# Benefits and Requirements of Using SiC and/or GaN Power Switching Devices for "Real" Power Control Systems

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**Keywords: SiC, GaN, Power Switching, auto-mobile, power efficiency, Power module**

**Abstract**

**A very high impact example application of GaN/SiC devices is in the development of Hybrid Electric Vehicles. Toyota chose to use SiC devices in the power converter of their HEVs planned for introduction in year 2020, for three compelling reasons: (1) The SiC devices will enable a significant size reduction of the cooling system for the Power Converter Unit (PCU), or possibly even its complete elimination. (2) The superior power efficiency of SiC devices as compared with the usual Si-IGBT devices enables significantly improved fuel economy. (3) SiC devices also enable use of higher switching frequency (from 10kHz to 50kHz). This allows the use of smaller and less expensive passive components like capacitors, which results in a 10% cost reduction of the PCU.**

## INTRODUCTION

The usefulness of GaN/SiC devices for power switching has been often discussed, focusing on transistor or diode performance at a component level. However, the true value of these devices (as compared with conventional devices like the Si-IGBT) is most apparent when assessed at the system level. In this paper, we describe the merits and requirements for using wide band gap semiconductor devices, based on results obtained in the collaboration with end users of these devices at the system level.

It is anticipated that SiC power semiconductors will be in full mass production by 2020, because Toyota Motor Corporation has decided to use the SiC devices in the Power Converter Unit (PCU) in their Hybrid Electric Vehicles (HEV). There are three reasons that Toyota chose to use SiC instead of Si for the new PCU. (1) Simplification of the cooling system for the PCU: Using the more efficient SiC devices will enable a significant size reduction of the cooling system for the PCU, or possibly even its complete elimination. (2) Improvement of fuel economy: Toyota believes the improved efficiency of the SiC based PCU will reduce the engine load, and thereby significantly reduce fuel consumption. (3) The planned 5X Higher operating frequency of SiC based PCU will allow the use of lower loss and lower cost multilayer ceramic capacitors. This will enable a significant cost and size reduction of the PCU.

## SIMPLIFICATION OF COOLING SYSTEM

The present HEV has two separate cooling systems; one for the engine and one for the Si based PCU (see Fig 1(a)), where Si-IGBT is used for a power switching. The cooling line temperature of the engine reaches 110C and that of PCU is 65C in that case. The improved efficiency of SiC devices in the PCU will allow the engine and PCU to share a single water cooling system (see Fig 1(b)) in case of allowed junction temperature of the device over 175C, or it may even allow the PCU to be air cooled (Fig 1(c) with the allowed junction temperature over 200C. These simplifications would be directly enabled by the superior efficiency of the SiC based PCU, would significantly reduce both the size and cost of the cooling system for the HEV.

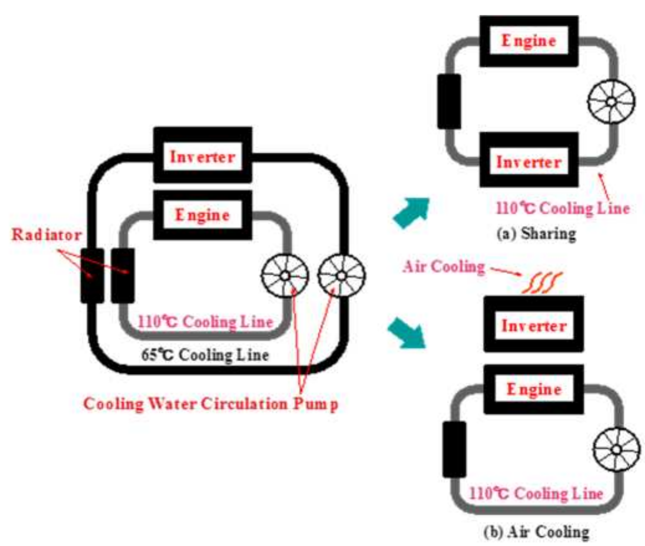


Fig. 1. Cooling System for PCU of HEV.

