of Ni/Au/Ni gate pads. Finally, gate-connected field plates (FP) were patterned (Ni/Au/Ni) on a 150 nm thick plasma-enhanced chemical vapor deposition (PECVD) deposited Si₃N₄ layer.

Figure 41 shows the equilibrium energy-band profiles for the MOSFET device under the gate/access regions (Fig. 41(a)) and the ohmic contact region (Fig. 41(b)), calculated using Schrodinger-Poisson simulator [34].

Figure 41. Calculated equilibrium energy-band profiles of the AlGaN MOSFET structure (a) under the gate (MOS) and access regions; and (b) under the ohmic contact region.
For the gate region in Fig. 41(a), an interface fixed charge of $+2 \times 10^{13}$ cm$^{-2}$ was assumed at the Al$_2$O$_3$/AlGaN interface, such that there is no accumulation of electrons or holes at that interface, and the channel depletion width matches the gate-source capacitance, $C_{GS}$. As seen in Fig. 41(b), the composition graded and heavily doped ohmic contact region enables a flat conduction band profile, $E_C$, between the metal contact and high composition AlGaN, and prevents abrupt conduction band discontinuities that could create energy barriers to the transport of electrons.

Capacitance-voltage profiling (Figure 42(a)) was done on circular diodes (radius = 100 μm) with a maximum negative bias of -25 V, which was the equipment limit. The extracted charge profile from C-V confirmed a charge/dopant concentration of $10^{18}$ cm$^{-3}$ in the channel (Figure 42(b)).

![Figure 42. Capacitance-voltage characteristics performed on large circular diodes (radius = 100 μm); and (b) extracted charge profile confirming a channel charge/doping density of $10^{18}$ cm$^{-3}$.](image-url)
The reduction in apparent charge for depths greater than \( \sim 125 \) nm suggested back depletion from the AlN buffer due to the negative polarization charge at the AlGaN channel/AlN interface. Hall measurement on Van der Pauw structure gave a total integrated charge density, \( n_{Hall} \), of \( 1.25 \times 10^{13} \, \text{cm}^{-2} \), and Hall mobility, \( \mu_{Hall} \), of 90 \( \text{cm}^2/\text{Vs} \) [96]. Transfer length measurement (TLM) gave sheet resistance, \( R_{SH} = 5.6 \, \text{k}\Omega/\square \), contact resistance, \( R_C = 14 \, \Omega.\text{mm} \), and specific resistivity, \( \rho_{sp} (= R_C^2/R_{SH}) = 3.5 \times 10^{-4} \, \Omega.\text{cm}^2 \). This is significantly higher than \( \sim 10^{-6} \, \Omega.\text{cm}^2 \) that was achieved on MBE-grown \( \text{Al}_{0.75}\text{Ga}_{0.25}\text{N} \) channels in the 1st generation devices. To ensure n-type conductivity and flat conduction band profile in the reverse graded contact layer, the nominal doping density must be sufficiently high to compensate the negative polarization charge. The high \( R_C \) suggests that there is a resistive layer, which may be due either the lower doping efficiency in MOCVD-grown high composition AlGaN layers, or self-compensation effects (DX center formation) [97] [98] and is discussed in more detail in the next section (section 4.3.1).

3-terminal DC characteristics of the field-plated MOSFETs were measured using an Agilent B1500 device parameter analyzer. Figure 43 shows the 3-terminal transfer and output characteristics of transistors with channel width, \( W = 100 \, \mu\text{m} \), gate-length, \( L_G = 1 \, \mu\text{m} \), and source-gate spacing, \( L_{SG} = 0.3 \, \mu\text{m} \).
Figure 43. MOSFET 3-terminal (a) transfer and (b) output characteristics for a standard MOSFET device with $W = 100 \, \mu m$, $L_G = 1 \, \mu m$, $L_{GD} = 1.4 \, \mu m$, $L_{SG} = 0.3 \, \mu m$.

Maximum current density, $I_{DS,\text{MAX}} \sim 0.35 \, A/mm$ and peak transconductance, $g_{m,\text{peak}} = \sim 9 \, mS/mm$ were measured. The transconductance is determined by the thick channel which leads to low gate-source capacitance, $C_{GS}$, and could be enhanced significantly by scaling the devices. The output characteristics also showed output conductance which we attribute to short-channel effects due to the low aspect ratio (ratio of $L_G$ to channel thickness) of 4. A field-effect mobility of $\sim 61 \, cm^2/Vs$ was extracted from the device characteristics, which was 30% lower than the Hall mobility. An on/off ratio $> 10^7$ was also measured in these devices, suggesting low leakage through the gate-dielectric and buffer layers.

3-terminal breakdown characteristics of the field-plated MOSFETs were measured at $V_{GS} = -100 \, V$ in Fluorinert (Figure 44).
Figure 44. 3-terminal breakdown characteristics of the field-plated MOSFETs at $V_{GS} = -100$ V ($L_G = 1 \mu m$, $L_{GD} = 1.4 \mu m$ and $L_{FP} = 0.2 \mu m$) plotted in (a) linear scale; and (b) logarithmic scale.

The gate-drain spacing ($L_{GD} = 1.4 \mu m$), and the field plate length ($L_{FP} = 0.2 \mu m$) were confirmed using scanning electron microscopy (SEM). Drain leakage current of 1 mA/mm (5 mA/mm) was reached at $V_{DS} = \sim 275$ V ($\sim 305$ V). These measurements lead to catastrophic device failure, and the drain leakage current was primarily due to source leakage, suggesting that improved aspect ratio (i.e. electrostatics) could enhance the breakdown voltage. At drain leakage of 5 mA/mm, the corresponding gate-drain voltage ($V_{DG}$) of 405 V, and $L_{GD} = 1.4 \mu m$ can be used to compute an average breakdown field, $F_{br} = 2.9$ MV/cm, which is 45% higher than that in 1st generation devices without field plates.

