Wide Band-gap FETs for High Power Amplifiers

Jinwook Burm and Jaekwon Kim

Abstract—**Wide band-gap semiconductor electron devices have made great progresses to produce very high power amplifiers for various wireless standards. The advantages of wide band-gap electronic devices and their progresses are summarized in this paper.**

Index Terms—**GaN, wide band-gap materials, FET, power amplifier**

I. INTRODUCTION

The wireless communication technologies require more efficient wireless components. Among the components for wireless communications, power amplifiers are one of the most important components. Modern wireless standards impose strict requirements for power amplifiers. Power amplifiers have to be linear enough to satisfy communication standards. In addition, power amplifiers should be power-efficient for a minimum heat generation and for a maximum battery life time. To increase the linearity of power amplifiers, many ingenious methods including pre-distortion and feed-forward methods have been developed.

The devices for power amplifiers must satisfy high standards to endure high current and high voltage stress even at an elevated temperature. For the power amplifier applications, wide band-gap semiconductor devices have demonstrated their superiority. The wide band-gap semiconductor is the material with the band-gap energy in the approximate range of 2 eV to 6 eV including nitrides (GaN, AlN, InN, and their compounds) and carbides (SiC). Wide band-gap materials provide a high breakdown voltage for a high power generation and a low dielectric constant for a better isolation and coupling characteristics. Being fabricated on wide band-gap semiconductor materials, both SiC and GaN based transistors have high breakdown voltage and environmental (both physical and chemical) endurance. These days wide band-gap device technologies become very much mature so that the commercial applications are impending. In this paper, basic properties of GaN-based FETs and their applications will be explained.

II. PROPERITES OF GaN BASED MATERIALS

Compared with other semiconductors such as GaAs and Si, GaN based materials have advantages. Table 1 shows that the saturation velocity of electron in GaN is faster than the other materials, about 2 times faster than that in GaAs. The high saturation velocity implies the potential of GaN devices working at high frequency. In addition, about 30 % low dielectric constant of GaN than that of GaAs is beneficial to reduce the internal and parasitic capacitances for high frequency operations.

When GaN based semiconductors are employed for FETs for power amplifiers, AlGaN/GaN heterojunction is utilized. The heterojunction helps to enhance electron mobility and to increase the amount of accumulated charge [1]. The charge accumulated at AlGaN/GaN heterojunction is much greater than those at AlGaAs/GaAs heterojunction. This is because the

Table 1. Comparison of GaN properties with other semiconductors.

	Saturation velocity of electron	Breakdown fields	Dielectric constants
Si	1×10^{17} cm/s	0.3 MV/cm	11.8
GaAs	1×10^{17} cm/s	0.6 MV/cm	12.8
4H-SiC	2×10^{17} cm/s	2 MV/cm	10
GaN	2.2×10^{17} cm/s	3.3 MV/cm	9

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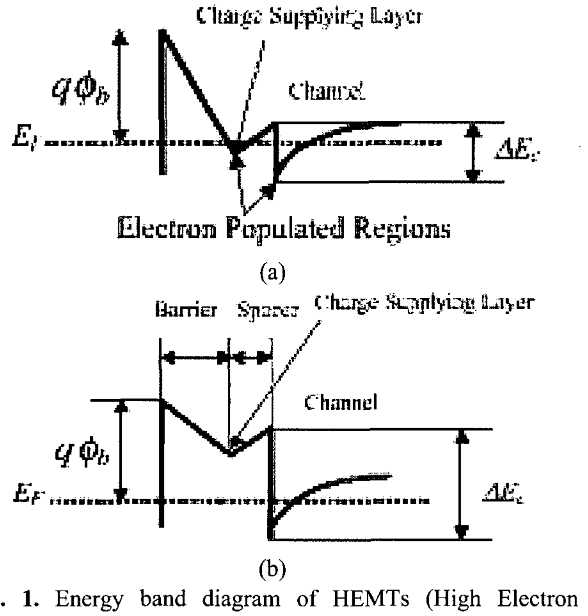
conduction band discontinuity of AlGaN/GaN is higher than that of AlGaAs/GaAs. The higher the conduction band discontinuity is, the more charge accumulates in the channel.

