This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

SiC MOSFETs - the Inevitable Trend for 800V Electric Vehicle Air Conditioning Compressors

He Xu, Lianjie Wang, *Student Member, IEEE,* Chushan Li, *Member, IEEE,* Wuhua Li, *Senior Member, IEEE,* Menglian Zhao, *Member, IEEE, Jingkui Shi, Bo Qu, Ying Mei, Li Xiang, Yonghui Deng, Huihui Xu*

Abstract—**Unlike traditional fuel vehicles, the air conditioning system of electric vehicles not only undertakes the thermal management of the cabin but also the thermal management of the battery system and even the thermal management of the electric motor control. The high demand for heating and cooling power leads to a significant reduction in cruising range. As the heart of the air conditioning system, E-compressors play the most critical role in the thermal management of electric vehicles. This paper shows that SiC MOSFETs are preferred for 800V electric vehicle E-compressors compared to Si IGBTs. A systematic comparison of SiC MOSFET and conventional IGBT solutions for E-compressor application in terms of system energy efficiency, compressor operation boundary, NVH performance, and system miniaturization trend is described in this paper. Besides, the cost reduction potential and gate oxide reliability issues of SiC MOSFET are also discussed.**

Index Terms—**Battery industry, compressors, electric vehicles, hybrid electric vehicles, IGBTs, SiC MOSFETs, wide bandgap (WBG) devices**

I. Introduction

RESEARCH on SiC MOSFETs and their applications has been ongoing in academia for decades, but the strong inertia inherent in the industry has made SiC MOSFETs not considered to be widely used in electric vehicles and new energy industries until the last two to three year [1]. One of the turning points was the pioneering use of all-SiC MOSFETs in the powertrain inverter of the Model 3, a production model released in 2017 by the renowned American automaker Tesla [2]. In addition to its technical impact, this event was more significant in setting a benchmark for the traditional, conservative automotive industry that adopting all-SiC MOSFET solutions is economically feasible, and the reliability risk of this new device is manageable.

The first priority to be considered when developing auto parts products is cost. The driving force behind the successful rollout of SiC MOSFETs in many industries is cost in the broad sense, i.e., the economic benefits at the system level that result from adopting this type of device will outweigh the increased procurement costs. For example, in electric vehicle powertrain inverters, the unipolar characteristics and low switching losses of SiC MOSFET devices can save battery costs for car OEMs [3]; in photovoltaics, the high efficiency of SiC MOSFET devices under light-load makes power generation costs lower [4][6]; For on-board charger or DC/DC converters used in electric vehicles, the high-frequency characteristics of SiC MOSFETs enable the reduction of overall size and weight while saving the cost of passive energy storage devices such as capacitors and inductors [7]; in fuel cell air compressor applications, the high switching frequency of SiC MOSFET devices enables the ultra-high speed of compressors, which in turn can improve compressor efficiency and reduce size and cooling requirements, thus achieving cost reduction at the system level [8].

In electric vehicle applications, SiC MOSFET devices have a high penetration rate in OBC (on-board charger), DC/DC converter, powertrain inverter, etc. [9]-[14], while electric vehicle air conditioning compressors are rarely involved in SiC MOSFET solutions, mainly because air conditioning compressor manufacturers are extremely demanding in cost control, and many practitioners' first reaction is to exclude this new device from the options. Thus, this application lacks a comprehensive and rational assessment of the advantages of SiC MOSFETs from the system level.

Unlike traditional fuel cars, the air conditioning system of electric vehicles takes on the thermal management of the cabin, the battery system, and even the powertrain [15][18]. As the heart of the air conditioning system, the e-compressor's function is to inhale and compress the low-temperature low-pressure gaseous refrigerant from the low-pressure side so that its temperature and pressure rise and then is pumped into the high-pressure side of the high-temperature, high-pressure gaseous refrigerant, thus reciprocating the cycle, to achieve the role of a heat exchanger between the external environment and the vehicle system [19]. Table. 1 shows the merits and demerits of using an E-compressor for different cooling/heating loads for EV application: The greatest benefit of using an E-compressor for thermal management of battery and cabin is that it can achieve high COP (coefficient of performance) during summer and winter thus enables high fuel efficiency of the electric

