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Advanced GaN Power Devices for Automotive Applications

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Abstract

Many power switching devices are used in hybrid vehicle (HVs) and electric vehicles (EVs) systems. For future development of the HV/EV, higher performances than Si power device, for example, low on-resistance, high speed, high operation temperature, are strongly required. GaN power devices are promising candidate for the requirements. Present status of the GaN power device development is presented. Reliability of the GaN power device was also discussed.

1. Introduction

Hybrid vehicles (HVs) and electric vehicles (EVs) are now widely recognized as eco-cars. These vehicles are using high electric power inverters to drive high power motors and other many power modules. For the next generation vehicle, higher efficiency is required to reduce the electric power losses. This requirement is the same as an achievement of high performance power devices. GaN power devices have been developed as the high performance power devices for the next generation. In this paper, we discuss the power modules used in the HV/EV and the recent status of the GaN power devices for automotive applications.

2. Power electronics in HV/EV

Figure 1 shows power modules used in the HV/EV schematically. For driving the main motor, a high power inverter module is used. In recent TOYOTA HV system, the battery voltage is raised to 650V by a voltage booster (DC-DC converter) and then supplied to the motor through the inverter. The DC-DC converter and the inverter control the power over 50kW. Si-IGBTs are used as the power devices.

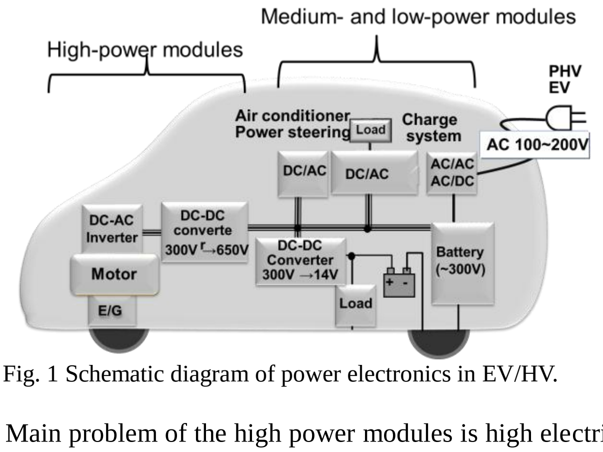


Fig. 1 Schematic diagram of power electronics in EV/HV.

Main problem of the high power modules is high electric power loss, which requires the water cooling system. If very low on-resistance and high temperature operation are achieved on the future power devices, we can reduce the power loss and simplify the HV/EV system.

On the other hand, for the medium and low power modules, of which power level is lower than ~5kW, required breakdown voltage is lower than 600V. For these applications, high frequency operation is important as well as low on-resistance. High frequency operation leads to small capacitors and reactors, which contribute to module compactness and low cost.

3. GaN power devices

To realize above requirements, new materials are expected. GaN has the best potential as the post Si power device among realistic wide-gap semiconductor materials [1]. There are two types in developing GaN power devices, which are lateral structure and vertical structure.

Lateral structure Dvices

Most developing GaN devices are lateral device structure because the device structure is based on high electron mobility transistor (HEMT). In general, the lateral device is not suitable for high power switching because of high conduction loss. However, GaN lateral devices have performances for higher power switching compared with Si lateral power MOSFETs. For the GaN lateral device, low on-resistance is performed by high breakdown performance of GaN material and a 2DEG drift layer. Moreover, the lateral structure is suitable for high frequency operation. Recent on-resistance of the GaN lateral device reaches the 4H-SiC limit [2].

However, there are two problems in the GaN lateral device. One is the current collapse under high voltage switching. Current collapse means the reduction of the drain current during the switching. This phenomenon will be caused by negative fixed charges on the surface and/or in the buffer layer. Many researchers are carrying out the research for suppressing the current collapse. It is well known that the field plates are effective to suppress the current collapse. However, the current collapse is not suppressed perfectly as yet.

Another problem is normally-off operation. High 2DEG density makes the normally-off operation difficult. Several gate structures have been proposed as shown Fig. 2. Required threshold voltage is over ~3V to avoid error operation caused by noises. However, there is no method at present to control the threshold voltage well. To operate the GaN lateral devices stably, driving circuits suitable to the each device are developed simultaneously.

