GaN-based Electrified Mobility for Sustainable Society

Koji Shiozaki
Y. Nakayama[1], Y. Kanazawa[2]

Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, JAPAN
Tel:81-52-734-6967, e-mail: kshiozaki@imass.nagoya-u.ac.jp
[1]Nagoya university, [2]Naturanix Co.

Keywords: GaN inverter, lateral GaN device, automotive application, motor control

Abstract

A novel concept mobility driven with GaN-based electronics which is called All GaN Vehicle (AGV) has been being developed. AGV is a future electrified mobility designed for the sustainable society. GaN-based electronics such as a driving inverter, a DC-DC converter, an on-board charger, etc. have prototyped and demonstrated great performance on their power consumption. With respect to GaN driving inverter, more than 70% of the inverter loss reduction is achieved in comparison with an IGBT inverter. Applying low loss characteristics of the GaN inverter at higher carrier frequencies, a total loss of the inverter and a motor is further improved. GaN-based electronics can contribute to the reduction of power consumption and CO2 emissions of future mobilities to realize the sustainable society.

INTRODUCTION

Climate changes and extreme weather events caused by carbon dioxide emissions, and atmospheric pollution caused by exhaust gases have become an important topic for our living environment. An increasing focus on energy security is sparking research for energy saving technologies. Si power semiconductor devices are the most widely used switching devices for power electronics. To innovate power electronics technology, wide bandgap power semiconductors have attracted much attention as the Si alternative for its supreme characteristics of high voltage blocking and low on-resistance make it possible for low loss operation. GaN is the best Si alternative that has great potential and GaN-based electronics will be applied in a wide range of fields, power application, wireless application, communication, etc. [1-2] In the automotive sector, a rapid expanding of the electrified vehicle market is expected in the next decade to respond to customer's expectations and sustain the long-term economy growth keeping the global environment. In this work, challenges of GaN-based power electronics for the automotive application have been investigated and GaN potential for a future electrified mobility is demonstrated.

ALL GAN VEHICLE

To accelerate research, development and demonstration (RD&D) of GaN power electronics, AGV has been being developed to demonstrate the future mobility and GaN potential. Fig.1 is a configuration of AGV. AGV is the world's first mobility powered by GaN electronics and various GaN modules such as a driving inverter, a DC-DC converter, an on-board charger, high performance lighting devices are installed. AGV is an ultra-light weight compact sports electric vehicle designed for the sustainable society targeted a wide range of age groups from a younger generation to a middle-aged generation, and its occupant is 2+ α, designed for an urban usage. For that purpose, an actual-gap structured in-wheel motor [3] is adopted in a drive system to secure a degree of freedom for a design of an interior space.

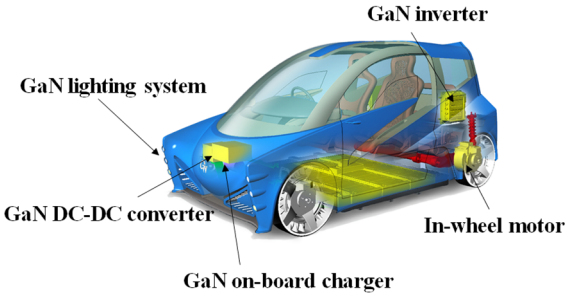

Fig. 1. Configuration of All GaN Vehicle.

GAN INVERTER

The driving inverter is optimized for an in-wheel motor using GaN lateral power transistors. Design of a half-bridge module is shown Fig.2. The half-bridge module consisting of a three-phase inverter is designed considering parasitic inductances and heat radiation. GaN power transistors and a gate drive circuit are integrated on a same circuit board. GaN transistors are on the surface side and the back side of the circuit board. For a cooling system, a water cooler is mounted on GaN transistors and a thick bus bar substrate is inside the

