SELECTED TOPICS IN APPLIED PHYSICS

GaN transistors on Si for switching and high-frequency applications

Japanese Journal of Applied Physics **53**, 100214 (2014)
http://dx.doi.org/10.7567/JJAP.53.100214

GaN transistors on Si for switching and high-frequency applications

Tetsuzo Ueda[1,2*], Masahiro Ishida[2], Tsuyoshi Tanaka[2], and Daisuke Ueda[3]

[1]*Power Electronics Development Center, Automotive & Industrial Systems Company, Panasonic Corporation, Moriguchi, Osaka 570-8501, Japan*
[2]*Green Innovation Development Center, Automotive & Industrial Systems Company, Panasonic Corporation, Nagaokakyo, Kyoto 617-8520, Japan*
[3]*R&D Division, Panasonic Corporation, Moriguchi, Osaka 570-8501, Japan*
E-mail: ueda.tetsuzo@jp.panasonic.com

Received May 26, 2014; accepted July 22, 2014; published online September 29, 2014

In this paper, recent advances of GaN transistors on Si for switching and high-frequency applications are reviewed. Novel epitaxial structures including superlattice interlayers grown by metal organic chemical vapor deposition (MOCVD) relieve the strain and eliminate the cracks in the GaN over large-diameter Si substrates up to 8 in. As a new device structure for high-power switching application, Gate Injection Transistors (GITs) with a p-AlGaN gate over an AlGaN/GaN heterostructure successfully achieve normally-off operations maintaining high drain currents and low on-state resistances. Note that the GITs on Si are free from current collapse up to 600 V, by which the drain current would be markedly reduced after the application of high drain voltages. Highly efficient operations of an inverter and DC–DC converters are presented as promising applications of GITs for power switching. The high efficiencies in an inverter, a resonant LLC converter, and a point-of-load (POL) converter demonstrate the superior potential of the GaN transistors on Si. As for high-frequency transistors, AlGaN/GaN heterojuction field-effect transistors (HFETs) on Si designed specifically for microwave and millimeter-wave frequencies demonstrate a sufficiently high output power at these frequencies. Output powers of 203 W at 2.5 GHz and 10.7 W at 26.5 GHz are achieved by the fabricated GaN transistors. These devices for switching and high-frequency applications are very promising as future energy-efficient electronics because of their inherent low fabrication cost and superior device performance.

1. Introduction

GaN transistors have been attractive targets for research on next-generation energy-efficient electronics, since they can be used in high-power and high-frequency operations because of their high breakdown strength and high carrier velocity. Researchers started paying attention to the material for transistors after the demonstration of the extraordinarily high carrier concentration of two-dimensional electron gas (2DEG) formed at the AlGaN/GaN heterostructure even without any intentional doping.[1] This 2DEG is due to the high electric field induced by the material's unique polarization that would extend the use of GaN as electron devices utilizing the so-called polarization engineering.[2,3] The first commercial products of the GaN transistors were formed on SiC substrates and operated at microwave frequencies as power amplifiers mainly for cellular base stations.[4,5] Although the operating voltage was as low as 50 V for the output power of 100 W at 1 GHz or higher, the successful commercialization with the established reliability suggested that GaN can be applied also to power switching at higher voltages for which a far larger market has been expected. Although the use of SiC for the GaN transistors enables high-performance devices, cost reduction, which is mandatorily required for promising switching applications, would be limited because of SiC wafer's high cost and small size. GaN on cost-effective Si substrates has emerged as a very promising alternative for power switching applications after the demonstration of epitaxial growth of high-quality GaN on it.[6–9] So far, the wafer diameter of Si for GaN growth has been increased to 8 in. with various innovative device structures for desired normally-off operations.[10–12] By using the GaN transistors with breakdown voltages up to 600 V, highly efficient switching systems exhibiting a great potential of the new material have been demonstrated.[13,14] High-frequency applications can also receive the benefit of the established GaN-on-Si technology for further cost reduction. Thus, GaN transistors on Si are very promising in various applications because of their inherent low cost fabrication and highly efficient operations.

In this paper, GaN transistors on Si substrates for both power switching and high-frequency applications are reviewed. After summarizing the data on successful epitaxial growth of GaN on Si by metal organic chemical vapor deposition (MOCVD) up to 8 in. in diameter, normally-off Gate Injection Transistors (GITs) and highly efficient switching systems using GITs are presented. The material and processing technologies are also applied to power amplifiers at microwave and millimeter-wave frequencies, demonstrating as comparably high power as those by conventional GaN devices on SiC.

2. Epitaxial growth of GaN on Si substrates

Since no native GaN substrate is available, investigations on the formation of GaN crystals were focused on the so-called heteroepitaxial growth on substrates other than GaN. Pioneering works on the epitaxial growth were carried out on sapphire substrates with novel buffer layer techniques.[15,16] The heteroepitaxial growth has enabled the commercialization of bright light-emitting diodes with sufficiently long lifetime even with high dislocation density on the order of $10^9\,\mathrm{cm}^{-2}$.[17] Among substrate materials for the epitaxial growth of GaN, Si was considered as a promising one because of its high quality and large diameter at a cost lower than others. The use of Si is particularly promising for power switching transistors that require large chips; however, the large lattice and thermal mismatches between GaN and Si are apparent obstacles for the growth of high-quality GaN films, as shown in Fig. 1. The introduction of novel buffer layers to overcome the above mismatches has enabled the development of crack-free and mirror surfaces of GaN over Si substrates.[6–9] Figure 2 shows a schematic cross section of AlGaN/GaN on Si with buffer layers. This structure enables the successful epitaxial growth of GaN on Si with mirror surfaces, where the initial AlN layer prevents Si from diffusing into the GaN overgrown layer. The AlN/GaN superlattice layers relaxing the strain between GaN and the Si

