Quaternary Barrier InAlGaN HEMTs With $f_T/f_{\text{max}}$ of 230/300 GHz

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Abstract—Depletion-mode quaternary barrier In$_{0.13}$Al$_{0.83}$Ga$_{0.04}$N high-electron-mobility transistors (HEMTs) with regrown ohmic contacts and T-gates on a SiC substrate have been fabricated. Devices with 40-nm-long footprints show a maximum output current density of 1.8 A/mm, an extrinsic dc transconductance of 770 mS/mm, and cutoff frequencies $f_T/f_{\text{max}}$ of 230/300 GHz at the same bias, which give a record-high value of $\sqrt{f_T \cdot f_{\text{max}}} = 263$ GHz among all reported InAlGaN barrier HEMTs. The device speed shows good scalability with gate length despite the onset of short-channel effects due to the lack of a back barrier. An effective electron velocity of $1.36 \times 10^7$ cm/s, which is comparable with that in the state-of-the-art deeply scaled AlGaN/GaN HEMTs, has been extracted from the gate-length dependence of $f_T$ for gate lengths from 100 to 40 nm.

Index Terms—Cutoff frequency, electron velocity, high-electron-mobility transistor (HEMT), HFET, mobility, quaternary, regrown ohmic contact, T-gate.

I. INTRODUCTION

ATTICE-matched In$_{0.17}$Al$_{0.83}$N barrier high-electron-mobility transistors (HEMTs) have been extensively studied as an alternative to AlGaN/GaN HEMTs for RF and millimeter-wave power applications. A 370-GHz current-gain cutoff frequency $f_T$ has been recently demonstrated using rectangular cross-sectional gates as a means of revealing scalability with minimum total gate capacitance [1]. For practical device and circuit applications, particularly for power amplifications in the field of wireless communication, highly conductive T-gates are desired to achieve high power-gain cutoff frequency $f_{\text{max}}$ as in AlGaN HEMTs [2] and N-polar GaN/InAlN HEMTs [3]. However, such a structure introduces additional gate parasitic capacitance, resulting in a decrease in $f_T$. One needs to balance the gate resistance and parasitic capacitance by optimizing the T-gate profile to achieve a high $f_T$ and $f_{\text{max}}$ simultaneously.

To date, the best performing device with balanced $f_T/f_{\text{max}}$ in InAlN HEMTs is 205/220 GHz, achieved with a 30-nm-long gate footprint $L_g$ [4]. Quaternary barrier InAlGaN/GaN HEMTs with electron mobility up to 1900 cm$^2$/V·s [5]-[7], which is higher than the typical mobility of $\sim$1300 cm$^2$/V·s in ternary InAlN HEMTs [8], have been explored to obtain better speed performance. High-speed devices based on these structures have been demonstrated, achieving $f_T$ up to 220 GHz with alloyed contacts (contact resistance $R_c = 0.36$ $\Omega$·mm) and $L_g$ of 66 nm [6], [7]. $f_T$’s approaching 300 GHz were achieved by adopting regrown contacts ($R_c = 0.12$ $\Omega$·mm) with $L_g$ less than 30 nm [9]. These results suggest that InAlGaN barrier HEMTs may offer good scalability in terms of high-frequency operation; however, high-performance T-gate device results on this structure have not yet been reported. In this letter, we report the performance of the state-of-the-art In$_{0.13}$Al$_{0.83}$Ga$_{0.04}$N/GaN HEMTs with regrown ohmics and T-gates and study the device scaling behavior with gate length. Depletion-mode (D-mode) HEMTs on a SiC substrate with 40-nm-long gate footprints and 12-nm-thick top barriers (corresponding to a gate-length-to-barrier-thickness aspect ratio $L_g/t_{\text{bar}}$ of 3.2) showed record-high $f_T/f_{\text{max}}$ of 230/300 GHz in the InAl(Ga)N/GaN HEMT material system.

II. EXPERIMENTS

The quaternary HEMT structure consists of an 11-nm In$_{0.13}$Al$_{0.83}$Ga$_{0.04}$N barrier, a 1-nm AlN spacer, a 55-nm unintentionally doped GaN channel, a 1.8-µm semi-insulating GaN buffer, and a 100-nm AlN nucleation layer on a SiC substrate grown by metal–organic chemical vapor deposition.

The device fabrication with regrown ohmic contacts follows a similar process flow to that described in [10], with a Ti/Au (20/100 nm) metal stack deposited on a 140-nm-thick Si-doped n-GaN, regrown by molecular beam epitaxy (MBE). The transmission-line method yielded a total metal-to-channel contact resistance of 0.27 $\Omega$·mm, of which 0.20 $\Omega$·mm is attributable to the metal/GaN interface because of a low Si doping level. T-gates were fabricated by electron-beam lithography (EBL) using a ZEP/PMGI/ZEP resist stack, followed by Ni/Au (20/400 nm) evaporation and liftoff, without surface passivation. On as-processed van der Pauw test structures, Hall effect measurements revealed a sheet resistance of 195 $\Omega$/sq with $n_s = 1.8 \times 10^{13}$ cm$^{-2}$ and $\mu = 1770$ cm$^2$/V·s. The devices have a source–drain distance $L_{sd}$ of 0.8 µm, a gate width of 2 $\times$ 25 µm, a T-gate stem height of $\sim$100 nm, nominal footprint lengths ranging from 40 to 100 nm, and a head size of

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350–400 nm. The gate lengths were carefully estimated based on EBL dose test results on pieces from the same wafer with a consistent uncertainty less than ±3 nm for all gate lengths.

