Development of Gallium Nitride High Electron Mobility Transistors for Cellular Base Stations

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High power and high efficiency devices are increasingly required for the 3rd generation and other future base station transmitter systems (BTSs). Gallium nitride (GaN) is ideal for these applications because of its wide band gap and high saturated electron velocity. We have developed the GaN high electron mobility transistor (HEMT) grown on the silicon carbide (SiC) substrate and released the world's first commercial GaN HEMT products. We have also studied efficiency enhancement of the modern BTS amplifiers using Doherty and Class-E circuits. This paper summarizes the GaN HEMT development for the BTS amplifier applications and the efficiency enhancement techniques.

Keywords: GaN, HEMT, wireless, cellular, amplifier, efficiency, WiMAX, LTE

1. Introduction

Gallium Nitride (GaN) is suitable for high power and high frequency applications because of its wide band gap property and high saturated electron velocity.

We have developed the GaN high electron mobility transistor (HEMT) on the silicon carbide (SiC) substrate targeting the frequency range of L/S band mainly for the amplifier used in base station transmitter systems (BTSs). Especially in the 3rd generation or more recent BTSs, the quest for higher data rate systems has been continued. At present, IEEE802.16e (WiMAX) and Long Term Evolution (LTE), known as the 3.9th generation technology, are in preparation for the deployment.

Until now, silicon laterally diffused metal oxide semiconductor (Si-LDMOS) was the dominant technology for the BTS application owing to its sufficient performance with the reasonable price.

However, the GaN HEMT realizes about 10 points higher saturated drain efficiency and wider frequency response by reflecting its material property. In addition, the excellent thermal conductance with the high drain efficiency enables much compact amplifier systems with simple thermal design. We have focused on these abilities of GaN HEMTs, and successfully developed the world's first commercial GaN HEMT products. Until now, more than five hundred thousand pieces of the GaN HEMT products have been shipped, and the demand is continuously expanding.

This paper summarizes our high power and high efficiency GaN HEMT development for the BTS amplifier applications.

2. Transistor Technology

2-1 Material property

Table 1 shows the key material parameters of the major materials used in high frequency applications. GaN exhibits two times higher saturated electron velocity and eight times larger critical breakdown field than GaAs. Actually, the GaN HEMT realizes about ten times larger power density than the GaAs field effect transistor (FET) by reflecting its material superiority.

Table 1. Material parameters comparison

Material	Bang Gap Energy (eV)	Critical Breakdown Field (MV/cm)	Thermal Conductance (W/cm·K)	Mobility ($cm^2/V{\cdot}s$)	Saturated Velocity (10^7 cm/s)
Si	1.1	0.3	1.5	1300	1
GaAs	1.4	0.4	0.5	6000	1.3
SiC	3.2	3	4.9	600	2
GaN	3.4	3	1.5	1500	2.7

Johnson's figure of merit (JFOM) is commonly used in the benchmark of the high frequency and high power devices.

JFOM is expressed as $v_s \cdot E_b/2\pi$, where v_s means the electron saturated velocity and E_b means the critical breakdown field. GaN is 27 times higher than Si in the view of JFOM, while GaAs is only 1.7 times higher.

GaN crystal forms Wurtzite structure and has no inversion symmetry to the c-axis direction, which causes spontaneous polarization. In addition, the crystal distortion at the AlGaN/GaN interface causes piezo polarization. By utilizing those two types of polarizations, GaN HEMT structure generates extremely high density of two dimensional electron gas (2DEG). In the case that the Al content is 30%, the 2DEG density is the order of 10^{13} cm^{-2} at the AlGaN/GaN interface.

The epitaxial layers of the GaN HEMT are commonly grown on the different material substrate, for example, on SiC, by metal organic chemical vapor deposition (MOCVD). This combination of GaN on SiC substrate, which exhibits excellent thermal conductance, is ideal in the view of the thermal management of high power devices.

2-2 1st generation technology

In the early development stage, the biggest challenge was the overcome of the transient phenomenon so-called current collapse, which means the transient drain current reduction right after high voltage is biased to the drain electrode.

