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Current Stability in Multi-Mesa-Channel AlGaN/GaN HEMTs

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(Invited Paper)

Abstract—We have developed and characterized multi-mesa-channel (MMC) AlGaN/GaN high-electron-mobility transistors (HEMTs), in which a periodic trench structure is fabricated only under the gate electrode. A surrounding-field effect in the MMC structure resulted in a shallower threshold voltage and a smaller subthreshold slope than those of the standard planar-type HEMT. In addition, the MMC HEMT showed a low knee voltage and a weak dependence of on-resistance (R_{ON}) on the gate-drain distance. Following identical off-state bias stress, the MMC HEMT exhibited low current collapse. The relative decrease in access resistance of the MMC device compared to the planar device can reduce the effects of access resistance on the drain current. It is likely that a high impedance of each nano-channel also contributes to current stability of the MMC HEMT.

Index Terms—Access resistance, current collapse, GaN, HEMT, multi-mesa channel, off-state stress, subthreshold slope, threshold voltage.

I. INTRODUCTION

GaN-based heterostructure transistors are considered to be a prime candidate for post-Si next-generation power applications because of material advantages, such as high breakdown electric field, high saturation electron velocity, and high carrier density at the heterointerface. Indeed, some groups have reported AlGaN/GaN and InAlN/GaN high electron mobility transistors (HEMTs) with excellent device performances such as high blocking voltages and low on-state resistances, which are very attractive for high-efficiency power-switching applications [1-11]. In addition, AlGaN/GaN HEMTs have been demonstrated to operate with good switching characteristics and high power conversion efficiencies when used in DC/DC converters and DC/AC inverters [7, 12-14].

However, the widespread implementation of GaN-based transistors is still restricted by reliability issues [15-18], particularly by the well-known current collapse phenomenon.

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Current collapse is the temporary reduction of the drain current following the application of high voltage and/or high power at both on- and off-state operations [19-22]. Field-plate structures have been applied to AlGaN/GaN HEMTs [23-27] to mitigate the concentration of electric field at the gate edge of the drain side, which is effective in reducing the current collapse. However, several reliability issues still remain in GaN HEMTs. To further improve the performance and operation stability of devices utilizing AlGaN/GaN structures, it is important to design a suitable device structure with a successful surface passivation scheme.

We have developed a multi-mesa-channel (MMC) AlGaN/GaN HEMT schematically shown in Fig. 1 [28]. By forming a periodic trench, the MMC HEMT has parallel mesa-shaped channels with two-dimensional electron gas (2DEG) surrounded by the gate electrode. The device showed good gate controllability due to a lateral field effect that shifts the threshold voltage toward the positive bias direction. The threshold voltage shift can be increased by reducing the top width of the mesa channel. In addition, we have found that the MMC structure demonstrates lower off-state-stress-induced current collapse [29]. Very recently, similar device structures were reported by Liu *et al.* [30] and Lu *et al.* [31]. They demonstrated a similar V_{TH} shift and good normally-off operation in nano-channel array AlGaN/GaN HEMTs [30] and tri-gate GaN metal-insulator-semiconductor field-effect transistors [31], respectively.

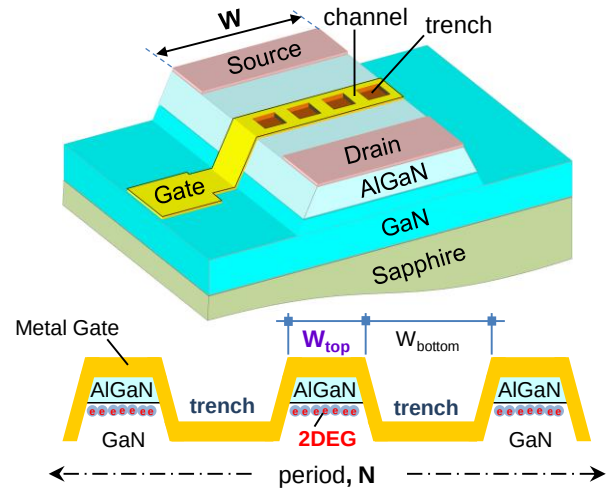


Fig. 1. Schematic illustration of the multi-mesa-channel (MMC) HEMT showing the periodic trench structure under the gate electrode. W_{top} is the width of the mesa channel.

In the present study, we further investigated gate controllability and current stability of the MMC HEMT, focusing on their subthreshold characteristics, drain current dependence on the gate-drain spacing and current collapse behavior, in comparison with those of the conventional planar HEMT.

II. DEVICE STRUCTURE AND FABRICATION

We used an $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ hetero structure grown on a (0001) sapphire substrate by metal organic chemical vapor deposition. The thickness of the AlGaN layer is 30 nm. Typical values of concentration and mobility of the 2-dimensional electron gas (2DEG) are $9.0 \times 10^{12} \text{ cm}^{-2}$ and $1330 \text{ cm}^2/\text{Vs}$, respectively, at room temperature (RT).

