# GaN Device and Bulk Growth

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**AlGaN/GaN Hetero Field Effect Transistor for a (Late News) Large Current Operation**
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# Recent Progress of AlGaN/GaN Heterojunction FETs for Microwave Power Applications

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Keywords: AlGaN, GaN, heterojunction, FET, power device, sapphire substrate, SiN, passivation

**Abstract.** Power AlGaN/GaN heterojunction field effect transistors on thinned sapphire substrates are demonstrated with improved power capability. A 16 mm-wide FET on a 50 μm-thick sapphire substrate exhibited a record output power of 15.9 W (on sapphire) with 9.0 dB linear gain, and 29.1 % power-added efficiency (PAE) at 34 V drain bias.

**Introduction**

AlGaN/GaN heterojunction field effect transistors are attracting much attention for microwave high-power applications because of their high breakdown voltage, high carrier carrying capability and high saturation velocity. Output power density values of 9.8W/mm for a 100 μm-wide device on a SiC substrate [1] and 4.6 W/mm for a 150 μm-wide device on a sapphire substrate [2] have been achieved. Total output power values of 22.9 W (CW) for a 4mm-wide hybrid-matched device [3], 51 W (pulsed) for 8 mm-wide MMIC on a SiC substrate [4], and 7.6 W (CW) for a 6 mm-wide device on a sapphire substrate [2] were reported. Relatively inferior power performance of a large periphery device on the sapphire substrate is due to the low thermal conductivity of sapphire.

In this paper, improved power performance of large periphery devices (16mm) on thinned sapphire substrates is reported.

**Device Structure and Fabrication**

An undoped AlGaN/GaN heterostructure was grown by metal organic chemical vapor deposition (MOCVD) on a 330 μm-thick (0001) sapphire substrate. Ti/Al ohmic electrodes were evaporated and alloyed at 650 °C for 30 sec. 0.9 μm-long Ni/Au gate electrodes were formed using optical lithography process. A standard Au-plated air-bridge process was used to fabricate multi-fingered FETs. After accomplishment of the front side process, the back side of the sapphire substrates were mechanically polished and the substrate thickness was reduced from 330 to 50 μm [5]. Ti/Pt/Au was evaporated on the mechanically thinned surface.

**Device Performance and Discussion**

Current-voltage characteristics for 50 and 330 μm thick FETs were measured. No degradation in DC characteristics was observed after the polishing process. 40 μm-wide device exhibited a maximum drain current of 450 mA/mm and maximum transconductance of 70 mS/mm. The threshold voltage was typically -6 V. The two-terminal gate-drain breakdown voltage was typically 100V.

Large-signal characteristics for 1mm-wide devices with 50 and 330 μm-thick were evaluated with an on-wafer load-pull system. Figure 1 shows drain bias dependence of saturated power at 1.95 GHz. The 50 μm-thick device exhibited a CW saturated output power of 1.4-1.5 W/mm with 21 dB linear gain and 40 % power-added efficiency at 40 V drain bias. This output power density is approximately 25 % higher than that of the 330μm-thick device (1.1-1.2 W/mm).

A 16 mm-wide device on the 50 μm-thick sapphire substrate was packaged into a ceramic carrier and measured with a load-pull system. Figure 2 shows the output power, the power-added efficiency and the gain as a function of the input power operated at Vd=34V. 15.9 W CW (1.0 W/mm)

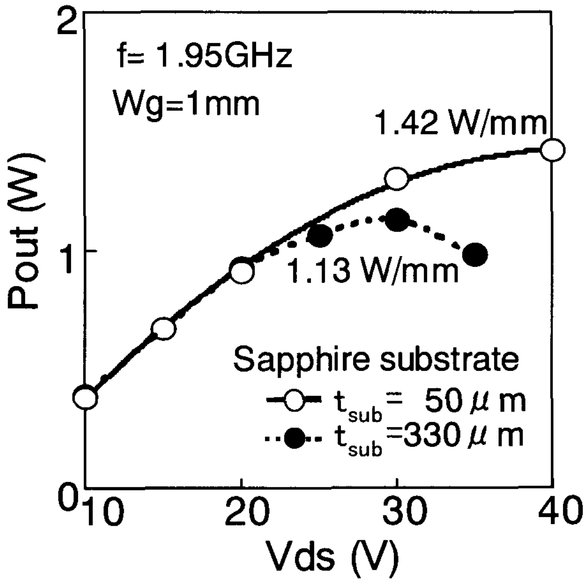


Fig. 1. Drain bias dependence of a saturated power at 1.95 GHz for 1mm-wide GaN FETs for $t_{sub}$=50 μm (open) and 330 μm (closed).

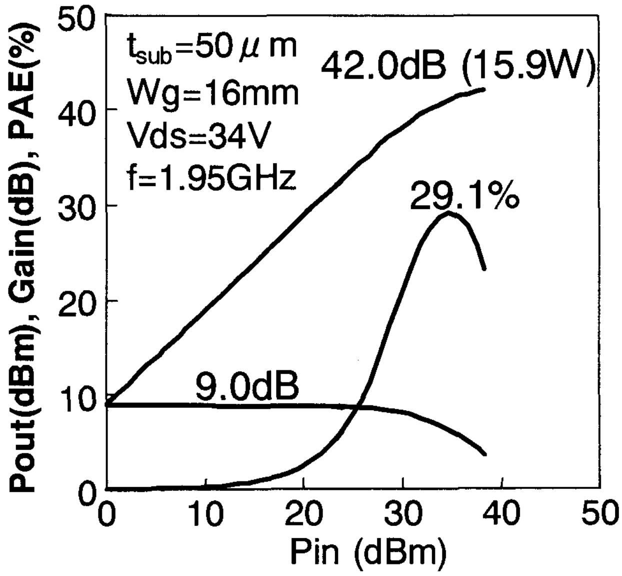


Fig.2. 1.95 GHz power sweep for 16 mm-wide FET ( $t_{sub}$=50μm, Vds=34V).

saturated output power, 9.0 dB liner gain, and 29.1 % PAE were measured. To our best knowledge, 15.9 W output power is the highest achieved for AlGaN/GaN FETs on sapphire substrates.

