Impact of Fin Width on Tri-Gate GaN MOSHEMTs

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Abstract—In this paper, we present a detailed investigation of the impact of fin width (w_{fin}) on tri-gate AlGaIn/GaN metal–oxide–semiconductor high electron mobility transistors (MOSHEMTs). As w_{fin} is reduced, the threshold voltage (V_{TH}) increases, which is due to the enhanced gate control (especially for $w_{\text{fin}} < 200$ nm) thanks to the 3-D geometry of the tri-gate, and the reduced carrier concentration (N_s) caused by a more pronounced strain relaxation and sidewall depletion, as explored using Hall and capacitance–voltage (C – V) measurements. The normally-OFF operation was achieved for w_{fin} close to the sidewall depletion width (w_{dep}) of 19.5 nm, since the fin is depleted from its two sidewalls. The impact of w_{fin} on ON-resistance (R_{ON}) and current capability ($I_{\text{D,max}}$) was also investigated, along with the influence of the effective source injection, the trench conduction and the filling factor (FF) on these key characteristics. The degradation caused by the tri-gate fin etching could be fully recovered by increasing the FF. Finally, we show that the tri-gate can reduce gate capacitance (C_{G}) and charge (Q_{G}) in normally-ON MOSHEMTs, depending on the design of the tri-gate and the gate voltage (V_{G}), leading to a smaller $R_{\text{ON}} \cdot Q_{\text{G}}$ product that is beneficial for high-frequency switching applications. The results in this paper offer insights into important phenomena in tri-gate GaN devices and are fundamental for the further advance of this technology.

Index Terms—Drain current, fin width, GaN, gate capacitance, threshold voltage, tri-gate.

I. INTRODUCTION

TRI-GATE technologies have recently attracted considerable attention for lateral GaN electronic devices [1]–[20], thanks to many advantages over conventional planar gates. First, the V_{TH} in tri-gate GaN metal–oxide–semiconductor high electron mobility transistors (MOSHEMTs) increases as w_{fin} decreases, hence, the normally-OFF operation can be

achieved by reducing w_{fin} [21], by recessing the tri-gate [22], or with novel gate oxides such as MgCaO [23]. Meanwhile, the dependence of V_{TH} on w_{fin} in tri-gated GaN heterostructures offers a lateral scheme to design and construct novel field plates (FPs) for high-voltage power devices [24]–[26], such as the slanted tri-gate, which resulted in power GaN-on-Si MOSHEMTs with state-of-the-art performance [24], and in power GaN-on-Si Schottky barrier diodes (SBDs) with record breakdown voltage (~ 2000 V at $1 \mu\text{A}/\text{mm}$) and ultralow reverse leakage current ($5 \text{ nA}/\text{mm}$ at -650 V) [25]. In addition, the tri-gates also offer a unique opportunity to control multiple parallel 2-dimensional-electron-gas (2DEG) channels, leading to novel multi-channel tri-gate devices with much reduced R_{ON} and enhanced current capability [22], [27], which are essential to enhance the energy efficiency and power density of GaN power and RF devices. Furthermore, the tri-gate can provide excellent linearity [28]–[32], high g_{m} [13], small subthreshold swing (SS) [19], high ON/OFF-state current ratio [7], [27], and diminished short channel effect [7], [22], [33], along with many other merits that are beneficial for switching and amplifying applications.

While most of these remarkable properties of the tri-gate depend on w_{fin} (or the tri-gate width), the full impact of w_{fin} on characteristics of tri-gate GaN transistors has not yet been well understood. A better comprehension of this key designing parameter is fundamental and highly desirable to unleash the full potential of the promising tri-gate technology.

In this paper, we present a detailed investigation of tri-gate GaN MOSHEMTs and reveal the impact of w_{fin} on device characteristics such as V_{TH} , g_{m} , $I_{\text{D,max}}$, R_{ON} , C_{G} , and Q_{G} . We explore the major reasons for the dependence of V_{TH} on w_{fin} , quantified the dependence of N_s on w_{fin} , and show that the sidewall depletion is critical to achieving normally-OFF tri-gate GaN transistors. In addition, we analyze the impact of w_{fin} on $I_{\text{D,max}}$, and R_{ON} , discuss the importance of effective source injection, trench conduction, and FF and present the potential of tri-gates in reducing C_{G} and Q_{G} for normally-ON GaN (MOS)HEMTs. These results provide important insights for optimizing tri-gate GaN devices and addressing the tradeoffs for different applications.