The fabrication process started with the formation of a SiO_2 mask pattern on the AlGaN/GaN structure by electron beam lithography and wet etching. Then, we carried out reactive ion-beam etching of the patterned sample to form a periodic trench, assisted by electron-cyclotron-resonance plasma using a gas mixture of $\text{CH}_4/\text{H}_2/\text{Ar}/\text{N}_2$. To completely eliminate the 2DEG in the trench region and to minimize plasma damage, etching depth was set to 50 to 70 nm. Figure 2 (a) shows an AFM image of the AlGaN surface after the trench formation. A periodic trench structure was successfully fabricated, resulting in the formation of multi nano-channels with a width ranging from 50 to 200 nm. Figure 2 (b) shows a typical AFM line profile along the mesa-trench structure, which in this case

revealed an etching depth of approximately 60 nm and W_{top} of about 50 nm. After the dry etching, the SiO_2 mask pattern was removed in a buffered HF solution, and a Ti/Al/Ti/Au multilayer was deposited and annealed at 800 °C for 1 min to form source and drain ohmic contacts. The gate electrode was then defined by electron beam lithography and fabricated using Ni/Au. For the MMC HEMT, the gate electrode covered the periodic-trench region, as shown in the SEM image given in Fig. 2(c). Finally, for surface passivation, a 20-nm-thick Al_2O_3 film was deposited on the AlGaN surface by atomic layer deposition (ALD) system (SUGA-SAL100H) at 350 °C [32, 33]. In the ALD process, water vapor and trimethylaluminum were introduced into an ALD reactor in alternate pulse forms. The deposition rate of Al_2O_3 was 0.11 nm/cycle. All the fabricated devices have a gate length, L_G , of 0.5 μm and a gate-source distance, L_{SG} , of 1 μm . The gate-drain spacing, L_{GD} , ranged from 1 to 20 μm .

III. RESULTS AND DISCUSSION

A. V_{TH} control and subthreshold characteristics

Typical drain current-voltage ($I_{DS}-V_{DS}$) characteristics of planar and MMC HEMTs with $L_G = 0.5 \mu\text{m}$ and $L_{GD} = 10 \mu\text{m}$ are shown in Fig. 3. The MMC HEMT in this figure has a mesa-top width W_{top} of 70 nm and 250 periods of mesa/trench structures within a gate-electrode width W of 100 μm . Thus, the effective gate width, i.e., the sum of W_{top} values, was 17.5 μm

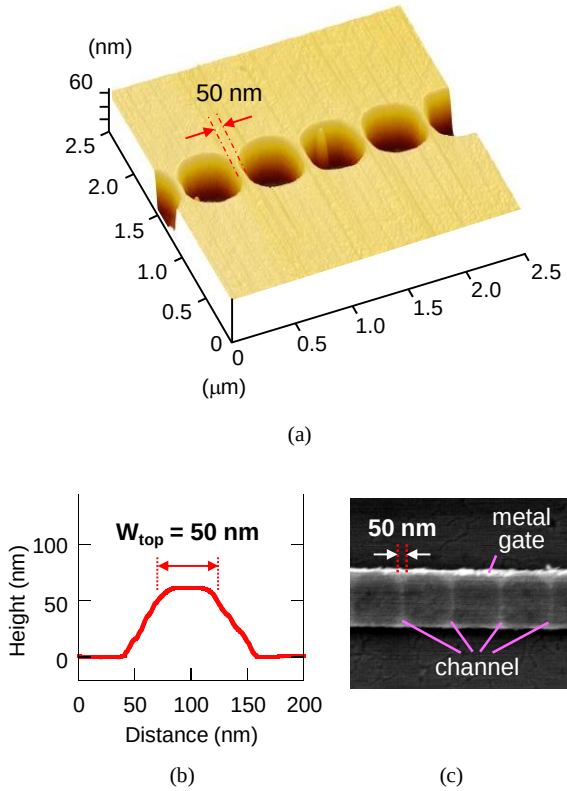


Fig. 2. (a) Bird's eye view AFM image of the AlGaN surface after the formation of the mesa-trench structure. (b) AFM line profile along the mesa-trench structure revealed an etching depth of approximately 60 nm and W_{top} of about 50 nm. (c) SEM plan view image of the mesa-trench structure.