circuit board. Challenges of GaN modules are a circuit implementation to minimize inductances and a design of a heat radiation structure. For high output power, a multi-parallel arrangement of GaN transistors and a symmetrical circuit design, and optimizations of circuit parameters enable the GaN modules to reduce a gate voltage oscillation. Fig.3 is simulation results of parasitic inductance on a half-bridge circuit. 10nH of parasitic inductance is put and an oscillation of gate voltage is quite severe and there is a danger of malfunction. Suppressing parasitic inductance is a crucial issue for GaN circuit design. To optimize circuit parameters for the half-bridge module, adding a RC snubber, adding a mirror clamp circuit, and adding a ferrite bead are implemented on the half-bridge module. Adding the RC snubber and adding the mirror clamp circuit are effective for improvement of the gate voltage oscillation. Adding gate resistance is effective but reduces the current of the module.

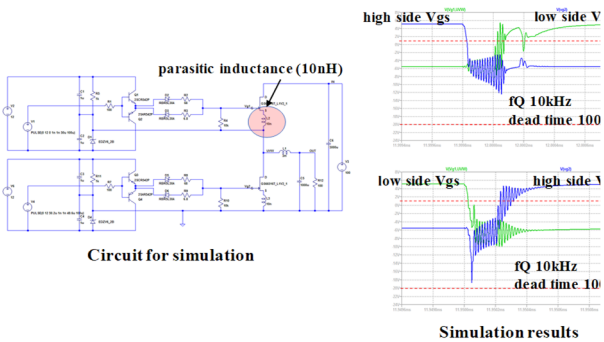

Fig. 3. Simulation of parasitic inductance affects on the half-bridge circuit.

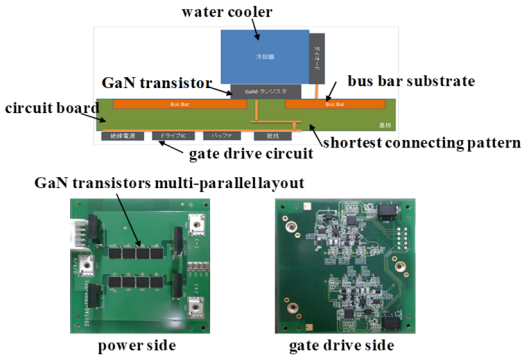

Fig. 2. Design of the half-bridge module

According to the parameter optimization, RC snubber and the mirror clamp circuit are implemented on the half-bridge module. Fig.4 is an efficiency curve of the module, a peak efficiency of the GaN half-bridge module is 99.5%, and 6.4kW maximum output power is achieved on a quadruple layout GaN module. With increase of the output power, the efficiency is slightly decreased due to a circuit temperature rising. A countermeasure of the heat radiation is needed for much higher output power module. The three-phase inverter is built up with the quadruple layout GaN module and three GaN modules are transversely arranged as shown Fig.5. Fig.6 is a loss comparison of GaN inverter and IGBT inverter. A power loss of the GaN inverter is quite lower and more than 70% of the total power loss reduction is achieved in comparison with an IGBT's.

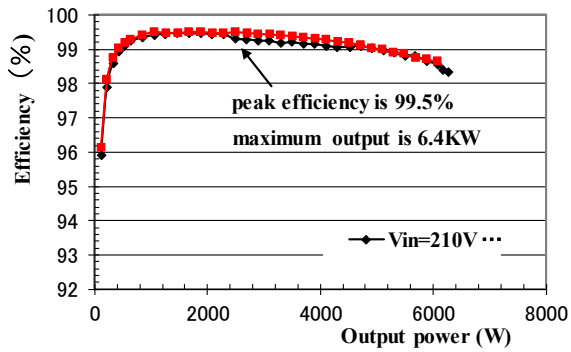

Fig. 4. Efficiency curve of quadruple GaN half bridge module.