II. DEVICE FABRICATION

The AlGaIn/GaN-on-Si epitaxy in this paper consisted of $3.75 \mu\text{m}$ of the buffer, $0.3 \mu\text{m}$ of undoped GaN (u-GaN)

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Fig. 1. (a) Top view schematic of a tri-gate AlGaIn/GaN MOSHEMT. (b) Cross-sectional schematic of the tri-gate region. Important geometric parameters of the tri-gate regions are defined here, including the width of a fin (w_{fin}), the width of a trench (s), the number of fins in a given device (N_{fin}), the length of the fins (l_{fin}), the FF, the width of device footprint ($w_{footprint}$), the effective channel width ($w_{channel} = w_{fin} \times N_{fin}$), and the total width of the trenches ($w_{trench} = s \times N_{fin}$).

Fig. 2. Average (a) I_D-V_G and (b) g_m-V_G characteristics in tri-gate AlGaIn/GaN MOSHEMTs, measured at $V_D = 5$ V. The gate leakage current of all these devices was below 0.1 nA/mm at $V_G = -8.5$ V. (c) Summarized dependence of V_{TH} on w_{fin} , in which w_{fin} was measured by scanning electron microscopy (SEM) and V_{TH} was defined at 10 μ A/mm. The inset in (c) illustrates the effect of sidewall depletion in distributing the 2DEGs across a fin.

channel, 23.5 nm of AlGaIn barrier, and 2 nm of u-GaN cap layers. The sheet resistance was about 360 Ω /sq, and the electron mobility was about 2000 $\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$. Three types of devices were fabricated and studied: MOSHEMTs and MOS capacitors with planar and tri-gate topologies, and nanoscale Hall crosses. The MOSHEMTs had different w_{fin} but the same nominal FF of 50% (s and w_{fin} shown in Fig. 1 were about the same), along with the same width of the device footprint ($w_{footprint} = 60 \mu\text{m}$). The fins were 700-nm long (l_{fin}), 166-nm high, and 2 and 11.3 μm apart from the source and drain electrodes, respectively. The gate metal was 2.5- μm long, covering the entire length of the fins and extending 0.5 and 1.3- μm toward the source and drain electrodes, respectively. Details about the MOS capacitors and hall crosses are introduced later.

The device fabrication started with e-beam lithography to define the fins and mesa, which were etched using Ar/Cl₂-based inductively coupled plasma (ICP). Ohmic metals were then formed by lift-off and annealing processes, followed by 20-nm Al₂O₃ as the dielectric and Ni/Au as the gate metals.

Crucial geometrical components of the fins are shown in Fig. 1. In addition to w_{fin} , s , and FF, we define the number of fins in a given device as N_{fin} , the effective channel width as $w_{channel}$, and the total width of the trenches as w_{trench} , which are important terms to understand the influence of tri-gates on device characteristics. All measured current values in this paper were normalized by $w_{footprint}$, and the standard deviation was determined from about ten devices of each type.

III. IMPACT ON TRANSFER CHARACTERISTICS

Transfer characteristics of tri-gate GaN MOSHEMTs are significantly impacted by w_{fin} . As shown in Fig. 2(a), V_{TH} increased and SS reduced as w_{fin} was reduced. In planar MOSHEMTs, V_{TH} was -7.43 ± 0.07 V and SS was 98 ± 14 mV/dec, which were improved by the tri-gate with

w_{fin} of 123 nm to -1.68 ± 0.26 V and 83 ± 5 mV/dec, respectively. These results are consistent with other works in the literature [1], [7], [22] and indicate a better electrostatic control using the tri-gate.

The enhanced control in tri-gate GaN transistors, however, does not necessarily improve the g_m as usually expected. As shown in Fig. 2(b), g_m first reduced to 59.1 ± 2 mS/mm when w_{fin} was decreased to 473 nm, which is smaller than in planar devices (66.1 ± 2 mS/mm), but then increased to 71.9 ± 2 mS/mm at w_{fin} of 123 nm. This phenomenon is mainly caused by the tradeoff between the electric conductivity of the channel and the electrostatic control of the tri-gate. By replacing the planar gate with wide tri-gates, the electrical conductivity of the device was degraded due to the fin etching, along with limited enhancement in electrostatic control, resulting in a decreased g_m . By narrowing the fins further, the tri-gate control was greatly enhanced, overcoming the degradation in conductivity and resulting in a higher g_m .