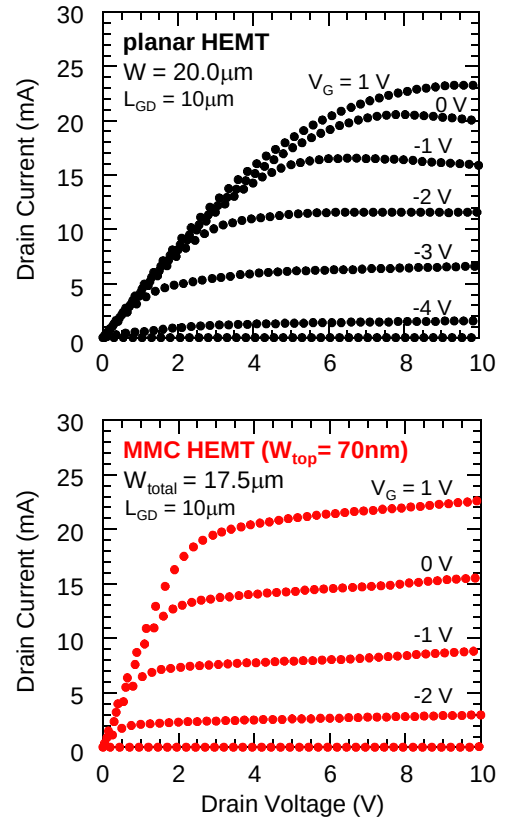


Fig. 3. Comparison of drain current-voltage ($I_{DS}-V_{DS}$) characteristics of a planar HEMT and an MMC HEMT. At the same gate voltage V_G of 1 V, the MMC HEMT showed a lower knee voltage compared with the standard planar HEMT.

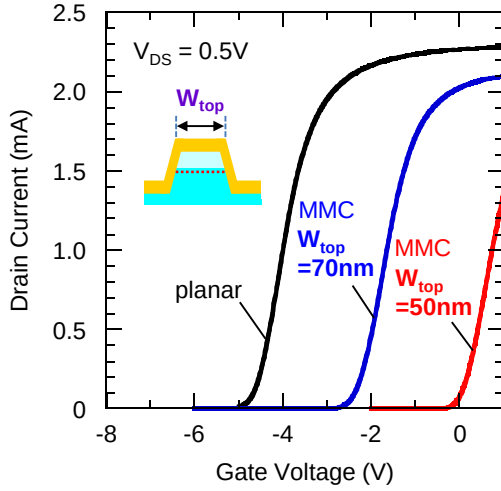


Fig. 4. Transfer characteristics in the linear region ($V_{DS} = 0.5$ V) of MMC HEMTs compared with that of a planar HEMT. For the MMC HEMTs, decreasing the channel width W_{top} (illustrated on the inset), shifted the threshold voltage toward the positive gate bias direction.

for the MMC structure. The MMC HEMT demonstrated good I-V behavior, particularly showing a lower knee voltage than the conventional planar HEMT.

We also measured the breakdown characteristics of the planar and MMC HEMTs with $L_{GD} = 10$ μm under off-state condition [28]. Both devices exhibited a breakdown voltage of about 250 V, which is similar to reported data for the AlGaIn/GaN HEMTs without field-plate technology [34]. The results obtained indicate that the periodic trench structure under the gate electrode does not lead to significant degradation of AlGaIn/GaN HEMTs breakdown characteristics.

To investigate the gate controllability of the MMC device, we measured the transfer and the subthreshold characteristics. Figure 4 shows the transfer characteristics of the planar and MMC HEMTs in the linear region ($V_{DS} = 0.5$ V). For the MMC device having 50 nm W_{top} , there are 263 periods of mesa/trench structures within a gate electrode width of 100 μm , resulting in an effective gate width of 13 μm . As the mesa-top width was decreased, a systematic shift of the threshold voltage (V_{TH}) toward the positive voltage direction was observed in MMC HEMTs. In particular, the MMC HEMT with $W_{top} = 50$ nm showed a V_{TH} nearly equal to 0 V. Liu *et al.* [30] and Lu *et al.* [31] reported a similar V_{TH} shift and good normally-off operation in nano-channel array AlGaIn/GaN HEMTs and tri-gate GaN metal-insulator-semiconductor field-effect transistors, respectively.

Figure 5(a) shows the comparison of the subthreshold characteristics in the linear region at a drain voltage of 0.2 V. The gate leakage currents are also plotted by broken lines. Low gate leakage currents were observed for the MMC HEMTs at reverse bias. However, the MMC device showed initially higher leakage currents than that of the planar device at around $V_G = 0$ V. The gate contact of the MMC device includes Schottky interfaces with the AlGaIn surface, the 2DEG edge and the dry-etched GaN surface, indicating that the leakage mechanism is rather complicated for the MMC device. In

