Development of High-Efficiency GaN-HEMT Amplifier for Mobile WiMAX

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Base stations for Mobile Worldwide Interoperability for Microwave Access (WiMAX) will require much higher power efficiency to dramatically reduce the increase in power consumption. High-efficiency amplifiers with high gain will be required to decrease the power consumption of the base stations. Gallium nitride high electron mobility transistors (GaN-HEMTs) have been attracting a lot of attention as high power amplifiers because of their high breakdown voltage characteristics. This paper describes the development of a highly efficient GaN-HEMT for the high-efficiency amplifiers. First, gate length and unit gate width were designed to improve gain performance. The key feature for improving efficiency was found to be the electrical trap characteristics. Drain efficiency of 50% with adjacent channel leakage ratio of less than −50 dBc was obtained with Mobile WiMAX signals, resulting in a small base station.

1. Introduction

The transmission speeds of next-generation wireless mobile networks, including Mobile Worldwide Interoperability for Microwave Access (WiMAX) and long term evolution (LTE) networks will be several tens of megabits per second. Higher speeds will require increased output power, leading to increased power consumption by transmission amplifiers, so base stations will require significantly higher power and more physical space. Therefore, there is a need to develop compact base stations that offer easy implementation and low operation costs.

To make possible a small base station with lower power consumption, high-efficiency power amplifiers are currently being developed using gallium nitride high electron mobility transistors (GaN-HEMTs). The GaN-HEMT has a higher breakdown voltage with higher cutoff frequency than devices based on other materials such as a silicon laterally diffused metal oxide semiconductor (Si-LDMOS) transistor and gallium arsenide field effect transistor (GaAs-FET), as shown in **Figure 1**. It is obvious that the advantage of the GaN-HEMT is high efficiency due to high operation voltage and high impedance with a small chip die size, as shown in **Table 1**. We have already made 250-W GaN-HEMT push-pull amplifiers with high efficiency for wideband code division multiple access (W-CDMA) signals.[1] However, higher gain and efficiency are currently required in Mobile WiMAX and LTE. High gain is required to reduce the size of the power amplifier. Gain is affected by the gate dimensions. We have developed high-gain GaN-HEMT technology by optimizing both the gate length and gate width.

We have also developed high-efficiency GaN-HEMT technology by suppressing the effect of traps. Their effects were observed during power measurements. The quiescent drain current (Idsq) was monitored just after power measurement. We found that Idsq was lower after power measurement. We treat this phenomenon as Idsq drift in this paper.

Distortion characteristics such as the memory effect were also studied to improve the digital predistortion (DPD) correction with high efficiency.[2] For DPD correction, the memory effect should be made small. We found that improving the Idsq drift improved the memory effect.

Based on these new GaN-HEMT technologies, we were able to successfully demonstrate a small radio-frequency (RF) unit that included power amplifiers, a DPD system, and a power supply.

2. Experimental

Our GaN-HEMT transistors have an n-GaN/n-AlGaN/GaN structure grown by metal organic vapor phase epitaxy (MOVPE), which we call the surface-charge-controlled structure, as shown in **Figure 2**.[3] Recessed ohmic technology was used to reduce the ohmic contact resistance. The gate length was reduced from 0.8 to 0.5 µm to improve the power gain. Silicon nitride (SiN) passivation was applied. Photoluminescence (PL) measurements of yellow luminescence were used to evaluate the deep traps in the GaN buffer layer. Buffer growth and SiN passivation were optimized to obtain device structures with lower trap densities. No significant current collapse was observed. Idsq drift was estimated from power measurements and the Idsq transient was monitored just after the power measurements.

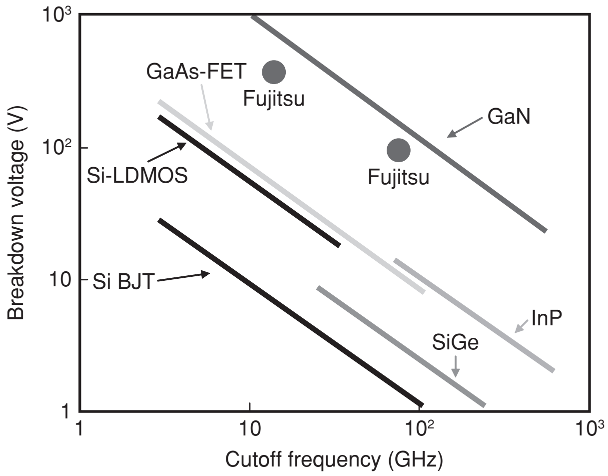


Figure 1
Johnson's figure of merit.