**Conclusions**

Power AlGaN/GaN FETs on thinned sapphire substrates have been demonstrated with improved power capability. A 16 mm-wide FET on a 50 μm-thick sapphire substrate exhibited a record output power of 15.9 W (on sapphire) with 9.0 dB linear gain, and 29.1 % power-added efficiency (PAE) at 34 V drain bias.


**Acknowledgments**

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**References**


[1] Y.-F. Wu, D. Kapolnek, J. Ibbestson, P. Parinkh, B. Keller and U. Mishra: IEEE Trans. Electron Devices, Vol.48 (2001), p.586

[2] Y. -F. Wu, B. P. Keller, S. Keller, J. J. Xu, S. P. Denbaars and U. K. Mishra: IEICE Trans. Electron. E82-C (1999), p.1895

[3] C. Nguyen, M. Micovic, D. Wond, A. Kurdoghlian, P. Hashimoto, P. Janke, L. McCray and J. Moon: *in 2000 IEEE GaAs Digest*

[4] Y. -F. Wu, P. M. Chavarkar, M. Moore, P. Parkh, B. P. Keller and U. K. Mishra: *in Proc. IEDM 2000*

[5] N. Hayama, K. Kunihiro, Y. Okamoto, K. Kasahara, T. Nakayama, Y. Ohno, K. Matsunaga, H. Miyamoto, Y. Ando, and M. Kuzuhara: *2001 MRS Spring Meeting Digest, E10.3, (2001), p.117*

# Broadband Push-Pull Microwave Power Amplifier Using AlGaN/GaN HEMTs on SiC

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AlGaN/GaN high electron mobility transistors (HEMTs) on high thermal conductivity SiC have yielded 6.9 W/mm at 10 GHz and 9.1 W/mm at 8.2 GHz in small periphery devices [1], [2]. To achieve this power density level in large periphery devices requires good management of thermal dissipation. Lower thermal dissipation can be achieved through the potentially higher power-added-efficiency (PAE) of Class B operation, relative to linear Class A operation. We demonstrate broadband Class B push-pull operation of GaN HEMTs, thereby taking advantage of the lower thermal dissipation while achieving linear operation and allowing higher power density in large-area devices.

The device fabrication, and DC and RF testing results have been reported previously [1]. The AlGaN/GaN HEMTs were grown on a semi-insulating SiC substrate using MOCVD. A 0.25 mm device with $L_G$=0.35 $\mu$m showed more than 800 mA/mm drain current, 220 mS/mm transconductance, and more than 60 V breakdown voltage. A 1.5 mm device (12 $\times$ 125 $\mu$m) provided 13.5 dB gain at 10 GHz (in a 50 $\Omega$ system), a $f_T$ of 25 GHz and a $f_{max}$ of 43 GHz, as shown in Fig. 1. A temperature dependent large signal model for these HEMTs has been developed for amplifier design.

Class B push-pull operation was achieved using two 1.5 mm GaN HEMTs and a new broadband balun at the input and output of the push-pull pair. This balun was implemented using three symmetric coupled lines and showed excellent loss, having less than 0.5 dB per balun over 5-11 GHz (3 dB bandwidth was 4-12 GHz) [3]. The fabricated amplifier is shown in Fig. 2. The balun and matching network, designed for broadband performance, were fabricated on a high thermal conductivity AlN substrate ($\epsilon_r$ = 8.5). Small-signal S-parameter measurements at $V_{DS}$ = 15 and $V_{GS}$=-2.9 V resulted in a gain of 8 dB at 5 GHz for the amplifier, including input and output baluns, and a 3-dB bandwidth of 3-10 GHz, as shown in Fig. 3 . Figure 4 shows the continuous wave power sweep at 5 GHz, with $V_{DS}$=22 V and $V_{GS}$ = -3.2 V. The output power was 2.5 W at about the 3-dB compression point, and the peak PAE was 14 %, being compromised for broadband operation.

To assess the linearity of the push-pull amplifier, single tone harmonic content and two-tone inter-modulation measurements were performed. Figure 5 shows the measured second and third harmonic levels of the push-pull amplifier biased at $V_{DS}$= 12 V and $V_G$ = -3.2 V. The second harmonic levels measured at about the 1-dB gain compression point gradually decreased with frequency, reaching 40 dBc at the mid to high end of the band. Figure 6 shows the measured two-tone inter-modulation performance of the push-pull amplifier, with an input $IP_3$ of 32 dBm, indicating good linearity.

**Acknowledgments**: This work is supported by ONR under N00014-98-1-0371, N00014-98-1-0371 and N00014-99-C-0172 (John Zolper). The devices were fabricated by Cree Inc. under ONR contract N00014-99-C-0172 (John Zolper).

