High Power Added Efficiency Enhancement-Mode Γ-Gate RF HEMT with Engineered Mg Doping Profile in p-GaN Layer

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Abstract

E-mode p-GaN Γ-gate RF HEMT with engineered Mg doping profile was developed and demonstrated for high power amplifier application. Through the design of a low-temperature MOCVD Mg doping profile and a reduction in Mg doping concentration, the diffusion of Mg into AlGaN is minimized compared to traditionally high Mg-doping grown p-GaN. This design enhances the gate modulation capability of p-GaN for RF applications, resulting in a higher gm peak. In addition, the Poole–Frenkel (PF) tunneling induced flicker noise was also suppressed at high input power swing due to low inactivated Mg induced traps. With the engineered Mg-doping profile design, a 61.4 % PAE was achieved together with an output power density close to 1 W/mm at V_{DS} of 10 V which exhibit a highly potential for satellite direct-to-cell and FR3 mobile phone single voltage supply PA applications.

INTRODUCTION

GaN HEMTs have demonstrated great potential for high output power and high-frequency applications due to their excellent carrier transport properties and large critical electric field. In addition, a superior carrier confinement in build-in 2DEG channel of GaN HEMT also resulted in its rapid adoption in 4G/5G infrastructure PA to replace Si-based LDMOS [1-2]. However, AlGaN/GaN heterostructure induced 2DEG also lead to its depletion-mode operation which the negative voltage supply becomes necessary to bias the gate voltage correctly for class AB operation. This mechanism of GaN HEMT also strongly limited its application on portable device such as mobile phone and tablet devices. In this study, the p-GaN Γ-gate RF HEMT with engineered Mg doping profile was developed for E-mode RF PA application [3-5]. Based on low temperature Mg doping profile, the low doping p-GaN (1E19 cm^{-3}) can effectively reduce the input gate capacitance. The engineered Mg doping profile provides a high gate to channel modulation capability based on the gm rapid ramp-up profile. Meanwhile, under the class-AB (1/10 I_{dsmax}) operation, the RF GaN HEMT was biased at high V_{DS} together with certain current thus vertical and lateral electric field management are necessary. Therefore the Γ-gate design in this study can reduce the vertical electric-field of p-GaN sidewall and less sacrifice the gate-to-source resistance compared to traditional symmetric T-shaped gate.

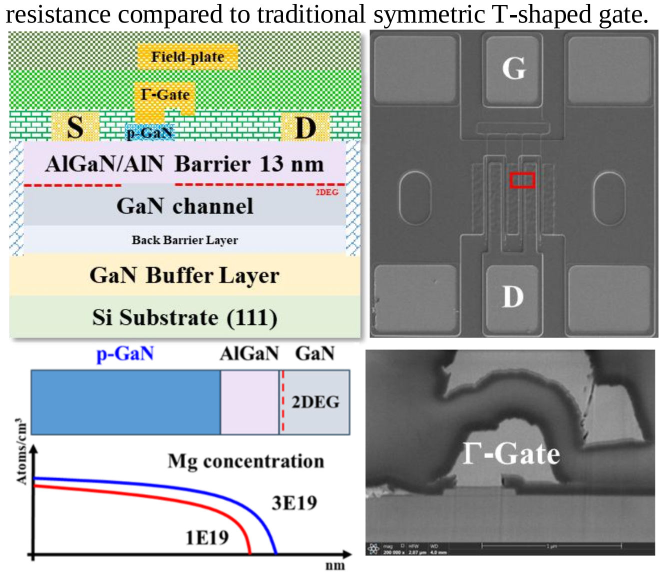


Fig. 1. The SEM top view, cross-sectional photos and schematic diagram of Mg doping distribution of p-GaN Γ-gate HEMT with sourced field-plate.

