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Study of SiC power device application for various electrified vehicle

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ABSTRACT: As part of its efforts to achieve carbon neutrality, Toyota offers a full lineup of electrified vehicles to its customers around the world, including battery electric (BEVs), hybrid electric (HEVs), plug-in hybrid electric (PHEVs), and fuel cell electric (FCEVs) vehicles as multi pathway approach. All these vehicles use power semiconductors to switch large currents on and off at high speeds. For this reason, power semiconductor performance has a major impact on vehicle power consumption efficiency, as well as the size and weight of powertrain components. SiC Power device is one of the promising devices for motor drive application. This article describes up-to-date example of SiC power device application for electrified vehicle and case study of comparison of advantage point by which inverter should be used.

KEY WORDS: electrification, power device, SiC, power control unit, inverter, converter

1. INTRODUCTION

As part of its efforts to achieve carbon neutrality, Toyota offers a full lineup of electrified vehicles to its customers around the world, including battery electric (BEVs), hybrid electric (HEVs), plug-in hybrid electric (PHEVs), and fuel cell electric (FCEVs) vehicles as "multi pathway approach" (Fig.1). Fig. 2 shows an outline of the core powertrain components that enable Toyota to offer this extensive lineup. Alongside the motor and battery, the power control unit (PCU) is one of the most important power conversion components in the energy management system at the heart of every type of electrified vehicle. As shown in Fig. 3, a PCU consists of a large number of power semiconductors. The purpose of these power semiconductors is to rapidly switch large currents on and off as part of the process by which direct current (DC) from the battery is converted into alternating current (AC) and supplied to the motor. Large numbers of power semiconductors are also found in the chargers used in BEVs and PHEVs, as well as in components such as the DC converter used in the fuel cell (FC) of FCEVs. For this reason, power semiconductors are key devices that have a significant impact on the performance and cost of all types of electrified vehicles. Firstly, this paper shows Toyota's up-to-date application example of SiC MOSFET as promising power device. And we also discuss some case study results of application of SiC MOSFET for PHEV and HEV as the expectations for the next generation of power control unit.

Fig.1 Toyota's multi-pathway approach

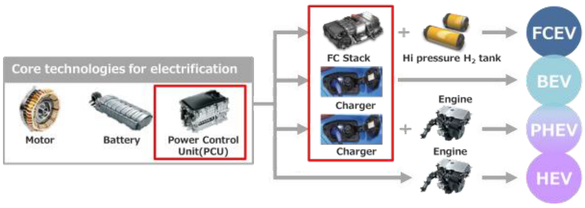


Fig.2 Core technologies for electrification

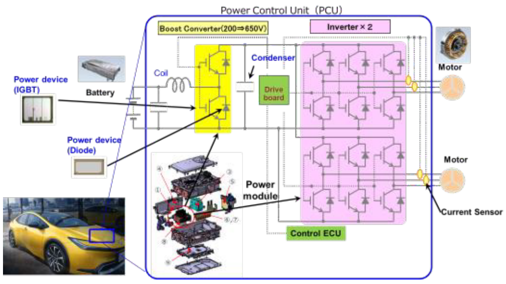


Fig.3 Schematic circuit of power control unit

2. APPLICATION EXAMNPLE OF SIC POWER DEVICE

Figure.4 shows characteristic physical properties of wide band gap materials. As shown graph, SiC is promising material and power device for power electronics, because it has excellent physical properties.

Recently Toyota have developed BEV which used SiC power device for the power control unit of rear inverter. A field-relaxed trench MOS structure is used to achieve high breakdown voltage and low ON-resistance. This reduces power loss by more than 50% and improves the output density per unit area by 2.8 times. In addition, by replacing a RC-IGBT with a SiC-MOSFET, the same package can be used, which greatly contributes to development efficiency. (fig.5) Also large size SiC chip has been adapted to this PCU thanks to high quality and low crystal defect SiC wafer.

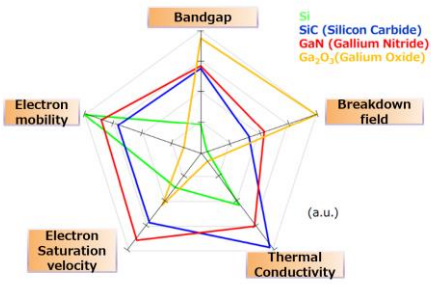


Fig.4 physical properties of wide bandgap material

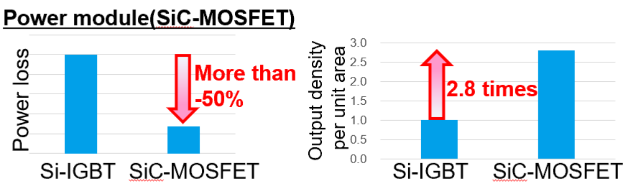


Fig.5 Effect of SiC device application for rear inverter

Next, we will discuss the three issues that arose from the adoption of SiC.