## References

[1] S. T. Sheppard et al., *IEEE Electron Dev. Lett.*, **20**, 161 (1999)
[2] Y.-F. Wu et al. *IEEE Int. Electron Dev. Meeting Digest*, 925 (1999)
[3] J.-W. Lee and K. J. Webb, *IEEE Int. Microwave Symp. Digest* (2001)

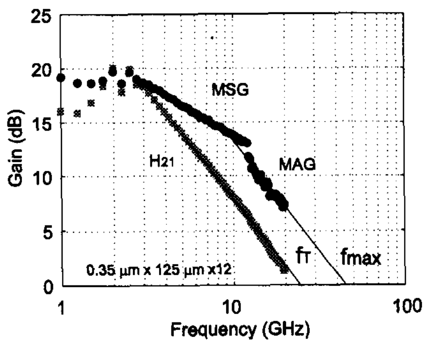


Fig. 1. Measured current gain ($|H_{21}|$) and power gain versus frequency of a 0.35 $\mu$m gate-length, 1.5 mm AlGaN/GaN HEMT on SiC

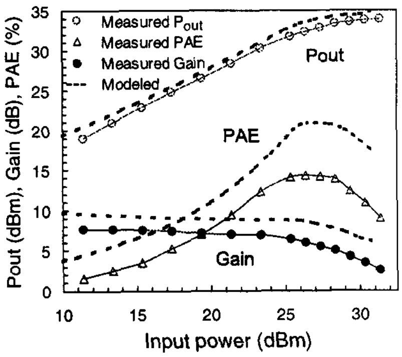


Fig. 4. Power output of Class B push-pull amplifier biased at $V_{DS}$=22 V, $V_{GS}$=-3.2 V. Simulated results are shown with a dotted line.

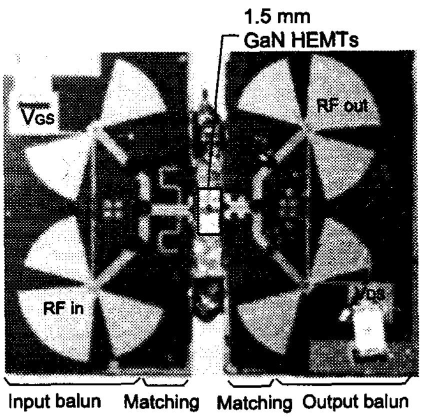


Fig. 2. Photograph of the fabricated amplifier.

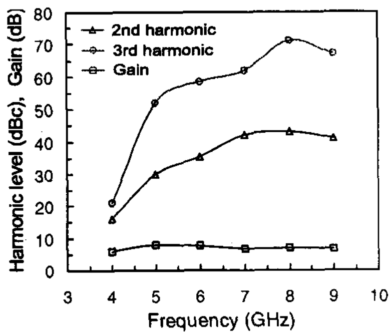


Fig. 5. Measured second and third harmonic levels of the push-pull amplifier versus frequency, biased at $V_{DS}$=12 V and $V_G$=-3.2 V. The harmonic levels were measured at about the 1-dB gain compression point.

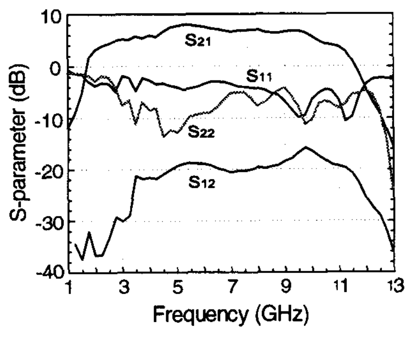


Fig. 3. Measured small-signal S-parameters for the push-pull amplifier ($V_{DS}$=15 V, $V_{GS}$=-2.9 V).

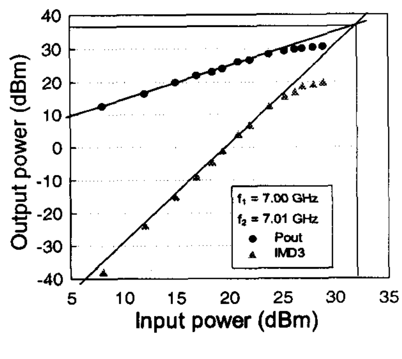


Fig. 6. Measured two-tone inter-modulation performance of the push-pull amplifier.

# Gallium Nitride Power Device Design Tradeoffs

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Gallium nitride is of interest for high-voltage devices because of its wide-bandgap and high breakdown electric field. Many devices have been fabricated using the AlGaN/GaN system, including Schottky rectifiers, HBTs, and HEMTs. For high-voltage devices, it is important to understand the design tradeoffs for optimal device performance. This paper investigates these design tradeoffs for GaN power devices and compares with Silicon and 4H-SiC.

The ionization coefficients for 2H-GaN (hexagonal) were estimated using Fulop's approximation from theoretical ionization coefficients[1]. From the estimated ionization coefficient, the one-dimensional breakdown voltage and depletion width are calculated versus doping concentration (Figure 1). For unipolar devices the main device performance consideration is the specific on-resistance, with calculated results for vertical devices in 2H-GaN shown in Figure 2. For bipolar power devices, switching time, of the order of the carrier lifetime, is the key metric. The minimum carrier lifetime to achieve full conductivity modulation in the drift region of GaN devices versus breakdown is shown in Figure 3.

Termination of wide bandgap power devices must be carefully designed to prevent high fields in insulating layers on the device. Standard field-plates cannot be used without overly stressing the insulating materials. Termination structures must be used that do not expose insulating materials to high electric field, one example being epitaxial junction termination extension (JTE) which does not require implantation as shown in Figure 4.

For high-voltage HEMT structures, spontaneous and piezoelectric charge creates a high vertical electric field reducing the effective horizontal field that can be supported in lateral device structures such as the AlGaN/GaN HEMT. By estimating the polarization charge, the reduction in effective lateral critical field is calculated (Figure 5).