This work was supported in part by the National Nature Science Foundation of China (51925702, 52477200), and in part by the National Key Research and Development Program of China (2022YFE0138400). *(Corresponding author: Chushan Li)*

He Xu, Lianjie Wang, Chushan Li, Wuhua Li, and Menglian Zhao is now with Zhejiang University, Zhejiang, China (e-mail: xuhe0314@zju.edu.cn, lianjie.21@intl.zju.edu.cn, chushan@intl.zju.edu.cn, woohualee@zju.edu.cn, zhaoml@zju.edu.cn)

Jingkui Shi, Bo Qu, Ying Mei, Li Xiang, Yonghui Deng, and Huihui Xu is now with Zinsight-Tech, Shanghai, China. (e-mail: Jingkui.shi@zinsight-tech.com, bo.qu@zinsight-tech.com, ying.mei@zinsight-tech.com, li.xiang@zinsight-tech.com, yonghui.deng@zinsight-tech.com, huihui.xu@zinsight-tech.com).

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

vehicles. The disadvantage lies in the fact that a high-power E-compressor needs to be adopted since it undertakes more needs in terms of thermal management during summer and winter.

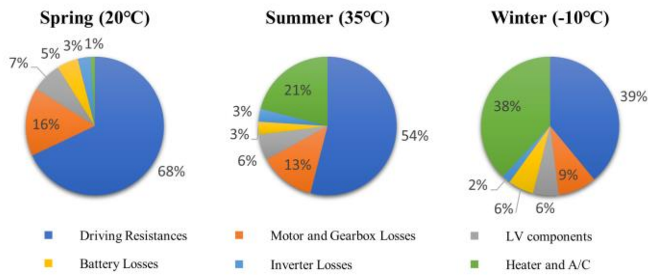


Fig. 1. Energy consumption share of each component in a medium-sized electric vehicle under WLTP operating conditions [22]

Similar to the three-in-one powertrain system of electric vehicles, electric air conditioning compressors are a "small three-in-one" system, which includes three major components: inverter, permanent magnet synchronous motor (PMSM), and mechanical scroll structure [20], as shown in Fig. 2. The mainstream inverter solution in the market currently adopts a three-phase full-bridge topology. It mostly uses IGBT discrete devices in TO-247 packages or IGBT IPM modules to achieve speed control of the compressor under different operating conditions [21].

TABLE I
MERITS AND DEMERITS OF USING E-COMPRESSOR FOR DIFFERENT COOLING/HEATING LOADS FOR EV APPLICATION

Cooling/Heating Loads	Working Parts	Merits	Demerits
Cabin-cooling	E-Compressor	High COP	NA
Cabin-heating	E-compressor PTC heater	High COP above -15°C	Low COP below -15°C High power needed for e-compressor
Battery-cooling	E-compressor Water cooling	Strong cooling capability enables fast/supercharging Fast & accurate battery Temperature control	High power needed for e-compressor
Battery-heating	E-compressor PTC heater	High COP above -15°C Fast & accurate battery Temperature control	Low COP below -15°C High power needed for e-compressor

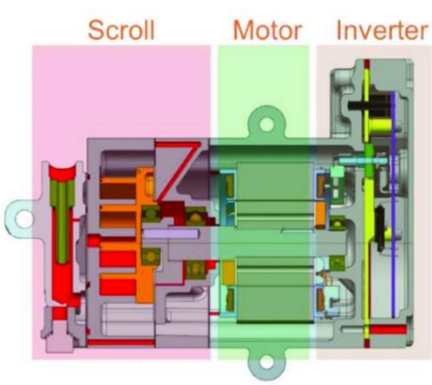


Fig. 2. E-compressor structure used in EV application

However, this paper has come to the following conclusion: SiC MOSFET is the superior choice for 800V electric air conditioning compressor inverters compared to traditional IGBT solutions. Due to the industry's inertia and the current thermal management system design level, IGBT solutions may dominate initially. However, as E-compressor suppliers' design and development capabilities improve, SiC MOSFET inverter solutions will gradually replace traditional IGBT-based solutions. The following table shows some key specs of the normally used E-compressors in different car models.