The observation of the smaller g_m in tri-gate ($w_{fin} \geq 276$ nm) than in planar devices in this paper differs from many prior arts, in which an enhanced g_m is usually reported. This is a result of the difference in normalization methods for the I_D in this paper and the previous reports. While often in the literature, the I_D is normalized by $w_{channel}$ ($w_{fin} \times N_{fin}$) for tri-gate GaN devices, i.e., the width of the 2DEG in the tri-gate region, and in this paper, it was normalized by $w_{footprint}$ ($(w_{fin} + s) \times N_{fin}$). The former better reveals the characteristics of the fins locally,

but it may underestimate the effect of the access regions on the device behavior, which, for instance, may result in a reduced relative source resistance. The latter considers the entire device globally, including the combined effect from the access and trench regions, which may, in turn, hinder the local properties of the fins. For instance, a smaller g_m was observed in this paper because it was normalized by $w_{\text{footprint}}$. Normalizing device characteristics per footprint is more adapted when scaling up the devices and comparing the performance per cost of the technology.

The tri-gate does not always improve the linearity of g_m either, and such effect can depend on w_{fin} , as shown in Fig. 2(b). While devices with wider tri-gates did exhibit flatter g_m peaks than in planar devices, the full-width at half-maximum (FWHM) of the g_m was only about 2.9 V at $w_{\text{fin}} = 123$ nm, which was much smaller than that of the planar device (5.5 V). A similar phenomenon has also been observed in [3], [4], and [14]. While the underlying mechanism for this observation is not yet fully clear, it is likely due to the significant increase in capacitance per fin area (C_{fin}) with narrowing fins (which will be discussed later). An alternative approach to enhance the linearity is to integrate parallel fins with different w_{fin} in a single tri-gate device [31]. Such multi- w_{fin} tri-gate transistors function as parallel transistors with different V_{TH} , which can greatly enhance the linearity, thanks to the smooth dependence of V_{TH} on w_{fin} in tri-gate GaN transistors [Fig. 2(c)]. In addition to such tri-gate technologies, planar nanostrip channels are also very promising to enhance the linearity of the device, as demonstrated in [34].

IV. IMPACT ON THRESHOLD VOLTAGE

The dependence of V_{TH} on w_{fin} [Fig. 2(c)] is one of the most important features of tri-gate GaN devices, which can be used to control the breakdown voltage, leakage current, as well as the linearity, and can be further adapted to form lateral AlGaIn/GaN field effect rectifiers [35] or current limiting diodes [36]. This dependence of V_{TH} on w_{fin} is determined by several reasons, including the increased C_{fin} and the reduced N_s in narrower fins caused by strain relaxation and sidewall depletion, which can be described in more detail as follows.

- 1) Increased capacitance: a simplified model of a tri-gated fin includes three capacitors [inset in Fig. 2(c)]. The top capacitor (C_{top}) is formed by the gate dielectric and the barrier layer, and the two sidewall capacitors ($2 \cdot C_{\text{side}}$) are formed by the oxide and parts of the fin body. C_{side} is a dynamic value that depends on both w_{fin} and V_G , and increases as w_{fin} reduces, similar to double-gate junctionless transistors. It should be noted that the C_{top} could also increase as w_{fin} decreases due to the fringing electric field, especially when w_{fin} approaches the thickness of the barrier and the dielectric layers.
- 2) Strain relaxation: the strained AlGaIn/GaN heterostructure starts to relax after the fin etching by elastic deformation [37]–[40], which is nonuniform [41] and depends on the dimension of the fins [42], partially relieving the strain and reducing the N_s .
- 3) Sidewall depletion: carriers within the fins are depleted within a certain width (w_{dep}) from the sidewalls toward

Fig. 3. (a) Schematic of the fabricated tri-gate MOS capacitor. (b) Cross-sectional SEM image of a tri-gate MOS structure fabricated on a dummy sample, tilted by 52°. (c) Average capacitance per fin area (C_{fin}) with different w_{fin} , measured at 1 MHz. (d) Calculated effective capacitance per fin area ($C_{\text{fin,eq}}$) versus w_{fin} . All capacitors had the same $w_{\text{footprint}}$ of 60 μm and FF of 0.25. The length of the anode (l_{MOS}) metal was 3 μm and the l_{fin} was 4 μm . Capacitance values here were normalized by the top surface area of the fins ($w_{\text{fin}} \times l_{\text{MOS}} \times N_{\text{fin}}$) to understand the control of the 2DEG which was only in the fins.

the fin center [inset in Fig. 2(c)]. Thus N_s , even at the center of the fin, can be affected by sidewall depletion, which is a crucial factor that allows achieving normally-OFF tri-gate GaN transistors. In addition, w_{dep} is also important to determine the equivalent width of the 2DEG (w_{2DEG}) within each fin and extract an equivalent N_s .