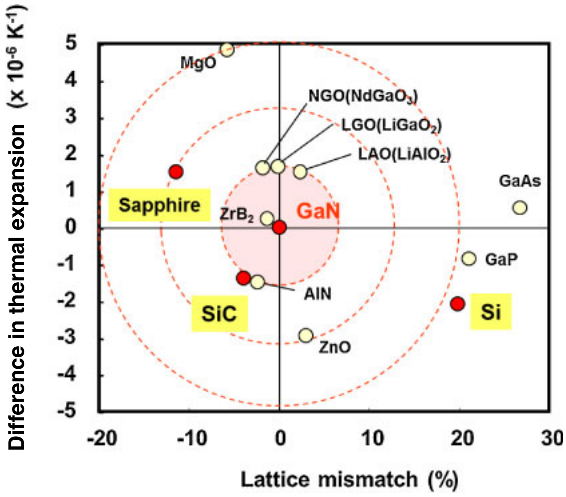

Fig. 1. (Color online) Summary of lattice and thermal mismatches between GaN and various substrates for the epitaxial growth.

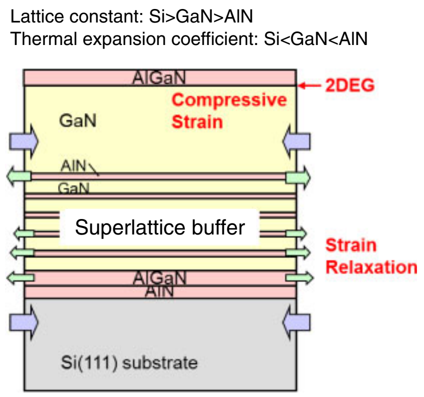

Fig. 2. (Color online) Schematic cross section of an AlGaN/GaN heterostructure on a Si substrate. The arrows in the figure correspond to the magnitude of the tensile or compressive stresses in the film.

substrate eliminate the cracks in the film and reduce the degree of wafer bowing. A transmission electron microscopy (TEM) image of the AlGaN/GaN film containing multilayers with very flat interfaces is shown in Fig. 3. The electron mobility at AlGaN/GaN on silicon reaches 2110 $cm^2 V^{-1} s^{-1}$, which is as comparably high as that on a sapphire or SiC substrate. The uniformity is sufficiently good over 6 in. Si, as shown in Fig. 4. The size of the wafer is extended to 8 in., the photograph of which is shown in Fig. 5.[12] Figure 6 shows the measured breakdown voltages of the fabricated normally-off GaN transistors on Si plotted as a function of the spacing between the gate and the drain (L_{gd}). The breakdown voltages are increased by the extension of L_{gd} up to a certain value owing to the lateral device configuration. Since the Si substrate is conductive, the electric field around the drain is formed along the vertical direction by further extending L_{gd}. When the Si substrate is grounded, the saturation of the off-state breakdown voltages is observed for L_{gd} values smaller than those measured for the floating condition. Since the potential at the substrate underneath the drain is between the drain bias and the source bias under the floating condition, the maximum electric field is smaller than that obtained when the substrate is grounded. Thus, the saturation of the

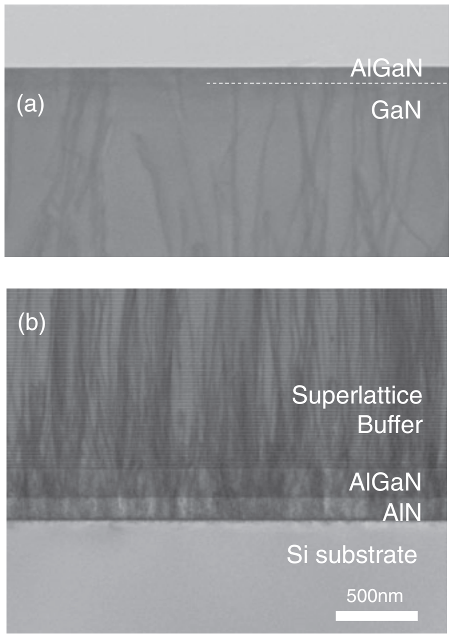

Fig. 3. Cross-sectional TEM images of AlGaN/GaN on Si (a) on the surface and (b) at the interface between the GaN-based layers and the Si substrate. Flat interfaces of AlN/GaN superlattice interlayers are confirmed in (b).

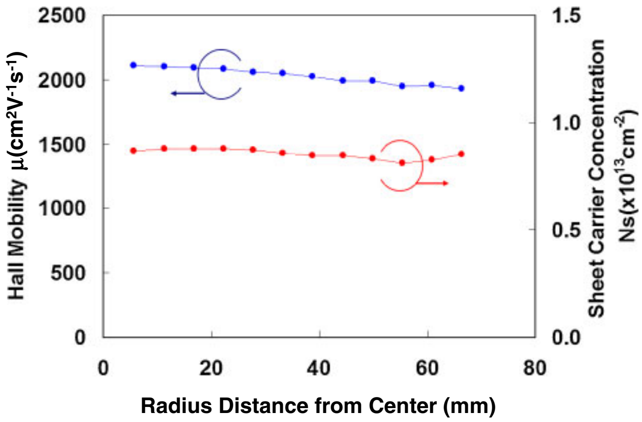

Fig. 4. (Color online) Variations in electron mobility and sheet carrier concentration at AlGaN/GaN heterointerfaces over a 6 in. Si substrate.