TABLE II
KEY SPECS OF THE NORMALLY USED E-COMPRESSORS IN DIFFERENT CAR MODELS

Class	Medium SUV	Sedan-Class B
Representative car models	Model Y- Tesla E12- AVATR	S7 – Luxeed P7 - XiaoPeng
Voltage level	400V/800V	400V/800V
Compressor displacement	45cc	27cc/33cc/45cc
Max. rotation speed	8500~11000 rpm	8500~11000 rpm
Max. Electric Power	12kW	9kW

The paper is structured into three sections. Section II discusses the advantages of adopting SiC MOSFET in E-compressor applications, including system energy efficiency, maximum operating boundaries, NVH performance, and system miniaturization. Section III acknowledges the cost reduction potentials of SiC MOSFET. Finally, Section IV presents the conclusions of this research.

II. Advantages of Adopting SiC MOSFET in E-Compressor Applications

In this section, the advantages of applying SiC MOSFETs in E-compressors are analyzed. The benefit will not just come from the inverter's efficiency and power density. Detailed quantitative analysis is carried out to show that more comprehensive benefits do exist in SiC MOSFET-based solutions.

A. E-compressor Energy Efficiency will be Greatly Improved

Four main sub-arguments support this statement:

1) The energy consumption of air conditioning systems in electric vehicles is second only to the driving energy consumption, with the newly enacted CLTC road conditions in China expected to increase this share further. In summer and winter, the mileage of electric vehicles decreases due to high energy consumption by air conditioning and heating systems. German IAV research [22] found that these systems can account for up to 21% and 38% of energy consumption during summer and winter, respectively, in medium-sized electric vehicles (WLTP conditions). The mileage of electric vehicles decreases drastically in winter due to the lower energy efficiency of PTC heating commonly used in mainstream EVs. Although the Tesla Model Y uses heat pump technology to improve heating efficiency, it still reduces vehicle range significantly, in which an E-compressor is adopted. [23]