To investigate the effects of high contact resistance, I-shaped transistors with contact periphery (100 \mu m) much larger than the constriction width (1.7 \mu m) were
measured and compared with the standard large periphery devices. Figure 45 shows the scanning electron microscopy (SEM) image of an I-shaped MOSFET (top view).

![TOP view](image)

**Figure 45.** Scanning electron microscopy (SEM) image of an I-shaped MOSFET.

The device mesa is highlighted, and the device dimensions/features are depicted. This design is similar to the ungated I-shaped test structures discussed in detail in chapter 2. Figure 46 shows the 3-terminal characteristics on an I-shaped transistor with $W = 1.7 \, \mu m$, $L_G = 1 \, \mu m$, $L_{SD} = 0.5 \, \mu m$, and $L_{GD} = 1.7 \, \mu m$. 
Figure 46. MOSFET 3-terminal (a) transfer and (b) output characteristics for an I-shaped structure (Inset: structure schematic) with $W = 1.7 \ \mu m$ (contact periphery = 100 $\mu m$), $L_G = 1 \ \mu m$, $L_{GD} = 1.7 \ \mu m$, $L_{SG} = 0.5 \ \mu m$.

The maximum current density and transconductance in these structures were $I_{DS,\text{MAX}} > 0.5$ A/mm, and a $g_{m,\text{peak}} = \sim 15$ mS/mm. The higher current values in the wide-contact geometry I-shaped devices suggests that the contact resistance plays a role in limiting the current density, and that the intrinsic current density for the AlGaN channel can be as high as 0.5 A/mm. This is the highest current density reported for AlGaN channels with Al composition > 0.25 [52] [71] [72] [76] [99] [74] [93]. A rising $g_m$ is observed with increasing $V_{GS}$, which is characteristic of MESFET-like structures as the gate-source capacitance increases.
3-terminal breakdown characteristics of the I-shaped field-plated MOSFETs were measured at $V_{GS} = -100$ V in Fluorinert (Figure 47).

![Graphs showing 3-terminal breakdown characteristics](image)

Figure 47. 3-terminal breakdown characteristics of the I-shaped field-plated MOSFETs at $V_{GS} = -100$ V ($L_G = 1$ μm, $L_{GD} = 1.7$ μm, and $L_{FP} = 0.2$ μm) plotted in (a) linear scale; and (b) logarithmic scale.

For device dimensions of $L_G = 1$ μm, $L_{GD} = 1.7$ μm, and $L_{FP} = 0.2$ μm, drain leakage current of 1 mA/mm (5 mA/mm) was reached at $V_{DS} = \sim 400$ V ($\sim 520$ V). This measurement was non-destructive and repeatable, which could be due to efficient heat dissipation in smaller devices. At drain leakage of 5 mA/mm, the corresponding $V_{DG}$ of 620 V, and $L_{GD} = 1.7$ μm give an average $F_{br} = 3.6$ MV/cm. A higher $F_{br}$ in I-shaped structures may be attributed to superior electrostatics due to FinFET-like gate geometry. Although this value is much lower than the theoretical estimates in Al$_{0.7}$Ga$_{0.3}$N ($\sim 9$ MV/cm), it is nevertheless
significantly higher than that seen in AlGaN/GaN HEMTs, where the maximum lateral field is limited to ~ 1 MV/cm for similar device dimensions. The true maximum field in the structure should peak near the gate-edge towards the drain, and must be higher than the average value of 3.6 MV/cm. Additional field plates and optimization of the design/dimensions could further improve the field profile, and hence enhance breakdown in these transistors.

Device simulations can provide a method to predict the field profile in the device at breakdown condition. However, it is challenging to estimate it accurately, since the presence of any buffer and/or surface traps can considerably modify this profile. Nevertheless, 2D TCAD simulator Silvaco ATLAS was used to estimate the ideal electric field profile in the device (without the presence of surface/buffer traps). Figure 48 shows the simulated electric field profile in the AlGaN channel, 1 nm below the gate-dielectric, at bias conditions of $V_{GS} = -100$ V, and $V_{DS} = 400$ V (Fig. 48(a)) and 520 V (Fig. 48(b)).
Figure 48. Simulated lateral \((E_X)\) and total \((E_{TOTAL})\) electric field profiles in the AlGaN channel, at bias conditions of \(V_{GS} = -100\) V, and (a) \(V_{DS} = 400\) V and (b) \(V_{DS} = 520\) V.

The total field, \(E_{Total}\), and the x-component, \(E_X\) are plotted along the device with gate-edge towards the drain as the zero reference on the x-axis. The two peaks in the profiles correspond to the gate and gate-connected field plate due to the distribution of the charges. The peak \(E_X\) in the case of \(V_{GD} = 500\) V is \(\sim 8\) MV/cm, whereas it is \(\sim 8.5\) MV/cm for \(V_{GD} = 620\) V. No conclusion is drawn since the ideal electric field profiles are likely to be overestimated.

4.3.1. Limitation of MOCVD-grown AlGaN contact layers

Thus far, AlGaN films grown by MOCVD have evident advantage in terms of mobility, as seen in 2\textsuperscript{nd} generation devices. However, these devices are still limited by high contact resistance which dominated the device characteristics. In Figure 4.14(b), at maximum...
output current at $V_{DS} = 20$ V, the voltage drop across source and drain contacts can be estimated from contact resistance ($2R_C = 28 \ \Omega$.mm) and the current density ($\sim 0.35$ A/mm) to be approximately 10 V. The high source resistance also results in a large voltage drop in the source-gate region, therefore causing charge depletion at the gate-edge towards the source (source choking effect).

