Promising Results of National Project by Japanese Ministry of the Environment to Develop GaN on GaN Power Devices and Prove their Usefulness in Real Systems

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Abstract

Exciting high performance power electronic devices have been widely demonstrated and manufactured using GaN epitaxial layers, but the majority of these devices have been fabricated on lattice mismatched substrates, including SiC, Si, or sapphire. Unfortunately, using lattice mismatched substrates inevitably introduces high concentrations of point defects and dislocations into the GaN epilayers, and these defects degrade the electrical performance of the fabricated GaN devices. Also, the mismatch of lattice constant and coefficient of thermal expansion cause strain and wafer bowing in the GaN epi, which further degrade the quality material for device fabrication. Using lattice matched GaN substrates provides solutions to these problems. In 2014, the Ministry of the Environment launched a national project to develop the required technology and to prove the superiority of GaN on GaN devices in real systems, with more than 10 partnerships from academia and industry.

The project included work in several areas, including GaN substrate growth, GaN epitaxy, material characterization, and fabrication of devices and ICs for application in various systems. Large area GaN substrates have been grown with low defect densities, which has enabled fabrication of new types of vertical and horizontal GaN devices. The GaN devices have been used in servers, solar cell power conditioners, microwave ICs, distribution transformers, electric vehicle power converters. The performance improvements were compared with conventional approaches in each case. An "ALL GaN vehicle" has also been demonstrated, in which GaN devices are used in all power components. In this talk, we will present these results which show the great potential of GaN on GaN devices in the industry.

INTRODUCTION

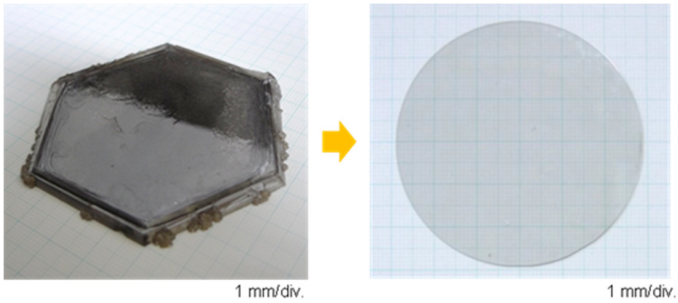
GaN has already made a huge contribution to energy savings through GaN optical devices such as LEDs and LDs. The unique GaN material properties have also enabled very high performance electronic devices. The majority of GaN electronic devices have been fabricated on lattice mismatched substrates (i.e., Si, SiC, and sapphire). Unfortunately, the mismatch of lattice constant between the substrate and the GaN epi introduces extremely high dislocation densities $10^8 cm^{-2}$ to $10^{10} cm^{-2}$, as well has high concentrations of point defects in the GaN epi active layers. Even the best quality GaN devices fabricated on lattice mismatched substrates like SiC still show significant degradation from the presence of these defects, due to trapping effects, band bending, and mobility degradation contributed by the charged defect states. Growth of the GaN epi on high quality low defect density GaN substrates provides an obvious solution to these mismatch related GaN epi quality problems.

The Ministry of the Environment of Japan started a national project in 2014 with the aim of developing a GaN power device manufactured on a GaN substrate and demonstrating its effect in the power system. The objective is to decrease the global CO_2 generation by using these newly developed devices in the future. In this project, we developed high-quality and large-diameter GaN substrates, and high-efficiency power devices and ICs. In parallel, the demonstrations to prove the usefulness of GaN was carried out by using existing GaN power devices, they are incorporated into actual systems such as solar cell power conditioners, servers, microwave ovens, and electric vehicles. Then, GaN on GaN devices is used in the demonstration now. This paper reports the promising results of the project.

MATERIALS

(1) High Quality seed crystal by Na flux method

It is desirable to keep the defect density in GaN epi of the final power device as low as possible. This begins with producing a GaN seed crystal with the lowest possible dislocation density, because these defects will propagate into the GaN material grown from the seed.



