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GaN TRANSISTORS FOR POWER SWITCHING AND MILLIMETER-WAVE APPLICATIONS

TETSUZO UEDA, YASUHIRO UEMOTO, TSUYOSHI TANAKA, and DAISUKE UEDA[*]

Semiconductor Device Research Center, Semiconductor Company, Panasonic Corporation
1 Kotari-yakemachi, Nagaokakyo-shi, Kyoto 617-8520, JAPAN
ueda.tetsuzo@jp.panasonic.com

We review our state-of-the-art GaN-based device technologies for power switching at low frequencies and for future millimeter-wave communication systems. These two applications are emerging in addition to the power amplifiers at microwave frequencies which have been already commercialized for cellular base stations. Technical issues of the power switching GaN device include lowering the fabrication cost, normally-off operation and further increase of the breakdown voltages extracting full potential of GaN-based materials. We establish flat and crack-free epitaxial growth of GaN on Si which can reduce the chip cost. Our novel device structure called Gate Injection Transistor (GIT) achieves normally-off operation with high enough drain current utilizing conductivity modulation. Here we also present the world highest breakdown voltage of 10400V in AlGaN/GaN HFETs. In this paper, we also present high frequency GaN-based devices for millimeter-wave applications. Short-gate MIS-HFETs using in-situ SiN as gate insulators achieve high f_{max} up to 203GHz. Successful integration of low-loss microstrip lines with via-holes onto sapphire enables compact 3-stage K-band amplifier MMIC of which the small-signal gain is as high as 22dB at 26GHz. The presented devices are promising for the two future emerging applications demonstrating high enough potential of GaN-based transistors.

Keywords: AlGaN/GaN; heterojunction FET; Gate Injection Transistor; on-state resistance; breakdown voltage; MIS-HFET; microstrip line

1. Introduction

AlGaN/GaN heterojunction field effect transistors (HFETs) have been widely investigated primary for power amplifiers at microwave frequencies to be used for wireless communications taking advantage of the superior material properties. So far, these power amplifiers mainly for cellular-phone base stations have been commercialized which should make the system highly efficient and very compact. Besides such microwave applications, high power switching at low frequencies and further extension of operating frequencies to millimeter-wave range are promising as future emerging applications of GaN-based devices. In this paper, we review our state-of-the-art device technologies for such two future applications of GaN transistors.

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[*] Present affiliation: *Advanced Technology Research Laboratories, Panasonic Corporation, 3-4 Hikaridai, Seika-cho, Soraku-gun, 619-0237 Kyoto, JAPAN.*

2. GaN Transistors for Power Switching

GaN-based power switching transistors have been expected to replace the currently used Si-based MOSFETs and IGBTs enabling highly efficient switching owing to the low on-state resistance and the high breakdown voltage. Lowering the fabrication costs of these GaN devices is critical for the widely-spread use of them, and so far the cost of the substrate for epitaxy such as SiC has been dominant in the total costs. We establish the epitaxial growth of GaN on cost-effective Si using AlN/GaN superlattice interlayer which relaxes the epitaxial strain caused by the lattice and thermal mismatches. Crack-free and mirror surfaces of AlGaN/GaN are obtained over 6-inch diameter Si substrate as shown in Fig.1, where the highest electron mobility of 1653cm^2/Vsec is confirmed. Using the epitaxial growth technologies, we have demonstrated high enough performance of AlGaN/GaN power switching transistors on Si substrates[1].

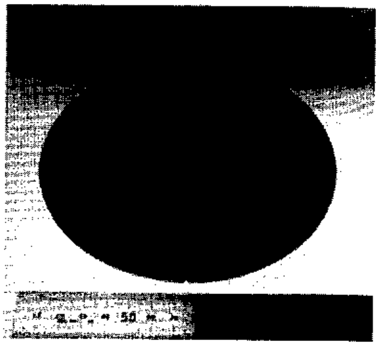


Fig. 1 Photograph of a crack-free AlGaN/GaN epitaxial wafer on a 6-inch diameter Si substrate.