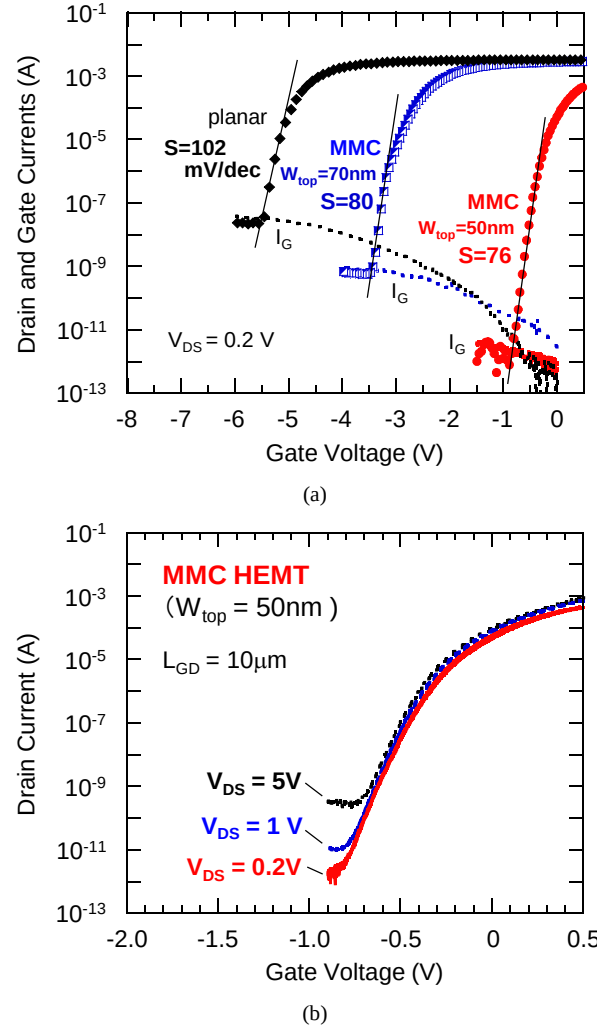


Fig. 5. (a) Subthreshold characteristics in the linear region ($V_{DS} = 0.2$ V) of the MMC HEMTs compared with that of the planar HEMT. (b) Subthreshold characteristics as a function of V_{DS} for the MMC HEMT with $W_{top} = 50$ nm.

addition, it was found from calculations that for the MMC devices, the potential modulation through the mesa side-walls and undoped GaN layer becomes marked at reverse bias. It is likely that such potential distribution different from that of the planar HEMT is responsible for the difference in leakage behavior. As the gate structure of the MMC device includes metal/2DEG interfaces, we were expecting serious leakage through such interfaces. However, the result shown in Fig. 5(a) indicated that the metal/2DEG interface at the side wall does not cause severe leakage current. Lu *et al.* [31] also reported relatively low gate leakage currents for a similar device structure. In the MMC HEMTs, improvement of the subthreshold slope was observed with narrowing of the mesa-top width. In particular, the MMC HEMT with $W_{top} = 50$ nm showed a subthreshold slope of 76 mV/dec and a drain-current on/off ratio of 10^8 . Figure 5(b) shows the subthreshold drain currents of the MMC HEMT as a function of drain voltage. The subthreshold slope remained almost unchanged at different values of V_{DS} , indicating that the MMC

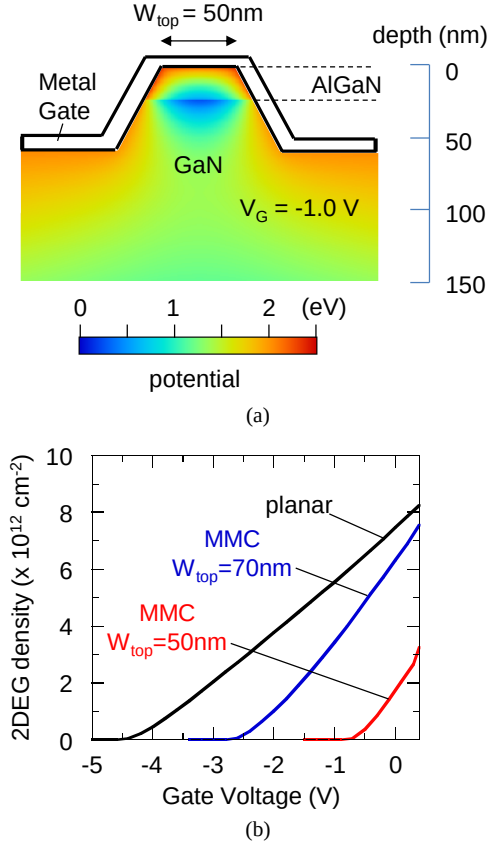


Fig. 6. (a) 2D potential distribution in MMC structure with W_{top} of 50 nm. The gate and drain voltages were set to -1.0 V and 0 V, respectively. (b) Simulated 2DEG density as a function of gate voltage for a planar and MMC HEMTs showing better gate controllability of the 2DEG with decreasing W_{top} .

structure mitigates the drain-induced electric field effect on the gate controllability of the drain current.