We investigated these three factors to understand the $V_{\text{TH}}-w_{\text{fin}}$ dependence in tri-gate GaN transistors. Tri-gate AlGaIn/GaN MOS capacitors were fabricated [Fig. 3(a) and (b)], and their capacitance–voltage ($C-V$) characteristics were measured [Fig. 3(c)], in which the C_{fin} was normalized by the top surface area of the fins, namely $w_{\text{fin}} \times l_{\text{MOS}} \times N_{\text{fin}}$, in order to represent the control of the 2DEG, which is only present within the fins. The planar capacitor presented a nearly constant capacitance, which dropped sharply when V reached V_{TH} . In contrast, the depletion of tri-gate capacitors was progressive with applied V . C_{fin} reduced gradually as V approached V_{TH} , with a steeper slope for smaller w_{fin} , since the sidewall gates progressively depleted the 2DEG from the sides to the center of the fin. Considering that C_{fin} of the tri-gate varies with the voltage and is difficult to quantify, here we propose an effective $C_{\text{fin,eq}} = Q/|V_{\text{TH}}|$, in which Q was the charge determined from the integration of C_{fin} , to explore the dependence of tri-gate control on w_{fin} . As shown in Fig. 3(d), $C_{\text{fin,eq}}$ increased with narrowing fins, especially for $w_{\text{fin}} < 200$ nm. When $w_{\text{fin}} = 123$ nm, $C_{\text{fin,eq}}$ was as high as 342 ± 34 nF/cm², which is about twice the value of the planar capacitor (177 ± 17 nF/cm²). This effect reflects the enhanced electrostatic control that contributed to the positive shift in V_{TH} with reduced w_{fin} . Fig. 3(d) offers general guidelines

Fig. 4. (a) Schematic and SEM image of the fabricated hall cross. (b) R_{xx} versus magnetic field measured at 4.2 K. (c) N_s versus w_{fin} , extracted from both MOS capacitors and Hall crosses. The N_s from C-V measurements was normalized by $w_{2\text{DEG}} \times l_{\text{MOS}} \times N_{\text{fin}}$, in which the $w_{2\text{DEG}}$ was equal to $(w_{\text{fin}} - 2 \cdot w_{\text{dep}})$. The inset shows the V_{TH} at $1 \mu\text{A}/\text{mm}$ in tri-gate GaN MOSHEMTs with w_{fin} from 20 to 40 nm using different epi structures, in which epi-A and epi-B had N_s of $1 \times 10^{13} \text{ cm}^{-2}$ and $1.5 \times 10^{13} \text{ cm}^{-2}$, respectively.

for the application of tri-gate structures: the large $C_{\text{fin,eq}}$ for $w_{\text{fin}} < 200 \text{ nm}$ is suited for addressing the short channel effect, while w_{fin} , around 200 nm, is more favorable for power and RF devices, offering the benefits of the tri-gate, such as in tuning the V_{TH} , the g_m , and the linearity in a wide range (Fig. 2), but without the significant increase in $C_{\text{fin,eq}}$.

Strain relaxation and sidewall depletion also cause a positive shift of V_{TH} by reducing the N_s in the fins. To extract N_s , it is crucial to precisely determine $w_{2\text{DEG}}$, which was extracted from AlGaIn/GaN fin-based Hall crosses [Fig. 4(a)] [43], [44]. R_{xx} between two opposite electrodes was measured as a function of the applied magnetic field B , which shows two shoulders at $B = \pm 3.34 \text{ T}$ [Fig. 4(b)]. This is due to the electron backscattering effect, which is a geometrical phenomenon that results in the observed peaks in R_{xx} when $w_{2\text{DEG}} \approx 0.55 \cdot l_c$ [43]. Here, the l_c refers to the cyclotron radius of the circular orbit of electrons in magnetic fields, which is equal to $m^* v / qB$. $w_{2\text{DEG}}$ was calculated to be 48 nm using $w_{2\text{DEG}} = \hbar k_F / qB$, and w_{dep} was found to be 19.5 nm using $w_{\text{dep}} = (w_{\text{fin}} - w_{2\text{DEG}}) / 2$.