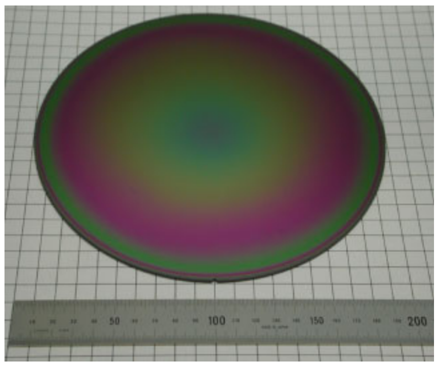

Fig. 5. (Color online) Photograph of AlGaN/GaN over an 8 in. Si substrate.

breakdown voltages appears at larger L_{gd} values for the floating condition. The saturation value with the extended L_{gd} is determined by the thickness of the GaN-based epitaxial

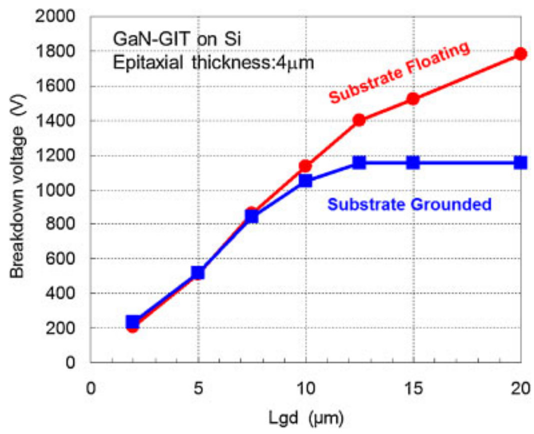

Fig. 6. (Color online) Off-state breakdown voltages of normally-off GaN transistors with various L_{gd} values, where those measured with the substrate biased as grounded and floating are compared.

films on Si. A maximum breakdown voltage of 1150 V is achieved for the 4.6-μm-thick GaN on Si, where the breakdown strength is as high as 2.9 MV/cm. Further improvement of the epitaxial growth method aimed at obtaining a thicker film with the reduced degree of bowing on Si would increase the applicable voltages in the practical switching systems using GaN transistors on Si, which would make the GaN devices more promising.

3. GaN transistors for switching applications

3.1 Gate injection transistors with normally-off operations

Power switching systems strongly require normally-off operations of the employed switching transistors for their safe operations. Although the inherent high carrier concentration at AlGaN/GaN is a technical advantage of the GaN transistor, this makes the normally-off operation very difficult to achieve. The examination of various gate structures has been a subject of research for GaN transistors, which includes p-type gates, metal–insulator–semiconductor (MIS) gates, and fluorine doping.[11,18–20] In addition to the normally-off operation by a single GaN transistor, cascode connection of a normally-on GaN transistor and a Si metal–oxide–semiconductor (MOS) transistor has been demonstrated as an alternative.[21] The cascode configuration has disadvantages of high cost due to the two devices and insufficient controllability of the switching speed, although the driving voltages are compatible with that for the existing Si devices. In the course of the investigation of the p-type gate, it is experimentally found that the injected holes from the p-type AlGaN gate formed over the AlGaN/GaN heterostructure increase the drain current by conductivity modulation. The injection of holes makes it possible to obtain a low on-state resistance with a high drain current maintaining the normally-off operation. The device structure is named the GIT, the schematic cross section and the operation principle of which are shown in Fig. 7.[11] I_{ds}–V_{gs} characteristics of the fabricated GIT in Fig. 8 show the second peak of the transconductance g_m at higher gate voltages indicating the conductivity modulation. Typical values of the specific on-state resistance and breakdown voltage are 2.0 mΩ cm^2 and 700 V, respectively.[22] Currently, larger chips of the GIT on Si that can handle current up to 15 A with very low $R_{on}Q_g$ (R_{on}: on-state

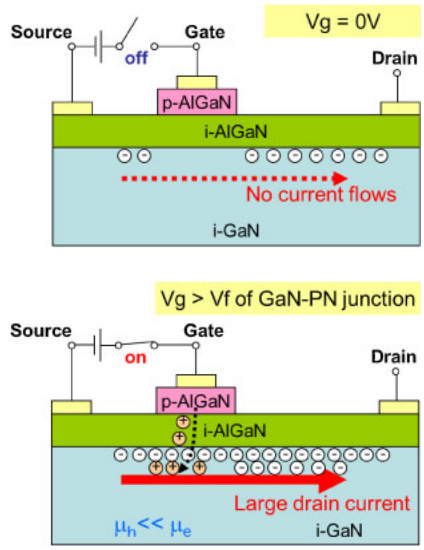

Fig. 7. (Color online) Schematic cross section and operating principle of GIT.

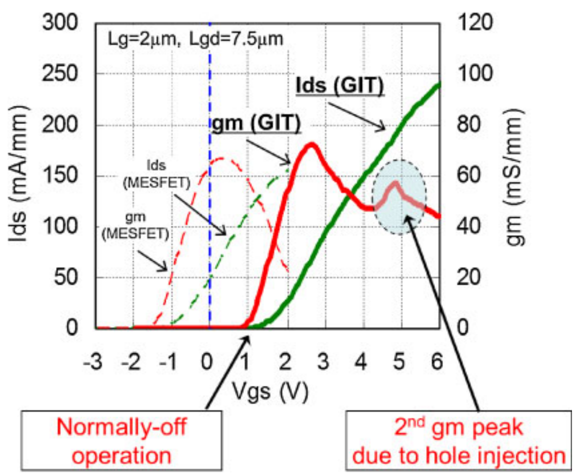

Fig. 8. (Color online) I_{ds}–V_{gs} characteristics of the fabricated GIT, where those of conventional AlGaN/GaN Schottky-gate MESFET are also shown.

resistance, Q_g: gate charge) of 700 mΩ nC are available for the examination of practical switching systems. $R_{on}Q_g$ as a figure-of-merit of the high-speed switching is one thirteenth that by state-of-the-art Si superjunction MOSFETs. So far, current collapse, in which the drain current is reduced after an off-stress is applied to GaN-based transistors, has been a critical issue in the stable operations of switching systems. On-state resistances are also increased by the collapse, which is more distinctly observed after the application of higher drain voltages at the off-state. This is believed to be due to the trapped electrons in AlGaN/GaN and/or passivation films.[23] By the improvement of the device structures and processing, no significant increase in on-state resistance after the off-state stress is observed in GITs on Si up to 600 V, as shown in Fig. 9. The improvements include the elimination of traps in the device and the relief of electric fields that induce trapping. Since the multiple off-state pulses of the drain voltages are used in the test, the slight increase in on-state resistance at the increased drain voltages is presumably caused by the increase in channel temperature. The fabricated

