77 GHz Power Amplifier MMIC using 0.1 µm Double-Deck Shaped (DDS) field-plate gate AlGaN/GaN HEMTs on Si Substrate

Dong-Hwan Kim, Ji-Hoon Kim, Su-Keun Eom, Min-Seong Lee, and Kwang-Seok Seo

Department of Electrical and Computer Engineering and ISRC, Seoul National University.
San 56-1 Shillim-dong Gwanak-gu Seoul 151-744, Republic of Korea
Phone: +82-2-877-0298 E-mail: ksseo@snu.ac.kr

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Abstract

This paper describes the demonstration of 77 GHz gallium nitride (GaN) power amplifier (PA) on a silicon substrate. The PA monolithic microwave IC (MMIC) was fabricated by using developed AlGaN/GaN HEMTs on Si with double-deck shaped (DDS) field-plate gate with f_{max} of 160 GHz (f_T = 70 GHz) and a breakdown voltage of over 70 V. The demonstrated 3-stage power amplifier exhibited output power with 20.1 dBm at 77 GHz for 18 V drain bias.

INTRODUCTION

Monolithic Microwave Integrated Circuits (MMICs) become critical components as the importance of wireless communications, satellite communications and military applications increases more and more. In millimeter-wave device and power amplifier technologies GaAs and InP were widely investigated and used, but those have limited the high-power amplifiers due to the properties of those semiconductor materials. For high frequency and high power operation, devices should be based on semiconductor materials with high breakdown voltage and high electron velocity. GaN material is preferable for these aspects due to the property with wide bandgap and high electron saturation velocity [1].

In this paper we especially present GaN-on-Si RF devices which can be the promise candidates of the next generations millimeter-wave applications with lower cost and reasonable characteristics. In spite of the difficulty of the epitaxial growth for GaN-on-Si, there are some number of groups demonstrate high performance with maximum oscillation frequency over 150 GHz [2]. However, there are few results of large size GaN-on-Si devices and MMICs due to the lack of stable technologies. Only GaN-on-Si power amplifier MMICs for millimeter-wave with output power of over 12 dBm at 76 GHz was reported [3]. We demonstrated 0.1 µm AlGaN/GaN HEMTs with double-deck shaped field-plate gate structure to improve device performance in typical epitaxial structure, and power amplifier MMIC was fabricated using this process.

DOUBLE-DECK SHAPED GATE STRUCTURE

GaN-on-Si devices suffered from lower breakdown voltage, more serious current collapse, and higher RF loss than devices used SiC substrates, because of high dislocation density on epitaxial layer from Si substrate. Although, ultimately reduction of dislocation density is the key technology for GaN-on-Si, unit processes can provide device better RF performance either. The gate structure that we proposed was considering improvement of current collapse phenomenon with minimized parasitic effects and decrease of gate resistance, so a maximum oscillation frequency could be improved. Figure 1 shows a schematic of AlGaN/GaN HEMTs used in MMICs. First gate metallization with 50 nm field-plate was performed and second wide metallization was followed by resist planarization process. We expected that this gate structure could reduce the current collapse compared with high-stem T-gate and decrease gate resistance which is the important factor of f_{max}.

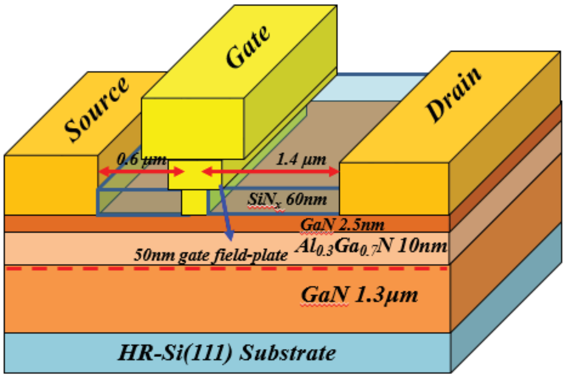

Figure 1. Cross-sectional image of fabricated AlGaN/GaN HEMTs structure.

DEVICE FABRICATION AND CHARACTERISTICS

The used AlGaN/GaN epitaxial structure from *NTTAT Corp.* consisted of a 2.5 nm GaN cap layer, a 10 nm $Al_{0.3}Ga_{0.7}N$ thin barrier for high transconductance and high aspect ratio, a 1 nm AlN spacer layer, a 1.3 µm undoped

GaN buffer grown on a high-resistivity silicon (111) substrate. The material showed carrier mobility of 1700 cm^2/V.

