# AlGaN/GaN HEMTs on SiC with over 100 GHz $f_T$ and Low Microwave Noise

Wu Lu, *Member, IEEE*, Jinwei Yang, M. Asif Khan, and Ilesanmi Adesida, *Fellow, IEEE*

***Abstract*—High performance AlGaN/GaN high electron mobility transistors (HEMTs) with 0.12 $\mu$m gate-length have been fabricated on an insulating SiC substrate. The devices exhibited an extrinsic transconductance of 217 mS/mm and current drive capability as high as 1.19 A/mm. The threshold voltage of the devices was −5.5 V. For AlGaN/GaN HEMTs with the same gate-length, a record high unity current gain cut-off frequency ($f_T$) of 101 GHz and a maximum oscillation frequency ($f_{\rm MAX}$) of 155 GHz were measured at $V_{ds} = 16.5$ V and $V_{gs} = 5.0$ V. The microwave noise performances of the devices were characterized from 2 to 18 GHz at different drain biases and drain currents. At a drain bias of 10 V and a gate bias of −4.8 V, the devices exhibited a minimum noise figure ($NF_{\min}$) of 0.53 dB and an associated gain ($G_a$) of 12.1 dB at 8 GHz. Also, at a fixed drain bias of 10 V with the drain current swept, the lowest $NF_{\min}$ of 0.72 dB at 12 GHz was obtained at $I_{ds} = 100$ mA/mm and a peak $G_a$ of 10.59 dB at 12 GHz was obtained at $I_{ds} = 150$ mA/mm. With the drain current held at 114 mA/mm and drain bias swept, the lowest $NF_{\min}$ of 0.42 dB and 0.77 dB were obtained at $V_{ds} = 8$ V at 8 GHz and 12 GHz, respectively. To our knowledge, these are the best microwave noise performances of any GaN-based FETs ever reported.**

***Index Terms*—$f_T$, $f_{\rm MAX}$, GaN, HEMTs, microwave noise.**

## I. INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs) have attracted attention because of their excellent microwave performance, high current drive capability, and high microwave power performance [1]–[6]. AlGaN/GaN HEMTs on sapphire substrate with 0.15 $\mu$m gate-length have demonstrated a unity current gain cut-off frequency ($f_T$) of 67 GHz and a maximum oscillation frequency ($f_{\rm MAX}$) of 137 GHz [7]. Recently, an $f_T$ of 110 GHz was demonstrated in an AlGaN/GaN HEMT on SiC substrate with a gate length of 50 nm [8]. AlGaN/GaN HEMTs on SiC substrate with a power density as high as 9.2 W/mm at 8 GHz have also been demonstrated [5]. Although GaN-based FETs are primarily considered for high power and high temperature applications, it is important to investigate their noise characteristics. The low-frequency noise properties of AlGaN/GaN HEMTs have been reported [9]–[12]. In these studies, the noise behavior was found to exhibit $1/f$ (flicker) characteristics. However, little work has been reported on the high frequency noise performance of GaN FETs. Preliminary investigations have shown that AlGaN/GaN HEMTs do have respectable microwave noise properties that are comparable to those of AlGaAs/GaAs HEMTs. Specifically, 0.25 $\mu$m AlGaN/GaN HEMTs with a minimum noise figure ($NF_{\min}$) of 0.77 dB at 5 GHz and a $NF_{\min}$ of 1.06 dB at 10 GHz were reported [13]. An $NF_{\min}$ of 0.60 dB at 10 GHz was achieved in an AlGaN/GaN HEMT with a gate-length of 0.15 $\mu$m [14]. Though the devices exhibited relatively high noise figures at higher frequencies (about 2.4 dB at 18 GHz), these results are quite counterintuitive to what might be expected due to the material properties (especially defect density) of GaN. However, the results do motivate further investigations on the noise properties of AlGaN/GaN HEMTs. In this paper, we report our recent results on dc, rf, and high frequency noise characteristics of AlGaN/GaN HEMTs. A bandwidth of 100 GHz and a minimum noise figure ($NF_{\min}$) of 0.53 dB at 8 GHz and 0.99 dB at 18 GHz are demonstrated for devices with a gate-length of 0.12 $\mu$m.