3. Developed GaN-HEMT

3.1 Gain improvement

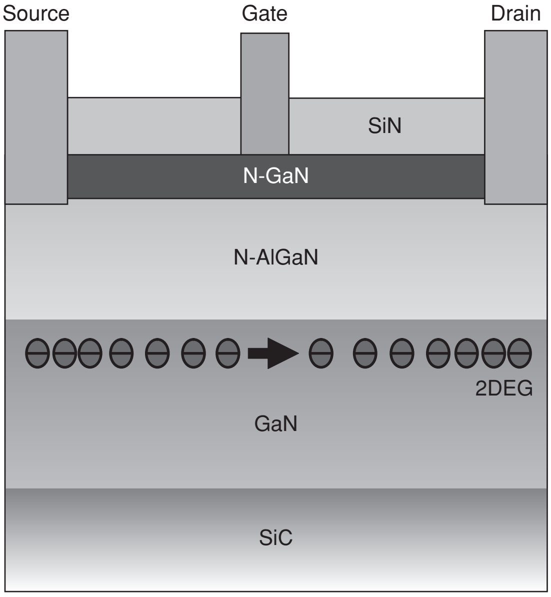
The power gain as a function of input power back-off is shown in **Figure 3**. The input power back-off was defined as the difference in input power from the saturated input power. The gate length and unit gate width were varied. The gate length was 0.8 µm (conventional) or 0.5 µm (improved). The gate width was either the conventional width (100%) or reduced width (75%). 100-W-order packaged devices were measured with an internal matching circuit. The conventional GaN-HEMT showed a gain of only 14–15 dB at an input power back-off of 20 dB. Compared with conventional devices, GaN-HEMTs with (a) the conventional gate length of 0.8 µm and reduced unit gate width

Table 1
Key features of GaN-HEMT.

Material features	Merits for power FET	Merits for power amplifier
• High breakdown voltage	• High voltage operation • High load impedance • Better linearity	• High efficiency • Low loss matching circuit • Better DC/DC converter efficiency
• Wide band gap	• High temperature operation	• Small & light cooling system
• High thermal conductivity • High current density	• High power density • Small periphery and small chip size	• Small and light SSPA

SSPA: Solid-state power amplifier

of 75% GaN-HEMT or (b) only the reduced gate length with the conventional unit gate width showed gains of around 16 dB at 20-dB input power back-off. (c) The shorter gate length with reduced unit gate width showed an additional 2–2.5 dB improvement, resulting in 18-dB gain at 20-dB input power back-off. Thus, we confirmed an improvement of at least 3 dB for 100-W-order packaged GaN-HEMTs. Increasing the gain of the final amplifier will lead to the introduction of a small power driver amplifier, which is also important. No degradation of breakdown voltage or area of safe operation was observed after the gate length was reduced.



2DEG: Two-dimensional electron gas

Figure 2
Recessed-ohmic surface-charge-controlled GaN-HEMT structures used in this study.

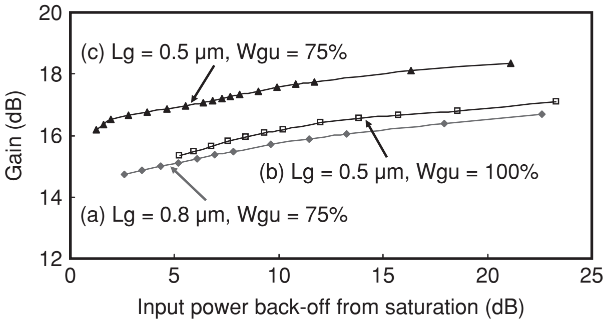


Figure 3
Gain as a function of power back-off. 100-W-order packaged devices were measured with an internal matching circuit. Gate length and unit gate width were varied.

