Which are the Future GaN Power Devices for Automotive Applications, Lateral Structures or Vertical Structures?

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Abstract

The GaN is a promising material for future electric power devices because of its excellent material potential compared with Si or SiC. Recently, high quality GaN on Si substrates have been developed and AlGaN/GaN lateral power HEMTs fabricated on the GaN on Si substrates which had more than 1kV breakdown voltage have been reported. In this paper, we compare the lateral structures and the vertical structures of the GaN power devices and discuss which the next power devices will be from viewpoints of automotive applications.

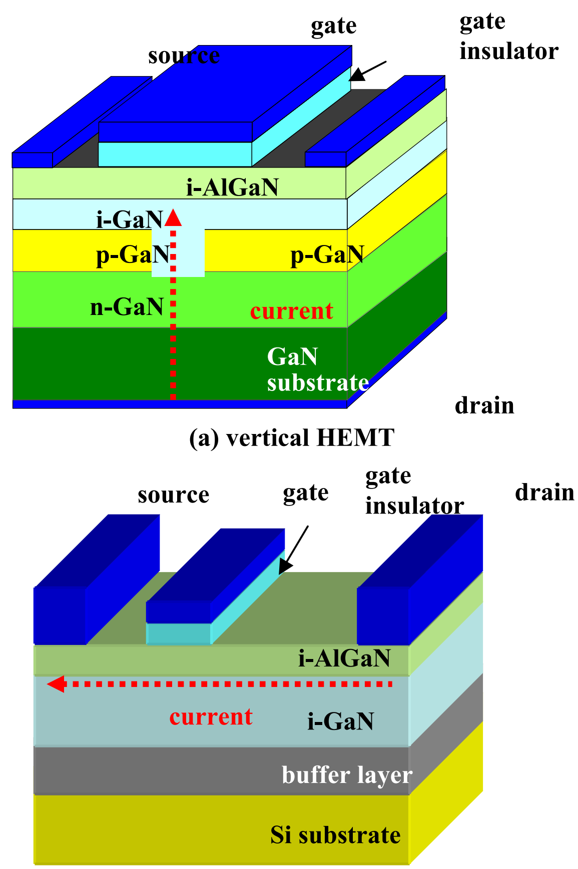
1. Introduction

Wide band gap semiconductors like SiC or GaN have a high electron mobility and a wide band gap energy. Then, these power devices are useful for operation under a high voltage and high temperature environment, for example, in automotive applications. Especially, GaN has a high dielectric strength and a high electron mobility compared with SiC. So the Baliga's figure of merit and the Baliga's high-frequency figure of merit of GaN are both larger than those of SiC(1) (2). This indicates that the GaN power devices have excellent performance. In addition, GaN High Electron Mobility Transistors (HEMT) have a extremely low on-resistance with using 2-dimensional electron gases (2-DEG).

The GaN power devices, however, have some problems to adapt to the future automobiles. The most serious problem is a cost of a GaN substrate in which the GaN power devices are fabricated. Sapphire substrates are relatively low cost compared with GaN free standing substrates, but the sapphire substrates have poor thermal conductivity, and then it is difficult to sink heat produced under device operations.

Recently, a GaN on Si substrate technology have been developed. This substrates are cheap and large size compared with the GaN free standing substrates and have a large thermal conductivity compared with the sapphire substrates. This technology is expected to solve the substrate's cost and heat sink capability. Up to date, we can obtain a 6-inch diameter GaN on Si substrates. This wafer size is enough to use for products.

In this paper, we focus on the GaN lateral devices and think about what will be useful for future automobiles.



(a) vertical HEMT

(b) lateral HEMT

Fig.1 GaN HEMT structures.

2. Compare with Lateral and Vertical HEMTs

In this section, we compare the lateral GaN power devices and the vertical GaN power devices. The GaN lateral HEMT and the GaN vertical HEMT are shown in Fig.1. In the vertical structures, current flows vertically in the devices. On the other hand, current flows at near surface in the lateral structures.

The lateral HEMT structures have following advantages;

(1) The devices are formed from non-doped AlGaN and GaN. Then, the lateral HEMTs have a low parasitic

capacitance. This means that these devices have both low conduction losses (low on-resistance) and low switching losses.

(2) We can use Si substrates instead of GaN free standing substrates. The Si substrates are much cheaper and lather than GaN substrates. This means that GaN lateral HEMTs fabricated on Si substrates are very inexpensive.