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

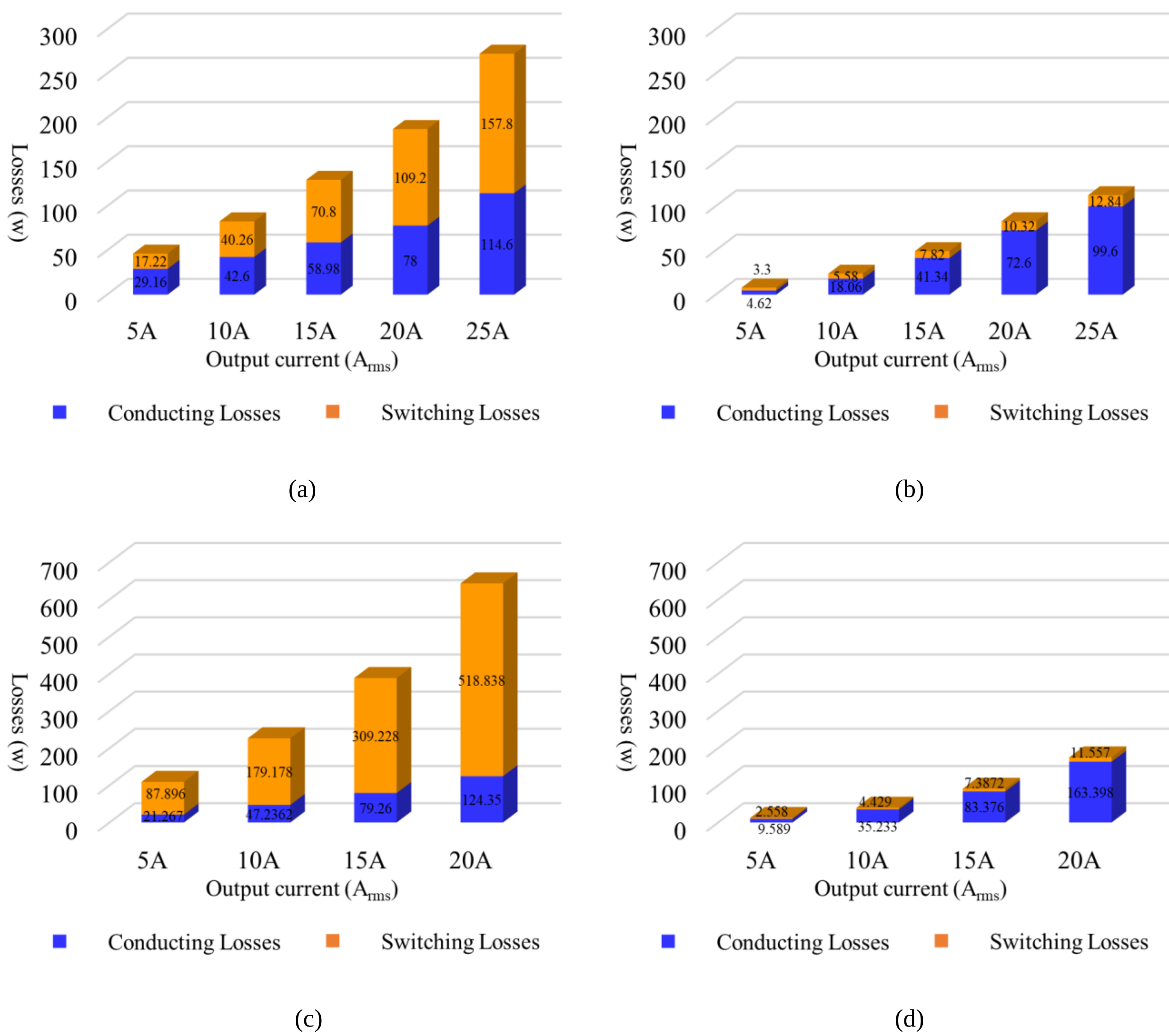


Fig. 3. Comparison of power device losses between IGBT and SiC MOSFET @switching frequency=20kHz (a) Vdc=400V (for 650V IGBT), (b) Vdc=400V (for 650V SiC MOSFET), (c) Vdc=800V (for 1200V IGBT IPM) , (d) Vdc=800V (for 1200V SiC MOSFET)

In addition, China's newly implemented CLTC conditions emphasize urban road conditions that are friendlier to EVs. According to Fig. 4, CLTC results in lower average speed and longer driving time for the same range due to suburban road conditions. This leads to longer air conditioning usage, and higher compressor energy consumption and impacts the range of electric vehicles in high and low-temperature environments (-7℃ to 35℃). China Automotive Consumer Research and Testing Centre (CCRT) regulations include these temperature ranges for electric vehicle testing [24][25].

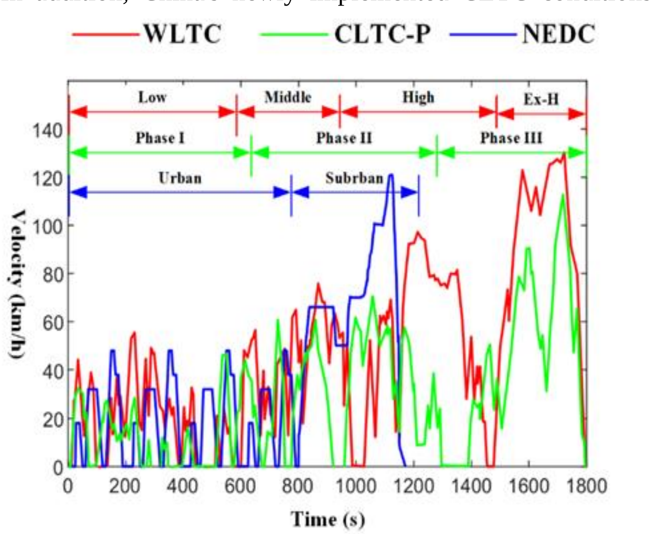


Fig. 4. Light vehicle test conditions in China

2) The light load conditions of E-compressors are ideal for SiC MOSFET devices. The promotion of the 800V electric vehicle platform is due to its ability to achieve shorter charging times through fast and supercharging, reducing range anxiety and improving user experience. Mainstream supercharging could enable power batteries to charge from 20% to 80% in 12-15 minutes [26]. However, this process causes the battery to