Fig. 1 shows two cases with small and large conduction band-gap discontinuity. In general, at a heterojunction, as the charge density in the channel increases, the minimum energy level in the barrier approaches Fermi level. If the minimum energy level in the barrier approaches Fermi level within ~3kT or less, the barrier starts to accumulate free charges near the minimum energy level at the barrier. The free charge at the barrier can screen the electric field from the gate to the channel making further charge increase in the channel impossible. In addition once the screening of the electric field from the gate to the channel occurs, channel charge modulation is no longer possible. At this point, the charge in the channel (when the barrier starts to accumulate free charges) is the maximum charge. For a devices with a large conduction band discontinuity, the channel energy can be go far below Fermi level without a charge accumulation at the barrier, so that a large amount of charge can be accumulated at the channel. A large E_c can be easily created in GaN/AlGaN heterojunction. The conduction band discontinuity E_c of GaN/$Al_xGa_{1-x}N$ heterojunction is E_c~1.4x eV (75% of the calculated E_c ~1.9x [2] due to strain), which compares with E_c=0.797x eV in GaAs/$Al_xGa_{1-x}As$ heterojunction and E_c=0.8x eV in GaAs/$In_xGa_{1-x}As$ heterojunction. Thus The conduction band discontinuity in $Al_{0.3}Ga_{0.7}N$/GaN system is about 0.4 eV whereas that in $Al_{0.3}Ga_{0.7}As$/GaAs is about 0.2 eV.



(a)

(b)

Fig. 1. Energy band diagram of HEMTs (High Electron Mobility Transistors) with a separate channel formed by a heterojunction (a) large and (b) small conduction band discontinuities at the heterojunction and their effect on the channel charge [1].

GaN is a polar material with both spontaneous polarization and piezoelectric polarization existing inside of the material. The direction of the polarization depends on the direction of the crystal, which normally distinguished by naming N-face or Ga-face material. It is known that the effect of spontaneous polarization is greater than that of piezoelectric polarization. The spontaneous polarization also helps to accumulate additional charges in the channel. From the effect of the large conduction band-gap discontinuity and the spontaneous polarization, GaN-based devices can accumulate substantial charges at the channel [3]. Some GaN based transistors have high drain current more than 1 A/mm from the large charge density [4].

GaN based transistors have high breakdown voltage from the large energy band-gap compared with other semiconductors. The high current and high breakdown voltage makes GaN-based transistors ideal for power device applications. To compare the power devices, Johnson's Figure of merit (JFM) and Keyes' Figure of merit (KFM) are often used. JFM compares the potential of output power levels. KFM considers the heat dissipation capability during high power output at the same time. The formula for JFM and KFM are given as follows [5].

$$JFM=\left(\frac{E_m v_s}{2\pi}\right)^2 \quad \text{and} \quad KFM=K\left(\frac{c v_s}{2\pi\varepsilon}\right)^{1/2}$$

Where E_m is the breakdown electric field, v_s is the saturation velocity of electron, K is thermal conductivity, c is the speed of the light, ε is the dielectric constant of the material.

JFM and KFM of many semiconductors including Si are listed at table 2. As shown at table 2 GaN has very good JFM, but rather worse KFM. This is because the thermal conductivity of GaN itself is low and heat from a GaN power amplifier cannot dissipated efficiently. To solve this problem, SiC substrates are frequently used instead of sapphire substrates. With proper heat

Table 2. JFM and KFM of various semiconductors [5].

materials	JFM		KFM	
	JFM (V^2/S^2)	Ratio with respect to Si	KFM ($W/cm^{1/2}s^{1/2}$)	Ratio with respect to Si
Si	9.1×10^{23}	1.0	13.8×10^{2}	1.0
GaAs	64.8×10^{23}	7.1	6.25×10^{2}	0.45
GaN	18466×10^{23}	2029	22.5×10^{2}	1.6
6H-SiC	6485×10^{23}	712	71.8×10^{2}	5.2
3H-SiC	6485×10^{23}	712	71.8×10^{2}	5.2
Diamond	73863×10^{23}	8117	443.1×10^{2}	32.1

dissipation, GaN-based power devices are expected to be outstanding in performance.