## II. DEVICE STRUCTURE AND FABRICATION

The layer used in this study was grown by metal-organic vapor phase epitaxy (MOVPE) on highly resistive 4H–SiC substrate. The epilayer consisted of, from bottom to top, an AlN buffer, 2 $\mu$m GaN, a 5 nm undoped $Al_{0.2}Ga_{0.8}N$ spacer, a 15 nm $Al_{0.2}Ga_{0.8}N$ Schottky layer with a doping level of $1 \times 10^{19}$ cm$^{-3}$, and a 10 nm undoped $Al_{0.2}Ga_{0.8}N$ cap layer. Hall measurements revealed a two dimensional electron gas concentration of $1.1 \times 10^{13}$ cm$^{-2}$ and an electron mobility of 1100 cm$^2$/Vs. The mesa etching for isolating devices electrically was achieved by chemically assisted ion beam etching. Ohmic contacts were obtained by Ti/Al/Ti/Au evaporation and rapid thermal annealing at 850 °C for 30 s. Ni/Au mushroom-shaped gates with a gate-length of 0.12 $\mu$m were fabricated using electron beam lithography with a trilayer resist system. The devices had a gate-width of 100 $\mu$m and a source-drain spacing of 2 $\mu$m.

## III. DEVICE PERFORMANCE AND DISCUSSION

### A. DC Characteristics

On-wafer dc measurements were performed using an HP4142 semiconductor parameter analyzer. Fig. 1 shows the current–voltage (*I*–*V*) characteristics of a typical device. The gate was biased from 2 V to −7 V in a step of −1 V. The device exhibited very high drain current drive capability and excellent pinch-off characteristics. The maximum drain current was 1.19 A/mm at a gate bias of 2 V and a drain bias of 10 V. The device

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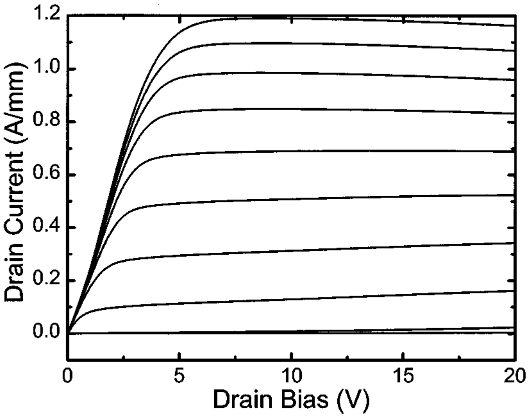

Fig. 1. *I–V* characteristics of a 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 100 $\mu$m. The gate bias was swept from 2 V to $-7$ V in a step of $-1$ V.

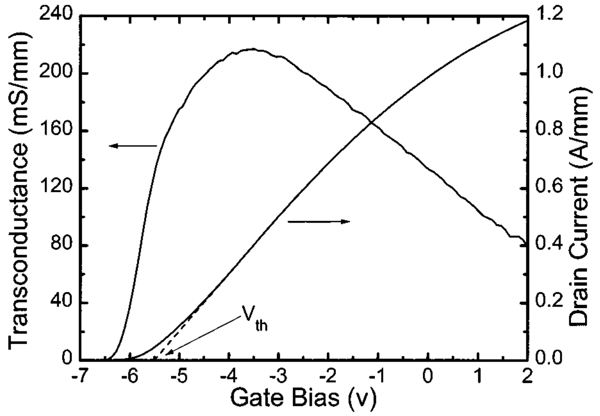

Fig. 2. DC transfer characteristics of the 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 100 $\mu$m. The drain bias was 7 V. The extrinsic transconductance peaks at $Vgs = -3.5$ V with a value of 217 mS/mm. The threshold voltage ($V$th) is determined to be $-5.5$ V by defining the gate bias intercept of the extrapolation of $I_{ds}$ at the point of peak extrinsic transconductance.

