

## WIDE-BANDGAP SEMICONDUCTOR DEVICES FOR AUTOMOTIVE APPLICATIONS

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In this paper, we discuss requirements of power devices for automotive applications, especially hybrid vehicles and the development of GaN power devices at Toyota. We fabricated AlGaN/GaN HEMTs and measured their characteristics. The maximum breakdown voltage was over 600V. The drain current with a gate width of 31mm was over 8A. A thermograph image of the HEMT under high current operation shows the AlGaN/GaN HEMT operated at more than 300°C. And we confirmed the operation of a vertical GaN device. All the results of the GaN HEMTs are really promising to realize high performance and small size inverters for future automobiles.

*Keywords:* GaN, HEMT, HV, inverter, normally-off, vertical device

### 1. Introduction

Development and improvement of hybrid vehicles (HVs), electric vehicles (EVs) and fuel cell hybrid vehicles (FCHVs) are now widely recognized as one of the solutions of the CO<sub>2</sub> problem of the earth and the exhaust gas problem of urban areas. These vehicles need high electric power inverters with high energy conversion efficiency. Si Insulated Gate Bipolar Transistors (Si-IGBTs) are widely used in the inverters, but these devices have a limitation of performance due to their material properties. Devices with higher performance have been strongly required for future vehicles. In this paper, we discuss requirements of automotive applications of wide-bandgap semiconductor devices, especially hybrid vehicles, and our development of GaN power devices.

Figure 1 shows the road map of the power density [1]. The power density has been increasing year after year. The inverters installed in Toyota's hybrid vehicles, such as Prius and RX400h have 3 times higher power densities than other applications as shown

in the figure. However, HV and FCHV systems of the next generation will require much higher power densities with lower energy loss, smaller size and lower cost. It is difficult to realize such higher power density systems with Si-IGBTs, because of their material properties. Therefore, we should develop novel power devices made of new materials for these systems. Theoretical performance of several semiconductor materials are shown in Table 1, where wide-bandgap semiconductors clearly have advantages compared with Si. This is the big motivation for us to develop novel switching devices made of wide-bandgap semiconductors such as SiC and GaN.

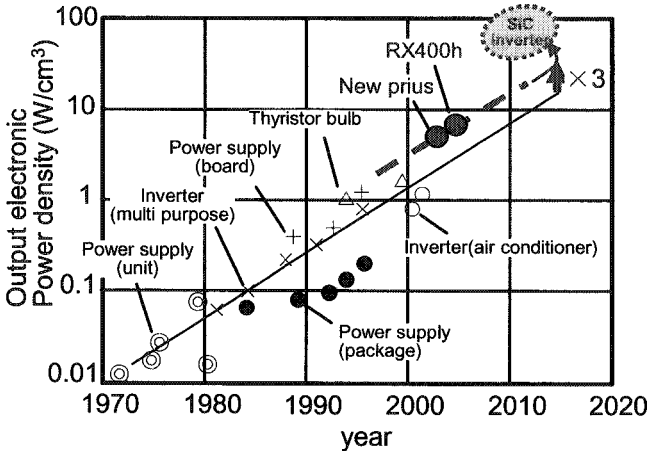


Fig.1 Road map of power density

Table 1. Normalized figures of merit of various semiconductors

	Si	GaAs	4H-SiC	GaN
JFM	1	11	410	790
KFM	1	0.45	5.1	1.8
BFM	1	28	290	910
BHFM	1	16	34	100

- JFM : Johnson’s figure of merit for high frequency devices  $= (E_b V_s / 2\pi)^2$
- KFM : Keyes’s figure of merit considering thermal limitation  $= \kappa (E_b V_s / 2\pi \epsilon)^{1/2}$
- BFM : Baliga’s figure of merit for power switching  $= e m E_g^3$
- BHFM: Baliga’s figure of merit for high frequency power switching  $= \mu E_b^2$

## 2. Requirements of Automotive Applications for Power Device in the Future

To realize the next generation hybrid systems, the following performance will be required for power devices in the future.

### 2.1. Normally-off operation

Most effort on GaN based devices has been directed toward normally-on ones, and only a few normally-off ones have been reported. In normally-off devices, the drain current does

not flow at the gate voltage of 0V. Si-IGBTs used in the present inverters are normally-off operation devices. Likewise, a normally-off operation device is required for future automobiles in order to simplify the inverter circuit and make effective use of design techniques and mounting technologies for the inverters.

### 2.2. High breakdown voltage

Figure 2 shows the relationship between the motor power of Toyota's HVs and power source voltages of these systems. The first generation Prius was on the market in 1997. Through the inverter of this hybrid system, the battery voltage of 277V was directly connected to the motor. The new Prius has been on the market since 2003. In its HV system, the battery voltage is once raised to a power source voltage by a voltage booster and then supplied to the motor through the inverter. The raised voltage can take values from 202V of the battery up to a maximum of 500V [2]. The new Toyota's HVs need high motor power with high power source voltage as shown in Fig. 2. The breakdown voltage of devices used in these inverters is about 1.1kV [3]. The breakdown voltage of devices used in the inverters will probably become higher in the future due to protection against surge voltage and so on. On the other hand, A upper limit of the breakdown voltage of them may depend on the withstand voltage of condensers, discharge inception voltages between phases of the motors, etc.