III. GAN-BASED ELECTRONIC DEVICES

After the successful demonstration of GaN epi-layer on top of sapphire substrates in 1986 [6], the research on GaN-based electronic devices have started. By the beginning of early 1990s, studies on dry and wet etching and ohmic and rectifying contacts were actively performed. GaN-based MESFETs were realized at the beginning. However the research has quickly migrated into AlGaN/GaN HFETs (Heterojunction Field-Effect Transistors) knowing the outstanding properties of AlGaN/GaN heterostructure.

1. Device Structures

GaN-based FETs are composed of a GaN channel, an AlGaN barrier grown either on sapphire substrates or SiC substrates. The structure using AlGaN/GaN heterojunction is shown at Fig. 2.

The barrier thickness is quite thin to be only 100-300 Å. The Al composition in AlGaN is normally 20-40 %. As the Al composition increases, the conduction band-gap discontinuity increases to improve the device performance as explained above, but at the same time, a high Al composition results in the degradation of the epi-layer (crystal) quality due to defects from the lattice mismatch between AlGaN and GaN. A thin barrier is also helpful to increase the transconductance and to decrease the parasitic effects. However an excessively thin barrier is difficult to grow in a good quality.

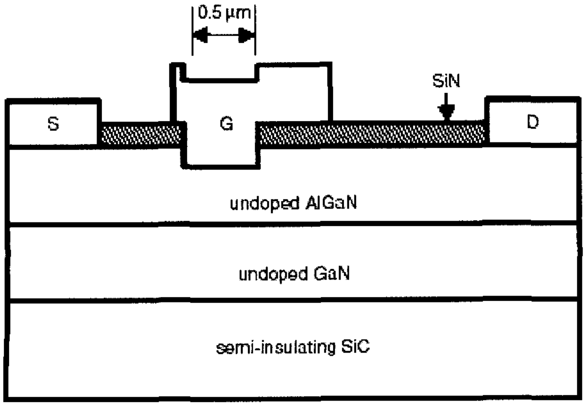


Fig. 2. AlGaN/GaN heterostructure FETs with field modulating gate [7].

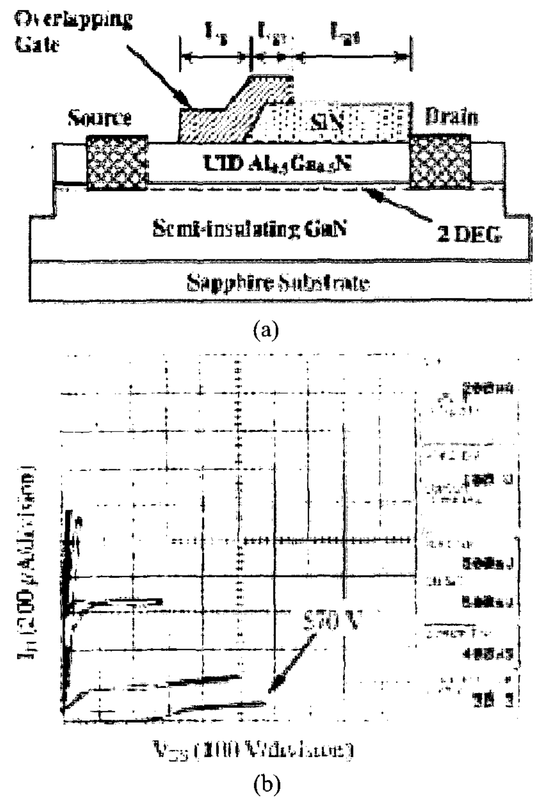
GaN HFETs are normally fabricated through isolation, ohmic contact, passivation, and gate formation. Ti/Al based metal alloys are for ohmic contacts and Ni/Au based metals for Schottky contacts. Surface passivation is very important for GaN HFETs. Due to surface defects, drain current dispersion effects (the different current levels between dc and pulsed I-V characteristics) appear implying difference in DC and RF currents. It is believed that donor-like trap on the surface with the activation energy of 0.3 eV is causing the phenomena. The dispersion effect can easily be cured through surface passiviation using, normally, SiN [8].