III. RESULTS AND DISCUSSION

Fig. 1(a) presents the common-source $I–V$’s for a 40-nm-long InAlGaN HEMT. The gate–source bias $V_{gs}$ was stepped from $+1$ to $-6$ V, and the gate–drain bias $V_{ds}$ was swept from 0 to 10 V. At $V_{gs} = 1$ V, a maximum output current density $I_{ds,max}$ of 1.8 A/mm is reached, and the on-resistance $R_{on}$ is calculated to be 0.8 Ω·mm in the linear region. The dc output conductance $g_{ds}$ is approximately 80 mS/mm at $V_{gs} = -3$ V and $V_{ds}$ ranging from 5 to 8 V (near the peak $f_T$ bias condition), implying moderate short-channel effects. The three-terminal off-state breakdown voltage was measured to be 14 V at $V_{gs} = -6$ V using the criterion of $I_d = 1$ mA/mm. Pulsed $I–V$ measurements were performed in air on one of the 2 $\times$ 25 $\mu$m gate fingers using a 300-ns pulsewidth and a 0.5-ms pulse period from the following quiescent bias points: $(V_{gs}, V_{ds}) = (0, 0)$ as the cold pulse, $(\sim 6$ V, 0), and $(\sim 6$ V, 10 V). As shown in Fig. 1(b), the cold pulse $I–V$ did not exhibit saturation due to short-channel effects, and the higher current density than dc implies the presence of self-heating effects; gate lag and drain lag of 13% and 4%, respectively, were moderate and lower than that has been observed in similar unpassivated devices fabricated with alloyed contacts.

The 40-nm-long device transfer characteristics are plotted in both linear and logarithmic scales in Fig. 2. At $V_{ds} = 5.6$ V, a peak extrinsic dc transconductance $g_{m,ext}$ of 770 mS/mm and a threshold voltage $V_{th}$ of $-3.9$ V (from linear extrapolation of $I_d$) are obtained. The transistors maintain a high output current on/off ratio of $10^7$, and the drain-induced barrier lowering (DIBL) is calculated to be 145 mV/V at $I_d = 10$ mA/mm between $V_{ds} = 5.6$ and 1 V.

Small-signal RF measurements were taken from 100 MHz to 110 GHz with an Agilent N5250C vector network analyzer calibrated using Line-Reflect-Reflect-Match off-wafer impedance standards. Measured $S$-parameters were deembedded using on-wafer open and short structures to subtract pad parasitic capacitance and inductance. The deembedded current gain $|h_{21}|^2$, unilateral power-gain $U$, and maximum available power gain MAG are plotted in Fig. 3(a) as a function of frequency at the peak $f_T$ bias condition of $V_{ds} = 5.6$ V and $V_{gs} = -3.3$ V. The extrapolation of $|h_{21}|^2$ and $U$ at a $-20$-dB/dec slope gives $f_T$ and $f_{max}$ of 230/300 GHz, corresponding to $\sqrt{f_T \cdot f_{max}} = \sqrt{230 \cdot 300} = 263$ GHz. The values before deembedding were 133/260 GHz. Since the equivalent circuit modeling showed HEMT capacitance $(C_{gs} + C_{gd})$ of $\sim 22$ fF and pad capacitance $C_{pds}$ of $\sim 12$ fF, the $f_T$ increase after deembedding is reasonable. Fig. 3(b) compares the measured $f_T$ and $f_{max}$ in this letter with the state-of-the-art D-mode GaN-based HEMTs from literature.

Fig. 4 shows the device gate-length scaling behavior. DIBL of 75 mV/V, $g_{ds}$ of 46 mS/mm, and $V_{th}$ of $-3.6$ V are extracted for the 100-nm-long devices. With $L_g$ scaled down to 40 nm, both DIBL and $g_{ds}$ increase, and $V_{th}$ becomes more negative, implying enhanced short-channel effects. The gate-length dependence of $f_T / f_{max}$ in Fig. 4(b) shows an increase from 146/243 GHz with $L_g = 100$ nm to 230/300 GHz with $L_g = 40$ nm, suggesting good device scalability. A linear fit to the slope of the total delay time $\tau = 1/(2\pi \times f_T)$ as a function of $L_g$ yields an effective electron velocity $v_e$ of $1.36 \times 10^7$ cm/s, with an extrinsic parasitic delay time $\tau_{ext}$ of 0.35 ps from the intercept. For comparison, the measured delay time for InAlGaN HEMTs with rectangular gates is also presented in Fig. 4(c); $v_e = 1.33 \times 10^7$ cm/s and $\tau_{ext} = 0.20$ ps [11]. Since the HEMTs with T-gates and rectangular gates were fabricated on wafers with similar transport properties, the similar
extracted velocities are expected. It should be noted that these velocities are comparable to the effective velocity reported in the state-of-the-art deeply scaled AlN/GaN HEMTs. The shortest gate lengths were excluded in the extraction of \( v_e \) from the linear fitting in (c) for this letter and [11]–[13].

IV. CONCLUSION

D-mode In\(_{0.13}\)Al\(_{0.87}\)Ga\(_{0.04}\)N/GaN HEMTs with MBE regrown ohmic contacts and T-gates have been fabricated. The 40-nm-long-gate device showed record-high \( f_T/f_{\text{MAX}} \) of 230/300 GHz and \( \sqrt{f_T} : f_{\text{MAX}} = 263 \) GHz in the InAlGaN barrier HEMT family. A high effective electron velocity of 1.36 \( \times 10^7 \) cm/s is believed to benefit from the excellent transport properties obtained in quaternary barrier InAlGaN HEMT structures.

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REFERENCES