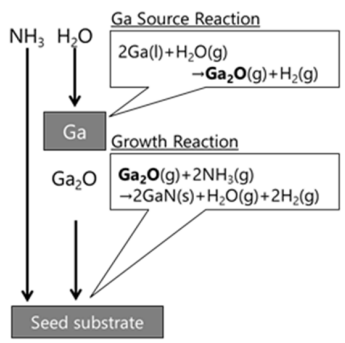
(a)As-grown (b) as-polished (φ58-mm diameter)

Fig.1 GaN wafer grown by Na-flux [1]

For this reason, we developed a very low dislocation density GaN seed crystal using the Na flux "point seed" method.[1] The dislocation density was very low from 10^3 cm^{-2} to 10^5 cm^{-2}, and the lattice radius of curvature is very large (>70 m). A 160mm diameter GaN seed crystal has been successfully grown in this way.

(2) Low resistivity and low defects GaN substrate by OVPE

GaN substrates are typically grown by HVPE (hydride vapor phase epitaxy) which uses a chlorine based carrier gas. An alternate method for growing high quality crystals was developed in this project [2] which is called OVPE (oxide vapor phase epitaxy). Figure 2 shows the OVPE system and growth condition. Since OVPE does not use the chlorine based gases, the reaction products are cleaner (mainly water and hydrogen), so reactor maintenance is much easier than in HVPE. Also, the oxygen in the OVPE growth ambient incorporates in GaN as a donor, so very high n-type GaN doping is possible.



Growth temperature	1170 ℃
Source temperature	1030 ℃
Growth rate	200 μm/h

Fig.2 OVPE System and growth condition

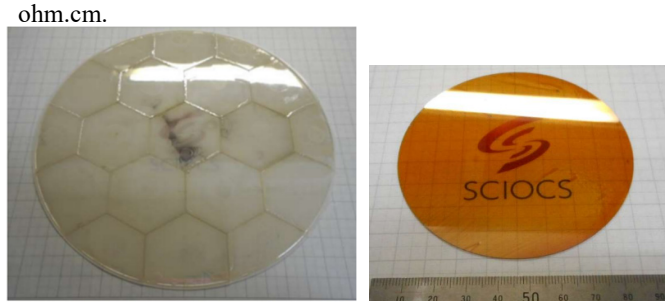
Oxygen concentration	5×10^{21} cm^{-3}
Resistivity	**5×10^{-4} Ω·cm**
Dislocation density	**$1.5\text{-}1.8\times 10^5$ cm^{-2}**

Fig.3 two inch GaN substrate grown by OVPE method

Fig.3 shows GaN substrates grown by OVPE method. Ultra-low resistivity GaN, more that 10X lower than conventional HVPE GaN, were obtained because of the high oxygen doping. The extremely low resistivity of OVPE GaN substrates will enable correspondingly low on-resistance and high efficiency in vertical GaN power devices. Furthermore, the OVPE GaN dislocation density was also 10X lower [3] than conventional HVPE.

(3) Large size wafers (4) High resistive wafer by Mn doped

A very large diameter HVPE single crystal substrate (7 inch = 178mm) was demonstrated by a "tiling method" (see Fig. 4(a))[4] Adding to the very low resistivity substrate mentioned in the previous paragraph(2), very high resistivity wafers are also developed by doping of Mn, which has much deeper energy level from the conduction band in GaN crystal than that of Fe normally used for high resistivity. It realized over 4×10^9 ohm.cm.



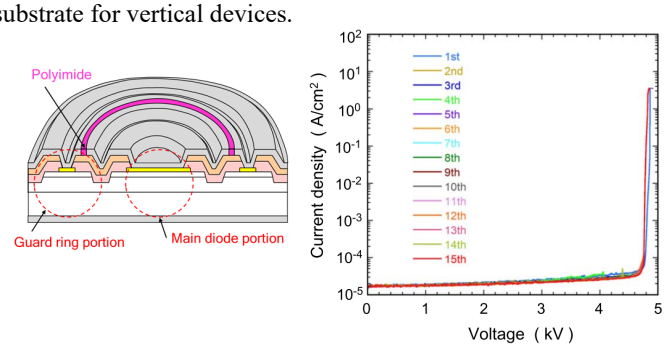
(a) 7 inch substrate (b) 4 inch Mn doped substrate