For power switching devices, a normally-off device is desirable. A normally-off HEMT has been fabricated[2] but suffers from a large gate-drain and gate-source parasitic resistance, because no 2DEG exists in these regions. Recessed-gate structures are proposed that provide normally-off operation with a reduction in the parasitic resistance by creation of a 2DEG in gate-drain and gate-source regions.

Power device design curves have been generated for 2H-GaN and compared with silicon and 4H-SiC. Unipolar and bipolar performance metrics have also been calculated. The polarization charge is shown to significantly reduce the effective lateral critical electric field for AlGaN/GaN HEMT devices.

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[1]I.H. Oguzman, E. Bellotti, K.F. Brennan, J. Kolnik, R. Wang, P.P. Ruden, "Theory of hole initiated impact ionization in bulk zincblende and wurtzite GaN," J. Appl. Phys. **81**, p. 7827-34.

[2]M.A. Khan, Q. Chen, C.J. Sun, J.W. Yang, M. Blasingame, M.S. Shur, H. Park, "Enhancement and depletion mode GaN/AlGaN heterostructure field effect transistors," Appl. Phys. Letters **68**, p. 514-6.

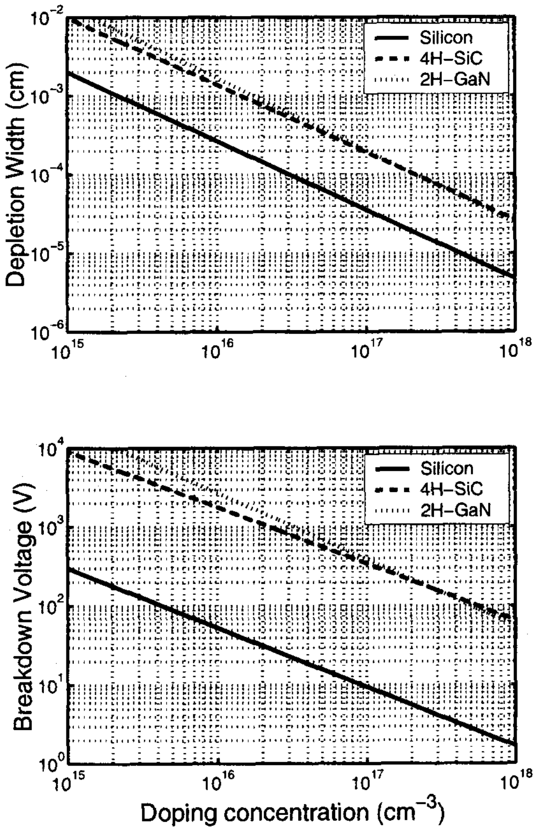


Figure 1: Parallel plate breakdown depletion width and breakdown voltage as a function of doping concentration for Si, 4H-SiC, and 2H-GaN.

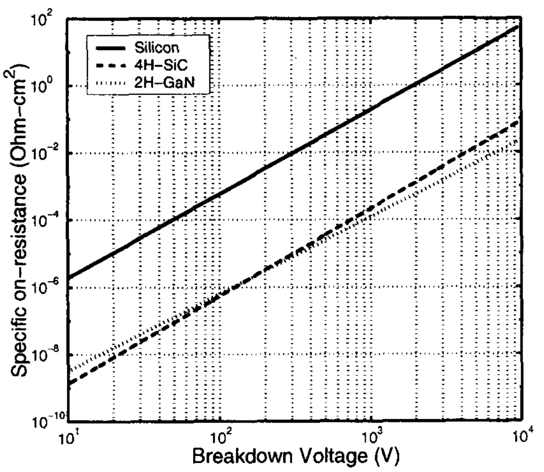


Figure 2: Specific on-resistance for Si, 4H-SiC, and 2H-GaN, using using data from Fig. 1.

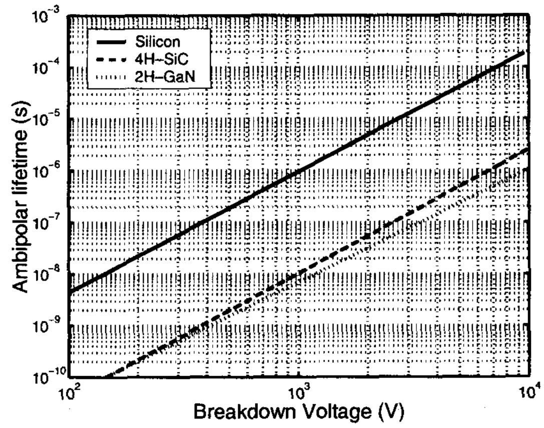


Figure 3: Ambipolar lifetime requirement for $W_d = 2L_a$, for Si, 4H-SiC, and 2H-GaN.

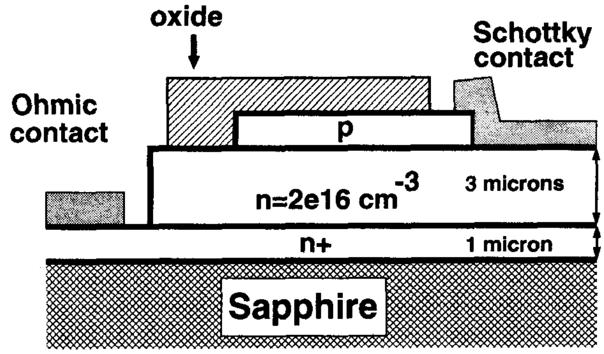


Figure 4: Epitaxial junction termination extension (epi-JTE) design for an 800 V GaN-Schottky rectifier.