The first is the rise in device temperature during transients.

This is due to the reduced chip size compared to Silicon, resulting in lower thermal capacitance and faster temperature rise of the power device.

This was resolved by reviewing the distribution of driving force between front and rear.

The second is the deterioration of EMC performance and increase in surge voltage.

This is due to the factor that the switching speed is about 3 times faster than that of Silicon.

EMC performance was resolved by optimizing the Y capacitance and the surge voltage was resolved by optimizing the gate resistance.

Third is malfunction.

This is due to the lower gate threshold voltage when the SiC device enters the ON state.

This was resolved by adopting the negative gate voltage during the OFF state.

However, increasing advantages of SiC devices much more, more suitable solutions of power electronics are needed, such as high thermal conductivity power module, RC snubber circuit, active gate control and so on.

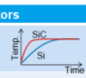
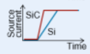
Disadvantages	Factors	Countermeasures
Device overheating during transients	Lower thermal capacity 	Reviewing the distribution of driving force between front and rear
Deterioration of vehicle EMC Increased surge voltage	3.0 times Faster Switching speed 	EMC Optimizing the Y capacitor Surge voltage Optimizing gate resistance
Malfunction	Low gate voltage threshold	Adopting a negative gate voltage

Fig. 6 Countermeasures for disadvantages of SiC device application

3. FUTURE CASE STUDY OF SIC APPLICATION FOR HEV/PHEV

To realize carbon neutrality, application expansion of SiC device for not only BEV, but also HEV and PHEV is desired. One of the advantages of SiC device application for HEV and PHEV is improving fuel economy. In case of HEV, it will obtain CO2 reduction. While in case of PHEV, it will obtain not only CO2 reduction but also battery volume reduction by acquiring longer driving range as a result of improving fuel economy.

However, HEV and PHEV is normally requested low cost, so appropriate and effective application of SiC device is needed especially for HEV and PHEV. So, we studied effect of SiC device application for various vehicle types.

Fig. 7 shows calculation result of improving effect in WLTP HV mode for fuel economy by adapting SiC devices for various vehicle types.

Firstly, Large-size vehicles PHEV has relatively lower fuel economy, so effect of SiC device is higher than small size vehicles. And one interesting point is that improving effect is low by adapting to converter. This result is caused operation ratio of converter is relatively low in large-size PHEVs in THS II because of battery size.

While, small-size HEVs have also have good improving effect as total fuel economy of SiC devices. Small size HEVs has lower improving effect of SiC device application to MG1 inverter and MG2 inverter, but it also has higher improving effect of SiC device application to converter. This is because operation ratio of converter and power ratio of motor power. So, we can see the good effect by adapting SiC devices both large size and small size PHEVs and HEVs.

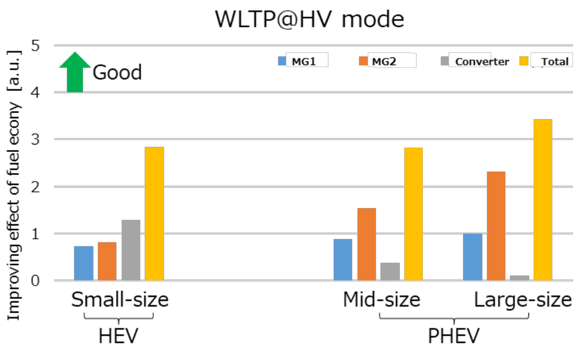


Fig.7 Improving effect in WLTP@HV mode

Figure 8 shows alternative driving mode as US Comb. as HV mode. Large size vehicles are popular in US. We can see similar improving effect to WLTP@HV mode by adapting SiC devices. Also improving effect of MG2 inverter in large size vehicles is larger than as of mid-size vehicles in both case WLTP@HV mode and US Comb.HV mode. So, we can see improving effect of MG2 depending on vehicle size as motor size.