Fig.4 Large size substrate and high resistivity substrate

DEVICES

(1) PN-Diode

A very high breakdown voltage of 5 kV was achieved for PN diode on GaN substrate with a guard-ring structure (Fig.5(a)) [5] and an excellent reversibility was also realized(Fig.5(b)) [6]. On-resistance (Ron) was reduced by lowering threading dislocation density (TDD) in the diodes with our low TDD substrate (Fig.6(a))[7]. This interesting phenomenon was well explained by "photon-recycling effect" [8] which only occurs in direct transition material like GaN. Ron was also dramatically reduced by using very low resistivity substrate grown by OVPE mentioned in Fig.3 as shown in Fig.6(b). [9] This big reduction can't be explained only by reduction of substrate's resistivity. Carrier diffusion from substrate into drift-layer under positive bias voltage must be taken account.[10] These results show new advantage to use the low TDD with low resistivity GaN substrate for vertical devices.



(a)Structure (b) Breakdown voltage

Fig.5. Structure of PN diode and high breakdown capabilities.
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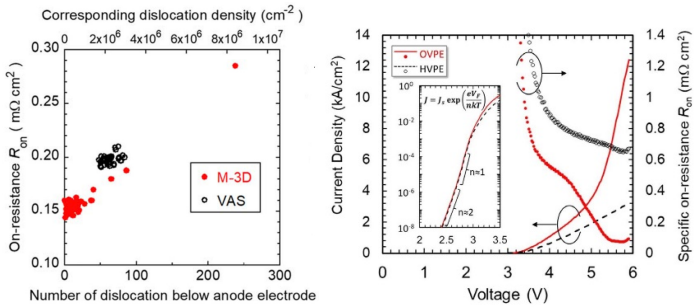
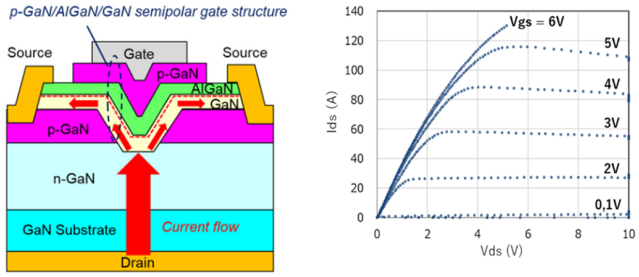


(a) Dislocation density (b) Resistivity

Fig.6 . Dramatic reduction of Ron by lowering (a) dislocation resistivity (Copyright The Japan Society of Applied Physic (2020)[7]) and (b) Substrate resistivity.

(2) Vertical GaN on GaN power transistor

A vertical transistor with the unique structure shown in Fig.7 has been developed [11]. It is expected to have low resistance and large current by using 2DEG layer with very high mobility as channel. In addition, by using a semi-polar surface for a part of the channel and using a p-GaN gate, it is easy to realize normally off operation. This device realized perfect normally off operation with over 100A current as shown in Fig.5 (b).

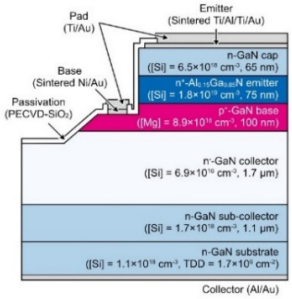


(a)Structure (b)I-V Characteristic

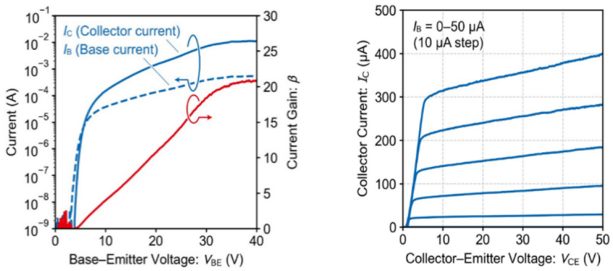
Fig.7 Structure and performance of vertical GaN transistor