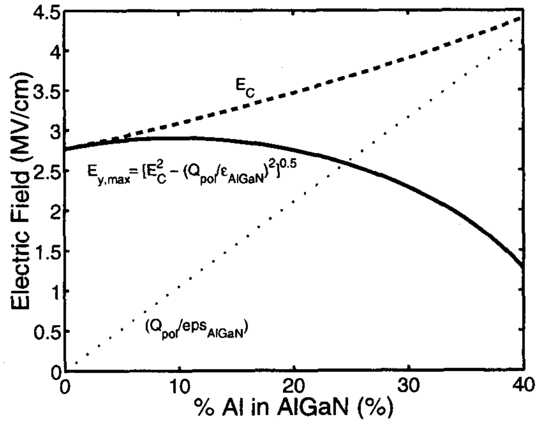


Figure 5: Critical electric field ($E_C$, dashed), polarization-induced field ($Q_{pol}/\epsilon_{AlGaN}$, dotted), and effective lateral critical electric field ($E_{y,max}$, solid) as a function of Al percent in $Al_xGa_{1-x}N$.

# Temperature dependence of DC characteristics of AlN/GaN Metal Insulator Semiconductor Field Effect Transistor

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AlGaN/GaN heterojunction field effect transistors (HJFETs) are promising for high temperature and high power microwave applications, and their high temperature operations at 300-450℃ [1-3] and at 800℃ [4] have been demonstrated. In these studies, the degradation of the DC characteristics at high temperature has been observed as follows: i) saturation drain current is suppressed, ii) transconductance decreases, iii) gate leakage current increases, and iv) pinch-off characteristic becomes vague.

Previously, we fabricated AlGaN/GaN HJFET with Al-content up to 100%, namely AlN/GaN metal insulator semiconductor FET (MISFET).[5] The MISFET has shown better DC characteristics at room temperature as compared with AlGaN/GaN HJFET using the conventional fabrication processing.

In this study, we investigated the DC characteristics of AlN/GaN MISFET when the device temperature was varied.

Figure 1 shows the schematic diagram of AlN/GaN MISFET. AlN/GaN heterojunction structure was grown on sapphire (0001) substrates by nitrogen plasma-assisted molecular beam epitaxy. This structure for device consists of 200-nm AlN buffer layer, 1.5-$\mu$m GaN layer, 15-nm $n^+$-GaN channel layer and 5-nm AlN barrier layer. After mesa isolation, in order to form Ohmic contact electrodes for source and drain, AlN barrier layer was removed by the wet chemical etching with hot phosphoric acid at 170℃ for 3min. Ti/Al/Pt/Au Ohmic contacts were formed onto the $n^+$-GaN channel layer. Ohmic contact resistivity $\rho_c$ was $8.25\times10^{-6}\Omega$-cm$^2$. Schottky contact for the gate was formed by Al/Pt/Au e-beam evaporation. The gate length is 3$\mu$m.

The DC characteristics of the sample were measured in vacuum chamber with pressure lower than 50 Torr. Semiconductor parameter analyzer (HP4156B) was used to measure the DC characteristics. The sample was set on the stage that consists of sapphire plate, Au seat, Ti plate, sapphire plate and the heater. During the DC measurement, temperature was monitored by thermo couple set under the heater.

The DC characteristics of the MISFET were measured from 25℃ to 500℃. Figure 2 shows the drain current-voltage characteristics of the MISFET at 25℃. The gate voltage $V_{GS}$ has been changed from -5 to +3V by steps of 1V. The threshold voltage of the MISFET is –4V. When the drain voltage $V_{DS}$ is high, the drain current $I_D$ is saturated and becomes constant. Maximum transconductance $g_{mmax}$ was 105mS/mm, and maximum drain current $I_{Dmax}$ was 610mA/mm. When temperature increases, the saturation characteristic becomes vague, and $I_D$ is not completely saturated. Also, sufficient pinch-off characteristic is not observed.

Figure 3 shows the temperature dependence of $g_{mmax}$. When temperature increases over 200℃, the value of $g_{mmax}$ decreases. The value of $g_{mmax}$ at 500℃ was 17mS/mm. However, after cooled down to 25℃, the MISFET showed to the initial characteristics before increasing temperature. Therefore, the Schottky contact metal for the gate electrode was not annealed by high temperature operation.

The detail will be discussed in the presentation.

**References**


[1] O. Aktas, Z. F. Fan, S. N. Mohammad, A. E. Botchkarev and H. Morkoc, Appl. Phys. Lett. **69** (1996) 3872.

[2] R. Hickman, J. M. Van Hove, P. P. Chow, J. J. Klaassen, A. M. Wowchack and C. J. Polley, Solid-State Electron. **42** (1998) 2183.

[3] N. Maeda, T. Saitoh, K. Tsubaki, T. Nishida and N. Kobayashi, Jpn. J. Appl. Phys. **38** (1999) L987.

[4] I. Daumiller, C. Kirchner, M. Kamp, K. J. Ebeling and E. Kohn, IEEE Electron. Device Lett. **20** (1999) 448.

[5] T. Ide, M. Shimizu, A. Suzuki, X. –Q. Shen, H. Okumura and T. Nemoto, to be published in Jpn. J. Appl. Phys.


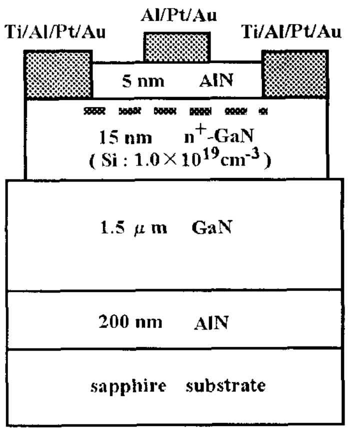


Fig. 1 : Schematic diagram of AlN/GaN MISFET.

