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Ultra-wide band gap AlGaN polarization-doped field effect transistor

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Ultra-wide band gap (UWBG) semiconductors are attractive for high voltage power electronics1–6 and high power rf electronics because the power density of these devices is expected to scale aggressively with band gap energy ($E_g$). For example, the lateral figure-of-merit (LFOM) for power switching increases as the square of the critical electric field ($E_{crit}$), implying that LFOM increases for high voltage power electronics1

We report an UWBG AlGaN polarization-doped field effect transistor (PolFET).20–24 AlGaN PolFETs have potential to overcome challenges to ohmic contacts on the fully depleted region of AlGaN HEMTs because the PolFET conductive channel extends all the way to the surface, where as a fully depleted HEMT barrier layer physically separates the channel of an Al-rich AlGaN HEMT. A PolFET operates similarly to a MESFET23) in that conductivity is controlled by changing the depth of a uniformly-doped, volumetric channel through depletion from a reversed biased gate. A key difference between PolFETs and MESFETs is that a PolFET employs polarization-induced doping20) via compositional grading of Al to form the channel, while the MESFETs use impurity doping. Thus, AlGaN PolFETs overcome low $E_g$ because, unlike impurity doping, polarization-induced doping is effective for $x > 0.8$ where Al-rich AlGaN $E_g$ is high. PolFETs can achieve a higher $\mu \cdot n_t$ product than a HEMT for a given Al contrast because the regions of highest Al composition (i.e., highest $x$) in a PolFET contribute to average channel $\mu$, whereas only the lowest Al composition region of HEMT is conductive. Moreover, ohmics become easier to achieve for Al-rich AlGaN PolFETs compared to Al-rich AlGaN HEMTs because the PolFET conductive channel extends all the way to the surface, where as a fully depleted barrier layer physically separates the channel of an Al-rich AlGaN HEMT from the ohmic contacts. Accordingly, we demonstrate an AlGaN PolFET with linear ohmic contacts of specific contact resistivity ($\rho_{ct} = 1.1 \times 10^{-3}$ $\Omega$ cm and $\mu = 210$ cm$^2$ V$^{-1}$ s$^{-1}$ to achieve a current density of 24 mA/mm, >10$^9$ on/off ratio, and gate leakage <10 nA/mm. This is the first demonstration of an UWBG AlGaN transistor combining $\mu > 100$ cm$^2$ V$^{-1}$ s$^{-1}$ and linear ohmic contacts, which has great promise for high voltage switching and high frequency devices.

1. Introduction

Ultra-wide band gap (UWBG) semiconductors are attractive for high voltage power electronics1–6 and high power rf electronics because the power density of these devices is expected to scale aggressively with band gap energy ($E_g$). For example, the lateral figure-of-merit (LFOM) for power switching increases as the square of the critical electric field ($E_{crit}$), implying that LFOM increases for high voltage power electronics1

We report an UWBG AlGaN polarization-doped field effect transistor (PolFET).20–24 AlGaN PolFETs have potential to overcome challenges to ohmic contacts on the fully depleted region of AlGaN HEMTs because the PolFET conductive channel extends all the way to the surface, where as a fully depleted HEMT barrier layer physically separates the channel of an Al-rich AlGaN HEMT. A PolFET operates similarly to a MESFET23) in that conductivity is controlled by changing the depth of a uniformly-doped, volumetric channel through depletion from a reversed biased gate. A key difference between PolFETs and MESFETs is that a PolFET employs polarization-induced doping20) via compositional grading of Al to form the channel, while the MESFETs use impurity doping. Thus, AlGaN PolFETs overcome low $E_g$ because, unlike impurity doping, polarization-induced doping is effective for $x > 0.8$ where Al-rich AlGaN $E_g$ is high. PolFETs can achieve a higher $\mu \cdot n_t$ product than a HEMT for a given Al contrast because the regions of highest Al composition (i.e., highest $x$) in a PolFET contribute to average channel $\mu$, whereas only the lowest Al composition region of HEMT is conductive. Moreover, ohmics become easier to achieve for Al-rich AlGaN PolFETs compared to Al-rich AlGaN HEMTs because the PolFET conductive channel extends all the way to the surface, where as a fully depleted barrier layer physically separates the channel of an Al-rich AlGaN HEMT from the ohmic contacts. Accordingly, we demonstrate an AlGaN PolFET with linear ohmic contacts of specific contact resistivity ($\rho_{ct} = 1.1 \times 10^{-3}$ $\Omega$ cm and $\mu = 210$ cm$^2$ V$^{-1}$ s$^{-1}$ to achieve a current density of 24 mA/mm, >10$^9$ on/off ratio, and gate leakage <10 nA/mm. This is the first demonstration of an UWBG AlGaN transistor combining $\mu > 100$ cm$^2$ V$^{-1}$ s$^{-1}$ and linear ohmic contacts, which has great promise for high voltage switching and high frequency devices.