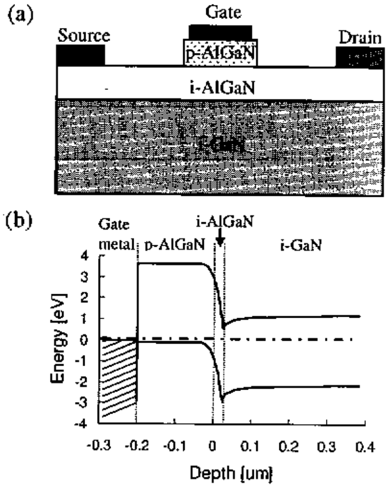
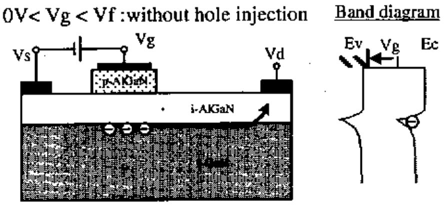


Fig. 2 A schematic illustration of
(a) GIT structure and
(b) calculated band diagram of GIT at the gate bias of 0V. The epitaxial structure is designed to serve normally-off operations.

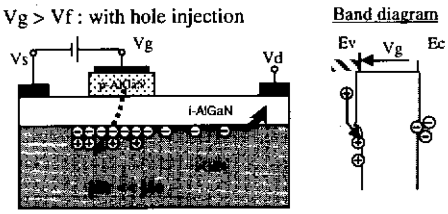
The most crucial task left for the GaN transistors is to achieve normally-off operation which is strongly desired for the safety operation, however, it has been very difficult because of the built-in polarization electric field in the GaN-based material systems. Our solution for the normally-off operation is a new device called GIT (Gate Injection Transistor) as shown in Fig.2(a)[2]. The GIT features the p-AlGaN gate formed over the undoped AlGaN/GaN hetero-structure. The p-AlGaN lifts up the potential at the channel, which results in normally-off operation as shown in the band diagram of Fig.2(b). Fig.3 illustrates the basic operation of the GIT utilizing conductivity modulation. At the gate voltages up to the forward built-in voltage V_f of the pn junction at the gate, the GIT is operated as a field effect transistor. Further increase of the gate voltage exceeding the V_f results in the hole injection to the channel from the p-AlGaN. The injected holes generate the equal numbers of electrons to keep charge neutrality at the channel. The generated electrons are moved by the drain bias with high mobility, while the injected holes stay around the gate because the hole mobility is two order of magnitude lower than that of the electron. This results in significant increase of the drain current keeping the low gate current. Fig.4

shows the I_{ds}-V_{gs} and g_m-V_{gs} characteristics of the fabricated GIT comparing with those of the conventional Schottky-gate FET. The GIT exhibits peculiar transconductance characteristics with two peaks. Followed by the FET operation up to the V_{gs} of 3V, the I_{ds} is super-linearly increased corresponding to the second g_m peak, which is a direct evidence of the conductivity modulation caused by the hole injection.

(a) 0V< Vg < Vf :without hole injection



(b) Vg > Vf : with hole injection



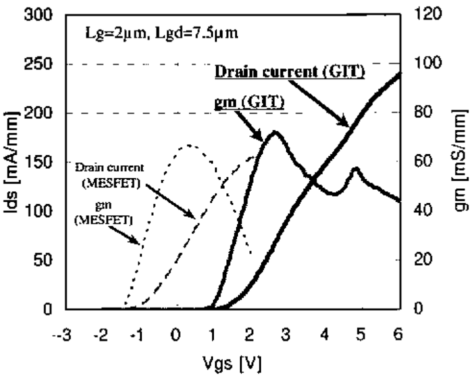


Fig. 3 A schematic illustration of GIT operation varying gate voltages :
(a) without hole injection at Vg < Vf,
(b) with hole injection at Vg > Vf.