(3) HBT

GaN HBT on GaN substrate was developed, using AlGaN as hetero-emitter layer as shown in Fig.8 (a). The low defect density in the active layer by using GaN substrate was quite useful for this type of minority device especially. The key to this device process is to reduce the contact resistance of the base electrode. The regrowth method is usually used, that is, p-layer is partially re-grown on the base layer revealed by dry etching. However, this method is very costly. In this development, the dry etching was applied to minimize the surface damage in the process of exposing the base layer to the surface.[12] As a result, good contact resistance was obtained without using re-growth, and good electrical characteristics with a gain β of 22 were obtained [13] as shown in Fig.8 (b) with fine I-V characteristics (Fig. 8(c)). This result indicates the high possibility to realize GaN-HBT in production by this improved process and using GaN substrate.



(a) Structure

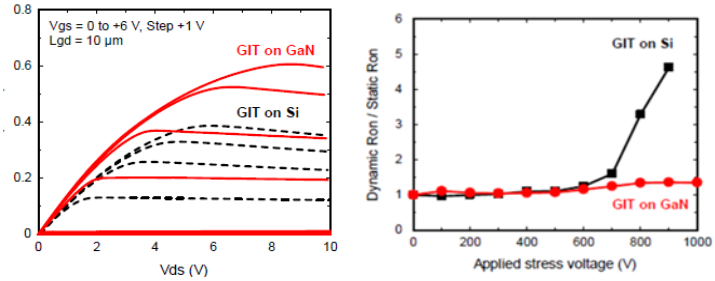


(b)Gummel plot (c) I-V

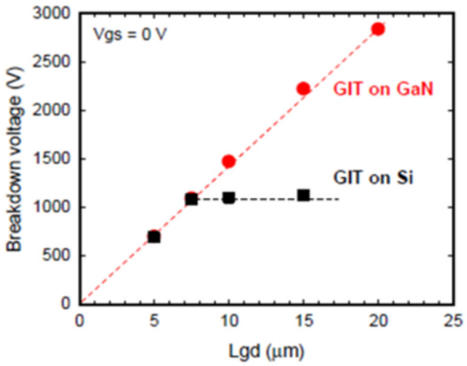
Fig.8 HBT fabricated by using low damage dry etching

(4) GaN on GaN HEMT for Power

Fig.9 shows significant improvement of GaN-HEMT device performance for devices fabricated on GaN epi on GaN substrates, as compared with same devices fabricated on GaN epi on Silicon substrates [14]. The GaN on GaN HEMTs showed much higher saturated current Ids, and lower on-resistance as shown in Fig.9 (a), which promises higher output power and higher efficiency. They also showed a large improvement in the stability of drain current after drain bias stress, as shown in Fig.9 (b). They were stable even at 1000V stress, while that on Si degraded over 700V (this is good data as GaN on Si device). This means so-called "current collapse" was dramatically suppressed by using GaN substrate with very low defect density. The GaN on GaN HEMTs also showed significantly higher breakdown voltages (>3kV) by enlarging the gate-drain distance, compared with the GaN on Si HEMTs which had breakdowns of only ~1kV (Fig.9(c)) All these data confirm the dramatic improvement of device performance which is obtained when using GaN on GaN technology.



(a) I-V characteristics (b) Current collapse



(c) Dependence of Breakdown voltage on gate-drain distance

Fig.9 Improvement of device performance by using GaN substrate in comparison with that on Si

(5) GaN on GaN HEMT for RF

GaN HEMTs were fabricated on semi-insulating GaN substrates. Usually, the epi/substrate interface is contaminated with impurities such as Si, which degrades device performance. Therefore, the surface of the substrate was etched off by wet-chemical etching before epitaxial growth, to reduce this contamination. [15] As a result, this device achieved a very high power added efficiency (PAE) > 80% at 2.45GHz operation. Figure 10 compares the efficiencies of GaN on Si, GaN on SiC, and GaN on GaN around 2.5 GHz. It can be seen that the PAE for GaN on GaN is the highest, by far.