3.2 Efficiency improvement

3.2.1 *Idsq drift phenomena*

The method used to investigate Idsq drift is shown in **Figure 4 (a)** and typical Idsq recovery phenomena, i.e., drift phenomena, are shown in **Figure 4 (b)**. Idsq recovery rates are shown as a function of time after power measurements. Idsq decreased from the initial Idsq of the idling stage just after power measurements. It then recovered slowly, taking over 1 min to recover to the original value. Even if these phenomena occur in practice, GaN-HEMT could still provide over 100 W with over 60% drain efficiency at 50 V. These values are higher than any ever observed for GaAs-FETs. In addition, Idsq drift phenomena were different from saturation current (Idss) drift, which has been reported for Si-LDMOS.[4] Current collapse, such as on-resistance (Ron) change, is a microsecond-order phenomenon and usually observed in pulsed current-voltage (I-V) measurements from the pinched-off bias point.[1,3,5] This Idsq drift is quite different from the current collapse. Idsq drift causes a larger memory effect and lower efficiency with instability.

When initial Idsq increased, the Idsq recovery time became drastically shortened from over 1 min to less than 30 s. Thus, when GaN-HEMTs were used in the deep class AB operating regime, these Idsq drift phenomena became obvious.

Idsq drift was also affected at ambient temperature. A higher ambient temperature resulted in a shorter recovery time, reduced from over 1 min to less than 30 s, suggesting that the Idsq drift was caused by deep traps.

3.2.2 *Mechanism of Idsq drift*

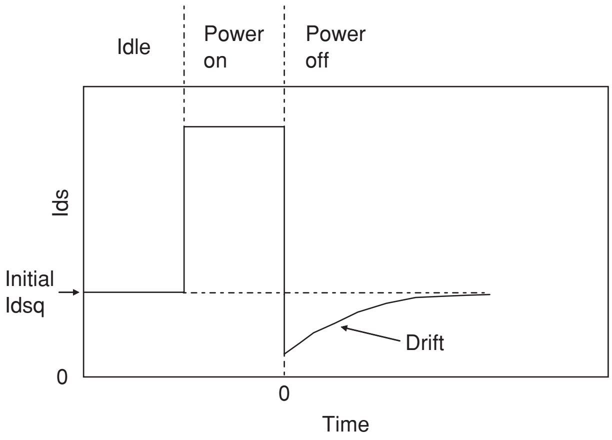
To investigate the origin of this trap, we investigated the drain lag effect, which we measured as follows.

1) Drain current (Ids) was set to the same value of Idsq for power measurements such as 2% maximum current (Imax). Thermal issues can be ignored because Ids was too small.
2) Then only drain voltage (Vds) was changed from 50 V to 30 V. Gate voltage (Vgs) was not changed during these measurements.
3) The change in Ids was monitored after Vds was changed.

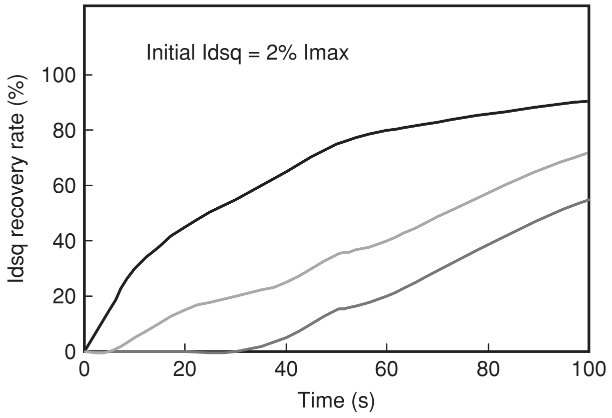
Ids dropped when Vds was decreased rapidly from 50 V. Then Ids recovered for several minutes. This phenomenon was similar to the Idsq drift after power measurements. Thus, we attribute the Idsq drift to the effect of drain lag when Ids was small compared with Imax.

We also evaluated the GaN channel quality by PL measurement, which can detect deep traps in the GaN channel layer. An ultraviolet laser was used to evaluate the PL characteristics of GaN, concentrating on yellow luminescence around 540 nm from the GaN channel layer to investigate the effect of drain lag.

As shown in graph (a) of **Figure 5**, strong yellow luminescence was observed, suggesting that the origin of the drain lag effect was located in the GaN buffer. The origin of the yellow luminescence was considered to be Ga vacancies and carbon impurities, which might cause deep electron traps.[6] We improved the yellow luminescence of the GaN channel layer by changing the MOVPE growth conditions, as shown in graph (b) of Figure 5. The Idsq drift of the GaN-HEMT for



(a) Method of investigating Idsq drift



(b) Conventional Idsq transient phenomena

Figure 4
Saturation power was applied at 50 V. After the power was turned off, Idsq was decreased from the initial value. Then Idsq recovered slowly to the initial value (a). Initial Idsq was set to 2% of the maximum current (Imax). Deep class-AB was used in this study for base station applications. Three lines show the data variation of the typical device structures (b).

