Electron gas dimensionality engineering in AlGaN/GaN high electron mobility transistors using polarization

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We propose and demonstrate a two dimensional/three dimensional hybrid channel AlGaN/GaN high electron mobility transistor (HEMT) structure with a flat transconductance profile using polarization-induced channel engineering. A quasi three dimensional electron gas profile with 5–6 nm of vertical channel depth was formed by grading the channel region linearly from GaN to Al0.15Ga0.85N over 50 Å. We demonstrate a flat $g_m$ profile in an AlGaN/GaN HEMT with high current density of 1 A/mm and peak $g_m$ of 168 mS/mm over 85% of the input bias range under dc conditions. This approach simultaneously enables vertical device scaling and transconductance engineering in a HEMT structure.

III-nitride field-effect transistors (FETs) have been of interest for RF applications due to their excellent power performance and high efficiency. The spontaneous and piezoelectric polarization fields enable channel engineering such as two-dimensional electron gas (2DEG) in HEMTs and 3DEG for polarization-doped FETs (PolFETs) without any impurity doping. In many upcoming wireless applications, devices need more bandwidth for faster communications and are required to have both high linearity and high gain at the same time. The magnitude and linearity of gain in a transistor are highly dependent on the transconductance profile of a transistor. The ability to maintain vertical device scaling (for high gain) and $g_m$ tailoring (for linearity) could therefore enable large-signal operation at high frequency while maintaining efficiency and linearity.

Conventional GaN-HEMT structures have been scaled down to gate-channel distance of few nanometers and have been obtained very high peak $g_m$ value from the scaling. However, as in conventional AlGaN/GaN HEMTs, their $g_mV_{gs}$ profile is also found to be non-linear with a steep decrease in the $g_m$ profile as the output current is increased. In MESFET structures, the $g_mV_{gs}$ curve can be engineered by introducing a three-dimensional electron gas (3DEG) with a graded doping scheme. Similarly, it was shown that a polarization-graded structure in GaN-FET devices can introduce 3DEG into the channel and tailor the $g_mV_{gs}$ profile without impurity doping. The polarization-doped channel also improves the gate leakage, breakdown, and mobility characteristics, but the vertical scaling down of these structures is limited.

In this work, we describe a hybrid approach for HEMTs where the charge profile consists of a two-dimensional as well as a three-dimensional electron gas by inserting a polarization-graded layer into a HEMT structure, and show that such an approach leads to a highly constant or flat transconductance profile over the input voltage range. The 2D electron gas formed by the abrupt spontaneous and piezoelectric polarization sheet charges at the hetero-interface is similar to that in a conventional HEMT, while the 3D component arises from polarization grading of the channel layer from GaN to low composition AlGaN layer (Fig. 1) such that the polarization-induced charge is smeared over the graded region. The integrated 3DEG sheet carrier density in this hybrid HEMT structure is still given by the total spontaneous and piezoelectric polarization sheet charge densities across the Al$_x$Ga$_{1-x}$N/GaN hetero-interface. This graded channel HEMT combines the advantages of HEMTs and MESFETs by offering high $g_m$ and tailored $g_mV_{gs}$ profile simultaneously. In addition to achieving high linearity and high gain, gate leakage and channel breakdown are also improved by high Al-composition AlGaN barrier layer and a graded AlGaN channel layer. Finally, the effective velocity in AlGaN/GaN 2DEGs has been found to be lower than the reported bulk or 3D values. Tuning of dimensionality could therefore provide another approach to improving velocity characteristics in AlGaN HEMT channels and ultimately achieving higher frequency performance.