(3) A fabrication process of the GaN lateral HEMTs is very simple.

(4) It is very easy to obtain a bi-directional switch using the GaN lateral HEMTs.

On the other hand, the GaN lateral HEMTs have following disadvantages;

(1) Increase of a breakdown voltage directly makes the chip size larger because a drift length, which is defined by a distance between the gate and the drain region, should be larger.

(2) Current flows in source and drain electrodes, then a resistance and a current capacity of the electrodes limits the device performance.

(3) Current flows in balk region in the GaN vertical HEMTs, on the other hand, current flows at near surface in the GaN lateral HEMTs. Then, a current collapse phenomenon in the GaN lateral HEMTs is more serious that in the GaN vertical ones.

Advantages and disadvantages of the GaN lateral HEMTs compared with the vertical ones are summarized in Table.1.

Table.1 Advantages and disadvantages of the lateral GaN structures.

Advantages	Disadvantages
· Low cost and/or large scale substrates can be applied. · Compatibility both low on resistance and low parasitic capacitance. · Symmetrical structure → bi-directional operation	· Large breakdown voltage directly increases a chip size. · Resistance and current capability of source and drain electrodes. · Current collapse

3. VOLTAGE SOURCES IN FUTURE AUTOMOBILES

The Hybrid vehicles (HVs) have two batteries, one is 12V for sub-systems, the other is 208V or 288V for main systems. Hereafter, we call the 12V battery "low voltage battery" and the 208V or 288V battery "high voltage battery". In addition, the voltage source used in present HVs is boosted up from battery voltage of high voltage battery to 500V or 650V in order to provide to high power electric motors, namely the present HVs have 3-voltage source systems.

Systems that use the 500V or 650V voltage source are inverter for 3-phase electric motor and DC-DC converter that boost up the high voltage battery. These systems require both high voltage and high current.

From discussion in section 2, the GaN lateral HEMTs are not effective to apply to the high voltage systems or the high current systems. This means that it is difficult to apply the GaN lateral HEMTs to the inverter systems for 3-phase motor or the DC-DC boost-up converter systems.

On the other hand, the GaN lateral HEMTs are effective to apply to sub-systems which directly use the high voltage battery. Up to now, there is no system which directly uses the high voltage battery. High power sub-systems like an electric air conditioner or an electric power steering, however, will directly use the high voltage battery in near future.

The feature of GaN material, the device performance, and several automotive systems used in future automobiles that are related with HVs or EVs are summarized in Fig.2. For example, the compatibility of the low on-resistance and the low switching loss with HETERO structure is useful for DC-DC step down converter from the high battery voltage to 12V voltage. The high speed characteristics brings the advantage to the wireless charger systems which operate at 10 MHz frequency band. The bi-directional switching operation may be applied to AC-AC matrix converters in the charger systems of the plug-in HVs or the EVs from commercial frequency (50 or 60Hz in Japan) to, for example, 100kHz.

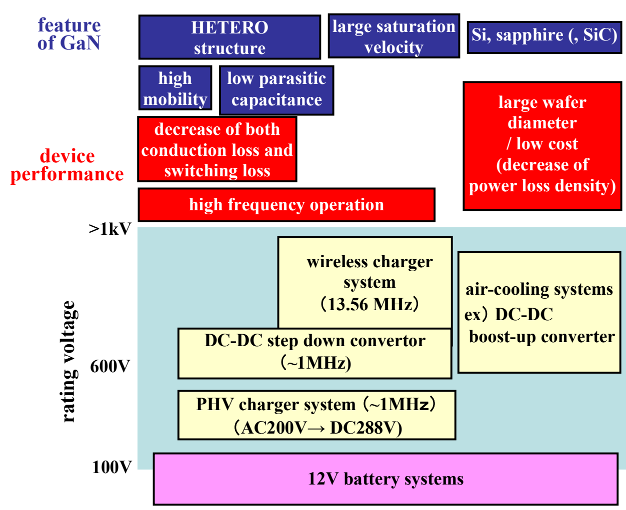


Fig.2 Features of the lateral GaN devices and application in future automobiles.

Relatively large chip size of the GaN lateral HEMTs may be acceptable, because the GaN on Si wafers are large and low cost. This brings the decrease of the power loss density. And then, we will obtain air cooling automotive systems with the GaN lateral HEMTs for the first time.

From above discussion, there are many automotive applications in which the GaN lateral HEMTs will be used in future.