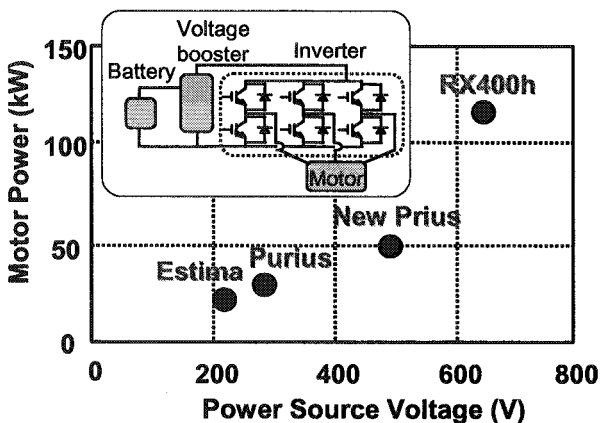


Fig.2 Power source voltage vs. motor power

### 2.3. Low on-resistance and high current density

In order to increase the energy conversion efficiency of inverter systems, it is necessary to decrease the on-resistance of the devices. Moreover, it is demanded for miniaturization of inverters to increase the current capacity up to several hundreds  $A/cm^2$ .

### 2.4. High temperature operation

Si devices stop working over  $150^\circ C$ , because a power loss increases due to an increase of a leakage current in the off state under high temperature environments. Whereas, GaN devices can probably work over  $200^\circ C$ , because the energy bandgap of GaN is wider than

that of Si. The present hybrid systems have two cooling systems, one is for the engine and the other is for the inverter, and the temperature of coolant water for the inverter is lower than that for the engine. If GaN devices work over 200°C, the cooling system of hybrid vehicles will be simplified and its cost will be reduced.

**2.5. Vertical operation**

Up to date, most of efforts on development of GaN based devices have been directed toward lateral operation ones. However, vertical operation devices are demanded for automotive applications. First, vertical devices will meet the requirement of the above 3). Secondly, design techniques and mounting technologies developed for Si IGBT will be utilized effectively.

**3. Our Development of GaN Power Devices**

**3.1. Normally-off operation**

Studies of GaN based device have been mainly focused on the normally-on operation devices for microwave power applications, for example, the base station. Recently, a few normally-off operation GaN devices for power electronics applications have been reported, and the threshold voltages ( $V_{th}$ ) of these devices are around +0.3V [4] [5]. However, no device with a high drain current and a very low on-resistance has been realized yet, because most of these devices are Schottky gate type. In the Schottky type devices, a current begins to flow drastically from the gate to the source at the gate voltage of around +2V. Therefore, it is impossible to control high current by the Schottky gate electrode. On the other hand, in case of insulated gate type devices, the higher voltage than around +2V can be applied to the gate electrodes. In order to realize the normally-off devices with the high current operation and the low on-resistance, the key issue is formation of gate insulator films with good quality. We investigated SiO<sub>2</sub> films formed by Low Pressure Chemical Vapor Deposition (LP-CVD) at a high temperature [6]. Results of the interface-state density calculated by the Terman method are shown in Fig. 3. The curve of the interface state density had two peaks at about -0.4eV and -0.7eV from

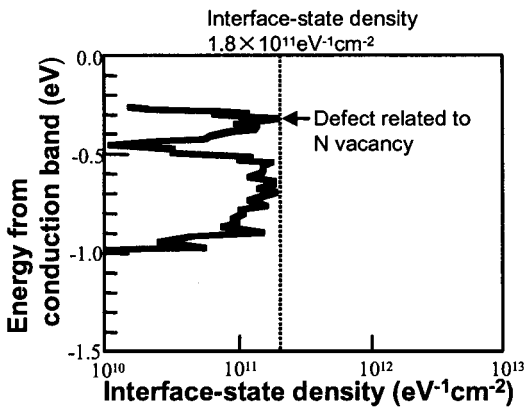


Fig. 3 SiO<sub>2</sub>/GaN interface-state density

the conduction band, and both of the interface state densities were about  $2 \times 10^{11}/\text{cm}^2\text{eV}$ . We are developing normally-off devices using  $\text{SiO}_2$  films. We will show some of their characteristics next.

### 3.2. High breakdown voltage

A GaN-HEMT with break down voltage of 1.3kV was reported in recent years [7]. We fabricated the insulated gate HEMTs, and measured the breakdown characteristics. Figure 4 shows the result of breakdown characteristic at the gate bias of -30V. The gate-drain length and the gate width of this device are  $20\mu\text{m}$  and  $440\mu\text{m}$ , respectively. The breakdown voltage was over 600V.