After knowing $w_{2\text{DEG}}$, we integrated the C-V results (measured at 1 MHz) from the capacitors, normalized the number of carriers by $w_{2\text{DEG}} \times l_{\text{MOS}} \times N_{\text{fin}}$, and extracted the N_s as a function of w_{fin} , as shown in Fig. 4(c). The N_s extracted from the measured Hall crosses were also included in the same plot for comparison, showing consistency with the C-V results, which supports the determined w_{dep} . Possible effects of the fixed charge were not considered in the C-V measurements based on two reasons: the difference in N_s caused by the oxide was only around 8%, as revealed by planar capacitors with and

Fig. 5. (a) Average output characteristics of tri-gate and planar MOSHEMTs, measured at $V_G = 5 \text{ V}$ and normalized by $w_{\text{footprint}}$. (b) Summarized dependences of $I_{D,\text{max}}$ and R_{ON} on w_{fin} .

without the oxide in a dummy sample, and the impact of the fixed charges for tri-gate capacitors with different w_{fin} is not easy to be quantified.

The reduction in N_s from planar to narrow tri-gates can be analytically modeled as

$$N_{s,\text{fin}} = (1 - \beta) \cdot N_{s,p}$$

in which $N_{s,\text{fin}}$ and $N_{s,p}$ are the carrier densities in AlGaIn/GaN fin and planar structures, respectively. $\beta(w_{\text{fin}})$ describes the strain relaxation with reducing w_{fin} , and can be written as [37], [38], [42]

$$\beta = \alpha \cdot e^{-w_{\text{fin}}/w_c}$$

which resulted in $\alpha = 0.623$ and $w_c = 187 \text{ nm}$ from fitting this model with the experimental data shown in Fig. 4(a). The values of α and w_c can be impacted by different fin heights, lengths, and epi structures. The quantity w_c represents a characteristic width for relaxation such that the N_s - w_{fin} dependence is relaxation-limited when w_{fin} is below $3 \cdot w_c$ [Fig. 4(c)]. When w_{fin} is greater than $3 \cdot w_c$, the effect of relaxation is minor, thus N_s is limited by the design and growth of the AlGaIn/GaN heterostructure, varying little with w_{fin} . When w_{fin} is smaller than $2 \cdot w_{\text{dep}}$, N_s is limited by the sidewall depletion, and reduces much faster than the model prediction, as the fins get narrow enough so that the sidewall depletion affects the 2DEG even at the center of the fin. This defines three main regions of the N_s - w_{fin} characteristics: sidewall-limited, relaxation-limited, and epitaxy-limited regions [Fig. 4(c)].

The sidewall depletion is a crucial factor to achieve normally-OFF operation, as it can even remove most of the 2DEG in the fins when w_{fin} is sufficiently small ($\leq w_{\text{dep}}$). As shown in the inset in Fig. 4(c), the normally-OFF operation could be achieved for $w_{\text{fin}} = 20 \text{ nm}$ ($\approx w_{\text{dep}}$) with V_{TH} of 0.04 V at $1 \mu\text{A}/\text{mm}$, regardless of different epi structures with different N_s , indicating the effective depletion of the 2DEG by the sidewalls. This value of w_{fin} agrees well with previous reports showing that the effective nonconductive width in GaN fins was between 19 and 26 nm [44].

V. IMPACT ON OUTPUT CHARACTERISTICS

In addition to transfer characteristics, the ON-state performance of the device is also impacted by w_{fin} , as narrowing

Fig. 6. (a)–(d) Top view schematic of the four types of transistors with similar dimensions but different gate regions. (e) Average output characteristics at $V_G = 5$ V. (f) Dependences of $I_{D,\text{max}}$ and R_{ON} on FF at $V_G = 5$ V.

