The Application of Silicon Carbide in PCU

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Abstract—The development of new energy vehicles has brought unlimited possibilities for the development of the automotive industry. One of the critical components is the Power Control Unit (PCU) in the motor. Nowadays, silicon-based power semiconductors no longer meet the needs of today's new energy vehicles, so siliconized synthetic materials has become the development direction. This paper briefly introduces the vital role of PCU in EV / HEV and analyzes the significance of new materials in this field.

1. Introduction
It is well known that diesel and gasoline engines power today's popular cars. In contrast, new energy vehicles are cars powered by unconventional fuel sources. In the era of the rapid development of new energy vehicles, its "heart" battery is undoubtedly the focus of research for various automobile brands. One of the critical components is the PCU that I want to discuss. From the perspective of the entire vehicle application, the PCU controls the current supply of the motor while the vehicle is running. When the vehicle is moving forward, accelerating and retreating (including deceleration), it uses the recovered electrical energy to charge the battery, which can be said to play an essential role in the system.

In terms of the current market and R&D related progress, Toyota is undoubtedly at the forefront of the world. Since Toyota introduced the world's first mass-produced hybrid vehicle in 1997, it has been a pioneer in the development of electric vehicles. It has productive technology and experience in R&D, manufacturing, and sales. Besides, BYD, which is a thick and thin film, has also been innovated in the power control unit. And bring their latest work - IGBT 4.0 technology. At the same time, some foreign companies, such as Volkswagen, Audi, BMW, Volvo, etc., have introduced plug-in hybrid models. Unfortunately, these cars are relatively small, so their control units not be analyzed in the paper.

In the R&D process, the PCU’s power consumption accounts for 20% of the vehicle's power loss. This problem is, therefore, also the main problem of current new energy vehicles. The choice of materials is a critical way to improve[3]. Therefore, this paper will show the core idea of this article below, the feasibility and importance of replacing silicon-based materials with new materials such as silicon dioxide.

2. The importance of PCU in new energy vehicle
As a new energy vehicle, the advantages are apparent. One of the example is the hybrid car. First, after the hybrid power is applied, the maximum power of the internal combustion engine can be determined based on the average required power. The engine is relatively small in size and operates under optimal operating conditions with low fuel consumption and low pollution. Since the internal combustion engine operates continuously and the battery can be continuously charged, the stroke is the same as that of a typical car. Secondly, due to the battery, it is easy to recover kinetic energy when going downhill. Finally, because there are multiple power sources, the vehicle can work at the same time. However, in terms of
the current manufacturing level of human society, the system structure is relatively complicated. The fuel economy effect of high-speed, long-distance driving is not apparent. For the second question, the core is the battery system of the entire car. Both electric and hybrid vehicles are equipped with a controller PCU that controls the current intensity for vehicle control. Then I will introduce what a PCU is.

![Energy Type of Vehicles](image1.png)

**Figure 1.** The energy type of vehicles.

From the internal structure, at present, the electric drive parts of electric vehicles and hybrid vehicles are mainly composed of silicon (Si)-based power devices. With the development of electric vehicles, higher requirements have been placed on miniaturization, lightweight, and energy-saving of electric drives. However, due to material limitations, traditional silicon-based power devices have reached or even reached the inherent limits of materials in many respects, such as voltage blocking capability, forward voltage drop, device switching speed, and the like. Especially in the high voltage field frequency and high power, it shows its limitations. As a result, many automakers are beginning to focus on next-generation silicon carbide semiconductor power devices. It is expected that the use of silicon carbide power devices significantly reduces the size, weight, and energy savings of drive systems in electric vehicle inverters and DC-DC converters. I use the BMW i3 for instructions. The PCU, which consists of a motor DC/DC converter (to12 V, 360 V) and a 3.7 kW charger, weighs 19 kg, and its structure and components are shown below (Figure 2, Figure 3). The motor controller of the BMW i3 uses the 32-bit dual system of the Infineon TC1797 as the system platform to ensure the high performance and reliability of the system operation. The inverter uses Infineon 650V / 800A FS800 series IGBTs[6].

![PCU Assembly](image2.png)

**Figure 2.** The consist of the PCU.
Therefore, replacing silicon-based power devices with silicon carbide power devices will be an irreversible trend.

3. The application of SiC in PCU
The Toyota Central Research and Development Laboratory (CRDL) and the manufacturer of the well-known parts DENSO have jointly developed SiC semiconductor materials since 1980. In May 2014, they officially released components based on SiC semiconductor devices - Power Control Units (PCUs) for new energy vehicles. In May 2015, Toyota Motor Corporation announced road test results for a hybrid vehicle (HEV) equipped with a SiC semiconductor power control unit (PCU)[7]. The experiment began in February 2015 in Aichi Prefecture, Japan, and fuel efficiency was confirmed at the end of May. By optimizing the motion control, the goal of increasing fuel efficiency by 10% can be achieved compared to the initial 5% improvement. Figure 4 is a comparison of the Power Control Unit (PCU) configured on the HEV. At the same time, as the semiconductor device technology, it has reduced the size of the power control unit by 80%.