pinched-off completely at $V_{gs} = -7$ V, with drain currents as low as 1.1 mA/mm at $V_{ds} = 10$ V and 3.6 mA/mm at $V_{ds} = 20$ V, respectively. The on/off state current ratio is as high as 1081 at $V_{ds} = 10$ V. The knee voltage was less than 5 V at gate-biases up to 2 V. At gate biases of 1 V and 2 V, only a slight current drop was observed for $V_{ds}$ up to 20 V. This indicates the effectiveness of the i–SiC substrate in removing the channel heat engendered by high current density. Measured $I_{dss}$ values are 985 mA/mm and 960 mA/mm at $V_{ds} = 10$ V and 20 V, respectively. The dc transfer characteristics are shown in Fig. 2. The drain was biased at 7 V. A peak extrinsic transconductance ($g_m$) of 217 mS/mm was measured at $V_{gs} = -3.5$ V and $V_{ds} = 7$ V. It is worth noting that even at a drain current of 1 A/mm, the device still exhibited an extrinsic transconductance of 122 mS/mm, which indicates the potential of these devices for high power and high frequency applications. By defining the threshold voltage ($V$th) as the gate bias intercept of the extrapolation of $I_{ds}$ at the point of peak $g_m$, the $V$th of the device was determined to be $-5.5$ V, as shown in Fig. 2. The subthreshold characteristics exhibited an excellent pinch-off capability as shown in Fig. 3. The drain was biased at 6 V in this measurement. A subthreshold slope of 324 mV/decade and low off-state current (0.2 mA/mm), shown in Fig. 3, were achieved, which indicated good gate control of carriers in the channel region. Fig. 4 shows the excellent gate Schottky diode characteristics. In this measurement, the drain was shorted to the source and the gate width of the device was 50 $\mu$m. A high forward-bias turn-on voltage of 2.48 V was observed at a gate current of 1 mA/mm. Under reverse bias, no soft breakdown was observed up to 47 V where the gate leakage current was as small as 9.07 $\mu$A.

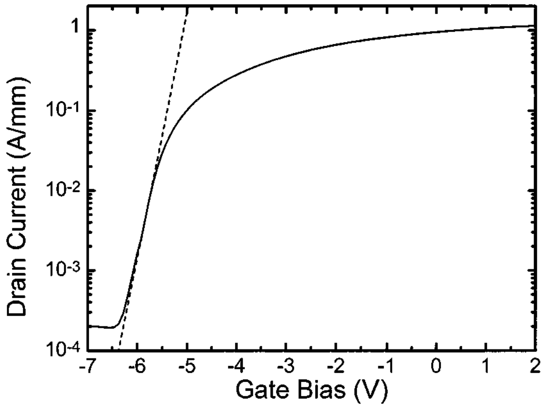

Fig. 3. Subthreshold drain current characteristics of the 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 100 $\mu$m. The drain bias was 6 V. The dashed straight line shows that a subthreshold slope of 324 mV/decade was achieved.

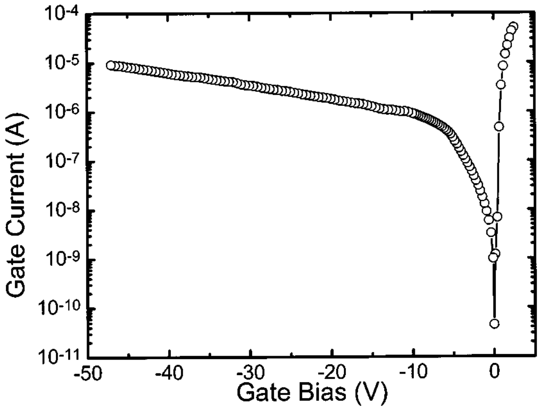

Fig. 4. Gate Schottky diode characteristics of a 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 50 $\mu$m. In this measurement, the drain was shorted to the source. The turn-on voltage of the diode was determined to be 2.48 V.

