GaN Vertical Power Devices for Electric Vehicles

Tetsu Kachi

Institute of Materials and Systems for Sustainability, Nagoya University
Furo-cho, Chikusa-ku, Nagoya, 464-8601 Japan
e-mail: kachi@imass.nagoya-u.ac.jp

Keywords: GaN, Power device, Electric vehicle

Abstract

Automotive companies recently accelerate the development of electric vehicles (EVs) and fuel cell vehicles (FCVs) because reduction of CO_2 emission. To drive and control the high-power motor, low on-resistance, high-speed and high-current-capacity are required to the power devices. GaN vertical devices have suitable potential for EV applications. In this paper, electric vehicle system and the progress of the fabrication processes of GaN vertical devices are reviewed.

INTRODUCTION

Automobiles are now under the changing period of energy source from fuel to electricity. Recent global warming is pushed to reduce CO_2 emission and the regulation CO_2 emission from automobiles become harder year by year. Therefore, automotive companies in the world have started to develop electric vehicles (EV) and a fuel cell vehicles (FCV). For these eco cars, high-efficiency of power electronics which includes high performance power devices will be required strongly.

Wide band gap semiconductors like SiC and GaN are recognized as next generation power device materials, which have the potential of high breakdown voltage and low on-resistance. Moreover, GaN has the best theoretical material properties among semiconductors that the conductivity control can be possible. Most of all reports of GaN power devices focus on lateral devices, namely high electron mobility transistor (HEMT). However, for high-power application like automobiles, a vertical structure device is desirable because performances of high current density and high breakdown voltage are required to control the driving motor. Therefore, we have been developing GaN vertical devices for automotive applications. In this paper, automotive applications of power devices and current status of GaN vertical devices are reviewed.

POWER ELECTRONICS IN ELECTRIC VEHICLES

Many power modules are used in the EV system as shown schematically in Fig. 1. The power electronics used in EVs and FCVs is basically the same except for the charge system.

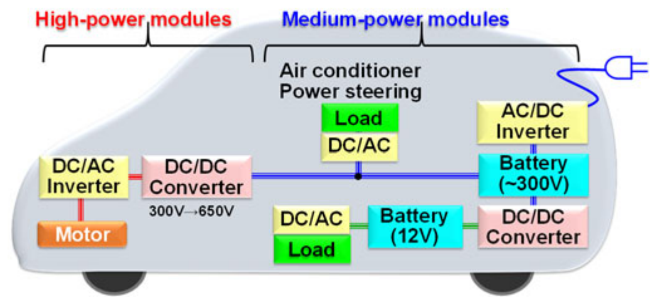

Fig. 1. Power modules used in EV. The power modules can be divided into two categories by control power level: high-power modules and medium- and low-power modules.

These power modules are divided into two categories by power level: high-power modules used to drive the main motor, and medium- and low-power modules used to drive the subsystems.

The high-power modules for controlling the main motor consist of a bidirectional DC-DC converter and an inverter. The battery voltage is raised to the motor source voltage by the DC-DC converter and then the source voltage is supplied to the motor through the inverter. The boost ratio changes depending on the driving condition. The output power of the main motor of EVs is about 100 kW, in the case of a large sedan, the required motor power is over 150 kW. Therefore, the DC-DC converter and the inverter must control such a high power. Moreover, the modules must provide guaranteed operation under any driving condition, so a large current capacity, such as over 200 A per chip, is required for these power devices. In these modules, Si-IGBTs and pin diodes, which have sufficient current capacity and reliability, are now used. The breakdown rating of the devices is 1.2 kV owing to the maximum source voltage of 650 V. The efficiency of the inverter is very high (>95%) under the maximum output condition. However, there are few opportunities to use the maximum power under general driving conditions. The average power used for driving will be lower than half the maximum output power. The efficiency of Si-IGBTs is lower under low-power conditions than under high-power conditions because of the junction voltage, which are bipolar device characteristics. Therefore, unipolar devices such as MOSFETs with sufficient low on-resistance are required to improve the total efficiency of the inverter in next-generation systems. Moreover, in pulse width modulation (PWM) control for the inverter, high carrier frequency reduces ripples in the output voltage, which improves the motor efficiency. High-speed MOSFETs will make the high carrier frequency possible. High-speed performance of the power device is also desirable in the DC-DC converter. In the present DC-DC converter, the switching frequency is 5-10 kHz, which requires a large capacitor and a large inductor. Higher frequency operation permits the use of a small capacitor and a small inductor.