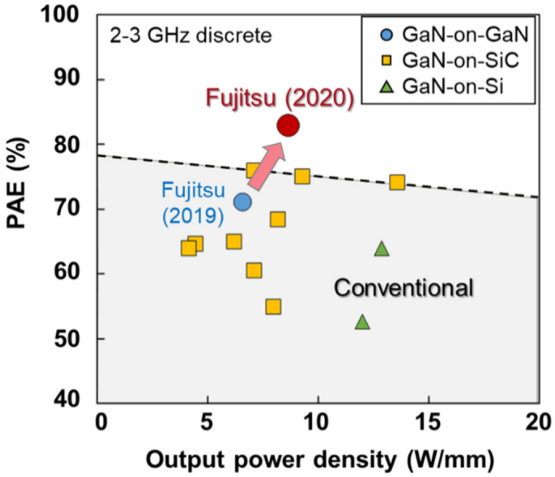


Fig.10 Comparison of Load-pull measurement results of discrete GaN HEMTs at around 2.45GHz ISM band

DEMONSTRATION OF REAL SYSTEM

(1) Power Conditioner for Solar Cell Panel

GaN transistors (GaN on Si in this case) are used for all switching elements in the system of Power Conditioner for Solar Cell Panel. The power efficiency was compared with that using conventional Si transistors. The circuit is shown in upper part of Fig.11 indicated as "PV → System Mode". Very high efficiency operation of 98% or more in a high output range (1kW~) with a single PV power conditioner was achieved as shown in Fig.8 as red circle dots. The power loss was reduced by about 58% compared to conventional PV power conditioners using Si transistors. [16]

This inverter shows a very high efficiency in the high output range at 1kW or more, but shuts down due to unstable operation at 180 W or less. To improve the issue, a storage battery system has been added to this system as shown in Fig.11. The performance is also shown in Fig.12 as a red data points. When the amount of power generated by PV is small, the storage battery is charged from PV. This new system realized effective use of PV even at low output, together with the loss is reduced by about 66% compared to the conventional PV power conditioner. [17]

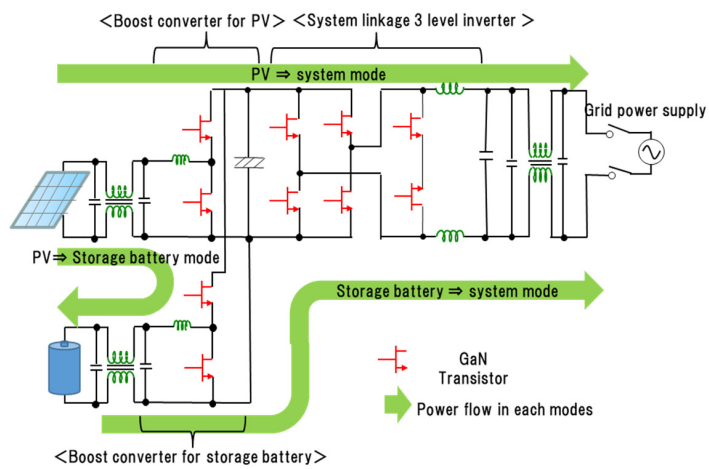


Fig.11 Circuit configuration diagram of ZEH compatible PV power conditioner

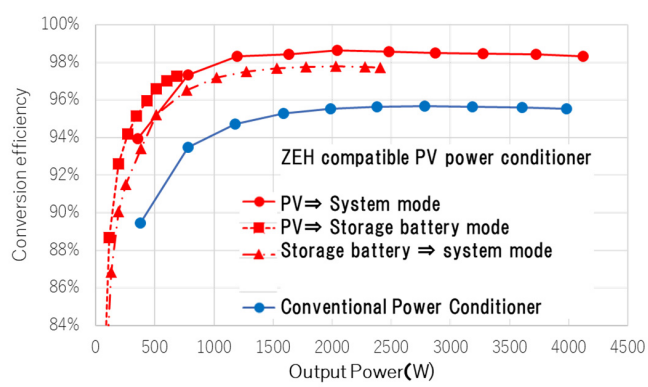


Fig.12 Significant improvement of conversion efficiency by GaN devices with storage battery mode