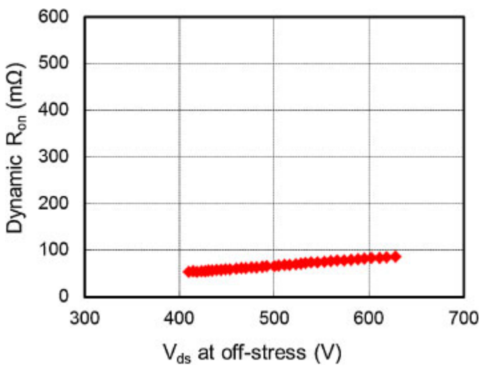

Fig. 9. (Color online) Dynamic on-state resistances of GaN GITs after off-state stress at various drain voltages.

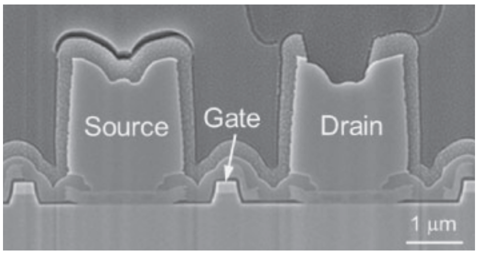

Fig. 10. Cross-sectional SEM image of the fabricated GaN GIT with the gate length of 0.5 μm.

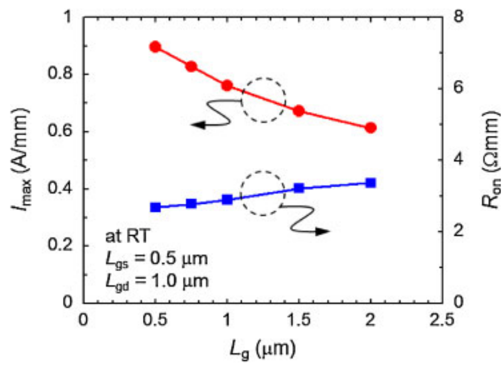

Fig. 11. (Color online) I_{max} and R_{on} of GaN GITs with various gate lengths. The spacing between the gate and the drain is 1.0 μm, which achieves the breakdown voltage of 30 V.

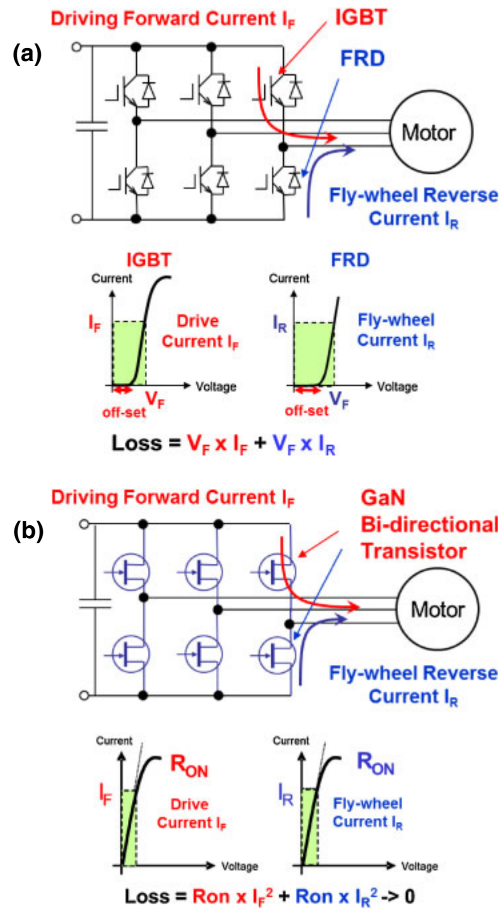

Fig. 12. (Color online) Circuit diagrams of inverters for motor drive using (a) IGBT and (b) GaN, where the forward and reverse I–V characteristics are also shown.

GITs are free from the current collapse up to 600 V; thus, they enable the sufficiently stable operation of the power switching systems. Aiming at further reduction in $R_{on}Q_g$ required for low-voltage applications, gate lengths of the GITs are successfully reduced down to 0.5 μm with sufficient elimination of the processing damage around the gate. A cross sectional scanning electron microscopy (SEM) image of the fabricated GIT with a 0.5 μm gate is shown in Fig. 10. The increase in I_{max} and the reduction in R_{on} for the device with a breakdown voltage of 30 V by reducing the gate lengths are shown in Fig. 11.[24] I_{max} reaches 0.9 A/mm, maintaining the normally-off operations. The presented GITs on Si cover a wide range of operating voltages in the switching systems that extract the superior characteristics of the GITs free from the current collapse with an inherently low fabrication cost.

3.2 Power switching systems using GITs

The presented GITs on Si are applied to various power switching circuits, enabling a higher operating efficiency and a smaller system size. Inverters for motor drive and converter circuits in power supplies with DC voltages up to 600 V are possible applications of currently available GaN devices on Si.