the fins degrades the $I_{D,\text{max}}$ and R_{ON} [Fig. 5(a) and (b)]. $I_{D,\text{max}}$ reduced from 565 ± 25 mA/mm in the planar device to 261 ± 10 mA/mm in the tri-gate device with w_{fin} of 123 nm, corresponding to a significant reduction of 53.9%. This is due to the narrower effective channel width ($w_{\text{channel}} = w_{\text{fin}} \times N_{\text{fin}}$) in tri-gate devices and also the increased sidewall scattering in narrow fins. From planar to $w_{\text{fin}} = 123$ nm, R_{ON} increased by 15.5%, which is likely due to the degraded electron mobility and larger spreading resistance in narrower fins [45]. The degradation in R_{ON} was much less pronounced than in $I_{D,\text{max}}$, as the length of the etched region (the trenches) was small with respect to the length of the entire active region of the device, but I_D was greatly affected by the bottleneck on the current path from the narrow fins. The different V_{TH} in the devices was not considered here since the devices were all normally-ON and $V_G = 5$ V was sufficiently large to nearly saturate their R_{ON} .

When investigating the impact of w_{fin} on $I_{D,\text{max}}$ and R_{ON} , it is very important to isolate it from other factors, such as the effective source injection, the trench conduction, and the FF, since they all can influence the performance of the device. To illustrate the effect of effective source injection and trench conduction, we compared four types of transistors with similar dimensions but different gate regions.

- 1) The Planar [Fig. 6(a)] was a planar-gate MOSHEMT with $w_{\text{channel}} = w_{\text{footprint}}$ of 60 μm .
- 2) The Half-planar [Fig. 6(b)] had one 30- μm wide “fin” (w_{channel}) and two 15- μm wide trenches ($w_{\text{trench}} = 30 \mu\text{m}$) in its gate region, corresponding a FF of 0.5.

3) The Tri-gate [Fig. 6(c)] was a tri-gate MOSHEMT with FF also of 0.5, in which 600-nm wide fins were evenly distributed in the tri-gate region, resulting in w_{channel} and w_{trench} of both 30 μm , the same as the Half-planar.

4) The Trench [Fig. 6(d)] was similar to other devices except for its fully recessed gate region, resulting in w_{channel} and w_{trench} of 0 and 60 μm , respectively. The recess depth was the same as the fin height in the Tri-gate.

The output characteristics of these devices at $V_G = 5$ V were measured and compared in Fig. 6(e), all normalized by $w_{\text{footprint}}$ of 60 μm . While the Half-planar had a w_{channel} of 30 μm (e.g., half of the channel width of the Planar), it exhibited $I_{D,\text{max}}$ of 333 ± 6 mA/mm, which is larger than half of $I_{D,\text{max}}$ in Planar (565 ± 21 mA/mm). This is because the width of the effective source injection (w_{source}) in the Half-planar was greater than its w_{channel} . Assuming a uniform injection from the source and ignoring the crowding effect, w_{source} in Half-planar can be estimated using

$$w_{\text{source}} = \frac{(I_{D,\text{max}}^{\text{Half-planar}} - 0.5 \times I_{D,\text{max}}^{\text{Planar}}) \times w_{\text{footprint}}}{I_{D,\text{max}}^{\text{Planar}}}$$

which is 35.4 μm , indicating that the effective source extended 2.7 μm from each side of the channel toward the mesa edge. This results in a larger $I_{D,\text{max}}$ ratio between the Half-planar and Planar (58.9%) than the FF of 50% of the Half-planar.

$I_{D,\text{max}}$ can be further enhanced by increasing w_{source} for a fixed FF, by dividing the 30- μm wide “fin” (Half-planar) into many narrower fins and distributing them evenly in the device (Tri-gate). As shown in Fig. 6(e), the Tri-gate presented much larger $I_{D,\text{max}}$ (429 ± 10 mA/mm) than the Half-planar, although they had the same w_{channel} and FF. This is due to the much larger w_{source} in the Tri-gate, which can be comparable to that in the Planar as the spacing between the fins was 0.6 μm , which is much smaller than the extension length (2.7 μm) of the effect source injection (here we assumed that w_{fin} did not significantly change the extension length of the effective source).

The trenches also contributed to the ON-state conduction of the transistors, as they function as trench MOSFETs in parallel with the fin-MOSHEMTs, which can be seen from the I_D - V_D characteristics of Trench shown in Fig. 6(e). The trench conduction is small in normally-ON transistors, due to the large difference in V_{TH} of these MOSFETs and MOSHEMTs, as well as the poor electron mobility of the trench MOSFETs, which is limited by the MOS interface and the damages caused by the trench etching [16]. However, it may not be negligible in normally-OFF tri-gate GaN transistors, depending on the design of the tri-gate region.