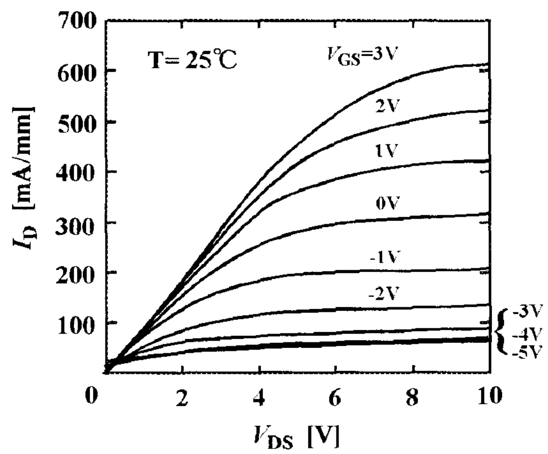


Fig. 2 : Drain current $I_D$ as a function of drain-source voltage $V_{DS}$ at 25℃

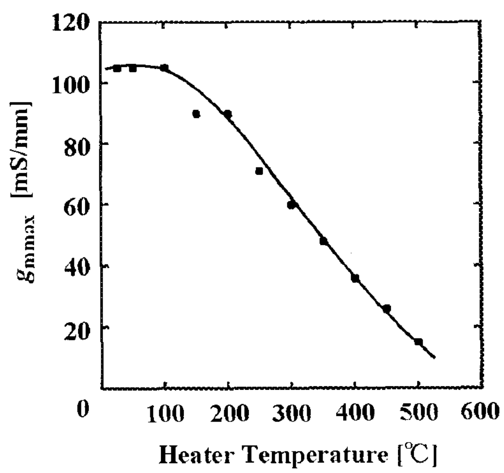


Fig. 3 : Temperature dependence of maximum transconductance.

## High Performance AlGaN/GaN HEMTs with Recessed Gate

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High performance AlGaN/GaN high electron mobility transistor (HEMT) with recessed gate was successfully fabricated on sapphire substrate, as shown in Fig. 1. In order to realize high performance HEMT, it is very important not only to improve 2-dimensional electron gas (2DEG) but also to reduce the parasitic resistance. However, the increase of aluminum content in AlGaN to get high density 2DEG results in poor ohmic contact. Fig. 2 shows the comparison of contact resistances to GaN and AlGaN. Contact resistances were $8x10^{-6}\,\Omega cm^2$ in case of n-GaN ($1x10^{19}cm^{-3}$), and as high as $7x10^{-5}\,\Omega cm^2$ in case of n-AlGaN ($1x10^{18}cm^{3}$). In our recessed gate structure, ohmic contact with low resistivity can be formed on n-GaN with high electron density, which is formed on AlGaN layer with high aluminum content [1].

The substrate used here consists of a thin GaN nucleation layer, a 2.5-um-thick undoped GaN layer, a 10-nm-thick $Al_{0.26}Ga_{0.74}N$ spacer layer, a 20-nm-thick n-$Al_{0.26}Ga_{0.74}N$ ($1x10^{18}$ $cm^{-3}$) layer and a top 20nm-thick $n^+$-GaN ($1x10^{19}$ $cm^{-3}$) layer on sapphire substrate grown by MOCVD. Electron density and electron mobility of 2DEG were $1x10^{13}$ $cm^{-2}$ and 736 $cm^2$/Vs, respectively.

Drain and source ohmic contacts were formed with Ti (15nm)/ Al (250nm) and annealed at 550℃ for 1 min. Gate recess etching was done by reactive ion etching (RIE) in a $Cl_2/H_2$ plasma and gate metal (Ni/Au) was deposited on recessed area.

The HEMT with 0.5um gate length showed excellent current saturation properties, as shown in Fig.3. The maximum trans-conductance(gm) was as high as 327 mS/mm. Measured current gain cutoff frequency (fT) was as high as 32.3GHz and a maximum frequency of oscillation (fmax) was 39GHz, as shown in Fig.4. Source resistance( Rs) between source and gate were also measured.

These characteristics were compared with that of non-recessed 0.75um gate HEMT which has the same hetero structure, as shown in Table 1. Rs of recessed gate HEMT was smaller than one third of that of non-recessed gate HEMT. This will be the reason why the trans-conductance of recessed gate HEMT is three times lager than that of non-recessed gate HEMT. The gm x gate-length product and fT x gate-length product were also compared. In the recessed gate HEMT, these products were greatly improved and also nearly equal to that of the highest achieved for GaN-HEMT[2][3].

To evaluate effective electron velocity in the channel and intrinsic fT, we measured the relation of $\tau$ ($=1/2\pi$ fT) and reverse of drain current (1/Id), as shown in Fig 5. The interceptof, $\tau_0$, of $\tau$ and 1/Id relation means the effective transit time of electron flowing beneath the channel [3]. Effective electron velocity and intrinsic fT calculated from $\tau_0$ were as high as 1.56 x $10^7$ cm/sec and 49.7GHz, respectively. Effective electron velocity obtained here is the highest value reported to date for GaN-HEMT.

In conclusion, it can be said that AlGaN/GaN HEMT with recessed gate is a very promising device for high power and high frequency applications.