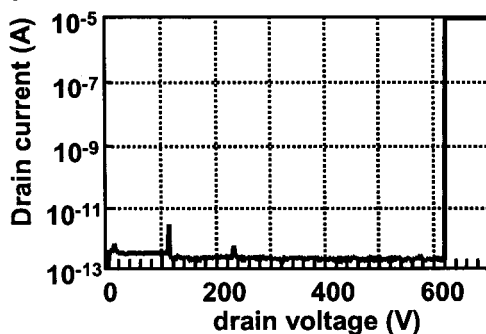
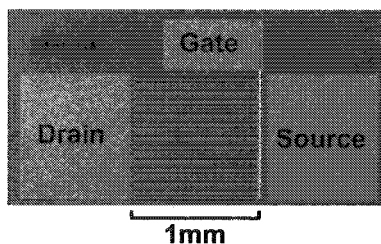


Fig. 4 Breakdown characteristics

### 3.3. Low on-resistance and high current operation

To examine a possibility of GaN power devices, we fabricated a large size GaN power HEMT with a gate width of 31 mm (Fig. 5), and verified a high current operation [6]. The drain current reached over 8A under pulse measurement (Fig.6). The specific on-resistance was about  $5\text{m}\Omega\text{-cm}^2$ .



Gate width:31mm, Active area:1mm<sup>2</sup>

Fig. 5 Photograph of fabricated GaN-HEMT

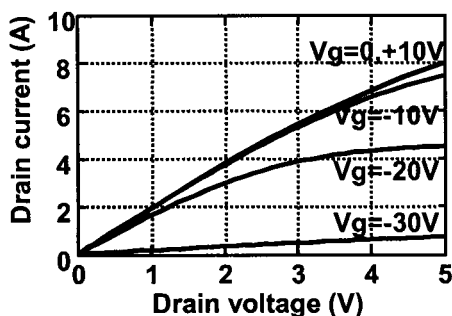


Fig. 6  $I_D$ - $V_D$  characteristics under pulse condition

### 3.4. High temperature operation

An observation on the device under high current operation with thermograph (Fig.7) showed the GaN HEMT operated at more than  $300^\circ\text{C}$  [8]. The gate width and the chip

size of this device were 31mm and  $2 \times 4 \text{mm}^2$ , respectively. The active area was about  $1 \times 1 \text{mm}^2$ . The bias condition was  $V_D = 2.6 \text{V}$  and  $I_D = 1.3 \text{A}$  under DC condition. These results indicate that GaN power devices are promising for future automotive systems operated in high temperature circumstance.

### 3.5. Vertical operation

In order to decrease the on resistance, we also fabricated a vertical operation device on a free-standing n-type GaN substrate[9]. Figure 8 shows the current-voltage characteristics. A drain current didn't rise at a voltage of 0V because of poor characteristics of ohmic contacts. But by using a free-standing GaN substrate, vertical current between source and drain was really well controlled by the gate bias. A device with a gate length of  $4 \mu\text{m}$  and a gate width of  $300 \mu\text{m}$  showed a leakage current in off state was less than  $10^{-9} \text{A}$ .

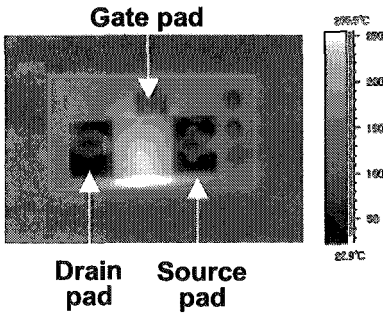


Fig. 7 Thermograph image under high current operation

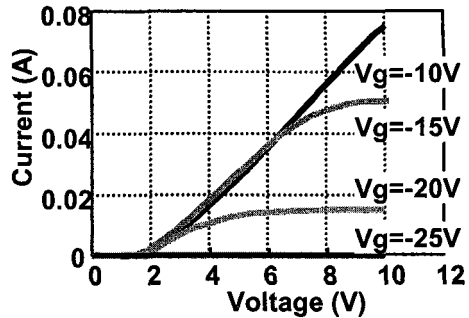


Fig. 8 I-V characteristics of vertical operation device

## 4. Conclusions

We explained the inverter in the Toyota's hybrid systems and requirements of future hybrid systems for power devices. And we find that GaN power devices are excellent candidates for future automotive applications.

We fabricated AlGaIn/GaN HEMTs and measured their characteristics. The maximum of the breakdown voltage was over 600V. The drain current was over 8A at a device with a gate width of 31mm. All the results of our GaN technology are really promising to realize high performance small size inverter for future automotive applications.

On the other hand, many issues which should be solved also become clear, for example, an improvement of the breakdown voltage, an achievement of good balance between a reduction of the specific on-resistance and the normally-off operation and a realization of vertical operation devices.

Other important issues we don't refer are an evaluation and a securing of long-term stability and a development of free-standing GaN substrate with lower defect density, larger size and lower cost.

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