Mitsubishi Electric developed a new built-in inverter in 2014. The EV motor that constitutes the inverter uses SiC (silicon carbide) for both the transistor and the diode. The new motor has an output of 60 kW and a volume of only 14.1 L (previously the EV motor and inverter were independent, with a total inverter and motor volume of 25 L), achieving the industry's smallest size[4]. Compared to inverters that previously used silicon components, SiC inverters are more efficient and therefore generate less heat.
Hitachi Automotive Systems announced on September 28, 2015, that it has developed efficient, high-power inverters for hybrid and pure electric vehicles. Compared with Hitachi’s original products, the power consumption of the new products is reduced by 60%, and the power capacity under the same volume is expanded by about 2 times. It helps drive long distances and increase acceleration. This time, Hitachi used the previously developed SiC and GaN parallel packaging technology and double-sided cooling power module technology. A complete SiC power module and an HEV / EV inverter using the module were developed. To equalize the switching time of each SiC power semiconductor, Hitachi adopted the previously developed parallel packaging technology[4]. As a result, it can make full use of the low resistance characteristics of SiC power semiconductors and expand the power capacity.

4. Discussion
The MOSFET plays a decisive role in the silicon carbide semiconductor in the PCU. The on-resistance of the SiC MOSFET has a low rate of change with temperature, and the on-resistance is low at high temperatures, which can work well in harsh environments. At the same time, as the gate voltage increases, the on-resistance is smaller, and the performance is closer to the voltage-controlled resistor. The turn-on of the SiC MOSFET requires a small gate charge, a low overall drive power, and a high body diode Vf, but reverse functional recovery and can reduce turn-on losses. Moreover, its switching loss is small, high-frequency switching operation can be performed, and passive components such as filters can be miniaturized to increase power density. Finally, the turn-on voltage of the SiC MOSFET is higher than that of the SI device. It is recommended to use Vgs of 18V or 20V. Although the turn-on voltage is only 2.7V, it can be fully turned on only when the drive voltage reaches 18V~20V[5].

Therefore, the replacement of silicon-based IGBTs by SiC MOSFETs is an inevitable trend in the development of electric drive systems. It is expected that this market will be fully launched after the maturity and reliability of silicon carbide MOSFETs next year. At present, Tesla Model 3's electric drive system has adopted the silicon carbide device provided by ST. Toyota will also officially launch an electric vehicle equipped with silicon carbide devices in 2020[1].

At this stage, improving silicon carbide semiconductors remains a serious challenge. Toyota acknowledges that to equip production cars with silicon carbide semiconductors, cost reduction must be considered. The large diameter of the SiC wafer is one of the ways to reduce the cost. A 6-inch silicon carbide epitaxial wafer has a significant cost advantage over a 4-inch silicon carbide epitaxial wafer. A 2X2mm ^ 2 mold can be an example. A 4-inch silicon carbide epitaxial wafer can only produce 1,625 dies, while a 6-inch epitaxial wafer can only produce 3,917 dies, which is 2.4 times that of a 4-inch epitaxial wafer. Toyota is preparing to use 6-inch wafers during the mass production phase. In addition to cost and stability issues, Toyota is fueling the world's most stringent JC08 fuel model. Finally, the actual fuel consumption of a hybrid vehicle equipped with a SiC power semiconductor chip PCU is reduced by more than 5%[2].

In the opinion of the author, in addition to the above challenges, there are also problems in the chemical structure of silicon carbide, and the unique micro pipet defects of silicon carbide will seriously affect the use of devices at high power. I think this is also a crucial problem to be solved for carbonized silicon single crystal. First, silicon carbide is grown using a two-step process. The first step is to grow the buffer layer and then epitaxially grow the silicon carbide on the buffer layer. Although some technology companies have made some progress, commercial epitaxial wafers are still a long way off, so the people think third-generation semiconductor research should focus on the selection of epitaxial substrate materials and the improvement of the growth process.

5. Conclusion
Therefore, SiC is still the primary material in the current power control unit, although developers need to optimize it in various aspects. At the same time, automotive research and development not only needs to develop in the direction of low energy consumption but also needs to improve the mileage of the car. In the subsequent improvements, the material improvement of the PCU is the basis of the entire R&D project. Only by reducing the other losses, the output power or power can bring a constant source of
power to the car. Hence, the application of SiC will be a catalyst for the rapid spread of new energy vehicles. This paper focuses on the selection and application of PCU materials. Other factors affecting new energy vehicles, such as batteries and motors, are also a way of thinking. Therefore, the new energy vehicles should be improved in all aspects.

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