We also calculated the 2D potential distribution around the channel region for the MMC structure with $W_{\text{top}} = 50$ nm to gain more understanding of the surrounding-field effect. The gate bias was set to -1 V, which is near the threshold voltage, and the drain bias was set to 0 V. The calculation result is shown in Fig. 6(a). The mesa-sidewall gate has a lateral field effect on the edges of the 2DEG. Moreover, as the width of the top gate decreases, the potential modulation through the undoped GaN layer becomes stronger, resulting in a field surrounding the 2DEG. This leads to a more effective gate control of the 2DEG density, as shown in Fig. 6(b), resulting to shallower V_{TH} and good subthreshold characteristics for the mesa-gate HEMT with smaller channel width.

B. Improvement of current stability

As shown in Fig. 3, a small knee voltage (V_{knee}) is one of the characteristic features of the MMC HEMT. We thus investigated the L_{GD} dependence of the drain I-V characteristics of the planar and the MMC HEMTs. The drain I-V curves of both devices at $V_{\text{GS}} = 0$ V are shown in Fig. 7 for different values of L_{GD} . Note that horizontal axis scales are different for

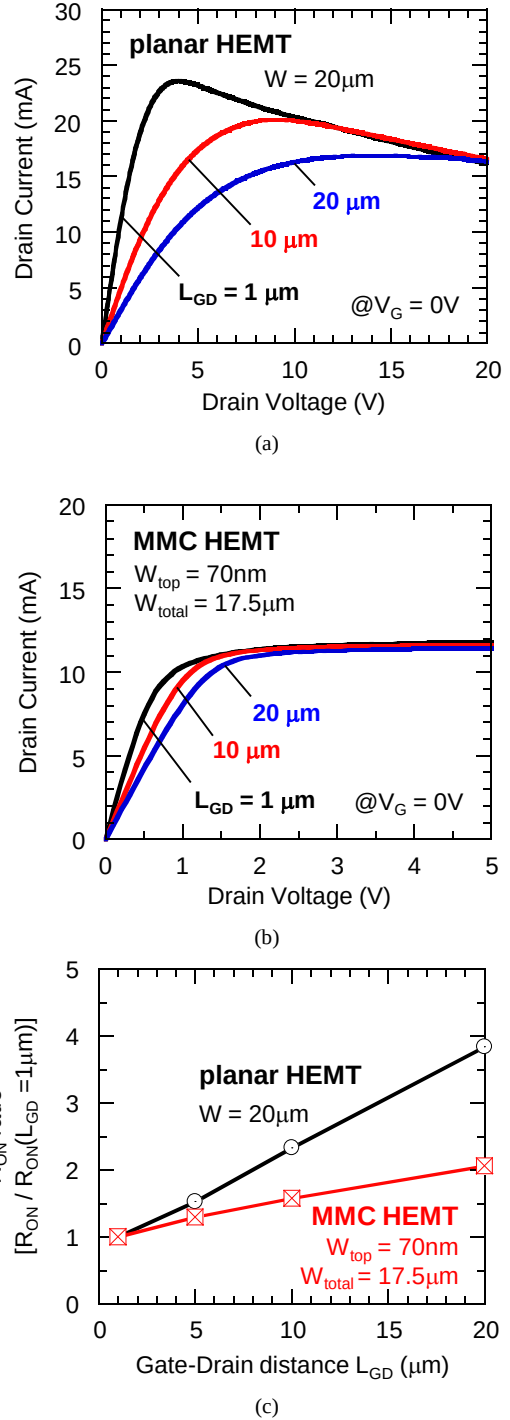


Fig. 7. $I_{\text{DS}}-V_{\text{DS}}$ characteristics at $V_{\text{G}} = 0$ V for different values of L_{GD} of (a) planar and (b) MMC HEMTs, and (c) R_{ON} values at any given L_{GD} normalized to its value at L_{GD} of 1 μm .

the two devices. The I-V curves of the planar HEMT showed pronounced L_{GD} dependence as can be seen in Fig. 7(a). As the L_{GD} increased, the V_{knee} increased and the I-V slope in the linear region decreased. This is typical in planar-type AlGaIn/GaN HEMTs [35, 36]. The planar device also exhibited pronounced current decrease in the high drain bias region. Since the peak current density exceeded 1 A/mm, this is due to the self-heating effect in the channel. In fact, no reduction of the saturation

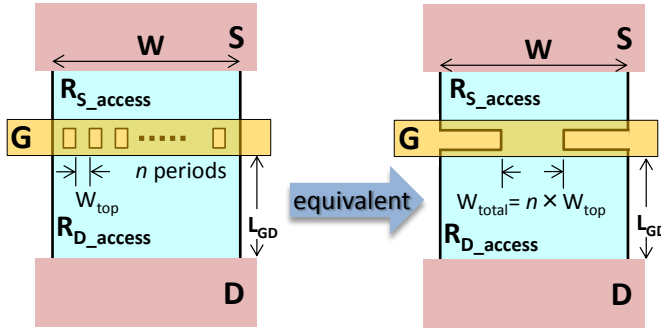


Fig. 8. The MMC device with n periods of nano-channel each having a width of W_{top} and the equivalent single channel planar structure with a channel width of $W_{total} = n \times W_{top}$.