MBE-grown highly Si-doped AlGaN films in 1st generation device contact layers exhibited high conductivity. In contrast, experiments revealed that the conductivity of MOCVD-grown $\text{Al}_{0.7}\text{Ga}_{0.3}$N layers dropped as the Si concentrations increased beyond $\sim 10^{19}$ cm$^{-3}$, with highly resistive layers for Si concentrations greater than $\sim 10^{20}$ cm$^{-3}$. Some studies also reported similar behavior, wherein highly doped films grown by MBE were conductive [86] [87], however were insulating when grown by MOCVD [90]. Studies which investigated the properties of Si donor in AlGaN, both theoretical and experimental, have in the past debated its behavior. While some studies predicted Si to be a conventional shallow donor in AlGaN [100], others claimed it forms DX centers (negative-U centers) [101]. Recently, more evidence has supported the latter claim [102] [97] [98], where the energy of the DX$^-$ state (considered as activation energy) abruptly increases with the Al-content for $\sim 80$-100\%, approaching $\sim 250$ meV in AlN.

It is not clear why MBE-grown films do not manifest these self-compensation effects, which could be due to background Carbon, Oxygen, or defect-related compensation inherent to MBE-grown films [67]. Nevertheless, this opens a path toward achieving low contact resistance to UWBG AlGaN channels by hybrid MOCVD/MBE technique. The 3rd generation devices were aimed at realizing high mobility MOCVD-
grown channels, integrated with MBE-grown low-resistance reverse graded contacts layers.

4.4. 3rd generation: MBE-regrown contacts on MOCVD-grown channels

A HEMT structure, such as AlN/AlGaN, is appropriate for highly scaled devices. In particular, the two-dimensional electron gas (2DEG) and thin barrier layer render the best design in terms of device scaling (aspect ratio of gate-length to barrier thickness). However, graded AlGaN channels with high-Al content can have some advantages over the HEMT structure. Firstly, composition graded contact layers are easier to accommodate for graded AlGaN channels. As discussed in chapter 3, contact layers grown epitaxially over graded channel layers yield very low contact resistances due to flat conduction band profiles and no barriers for electrons. A HEMT structure on the other hand would require removal of the barrier layer and epitaxial regrowth of composition graded contact layer, such that a side ohmic contact to channels is formed. Moreover, graded AlGaN channels offer the design and control of capacitance/velocity/transconductance profiles that directly impact the device intrinsic gain linearity, as described in chapter 3. Finally, the electron mobility in high Al-content HEMT and PolFET channels is estimated to be comparable, with alloy scattering being the dominant scattering mechanism in both (chapter 2).

The structures for the 3rd generation devices were grown on AlN on Sapphire templates by MOCVD (Dr. Seongmo Hwang and Prof. Asif Khan, USC) (Figure 49).
Figure 49. Structure schematic of the high-Al content graded PolFET with 60 nm up graded channel layer (MOCVD) and reverse graded contact layer (MBE).

The epitaxial stack consisted of 0.5 μm insulating Al$_{0.65}$Ga$_{0.35}$N buffer, followed by 60 nm n-AlGaN channel (Si: $\sim$10$^{18}$ cm$^{-3}$), linearly graded from Al composition of 65% to 88% confirmed by X-ray diffraction scan. A 50 nm n$^{++}$ (Si: $\sim$10$^{20}$ cm$^{-3}$) reverse Al composition graded ohmic contact layer was then regrown using MBE over the entire sample. The nominal Al composition of $\sim$ 85% to 0% (linear grade) was aimed for the graded contact layer. Device structures were fabricated using standard processing techniques. Non-alloyed Ti/Al/Ni/Au ohmic contacts were evaporated on the n$^{++}$ GaN as-grown surface (MBE), followed by device mesa isolation using Cl$_2$-based inductive plasma etching. To form the active (gate) region, the graded contact layer was removed between the contacts using low-power (6W) Cl$_2$-based inductive plasma etching. A 65 nm deep recess was performed, as confirmed by atomic force microscopy, removing the graded contact layer completely and leaving a 45 nm thick graded channel. Finally, Ni/Au/Ni gate pads were deposited using e-beam evaporation.
2-terminal I-V measured between source-drain pads gave highly non-linear (Schottky-like) behavior, with a large turn-on voltage of 2-3 V. To probe this issue further, the layers were studied in dark-field STEM (Figure 50(a)).

Figure 50. (a) Dark-field STEM image of the hybrid MOCVD/MBE layers showing AlN interlayer at the regrowth interface; and (b) energy-band diagram calculated in the channel region and ohmic contact region with AlN interlayer.
The composition grading in the MOCVD channel layer and MBE contact layer was evident, however a thick AlN interlayer (~ 8 nm) was observed at the regrowth interface, i.e. between the channel and the regrown contact layer. The energy-band profiles were calculated in the gate region (also charge profile) and the contact region with AlN interlayer (Figure 50(b)) [34]. The unintentional AlN interlayer causes a large tunneling barrier for electrons, as seen in the conduction band profile, hence resulted in poor Schottky-like ohmic contacts. STEM images also showed an abrupt AlGaN/AlN interface above the AlN interlayer, with AlGaN composition similar to that at the channel surface (i.e. below AlN interlayer), followed by linear grading in the regrown contact layer. The AlN interlayer growth is currently being investigated, and may result due to a combination of reasons, including high starting Al flux during MBE regrowth, AlGaN surface decomposition prior to regrowth, MBE growth kinetics with high-Al content, or Al rich surface resulting from MOCVD growth. Additional regrowth experiments also revealed that the AlN interlayer thickness reduced to ~ 1 nm as the starting Al composition of the contact layer was decreased to ~ 60%, suggesting that the unintentional growth occurred during MBE regrowth. However, 2-terminal I-V characteristics showed that the contacts degraded further (lower current) as the starting composition was reduced below 70% (Figure 51(a)).
Figure 51. (a) 2-terminal source-drain characteristic (no gates) with varying starting Al composition of MBE contact layer; (b) conduction band profiles of the heterointerface between regrown contact/n-Al$_{0.85}$Ga$_{0.25}$N channel calculated for different starting Al composition of the contact layer (with 1 nm AlN interlayer); and (c) no AlN interlayer.