The current collapse is quantified by the pulse-operated maximum forward drain current. The mechanism of this phenomenon is understood as follows: The hot electrons are generated under the high electric field and captured by surface traps. The trapped electrons form thick depletion region, even in the forward gate bias condition. Since the captured electrons cannot be released as fast as the gate signal swing, the drain current is reduced by the depletion region. **Figure 1** is the schematic image showing the mechanism of the current collapse. We have found that the key items to suppress the current collapse are the reduction of the surface trap density and the electric field relaxation between the gate and the drain electrode. The various trials in the epitaxial layers, the wafer process and the chip structure design have been performed as shown in **Table 2** and successfully reduced this undesirable phenomenon.

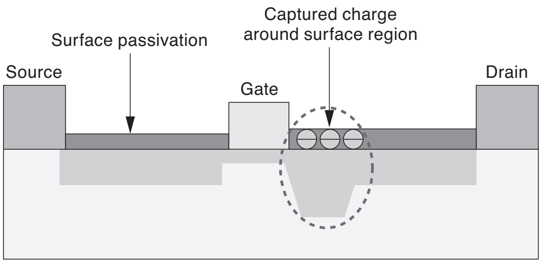

Fig. 1. Schematic image of current collapse

Table 2. Measures for current collapse improvement

Measures	Device parameters
Surface trap density reduction	Surface passivation, Surface treatment, Epitaxial structure
Electric field relaxation	Epitaxial structure, Electrode geometry

Figure 2 shows the distinct improvement of the pulsed I-V profile through the overall optimization. The left hand graph corresponds to the I-V curve with the previous chip, and the right hand corresponds to the I-V curve with the optimized chip.

The overcome of the current collapse brings the excellent output power density and the drain efficiency. **Figure 3** shows the output power and the drain efficiency profiles of the 100 W class device at the frequency of 2.14 GHz with the drain voltage (V_{ds}) of 50 V.

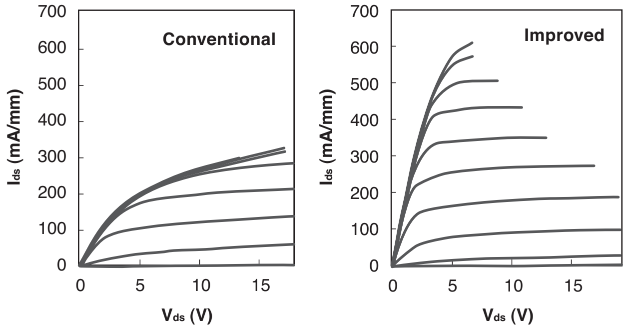

Fig. 2. Pulsed I-V profile of conventional and improved chip

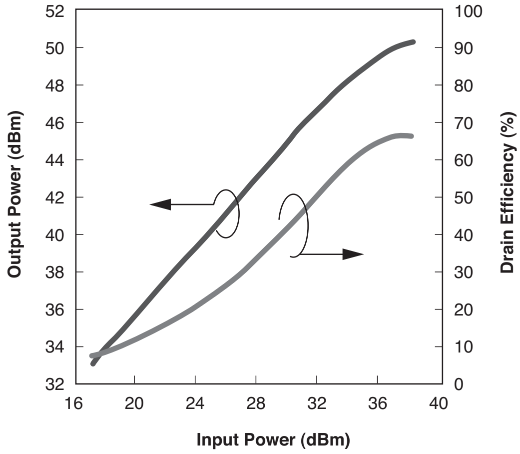

Fig. 3. P_{in}-P_{out} profile of 100 W class GaN HEMT

The structure optimization was also performed in view of the commercial level reliability. Through the investigation, it turned out that the reduction of the gate leakage current was critical for the reliability. We have successfully reduced the leakage current by optimization of the epitaxial layer design and the gate length.

2-3 2nd generation technology

The efficiency enhancement technique has been studied intensively in the modern BTS amplifier developments. Doherty amplifier is an attractive circuit technique and the circuit detail will be discussed in the chapter 3. In terms of the device technology, the device optimization for the Doherty operation is strongly required. Doherty amplifier requires the higher saturated drain efficiency to the chip. Thus, we have set the target of the 2nd generation GaN HEMT technology development on realizing high drain efficiency at saturated power operation, which is suitable for the Doherty operation.