2. Substrates and Heat Dissipation

Sapphire and SiC are employed as substrates for GaN-based device growth. Sapphire substrates has rather large 18 % lattice mismatch with GaN. The thermal conductivity of sapphire is poor (0.4 W/cm-K) to be used for power devices. However insulating sapphire substrates provide good device isolation. The cost of sapphire is much less than that of SiC, For SiC, the lattice mismatch with GaN is only 3.5 % to allow easy GaN growth. The thermal conductivity of SiC is 3.4 W/cm-K to dissipate the heat from a device easily. However, SiC substrates are normally conducting and expensive, though semi-insulating SiC substrates are available nowadays. Between SiC and sapphire, SiC substrates are used more frequently these days for high performance devices. To further increase the heat dissipation, SiC substrate is mechanically thinned down (~ 50 μm) and backside Au plating is performed. Due to the superb thermal conductivity of Au, the heat dissipation rate and the power handling capability are greatly improved [7].

To solve the problems of heat dissipation from devices on sapphire substrates, backside grinding process which makes sapphire substrate thin by grinding has been employed. In addition, the devices on sapphire substrate have been flip-chip bonded on AlN substrates with a larger thermal conductivity than sapphire. AlN substrates are selected because they provide a good device isolation and a good thermal conductivity. For flip-chip bonding, AlN substrates were patterned and process to make passive components, then GaN-based HFETs were flip-chip bonded on the AlN substrates.

The typical performance of GaN HFETs shows a saturation drain current of about 0.7-1.2 A/mm, a transconductance of 200-250 mS/mm. Some of devices with a good frequency response demonstrated a cut-off frequency 110 GHz (0.1 μm gate) [9] and a maximum oscillation frequency 190 GHz (0.07 μm gate) [10].



(a)

(b)

Fig. 3. (a) A GaN-HFET with overlapping gate and (b) the breakdown voltage of 570 V [11].

3. Improvements in Breakdown Voltage and Power Handling Capability

Many research results have been reported to improve the breakdown voltage of FETs. The breakdown voltage along with the maximum current at a device is the most important parameters to determine output power levels. To improve the breakdown voltage of a device, it is required to reduce the electric field between gate and drain where the field is the highest. Both overlapping gates and separate field plates help to increase the breakdown voltage by reducing the electric field between gate and drain. A breakdown voltage is determined as the drain-source bias where the drain current reaches 1 mA/mm. A breakdown voltage of 570 V was achieved with 13 μm gate and drain spacing (Fig. 3) [11].

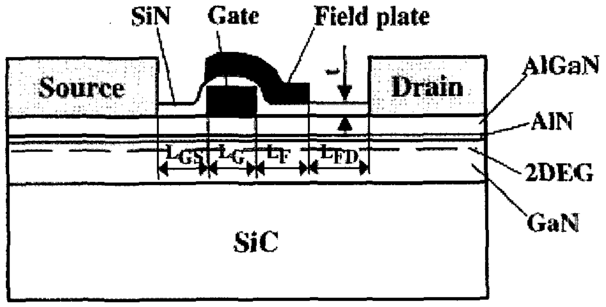


Fig. 4. Schematic of GaN HFET and field plates employed to achieve 32.2 W/mm output power density [12].

The output power density of GaN HFETs is the important factor comparing the devices characteristics assuming that any desired output power can be achieved by arranging a large size HFETs. The higher output power density implies that a high output power can be achieved with a smaller size device. The typical output power density of GaN FETs is on the order of 10 W/mm [7]. The output power density was boosted up to 32.2 W/mm (CW at 4 GHz) by a careful design of field plates [12]. The field plate used at ref [12] (Fig. 4) was not connected to the gate contrary to the field modulating plates used at ref [7] where the breakdown voltage was 140-170 V.

Various field plates (or field modulation plates), different shapes and configurations, have extensively used for high power devices. A field plate can be a separate electrode different from the gate or a part of the gate electrically connected. NEC has published many papers on GaN high power amplifiers. The reported results demonstrated 280 W [13] and 370 W [7] for W-CDMA applications. These results are compatible and better compared with the results from GaAs FETs or Si LD (lightly doped drain) MOSFETs.

For higher frequencies, prominent results have been reported. For C-band (5 GHz) 100 W CW power amplifier is reported [14]. The gate length and width were 0.5 μm and 4 mm respectively. A field-modulating plate was utilized for a high breakdown voltage of 200 V. The amplifier had 12.9 dB gain and 31 % power-added efficiency (Fig. 5). The amplifier could handle 155 W when the output power was pulsed, implying that the heat dissipation was the limit of high power operation.