This degradation in ohmic contact with lower starting Al composition can be explained by a larger mismatch in the Al compositions of MBE contact/MOCVD channel layers at the regrowth interface, and hence leading to a larger Al$_x$Ga$_{1-x}$N/Al$_y$Ga$_{1-y}$N barrier (where x < y).
Figures 51(b) and 51(c) show the conduction band profiles at the heterointerface between regrown contact/n-Al_{0.85}Ga_{0.25}N channel, calculated for different starting Al compositions of the contact layer. Two cases are illustrated, the first with 1 nm AlN interlayer present (Figure 51(b)), and the second without AlN interlayer (Figure 51(c)). In both the cases, lower starting Al composition of the contact layer results in larger energy (tunneling) barrier for electrons due to the negative polarization charge. As the starting Al composition becomes slightly higher than the channel surface composition, the positive polarization pulls the conduction band lower and induces electrons (2DEG). As the difference in Al compositions increases further, the conduction band offset ($\Delta E_C$) at Al$_x$Ga$_{1-x}$N/Al$_y$Ga$_{1-y}$N interface (where $x>y$) causes the electron tunneling barrier. In summary, an n++-Al$_x$Ga$_{1-x}$N contact/n-Al$_y$Ga$_{1-y}$N channel interface would yield the desired contact resistance provided that $x=y$ (perfectly matched compositions), or $x$ is slightly higher than $y$. A very thin (~1-2 nm) AlN interlayer may introduce acceptable tunneling resistance given that it is heavily doped.

Despite the poor ohmic contacts, 2-terminal current densities up to 0.45 A/mm were achieved, with a contact resistance, $2R_C$ of ~ 7 $\Omega$.mm extracted from the linear region of the I-V curve. High Al-content PolFET devices with Ni/Au/Ni Schottky-gates were fabricated and characterized. Capacitance-voltage profiling (Figure 52(a)) performed on large diodes (area = 100x100 $\mu$m$^2$) gave a threshold voltage of ~ -10 V, and a rising profile as expected from a MESFET-like channel with uniform charge profile.
However, near device pinch-off, a flat capacitance profile which is characteristic of a 2DEG channel was observed. The extracted charge profile (Figure 52(b)) confirmed a constant charge density of $\sim 3.5 \times 10^{18}$ cm$^{-3}$, with a 2DEG near the bottom of the channel. This could be attributed to an unintentional abrupt change in the Al composition at the beginning of the compositional grade, leading to a polarization sheet charge/2DEG as in the case of AlGaN/GaN HEMT structure. Hall measurement on Van der Pauw structure gave a total integrated charge density, $n_{\text{Hall}}$, of $1.1 \times 10^{13}$ cm$^{-2}$, and Hall mobility, $\mu_{\text{Hall}}$, of 85 cm$^2$/Vs.

Figure 53 shows the 3-terminal output and transfer characteristics of transistors with channel width, $W = 2 \times 75$ μm, gate-length, $L_G = 0.7$ μm, source-gate spacing, $L_{SG} = 0.5$ μm, and gate-drain spacing, $L_{GD} = 1.5$ μm.
The output characteristics showed saturation of the I-V curves, even though the ohmic contacts had large voltage drop across them with Schottky-like turn-on. Maximum current density, $I_{DS_{MAX}} \sim 0.27 \text{ A/mm}$ and peak transconductance, $g_{m_{peak}} = \sim 35 \text{ mS/mm}$ were measured. Once again, a rising $g_m$ was observed with increasing $V_{GS}$, which is characteristic of MESFET-like structures as the gate-source capacitance increases. The reverse gate leakage was measured to be high, $\sim 0.3 \text{ mA/mm}$, which could be due to the surface damage (defect states) from the recessing of the MBE regrown layer. The use of gate-dielectric as in the case of 2nd generation MOSFETs can significantly reduce this leakage, and enhance the breakdown voltage.
Gradual channel analysis of the device can give an insight on the intrinsic maximum current density that can be achieved with ideal ohmic contacts. The maximum current density, \( I_{D(sat)} \) of a MESFET structure can be given by the following expression [68].

\[
\frac{I_{D(sat)}}{W} = \frac{q \mu n_s L_G}{V_p^3} \left[ \frac{V_p}{3} - V_{bi} + V_{GS} + \frac{2(V_{bi} - V_{GS})^{3/2}}{3V_p^{1/2}} \right];
\]  

(13)

where \( \mu \) is the mobility, \( n_s \) is the total integrated density, \( V_p \) is the pinch-off voltage, \( V_{bi} \) is the built-in voltage. An intrinsic current density of \( \sim 0.8 \) A/mm can be estimated using the equation 13. The lower extrinsic current density can be explained by the high source resistance, \( R_S \) in the device, causing channel depletion at the source injection point (source “choking” effect). The voltage drop across the source resistance, \( V_S (= I_D R_S) \) reduces the gate-channel voltage, \( V_{GC} \), and hence depletes the channel \( (V_{GC} = V_{GS} - I_D R_S) \). \( R_S \) can be given by the summation of source contact resistance, \( R_C \) and the sheet resistance over gate-source length, \( R_{SH} (L_{GS} = 0.5 \mu m) \), and is estimated to be \( \sim 9.5 \Omega \).mm. Therefore, \( V_S \sim 2.5 \) V, with the additional voltage drop (Schottky turn-on of \( \sim 2\text{-}3 \) V) in the ohmic contacts, result in a severe reduction in \( V_{GC} \), and hence the charge density by nearly \( \sim 50\% \).