For comparison, we designed two samples: a conventional HEMT and a graded channel HEMT in this study (Fig. 2). The samples were grown on Si-face 4H-SiC substrate by plasma-assisted molecular-beam-epitaxy (PAMBE). To reduce buffer leakage, dislocation density, and impurity incorporation, a 45 nm of AlN nucleation layer was first grown in
For both structures, the AlGaN cap layer consists of three layers, 15 nm of Si-doped \( N_D = 5 \times 10^{18} \text{ cm}^{-3} \) \( \text{Al}_{0.25}\text{Ga}_{0.75}\text{N} \), 5 nm of UID \( \text{Al}_{0.25}\text{Ga}_{0.75}\text{N} \), and 3 nm of \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{N} \) from top to bottom. The high composition \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{N} \) and \( \text{GaN} \) buffer layers of the conventional HEMT (top) was inserted into the abrupt junction between \( \text{Al}_{0.25}\text{Ga}_{0.75}\text{N} \), 5 nm of UID \( \text{Al}_{0.25}\text{Ga}_{0.75}\text{N} \), and 3 nm of \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{N} \) layer was grown to form a low ohmic contact to introduce additional charges in the access region. The entire \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{N} \) layer mainly supplies mobile charges into the channel and 15 nm of Si-doped \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{N} \) layer helps to introduce additional charges in the access region. The entire \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{N} \) layer was grown to form a low ohmic contact resistance with a typically alloyed Ti/Al/Ni/Au metal stack. For the graded channel HEMT structure, an additional 5 nm of a linearly graded layer from \( \text{GaN} \) (bottom) to \( \text{Al}_{0.15}\text{Ga}_{0.85}\text{N} \) (top) was inserted into the abrupt junction between \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{N} \) and \( \text{GaN} \) buffer layers of the conventional HEMT structure. Al-composition of each layer was confirmed by HRXRD measurements.

We calculated the energy band diagram using a self-consistent one-dimensional Schrödinger-Poisson solver (BandEng). The calculated band diagram of the graded channel HEMT structure at zero-bias and the carrier concentration profile in the channel are depicted and compared with the one for the conventional HEMT structure in Figs. 3(a) and 3(b). The gate region is recessed by 12 nm, and 3.0 eV of Schottky barrier height was determined by comparison of capacitance-voltage (C-V) measurements (Fig. 3(d)) and theoretical C-V curves from Schrödinger-Poisson simulations. As reported earlier, a higher Schottky barrier height was estimated in the gate recessed region due to a change in the surface donor density after the gate recess etch. The increasing C-V profile of the graded channel HEMT indicates 5–6 nm of channel thickness which matches well with the full-width half maximum (FWHM) of the calculated charge profile. In comparison to a deep quantum well in the conventional HEMT structure, the graded AlGaN layer forms a shallower but wider quantum-well in which two sub-bands are occupied \( (E_0 = -0.0559 \text{ eV}, \ E_1 = -0.0086 \text{ eV}) \). Two wave-functions in the sub-bands spread out the sheet charge density of \( 1.1 \times 10^{13} \text{ cm}^{-2} \) (after gate recess) over the wide quantum-well of the graded channel HEMT with a volume charge density of \( (1–1.5) \times 10^{19} \text{ cm}^{-3} \) (Fig. 3(c)). The width of this quasi-3D charge profile is 3–4 times wider than FWHM of Gaussian-like charge profile of the conventional HEMT (which is theoretically assumed 1.5–2 nm wide).

The fabrication of transistors started with the formation of ohmic contacts. Ti/Al/Ni/Au alloyed source and drain contacts were evaporated and annealed at 850 °C. Then, mesa isolation and gate recess were done using chlorine-based inductively coupled plasma reactive ion etching. A Ni/Au/Ni metal stack was evaporated to form the gate Schottky contact for gate after the gate recess step. The device dimensions of both HEMTs are \( W = 150 \mu\text{m} \) \( (2 \times 75 \mu\text{m}) \), \( L_g = 1.5 \mu\text{m} \), \( L_{gs} = 1 \mu\text{m} \), and \( L_{gd} = 1.5 \mu\text{m} \).

Hall and TLM measurements results agreed well with each other, and the measured charge density, mobility, sheet resistance, and contact resistance were \( 1.4 \times 10^{13} \text{ cm}^{-2} \) (before gate recess), 524 cm²/Vs, 872 \( \Omega\cdot\text{mm} \), respectively, for the graded channel HEMT and \( 1.5 \times 10^{13} \text{ cm}^{-2} \) (before gate recess), 635 cm²/Vs, 536 \( \Omega\cdot\text{mm} \), respectively, for the conventional HEMT. Compared to a typical mobility in a conventional AlGaN/GaN HEMT \( (>1000 \text{ cm}^2/\text{V}\cdot\text{s}) \), the conventional HEMT has relatively low mobility due to the use of \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{N} \) cap. However, the low mobility is not expected to affect the shape of the \( g_m \) profile in the saturated region. We expect that the mobility in both structures could be improved through the substitution of \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{N} \) layer with \( \text{AlN} \) for the cap layer.