4. THE SI POWER MOSFETS ARE BEST CHOICE FOR LOW VOLTAGE APPLICATION?

Many people think that the wide band gap semiconductor power devices are useful to only high voltage applications but not to low voltage applications.

In this section, we discuss the future power devices applied to the low voltage applications, that is, used in 12V automotive battery lines.

Main components of on-resistance in the power devices are a channel resistance and a drift resistance. The wide band gap semiconductor power devices have the low drift resistance which strongly depends on their breakdown voltage. On the other hand, the channel resistance does not depend on material parameters. Then, the wide band gap semiconductor devices are to be useful for the high breakdown voltage devices.

Recently, we can obtain commercial GaN power HEMTs[3]. Then, let's consider what is the best choice for the 12V automotive battery lines.

The device performance of the commercial GaN lateral HEMTs are summarized in Table.2. Values in parentheses at "Si limit" column indicate Si limit values at each rating voltage. Values of GaN specific on-resistance are calculated from catalog spec values of the chip sizes and the on-resistances.

The specific on-resistance of the 40V rating voltage device is almost same as the Si limit value. On the other hand, the specific on-resistance of the 100V and 200V rating devices are about 1/6 of the Si limit values. The Si limit value does not include the channel resistance, but GaN specific on-resistance values include the channel resistance. Figure 3 shows device performances of several power devices. Red star symbols indicate the performance of the GaN lateral HEMTs. From this figure, we can see that the specific on-resistances of the 100V and 200V rating voltages are about 1/10 of those of the Si power MOSFETs. Now, we use 100V rating voltage Si power MOSFETs for 12V battery systems, and then we should focus on the performance as the 100V rating device.

Next, we consider device structure and fabrication process. The structure of the Si power MOSFET and the GaN lateral HEMT structure are shown in Fig.5. HEMT structure are shown in Fig.4. In Si power MOSFETs, we should apply a trench gate structure in order to realize a high device performance. The trench structure is complex and increases device fabrication cost. On the other hand, fabrication process of the GaN lateral HEMTs is very simple and this makes the GaN lateral HEMT chip cheaper. In addition, a buffer layer structure of the low rating voltage devices is the high rating also very simple compared with that of the high rating voltage devices. The buffer layer structure of the high

Table.2 Device performance of the commercial GaN lateral HEMT [3].

Breakdown voltage (V)	Specific on-resistance (mΩ·mm²)	
	Si limit	GaN HEMT
70 (40V rating voltage)	24.6 (6.07)	21.4
170 (100V rating voltage)	226 (60.0)	37.5
250 (200V rating voltage)	592 (339)	104

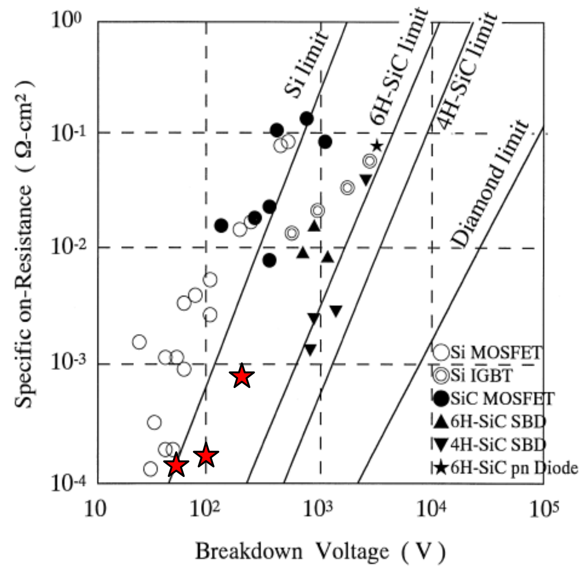


Fig.3 Device performance of the commercial GaN lateral HEMTs.

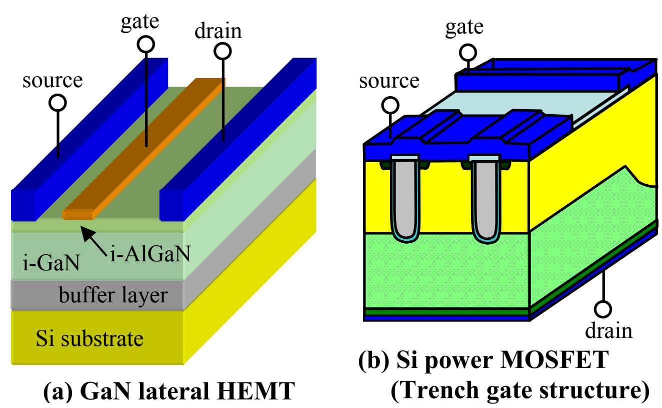


Fig.4 Comparison with GaN lateral HEMT and Si power MOSFET.

rating voltage should be a complex super lattice layer structure of AlN/GaN, on the other hand, that of the low rating voltage can be applied simple AlGaN single layer structure.