The main problem of the high-power module is the large amount of heat generated which gives rise to a need for a water cooling system for the power control unit as shown in Fig. 2(a). If power devices were capable of high-temperature operation, for example, above 200°C, we could simplify the cooling system. High-temperature operation is another required performance of the new power device. On the other hand, future EV will has another driving system, which is in-wheel motor drive as shown Fig. 2(b). For this system, output of the in-wheel motor and the source voltage will be around 30 kW and 200 V, respectively. Therefore, requirements for the power device used in this system are breakdown voltage of 600 V and current capacity of 150 A. Moreover, air-cooling of the inverter is essential for in-wheel motor drive because the storage space of a motor and an inverter is very narrow and under a vibration environment. For these request, on-resistance of the power device has to be sufficiently low to make air-cooling capable.

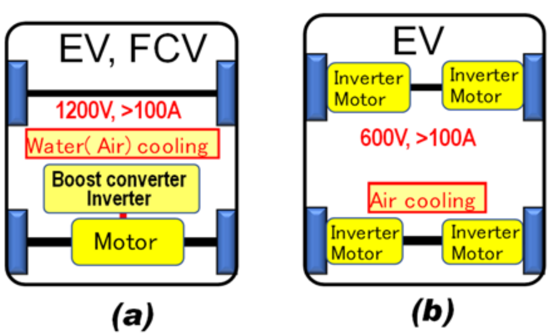

Fig. 2. Electric vehicle driving systems: (a) present system; (b) developing another system: in-wheel drive.

We can estimate the on-resistance of the power devices to make air-cooling capable as followings. Chip size the current of the device are assumed as 1 cm^2 and 200 A, respectively. If the on-resistance of the device was 10 $m\Omega \cdot cm^2$ and 1 $m\Omega \cdot cm^2$, the heat generation density was 400 W/cm^2 and 40 W/cm^2, respectively. On the other hand, maximum capability of an air-cooling system is about 50 W/cm^2, though it depends on environmental condition. Therefore, required on-resistance from the air-cooling capability is less than 1 $m\Omega \cdot cm^2$.

Fig. 3 shows well known theoretical on-resistance for Si, SiC and GaN. On-resistances for channel mobility of 20, 100

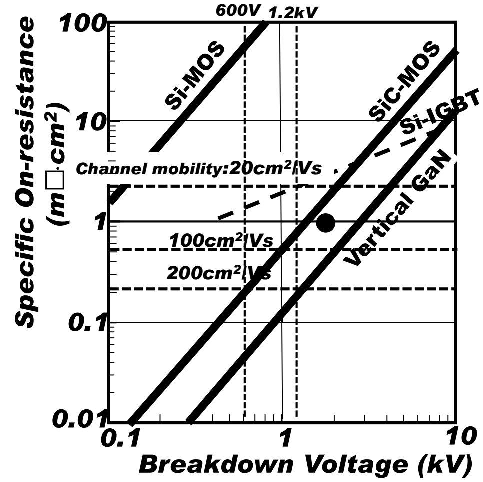

Fig. 3. Theoretical performance of on-resistance for Si, SiC and GaN.

and 200 cm^2/Vs are also presented. We can see that GaN has the enough margin to1 $m\Omega \cdot cm^2$ at 1.2 kV if the channel mobility is higher than 100 cm^2/Vs.

GaN Vertical Device

Structure

The vertical structure has the advantages of current-collapse-free operation, a small chip size, easy wiring and a high breakdown voltage. In 2014, two papers which reported over 1 kV GaN vertical power devices [1,2]. They were epoch-making reports for the GaN vertical research. However, their performances were not sufficient for the requests. Some issues to realize GaN performance at the maximum still remain. Requests to the GaN vertical device are normally-off operation, precise control of the threshold voltage higher than 3V, small threshold voltage shifts and low on-resistance. Unique structure of GaN devices is heterostructure like AlGaN/GaN for the gate channel [2]. However, it is difficult

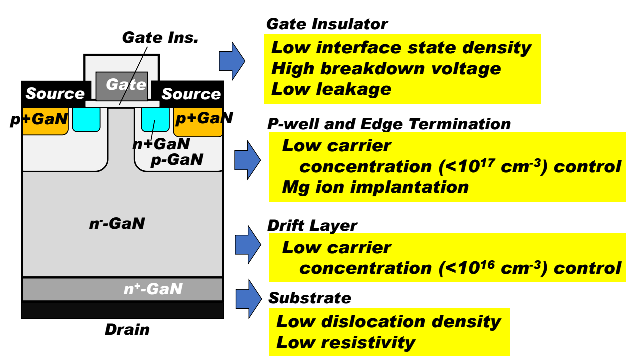

Fig. 4. Developing issues in GaN vertical power device.

to satisfy the requests of high threshold voltage using a heterostructure gate. Therefore, conventional MOS gate is the most adequate as the first generation GaN vertical power device. In ref. 1, trench MOS gate structure was developed but no inversion gate operation was achieved. There are two MOS gate structures: a planar gate and a trench gate structures. Both are under investigation and the issues of development are common except for trench forming.