Fig. 4 Ids-Vgs abd gm-Vgs characteristics of fabricated (a) GIT and (b) MESFET.

Another technical task for GaN power switching transistor is to further increase the breakdown voltage extracting the full advantage of the superior material properties of GaN. So far, the reported highest off-state breakdown voltage of AlGaN/GaN HFETs maintaining low on-state resistance has remained 1900V at highest[3]. Possible reason of such low value is surface flashover in the air or breakdown of passivation with low dielectric strength, which occurs between electrodes in the lateral device configuration[4]. Overcoming these issues, we have demonstrated ultra high breakdown voltages of AlGaN/GaN HFETs with a novel structure avoiding the undesired breakdown of which the schematic cross section is shown in Fig.5[5]. The most notable feature of the HFET is the via-hole through sapphire at the drain electrode of which the peripheral length can be designed as small as possible. Placing the small drain electrode at the center of the concentric unit cell of the transistor effectively suppresses the premature breakdown between the surface electrodes. A closely-packed array of the unit cell enables a very efficient chip layout as well. Since conventional wet or dry etching cannot be used for chemically stable sapphire, high power pulsed laser is used to form the via-holes. Thick gold plating, wafer thinning and backside metallization follow the laser drilling of sapphire. The thick AlN passivation also helps to increase the breakdown voltages owing to the high breakdown strength. The AlN is deposited by DC-sputtering technique which has 200 times higher thermal conductivity than that of conventional SiN and thus effectively reduces the thermal resistance of the HFET[6]. The optical microscopic image and cross sectional SEM image of the fabricated HFET are shown in Fig. 6 and Fig. 7, respectively.

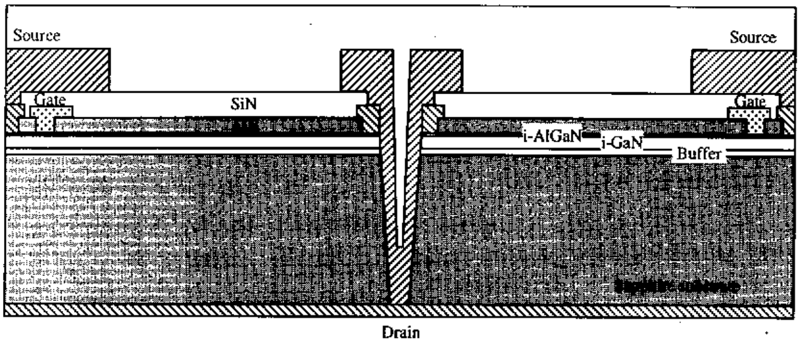


Fig. 5 A schematic cross-section of the fabricated ultra high voltage HFETs with via-holes through sapphire and AlN passivation.

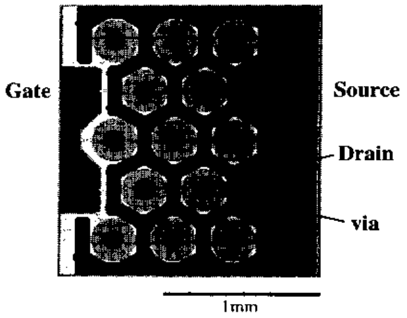


Fig. 6 Microphotograph of the fabricated ultra high voltage HFET.

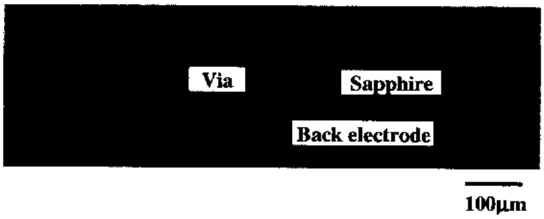


Fig. 7 Cross sectional SEM image of fabricated via-holes through sapphire.