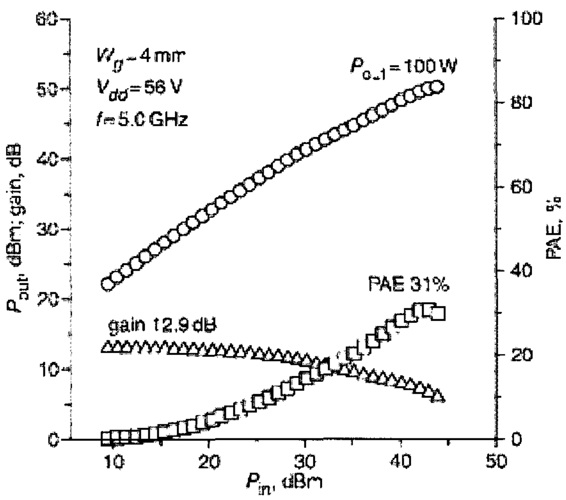


Fig. 5. Continuous-wave output power, gain and power added efficiency of a GaN HFET measured at 5 GHz [14].

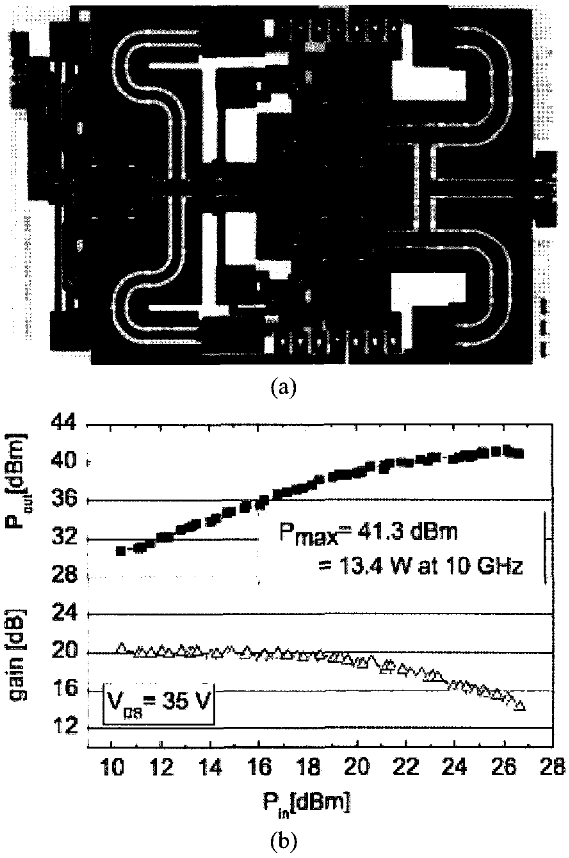


Fig. 6. (a) A two-stage X-band amplifier with AlGaN/GaN HFETs on S.I. SiC substrates and (b) its pulsed power and gain measurements [15].

The report for X-band (9-11 GHz) GaN HFET power amplifier showed 13.4 W output power (pulsed) and 20 dB small signal gain. The amplifier was made all on a chip (MMIC) (Fig. 6) [15]. At even high frequency (30 GHz) 5 W power amplifier was reported. The GaN HFET has 0.09 μm gate length to have a f_t of 81 GHz and a f_{max} of 187 GHz. The gain was 9.2 dB and PAE was 43.2 % [16].

Other than class A, AB, and B amplifiers, switching power amplifiers such as class E and F amplifiers have been made with GaN HFETs to increase efficiency. Reported class E power amplifiers achieved 37.5 dBm output power, 18.2 dB gain and 50% PAE at 4 GHz [17], and 37 dBm output power and 57% PAE at 1.9 GHz [18]. For a class F amplifier, PAE 50 %, 38 dBm output are reported [19]. Oscillators and mixers and other circuits have also been demonstrated using GaN HFETs, which we would not cover in this paper.

