GaN/AlN HEMTs MMICs for Applications Above 100 GHz

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***Abstract*—This report summarizes the latest progress of awardee's Ph.D. project in part supported by the 2021 IEEE MTT-S Graduate Fellowship Program. In this project, we have replaced conventional AlGaN/GaN HEMTs with AlN/GaN/AlN HEMTs. The wide bandgap of AlN improves carrier density and breakdown voltage; the higher thermal conductivity of AlN improves reliability. The n-type HEMTs show > 200 GHz cutoff frequencies, and >2 W/mm power density at 94 GHz. An empirical large signal model is developed to validate the measured data. Besides, p-type GaN/AlN HEMTs on AlN substrates show f_{max} of 45 GHz and 0.6 W/mm power density. Those values are the record of p-type GaN HEMTs reported.**

***Index Terms*—MMICs, HEMTs, Millimeter wave circuits.**

I. Introduction

Conventional GaN HEMTs based on a heterojunction of a thin $Al_xGa_{1-x}N$ barrier and a thick GaN buffer have an output power of 3 W/mm at 96 GHz. To further improve the performance, it is desirable to maximize the Al mole fraction x for greater discontinuity in the conduction band and higher density of the two-dimensional electro gas (2DEG). However, x is typically limited to 25% to avoid overstraining $Al_xGa_{1-x}N$ and nucleating dislocations. Recently, we have done the opposite by sandwiching a thin GaN channel between thick AlN barrier and buffer layers (Fig. 1) [1]. In this case, instead of being strained, the AlN is fully relaxed and lattice-matched to the SiC substrate. The GaN/AlN back junction can be designed to contain a two-dimensional *hole* gas, which can form the channel of a *p*-type HEMT for push-pull power amplifiers [2]. The relatively thick AlN back barrier can also serve as the piezoelectric layer for monolithic integration of acoustic filters with the AlN/GaN/AlN HEMTs. This takes advantage of superior electromechanical properties of epitaxial AlN to that of sputtered AlN commonly used for acoustic filters.

II. Major Outcomes

A. High-power AlN/GaN/AlN HEMTs for 140 and 220 GHz

The AlN/GaN/AlN epitaxial structures are grown by plasma-assisted molecular beam epitaxy on semi-insulating 6H SiC substrates. In the past year, we demonstrated an on current of 2.6 A/mm with excellent saturation for a gate length as short as

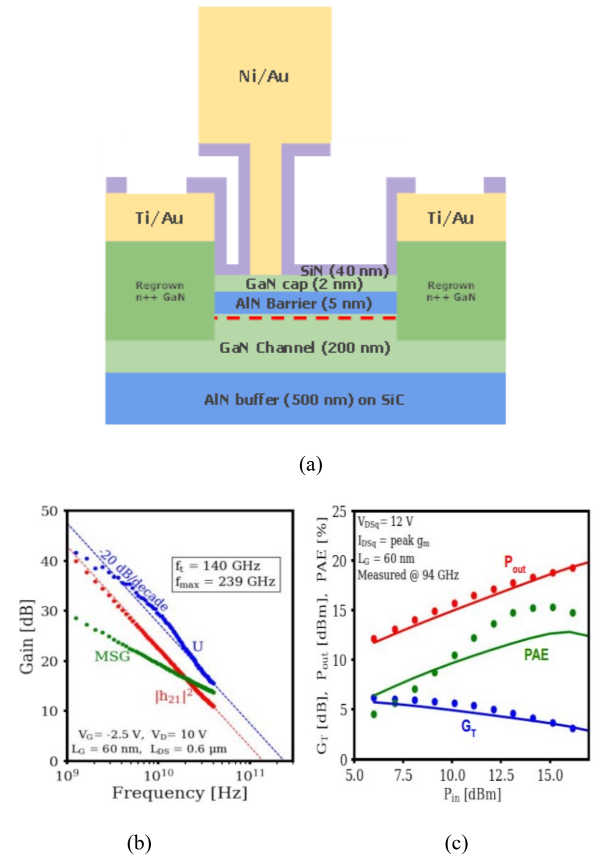

Fig. 1. (a) Cross-section schematics, (b) cutoff frequencies, and (c) measured and modeled large-signal performance at 94 GHz.

40 nm [1]. A low-power silicon-nitride passivation was developed to minimize DC-RF dispersion. Record small-signal characteristics were measured, with the forward current cutoff frequency f_t = 140 GHz and the maximum frequency of oscillation f_{max} = 239 GHz. The load-pull results (calss-AB) show 2.2 W/mm output power with an associated PAE of 15%, as shown in Fig. 1(c). Based on the large signal model, the output power is limited mainly by the DC-RF dispersion. Further improvement is possible by optimizing the SiN passivation process.