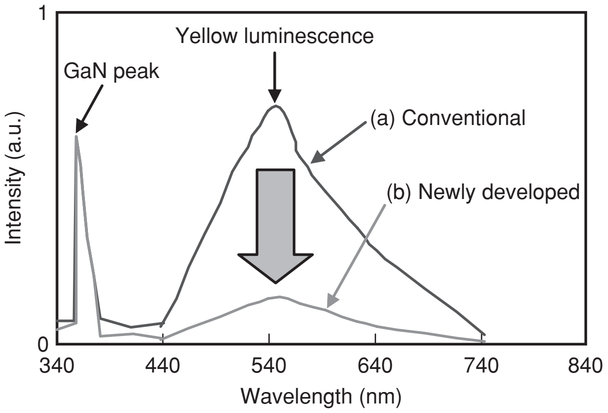


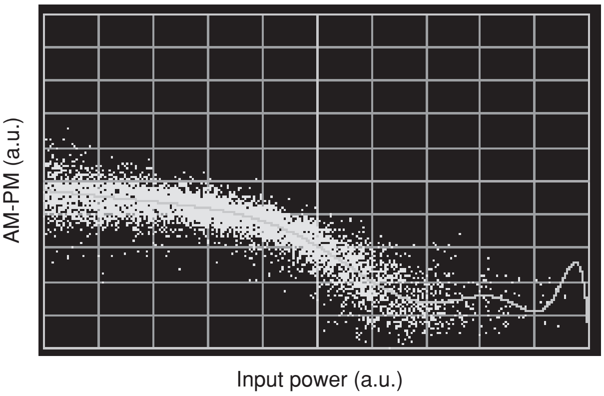
Figure 5
Photoluminescence of GaN-HEMT epilayers. Yellow luminescence in the range around 500–600 nm was improved by optimizing the growth conditions. (a) Conventional layer conditions and (b) improved layer conditions.

the improved yellow luminescence is shown in **Figure 6**. The Idsq recovery time was improved, indicating that the origin of the low yellow luminescence affected the Idsq drift.

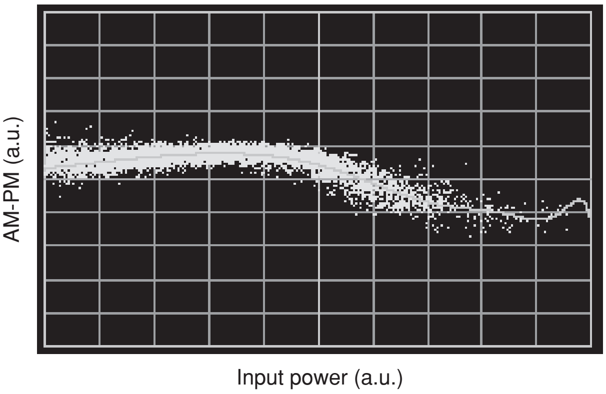
3.2.3 Power amplifier characteristics

The influence of Idsq drift on amplitude-modulation and phase-modulation (AM-PM) memory effects is a most important characteristic for DPD power amplifiers.[7)] We used a Mobile WiMAX signal (64 quadrature amplitude modulation: 64 QAM) at 2.5 GHz and a signal bandwidth of 20 MHz. The AM-PM characteristics of a conventional GaN-HEMT with a large Idsq drift are shown in **Figure 7 (a)**. Scattered AM-PM characteristics were observed, suggesting a large memory effect. The AM-PM characteristics of our improved GaN-HEMT are shown in **Figure 7 (b)**. The improved-drift devices exhibited a smaller memory effect. This indicates that Idsq drift is influenced by the memory effect in the power amplifier.

The drain efficiency as a function of output power back-off for a Mobile WiMAX signal (16QAM) at 2.5 GHz is shown in **Figure 8**. Improved-drift devices showed higher back-off efficiency. The drain lag effect might cause difficulties for high efficiency matching. Our developed GaN-HEMT power amplifier with DPD



(a) Conventional



(b) Newly developed

Figure 7
AM-PM measurements of GaN-HEMT for 20 MHz 2.5 GHz WiMAX signals. Memory effect became smaller by improving Idsq drift.