The small-signal RF performance of this transistor was measured using an Agilent E8361 network analyzer. On-wafer calibration was carried out using short-open-load-through (SOLT) off-wafer impedance standards in the frequency range from 100 MHz to 67 GHz. S-parameters were measured as a function of the gate bias (-4 to 2 V), at a drain bias of 20 V. Peak extrinsic \( f_T / f_{\max} \) of 3/9.6 GHz for \( L_G = 1 \mu m \), and \( f_T / f_{\max} \) of 5.4/14.2 GHz for \( L_G = 0.7 \mu m \) were measured at \( V_{GS} = -4 \) V and \( V_{DS} = 20 \) V (Figure 54).
Figure 54. Extrinsic RF gain characteristics of the high-Al content graded PolFETs at $V_{GS} = -1.5$ V, $V_{DS} = 9$ V for (a) $L_G = 1 \, \mu m$; and (b) $L_G = 0.7 \, \mu m$.

In section 2.3 of chapter 2, the effect of channel mobility on electron velocity and $f_T$ in a transistor was analyzed. Simulations revealed that channel mobility < 500 cm$^2$/Vs resulted in $f_T$ values that were lower than the saturated $f_T$ value due to the reduced effective velocity. It was also found that this reduction was less severe in shorter gate-lengths that have higher electric field. Figure 55 shows the simulated $f_T$ values as a function of channel mobility and gate-length, plotted with the experimental value for $L_G = 0.7 \, \mu m$. 

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Figure 55. Simulated $f_T$ values as a function of channel mobility and gate-length, plotted with the experimental value for $L_G = 0.7$ μm (Figure courtesy of Zhanbo Xia, OSU).

The figure illustrates that $f_T \sim 8-9$ GHz is achievable (upper limit for $L_G = 0.7$ μm) with a channel mobility of 85 cm$^2$/Vs. The demonstrated device performance was mainly limited by the highly resistive ohmic contacts. A modest increase in $f_T L_G$ product from 3 to 3.8 GHz.μm was measured as the gate-length decreased from 1 to 0.7 μm, suggesting that further scaling could enhance this product, which is also indicative of the effective velocity in the device. While a $f_T L_G$ product $\sim 10$ GHz.μm would possibly make high-Al content AlGaN transistors feasible, it is nevertheless a promising first demonstration of RF operation.
4.5. AlGaN transistors for extreme temperature operation

Wide bandgap semiconductors are suitable for high temperature, harsh environment applications due to their inherent low intrinsic carrier concentration \( n_i \sim e^{E_g/2kT} \), where \( E_g \) is bandgap and \( k \) is Boltzmann’s constant) and stability. This section presents an AlGaN transistor design with all-refractory metal process, suitable for high temperature electronics for applications such as those involving automotive engines, industrial furnaces etc. GaN HEMTs reported previously have shown notably robust operation at high temperatures [103] [104]. At ambient temperatures above ~ 300ºC, device characteristics were found to deteriorate primarily due to degradation of metal contacts [105] [106]. AlGaN transistors with high Al-content have also shown good characteristics at ambient temperatures of ~ 200ºC [107] [108].

4.5.1. AlGaN structures with all-refractory metal process

A device design consisting of ultra-wide bandgap AlGaN barrier/channel layers with all-refractory metal contacts could enable superior stability in extreme environments. Refractory metals are ideal for exceedingly high temperatures, and have work functions in the range of ~ 4.3 eV to 4.7 eV (Figure 56).
Due to the low electron affinity of AlN, a sufficiently large Schottky barrier height on AlGaN can be expected with this range of work functions. Furthermore, low-resistance ohmic contacts could also be achieved by employing reverse Al composition graded contact layers, which provide a higher electron affinity under ohmic contacts, as discussed in section 4.1. This new concept is demonstrated using the 2\textsuperscript{nd} generation AlGaN transistor structures consisting of MOCVD-grown channel and contact layers, as described in section 4.3 (Figure 57).
Figure 57. (a) Structure schematic of the AlGaN MESFET with W metal ohmic and gate contacts; and (b) equilibrium energy-band diagram in the ohmic contact region and gate region.

Device fabrication commenced with mesa isolation, followed by recessing graded contact layer between the contacts, both using Cl$_2$-based inductive plasma etching. Finally, 200 nm thick W metal was sputtered using physical vapor deposition (PVD) to form ohmic and Schottky-gate contacts. These devices involved a total of three fabrication steps only, suggestive of a simple yet cost-effective process technology.

Figure 58 shows the 3-terminal DC characteristics of transistors with channel width, $W = 2\times75$ μm, gate-length, $L_G = 0.7$ μm, and source-drain spacing, $L_{SD} = 1.7$ μm.
Figure 58. 3-terminal DC characteristics of Al\textsubscript{0.7}Ga\textsubscript{0.3}N channel MESFET with W-gate and W-ohmic contacts; (a) output I-V characteristics, and (b) transfer characteristics.