B. Low-cost AlN/GaN/AlN HEMTs on Si Substrates

This task is to investigate and demonstrate AlN/GaN/AlN

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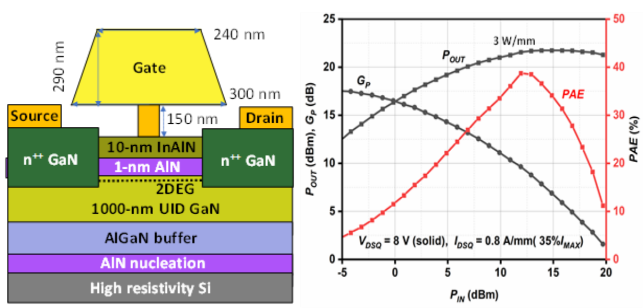
HEMT grown on a large Si wafer, allowing integration of GaN with CMOS VLSI circuits. By replacing the SiC substrate with the Si substrate, the output power is derated to 1.5 W/mm at 140 GHz and 1 W/mm at 220 GHz. We first started with the growth of the better established InAlN/GaN epitaxial structure by metal-organic chemical vapor deposition on 200-mm-diameter high-resistivity (3000 Ω·cm) Si substrates (Fig. 2). Despite the large substrate, the grown layers are very uniform with a surface roughness of 0.7 nm and a sheet resistance of ±1.5%. The average sheet resistance of 206.4 Ω/□ is consistent with that measured by the Hall effect, which also shows that the 2DEG has a density of 2.3×10^{13} cm^{-2} and a mobility of 1400 $cm^2/V\cdot s$ [3]. By using a T-gate and regrown n^{++}-GaN source/drain contacts, the InAlN/GaN HEMT on Si with a gate length of 55 nm and a source-drain spacing of 175 nm shows a maximum drain current of 2.8 A/mm and a peak transconductance of 0.66 S/mm. The same HEMT exhibits $f_T = 250$ and $f_{MAX} = 200$ GHz and an output power of 3 W/mm at 10 GHz [4]. These are among the best reported for GaN HEMTs on Si. Similar approaches are being used to demonstrate AlN/GaN/AlN HEMTs on 200-mm-diameter high-resistivity Si substrates. Given the low cost of Si and the high compatibility with CMOS circuits, GaN HEMTs on Si prove to be particularly attractive for cost-sensitive applications that can accept some trade-off in performance.

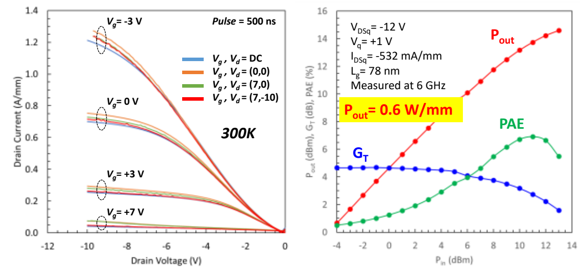


(a) (b)

Fig. 2. (a) Cross-section schematics and (b) power-sweep characteristics of an InAlN/GaN HEMT on a Si substrate.

C. Record Performance of GaN p-HEMTs on AlN Substrates

A strong need exists for a wide-bandgap p-type transistor counterpart of the n-channel GaN HEMTs for power electronics and novel RF circuits [2]. In 2020, we demonstrated the world-first *p-type* GaN HEMT on sapphire substrates that has 20 GHz cutoff frequencies and >400 mA/mm on-current. In the past year, by replacing the sapphire substrates with AlN susbtrates, we are able to demonstrate the state-of-the-art *p-type* GaN HEMTs with 1.2 A/mm on-current and f_{max} of 45 GHz at room temperature (Fig. 3). Furthermore, the load-pull measurement shows these devices have 0.6 W/mm output power at 6 GHz [6]. In addition, the pulsed I-V results show that the p-type GaN/AlN HEMTs are low in dispersion. All these results are the best reported and demonstrate the unique enabling role of the polarization discontinuity at the GaN/AlN semiconductor heterojunction and offer significant hope for a new high-speed and high-voltage wide-bandgap CMOS device platform.



(a) (b)

Fig. 3. (a) Pulsed I-V and (b) power-sweep characteristics of a p-type GaN/AlN HEMT on an AlN free-standing substrate.

III. Future Work

To push the f_T and f_{MAX} above 500 GHz, we are working on optimizing the SiN passivation process for the AlN/GaN/AlN HEMTs. Furthermore, contact resistance plays a significant role when the HEMTs' gate length becomes shorter, so further reduction of the contact would be necessary for high frequency HEMTs.

IV. Career Plans and Impact Statement

A. Career plans

I would like to continue my research on high power and high frequency III-V MMICs and certainly value any position that allow me to explore them at device, circuit, and system levels.

B. Impact statement

The recognition of the IEEE MTT-S Graduate Fellowship Award has strengthened my confidence greatly to pursue a career in academia or industry. Moreover, the financial support of this fellowship allows me more opportunities to travel to other universities for device measurement, and most importantly, meeting and learning from the experts in this field.

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