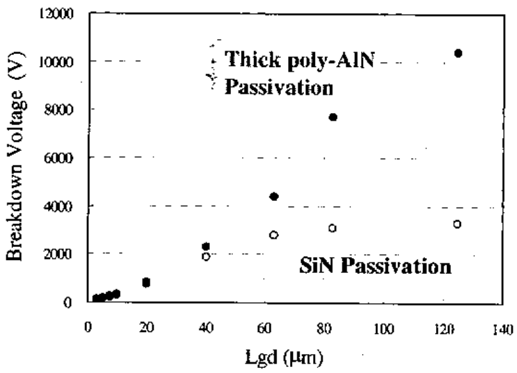


Fig. 8 The off-state breakdown voltages (BV_{ds}) of fabricated HFETs for various L_{gd}. BV_{ds} of 10400V at Lgd=125μm is obtained with AlN passivation.

Fig. 8 shows the resultant off-state breakdown voltages (BV_{ds}) as a function of the L_{gd} for various passivations. The BV_{ds} of the HFET with AlN passivation, proportionally increases as L_{gd} increases, while the BV_{ds} saturates at 3000V in the HFETs with SiN passivation. The obtained 10400V with L_{gd} of 125μm is the highest value ever reported for GaN-based transistors, which also shows a

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strong sign of further increase with the extension of L_{gd} over 125μm. The specific on-state resistance $R_{on}\cdot A$ is 186mΩ·cm^2 with the I_{max} of 150mA/mm for the ultra high voltage AlGaN/GaN HFET with L_{gd} of 125μm. The above two results of the normally-off GIT and the ultra high voltage HFET are plotted in Fig. 9 comparing those of the state-of-the-art Si-based power devices. The presented devices demonstrate that GaN is advantageous in wide range of the operating voltages for various applications.

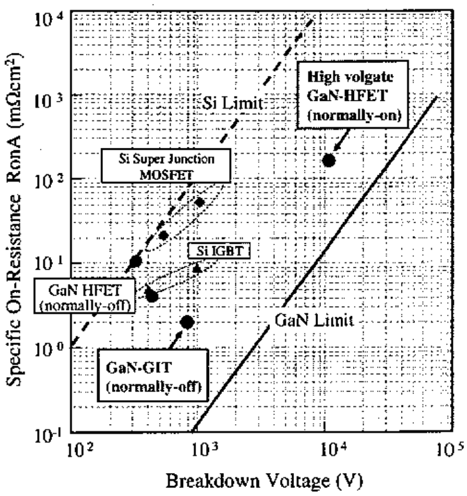

Fig.9 $R_{on}\cdot A$ and breakdown voltage of the fabricated Gate Injection Transistor and ultra high voltage AlGaN/GaN HFET comparing with those of state-of-the-art GaN-based and Si-based devices.

3. GaN HFETs/MMICs for Future Millimeter-wave Communications

GaN devices are also promising for millimeter-wave frequency range since the material system should be an only viable choice for high power amplifier at such high frequencies to increase the distance of the wireless communication. In addition, the GaN device is advantageous in the receiver devices in the millimeter-wave communication systems, because the robust devices can be operated under harsh environments typically at around the outside antenna. The inherent low noise feature is attractive as well[7]. Fig.10 shows the schematic cross section of our state-of-the art AlGaN/GaN MIS-HFET with short gate length down to 100nm[8]. The in-situ SiN is formed subsequently after the MOCVD in the same reactor without any exposure in the air. The SiN exhibits crystalline structure with abrupt interfaces as shown in Fig. 11, by which sheet carrier concentration at the 2DEG isdramatically

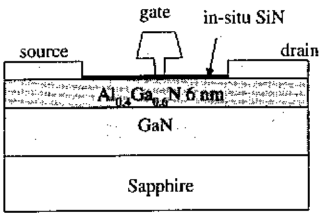

Fig. 10 Schematic cross section of the fabricated AlGaN/GaN MIS-HFET.