### *B. Microwave Characteristics*

For microwave characteristics, on-wafer measurements of $S$-parameters from 1 to 35 GHz using a Cascade Microtech Probe and an HP8510B Network Analyzer were used to determine unity current gain cut-off frequencies ($f_T$) and maximum oscillation frequencies ($f_{\mathrm{MAX}}$) of the devices. The devices were de-embedded from the effect of pad parasitics by the conventional $Y$-parameter subtraction. The current gain ($|h_{21}|$) and the maximum stable power gain (MSG) data are plotted against frequency in Fig. 5. Since the value of the stable factor ($k$) is less than 0.83 up to 35 GHz (not shown in Fig. 5), only MSG is shown in Fig. 5. $f_T$ and $f_{\mathrm{MAX}}$ were obtained by the extrapolation of $|h_{21}|$ and MSG using a $-20$ dB/decade slope. At a drain bias of 16.5 V and a gate bias of $-5.0$ V, an $f_T$

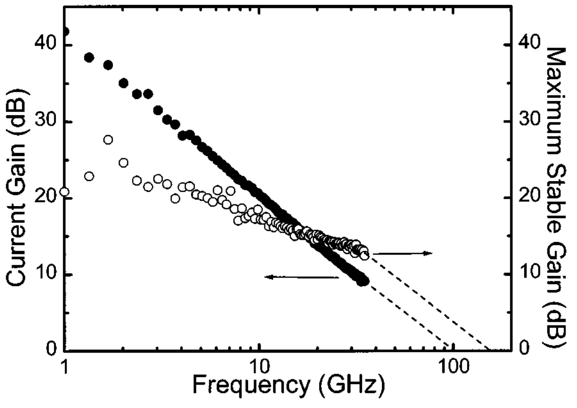

Fig. 5. Measured current gain ($|h_{21}|$) and maximum stable power gain (MSG) versus frequency for a typical 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 100 $\mu$m. The device was biased at $V_{ds} = 16.5$ V and $V_{gs} = -5.0$ V. The unity current gain cut-off frequency ($f_T$) and maximum oscillation frequency ($f_{\rm MAX}$) were determined to be 101 GHz and 155 GHz respectively by extrapolations of $-20$ dB/decade slopes.

of 101 GHz and an $f_{\rm MAX}$ of 155 GHz were measured. Since the transistor is potentially unstable at 35 GHz and we simply used a $-20$ dB/decade slope to determine the $f_{\rm MAX}$, the actual $f_{\rm MAX}$ should be higher than 155 GHz. Nevertheless, to our knowledge, these $f_T$ and $f_{\rm MAX}$ values are the highest data ever reported for any GaN FETs with the same gate-length. The $f_T$ and $f_{\rm MAX}$ values as functions of drain current for the same transistor are shown in Fig. 6. In these measurements, the drain was biased at 16 V while the gate was biased in the range of $-6$ V to 0 V. The drain current obtained was in the range of 16.3 mA/mm to 971.8 mA/mm. The $f_T$ values obtained ranged from 57 GHz to 101 GHz while $f_{\rm MAX}$ values varied from 52 GHz to 155 GHz. The highest $f_T$ and $f_{\rm MAX}$ were measured at the drain current of 150 mA/mm. It should be pointed out that the transistor still exhibited over 50 GHz $f_T$ and $f_{\rm MAX}$ at $I_{ds} = I_{dss}$, which indicates the potential for high power capability at high frequencies. Fig. 7 shows $f_T$ and $f_{\rm MAX}$ dependence on drain bias for the same device. The gate bias was $-4.75$ V. In Fig. 7, with increasing drain bias, $f_T$ values increased dramatically from 1 V to 2 V. At higher drain biases, the $f_T$ values increased slowly to a peak value of 101 GHz. $f_{\rm MAX}$ increased from 46.2 GHz at $V_{ds} = 1$ V to 103.4 GHz at $V_{ds} = 2$ V and saturated at 155.1 GHz at $V_{ds} = 16$ V.