EXPERIENTIAL RESULTS AND DISCUSSION

The E-mode p-GaN Γ-gate HEMTs epitaxial layers are grown on 150 mm high resistivity (8000Ω) FZ Si substrate. The epitaxial heterostructure (from bottom to top) features a 1.5-μm transition/buffer layer, the Ga out-diffusion into Si induced parasitic channel need to be suppressed less than 0.2μm. For better carrier confinement at high input power swing operation, the 50nm AlGaN back-barrier is a key layer. AlGaN/AlN/GaN heterostructure (barrier + 2DEG channel) for high mobility consideration. In conventional p-GaN epitaxy, the growth temperature is relatively high, leading Mg to diffuse into the AlGaN layer or even the channel. Therefore, in this study, we employed a low-temp MOCVD process to minimize Mg out-diffusion caused by high temperatures, thereby reducing defect formation due to Mg diffusion into AlGaN. The schematic was shown in Fig. 1.

Fig. 2 illustrates the depletion region and charge distribution model of a p-GaN HEMT, explaining its gate control mechanism. In this model, the acceptor ion charge (ρ_1) in the p-GaN layer forms a depletion region, affecting the electric field distribution. q represents the elementary charge ($\sim 1.6 \times 10^{-19}$ C). N_A denotes the acceptor concentration in p-GaN, corresponding to the Mg doping concentration [6].

The schematic shows that by employing low-temperature MOCVD to grow a lightly Mg-doped p-GaN layer, the N_A concentration is significantly reduced compared to conventional p-GaN layers. The charge density, primarily derived from ionized Mg acceptors, influences the overall electric field distribution and carrier modulation capability.

This charge participates in forming the gate electric field and also impacts the capacitance. A lower doping concentration results in a lower charge density, reducing the device's gate capacitance and thereby enhancing gate control capability and transconductance (g_m) behavior.

A lower capacitance allows the current to reach saturation more quickly, increasing gate modulation speed and transconductance (g_m). From the equation $f_T = g_m/2\pi C_{gs}$, it can be observed that an increase in gm leads to a higher f_T, enabling faster high-frequency response.

In our preliminary study, the Engineered Mg-doped p-GaN, grown at low temperatures, exhibited approximately 2 dB higher gain at 3.5 GHz compared to conventional p-GaN. Additionally, the high gm allows the HEMT to turn on at a lower gate drive voltage V_{GS}, reducing switching loss and on-resistance. By enhancing power gain, minimizing switching and conduction losses, and improving high-frequency performance and impedance matching, the PAE (Power-Added Efficiency) can be significantly improved.

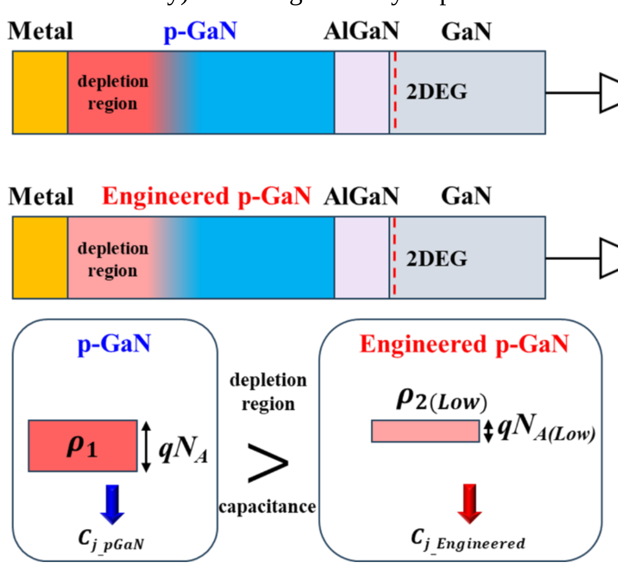


Fig. 2. The schematic diagram of depletion region and charge distribution model of p-GaN HEMT.

The temperature dependent DC and small signal curves of proposed device was shown in Fig. 3. Fig. 3(a) shows the I_{DS}-V_{GS} curve, measured at temperatures ranging from room temperature (300K) to 400K, with V_{DS} = 10 V and V_{GS} = 0 ~ 6 V. The results indicate that both the threshold voltage and leakage current exhibit no significant variation at elevated temperatures, demonstrating the temperature insensitivity of the engineered p-GaN layer.

