

Performance Enhancement by Using the n^+ -GaN Cap Layer and Gate Recess Technology on the AlGaIn–GaIn HEMT Fabrication

Wen-Kai Wang, Po-Chen Lin, Ching-Hua Lin, Cheng-Kuo Lin, Yi-Jen Chan, *Senior Member, IEEE*, Guan-Ting Chen, and Jen-Inn Chyi, *Senior Member, IEEE*

Abstract—Due to the low mobility and wide bandgap characteristics of the undoped AlGaIn layer used in the conventional AlGaIn–GaIn HEMT as a cap layer, the RF performance of this device will be limited by its high contact resistance and high knee voltage. In this letter, we propose using the n^+ -GaIn cap layer and the selective gate recess etching technology on the AlGaIn–GaIn HEMTs fabrication. With this n^+ -GaIn instead of the undoped AlGaIn as a cap layer, the device contact resistance is reduced from 1.0 to $0.4 \Omega \cdot \text{mm}$. The $0.3 \mu\text{m}$ gate-length device demonstrates an $I_{\text{ds,max}}$ of 1.1 A/mm , a $g_{\text{m,max}}$ of 220 mS/mm , an f_T of 43 GHz , an f_{max} of 68 GHz , and an output power density of 4 W/mm at 2.4 GHz .

Index Terms—AlGaIn–GaIn HEMTs, n^+ -GaIn cap layer, reactive ion etching (RIE) recess etching.

I. INTRODUCTION

HIGH-performance AlGaIn–GaIn HEMTs on sapphire or SiC substrates have been successfully applied to microwave power devices and circuits, which is due to the excellent characteristics of GaIn, namely a wide bandgap, a high electrical breakdown field, and a high saturation velocity [1], [2]. However, because of the low mobility and wide bandgap characteristics of undoped AlGaIn layers, the conventional approach of AlGaIn–GaIn HEMTs uses this undoped AlGaIn as the surface cap layer, limiting the device performance especially for microwave power applications. In order to reduce the contact resistance, the undoped or lightly doped thin GaIn cap layer has been used [3], but the device performance has not been improved due to the increase of gate-to-channel separation and the decrease of induced piezoelectric charges. Therefore by adding a highly doped n^+ -cap GaIn layer on top of the traditional AlGaIn–GaIn HEMT structure can enhance the device performance; however, this doped cap layer should be removed in the gate recess process before putting the Schottky gate metal, to reduce the gate leakage current.

Our previous letter focused on the process optimization of reactive ion etching (RIE) gate recess dry etching of this cap GaIn layer, to develop a low damage and high selectivity RIE dry etching process between GaIn and AlGaIn [4]. In this paper, we

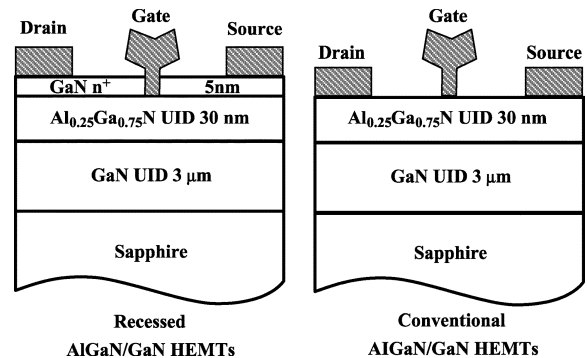


Fig. 1. Device cross-sectional structures of the recessed and conventional AlGaIn–GaIn HEMTs.

systematically analyze and compare this recessed GaIn HEMT dc and RF performance with the conventional approach, where the cap GaIn layer is not included. With this high doping concentration of GaIn layer ($1 \times 10^{19} \text{ cm}^{-2}$) as a cap layer, the parasitic resistance and the device knee voltage can be reduced. Therefore, in order to achieve a lower contact resistance, while maintaining a high breakdown voltage and a high transconductance, the selective gate recess dry etching is necessary to let the gate metal deposit on the undoped AlGaIn layer. After comparing the both recessed and conventional nonrecessed AlGaIn–GaIn HEMTs, a lower knee voltage, a higher current density, and a higher microwave output power have been achieved in the recessed AlGaIn–GaIn HEMTs.