After surface cleaning, 30 nm SiN_x film was pre-deposited using inductively coupled plasma chemical vapor deposition (ICP-CVD) in order to protect the GaN surface during high temperature annealing [4]. Then, the ohmic contacts were formed by recess etching and a metal stack of Si/Ti/Al/Mo/Au (5/20/80/35/50 nm), and followed by 780 °C annealing in N_2 ambient. Device isolation process was carried out using mesa etching, and the measured contact resistance was 0.38 Ω·mm and the sheet resistance was 298 Ω/sq. To improve GaN surface quality, the pre-deposited SiN_x film was removed by soft SF_6 plasma etching [6], and subsequently a 60 nm SiN_x film was re-deposited with *in-situ* N_2 plasma treatment [5]. Gate foot was defined by using e-beam lithography with ZEP, and SiN_x film was etched by SF_6 plasma again, the gate length was 0.1 µm. The 50 nm short gate field-plate was also defined with PMGI/ZEP to reduce electrical field near the gate electrode [7]. First gate metal with Ni/Au (40/360 nm) was evaporated, and double-deck shaped gate structure was fabricated with etch-back process of thick MMA resist by O_2 plasma until the top of the gate metals were disclosed. Final gate metallization was performed with PMGI/ZEP and Ni/Au (40/360 nm). Figure 2 shows a SEM view of the proposed gate structure.

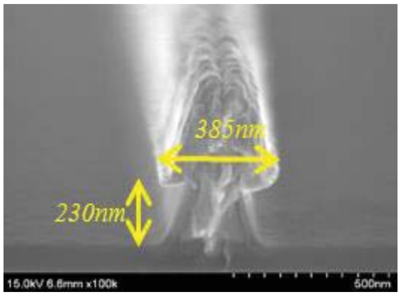

Figure 2. SEM view of fabricated 0.1 µm double-deck shaped field-plated gate structure used in GaN MMIC power amplifier.

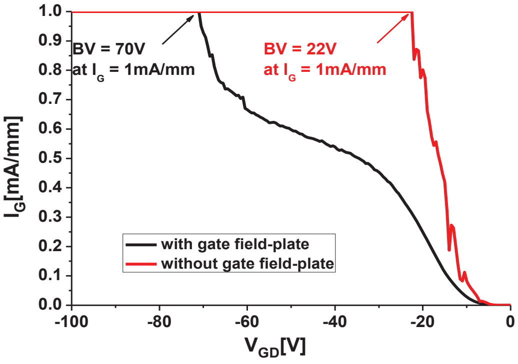

Figure 3. Three-terminal breakdown characteristics of Schottky gate with field-plate and without field-plate.

Figure 3 shows three-terminal gate breakdown voltage characteristics with short gate field-plate at double-deck shaped and without gate field-plate which means high-stem T-gate. We defined breakdown voltage at I_G=1 mA/mm, and much higher breakdown characteristic was achieved with gate field-plate device mainly due to the mitigated peak electric field at the edge of the gate electrode. I-V characteristics of the device were shown at figure 4 and 5. The fabricated device exhibited the average maximum extrinsic transconductance of 427 mS/mm at V_{DS} = 5 V and the threshold voltage variation of ±270 mV. A maximum drain current of the device with DDS field-plate gate structure was 910 mA/mm at V_{GS} = 0 V.

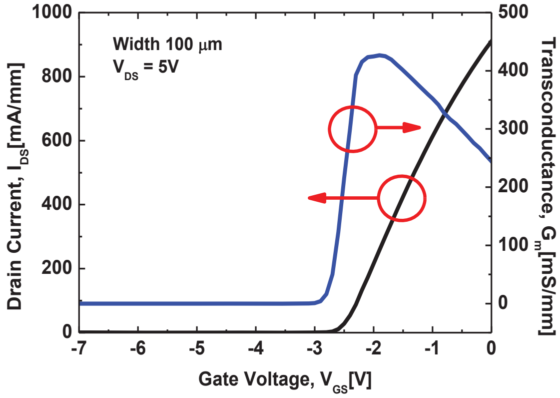

Figure 4. Transfer characteristic of DDS field-plate gate HEMT with the drain current and the transconductance at V_{DS} = 5V.