Because the low-temperature growth inherently reduces Mg diffusion into AlGaN and, in this study, a lower doping concentration was intentionally chosen to achieve lower capacitance and better RF characteristics, the device exhibits improved gate control, resulting in a higher and sharper transconductance (gm). Furthermore, at high temperatures, there are no additional defects affecting the threshold voltage and leakage current, ensuring a highly stable E-mode RF device. Biased at a V_{GS} of 6 V, the p-GaN gate HEMT exhibits a small ON-resistance (R_{ON}) of 1.9 Ω-mm and a low knee voltage of 2 V, which is suitable for low drain voltage (<12 V) applications. Figure 3(b) presents the I_DS-V_DS characteristics. At 400K, the Ron only decreases by 1.38 times, reaching 2.63 Ω·mm, which remains relatively low for RF applications.

Fig. 3(c) and 3(d) illustrate the temperature-dependent small-signal characteristics. From Fig. 3(c), the relationship between f_T/f_{max} and temperature is plotted in Fig. 3(d). At room temperature (300K), the device achieves f_T/f_{max} = 19.3/32.3 GHz, which decreases with increasing temperature at a rate of −0.03/−0.04 GHz/K. This result indicates that the device maintains stable RF performance even at elevated temperatures.

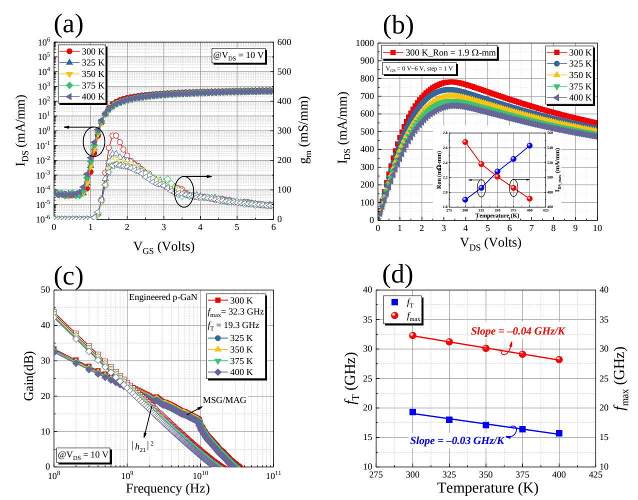


Fig. 3. The variable temperature DC and small signal curves results

A high wafer uniformity of the RF Engineered Mg doping p-GaN gate HEMTs was obtained due to p-GaN/AlGaN MOCVD control and the device uniformity behavior is similar to HBT thus process variation becomes a weak parameter. The V_{TH} was defined as I_{DS} reaches 0.1mA/mm and the V_{TH} is 1.1 V together with a standard deviation of 32 mV. The I_{GS} leakage current also performed a uniform distribution where the I_{GS} standard deviation is 1.5

μA/mm with a central I_{GS} of 11 μA/mm. Fig.4 depicts the proposed device achieving a high reproductivity and high uniformity for high volume production.

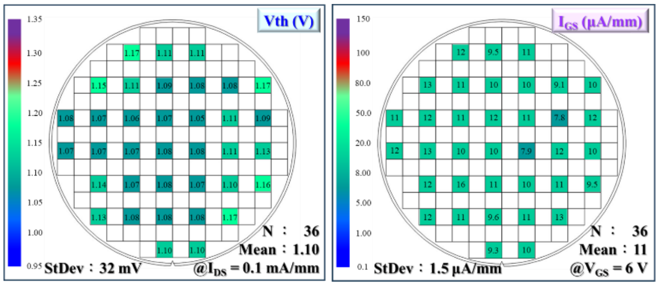


Fig. 4. V_{TH} and I_{GS} statistic result across 150 mm wafer

NF_{min} (Minimum Noise Figure) represents the lowest noise figure that an active device (such as BJT, FET, or HEMT) can achieve under optimal matching conditions, typically expressed in dB. It is an inherent noise performance metric of an amplifier or device, influenced by its internal physical characteristics, frequency, temperature, and fabrication process [7-8]. Fig.5 depicts the E-mode device performed a 1.3 dB NF_{min} together with a 9.83 dB associated gain which indicate its potential to PA and LNA monolithic ICs integration.