II. AlGaIn–GaIn HEMT DEVICE STRUCTURE AND FABRICATION

As shown in Fig. 1, the metal–organic chemical vapor deposition-grown AlGaIn–GaIn HEMT consists of the sapphire substrate, a $3\text{-}\mu\text{m}$ undoped GaIn buffer layer, a 30-nm undoped $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ Schottky layer, and a 5-nm GaIn ($1 \times 10^{19} \text{ cm}^{-3}$ n-doping) cap layer. The electron sheet charge density and mobility of this recessed HEMT structure were $9 \times 10^{12} \text{ cm}^{-2}$ and $1400 \text{ cm}^2/\text{Vs}$, respectively. As to the conventional AlGaIn–GaIn HEMT structure, where the top cap layer was not included, the electron sheet charge density and mobility of this structure were $1.14 \times 10^{13} \text{ cm}^{-2}$ and $1000 \text{ cm}^2/\text{Vs}$, respectively. The reduction of sheet charge density is caused by the antidirection of piezoelectric polarization between the GaIn cap layer and AlGaIn Schottky layer, where piezoelectric charges are the major carrier source in the AlGaIn–GaIn HEMTs [5], [6]. Moreover, the

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The authors are with the Department of Electrical Engineering, National Central University, Chungli 32054 Taiwan, R.O.C.

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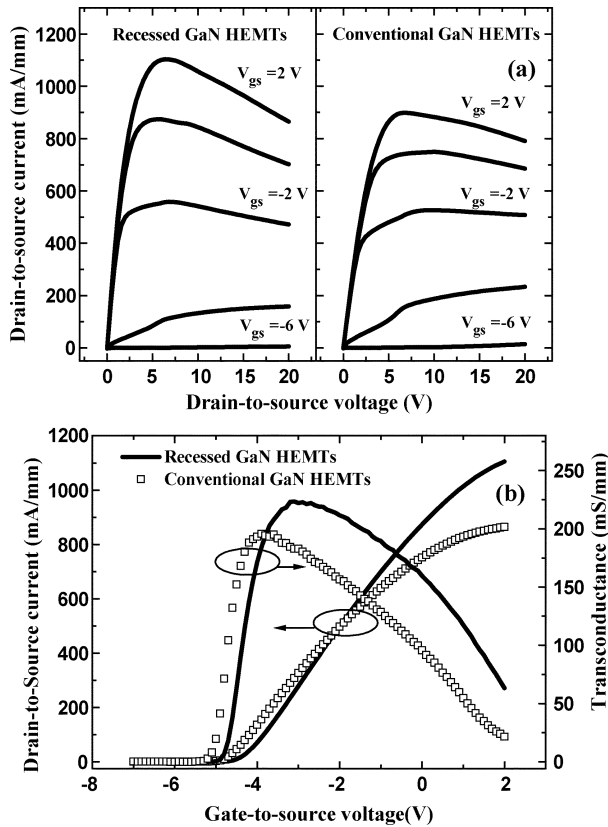


Fig. 2. (a) Comparisons of AlGaIn-GaN HEMT dc I - V curves, and (b) transfer characteristics at a V_{ds} of 5 V.

lower sheet charge density always results in a higher electron mobility of the two-dimensional electron gas than the conventional one [6]. After removing the GaN cap layer in the gate recess process, this antidirection of piezoelectric effect can be ignored, and the similar current density can still be expected in the recessed HEMTs, even though the original Hall measured sheet charge density is low. Device drain and source ohmic contacts were formed by using the Ti-Al-Ni-Au, followed by an annealing at 800°C for 30 sec in N_2 ambient. The contact resistance was $0.4 \Omega \cdot \text{mm}$ for the recessed AlGaIn-GaN HEMTs, and $1.0 \Omega \cdot \text{mm}$ for the conventional one, respectively. The mesa etching was done by using the Ar- Cl_2 mixture plasma of RIE mode with an etching rate of 100 nm/min for GaN material, and the gate recess etching was carried out by using the calibrated Ar- Cl_2 - CH_4 - O_2 mixture RIE mode plasma to achieve a high etching selectivity and a low surface damage [4]. After doing the recess etching, the $0.3\text{-}\mu\text{m}$ T-shaped gate with a Ni-Au metals were evaporated self-aligned with the recessed region without any post-etching annealing. Finally, these devices were passivated by a plasma-enhanced chemical vapor deposition, 300-nm Si_3N_4 film under 280 °C to stabilize the surface states of the devices [7]. As to the conventional device, the gate recess etching was not involved after the gate electron beam lithography.