### *C. Microwave Noise Performances*

High frequency noise performances of the devices were measured using an ATN NP5 noise parameter test set in conjunction with an HP8570B noise figure meter, an HP8971B noise figure test set, and an HP8510B Network Analyzer over 2 to 18 GHz frequency range. After the system was calibrated, the uncertainties in the minimum noise figure ($NF_{\rm min}$) and the associated power gain ($G_a$) for standard "through" and "10 dB" passive structures were first measured to check the calibration. Repeated measurements for the same structure showed that the uncertainties of $NF_{\rm min}$ and $G_a$ from 4 GHz up to 18 GHz are less than 0.1 dB. The system gave higher uncertainties at 2 GHz and 3 GHz. Therefore, the values of $NF_{\rm min}$ and $G_a$ at 2 GHz and 3 GHz are not shown in this paper. Fig. 8 shows $NF_{\rm min}$ and $G_a$ as a function of frequency. The straight line in Fig. 8 is a linear fit to the minimum noise figures. For these measurements, devices were biased at $V_{ds} = 10$ V and $V_{gs} = -4.8$ V. Compared to our previous results on 0.25

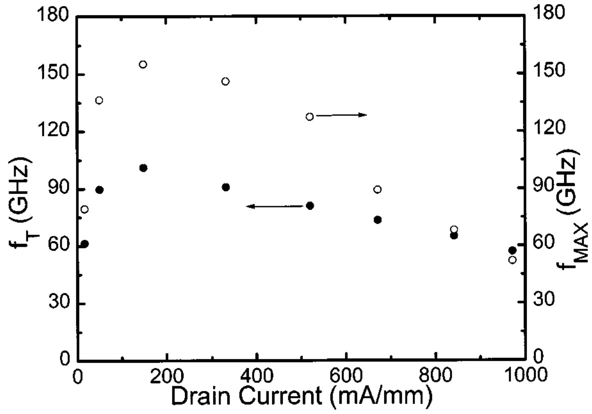

Fig. 6. Measured unity current gain cut-off frequency ($f_T$) and maximum oscillation frequency ($f_{\rm MAX}$) as a function of drain current of the 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 100 $\mu$m. The drain bias was kept at 16 V.

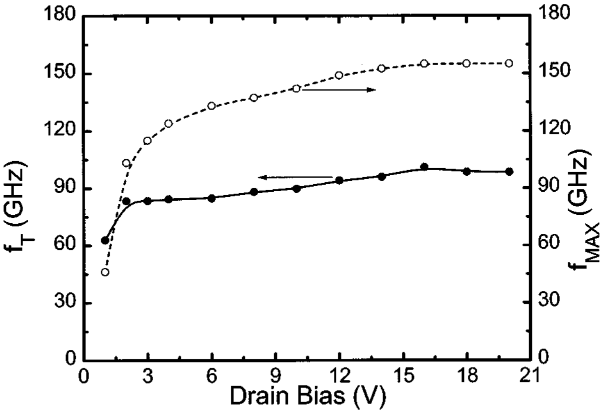

Fig. 7. Measured unity current gain cut-off frequency ($f_T$) and maximum oscillation frequency ($f_{\rm MAX}$) as a function of drain bias of the 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 100 $\mu$m. The gate bias was kept at $-4.75$ V.

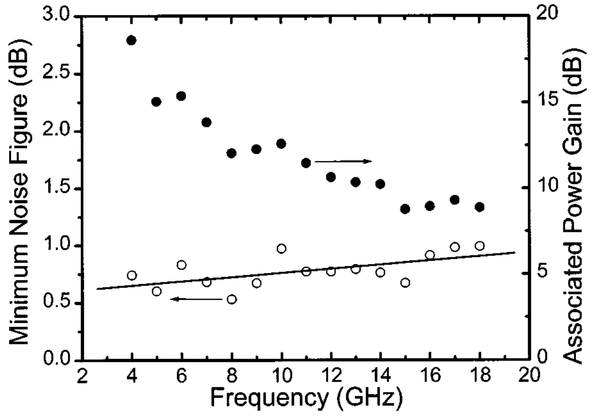

Fig. 8. Minimum noise figure ($NF_{\rm min}$) and associated power gain ($G_a$) versus frequency for the typical 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 100 $\mu$m. The device was biased at $V_{ds} = 10$ V and $V_{gs} = -4.8$ V. An $NF_{\rm min}$ of 0.53 dB was measured at 8 GHz. The solid straight line is the linear fit to the measured $NF_{\rm min}$.