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[1] T. Egawa et al.: Appl. Phys. Lett. 76 (2000) 121.
[2] M. Micovic et al.: Electronics Letters 28th September 2000 Vol. 36 No. 4, pp.358-359
[3] M. Akita et al : Electronics Letters 28th September 2000 Vol. 36 No. 20, pp.1736-1737

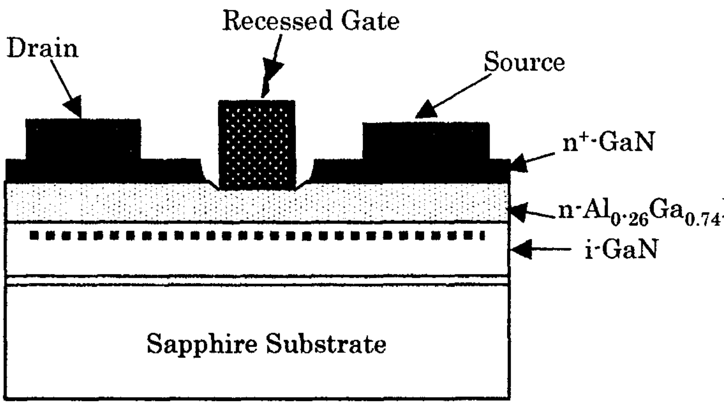


Fig. 1 AlGaN/GaN HEMTs with Recessed Gate.

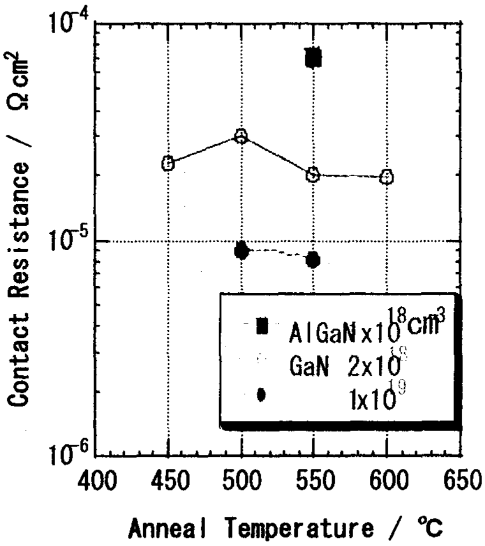


Fig. 2 Anneal temperature dependence of contact resistance.

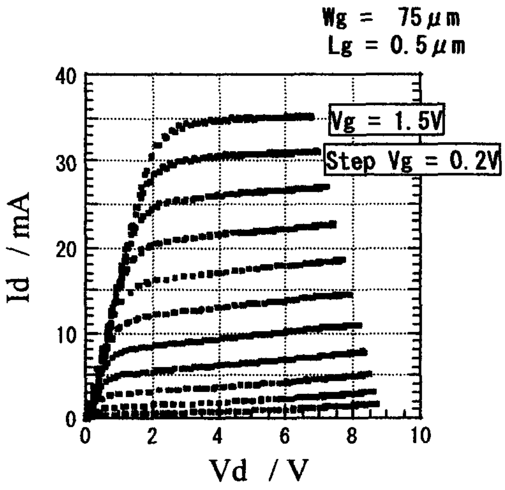


Fig. 3 DC I V characteristics of AlGaN/GaN HEMT.

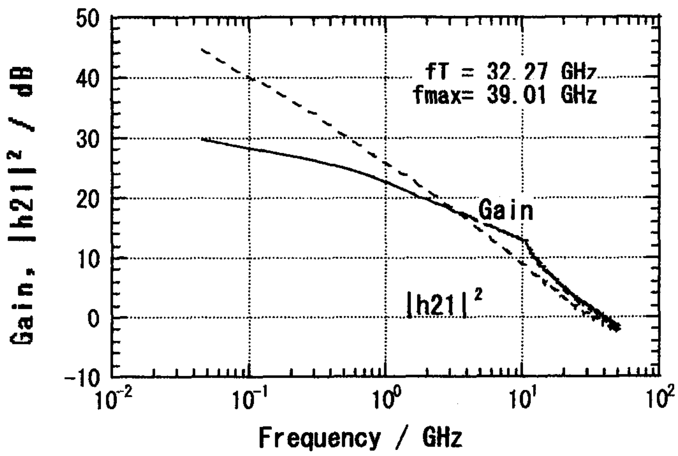


Fig. 4 Current Gain $|h_{21}|^2$ and MSG/MAG(Gain) of HEMT.

| Gate structure | Non-Recessed | Recessed (This work) |
|---|---|---|
| Gate Length (μm) | 0.75 | 0.5 |
| Rs (Ωmm) | 7.2 | 2.1 |
| gm (mS/mm) | 110 | 327 |
| fT (GHz) | 6.0 | 32.3 |
| fmax (GHz) | 25.5 | 39.0 |
| gm x Lg(μm-mS/mm) | 83 | 164 |
| fT x Lg(μm-GHz) | 4.5 | 16.2 |

Table 1 Comparison of characteristics between Non-recessed and recessed gate HEMT.

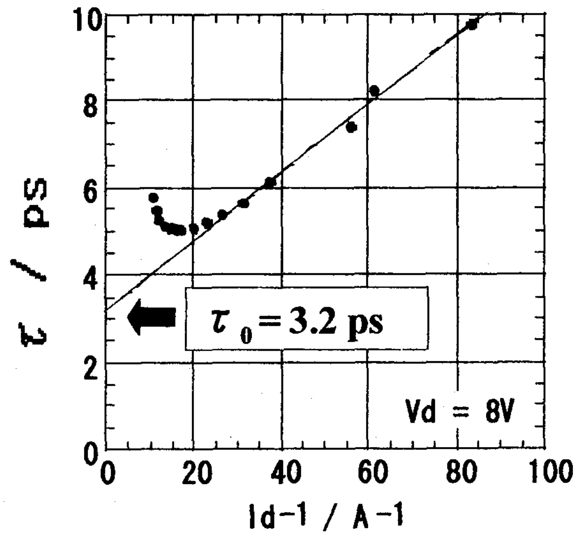


Fig. 5 Relation of $\tau = 1/2\pi fT$ vs 1/Id.