III. DEVICE DC, RF, AND POWER PERFORMANCE COMPARISONS

The device current-voltage (I - V) curves and transfer characteristics comparisons at drain-to-source voltage (V_{ds}) of 5 V are

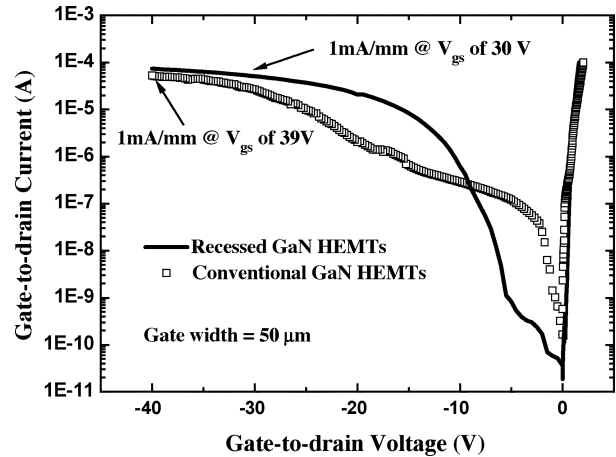


Fig. 3. Comparisons of AlGaIn-GaN HEMT Schottky gate characteristics.

shown in Fig. 2(a) and (b), and both devices demonstrate good channel pinch-off characteristics at a V_{ds} of 20 V. Notice that the additional n^+ -GaN cap layer provides a low resistivity conducting channel, and both the parasitic and channel resistances are reduced in the recessed AlGaIn-GaN HEMT. It therefore results in a lower knee voltage, a higher transconductance, and a higher current density. The maximum transconductance (g_m) and drain-to-source current density (I_{ds}) were 223 mS/mm and 1.104 A/mm for the recessed one, and 194 mS/mm and 0.86 A/mm for the conventional one, respectively. The current density in the recessed device is higher than the conventional one, even though its measured Hall carrier density is lower. Due to a high etching selectivity of the gate recess recipe, both devices presented similar threshold voltage (V_{th}). Fig. 3 compares Schottky gate characteristics between the recessed and the conventional AlGaIn-GaN HEMTs, the off-state Schottky gate breakdown voltages, defined by 1 mA/mm reversed gate leakage current, was 39 V for conventional GaN HEMTs and 30 V for the recessed GaN HEMTs, respectively. The turn-on voltages, also defined by 1 mA/mm gate turn-on current, were 1.8 V for conventional GaN HEMTs and 1.4 V for the recessed GaN HEMTs. However, owing to the high dislocation density ($\sim 10^9 \text{ cm}^{-2}$) of the GaN buffer, there were some leakage current paths between the electrodes which were on the etched GaN buffer layer. Consequently, some part of measured leakage current would derive from the material dislocation and the plasma etching induced damage. Therefore, the definition of breakdown voltage by using 1 mA/mm leakage current is an artificial approach to provide an easy way for device performance comparisons, which is not equivalent to the maximum dynamic operation of the V_{ds} . As can be seen in Fig. 3, the reversed leakage current of the recessed device became saturated and reaching 1 mA/mm at 30–40 V. However, the leakage current only reached about 2 mA/mm at 60 V, where the abrupt breakdown voltage happened at 85 V. In addition, due to the lower resistivity of n^+ GaN cap layer, the electrical field is easier to be localized in the gate-to-drain region, which results in the reduction of the defined off-state Schottky breakdown voltages and turn-on voltages in the recessed AlGaIn-GaN HEMTs. In conclusion, it could be observed that the Schottky leakage of the device with

TABLE I
SMALL-SIGNAL DEVICE PARAMETERS COMPARISONS BETWEEN THE RECESSED AND THE CONVENTIONAL GaN HEMTs (DEVICE DIMENSION: $0.3 \times 50 \mu\text{m}$)