(2) Selective Heating Microwave Oven

The thermal design of a 400-W/eight-channel selective heating microwave oven, which consists of eight patch antennas and power amplifier (PA) modules, involving a 50-

W-class GaN-on-GaN HEMT PA, a driving amplifier, an oscillator, and several circuits, was carried out. The fan and fin specifications and the enclosure configuration have been optimized to keep the temperature of the metal base on which the PA modules are mounted below 40C during operation. Excellent agreement between the oven thermal simulation and the prototype thermocouple measurements was confirmed for the temperature difference between the metal base and the ambient. Quite interestingly, thermal performance of GaN on GaN is almost equivalent of even better compared with GaN on SiC in proper design of the oven, although SiC has much better thermal conductivity. Main reasons are speculated by better thermal resistance at the epi/sub interface (homo-interface vs hetero-interface) and better efficiency of the device. [18]

Fig.13 shows the prototype oven with eight channel which realized partial heating in an oven as shown in Fig.14.

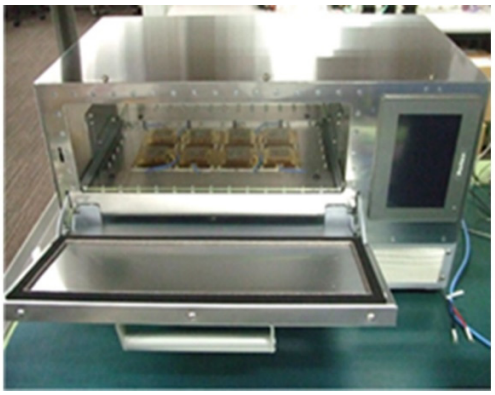
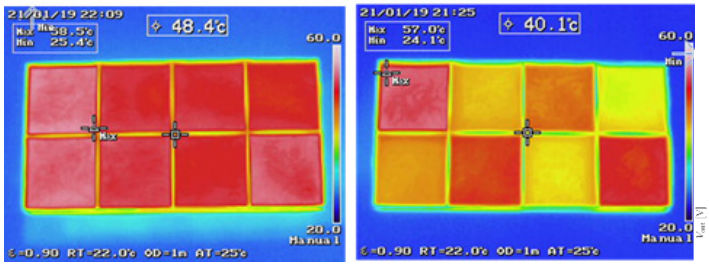


Fig. 13 Prototype of 400-W/eight-channel selective heating microwave oven



(a) uniform heating (b) Selective heating

Fig. 14. Thermographic images of an octa-divided vessel filled with water after microwave heating. (a) Uniform heating. (b) Selective heating.

(3) Soft Switching

Most of the power switching devices are operated with hard switching using the circuit as shown in Fig.15 (a) that has big oscillation as shown in Fig.17(a) in general. The oscillation requires the high breakdown voltage on the device and cause the switching loss. The new circuit to improve the problem, to realize the soft switching circuit was proposed and designed as shown in Fig.15(b), where auxiliary circuit was added using GaN-HEMT with high switching speed under high power output [19][20]. The circuit board was fabricated based on this new circuit design as shown in Fig.16, where SiC-PAs were used for output PA and GaN-HEMT for the auxiliary circuit as described. As a result, quite smooth switching performance with very small oscillation was obtained successfully as shown in Fig.17(b). It was indicated that this new circuit with GaN-HEMT enables us 1) to reduce the device cost due to the lower breakdown and 2) to improve the device efficiency due to the lower switching loss.