# GaN Substrates Grown by Hydride - Metal Organic Vapor Phase Epitaxy (H-MOVPE) on lattice-matched oxide and silicon substrates

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The III-V nitrides - wide band-gap semiconductors have demonstrated considerable promise for various optoelectronic, high-temperature and high-power device applications. Since a suitable commercial substrate matched to GaN in both lattice parameter and thermal expansion is not available, GaN films grown on sapphire typically contain a dislocation density on the order of ~ $10^{10}$ $cm^{-2}$. This leads to the formation of threading defects and residual strains which may effect both the optical and electrical properties of devices. Epitaxially laterally overgrown (ELOG) GaN on sapphire has been used to reduce the number of threading dislocation in the GaN layer, and laser diodes (LDs) with estimated lifetimes of more than 10,000 hours have been developed. An obvious solution to minimizing defect generation at the interface is to use a GaN substrate.

Bulk GaN or thick GaN films would be of highest interest as a base structure for the device fabrication. At present, GaN bulk single crystal substrates can be grown by high-pressure synthesis, by chloride-hydride vapor phase epitaxy, the sublimation sandwich technique and liquid-phase epitaxy on sapphire or SiC substrates with subsequent substrate removal by reactive ion etching, laser ablation, or polishing.

In the present work we report on successful growth of single crystal GaN substrates by combining the rapid growth rates afforded by HVPE with the nearly lattice-matched crystal structure of $LiGaO_2$ and $LiAlO_2$ substrates. A self-separation process was developed that leaves free-standing flat single crystal GaN without the need for mechanical or chemical treatment. No cracks or residual strain were observed in the GaN wafers. It was determined that surface nitriding and cooling processes were critical in film-substrate self-separation.

A novel chemistry that uses a group III MO source reacting with injected HCl along with $NH_3$ for the deposition of GaN was explored. This technique can alternate between MOVPE and HVPE growth chemistries, combining the advantages of both. The advantages of this approach include the possibility of performing MOVPE or HVPE in the same reactor, high growth rates, rapid reactant switching, potentially lower background impurities, in-situ etching, elimination of HVPE source problems, and improvement in $NH_3$ cracking.

Seed GaN crystals were grown by MOVPE on (001) $LiGaO_2$ and (100) $LiAlO_2$ to protect the substrate from the HCl attack. The GaN layers were grown on nitrided substrate surfaces. The MOVPE GaN seed layer thickness was 0.2 to 0.3 μm. A thick GaN layer was next grown by HVPE. The estimated growth rate was 50 to 70 μm/hr. Typical HVPE GaN thickness ranged from 100 to 300 μm. A thin (0.1 to 0.2 μm) MOVPE GaN layer was grown to improve the surface morphology of the layer. The substrate nitridation and subsequent cooling processes were found to be critical for film-substrate self-separation and caused the GaN film to "lift off". Therefore substrate removal by wet chemical etching was not needed.

High quality GaN layers were grown on (111) Si substrates using AlN buffer layer by H-MOVPE technique.

Different techniques were used to assess the substrate and film quality. The surface morphology was study by AFM and SEM, while the structural quality was analyzed by XRD and TEM. The chemical composition was investigated by AES, ESCA and SIMS. Micro Raman spectroscopy was applied for film and substrate characterization as well.

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# AlGaN/GaN HETERO FIELD-EFFECT TRANSISTOR FOR A LARGE CURRENT OPERATION.

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GaN and related semiconductors are very promising for electric devices which can be used under high-power, high-frequency, and high-temperature conditions. Especially, it is expected that the on-state resistance of a GaN field-effect transistor (FET) is expected to be lower than that of Si or GaAs devices. However, there is no experimental report concerning the on-state resistance of a GaN-based FET. In this paper, it is reported for the first time that an AlGaN/GaN hetero FET (HFET) was operated above 20 A, and that the on-state resistance of the HFET is lower than that of a Si-based FET. A undoped $Al_{0.2}Ga_{0.8}N$(30nm)/GaN(2μm) heterostructure was grown on the sapphire substrate using a gas-source molecular beam epitaxy. The mobility of $Al_{0.2}Ga_{0.8}N$/GaN heterostructure was about 1200 $cm^2/Vs$ at room temperature. We investigated the breakdown voltage of undoped GaN layer. The breakdown voltage of undoped GaN was over 2000 V (2 MV/cm). Before the formation of electrodes, Si-doped GaN with a carrier concentration of $5x10^{19}$ $cm^{-3}$ was selectively grown in the source and drain regions in order to obtain a very low contact resistance.

After that, a large-size $Al_{0.2}Ga_{0.8}N$/GaN HFET was fabricated. The FET structure was formed using a dry-etching technique. The gate width was 20 cm and the gate length was 2 μm. The distance of source and drain was 6μm. The source and drain also had a multi-finger structure. The electrode materials of the source and the drain were Al/Ti/Au and the Schottky electrodes were Pt/Au. The distance between the source and drain was 6 μm. Multi-electrode structures were also fabricated using $SiO_2$ for isolating the source, drain, and gate electrodes, respectively. The HFET was operated at a current of over 20 A. The on-state resistance of the HFET was about 2 $m\Omega cm^2$. The transconductance ($g_m$) of this HFET was about 120 mS/mm. It was also confirmed that the breakdown voltage of schottky property was over 600 V. Therefore, a high power AlGaN/GaN HFET was thus demonstrated.