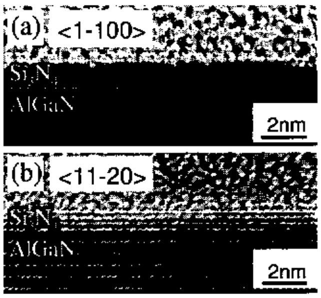

Fig. 11 Cross sectional TEM images at the in-situ SiN/AlGaN interface. The zone axis of (a) <1-100> and (b) <11-20> directions are shown.

increased[9]. Fig.12 shows the measured small signal RF characteristics of the MIS-HFET, where the current gain cut-off frequency (f_T) of 71 GHz and the maximum oscillation frequency (f_{max}) of 203 GHz are obtained keeping the high enough off-state breakdown voltage at around 200V. These results indicate that GaN transistors are also promising for millimeter-wave applications.

In order to implement the GaN devices for practical use especially as the receiving device, transmission lines need to be integrated. Sapphire is an attractive choice of a substrate for the GaN-based MMIC since its insulating nature would greatly help to reduce the loss of the transmission line. We demonstrate a compact 3-stage K-band GaN-based MMIC with integrated microstrip lines with high gain of which the chip photograph is shown in Fig 13[10]. The via-holes for the microstrip lines are successfully formed onto sapphire by the laser drilling technique. Note that the fully integrated matching networks were designed to give the gain matching for the input and output impedances of the three HFETs The measured small signal gain S_{21} of the 3-stage amplifier are shown in Fig. 14, where a small-signal gain as high as 22dB at 26GHz with a 3dB bandwidth of 25-29GHz is confirmed. The presented configuration of the MMIC would be applicable to future millimeter-wave communication systems to be used under harsh environments taking advantage of the robust nature of the GaN-based material systems.

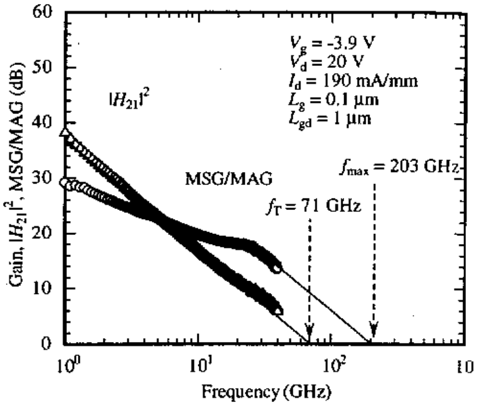

Fig. 12 Small signal RF characteristics of the AlGaN/Gan MIS-HFET.

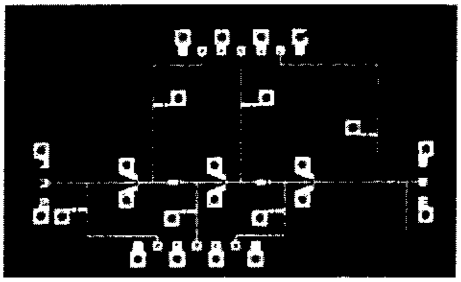

Fig. 13 A chip photograph of the fabricated K-band MMIC.

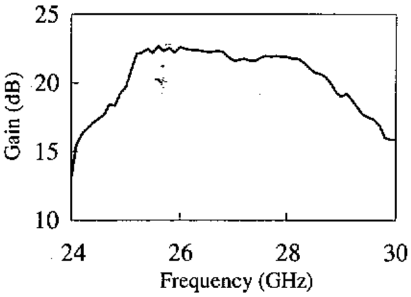

Fig. 14 Measured small signal gain of the 3-stage amplifier.

4. Conclusions

In this paper, we review our state-of-the-art GaN-based device technologies for power switching and future millimeter-wave communications. As for the power switching GaN devices, we present a novel device structure called GIT, which enables normally-off operation with high drain current utilizing conductivity modulation. Here we also present the world highest breakdown voltage of 10400V in AlGaN/GaN HFETs. The device structure with via-holes through sapphire and thick AlN passivation helps to eliminate undesired breakdown between electrodes via passivation dielectric. In the last part of this paper, we present GaN-based MIS-HFETs with in-situ SiN as gate insulators, which exhibit as high f_{max} as 203GHz. The successful integration of low-loss microstrip lines with via-holes onto sapphire enables compact 3-stage K-band amplifier MMIC. The MMIC exhibits a small-signal gain as high as 22dB at 26GHz with a 3dB bandwidth of 25-29GHz. The presented devices are promising for the two future emerging applications demonstrating high enough potential of GaN-based transistors.