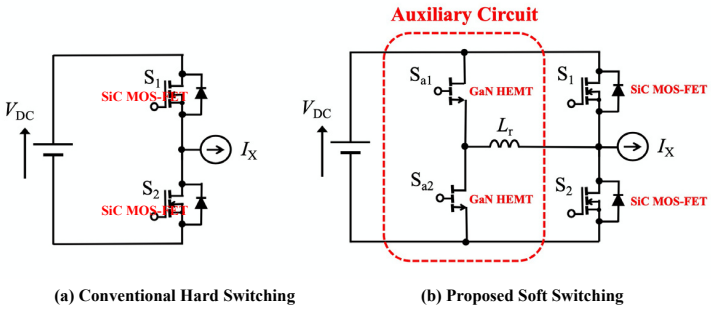


Fig.15 Circuit of hard switching and proposed soft switching

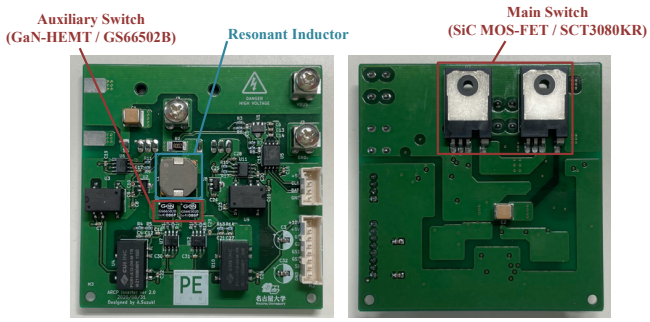
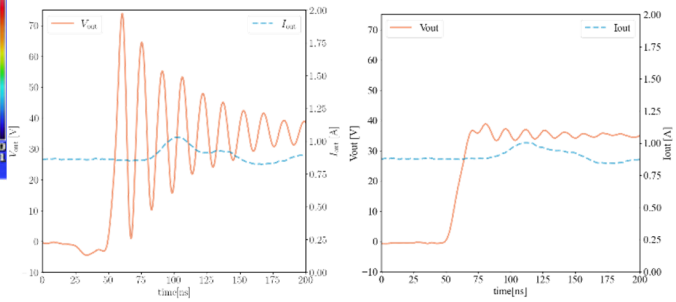


Fig.16 Circuit board developed based on circuit of Fig.15 (b)



(a)Hard switching (b)Soft switching developed here

Fig.17 Switching performance of hard switching (a) and soft switching developed here

(4) All GaN Vehicle

GaN power transistors are expected to be applied to power modules for high performance electric vehicles to reduce CO_2

emissions. A GaN traction inverter (Fig. 18) and a GaN DC-DC converter using GaN on Si transistors were developed for a low loss EV. An EV equipped with these GaN power modules was designed and manufactured for demonstration (Fig.19). [21][22] This EV, called the "All GaN Vehicle", has been successfully tested for the first time in the world and exhibited at 2019 Tokyo Motor Show (Fig. 20).

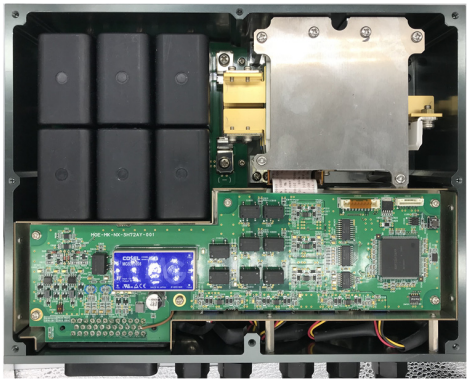


Fig.18 low-loss traction inverter and DCDC converter

Fig. 19 All GaN Vehicle

Fig.20 All GaN Vehicle in Tokyo Motor Show in 2019.
Minister of Environment Mr.Koizumi (left), Prof.Amano (middle) and Mr.Toyota, president of Toyota Morter (right) joined.

CONCLUSION

Many promising device and system results have been obtained using GaN on GaN technology during national project of Japanese Ministry of Environment, showing the enormous promise offered by GaN on GaN power electric devices. The first term of the project from 2014 to 2022 has been almost completed, but the challenge is still very much on-going to realize the energy saving and a greener society.

ACKNOWLEDGEMENTS

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ACRONYMS

LED: Light Emitting Diode
LD: Laser Diode
SI: Semi Insulating
HEMT: High Electron Mobility Transistor
2DEG: Two Dimensional Electron Gas
HBT: Hetero Bipolar Transistor
OVPE: Oxide Vapor Phase Epitaxy
HVPE: Hydride Vapor Phase Epitaxy
PV: Power Conditioner
PA: Power Amplifire