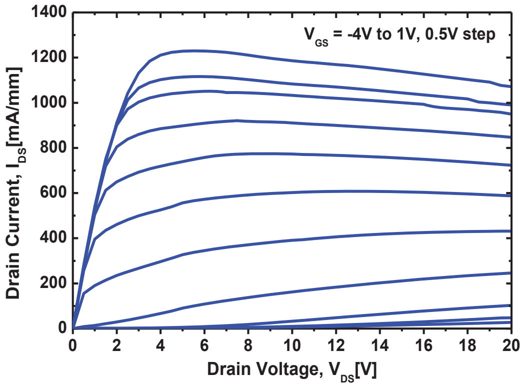

Figure 5. I_D-V_D characteristics of fabricated HEMT.

Figure 6 shows current collapse effects investigated with pulsed I-V measurements for 500 ns pulse duration at V_{GS} = 0 V. Even with 50 nm field-plate length, the current collapse phenomena were effectively suppressed by more than 50% at gate lagged with V_{GSQ} = -5V and drain lagged with V_{DSQ} = 20V compared with no gate field-plated HEMTs. This improvement might be reasonable value at typical epitaxial structure for short gate device that affect by high electric field, and this made device possible to operate at drain voltage over 15 V with small degradation of output gain.

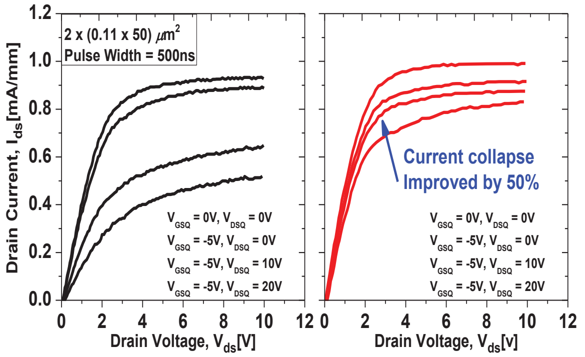

Figure 6. Pulsed I-V characteristics of the devices with T-shaped gate (left) and DDS field-plate gate having 50 nm field-plate length (right).

RF performance of manufactured device was estimated by the unity current gain cut-off frequency (f_T) and the maximum oscillation frequency (f_{max}) which were each determined by the extrapolation of the current gain $|H_{21}|$ and the Mason's unilateral power gain U as shown in figure 7, and the value of f_{max} was 160 GHz for 4×37 μm DDS-field-plate gate HEMT (f_T = 70 GHz).

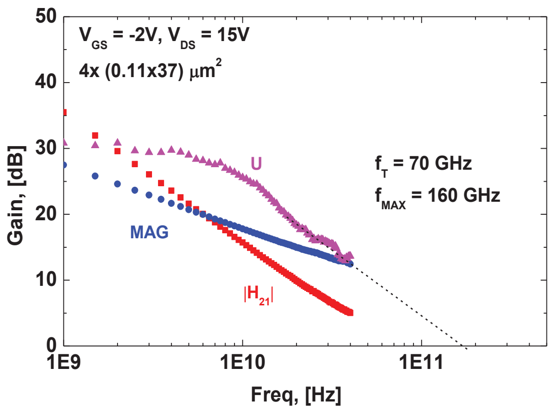

Figure 7. RF performances of HEMTs with DDS field-plate gate measured at V_{DS} = 15V and V_{GS} = -2V.

CIRCUIT DESIGN AND MMIC

For the design of the millimeter-wave MMIC, DDS field-plate gate HEMTs with a gate width of 4×37 μm and 8×37 μm were chosen. These devices were selected through the parametric study on GaN-on-Si HEMTs performed in our previous work [8]. DDS field-plate gate HEMTs with a gate width of 4×37 μm displayed 5 dB MAG (Maximum Available Gain) at 77 GHz. Figure 8 shows the chip image of the fabricated 77 GHz power amplifier MMIC. The circuit was designed with 3-stage common source type which consists of device with gate width of 4×37 μm at the first and second stage, and 8×37 μm at the third stage. Because the SRF (Self Resonance Frequency) of MIM capacitors cannot cover up to W-band range, coupled lines and λ/4 open stubs are applied for the purpose of DC block and RF short. The used coupled lines were 250 μm length and λ/4 open stubs for RF short were 380 μm. To reduce the size of MMIC, coupled lines were designed as meander type. Because they decide center frequency and bandwidth, careful design and accurate prediction are required. Thus, additional EM (Electro-Magnetic) simulation was performed by IE3D @ Mentor. Air bridges were inserted to confirm ground near signal lines.