2. Device realization

Figure 1(a) shows the epitaxial heterostructure and device geometry of PolFET devices, and Fig. 1(b) presents the corresponding energy band diagram and free carrier concentration calculated from a one-dimensional Schrödinger–Poisson solver. A PolFET designed with linear compositional grading features no abrupt heterointerface and therefore an approximately uniform free carrier concentration in the channel, i.e., graded region. All group-III nitride epilayers were grown by
metal–organic vapor phase epitaxy (MOVPE) in a Veeco D-125 system at 75 Torr using conventional precursors, including trimethylgallium (TMGa), trimethylaluminum (TMAI), and ammonia. Initially, a 2.3-µm-thick AlN epilayer was grown on (0001) c-plane sapphire substrates mis-oriented 0.2° toward the m-plane to serve as substrates for subsequent growth of AlGaN PolFETs. PolFET samples consisted of a 0.25-µm-thick unintentionally-doped (UID) Al0.7Ga0.3N buffer followed by a 110-nm-thick AlN epilayer over which x was increased linearly from 0.70 to 0.85. During the grade, both the TMAI and TMGa source flows were adjusted to maintain a constant group-III molar grade, both the TMAl and TMGa source.

Circular, long-channel PolFETs were fabricated. Devices utilized planar Zr/Al/Mo/Au (15/120/35/500 nm) source and drain contacts25) followed by rapid thermal annealing under a 1 mTorr nitrogen atmosphere for 30 s at 700 and 1000 °C anneal. After rapid thermal annealing, a passivating layer of SiN (1000 Å thick) was deposited by plasma-enhanced chemical vapor deposition over the entire wafer followed by etching of gate stems and source and drain vias by lithography and subsequent metal creep during rapid thermal annealing. It was found that $L_{gd}$ was on average 0.8 ± 0.2 µm shorter than the nominal value and $L_{sd}$ was 8.1 ± 0.2 µm.

3. PolFET and ohmic contact characterization

The electrical properties of the PolFET channel, ohmic contacts, and gate contacts were characterized by CTLM and $C–V$ measurements. Figure 2 shows current–voltage ($I–V$) data between ohmic contacts and the inset shows the geometry-corrected26) CTLM data. The linear $I–V$ data demonstrate the ohmic nature of the Zr/Al/Mo/Au contacts on the UID Al0.85Ga0.15N surface, and CTLM analysis indicated $\rho_e = 1.1 \times 10^{-2} \Omega \text{cm}^2$. Improvement in the ohmic contacts for the PolFET compared to UWBG AlGaN HEMTs is attributed to polarization-induced doping providing free carriers at the ohmic metal/semiconductor interface, whereas Al-rich AlGaN HEMTs are likely to have fully depleted barriers between source/drain contacts and the channel. The polarization-induced doping profile ($\rho_e$) of the channel shown in Fig. 3 was calculated from $C–V$ measurement of a Ni/Au Schottky contact surrounded by an annular ohmic contact. The measured $\rho_e$ value is close the expected value for linear compositional grading.24)

$$\rho_e = 5 \times 10^{13} \times (\Delta x)/d = 7 \times 10^{17} \text{ cm}^{-3},$$

where the leading term is the polarization charge associated with a GaN/AlN heterointerface, $\Delta x$ is difference in initial and final Al composition and d is the length of the grade, i.e., the channel thickness. The inset to Fig. 3 plots $A^2/C^2$, where $A$ is the Schottky contact area, and the x-intercept gives the Schottky barrier height ($\phi$) = 3.0 eV. This $\phi$ value is much larger than what is typically observed for Ni/Au contacts

![Fig. 1.](image1) (Color) (a) PolFET heterostructure and device geometry and (b) calculated energy band diagram and free carrier concentration.

![Fig. 2.](image2) (Color) CTLM $I–V$ data. The inset shows geometry-corrected resistance vs distance data.
to GaN HEMTs (ϕ ≈ 1 eV). Such a large ϕ bodes well for forming a low leakage gate to the PolFET and is conducive to engineering a normally-off device.