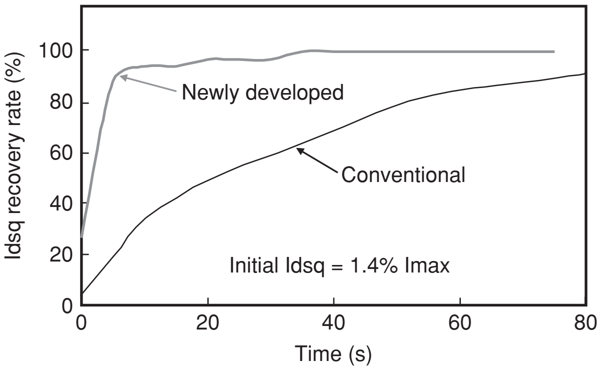


Figure 6
Results for GaN-HEMT compared with a conventional device. A shorter recovery time was achieved by focusing on improving the yellow luminescence.

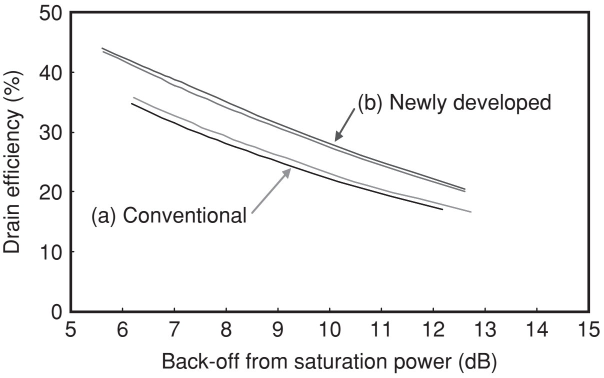


Figure 8
Effect of efficiency of back-off region. Improved Idsq drift resulted in higher efficiency for WiMAX signal. Two samples were measured.

for Mobile WiMAX signals (20-MHz 16QAM) is shown in **Figure 9**. A record average drain efficiency of over 50% and linear gain of 17.2 dB were obtained at 45 dBm, satisfying the full specifications of Mobile WiMAX.

4. Conclusion

In conclusion, we have developed high-gain and high-efficiency technology for power amplifiers. A gain improvement of 3 dB was achieved by optimizing the design of the gate length and unit gate width. We found Idsq drift phenomena just after the power measurements. This was a slow transient compared with current collapse. By focusing on yellow luminescence in PL measurements, we improved the GaN channel layer quality, resulting in a short Idsq recovery time. As a result, a power amplifier with small memory effects and high efficiency could be made using GaN-HEMTs. Drain efficiency of 50% with an adjacent channel leakage ratio of less than −50 dBc was obtained with Mobile WiMAX signals. This high efficiency made possible a small RF unit.[8] Fujitsu has successfully achieved a minimized base station in terms of both power consumption and dimensions. In the future, we will develop higher-efficiency technology using this GaN-HEMT for LTE. Cost reduction technology will also be considered.

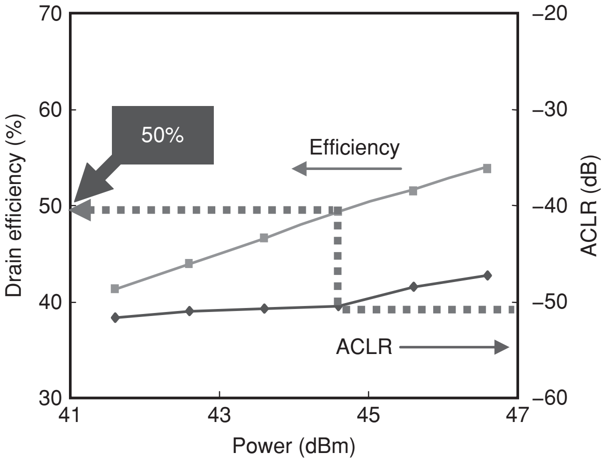


Figure 9
Performance of newly developed GaN-HEMT power amplifier for Mobile WiMAX. Adjacent channel leakage ratio (ACLR) of −50 dB for 20-MHz signal was achieved with a record 50% efficiency.

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