So far, Si-based insulated gate bipolar transistors (IGBTs) have been widely used for inverter systems. Fast recovery diodes (FRDs) must be connected in parallel to the IGBTs to allow the flow of the fly-wheel current. The conduction loss in both devices cannot be fully reduced because of the voltage offset in the current–voltage characteristics for both directions. The use of GaN transistors for inverters would eliminate external diodes since lateral transistors can allow the flow of the current for both directions. In addition, the current–voltage characteristics free from the voltage off-set result in the low conduction loss and high operating efficiency of inverters over a wide output power range. Figure 12 shows the advantages of using GaN transistors for inverters. The conversion efficiencies of the GaN-based inverter using GITs on Si for various output powers are shown in Fig. 13, where efficiencies higher than those obtained using conventional IGBTs are confirmed for all the output powers.[13] Note that the archived 99.3% efficiency

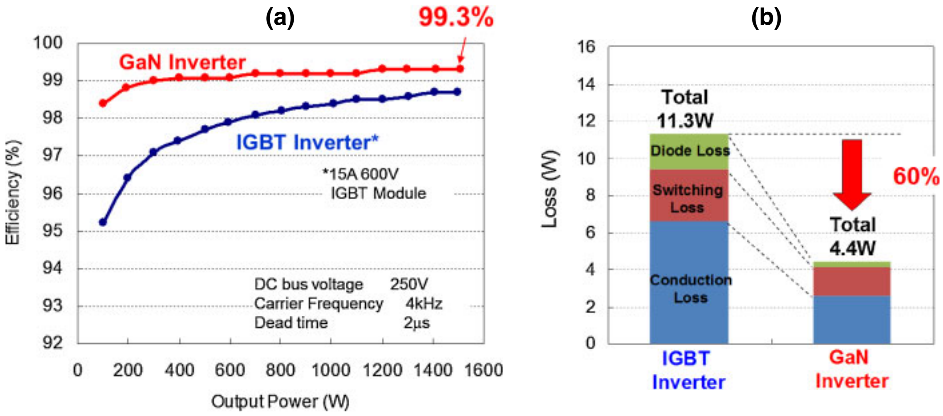

Fig. 13. (Color online) (a) Measured operating efficiencies of GaN-based inverter for various output powers up to 1.5 kW. (b) Details of the operating loss in the GaN-based inverter at 500 W. The efficiencies obtained using GaN are compared with those obtained using conventional IGBTs.

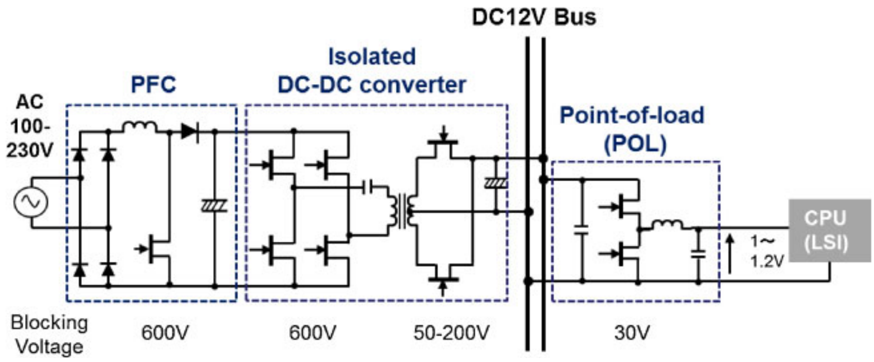

Fig. 14. (Color online) Typical circuit diagram of a power supply, in which an isolated DC–DC converter and a POL are shown.

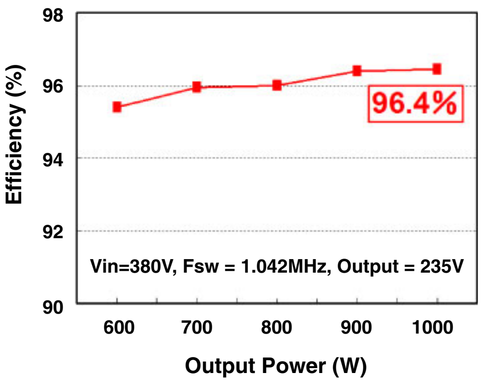

Fig. 15. (Color online) Measured efficiencies of a GaN-based resonant LLC converter at 1 MHz at various output powers.

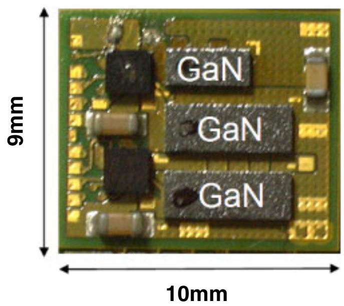

Fig. 16. (Color online) Photograph of the fabricated GaN-based POL module.

at the output of 1.5 kW is the highest value ever reported for a GaN-based inverter.

The size of a power supply can be reduced by increasing the operating frequencies by considering the advantages of smaller passive components. GaN transistors are very promising for various converters, since they enable high efficiencies even at higher frequencies. As a demonstration of the advantage of GaN in a power supply, a highly efficient resonant LLC converter and a low-voltage DC–DC converter called the point-of-load (POL) converter using GITs on Si are presented. These circuits are included in the circuit diagram of a typical power supply in Fig. 14. The LLC converter is a typical circuit topology of isolated DC–DC converters and the POL converter is typically placed in the vicinity of the high-performance large-scale integrated circuits (LSIs) to convert the bus voltage to the low voltage required by LSIs for their operation. The GaN-based LLC converter is successfully operated at 1 MHz with a high efficiency of 96.4% at 1 kW output, as shown in Fig. 15. DC–DC conversions using 600 V devices at such high frequencies have not been achieved by conventional Si-based power transistors, so far. The GITs with a short gate of 0.5 µm length are applied to the POL converter as a module, the top view photograph of which is shown in Fig. 16.[14] The breakdown voltage of the employed GITs is 30 V. Figure 17 shows the operating efficiencies of the POL for the down