The DC transfer characteristics and output curves of a PolFET with nominal $L_g = 3 \mu m$ are shown in Fig. 4, and the forward and reverse gate–source current ($I_{gs}$) are shown in Fig. 5. The PolFETs exhibited good gate control for gate-to-source bias ($V_{gs}$) up to +3 V and sharp pinch off with large on/off ratio >10$^3$. The drain current density reaches $I_{ds,max} = 24$ mA/mm for this long channel device. A threshold voltage ($V_{th}$) of −3.95 V was determined by defining the off condition as $I_{ds} = 10$ µA/mm. The linear $I_{ds}$ at low $V_{ds}$ gives $R_{on} = 195$ Ω mm and confirms that the PolFET source and drain contacts are ohmic, as expected from CTLM analysis.

Figure 5 presents excellent forward and reverse gate characteristics of the PolFET. The gate leakage remains <10 nA/mm for $-8 < V_{gs} < +1.8$ V, and gate-to-source conduction does not exceed 10 µA/mm until $V_{gs} > +2.45$ V. The low leakage and large turn-on voltage for the gate is consistent with the large ϕ extracted from C–V analysis.

Breakdown measurements were also performed on a device with a 2 µm nominal $L_g$ and a realized $L_{gd} = 3.2$ µm. Gate voltages were exercised out to −40 V $V_{gs}$, and breakdown occurred at $V_{gs} = 514$ V, i.e., $V_{gd} = 554$ V, with maximum gate and drain currents of ≈10 µA/mm. The effective critical electric field of 170 V/µm is similar to that measured for an Al$_{0.53}$Ga$_{0.47}$N/Al$_{0.38}$Ga$_{0.62}$N HEMT$^{27}$ but significantly less than the ideal critical electrical field for Al$_{0.5}$Ga$_{0.5}$N with $0.70 < x < 0.85$. Sudden device breakdown at relatively low leakage current suggests that dielectric breakdown in the SiN could be the mechanism for device failure rather than breakdown in the AlGaN itself. Regardless of specific physical mechanism for failure, the average breakdown field for the AlGaN PolFET is substantially better than −100 V/µm that is typically achieved in GaN HEMTs, despite no effort to optimize the PolFET device geometry, field plate design, or surface passivation. This substantiates the expectation of intrinsic, materials-based improvement of critical electric fields for UWBG AlGaN transistors relative to GaN. Further improvements in these aspects could produce even higher breakdown fields.

4. PolFET comparison to HEMTs and MESFETs

Despite achieving ohmic contacts, the $I_{ds,max}$ value for the PolFET is lower than the best previous reports for UWBG AlGaN HEMTs$^{2,3,9,10}$ and MESFETs$^{14,16}$ Lower $I_{ds,max}$ for the PolFET is due in part to a larger source-to-drain spacing but primarily to a lower Al contrast in the heterostructure that results in a higher $R_{on}$ and smaller knee voltage. Nonetheless, the PolFET compares well against prior HEMT and MESFET results in important aspects. Reference 9 reported Al$_{0.45}$Ga$_{0.55}$N/Al$_{0.38}$Ga$_{0.62}$N HEMT achieving $I_{ds,max} = 240$ mA/mm with $V_{th} = -12$ V, but the device pinch-off was soft due to over-doping in the barrier. A similar HEMT with a UID barrier exhibited sharp pinch-off with a lower $I_{ds,max} = 45$ mA/mm and $V_{th} = -10$ V, yet Schottky-like ohmic contacts resulted in $R_{on} > 350$ Ω mm,$^9$ which is larger than the PolFET in this study. A previous report of AlN/Al$_{0.65}$Ga$_{0.35}$N HEMTs achieved $I_{ds,max} = 38$ mA/mm with and $R_{on} = 284$ Ω mm.$^{13}$
Again, the HEMT attained larger $I_{ds,max}$ relative to the PolFET because the former had higher Al contrast and thus lower $R_{on}$, yet the PolFET in this study exhibits lower $R_{on}$ due to improved ohmic contacts. Similarly, Al$_{0.86}$Ga$_{0.14}$N/Al$_{0.51}$- 
Ga$_{0.49}$N HEMTs$^{13}$ have also been reported with comparable $I_{ds,max} = 24$ mA/mm relative to the PolFET but with also much larger $R_{on} \sim 1000$ μΩ mm. The ohmic contacts attained for the PolFET enabled a lower $R_{on}$ than has been observed for Al-rich AlGaN HEMTs with much higher Al contrast. This is a significant advantage for power switching applications where it is critical to minimize $R_{on}$.