4. Other Electronic Devices using III-nitrides

MOSHFETs (metal-oxide semiconductor heterostructure field- effect transistors) are developed for high power and high frequency switching. The reported MOSFET can switch 50 W at 10 GHz only with a 1 mm device [20]. GaN semiconductor is ideal to make a high speed and high power switches because of its low dielectric constant and high breakdown voltage. For switch applications, low gate leakage current is also important to increase the peak power in the OFF state [20]. MOS structure was formed using 7 nm thick SiO_2 layer on top of $Al_{0.25}Ga_{0.75}N$ barrier layer. For 0-10 GHz, the insertion loss was about 1 dB and isolation was higher than 20 dB. The MOSHFET structure has an advantage over the ordinary HFET structure without SiO_2 to have a larger switching power [20].

GaN MISFETs also have produced interesting results. The device had 2000 Å thick doped GaN and 40 Å SiN layer on top of the GaN. The SiN dielectric layer prevented the gate leakage current. The results are not as good as those from GaN HEMTs showing 6.2 W/mm output power density at 4 GHz [21].

IV. CONCLUSIONS

GaN based devices have greatly been developed to demonstrate their potential for high power devices even at high frequencies above 10 GHz. Among many electronic devices using GaN, HFETs have been most successful and demonstrating viable or superior results compared with other technologies such as Si and GaAs. The large output power reported using GaN HFETs were possible with carefully designed field plates to increase breakdown voltages. The GaN HFET technology has been improved substantially demonstrating 370 W power amplifiers so that it would be not so long before commercial employment. In addition to the advantages and achievements, GaN power amplifiers have additional advantages of high temperature operation. For a typical high power amplifier, a cooling unit to ensure the heat removal from the power amplifier is required. As GaN power amplifiers operate at high temperature, the cooling unit may not necessary.

In addition to GaN HFETs other types of devices such as MOSHETs and MISFETs are also being studied producing meaningful results.

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REFERENCES

[1] J. Burm and L. F. Eastman, Chapter 4.3, "AlGaN/GaN HFETs/HEMTs", *EMIS Datareview Series*, *IEE*, No. 23, 1999.

[2] S. N. Mohammad, A. A. Salvador, and H. Morkoç, *Proceedings of The IEEE* (*USA*) vol. 83, p.1326, 1995.

[3] H. Morkoç, R. Cingolani, B. Gil, "Polarization effects in nitride semiconductors and device structures", *Mat. Res. Innovat. 3*, pp.97-106, Springer-Verlag, 1999.

[4] M.A. Khan, Q. Chen, M.S. Shur, B.T. Dermott, J.A.Higgins, J. Burm, W. Schaff and L.F. Eastman, "Short-channel GaN/AlGaN doped channel heterostructure field effect transistors with 36.1GHz cutoff frequency," *Electron. Lett.*, vol. 32, no. 4, pp. 357-358, 1996.

[5] Y.S. Park, "Current Status of Group III-Nitride Semiconductors and Future Prospects," *J. Korean Physical Society*, vol. 34, pp. S199-S219, 1998.

[6] H. Amano, N. Sawaki, I. Akasaki, and Y. Toyoda, "Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer," *Appl. Phys. Lett.*, vol. 48, no. 3, pp.353-355, 1986.

[7] A. Wakejima, K. Matsunaga, Y. Okamoto, Y. Ando, T. Nakayama and H. Miyamoto, "370W output power GaN-FET amplifier for W-CDMA cellular base stations," *Electronics letters*, vol. 41, no. 25, pp. 1371-1372, 2005.

[8] G. Meneghesso, Giovanni Verzellesi, Roberto Pierobon, Fabiana Rampazzo, Alessandro Chini, Umesh K. Mishra, Claudio Canali, Associate , and E. Zanoni, "Surface-Related Drain Current Dispersion Effects in AlGaN–GaN HEMTs," *IEEE Trans. on Electron Devices*, vol. 51, no. 10, pp. 1554-1561, 2004.

[9] M. Micovic, N. X. Nguyen, P. Janke, W.-S. Wong, P. Hashimoto, L. M. McCray, and C. Nguyen, "GaN/AlGaN high electron mobility transistor with f of 110 GHz," *Electron. Lett.*, vol. 36, no. 4, pp. 358–359, 2000.