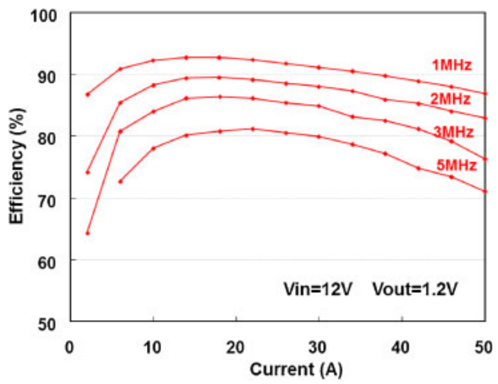

Fig. 17. (Color online) Measured efficiencies of a GaN-based POL at various frequencies up to 5 MHz plotted as a function of the operating current.

conversion from 12 to 1.2 V at various frequencies plotted as a function of the operating current. The peak operating efficiency at 2 MHz reaches 90%, while the operating current can be increased up to 50 A by a single converter module. The converter also exhibits a peak efficiency of 81% at 5 MHz, while conventional Si devices cannot be operated at such high frequencies. These superior characteristics of the GaN-based DC–DC converters would greatly help reduce the size of power supplies.

To extract the full potential of GaN switching transistors, a methodology of the system design suitable for GaN must be established in addition to the superior device performance. The so-called integrated design platform including the simulation of the thermal distribution, noise, and device parameters is proposed and would further improve the performance of the switching systems using GaN transistors.[25]

4. GaN transistors for high frequency applications

4.1 Microwave GaN transistors

Although the first GaN-based microwave power amplifier was commercialized on a SiC substrate, those on cost-effective Si substrates would be expected to further reduce the system cost and to increase the widespread use of GaN-based microwave transistors. Applying the above-mentioned epitaxial growth technologies to the microwave devices makes it possible to obtain power by GaN on Si as comparably high as that on SiC. Figure 18 shows a schematic cross section of the fabricated GaN heterojunction field-effect transistor (HFET) on Si for microwave power amplifiers.[26] The device structure is formed on a highly resistive Si substrate eliminating the undesired conduction at the interface and substrate. The source field plate reduces the feedback capacitance between the gate and the drain, thus increasing the linear gain of the amplifier. In addition, the optimization of the length of the field plate stabilizes the output impedance for the variation in drain voltage. The design of the field plate enables a high output power maintaining the high linear gain. Figure 19 shows the measured output power characteristics of the fabricated GaN HFET on Si, in which 203 W output at 2.5 GHz is achieved for the continuous wave operation. Note that the linear gain is as high as 16.9 dB. The performance is as satisfactory as those of conventional GaN HFETs on SiC.

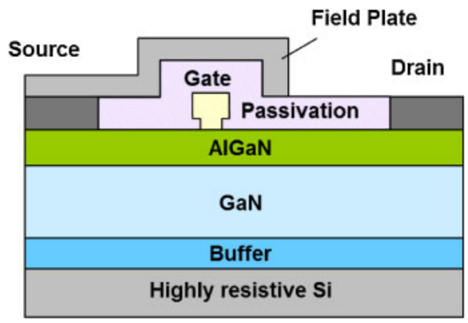

Fig. 18. (Color online) Schematic cross section of the fabricated AlGaN/GaN HFET on Si for microwave power amplifiers.

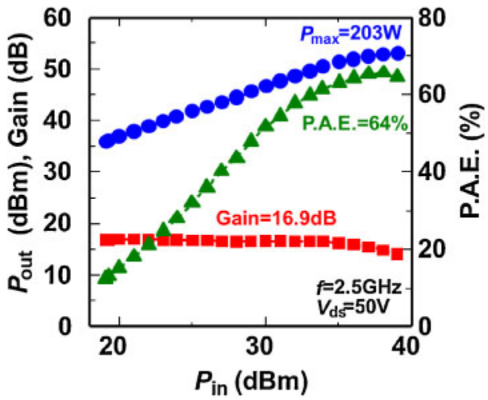

Fig. 19. (Color online) P_{in}–P_{out} characteristics of the AlGaN/GaN HFET with a gate width of 48 mm for CW operation.

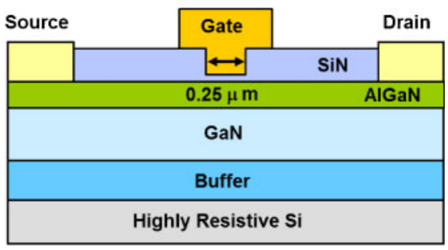

Fig. 20. (Color online) Schematic cross section of the fabricated millimeter-wave AlGaN/GaN MIS-HFET on Si.

4.2 Millimeter-wave GaN transistors

GaN transistors are also promising at frequencies higher than 2.5 GHz. High-power millimeter-wave GaN on Si would help reduce system cost by using it as the transmitter; thus, it would also help the widespread use of wide-band millimeter-wave communication systems. Figure 20 shows a schematic cross section of the fabricated AlGaN/GaN MIS HFET as a millimeter-wave power amplifier.[27] The gate length is reduced down to 0.25 μm to enable a sufficiently high gain at frequencies higher than 20 GHz. The gate structure includes thin SiN formed by high-temperature chemical vapor deposition (CVD) to increase the off-state breakdown voltage and drain current by increasing the applied gate voltages. The resultant breakdown voltage reaches 350 V at its highest. The small signal gain of the fabricated MIS HFET is as high as 10.4 dB at 26.5 GHz. The HFETs are mounted on a power amplifier module with the matching circuits, as shown in Fig. 21, which achieves a high output power of 10.7 W at a

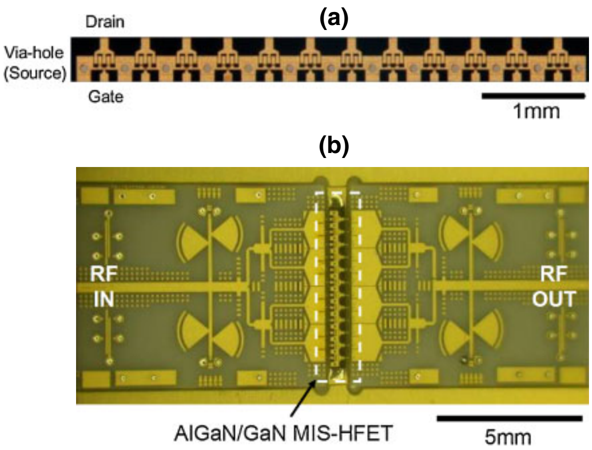

Fig. 21. (Color online) Photographs of the (a) fabricated GaN transistor chip and (b) GaN-based power amplifier module for millimeter-wave applications.