Figure 4 shows the schematic of the intrinsic equivalent circuit of a GaN HEMT. It contains three energy dissipation paths indicated by a,b,c in **Fig. 4**. The reduction of the source resistance (R_s), the drain conductance (g_d) and the source to drain capacitance (C_{ds}) were effective to improve the efficiency.

The linearity performance is another critical issue for BTS applications. We found the gate length (L_g) reduction is effective to improve the linearity. In addition, the shorter L_g makes the gain performance better. Therefore, the L_g of the 2nd generation technology was reduced to 0.6 μm from 0.9 μm which is used in 1st generation. The epitaxial structure and the electrode geometry were also optimized.

The qualification of the 2nd generation technology was completed in 2009, and the 2nd generation GaN HEMT products are now widely used in the Doherty amplifier applications.

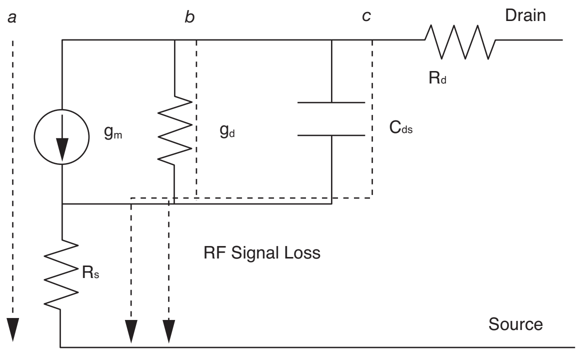

Fig. 4. Power dissipation path of GaN HEMT

2-4 Technology trend of base station amplifier

Figure 5 shows our prospect of the mobile communication system technology and required drain efficiency for the devices. Recent BTSs, especially WiMAX and LTE, require higher efficiency and smaller unit size for its amplifier. We believe GaN HEMTs become the mainstream, in accordance with the recognition of the intrinsic advantages of their high efficiency.

Needless to say, the combination of the chip technology and the circuit configuration is essential to realize the overall high performance. In the next chapter, various circuit techniques, such as Class-AB amplifier, Doherty amplifier and Class-E amplifier with the GaN HEMT technology, will be discussed.

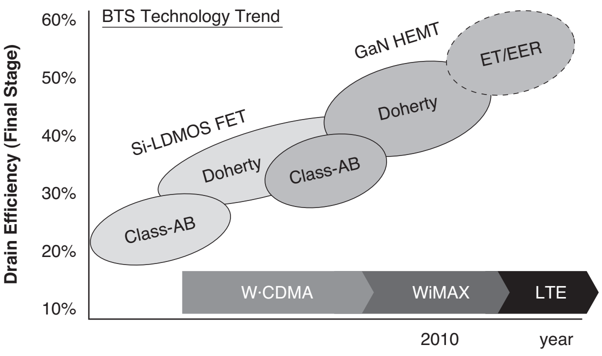

Fig. 5. BTS technology trend and required drain efficiency

3. Circuit Technology

3-1 Class-AB amplifier

Firstly we describe the development of Class-AB amplifier which is assumed to be the main operation mode of our 1st generation GaN HEMTs. Class-A operation means the operation with the gate bias which is set to adjust the drain current to the half of its maximum forward drain current. Ideally, it realizes the sinusoidal drain current and voltage waveforms. On the other hand, Class-B operation set the quiescent drain current to zero. The drain current waveform is rectified to half-wave. It could be summarized the features of Class-A to the better linearity but lower efficiency, while Class-B to the worse linearity but higher efficiency.

The Class-AB operation is the medium state of Class-A and Class-B. The gate bias is tuned to the optimum value by referring the trade-off of the linearity and the efficiency.

We developed the single-ended 200 W device[(1)]. The target impedance was set to the efficiency maximum point at 8 dB backed off power with the Class-AB operation. **Figure 6** shows the matching circuit of the developed device. The matching circuit was composed of two stages of λ/4 microstrip impedance transformers. The device achieved the high drain efficiency of 34% and the flat frequency response with the 200 MHz bandwidth, as shown in **Fig. 7**. This result proved that GaN HEMTs realize excellent performance for BTS amplifier application at the point in 2005.