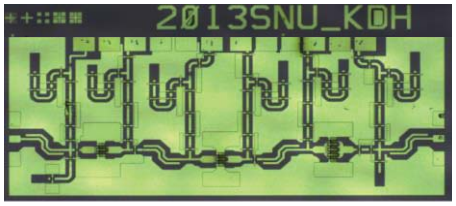

Figure 8. Chip image of 77 GHz power amplifier MMIC using GaN DDS field-plate gate HEMTs (size : 2.3×0.9 mm^2).

To consist MMIC circuit, a NiCr TFR with targeted sheet resistance of 20 Ω/sq and thick Ti/Au metallization of coplanar waveguide (CPW) line were followed. Figure 9 shows the measured S-parameter results. The measured power gain was 3.9 ~ 5.0 dB from 70.5 GHz to 78 GHz and the input/output return loss was below -10 dB from 71 GHz to 77.5 GHz. Although each HEMTs represent 5 dB MAG, gain is considered to degrade by coupling loss from coupled lines. Figure 10 (a) and (b) represents the measured output power at 77 GHz and the saturated power sweep according to frequencies. The fabricated 77 GHz PA MMIC represented the output power of 20.1 dBm at 77 GHz and 19 ~ 22 dBm from 72 GHZ to 78 GHz (the peak power at 72 GHz). This result was valuable for millimeter-wave GaN-on-Si MMIC PA compared with the result reported before. Moreover, this single power cell is expected to apply at power combining circuits such as Wilkinson combining, and exhibit more enhanced RF power characteristics.

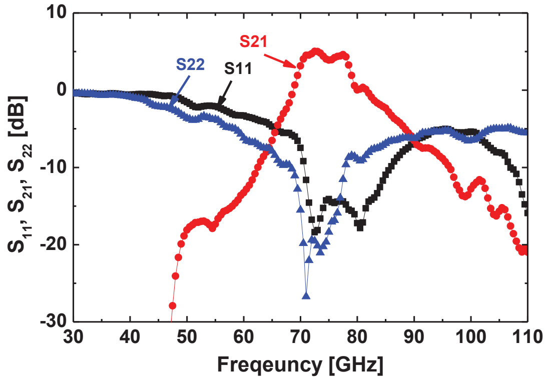

Figure 9. The results of measured S-parameters for the fabricated 77 GHz power amplifier MMIC.

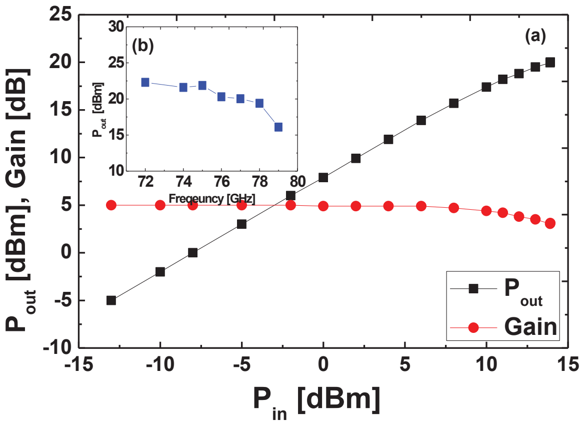

Figure 10. Measured output power of 77 GHz power amplifier MMIC ((a) P_{out} at 77 GHz (b) P_{sat} according to power sweep).

CONCLUSIONS

In this work, we demonstrated specific fabrication processes, especially gate structure for millimeter-wave that can be applied to GaN RF device technologies. The fabricated MMIC PA using the double-deck shaped field-plate gate process exhibited output power over 20dBm at 77 GHz. Though further improvements are needed such as a quality of GaN-on-Si material, this paper suggests that the gate configuration and the fabricated MMIC using GaN-on-Si epitaxial structure have a great potential for future RF device.

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ACRONYMS

HEMT: High Electron Mobility Transistor
PA: Power Amplifier
MMIC: Monolithic Microwave Integrated Circuit
MIM: Metal-Insulator-Metal
SRF: Self Resonance Frequency
TFR: Thin Film Resistor