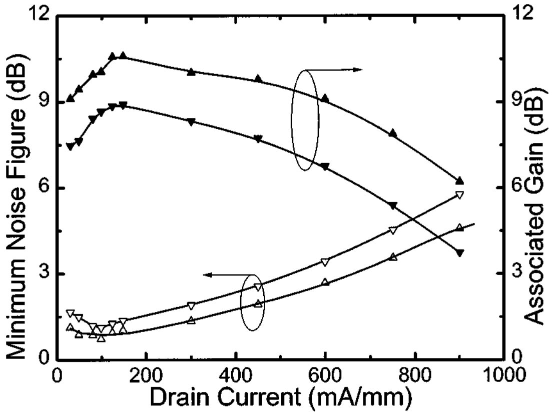

Fig. 9. Minimum noise figure ($NF_{\min}$) and associated power gain ($G_a$) at 12 GHz (up triangles) and 18 GHz (down triangles) against drain current for the typical 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 100 $\mu$m. The drain bias was 10 V.

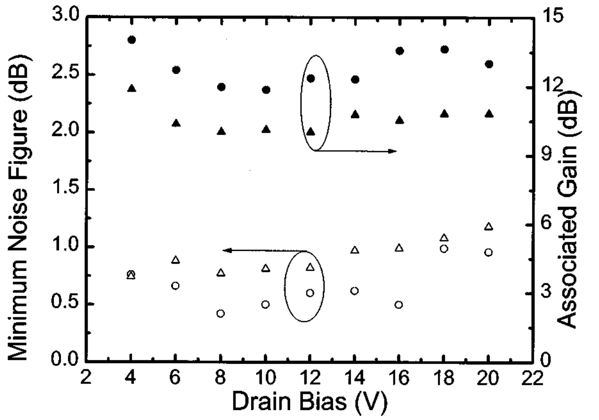

Fig. 10. Minimum noise figure ($NF_{\min}$) and associated power gain ($G_a$) at 8 GHz (circles) and 12 GHz (up triangles) as a function of drain bias for the typical 0.12 $\mu$m AlGaN/GaN HEMT with a gate width of 100 $\mu$m. The drain current was held at 114 mA/mm.