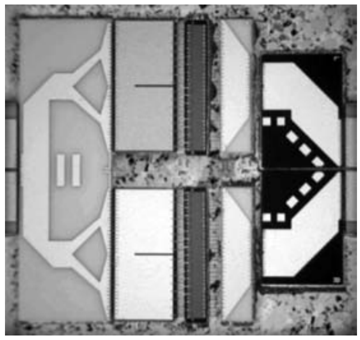

Fig. 6. Top view of 200 W GaN HEMT

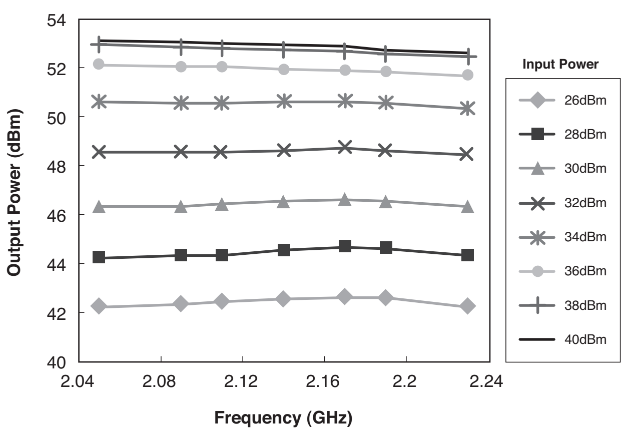

Fig. 7. Frequency response of output power

3-2 Doherty amplifier

Doherty amplifier configuration is an effective technique to boost the efficiency significantly in the backed-off region. As already mentioned, the 2nd generation GaN HEMT technology has been designed to suit for Doherty operation.

Figure 8 shows the schematic of Doherty circuit configuration and the efficiency profile. Doherty amplifier consists of the two amplifiers (main and peak) connected in parallel. The main amplifier is biased to Class-AB, and the peak amplifier is biased to Class-C. In the case that the main and the peak amplifiers have equal output power levels, the first efficiency peak is obtained at 6 dB backed off point from the saturation power. At a more than 6 dB backed off region, only the main amplifier operates and the output power doesn't flow into the peak amplifier, as the output impedance of the peak amplifier at the combining point is nearly open. The output impedance of the main amplifier is set to two times as high as its optimum impedance, thus the output power level at the first efficiency peak point is half of the maximum power. The peak amplifier has neither power output nor power consumption in a more than 6 dB backed off region. As the input power increases beyond 6 dB backed off level, the impedance of the main amplifier shifts lower by acting as an active load, and come close to the optimum point. Finally the optimum impedance for both the main and the peak amplifier are given at saturated output power level.

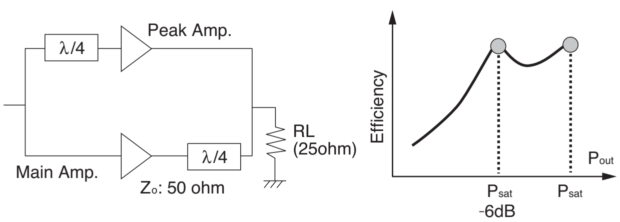

Fig. 8. Schematic of Doherty PA and efficiency profile

In general, a power amplifier for the BTS in modern communication systems operates satisfactorily below the saturated power level in order to maintain the adequate linearity level to meet the system requirement, and the typical backed off level is from 5 dB to 8 dB. However, the efficiency is not good at the backed off operation in the conventional amplifier. Doherty amplifier, which realizes the maximum efficiency at a 6 dB backed off point, has great advantage for the modern BTS amplifier.

We have developed an 80 W Doherty amplifier for W-CDMA with the 1st generation GaN HEMT technology as reported in 2007. The amplifier achieved the efficiency of 42% with V_{ds} of 50 V at the operation frequency of 2.57 GHz[2].

This result proved the excellent performance of combination of GaN HEMTs and Doherty configurations. Furthermore, our recent 2nd generation GaN HEMT technology and the circuit optimization achieved the drain efficiency of 55% with V_{ds} of 50 V at 2.57 GHz as shown in **Fig. 9**[3]. The development realizes the drastic reduction of power consumption of BTS amplifiers and contributes to reduction of the environment load.