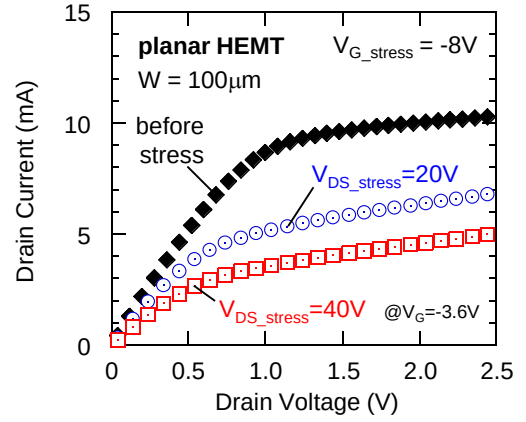
current was observed in pulsed I-V characteristics using a quiescent-bias condition of $V_{DS_base} = 0$ V and $V_{G_base} = 0$ V.

On the other hand, as evident in Fig. 7(b), we observed small change in V_{knee} for the MMC HEMTs. Figure 7(c) shows the change in the on-resistance (R_{ON}) at $V_G = 0$ V, calculated from the I-V curves in the linear region, as a function of L_{GD} . The R_{ON} values at any given L_{GD} are normalized to its value at L_{GD} of 1 μm . Both devices showed nearly linear relationship between R_{ON} and L_{GD} , very similar to the data reported by Choi *et al.* [37] and Visalli *et al.* [38]. This is due to the increase in drain access resistance with L_{GD} . However, the MMC HEMT showed much weaker R_{ON} dependence on L_{GD} .

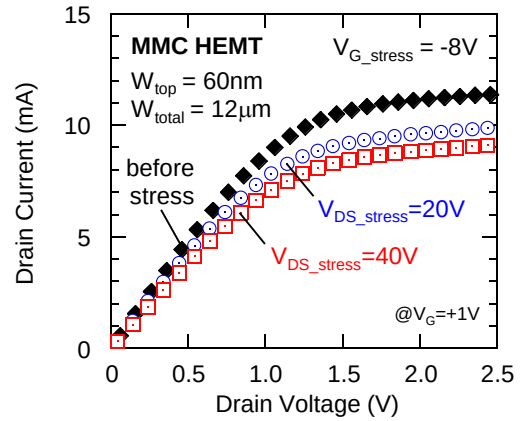
Although a mechanism for this is still underlined, it can be understood that the relative access resistance of the MMC HEMT is smaller than that of the planar device. In the MMC HEMT, the device width (W) is 100 μm , while the effective channel width (W_{total}) is 17.5 μm . This suggests that the equivalent drain access resistance of the MMC device is about the same factor lower compared with that of the planar device, as schematically shown in Fig. 8. We then carried out calculations of the drain I-V curves for both devices with different L_{GD} values, including the effect of drain and source access resistances. To avoid self-heating effect in the planar HEMT, as shown in Fig. 7(a), we compared the calculated results with the pulse-measured data under a quiescent-bias condition of $V_{DS_base} = 0$ V and $V_{G_base} = 0$ V. For the planar device, the measured I_{DS} - V_{DS} curves and their variation with L_{GD} shown in Fig. 7(a) are reasonably reproduced by the calculations. The calculated R_{ON} values for MMC device are higher than the experimental data. This indicates that there are other factors affecting the observed insensitivity of the MMC device with L_{GD} variation.

To investigate the operation stability of the MMC HEMT, we have performed off-stress-induced current collapse measurements. Initially, the drain I-V characteristics were measured. The devices were then subjected to off-state stress consisting of V_{DS_stress} ranging from 10V to 50V simultaneous with a V_{G_stress} of -8 V applied for 10 s. Immediately after removing the stress bias, the I_{DS} - V_{DS} characteristics were again measured. In between each current collapse measurement, the device under test was exposed to UV light with wavelengths ranging from 250 to 400 nm to quickly recover the drain current from the current collapse.