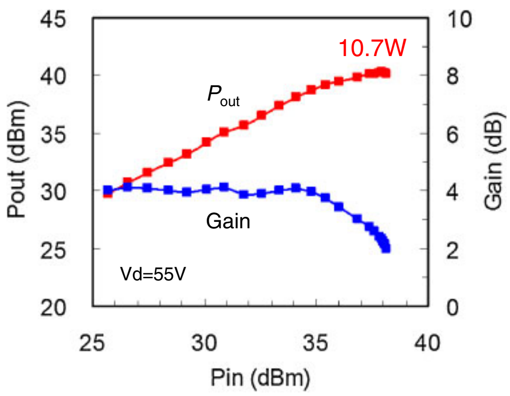

Fig. 22. (Color online) P_{in}–P_{out} characteristics of the AlGaN/GaN MIS-HFET with a gate width of 5.4 mm for pulsed operation.

drain voltage as high as 55 V. Figure 22 shows the resultant power output performance of the power amplifier. The output power is the highest ever reported for GaN devices on Si at millimeter-wave frequencies. The demonstrated high-frequency power amplifier using GaN HFETs on Si at microwave and millimeter-wave frequencies is very promising for cellular base stations and long-distance communication systems because of its inherent low fabrication cost and superior performance.

The demonstrated high-frequency GaN transistors can also be used to drive GaN power switching transistors by using them as high-power oscillators and mixers in the so-called "drive-by-microwave" technology for isolated gate driving.[28] The high-frequency signals are mixed with the switching signal and then transferred to the gate of the switching transistors by electromagnetic resonant coupling. The technology markedly reduces the total size of isolated gate drivers as a result of the high-frequency transmission and also enables faster switching.

5. Conclusions

State-of-the-art technologies of GaN transistors on Si substrates are reviewed. Novel MOCVD techniques using multilayer structures enable the growth of a high-quality GaN film on Si with a diameter of 8 in. at its largest. A new normally-off transistor with a p-AlGaN gate is called a GIT and achieves high drain currents together with low on-state resistances. The notable feature of a GIT on Si is that it is free from current collapse up to 600 V owing to the improvement of the device structure and processing. The high efficiency of 99.3% is confirmed at 1.5 kW by an inverter for a motor drive, and the 1 MHz operation of a resonant LLC converter and the 5 MHz operation of a POL converter are demonstrated to be applicable to a power supply by using GITs on Si. In addition, AlGaN/GaN HFETs for high-frequency application are also demonstrated on Si substrates. The microwave transistor exhibits a high output power of 203 W at 2.5 GHz, while the transistors for millimeter-wave frequencies achieve a high output power of 10.7 W at 26.5 GHz. These characteristics of the GaN transistors on Si demonstrate a great potential of GaN for next-generation energy-efficient electronics.

Acknowledgments

The authors would like to acknowledge Dr. Minoru Kubo and other members of Green Innovation Development Center and Power Electronics Development Center of Panasonic Corporation for their help and advice throughout the research works on GaN devices. The work on GaN power switching devices is partly supported by the New Energy and Industrial Technology Development Organization (NEDO), Japan, under the Strategic Development of Energy Conservation Technology Project and the Energy Saving Innovative Technology Development Project. The work on high-frequency GaN devices is partially supported by "The research and development project for expansion of radio spectrum resources" of the Ministry of Internal Affairs and Communications, Japan.

1) M. A. Khan, J. M. Van Hove, J. N. Kuznia, and D. T. Olson, Appl. Phys. Lett. **58**, 2408 (1991).
2) O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, and J. Hilsenbeck, J. Appl. Phys. **85**, 3222 (1999).
3) T. Ueda, T. Murata, S. Nakazawa, H. Ishida, Y. Uemoto, K. Inoue, T. Tanaka, and D. Ueda, Phys. Status Solidi B **247**, 1735 (2010).
4) K. Joshin, T. Kikkawa, H. Hayashi, T. Maniwa, S. Yokokawa, M. Yokoyama, N. Adachi, and M. Takikawa, IEDM Tech. Dig., 2003, p. 983.
5) Y. Okamoto, Y. Ando, K. Hataya, T. Nakayama, H. Miyamoto, T. Inoue, M. Senda, K. Hirata, M. Kosaki, N. Shibata, and M. Kuzuhara, IEEE Trans. Microwave Theory Tech. **52**, 2536 (2004).
6) H. Ishikawa, G.-Y. Zhao, N. Nakada, T. Egawa, T. Jimbo, and M. Umeno, Jpn. J. Appl. Phys. **38**, L492 (1999).
7) S. L. Selvaraj, T. Suzue, and T. Egawa, IEEE Electron Device Lett. **30**, 587 (2009).
8) T. Ueda, Y. Uemoto, T. Tanaka, and D. Ueda, Int. J. High Speed Electron. Syst. **19**, 145 (2009).
9) M. Yanagihara, Y. Uemoto, T. Ueda, T. Tanaka, and D. Ueda, Phys. Status Solidi A **206**, 1221 (2009).
10) M. Hikita, M. Yanagihara, K. Nakazawa, H. Ueno, Y. Hirose, T. Ueda, Y. Uemoto, T. Tanaka, D. Ueda, and T. Egawa, IEEE Trans. Electron Devices **52**, 1963 (2005).
11) Y. Uemoto, M. Hikita, H. Ueno, H. Matsuo, H. Ishida, M. Yanagihara, T. Ueda, T. Tanaka, and D. Ueda, IEEE Trans. Electron Devices **54**, 3393 (2007).
12) M. Ishida, T. Ueda, T. Tanaka, and D. Ueda, IEEE Trans. Electron Devices **60**, 3053 (2013).
13) T. Morita, S. Tamura, Y. Anda, M. Ishida, Y. Uemoto, T. Ueda, T. Tanaka, and D. Ueda, Proc. 26th IEEE Applied Power Electronics Conf. Expo. (APEC), 2011, p. 481.
14) H. Umeda, Y. Kinoshita, S. Ujita, T. Morita, S. Tamura, M. Ishida, and T. Ueda, PCIM Europe, 2014, PP45.