Issues of Developments

To achieve sufficient low on-resistance, development issues for the fabrication process of GaN vertical devices, which are summarized in Fig.4.

The main issue is the quality of GaN substrates. The requests to the GaN substrates are the followings.

1) Diameter: 4 or 6 inches. 2) Resistivity: <0.01Ωcm. 3) Distribution of c-axis direction: <0.1deg. 4) Dislocation density: $<10^3$ cm^{-2} (not sure). Recently, new approaches to high quality GaN substrates are being developed. These are liquid-phase growth technologies: the ammonothermal method [3] and the Na flux method [4]. Both substrates contain few screw dislocations and have sufficient quality for high voltage applications. However, the entire GaN substrate area does not yet have a uniform quality.

The second issue is low n-type doping control of the epitaxial layers. For example, a carrier concentration of lower than 1×10^{16} cm^{-3} is required for breakdown voltages above 2 kV. This carrier concentration is two order of magnitude lower than that of optical devices. Therefore, new growth condition and source supply system of metal-organic chemical vapor deposition (MOCVD) had to be developed. Figure 5 shows one example of low doping characteristics of Si. Si concentration was perfectly controlled. However, epitaxial layers grown by MOCVD in general contain carbon atoms from Ga source: trimethylgallium (TMG). These carbon atoms will compensate Si donors and reduce electron mobility. We have improved the epitaxial conditions to reduce the carbon inclusion, and the residual carbon concentration was reduced to 3×10^{15} cm^{-3}. However, this level is not sufficient for high voltage and effort to reduce the carbon concentration is needed.

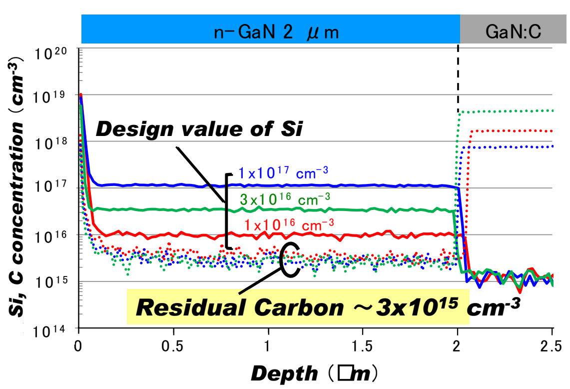

Fig. 5. Si concentration depth profile for 3 doping levels. Residual C concentration is also presented and the concentration was limited to 3×10^{15} cm^{-3}.

The third is p-GaN well layer. The p-well layer determins the threshold voltage, therefore, the control of the doping concentration is the key of the inversion operation. The threshold voltage of 5V, for exsample, equires Mg concentration of about 1×10^{17} cm^{-3}. Though the epitaxial growth can be applied to form the base layer, ion implantation is more suitable for devices fabrication process. Ths ion implantaion makes possible to simplify the fabrication process and to form edge terminations. However, p-GaN (Mg) ion implantaion has been not achieved yet. New approach for the activation of implanted Mg has been recently reported [5], which was capless annearing with the use of N-face instead of Ga-face because N-face was stable for high

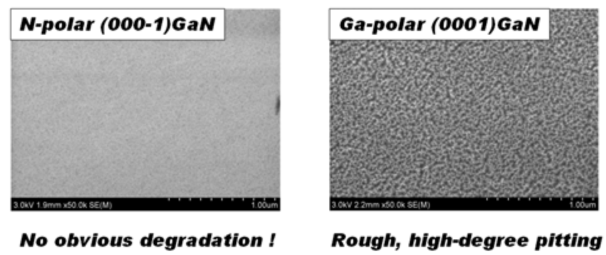

Fig. 6. Surfaces after high-temperature annealing.