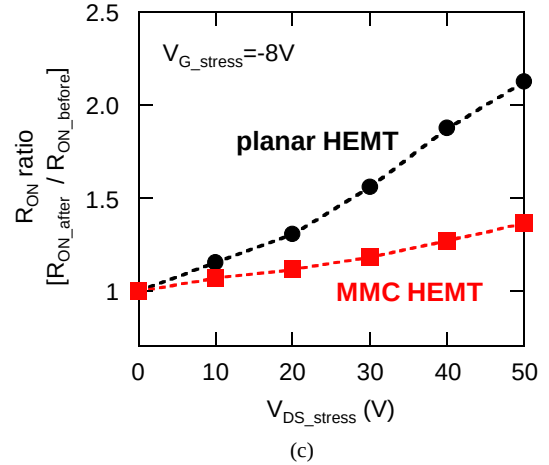
The I_{DS} - V_{DS} characteristics of the planar and MMC HEMTs



(a)



(b)



(c)

Fig. 9. Comparison of current collapse in (a) planar and (b) MMC HEMTs with $L_{GD} = 10$ μm . (c) Off-state stress induced change in R_{ON} ratio (ratio of the on-resistance after stress to its value before stress) as a function of the applied V_{DS_stress} .

with $L_{GD} = 10$ μm before and after the off-state stresses are shown Fig. 9. The gate drive voltages, $V_G = -3.6$ V for the planar and $V_G = +1$ V for the MMC HEMTs, were so chosen as to minimize the effect of self-heating and to compare the I-V characteristics at almost the same drain current level. For the planar HEMT, a significant decrease in drain current due to the off-state stress was observed. The current collapse becomes more pronounced with increasing the drain stress bias. On the

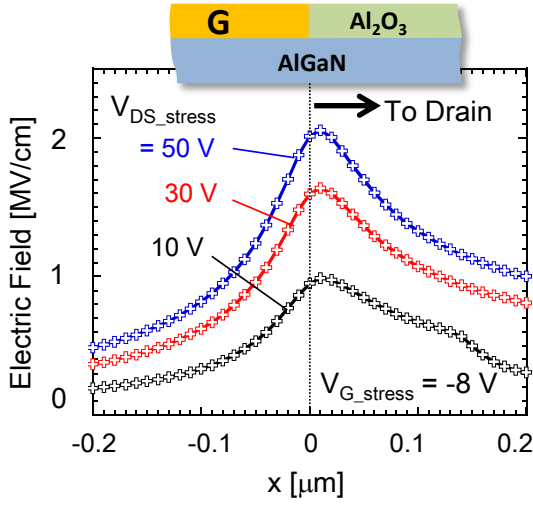


Fig. 10. Calculated electric field profiles along the 2DEG channel for different V_{DS_stress} with V_{G_stress} kept constant at -8 V.

other hand, as shown in Fig. 9(b), the MMC HEMT exhibited a much weaker current collapse behavior even after the application of high drain stress bias.

Figure 9(c) shows the ratio of the R_{ON} before and after the off-state stress as a function of the drain stress bias. For the conventional planar HEMT, R_{ON} drastically increased with increasing drain stress bias. In case of unpassivated HEMTs, greater increase in R_{ON} was observed in high drain stress range [29]. We have calculated electric field profile near the gate edge, and confirmed the peaking of the electric field at the gate edge of the drain side as shown in Fig. 10. The higher the V_{DS_stress} , the higher is the electric field peak, resulting in the more pronounced R_{ON} increase, as shown in Fig. 9(c). The given electric profile is valid for both devices because the gate electrode layout of the MMC HEMT is the same with that of the planar HEMT, i.e., the gate electrode edges are in contact with the entire width of the access regions. However, we observed less change in R_{ON} for the MMC HEMT even after the application of high drain bias stress.

In addition to the DC current collapse characterization, we have also performed pulsed current I-V measurements under two quiescent-bias conditions, $(V_{DS_base}, V_{G_base}) = (0 \text{ V}, 0 \text{ V})$ and $(V_{DS_base}, V_{G_base}) = (20 \text{ V}, -6 \text{ V})$. The pulse width is 5 μs while the pulse period is 500 μs (1% duty cycle). As shown in Fig. 11, the planar HEMT showed pronounced current dispersion between the two quiescent bias points. On the other hand, smaller dispersion in the drain current was observed in the MMC device, indicating resistance to the off-stress-induced current collapse.

One of the possible mechanisms for the current collapse is the surface charging effect arising from electron trapping at surface states of AlGaIn [20, 39-41]. The off-state stress can induce electron tunneling injection into the AlGaIn surface from the gate edges, leading to accumulation of negative charges due to electron trapping. Consequently, a local depletion of the 2DEG density particularly at the gate edge of the drain side causes the increase in R_{ON} . This is similar to the R_{ON} dependence on L_{GD} , as shown in Fig. 7. In addition, Fig.