The output characteristics (Figure 58(a))) showed poor ohmic characteristics with Schottky-like behavior, and current density moderately lower than the 2\textsuperscript{nd} generation devices with Ti ohmic contacts. This could be attributed to the higher work function of W (4.55 eV) as compared to that of Ti (4.1 eV) used in 2\textsuperscript{nd} generation devices. The transfer characteristics (Figure 58(b))) gave a peak transconductance, $g_{m\_peak}$ of $\sim 9$ mS/mm, a threshold voltage of $\sim -40$ V, and an $I_{on}/I_{off}$ ratio of $\sim 2 \times 10^4$. Similar MESFET devices with Pt Schottky-gates gave a higher $I_{on}/I_{off}$ ratio $> 10^7$ due to the lower reverse gate leakage current. Figure 59 shows a comparison of 2-terminal gate-drain characteristics for MESFETs with W and Pt Schottky-gate contacts.
Devices with W-gate and W-ohmic contacts (Figure 59(a)) showed a Schottky-barrier height of ~ 1 eV, and a reverse gate leakage of ~ $10^{-3}$ mA/mm. Contrastingly, devices with Pt-gate and Ti-ohmic contacts (Figure 59(b)) showed a Schottky-barrier height of ~ 2 eV, with a significantly lower on-resistance and reverse gate leakage. The difference in gate characteristics could again be due to the difference in the metal work functions, and possibly non-optimal (lower quality) W metal deposition resulting in defect states at the metal/semiconductor interface.
The high-temperature characterization was carried out using Lake Shore CRX 4K probe station (courtesy of Alex Potts, Dr. David Daughton). Temperature-dependent 3-terminal output characteristics were measured from 300K (~ 27°C) up to 675K (~ 400°C) under vacuum conditions (Figure 60).

Figure 60. Temperature-dependent 3-terminal output characteristics measured from 300K (~ 27°C) up to 675K (~ 400°C) under vacuum conditions (Figure courtesy of Alex Potts, OSU/Lake Shore).

A significant reduction in the maximum current density was observed as the temperature increased to 400°C, whereas the reverse gate leakage reduced marginally. The temperature dependent 2-terminal gate characteristics are plotted in Figure 61.
These characteristics are counter-intuitive, since the donor ionization in the channel and thermionic emission from the Schottky-barrier, both should increase with rising temperature. Figure 62 shows the temperature dependent 3-terminal $I_D-V_G$ transfer characteristics of the same device.

![Figure 61](image1.png)

**Figure 61.** Temperature dependent 2-terminal gate characteristics of the MESFET with W gate and ohmic contacts (Figure courtesy of Alex Potts, OSU/Lake Shore).

![Figure 62](image2.png)

**Figure 62.** Temperature dependent 3-terminal transfer $I_D-V_G$ characteristics of the MESFET with W gate and ohmic contacts (Figure courtesy of Alex Potts, OSU/Lake Shore).
A considerable decrease (positive shift) in the threshold voltage is observed as the temperature increased, resulting in reduced current density. The off-current also increased in the device with rising temperature, which is contributed from the source leakage (buffer leakage) since the gate leakage reduced at higher temperature (Figures 60 and 61).

The devices did not show any signs of physical degradation or damage, suggesting that the measured characteristics and trends at high temperature are related to other phenomena. Two plausible reasons may be related to the occupancy of the donor-like bulk traps, which might be present at the AlGaN/AlN interface, and to some extent the annealing effect on the W contacts enhancing gate contact and degrading ohmic contacts. Further investigation is needed to understand the density/energy of bulk traps, and their occupancy as a function of temperature. Such bulk traps, however, could be eliminated by engineering the device layers as shown by Rajan et al. in the case of N-polar GaN HEMTs [109] [66]. In particular, donors could be introduced at the AlGaN/AlN heterointerface to compensate the negative polarization charge and raise the Fermi level, while composition grading at the interface could prevent an abrupt valence band offset.

This work nevertheless presents the first proof of concept demonstration of high-Al content AlGaN transistors with simple yet unique design, and encouraging performance at 400ºC. Further design modifications to reduce the bulk trap related issues, and optimization of the refractory metals and the deposition conditions could substantially improve the performance of these devices.
4.6. Conclusions

This chapter presented the design and development of high Al composition AlGaN channel transistors. The key challenges, and the approaches taken to overcome those were discussed over three generations of devices. First, low-resistance ohmic contacts to high Al-content AlGaN channels were achieved through the use of composition (or electron affinity) grading. A specific contact resistance, $\rho_{sp}$ of $2 \times 10^{-6}$ $\Omega$.cm$^2$ was demonstrated on n-type Al$_{0.75}$Ga$_{0.25}$N channels grown by MBE, which was comparable to values typically achieved on narrower bandgap GaN channels. The 1st generation devices comprising of Al$_{0.75}$Ga$_{0.25}$N channel layer and composition graded contact layer, both grown by MBE, resulted in current density of $\sim$ 60 mA/mm, and average breakdown field of $\sim$ 2 MV/cm. The low channel mobility in MBE-grown films was recognized as the main limiting factor in the devices. In comparison, AlGaN channels grown by MOCVD exhibited considerably higher mobility values. The 2nd generation devices employing MOCVD-grown Al$_{0.7}$Ga$_{0.3}$N channel and graded contact layers demonstrated the highest current density (\sim 0.5 A/mm) and average breakdown field (\sim 3.6 MV/cm) among other reported AlGaN channel transistors with Al composition > 0.25. However, a higher contact resistance was observed in MOCVD-grown structures than in MBE-grown ones, which was attributed to the possibility of DX center formation in MOCVD-grown AlGaN films, especially at high Si donor concentrations. To combine the advantages of the previous generations, the 3rd generation devices were designed with a hybrid MOCVD/MBE approach, utilizing high mobility channel layer and low-resistance contact layer, respectively. The first
measurements resulted in a current density of \( \sim 0.27 \, \text{A/mm} \), and \( f_T \, L_G \) product of 3.8 GHz.\( \mu \text{m} \). Further optimization of the regrown contact layers and removal of unintentional AlN interlayers could significantly improve these characteristics. To end with, a unique AlGaN transistor design that used all-refractory metal process was discussed for extreme temperature applications.
Chapter 5
Conclusions and future work

5.1. Conclusions

The work presented in this dissertation focused on investigating and developing wider bandgap AlGaN channels to achieve superior gain linearity and output power density in III-Nitride transistors.