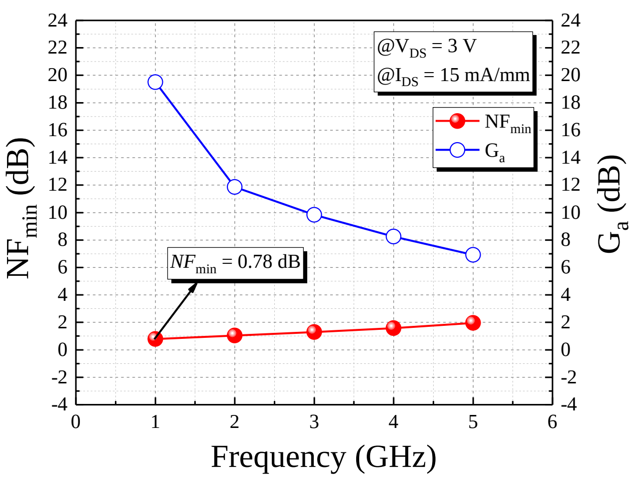
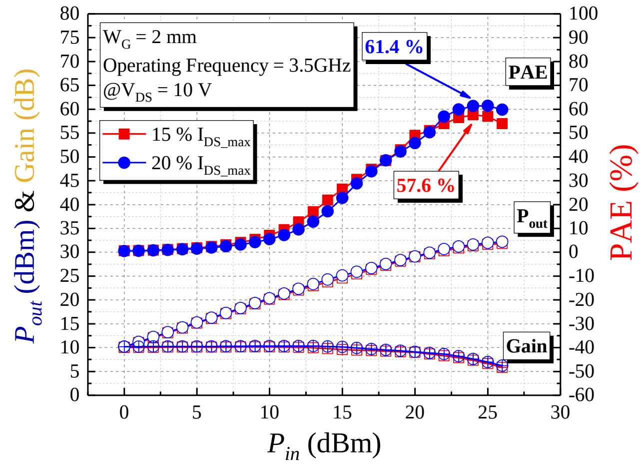


Fig. 5. The noise figure (NF_{min}) measurements at 1–5 GHz of engineered Mg doping p-GaN device.

The microwave power characteristics were evaluated by a load-pull system with automatic tuners, which provides conjugate matched input and harmonic tuned load impedances simultaneously for the maximum PAE. Microwave load-pull power performance was conducted at 3.5 GHz under a drain bias of 10 V. The gate bias was chosen at a class AB operation with an output current of 100 mA/mm for each device, which is compromised by considering PAE comparisons under identical dc power consumption (P_{DC}). Fig. 5 shows the output power and PAE as a function of the input power (P_{in}) for 2 mm gate-dimension devices. The proposed design device exhibited a saturated P_{out} of 32.19 dBm (0.82 W/mm), and a PAE of 61.4 %.



@V_{DS} = 10 V			
I_{DS_max} (mA/mm)		15 %	20 %
Pout	(dBm)	31.82	32.19
	(W/mm)	0.76	0.82
PAE (%)		57.66	61.4

Fig. 6. The load-pull power measured results

Conclusions

The engineered Mg doping profile was design to perform high g_m gate and small gate capacitance for RF PA and LNA application. In addition, the p-GaN Γ-gate RF HEMT can also achieve high breakdown voltage and low feedback capacitance. The V_{TH} and I_{GS} statistic reproductivity and uniformity through 6-inch wafer are also demonstrated. 61.4 % PAE close to 1W/mm @ $10V_{DS}$ operation of proposed device showed its highly potential for next generation direct-to-cell or FR3 smart phone RFFE PA+LNA applications.

Acknowledgements

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Acronyms

HEMT: High Electron Mobility Transistor
2DEG: Two dimensional electron gas
SIMS: Secondary Ion Mass Spectrometer