Parameter	Recessed GaN HEMTs	Conventional GaN HEMTs
$R_s (\Omega)$	17	26
$R_d (\Omega)$	23	38
$R_g (\Omega)$	6	7
$R_i (\Omega)$	8	22
$R_{ds} (\Omega)$	600	800
$C_{gs} (\text{fF})$	37	35
$C_{gd} (\text{fF})$	14	13.5
$C_{ds} (\text{fF})$	2	2.1
$g_{m,\text{int}} (\text{mS/mm})$	280	240
$f_T (\text{GHz})$	43	37
$f_{\text{max}} (\text{GHz})$	68	50

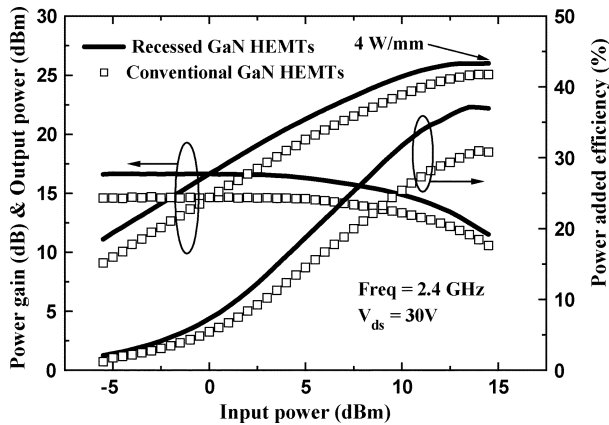


Fig. 4. Device microwave power performance comparisons ($0.3 \times 100 \mu\text{m}$). Both devices were biased at a V_{ds} of 30 V, and the I_{ds} was 25% of $I_{ds,\text{max}}$. The output matching gamma value ($|\Gamma_L|/\text{Ang.}\Gamma_L$) was 0.845/1.6° for recessed device and 0.86/0.028 for the conventional device.

n^+ cap layer will be a little higher than the conventional one owing to the more concentrated electric field in the gate-drain region, however this effect will not affect the excellent breakdown characteristic of the device obviously. Therefore by using the n^+ cap layer on the GaN HEMTs structure, the lower parasitic resistances could be achieved and a good breakdown characteristic could be maintained, either.

The f_T and f_{max} were 43 and 68 GHz for the recessed device, and 37 and 50 GHz for the conventional one. As to the small-signal device parameters comparisons, extracting from the Yang–Long method and cold-FET S -parameter measurements, the extrinsic parameters, R_d , R_g , and R_s can be obtained [8]. Owing to the advantages of lower contact resistance, the sum of R_s and R_d in the recessed device was lower than the conventional ones, i.e., 40Ω versus 64Ω for a $50\text{-}\mu\text{m}$ -wide device.

After transforming the measured S -parameters, the channel resistance (R_i) can also be extracted, which was only 8Ω in the recessed HEMTs, and the detailed comparisons of the small-signal device parameters are listed in Table I. The parasitic resistances are significantly reduced based on this additional GaN cap layer design; however, the associated capacitances are similar for both devices. Fig. 4 illustrates the microwave power performance comparisons evaluated by a load-pull system for a $100\text{-}\mu\text{m}$ -wide device. The maximum output power density was 4 W/mm for the recessed device and 3.4 W/mm for the conventional one at 2.4 GHz. The maximum power-added efficiency of the recessed device is also higher than the conventional device, which is due to the enhancements of the f_{max} and output power density. Therefore, through the course of previous comparisons, by using the n^+ -GaN cap layer and selective gate recess technologies on the AlGaIn–GaN HEMTs fabrication, the device parasitic resistances can be reduced and the better high-frequency characteristics can be achieved.

IV. CONCLUSION

Comparisons between recessed and conventional AlGaIn–GaN HEMTs have been demonstrated. By using a n^+ -GaN cap layer, the contact resistance and channel resistance can be significantly reduced. Therefore, the device RF and microwave power performance can be enhanced, and a 1.104 A/mm current density, a 223-mS/mm transconductance, and a 4-W/mm output power density have been demonstrated for recessed AlGaIn–GaN HEMTs.

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