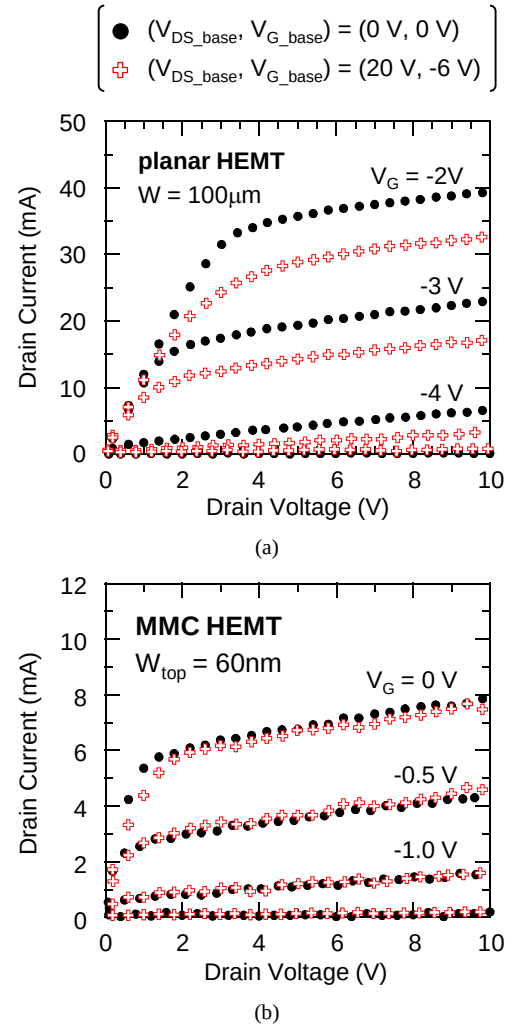


Fig. 11. Comparison of current dispersion between pulsed I_{DS} - V_{DS} characteristics of planar and MMC HEMTs. The pulsed I_{DS} - V_{DS} curves were obtained using two quiescent bias conditions: (1) $Q_1 = (V_{DS_base}, V_{G_base}) = (0 \text{ V}, 0 \text{ V})$ and (2) $Q_2 = (V_{DS_base}, V_{G_base}) = (20 \text{ V}, -6 \text{ V})$.

11(a) shows clear decrease of the saturation current under the stress bias condition. Tajima and Hashizume [41] recently carried out a unique characterization of current collapse using a dual-gate structure. When the gate-bias stress under the off state was applied to the additional gate between the main gate and the drain electrode, they observed a marked increase in R_{ON} but no effect on the saturation current. On the other hand, the off-state stress on the main gate itself caused a decrease in drain saturation current as well as an increase in R_{ON} . These results indicated that the off-state gate stress induces “virtual gates” in the gate edges expanding in both the drain and source directions [41]. Thus the decrease of the saturation current under the stress bias condition shown in Fig. 11(a) is due to a surface trapping effect at the source-gate region.

Using a numerical fitting to the data of the planar device shown in Fig. 9(a), as described in [29], we estimated the change in the drain access resistance (ΔR_D) after the bias stress. In case of the drain stress bias of 50 V, we obtained ΔR_D of 73 Ω . This is much higher than the channel resistance of about 16 Ω for the planar HEMT operating at $V_G = -3.6 \text{ V}$, leading to the

marked current collapse after the stress. For the MMC device, the relative reduction of drain access resistance, as explained above, can weaken the increase in R_{ON} even after applying similar stress bias. Indeed, simulation using the estimated ΔR_D of 73 Ω , showed more severe current collapse than the experimental result shown in Fig. 9(b). The resistance of each nano-channel for the MMC device is estimated to be about 5 k Ω at $V_G = +1$ V. Thus, the channel resistance of the MMC HEMT is more than one order of magnitude higher than the increase in access resistance induced by the off-state stress. On the basis of the results shown in Figs. 7, 9, 11, it is likely that such high impedance of a nano-channel also contributes to the fact that the MMC HEMT is rather insensitive to changes in access resistance.

IV. CONCLUSION

We have demonstrated the superior current stability of multi-mesa-channel (MMC) AlGaIn/GaN HEMTs over the standard planar HEMTs. The MMC HEMT with unique parallel mesa structures under the gate electrode led to surrounding-field effect resulting in a shallower threshold voltage and a smaller subthreshold slope than those of the standard planar-type HEMT. Moreover, the MMC HEMT had a lower knee voltage and a weaker dependence of on-resistance on the gate-drain distance. Following identical off-state bias stress, the MMC HEMT exhibited significantly less increase in R_{ON} compared with the planar HEMT. In the MMC HEMT, the total channel width (effective channel width) is smaller than the device width, resulting into a lower relative access resistance of the MMC HEMT compared with that of the planar device. This can reduce the effects of access resistance on the drain current. In addition, the resistance of nano-channel of the MMC structure is estimated to be more than one order of magnitude higher than the increase in access resistance induced by the off-state stress. It is likely that a high impedance of each nano-channel also contributes to current stability of the MMC HEMT.

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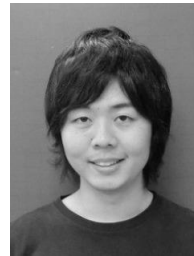
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