$\mu$m gate-length devices [13], the present noise performances improved significantly. An $NF_{\min}$ of 0.53 dB and a $G_a$ of 12.1 dB were measured at 8 GHz. In the frequency range of 4 GHz–18 GHz, $NF_{\min}$ is in the range of 0.53 dB to 0.99 dB and $G_a$ ranges from 18.6 dB to 8.87 dB. These improvements were not only demonstrated at low frequencies but also at high frequencies. For nitride-based transistors, the frequencies of interest are currently in the X-band and Ku-band ranges. For example, our devices exhibited an $NF_{\min}$ of 0.77 dB at 12 GHz and an $NF_{\min}$ of 0.99 dB at 18 GHz while the $NF_{\min}$ values of our reported 0.25 $\mu$m devices were 1.1 dB at 12 GHz and 1.8 dB at 18 GHz, respectively. This improvement is attributed to the higher gains engendered by the smaller gate length and the excellent gate Schottky characteristics. To our knowledge, these are the best $NF_{\min}$ and highest $G_a$ for GaN FETs ever reported. Though the noise figure shown in Fig. 8 is linear dependence of frequency, the slope of the dependence is relatively flat compared with known FET models. To explain this, currently we are developing a new noise model for GaN FETs with short gate-lengths. The detailed results will be published elsewhere. Fig. 9 shows the dependence of $NF_{\min}$ and $G_a$ at 12 GHz (up triangles) and 18 GHz (down triangles) on the drain current, $I_{ds}$. In these measurements, the drain bias was fixed at 10 V and the gate biases were adjusted to control the drain current. The drain current was in the range of 30 mA/mm to 900 mA/mm. At a drain current of 30 mA/mm, the $NF_{\min}$ was 1.12 dB and the $G_a$ was 9.11 dB at 12 GHz. At 18 GHz, the $NF_{\min}$ and $G_a$ were 1.65 dB and 7.48 dB, respectively. At a drain current of 900 mA/mm, the device still exhibited very respectable performances, 4.58 dB at 12 GHz and 5.77 dB at 18 GHz for $\mathrm{NF}_{\min}$, and 6.22 dB at 12 GHz and 3.74 dB at 18 GHz for $G_a$, respectively. It was observed that the minimum $NF_{\min}$ was measured at a drain current level of 100 mA/mm which gave $NF_{\min}$ values of 0.72 dB at 12 GHz and 1.12 dB at 18 GHz. Peak values of $G_a$ were observed at the drain current level of 150 mA/mm, with $G_a$ of 10.59 dB at 12 GHz and 8.91 dB at 18 GHz, respectively. The dependencies of $NF_{\min}$ and $G_a$ on drain bias ($V_{ds}$) at 8 GHz (circles) and 12 GHz (up triangles) are plotted in Fig. 10. For the measurements, the drain current was held at 114 mA/mm. The drain bias range was from 4 V to 20 V. It was found that the $NF_{\min}$ and $G_a$ were relatively independent of drain biases within the measured range. At 8 GHz, the $NF_{\min}$ varied from 0.42 dB to 0.99 dB and $G_a$ varied from 12.31 dB to 14 dB. At 12 GHz, the $NF_{\min}$ varied between 0.74 to 1.18 dB while the $G_a$ varied from 10.02 dB to 11.87 dB. The lowest $NF_{\min}$ values (0.42 dB at 8 GHz and 0.77 dB at 12 GHz) were measured at $V_{ds} = 8$ V. These noise performances of our AlGaN/GaN HEMTs are comparable with those of GaAs-based HEMTs [15], [16] and MESFETs [17], [18] but with much higher current drive capability and breakdown voltages hence much high power capability. Again, this is attributed to the high quality of the AlGaN/GaN epilayer and the optimized fabricating process. All these excellent dc, rf, and high frequency noise performances demonstrate the potential of AlGaN/GaN HEMTs for low noise applications in X-and Ku-band frequency ranges.

## IV. CONCLUSIONS

We have presented the fabrication and characterization of AlGaN/GaN HEMT's on SiC substrate with a gate length of 0.12 $\mu$m. The devices exhibited a high current drive capability of 1.19 A/mm and a peak extrinsic transconductance of 217 mS/mm. A record high $f_T$ of 101 GHz and an $f_{\mathrm{MAX}}$ of 155 GHz were obtained for GaN FETs with same gate-length. The microwave noise characteristics of these devices were characterized. At the drain bias of 10 V and the gate bias of $-4.8$ V, the devices exhibited an $NF_{\min}$ of 0.53 dB and a $G_a$ of 12.1 dB at 8 GHz. The $NF_{\min}$ values were less than 1 dB up to 18 GHz. The noise performance dependencies on drain bias and drain current were also characterized. With the drain bias fixed at 10 V, the peak $G_a$ and lowest $NF_{\min}$ were measured at $I_{ds} = 150$ mA/mm and 100 mA/mm, respectively. Also, the lowest $NF_{\min}$ (0.42 dB at 8 GHz and 0.77 dB at 12 GHz) were measured at $V_{ds} = 8$ V while drain current was held at 114 mA/mm. All these excellent performances indicate the low noise and high power application potentials of AlGaN/GaN HEMTs in X-band and Ku-band microwave frequency ranges. With the combined maturity of nitride-based growth techniques and further optimization of process technologies, it is expected that even better device performances will be obtained in the near future.

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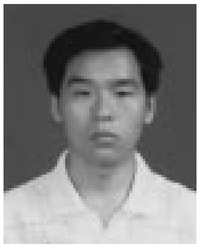

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