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

heat up quickly, requiring a high-power 800V electric air conditioning compressor to cool it down rapidly and ensure charging safety and efficiency. In this scenario, the air conditioning compressor's peak power capacity needs to be designed around 10kW. This means that E-compressors mostly operate in light-load conditions when there is no need for battery cooling, with power consumption typically ranging from 300-1000W in spring and autumn and 1000-2500W in summer and winter [22]. This suits the advantages of SiC MOSFET devices, which have low conduction loss due to their unipolar conduction characteristics and low switching loss thanks to the high switching speed and low reverse recovery loss of their body diode characteristics. In contrast, silicon-based IGBT devices and their anti-parallel commutation diodes, as bipolar devices, require a strong conductivity modulation effect to reduce the on-state voltage drop (especially for high voltage devices of 1200V and above), but this causes significant tail currents and higher reverse recovery charges, resulting in higher turn-off losses, reverse recovery losses, and turn-on losses. Fig. 3 quantitatively evaluates the E-compressor inverter for 400V and 800V battery systems, with peak power of 6kW and 10kW respectively. The evaluation is performed under the same operating conditions, including bus voltage, output current, power factor, modulation factor, and switching frequency. For the 400V battery system, the SiC MOSFET solution has significant advantages in switching loss and conduction loss under light load conditions, and the overall loss is only 17% to 29% of the traditional IGBT solution. Under heavy load conditions, the advantage of switching loss is obvious, and the overall loss is about 40% of the traditional IGBT solution. For the 800V battery system, the advantage of the SiC MOSFET solution is more pronounced due to the poor switching loss characteristics of 1200V IGBT devices and anti-parallel diodes. The overall loss under light load is only 11% to 17% of the traditional IGBT IPM solution, while under heavy load conditions, it becomes about 23% to 27%.

Fig. 5 shows the inverter efficiency improvement result under different operation points compared to the IGBT solution by adopting SiC MOSFET based solution for an 800V 45cc E-compressor: the overall efficiency increases ranges from 2.07%~25% with different output torque and rotation speed. Under light load conditions,

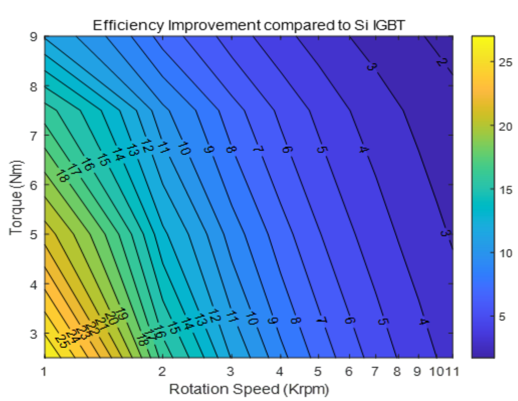


Fig. 5. Efficiency Improvement by using SiC MOSFETs compared with IGBTs (for 800V 45cc E-compressor)

3) The high switching frequency characteristics of SiC MOSFETs can improve the light-load efficiency of PMSM motors. Due to production process considerations, Automotive E-compressors generally use permanent magnet synchronous motors with simple centralized windings. In Fig. 6, the losses of PMSM can be divided into basic loss and harmonic loss [27], where the basic loss can be divided into mechanical friction loss and fundamental copper and iron loss. The fundamental copper and iron losses are mainly caused by the fundamental current,