DC I-V plots for the graded channel HEMT and the conventional HEMT are shown in Figs. 4(a) and 4(b). In the graded channel HEMT, the pinch-off voltage \( V_{p,\text{Graded channel}} = -3.2 \text{ V} \) is slightly more negative than the conventional HEMT case \( V_{p,\text{Conventional}} = -2.6 \text{ V} \). In the graded channel HEMT has a thicker and deeper channel than the

![FIG. 2.](image_url) (Color online) Epitaxial structure of the (a) graded channel HEMT and (b) conventional HEMT.

![FIG. 3.](image_url) (Color online) (a) Energy band diagram of the graded channel HEMT. (b) Simulated electron density profiles and the conduction band profiles in quantum well. (c) Two sub-bands occupied and the profile of the wave-functions. (d) Measured C-V profiles of graded channel HEMT and conventional HEMT.
conventional HEMT. Although the charge densities for both HEMTs were approximately the same from C-V measurement in Fig. 3(c), the maximum drain current ($I_{dr,max}$) for the graded channel HEMT (~970 mA/mm) was observed higher than the one for the conventional HEMT (~720 mA/mm).

The measured $g_m$ variation with the gate bias, $V_{gs}$, at 10 V of drain voltage, $V_{ds}$, is shown in Fig. 5(a). The graded channel HEMT shows a flat $g_m$ profile for wide input range (an average $g_m \sim 159$ mS/mm over $V_{gs} = -2.2–3.5$ V with a total gate voltage range $= -3.2–3.5$ V which is about 85% of total input bias range). The peak transconductance, $g_{m,peak}$, was measured to be 168 mS/mm which is comparable to the $g_{m,peak}$ of the convention HEMT, 159 mS/mm, and higher than the one reported for MESFET-like devices.

The source resistance ($R_S = R_{S,contact} + R_{S,Access}$) was measured to be fairly high, 3 Ω mm for the conventional HEMT, and 4.8 Ω mm for the conventional HEMT, due to the long gate-to-source distance with low mobility and gate-recess. Since a high source-resistance underestimates $g_m$ and extends the input voltage range, the intrinsic transconductance ($g_{mi} = g_m/(1 - R_s g_m)$) and the gate-to-channel bias ($V_{gc} = V_{gs} - R_S I_{DS}$) were extracted as depicted in Fig. 5(b). The peak intrinsic transconductance, $g_{mi,peak}$, for the graded channel HEMT and the conventional HEMT were found to be 318 and 674 mS/mm, respectively. The $g_{mi} V_{gc}$ of the graded channel HEMT maintains a consistent value of 300 mS/mm with a high averaged value (95% of $g_{mi,peak}$) over $V_{gc} = -1.7–0.5$ V (55% of total gate bias range) unlike the $g_{mi} V_{gs}$ profile of the conventional which is drops rapidly after reaching $g_{mi,peak}$. This clearly shows that 5–6 nm of the distributed charge profile in the graded channel HEMT is effective to tailor a flat $g_m$ profile while maintaining a high $g_m$ value.

The flat transconductance profile will improve the overall linearity and gain curves of large signal microwave amplifiers based on these graded channel devices. In addition to the obvious impact this graded channel design has on linearity, there may be other significant advantages from the nanoscale control of electron density in the channel. It has been reported that the electron velocity in low electron density GaN layers is significantly higher than in high electron density channels. The structure described will enable channel density in the channel to be varied with great precision while maintaining channel thickness dimensions that are suitable for high frequency scaled devices.

In conclusion, we have demonstrated a flat $g_m$ in AlGaN/GaN HEMTs using polarization-induced engineered channel design. High gain and high linearity are simultaneously achieved by distributing charges in the 3D channel of HEMT with an appropriate grading scheme. A flat $g_{mi} V_{gs}$ profile with a high $g_{mi,average}$ have been obtained over a wide input voltage ($V_g$) range. The performance of this device can be improved by achieving a lower source access resistance, $R_s$. This demonstrates the potential of 3D channel AlGaN/GaN HEMTs in achieving both high speed and high power RF performance without degrading in efficiency simultaneously. In addition, these results encourage the exploration of multi-wavefunction, or 3D electron gas channels for future AlGaN/GaN transistors.

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![FIG. 4. DC I-V characteristics of (a) the graded channel HEMT and (b) the conventional HEMT after gate recess.](image)

![FIG. 5. (Color online) (a) $g_m$ vs. $V_{gs}$ and (b) $g_{mi}$ vs. $V_{gc}$ for the graded channel HEMT and the conventional HEMT at $V_{ds} = 10$ V.](image)