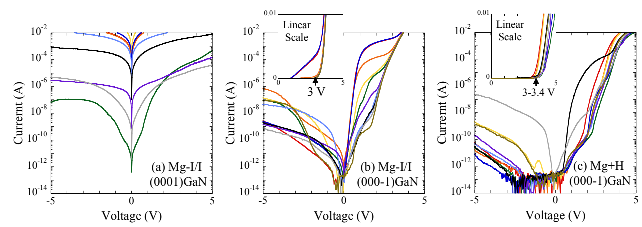

Fig. 7. I-V characteristics of pn diodes using ion implantation.

temperature as shown in Fig. 6. Moreover, hydrogen atoms were co-implanted with Mg atoms. The activation of Mg was confirmed using pn diodes which showed good I-V characteristics as shown in Fig. 7. This result will open the new process technology of GaN devices.

The last issue is a gate insulator. For the wide bandgap semiconductor like GaN, SiO_2 and Al_2O_3 are strong candidates of the gate insulator in terms of high barrier high for the conduction band and high breakdown voltage. Recently, clear inversion operation of the GaN MOSFETs was achieved using a SiO_2 gate insulator. The channel mobility over 100 cm^2/Vs was reported [6]. Al_2O_3 also showed low interface state density [7].

However, SiO_2 and Al_2O_3 films have weak points, which are low permittivity and low crystallization temperature, respectively. Therefore, to improve these weak points and to utirize merits of SiO_2 and Al_2O_3, which are high barrier hight to electrons: low leakage current, and high permittivity, respectively, we are developping an AlSiO nano-laminate fillm [8]. SiO_2 and Al_2O_3 films were depositted on GaN by atomoc layer deposition (ALD) method. AL and Si conposition in the film were controlled by layer numbers of the each film. Fig. 8(a) shows leakage current of the AlSiO film after annealing. This figure indicates that the AlSiO film was not crystallized at high temperature above 1000℃. Fig. 8(b) shows C-V curves of AlSiO film on n-GaN grown on a GaN substrate. No frequency dispersion was observed and coincidence between the measured curve and the ideal curve was good, which indicates that the surface state density was very low. Application to an inversion gate structure is now under investigation.

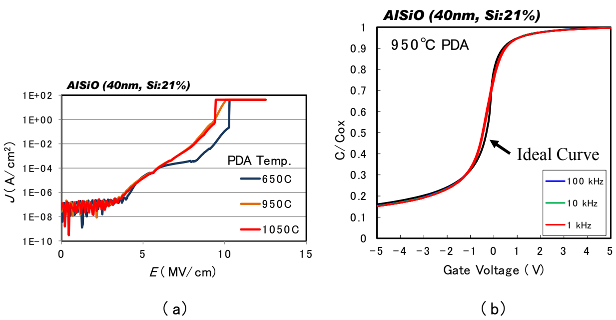

Fig. 8. (a) Leakage current characteristics of AlSiO nano-laminate film after post deposition annealing and (b) C-V characteristics on n-GaN layer.

CONCLUSIONS

GaN has high potential of low on-resistance over wide breakdown-voltage range as shown in Fig.3, which is the biggest merit of GaN. GaN has also potential to make paradigm shift in automobile systems by its capability of the low on-resistance. Though some issues to realize GaN potential still remain, elemental technologies of the GaN vertical device are progressing drastically. Recently, 1.7 kV/1m$\Omega \cdot cm^2$ GaN vertical device using p-GaN gate was reported in IEDM2016 [9]. This is the first report of lower on-resistance than theoretical one of SiC. It shows the advantage of high channel mobility using AlGaN/GaN heterostructure. Therefore, high channel mobility is also essential in MOS gate structure.

REFERENCES

[1] T. Oka, et al., Appl. Phys. Express, 7, 021002 (2014).
[2] H. Nie, et al., IEEE Elecron Lett. 35, 939(2014).
[3] R. Dwillinski, et al., Phys. Status Solidi A 208, 1489 (2011).
[4] Y. Mori, et al., Phys. Status Solidi A 207, 1269 (2010).
[5] T. Narita, et al., Appl. Phys. Express 10, 016501(2016).
[6] S. Takashima, et al., IWN2016 proceedings, C05.03(2016).
[7] S. Toiya and T. Hashizume, The 77th JSAP Autum Meeting, Niigata, Japan (2016)
[8] D. Kikuta, et al, J. Vac. Sci. Technol. A35, 01B122, (2017).
[9] D. Shibata, et al., IEDM2016 Technical Digest, 10.1(2016).