Transport in GaN and AlGaN channels, and its implications on device performance were studied. Density-dependent velocity-field characteristics in GaN HEMTs revealed that the saturated velocity reduced significantly as the charge density (or gate bias) increased. The effect of this reduction in velocity on small-signal characteristics, and large-signal linearity was discussed. To engineer the velocity dependence on gate bias to be constant, linearly polarization graded channels were explored. Simulations and experimental results, both showed constant $g_m/f_{rl}/f_{max}$ profiles over a large bias range, indicating a more constant velocity profile and superior linearity performance as compared to conventional GaN HEMTs.

AlGaN channels with high Al composition were investigated to achieve enhanced output power densities at high operation frequencies. Theoretical calculations suggested a lower 2DEG mobility in AlGaN channels as compared to GaN channel, mainly limited by alloy scattering. Implications of the lower mobility in AlGaN was explained on electron velocity through TCAD simulations, which showed that for channel mobility values $> 500 \text{ cm}^2/\text{Vs}$, the electrons transited at saturated velocity. However, for low channel mobility $< 500 \text{ cm}^2/\text{Vs}$...
500 cm²/Vs, a significant reduction in electron velocity was observed, which was less severe for shorter gate lengths. Experimental device development commenced with analyzing the formation of low-resistance ohmic contacts to high Al-content AlGaN channels. A specific contact resistance, $\rho_{sp}$ of $2 \times 10^{-6}$ $\Omega\cdot$cm² was achieved using heterostructure graded contact layers on n-type Al₀.₇₅Ga₀.₂₅N channels, which was comparable to values typically achieved on narrower bandgap GaN channels. The 1ˢᵗ generation devices comprising of Al₀.₇₅Ga₀.₂₅N channel layer and composition graded contact layer, both grown by MBE, resulted in current density of ~ 60 mA/mm, and average breakdown field of ~ 2 MV/cm. The low channel mobility in MBE-grown films was recognized as the main limiting factor in the devices. In comparison, AlGaN channels grown by MOCVD exhibited considerably higher mobility values. The 2ⁿᵈ generation devices employing MOCVD-grown Al₀.₇Ga₀.₃N channel and graded contact layers demonstrated the highest current density (~ 0.5 A/mm) and average breakdown field (~ 3.6 MV/cm) among other reported AlGaN channel transistors with Al composition > 0.25. However, a higher contact resistance was observed in MOCVD-grown structures than in MBE-grown ones, which was attributed to the possible DX center formation in MOCVD-grown AlGaN films, especially at high Si donor concentrations. The 3ʳᵈ generation devices were designed with a hybrid MOCVD/MBE approach, utilizing high mobility channel layer and low-resistance contact layer, respectively. The measurements resulted in a current density of ~ 0.27 A/mm, and $f_T \cdot L_G$ product of 3.8 GHz.μm, severely limited by the nonoptimized regrowth of the contact layer. Further regrowth optimization and removal of unintentional AlN interlayers could significantly improve these characteristics. To end
with, a unique AlGaN transistor design that used all-refractory metal process was introduced for extreme temperature applications.

5.2. Future work

5.2.1. PolFETs with advanced channel grading

The work presented in chapter 3 described the engineering of velocity profile as a function of gate bias using linearly graded channels. Polarization grading, however, provides much more flexibility in device design. For example, charge profiles can be altered such that the desired velocity profiles are achieved (Figure 63).

Figure 63. Cartoon illustration of the charge profile and the corresponding velocity profile for two cases: (a) constant charge profile; and (b) rising charge profile.
These designs can help achieve the appropriate $g_{m}/f_{1/2}$ profiles for large-signal linearity, which may not be constant as achieved in chapter 3. Further study of large-signal simulation and development of two-tone linearity predictive models can provide a better insight on the ideal channel design.

Grading can also be utilized in ways that would enhance channel mobility in high Al composition AlGaN transistors. For example, the 3rd generation graded channel devices could be optimized such that the polarization (composition) grading results in carriers pushed towards the higher Al-content AlGaN region. Figure 64 illustrates an example of such a structure.

Figure 64. Structure schematic of high Al-content PolFET showing the use of polarization grading to design the charge profile and enhance the channel mobility.

Because alloy scattering is the mobility limiting mechanism, pushing the electrons in the high Al-content region would enhance the mobility significantly. A scheme such as
quadratic/exponential grading upwards would result in a charge profile illustrated in the figure.

5.2.2. N-polar AlN/AlGaN HEMTs

HEMT structures with 2DEG have an intrinsic advantage of device scaling, hence the short channel effects are minimized. In conventional Ga-polar growth direction (0001), AlN barrier/AlGaN channel structures could induce a 2DEG at the heterointerface. Such structures consisting of Al$_{0.85}$Ga$_{0.15}$N channels have already been explored [74]. Material development of BN and its alloys could further extend the III-Nitride family, with the possibility of realizing B(Al)N/AlN heterostructures in future. Although BN does not naturally occur in the wurtzite structure [110] [111], BGaN and BAlN alloys with low B concentrations may maintain wurtzite structure.