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References

1. M. Hikita, M. Yanagihara, K. Nakazawa, H. Ueno, Y. Hirose, T. Ueda, Y. Uemoto, T. Tanaka, D. Ueda, and T. Egawa, "350V/150A AlGaN/GaN power HFET on Silicon substrate with source-via grounding (SVG) structure," *IEEE Trans. Electron Device*, vol.52, no.9, pp1963-1968, 2005.
2. Y. Uemoto, M. Hikita, H. Ueno, H. Matsuo, H. Ishida, M. Yanagihara, T. Ueda, T. Tanaka, D. Ueda, "Gate Injection Transistor (GIT)—A Normally-Off AlGaN/GaN Power Transistor Using Conductivity Modulation,"*IEEE Trans. Electron Device*, vol.54, no.12, pp3393-3399, 2007.
3. Y. Dora, A. Chakraborty, L. McCarthy, S. Keller, S. P. DenBaars, and U. K. Mishra, "High-Breakdown Voltage Achieved on AlGaN/GaN HEMTs With Integrated Slant Field-Plate", *IEEE Electron Device Letters*, vol.27, no.9, pp713-715, 2006.
4. N.Tipimeni, V.Adivarahan, G.Simin, and A.Khan, "Silicon Dioxide-Encapsulated High-Voltage AlGaN/GaN HFETs for Power-Switching Applications", IEEE Electron Device Letters, vol.28, no.9, pp784-786, 2007.

5. Y. Uemoto, D. Shibata, M. Yanagihara, H. Ishida, H. Matsuo, T. Ueda, T. Tanaka, and D. Ueda, "8300V Blocking Voltage AlGaN/GaN Power HFET with Thick Poly-AlN Passivation." *IEDM Technical Digests*, pp. 861-864, December 2007.
6. N. Tsurumi. H. Ueno, T. Murata, H. Ishida, Y. Uemoto, T. Ueda, K. Inoue, and T. Tanaka, "AlN Passivation over AlGaN/GaN HFETs for High Power Operation.", *7th Topical workshop on Heterostructure Microelectronics*, Kisarazu, Chiba, Japan , Aug. 2007.
7. Y. Hirose, Y. Ikeda, M. Ishii, T. Murata, K. Inoue, T. Tanaka, H. Ishikawa, T. Egawa, and T. Jimbo, "Low Noise and Low Distortion Performances of an AlGaN-GaN HFETs", *IEICE Trans. Electron.*, vol.E86-C, pp.2058-2064, 2003.
8. M. Kuroda, T. Murata, S. Nakazawa, T. Takizawa, M. Nishijima, M. Yanagihara, T. Ueda, and T.Tanaka, "High fmax with High Breakdown Voltage in AlGaN/GaN MIS-HFETs Using In-situ SiN as Gate Insulators." *2008 IEEE Compound Semiconductor Integrated Circuit Symposium*, Monterey, CA, U.S.A., October 2008.
9. T. Takizawa, S. Nakazawa, and T Ueda, "Crystalline SiNx Ultrathin Films Grown on AlGaN/GaN Using In-Situ Metalorganic Chemical Vapor Deposition," *J. Electron. Mater.*, vol. 37, pp.628-634, 2008.
10. T. Murata, M. Kuroda, S.Nagai., M. Nishijima, H. Ishida, M. Yanagihara, T. Ueda, H. Sakai, T.Tanaka, and M. Li, "A K-band AlGaN/GaN-based MMIC Amplifier with Microstrip Lines on Sapphire", 2008 *IEEE International Microwave Symposium*, Atlanta, GA, U.S.A., June 2008.

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