15) H. Amano, N. Sawaki, I. Akasaki, and Y. Toyoda, Appl. Phys. Lett. **48**, 353 (1986).
16) S. Nakamura, Jpn. J. Appl. Phys. **30**, L1705 (1991).
17) S. Nakamura, M. Senoh, and T. Mukai, Jpn. J. Appl. Phys. **32**, L8 (1993).
18) S. Sugiura, S. Kishimoto, T. Mizutani, M. Kuroda, T. Ueda, and T. Tanaka, Phys. Status Solidi C **5**, 1923 (2008).
19) M. Kanamura, T. Ohki, T. Kikkawa, K. Imanishi, T. Imada, A. Yamada, and N. Hara, IEEE Electron Device Lett. **31**, 189 (2010).
20) Y. Cai, Y. Zhou, K. J. Chen, and K. M. Lau, IEEE Electron Device Lett. **26**, 435 (2005).
21) X. Huang, Z. Liu, Q. Li, and F. C. Lee, 28th IEEE Applied Power Electronics Conf. Expo. (APEC), 2013, p. 1279.
22) Y. Uemoto, T. Morita, A. Ikoshi, H. Umeda, H. Matsuo, J. Shimizu, M. Hikita, M. Yanagihara, T. Ueda, T. Tanaka, and D. Ueda, IEDM Tech. Dig., 2009, p. 165.
23) K. Tanaka, M. Ishida, T. Ueda, and T. Tanaka, Jpn. J. Appl. Phys. **52**, 04CF07 (2013).
24) T. Morita, S. Ujita, H. Umeda, Y. Kinoshita, S. Tamura, Y. Anda, T. Ueda, and T. Tanaka, IEDM Tech. Dig., 2012, p. 151.
25) K. Mizutani, H. Ueno, Y. Kudoh, S. Nagai, K. Inoue, N. Otsuka, T. Ueda, T. Tanaka, and D. Ueda, IEDM Tech. Dig., 2011, p. 26.4.1.
26) S. Nakazawa, N. Tsurumi, M. Nishijima, Y. Anda, M. Ishida, T. Ueda, and T. Tanaka, Jpn. J. Appl. Phys. **51**, 081801 (2012).
27) N. Negoro, M. Kuroda, T. Murata, M. Nishijima, Y. Anda, H. Sakai, T. Ueda, and T. Tanaka, IEICE Trans. Electron. **E95-C**, 1327 (2012).
28) S. Nagai, N. Negoro, T. Fukuda, N. Otsuka, H. Sakai, T. Ueda, T. Tanaka, and D. Ueda, 2012 ISSCC Dig. Tech., 2012, p. 404.

Tetsuzo Ueda received the B.S., M.S. and Ph.D. degrees in electrical engineering from Kyoto University, in 1987, 1989, and 2011, respectively. In 1989, he joined Matsushita Electric (currently Panasonic), where he had been engaged in the development of GaAs MESFETs. From 1995 to 2001, he had been a visiting scholar at Stanford University, where he had been working on epitaxial growth of GaN. From 2001 to 2004, he had been working on GaN lasers and LEDs. Since 2004, he has been working on GaN power switching and high-frequency transistors as a technical director and a general manager at Panasonic.

Masahiro Ishida received the B.S. and M.S. degrees in electrical engineering from Kyoto University, Japan, in 1993 and 1995, respectively. He joined Matsushita Electric (currently Panasonic) in 1995, working on the development of GaN-based Lasers and LEDs. From 2005 to 2006, he has been working on the development of GaN-based laser diodes at University of California, Santa Barbara, U.S.A., as a visiting scholar. Since 2006, he has been working on the research and development of GaN-based devices, including GaN-based lasers, LEDs and switching power devices and is currently a manager at Panasonic.

Tsuyoshi Tanaka received the B.S. and M.S. degrees in applied physics from Osaka University, in 1983 and 1985, respectively. He received Ph.D. degree in electronics engineering from Osaka University in 2000. In 1985, he joined Matsushita Electric (currently Panasonic), where he had been engaged in the development of GaAs transistors. He was awarded Okochi-prize for the world first industrialization of GaAs MMICs with on-chip ferroelectric capacitors. Since 2002, he has been working on GaN transistors. He served a director of Semiconductor Devices Development Center, Panasonic. He also served a visiting professor of Hokkaido University from 2006 to 2007.

Daisuke Ueda received the B.S. and M.S. in electronics engineering from Kyushu Institute of Technology in 1977 and 1979, and Ph.D. degree from Osaka University in 1987. He joined Panasonic in 1979. He developed world-first trench power MOSFET and anode-short IGBT. After staying Stanford University, he started studying varieties of compound semiconductor devices in 1987. He developed front-end MMICs, RF switch, spike-gate power FET with gate-orientation of zero-temperature coefficient. For those achievements, he was twice awarded Okochi-prize in 1996 and 2002. He is a professor in Kyoto Institute of technology at present. He is Fellow of IEICE and IEEE.