AlGaN PolFETs can attain higher $\mu$ than AlGaN MESFETs, which is an advantage for high frequency applications, where the maximum operating frequency can be limited if $\mu$ is too low to reach $v_{sat}$ while transiting a non- 
scopnic $L_{q}$. Previous studies of Al$_{x}$Ga$_{1-x}$N MESFETs with $x = 0.65-0.75$$^{14}$ achieved $I_{ds,max}$ as high as 0.5 A/mm$^{16}$ but with $\mu \leq 90$ cm$^2$ V$^{-1}$s$^{-1}$. Improving AlGaN MESFET $\mu$ is challenging. Increasing the Al composition would improve $\mu$, but impurity doping is ineffective for $x > 0.8$. Large reduction the impurity doping level improves $\mu$, but diminution of free carrier concentration decreases $R_{on}$. Conversely, the UID PolFET in this study with $0.70 \leq x \leq 0.85$ attained $\mu = 210$ cm$^2$ V$^{-1}$s$^{-1}$ with $\rho_x = 7 \times 10^{12}$ cm$^{-1}$, and $\mu > 500$ cm$^2$ V$^{-1}$s$^{-1}$ can be achieved for UID UWBG AlGaN PolFET heterostructures with $x > 0.85$ because alloy scattering is greatly reduced as the composition approaches AlN$^{13}$.

These PolFET results combined with previous investigation of electron $\mu$ in UID graded AlGaN structures give an indication of what current density could be achieved by scaling the lateral geometry of the devices and changing the Al contrast of the grade. Writing a sub-μm gate with electron beam lithography and employing aggressive optical lithography could reduce $L_{sl}$ by $\sim 4x$ to $\sim 2\mu$m, which would provide $\sim 4x$ in- 
crease in $I_{ds,max}$. Extending the composition grade from $0.70 \leq x \leq 0.85$ to $0.70 \leq x \leq 1.0$ would increase $\rho_x$ by $2x \ $[see Eq. (1)] and thus increase $I_{ds,max}$ by an additional $-4x$. This follows from standard MESFET-like behavior when $V_{gs} = \phi_B$:

$$I_{ds,max} \propto \frac{W}{R_{q}L_{sl}} V_{p},$$

where $W$ is the channel width, the pinch off voltage $V_{p} = q\rho_x d^2/2\epsilon$, and $\epsilon$ is the permittivity. Thus, $I_{ds,max} \sim \rho_x^2$ because $R_{on} \sim 1/\rho_x$ and $V_{p} \sim \rho_x$. Taking together the effects lateral geometry scaling and increasing the Al contrast of the grade implies an increase $I_{ds,max}$ by $\sim 16x$ to $\sim 385$ mA/mm. Additionally, extending the grade to AlN would improve $\mu$ by incorporating higher mobility AlGaN compositions in the channel, further improving $I_{ds,max}$. One concern for this approach is maintaining sufficiently low $\rho_x$ for contacts on an AlN surface. Nonetheless, the potential combination of such high channel mobility and current density is attractive for high power and high frequency devices.

5. Summary

In this study, polarization-induced doping was used to demonstrate UWBG Al$_{x}$Ga$_{1-x}$N PolFETs with a UID channel region that was compositionally-graded linearly from $0.70 \leq x \leq 0.85$. A highly conductive channel with $\mu = 210$ cm$^2$ V$^{-1}$s$^{-1}$ was enabled by combining high Al composi- 
tion for reduced alloy scattering and eliminating the need for intentional doping and concomitant impurity scattering. Linear ohmic contacts to the Al$_{0.85}$Ga$_{0.15}$N surface with $\rho_x = 1.1 \times 10^{13}$ Ω cm$^2$ where realized and a maximum drain current of 24 mA/mm was measured. A large on/off ratio $>10^3$, low gate leakage $<10$ nA/mm, and a large gate-to- 
source turn-on voltage at $V_{gs} = +2.45$ V were achieved by virtue of a Ni/Au Schottky gate with a large barrier height of $3.0$ eV. This is the first demonstration of an UWBG AlGaN transistor combining $\mu > 100$ cm$^2$ V$^{-1}$s$^{-1}$ and linear ohmic contacts, which has great promise for high voltage switching and high frequency devices.

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