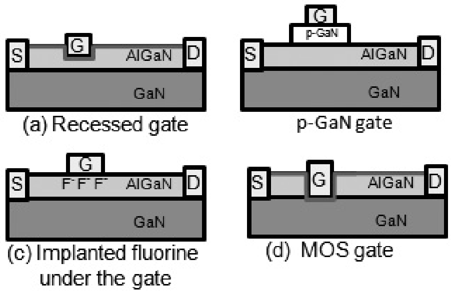


Fig. 2 Proposed normally-off gate structures.

On the other hand, lateral structure can be constructed on the several substrates, Si, sapphire, SiC and so on. A Si substrate is very suitable as a large size and low cost substrate. Fabrication process of the GaN lateral power device is simpler than the Si power MOSFET. These properties of GaN devices are very strong advantage to high cost performance. These characteristics of the GaN lateral devices are suitable for medium and low power systems in the HV/EV. The cost performance is very large factor for these applications. The GaN lateral device has the high cost performance compared with the Si power MOSFET as mentioned above.

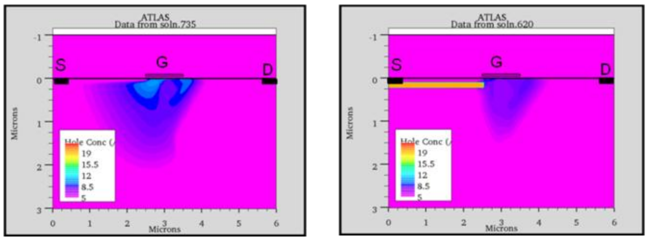
Vertical structure Devices

Vertical structure is general for power devices of Si or SiC, which is suitable for high power applications because high current density is possible. However, GaN vertical devices have not developed until recently caused by the lack of high quality free standing GaN substrates. Recently, high quality GaN substrates have become supplied from suppliers. Several reports of the GaN vertical devices have been published recently [3,4]. However, the performance of the GaN vertical device is inferior to SiC and Si power devices as yet though the material potential of GaN is the best.

4. Reliability

Reliability is very important to realize the practical use of the new power devices. Main evaluation items for power device reliability are following 4 items. One is avalanche resistance, the second is short circuit capacity, the third is electro static breakdown, and gate insulator reliability. First three items are related to sudden death of the device. Especially, avalanche resistance is very important for the automotive applications.

Avalanche breakdown is caused by counter electromotive force from inductive load. There are many inductive loads as motors in the HV/EV systems. However, GaN based lateral power devices have low avalanche resistance .GaN devices die catastrophically when the breakdown happens. One reason of this is the lack of low resistive p-type layer. As the electric field in the channel is increased, avalanche breakdown occurs in the channel at the drain or gate edge. If the generated holes accumulate anywhere, it induces the catastrophic breakdown. Therefore, to avoid the breakdown, low resistive p-type layer to flow the holes generated by avalanche is needed. We simulated the effect of the insertion of the p-type layer to the device structure. The p-type GaN layer is inserted beneath the source to the source-side gate edge. The simulated device had recessed gate structure with an Al_2O_3 insulated gate film, which was a normally-off device. Figure 3 represents the hole distribution with and without p-type layer. It shows that the hole accumulation occurs under the gate of the device without the p-type layer. Therefore, low resistive p-type layer to draw out the holes is very effective for protecting the catastrophic breakdown of the device. However, p-type layer is a weak point of GaN and related materials. Mg is used as p-type dopant, which has problems of deep acceptor level and diffusion. Breakthrough of the p-type GaN is strongly required.



(a) (b)

Fig. 3 Hole concentration under the gate (a) without p-GaN layer and (b) with p-GaN layer structure.

5. Conclusions

There are many applications of GaN power devices in the HV/EV systems. However, current status of the GaN power device doesn’t have enough performance and reliability as yet. Especially, there are many problems in the reliability items. We will have to adopt external circuit like snubber circuit or Zener diode for absorption of surge current to get the reliability on the first stage of GaN power device applications.

History of GaN power devices is shorter than that of Si and SiC power devices. Nevertheless, performance of the GaN power device has been progressing rapidly. Therefore, we expect that the present problems will be solved soon.

References

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