From above discussion, we obtain following conclusion about the GaN lateral HEMT of the low rating voltage.

(1) The specific on-resistance of the GaN lateral HEMT is about one order smaller than that of the Si power MOSFET even though in 100V rating voltage.

(2) The fabrication process is very simple.

(3) The on Si substrate has a very simple buffer structure.

These conclusion indicates that the GaN lateral HEMTs have an highly competitive in cost against the Si power MOSFETs. The future automotive systems in which the GaN lateral and the GaN vertical HEMTs will be applied are shown in Fig.5. This figure indicates that the GaN power devices will be widely applied in future automotive systems.

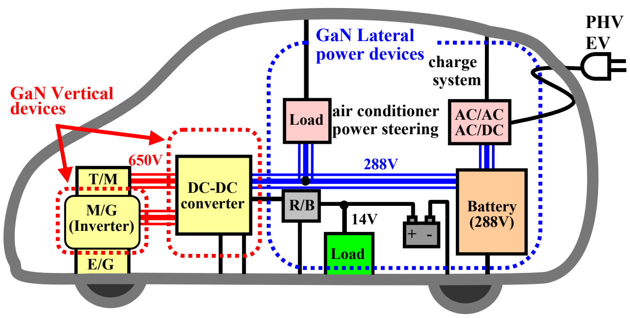


Fig.5 The future automotive systems in which the GaN lateral and the GaN vertical HEMTs will be applied.

5. Technical issues about the GaN lateral HEMTs

In this section, we discuss technical issues about the GaN lateral HEMTs. There are following 3 serious technical issues for automotive applications.

(1) Normally off operation

Normally off operation is strongly required for a fail safe. Several techniques have been developed, for example recessed gate structure, p-GaN or p-AlGaN structure, introduction of positive charge. But we have never gotten a enough solution. We should vigorously develop new technology for the normally off operation.

(2) Suppression of current collapse

The current collapse is a peculiar phenomena in GaN electric devices. The current collapse of several structures are shown in Fig.6. The on Si substrate or the GaN cap structure are effective for suppression of the current collapse phenomena.

(3) High surge capability

The power devices for automotive applications operate under noisy environment, and then the power devices used in automotive application must have a high surge capability. Conventional GaN HEMTs have no p type layers in their structures, and can not sink holes produced at impact ionization under high voltage application. In order to obtain the high surge capability, we should introduce the p type layers in the devices, which pull out holes produced at impact ionization under high voltage application.

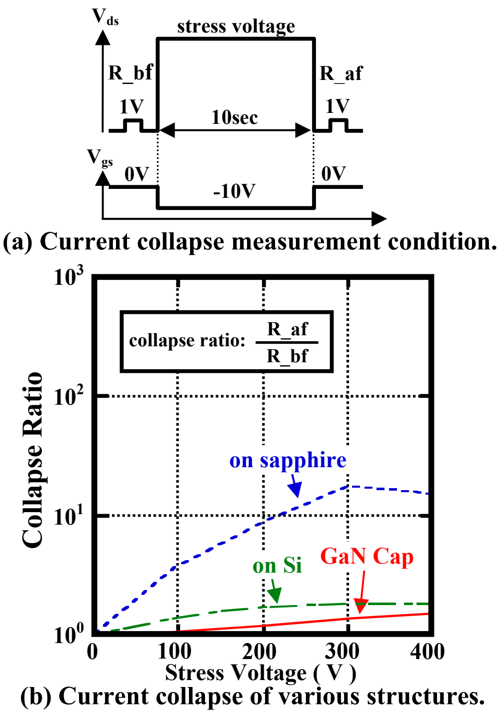


Fig.6 Current collapse phenomena of conventional on Sapphire device, GaN cap on Sapphire device, and conventional on Si device.

6. Conclusion

In this paper, we consider the GaN lateral HEMT for future automotive application. The GaN lateral HEMTs have several advantages compared with Si or SiC vertical power devices. If we solve the 3 serious technical issues, then it is sure that the GaN lateral power devices will be widely used in the future automobiles systems.

Reference

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