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## HIGH FUEL EFFICIENCY PERFORMANCE

A full quantitative analysis of the impact of improved PCU efficiency and fuel consumption cannot be done until the HEV design is further along. However, initial estimates of fuel consumption have been calculated by using a supercomputer model, including effects from the HEV mechanical structure and electrical mechanism. The traveling mode assumed is the JC08 Japanese standard. Fig. 2 shows a relationship between the overall efficiency of PCU and the fuel consumption. The model indicated that a one percent increase of the PCU efficiency would provide approximately 1 km/liter increase in fuel economy. Fig.3 shows the inverter efficiency comparison between the Si IGBT and SiC MOS-FET at the laboratory level. The SiC MOS-FET has approximately 2% higher efficiency than the SI IGBT which translates to approximately a 2 km/liter (4.7 miles/gallon) improvement in fuel economy for the HEV.

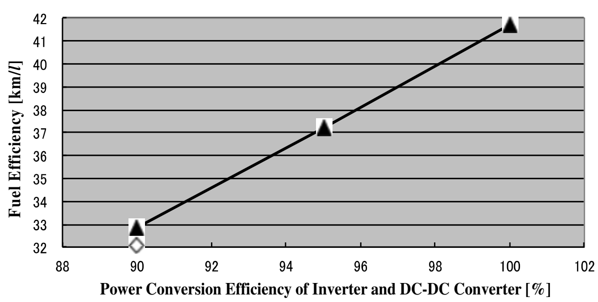


Fig. 2. Relationship between fuel efficiency and PCU efficiency.

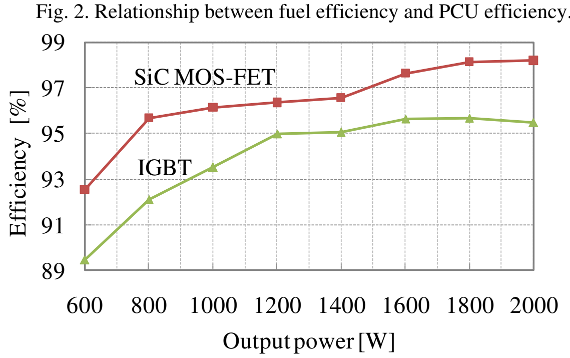


Fig. 3. Efficiency data (Si IGBT v.s. SiC MOS-FET).

Insertion of a capacitor Cgs between gate and source is sometimes used for the stabilization PCU operation (see Fig.4), but this capacitor should be omitted when using the SiC MOS-FET with its low gate threshold voltage, because the capacitor significantly degrades the efficiency of the PCU as shown in Fig. 5. Omitting this capacitor will improve the efficiency of the PCU by 1-2%, and thereby further reduce power dissipation and improve the fuel economy.

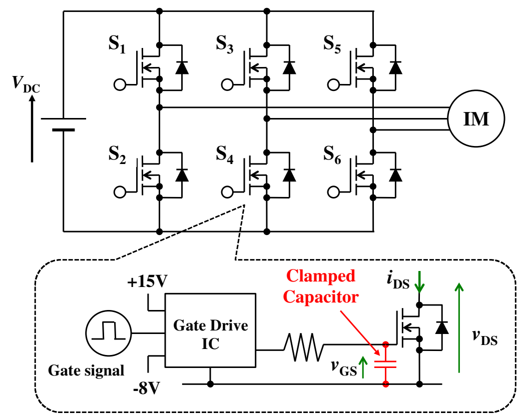


Fig. 4. Inverter System for PCU.

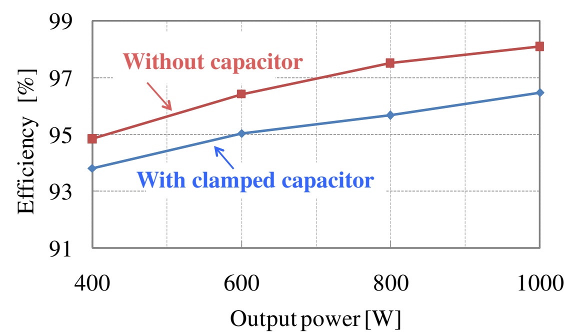


Fig. 5. Efficiency data (with $C_{GS}$ v.s. without $C_{GS}$).