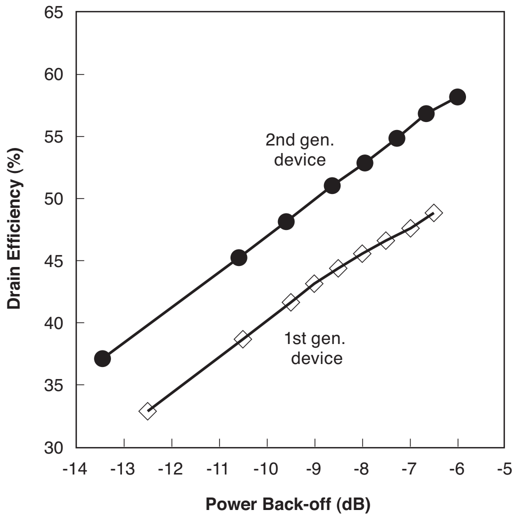

Fig. 9. Drain efficiency comparison of Doherty PAs with 1st gen. and 2nd gen. tech

3-3 Class E amplifier

In this section, the study of Class-E amplifier is explained. This is one of the most outstanding examples in our studies on efficiency boosting technique with the GaN HEMT. Class-E amplifier is a kind of switching amplifier[4] and its upper limit of the operation frequency is restricted by source-drain capacitance (C_{ds}). The GaN HEMT features high power density and the normalized C_{ds} by output power density is about one eighth of that of LDMOS device. While the Class-E amplifier studies with LDMOS devices have been limited in UHF band because of theirs frequency limitation due to large C_{ds}, GaN HEMT enables the Class-E amplifier which operates at as high as 2GHz range. **Figure 10** shows the circuit diagram of the Class-E amplifier. The simulation result of current and voltage waveforms of the Class-E amplifier is shown in **Fig. 11**.

Basically, the Class-E amplifier consists of three components; a switch, a parasitic capacitor, and an LCR oscillator. In the actual Class-E amplifier, the switch is replaced by the transistor. The gate signal switches the source-to-drain current and the fundamental frequency controls this switching cycle. Namely, the oscillation frequency of this LCR oscillator is equal to the fundamental frequency. The current flows into transistor port when the switch is on, while the current flows into the parasitic capacitor when the switch is off. The combined current waveform through the transistor and the capacitor becomes a sinusoidal by the function of the oscillator. In the ideal switch operation, either the current or the voltage is zero in every moment. Thus, electric power is transferred to RF power without any DC power consumption.

This Class-E operation also requires the high breakdown property to the device in addition to low loss and high frequency response. From a simulation result, the instant peak drain voltage is estimated to 2.8 times higher than the DC drain voltage in the case of conduction angle of 110 deg. By reflecting its wide gap material property, our GaN HEMT features high breakdown voltage of more than 250 V, which contributes to the realization of Class-E operation. Our Class-E amplifier achieved the efficiency of 45% at W-CDMA operation point and the saturated efficiency of 82% with V_{ds} of 50 V at 2.1 GHz[5]. **Figure 12** shows the comparison of the P_{in}-P_{out} profile of the developed Class-E amplifier and a conventional Class-AB amplifier. The efficiency improvement by 8 points was confirmed compared to the Class-AB amplifier.

The reliability of both the 1st and the 2nd generation GaN HEMT technologies have been confirmed. The detailed reliability data are available in our web site[6]. **Figure 13** shows the result of the RF step stress test up to 15 dB compression level[5]. Neither catastrophic failure nor significant degradation was observed even in such a severe RF overdrive test. This result suggests our GaN HEMT features sufficient breakdown voltage and reliability for future high efficiency amplifiers.