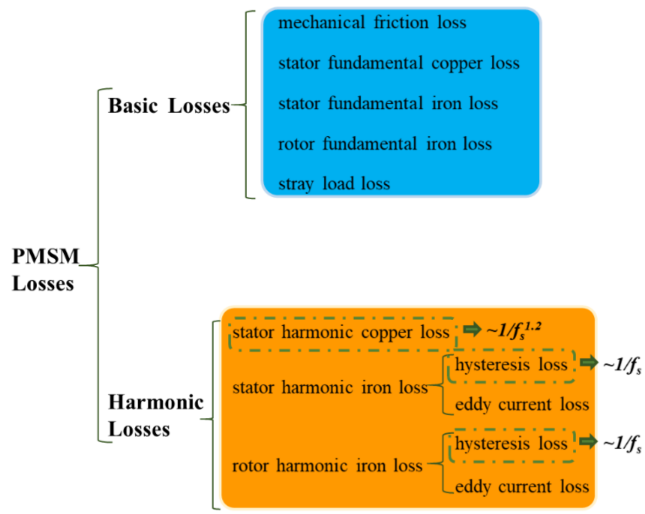


Fig. 6. High-speed PMSM motor loss decomposition

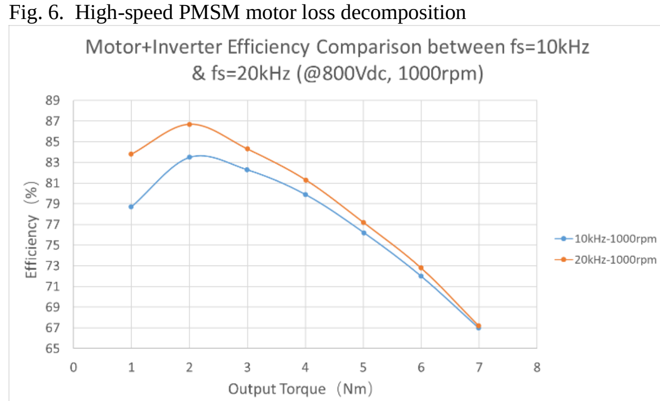


Fig. 7. SiC MOSFET inverter + motor assembly efficiency at low-speed operating conditions

which is involved in the mechanical work output of the motor, primarily depending on the fundamental current amplitude, the fundamental frequency, the stator winding resistance, the stator magnet design, the rotor core design, and other factors. E-compressor inverters can use optimized control strategies like MTPA to minimize fundamental copper and iron losses while meeting torque and speed requirements according to motor parameters [28]. However, harmonic loss from high-frequency harmonic currents cannot be ignored and depends on factors like bus voltage, switching frequency, and modulation methods. These losses can be divided into harmonic copper loss and harmonic iron loss, which are affected by the hysteresis effect and eddy current effect of the magnet and windings. Higher switching frequencies result in lower harmonic copper and

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

hysteresis losses.

During low-speed and light-load conditions, the motor's harmonic losses account for a larger proportion, and increasing the switching frequency can improve motor efficiency by reducing harmonic copper loss and hysteresis loss. In fact, the harmonic copper loss and the hysteresis loss are inversely proportional to 1.2 and 1 power of the switching frequency, respectively [29]. In the case of an E-compressor used for auxiliary functions such as defogging and defrosting, increasing the switching frequency can improve compressor motor efficiency. According to Fig. 7, an 800V E-compressor system (motor +inverter) can achieve up to 5.6% higher efficiency with a 20kHz switching frequency compared to a 10kHz switching frequency under light-load conditions.

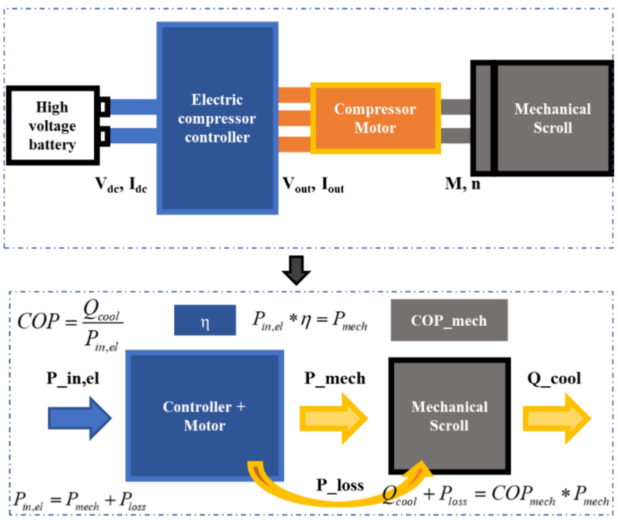


Fig. 8. Power flowchart of the electric air conditioning compressor system

4) Reducing losses in the inverter and motor will further improve the coefficient of performance (COP) of the E-compressor. When the air conditioning system works in a cooling state, as shown in Fig. 8, the heat loss of the inverter and the motor will be removed by the refrigerant through the compressor's Carnot cycle condition with the outside world [30]-[31]. Compared with the traditional silicon IGBT solution, the inverter and motor losses can be greatly reduced by using SiC MOSFET solution. This means that the cooling demand provided by the refrigerant will also be reduced simultaneously.