[10] T. Inoue, Y. Ando, K. Kasahara, Y. Okamoto, T. Nakayama, H. Miyamoto, and M. Kuzuhara, "Advanced RF characterization and delay-time analysis of short channel AlGaN/GaN heterojunction FETs," *IEICE Trans. Electron.*, vol. E86-C, no. 10, pp. 2065–2070, 2003.

[11] N.-Q. Zhang, S. Keller, G. Parish, S. Heikman, S. P. DenBaars, and U. K. Mishra, "High Breakdown GaN HEMT with Overlapping Gate Structure", *IEEE Electron Device Letters*, vol. 21, no. 9, pp. 421-423, 2000.

[12] Y.-F. Wu, A. Saxler, M. Moore, R. P. Smith, S. Sheppard, P. M. Chavarkar, T. Wisleder, U. K. Mishra, and P. Parikh, "30-W/mm GaN HEMTs by Field Plate Optimization," *IEEE Electron Device Lett.*, vol. 25, no. 3, pp. 117-119, 2004.

[13] A. Wakejima, K. Matsunaga, Y. Okamoto, Y. Ando,

T. Nakayama, K. Kasahara and H. Miyamoto, “280W output power single-ended amplifier using single-die GaN-FET for W-CDMA cellular base stations”, *Electronics Letters*, vol. 14, no. 18, pp. 1004 – 1005, 2005.

[14] Y. Okamoto, A. Wakejima, Y. Ando, T. Nakayama, K. Matsunaga and H. Miyamoto, “100W C-band single-chip GaN FET power amplifier,” *Electronics Letters*, vol. 42 no. 5, pp. 283 – 285, 2006.

[15] F. van Raay, R. Quay, R. Kiefer, F. Benkhelifa, B. Raynor, W. Pletschen, M. Kuri, H. Massler, S. Müller, M. Dammann, M. Mikulla, M. Schlechtweg, and G. Weimann, “A Coplanar X-Band AlGaN/GaN Power Amplifier MMIC on s.i. SiC Substrate,” *IEEE Microwave and Wireless Component Letters*, vol. 15, no. 7, pp. 460-462, 2005.

[16] Takashi Inoue, Yuji Ando, Hironobu Miyamoto, Tatsuo Nakayama, Yasuhiro Okamoto, Kohji Hataya, and Masaaki Kuzuhara, “30-GHz-Band Over 5-W Power Performance of Short-Channel AlGaN/GaN Heterojunction FETs,” *IEEE Trans. ON Microwave Theory and Techniques*, vol. 53, no. 1, pp. 74-80, 2005.

[17] Steven Gao, Hongtao Xu, Sten Heikman, Umesh K. Mishra, and Robert A. York, “Two-Stage Quasi-Class-E Power Amplifier in GaN HEMT Technology,” *IEEE Microwave and Wireless Components Letters*, vol. 16, no. 1, pp. 28-30, 2006.

[18] Hongtao Xu, Steven Gao, Sten Heikman, Stephen I. Long, Umesh K. Mishra, and Robert A. York, “A High-Efficiency Class-E GaN HEMT Power Amplifier at 1.9 GHz,” *IEEE Microwave and Wireless Components Letters*, vol. 16, no. 1, pp. 22-24, 2006.

[19] S. Gao, C. Sanabria, H. Xu, S.I. Long, S. Heikman, U. Mishra and R.A. York, “MMIC class-F power amplifiers using field-plated GaN HEMTs,” *IEE Proc.-Microw. Antennas Propag.*, vol. 153, no. 3, pp. 259-262, 2006.

[20] Z. Yang, A. Koudymov, V. Adivarahan, J. Yang, G. Simin, and M. A. Khan, “High-Power Operation of III-N MOSHFET RF Switches,” *IEEE Microwave and Wireless Components Letters*, vol. 15, no. 12, pp. 850-852, 2005.

[21] A. Chini, J. Wittich, S. Heikman, S. Keller, S. P. DenBaars, and U. K. Mishra, “Power and Linearity Characteristics of GaN MISFETs on Sapphire Substrate,” *IEEE Electron Device Letters*, vol. 25, no. 2, pp. 55-57, 2004.

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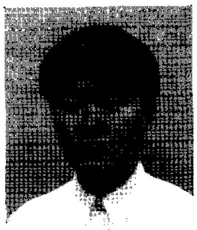

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