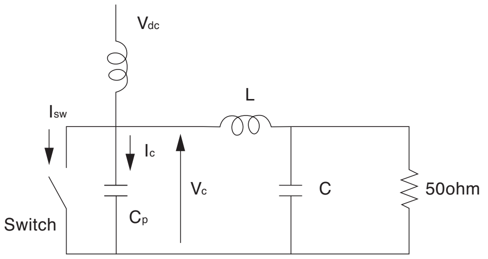

Fig. 10. Low pass type Class-E circuit

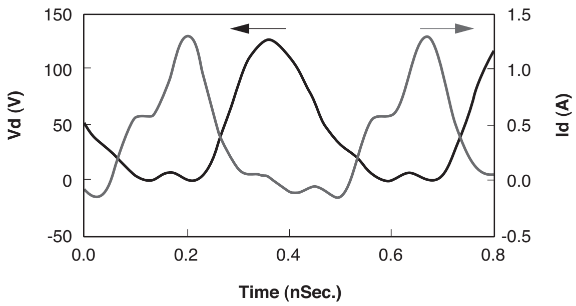

Fig. 11. Simulated waveform of low pass type Class-E amplifier at P_{out} = 10 W, V_{ds} = 50 V, freq. = 2.1 GHz

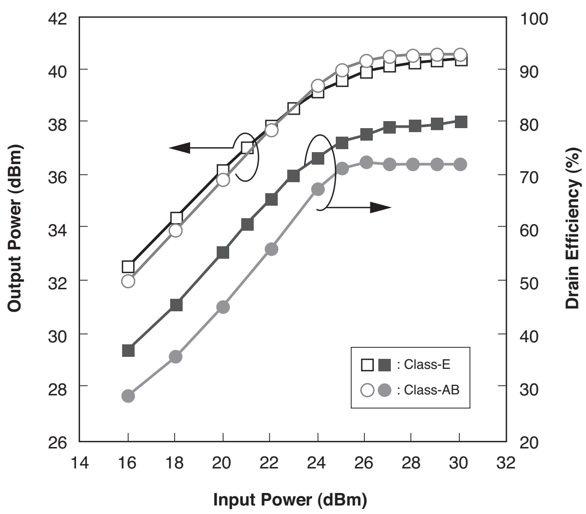

Fig. 12. P_{in}-P_{out} of Class-E amplifier

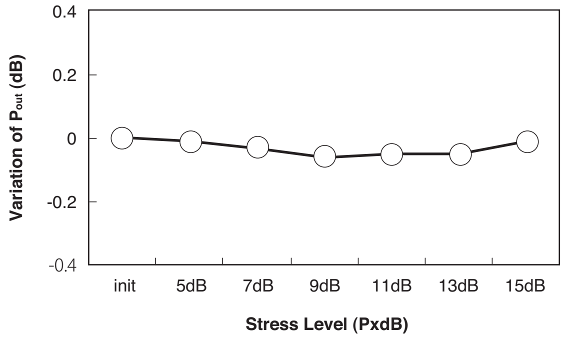

Fig. 13. RF step stress test result

4. GaN HEMT toward the Next Generation Systems

Remote radio head (RRH) is one of the remarkable design trends of the recent BTS. It is a compact outdoor transceiver unit which connects to the base station control unit via optical fiber. GaN HEMTs featured with the small size and high efficiency realize lightweight and compact RRH units, which strongly save the labor and cost in the BTS deployment.

The power consumption of BTSs is another key performance in the recent world which suffers from various environmental issues. The typical power consumption of a conventional BTS amplifier system is about 3 kW, whereas that of the amplifier with GaN HEMTs is about 2 kW. It means that the adoption of GaN devices reduces the electric power consumption by one third. It is quite sure that the effort toward further GaN HEMT chip technology improvement and further sophisticated circuit technologies to realize the better efficiency will go on.

Wireless communication networks are essential in the modern society. The service must be maintained and expanded with the minimum environmental load. For these requirements, we believe the GaN HEMTs adoption to the BTS is one of the most effective solutions. We continue the development and mass production of GaN HEMTs for the latest 3.9th generation systems such as LTE, and the 4th generation systems in the future.

5. Conclusion

We have developed a high power and high efficiency GaN HEMT for BTS applications, which utilizes its superior material properties of high breakdown voltage and high saturation velocity. The 1st generation GaN HEMT has been designed for Class-AB operation, and the 2nd generation GaN HEMT has been optimized for Doherty operation. In line with the trends of the size reduction of BTSs and so-called low-carbon society, GaN HEMTs are penetrating into the market with recognition of their high efficiency. We accelerate the technology and product development for LTE and the 4th generation mobile communication system.

* WiMAX is a trademark or registered trademark of the WiMAX Forum.

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