Compared to the conventional Ga-polar AlN/AlGaN structure, an N-polar HEMT structure can have several advantages. First, it would require the growth of AlN buffer or barrier layer that is lattice matched to the AlN substrate, followed by a thin AlGaN channel. Figure 65 illustrates such a design, consisting of Al$_{0.8}$Ga$_{0.2}$N channel and reverse graded contact layer. In contrast, Ga-polar structure would require a thick AlGaN buffer (which also forms the channel), that has a lattice mismatch with the substrate. On SiC substrate, however, the case might be reversed, where the lattice constant of SiC is close to that of Al$_{0.85}$Ga$_{0.15}$N. Second, the down-grading of Al composition in the ohmic contact layers induces positive polarization charge, as opposed to the negative charge in Ga-polar direction.
This implies that either n-type counter doping in the contact layers is not needed, or small dopant concentrations could result in low-resistance ohmic contacts. This might be very useful especially in case of heavily doped contact layers which showed self-compensation effects, as discussed in section 4.3.1. Finally, as understood by the work on N-polar GaN HEMTs [66] [112], this structure allows for superior channel scaling than Ga-polar HEMTs, or in other words lower short-channel effect due to more confined 2DEG wavefunction closer to the gate electrode. This advantage comes from the natural back-barrier structure that results from the reverse polarity.
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Appendix A

Process traveler: MBE Regrowth using SiO$_2$ mask layer

This appendix provides a summary of process steps which can be followed to prepare templates for MBE regrowth. Regrowth of contact layers is discussed on HEMTs (2D channel) and PolFETs (3D channel).

1. **Sample cleaning**
   - Solvent cleaning:
     - 5 min each of Acetone/IPA/DI (ultrasonication is recommended)
   - Acid cleaning (prior to PECVD SiO$_2$ deposition):
     - 1 min conc. HCl (49%) followed by 2 min DI rinse

   This step is optional but recommended. Dil. HCl or BOE may also be used.

2. **PECVD SiO$_2$**
   - 500 nm PECVD SiO$_2$ deposition:
     - Pressure = 900 mTorr; N$_2$O/SiH$_4$/He = 300/100 sccm
     - RF power = 22 W; substrate temperature = 250°C (or 300°C)
• Ellipsometry:
  - A dummy sample (such as Si substrate) to confirm the thickness is recommended. Measurement may be done before and after the process to estimate the difference.

3. **CF₄ based SiO₂ dry etch**

• Thick PR needed > 1.5 μm:
  - S1813 could be used with standard recipe
  - Stepper lithography of ohmic regrowth pattern

Stepper exposure time calibrated to be ~ 4 s for S1813, which is lower than standard time for SPR955CM.

• ICP-RIE etching:
  - Etching Condition “SBSIO2” : CF₄/Ar/O₂ = 20/5/2 sccm; Pressure = 5 mTorr
  - RIE/ICP = 120 W/ 120 W
  - He flow ON (etch in loops of 1 min to avoid excessive heating)
  - Etch rate calibrated to be ~ 68-70 nm/min; recommended etching 6-7 mins
  - Remove PR (solvent cleaning) + 10 min O₂ ashing
4. **60-100 nm wet etch SiO₂**

   - Etching calibration prior to the actual etching:
     - Etching Condition : BOE (10:1) : DI = 1 : 15, 30 min stirring prior to the calibration
     - 2 min DI rinse
     - Etch rate calibrated to be ~35 nm/min
     - 2-3 min dip + 2 min DI rinse

   This step is to wet etch remaining SiO₂ to avoid plasma on the substrate. For PolFET structures, regrowth may be carried out at this step for a top contact (skip steps 5 and 6). Steps 5 and 6 prepare substrate for side contact.

5. **Cl₂ based (Al)GaN dry etch**

   - Total Etch 100 nm for standard HEMT (may vary based on structure):
- BCl$_3$ = 10 [sccm]; RIE/ICP = 15/40 [W], 5 mTorr (1-2 mins) Native oxide removal
- Cl$_2$/BCl$_3$ = 50/5 [sccm], RIE/ICP = 40 V/40 W, Pressure = 5 mTorr
- Etch rate calibrated to be ~10 nm/min

Etch rate of SiO$_2$ ~ 1 nm/min.

![Diagram of HEMT substrate with etched area.](image)

6. **60-100 nm SiO$_2$ wet etch extension**

- Use the same diluted BOE solution:
  - 2-3 min dip + 2 min DI rinse

- SEM inspection

Etch extension is critical for intimate side contact.
7. **n++ (Al)GaN regrowth**

   - MBE regrowth
   - AFM / SEM inspection

Etch extension should avoid any crevice at interface between regrown contact and channel region.

8. **Wet etch poly-crystalline (Al)GaN**

   - Indium metal removal:
     - HCl dip 10 min + 2 min DI rinse
• Heated dil. KOH solution:
  - ~15% wt; KOH 45%:DI = 1 : 3.5
  - Solution heated at 75°C
  - Etch duration calibrated: ~ 5 min @ 75°C
  - 2 min DI rinse

This step may be done after SiO₂ lift-off to avoid long KOH dip. After lift-off, KOH dip can be done in (1 min dip + 1 min DI rinse + inspection) cycles until remaining poly-crystalline GaN is completely removed.

• SiO₂ lift-off process:
  - 15-30 min BOE (10:1) No Dilution No Ultrasonication
  - 10 min with Ultrasonication
  - 5 min DI rinse with Ultrasonication

• SiO₂ wet etch:
  - If lift-off is not done, SiO₂ regrowth mask can be removed using BOE
  - 5 min BOE dip + 2 min DI rinse