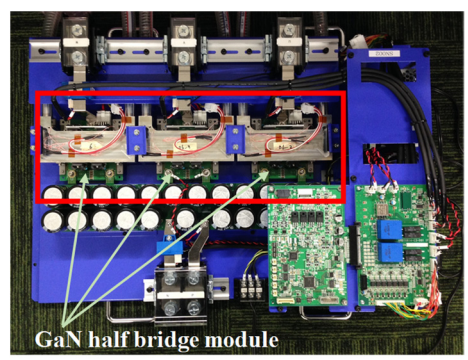

Fig. 5. Prototype of three phase inverter applied GaN half-bridge module. Three GaN modules are in a red box.

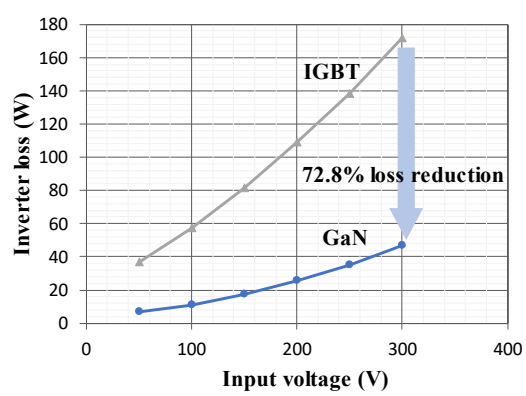

Fig. 6. Loss comparison of GaN inverter and IGBT inverter.

LOW LOSS MOTOR CONTROL APPLIED GAN INVERTER

In addition to the low power loss of GaN inverter, another advantage of the GaN inverter is a characteristic at higher carrier frequencies. Fig.7 shows a simulated loss comparison between GaN inverter and IGBT's. The IGBT inverter loss is drastically increased with the carrier frequency, however the GaN inverter loss is quite lower compared to IGBT's. This enables a new motor control for a lower power consumption for future mobilities [4]. A phase current is improved at the higher carrier frequency as shown in Fig.8 and this indicates a motor loss is improved at the higher carrier frequency [5]. Fig.9 shows efficiency maps with speed vs. torque of the GaN inverter, the motor, and a total with the inverter and the motor in comparison with 20KHz and 6.25kHz. The inverter loss slightly increases in all measured region, however the motor loss of the GaN inverter can be reduced. As a result, total loss of the inverter and the motor is improved. The low loss motor drive control technology with GaN inverter can contribute to the reduction of the power consumption and CO2 emissions.

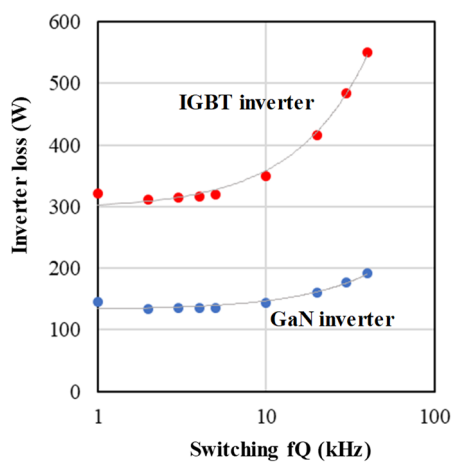

Fig. 7. Simulated loss comparison between GaN inverter and IGBT inverter.

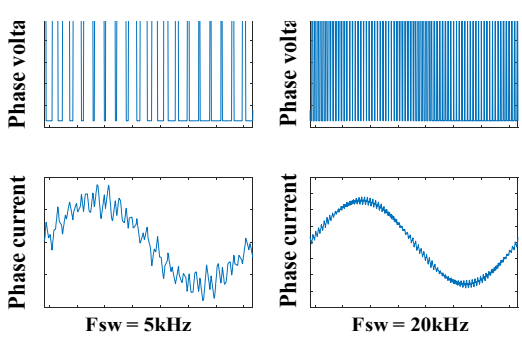

Fig. 8. Simulated phase current and phase voltage waves.