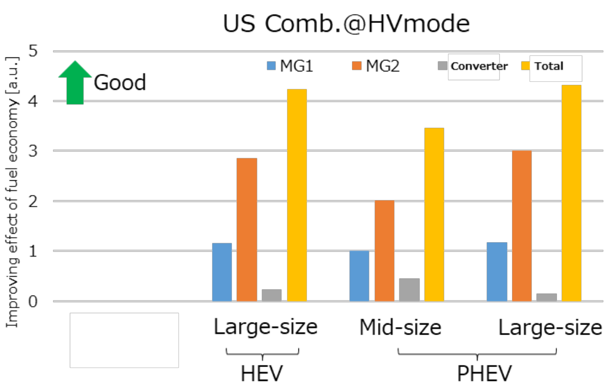


Fig.8 Improving effect in US Comb.@HV mode

We also calculate improving effect in EV mode. Figure 9 shows improving effect of SiC devices in WLTP@EV mode. We can obtain similar effect to HV mode. But we can see larger effect compared to HV mode. This is because ratio of MG2 driving power in EV mode as PHEVs is larger than HV mode so that we could get larger improving effect of not only MG2 but also total fuel economy. We also calculate improving effect for MGR(Rear Motor) by adapting SiC devices. Improving effect for MGR is relatively smaller than MG2's. This is also because ratio of MGR driving power and driving frequency.

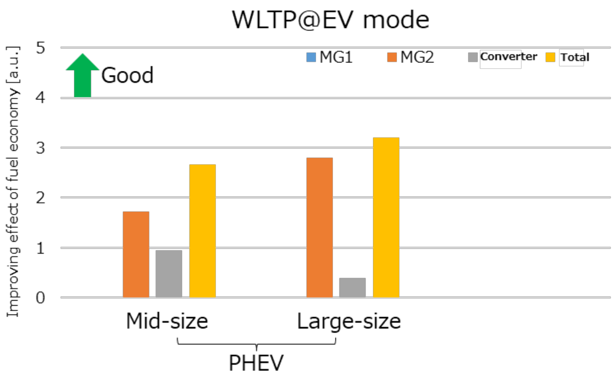


Fig.9 Improving effect in WLTP@EV mode

Figure 10 shows improving effect of SiC devices in US Comb.@EV mode as alternative driving cycle mode. We can obtain similar tendency to WLTP@EV mode, but amount of improving effect by adapting SiC devices is larger than WLTP@EV mode's one. This is because total amount of MG2 and MGR power area (power x driving time) as by difference of driving cycle pattern between WLTP and US Comb.

We also calculate improving effect of mid-size BEVs by adapting SiC devices. Of course, improving effect of mid-size BEVs is larger than improving effect of PHEVs's. But we can confirm improving effect by adapting SiC devices to HEVs and PHEVs is also acceptable in terms of fuel economy.

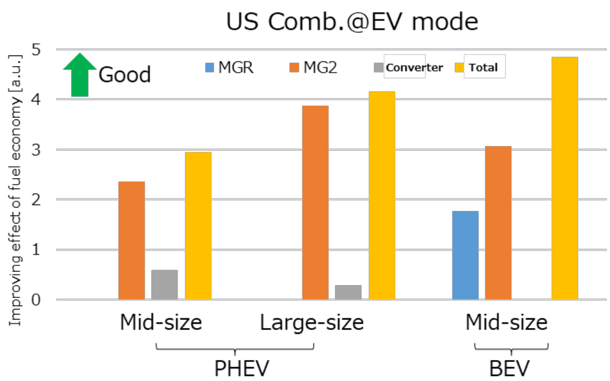


Fig.10 Improving effect in US Comb.@EV mode

4. CONCLUSIONS

In this paper, we show up-to-date example of SiC power device application for electrified vehicle and case study of comparison of advantage point by which inverter should be used. And also, effective application method of SiC devices depending on car size and character with various driving cycle modes. We can obtain similar improving effect by adapting SiC devices in HEVs and PHEVs to improving effect in BEVs. So adapting SiC devices is one of the great solution to reduce CO2 and improving fuel economy of HEVs and PHEVs. But the cost performance of adapting SiC devices for HEVs and PHEVs is bad, we cannot supply cost affordable HEVs and PHEVs for customers. Also we cannot contribute carbon neutrality. So, we will try to develop much less loss and cost SiC devices and with developing partner to contribute carbon neutrality with not spoiling driving pleasure for worldwide customers to realize muti-path way approach.

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REFERENCES

(1) K. Hotta, M. Senoo, S. Yasuda, “TOYOTA technical review”, vol. 69, no. 2, pp. 21-38 2024.