In addition to w_{source} and trench conduction, FF is another important factor that should be fixed when comparing tri-gate transistors with different w_{fin} . As shown in Fig. 6(f), $I_{D,\text{max}}$ in tri-gate devices was enhanced by increasing the FF, despite the same w_{fin} , thanks to the increased w_{channel} . Such increase was not linear, as w_{source} was wider than w_{channel} . At an FF of 0.8, the differences in $I_{D,\text{max}}$ and R_{ON} between the planar and tri-gate devices became very small, within the error bars,

Fig. 7. (a) Dependence of C_G and Q_G on w_{fin} normalized by $w_{footprint}$, extracted at $V_G = 0$ V. (b) Dependence of $R_{ON} \cdot Q_G$ on w_{fin} . All results were extracted at $V_G = 0$ V and FF = 0.5.

revealing that the degradation caused by the etching of the 2DEG to form tri-gates was eliminated.

VI. IMPACT ON GATE CAPACITANCE AND CHARGE

The tri-gate architecture can be an effective way to reduce C_G and Q_G in normally-ON GaN (MOS) HEMTs, depending on its design and V_G . It is often considered that the tri-gate geometry increases the C_G due to its 3-D nature, as it is the case in FinFETs. This is true when C_G is evaluated for a single fin with small w_{fin} , since, in this case, the gate capacitance per area of 2DEG is indeed increased, as discussed in Fig. 3(d). However, it is usually more important to understand how the tri-gate impacts C_G and Q_G in the entire device footprint consisting of multiple parallel fins, especially for device designers on power and RF electronics. In this scenario, C_G and Q_G can be both greatly diminished in tri-gate compared to planar transistors, because a portion of the 2DEG carriers is removed during the fin etching, which is determined by FF, and only the carriers present at the 2-D channels in the fins contribute to the C_G and the Q_G (before the sidewall channels turn on). This is very different to FinFETs, in which the entire 3-D periphery of the fins contributes to the C_G and the Q_G .

As shown in Fig. 7(a), the C_G of the tri-gate devices varied from 0.79 to 0.91 pF/mm, depending on w_{fin} , which were between 58.6% and 68.4% of the planar device (at FF = 0.5 and $V_G = 0$ V). The Q_G was also reduced by over 50%, resulting in a decreasing $R_{ON} \cdot Q_G$ product [Fig. 7(b)] and hence, a higher figure-of-merit for high-frequency switching.

These results indicate that, depending on its geometry and V_G , the tri-gate can reduce C_G , Q_G , and $R_{ON} \cdot Q_G$ in normally-ON GaN (MOS)HEMTs, which can be valuable for many applications.

VII. CONCLUSION

In this paper, we showed the impact of w_{fin} on the performance of tri-gate AlGaIn/GaN MOSHEMTs, including g_m ,

V_{TH} , R_{ON} , $I_{D,max}$, C_G , and Q_G . V_{TH} was increased when w_{fin} was reduced, thanks to the larger $C_{fin,eq}$ and the smaller N_s . A narrower fin degraded the R_{ON} and $I_{D,max}$, which, however, could be recovered by increasing the FF. Finally, the tri-gate reduced C_G and Q_G for normally-ON MOSHEMTs, which, however, depends on the V_G and the design of the tri-gate.

The dependence of these key characteristics upon w_{fin} in tri-gated GaN heterostructures offers additional tools to tailor the performance of GaN electronic devices for various applications. In addition to achieving normally-OFF operation by decreasing w_{fin} , the dependence of V_{TH} on w_{fin} makes the tri-gate technology very promising for new FPs for power GaN devices. While current FP technologies rely on vertical designs by tuning the thickness and the inclination of the dielectric to spread the electric field, tri-gates offer a lateral design approach for FPs that can be easily fabricated by merely tuning w_{fin} lithographically [24]–[26]. In addition, the V_{TH} – w_{fin} dependence in tri-gate GaN devices is excellent to enhance the linearity in GaN RF HEMTs, by integrating several w_{fin} in the tri-gate region, which can lead to a 20-dB reduction in harmonics and a 6-dB enhancement in the output third-order intercept point, as demonstrated in [31].

The results revealed in this paper provide broader and further insights about tri-gate GaN devices, shedding light on several subtle points, and offering important understanding to design tri-gate GaN devices for different applications, which are fundamental for the further advance of tri-gate GaN technologies.

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