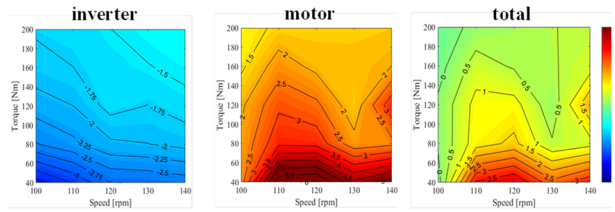

Fig. 9. Measured efficiency maps with GaN inverter compared Fsw 20KHz with 6.25KHz.

DEMONSTRATION OF AGV WITH GAN ELECTRONICS

To demonstrate the GaN inverter, a compact size vehicle mounting inverter has been developed. As shown Fig.11, a compact half-bridge module and a water cooler are newly designed for the inverter. The new designed half-bridge module is shrunk almost half-size maintaining the power output performance. The new cooler is designed for a stacked structure module. Three half-bridge modules and three coolers are stacked for a half-bridge module unit. The newly developed vehicle mounting inverter is 266 mm by 197 mm by 80 mm and almost 1/10 size of the prototyped inverter. Furthermore, GaN DC-DC converter as shown in Fig.11 is prototyped, output power is 2.4kW and a peak efficiency is 97.5%. Fig.12 is a test vehicle and the developed inverters is mounted on the vehicle and currently have been adjusting for driving.

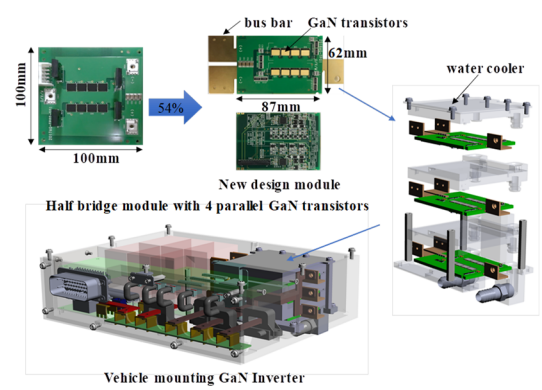

Fig. 10. Vehicle mounting GaN inverter with newly design half bridge modules and water cooler units.

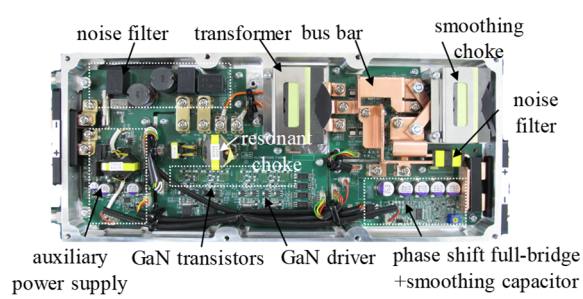

Fig. 11. 2.4kW GaN DC-DC converter.

Fig. 12. Test vehicle for GaN electronics.

CONCLUSIONS

To demonstrate the future electrified mobility realizing a sustainable society, GaN-based electronics is developed. The GaN inverter is designed for vehicle application with the circuit design of the high output power module applied GaN lateral transistors. A peak efficiency of the GaN half-bridge module is 99.5%, and 6.4kW maximum output power is achieved with the quadruple layout of GaN transistors. 15kW three-phase inverter is built up with the developed half-bridge modules. The inverter successfully works and more than 70% of a total power loss reduction is achieved in comparison with an IGBT's. In addition to the low power loss of GaN inverter, the total loss of the drive system can be improved at higher carrier frequencies. To install the GaN inverter in AGV, 1/10 size of the first prototype is developed with newly designed half-bridge module and water cooler. Furthermore, the GaN DC-DC converter and the on-board charger for automotive applications are developed with GaN lateral transistors. GaN based power electronics have great potential for the automotive application.

ACKNOWLEDGEMENTS

The authors would like to thank the participating organizations and people for their contributions on the vehicle development. This work is supported by Ministry of the Environment, Japan.

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ACRONYMS

AGV: All GaN Vehicle
IGBT: Insulated Gate Bipolar Transistor
CFRP: Carbon Fiber Reinforced Plastic