## POSSIBILITY TO USE MULTILAYER CERAMIC CAPACITOR APPLICATION

Using Si IGBTs in the PCU of the Toyota HEV limits the PCU operating frequency to 10kHz. However, using the SiC MOSFET, Toyota plans to increase the operating frequency to a value of around 50-80 kHz. This will allow a significant size reduction in the capacitors used in the PCU. For example, Fig. 6 shows the required capacitance value for the smoothing capacitor between the high capacity battery and the motor driving inverter as a function of operating frequency. At 10kHz a large 180μF capacitor is required, but at 50 kHz, a much smaller capacitance of only 30μF is acceptable. (For reference, the capacitor in the present Toyota HVE is 888 μF.) For capacitance values > 100μF, the unit price for multi-layer ceramic smoothing capacitors is more that $100/pc in 2015. However, this price drops to less than $10/pc for capacitance values < 100μF, which is a significant cost savings to the HEV. These multi-layer ceramic capacitors have the additional benefits, smaller size, low ESR, and high heat resistance.

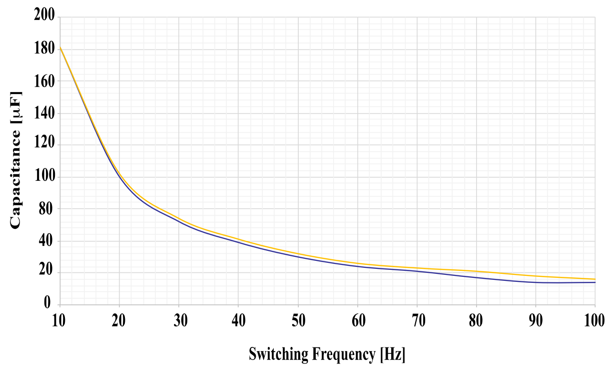


Fig. 6. Relationship between switching frequency and value of smoothing capacitor.

Figure 7 shows the equivalent circuit for the boost chopper is a component part of the PCU. It is desirable to minimize the total volume of the boost chopper, and also to minimize its cost. The minimum total volume ($cm^{-3}$) possible for the boost chopper is different for the different technologies used for the switching element (e.g., Si-IGBT, Si-MOSFET, SiC-MOSFET, or GaN ) and it is also a function of operating frequency (see Fig. 8). The increase in PCU operating frequency and the migration from Si-IGBT to SiC-MOSFET is expected to enable a 2X reduction in the volume and a corresponding cost reduction due to smaller passive components.

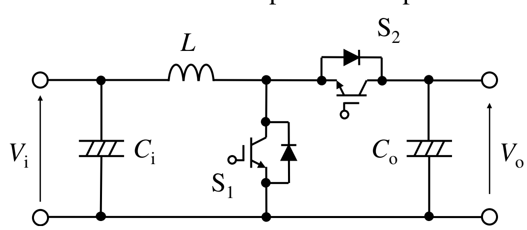


Fig. 7. Equivalent circuit of boost chopper.

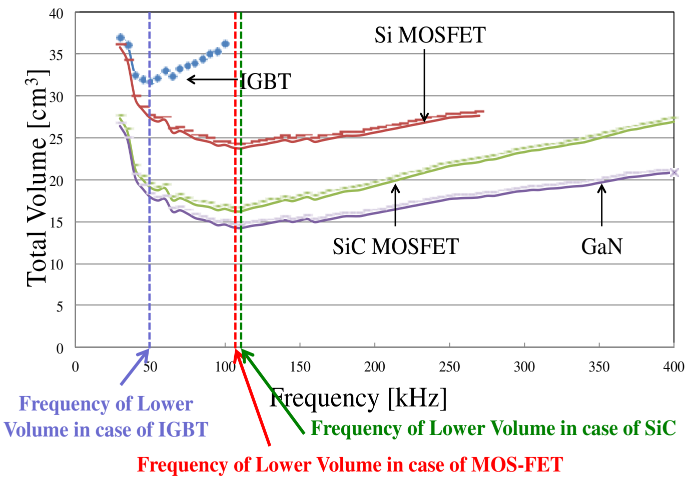


Fig. 8. Relationship between switching frequency and total volume of boost chopper.

## CONCLUSIONS

The three benefits were shown when the SiC power semiconductors are applied to HEV. Now, we have to prepare from various viewpoints as those who are in charge of application of power semiconductors, before the "SiC breakthrough era" starting from 2020.

## ACRONYMS

HEV: Hybrid Electric Vehicle
PCU: Power converter unit
IGBT: Insulated Gate Bipolar Transistor
MOSFET: metal-oxide-semiconductor field-effect transistor
ESR: Equivalent Series Resistance

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