In the case of ensuring the same mechanical power output, this saved cooling capacity due to loss reduction can be used to enhance the external cooling capacity of the system, thus further increasing the COP of the E-compressor. The ratio between COP with SiC MOSFET solution and with silicon IGBT solution is shown below.

$$\frac{COP_{SiC}}{COP_{IGBT}} = 1 + \frac{\Delta\eta}{\eta} + \frac{\Delta\eta}{\eta^2 (COP_{mech} + 1) - \eta} \tag{1}$$

Where Δη is the efficiency improvement in the motor and inverter between the SiC and IGBT solutions, according to the theoretical derivation in (1), with a COP of 2.6 for the original IGBT-based E-compressor, if the efficiency of the motor and inverter η is increased by 10%, the COP of the E-compressor system will be increased by 16% to 31% under different load conditions (assuming η is distributed in the range of 0.6~0.9), far exceeding 10%. As shown in Fig. 9, the compounding effect is most obvious in low-speed and light-load conditions where the motor and inverter efficiency are relatively low.

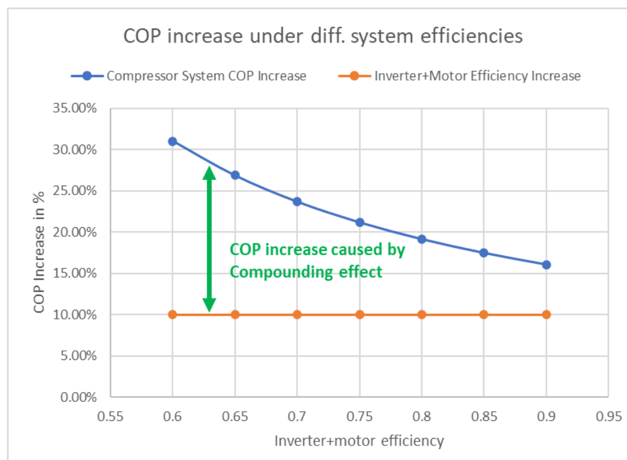


Fig. 9. E-compressor COP increase @10% inverter+motor efficiency increases under different system efficiencies

TABLE III
DETAILED SYSTEMATIC EVALUATION RESULTS ON Porsche Taycan Turbo S

Season	Working conditions	Efficiency increase	Benefits
summer	Ambient temperature=38°C Cabin temperature=25°C Cooling load = 4200W Cooling COP =2.2 E-compressor speed: 3000~4000 rpm	7% average efficiency increase	➢ 1095 Wh battery volume saving ➢ 7.35 km mileage increase
winter	Ambient temperature=-10°C Cabin temperature=20°C Cooling load = 4200W Cooling COP =1.7 E-compressor speed: 3000~4000 rpm	7% average efficiency increase	➢ 1353 Wh battery volume saving ➢ 9 km mileage increase

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

To show customers the benefits of adopting SiC MOSFETs-based E-compressor in an 800V electric vehicle, the Porsche Taycan Turbo S was taken as an example to give detailed systematic evaluation results, shown in the following table. After adopting SiC MOSFETs for the E-compressor, the mileage can be increased by 7.35 km and 9 km in summer and winter, respectively. In other words, the car OEM can achieve 1095 Wh and 1353 Wh battery volume savings during summer and winter while maintaining the same mileage, which means significantly reduced costs in car purchases for consumers.

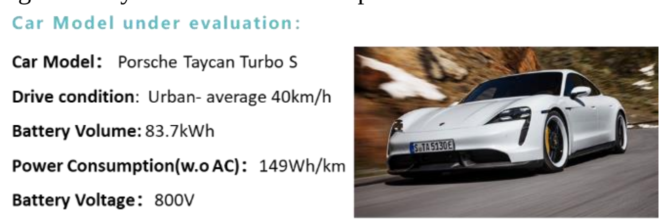


Fig. 10. Evaluation Information of Porsche Taycan Turbo S

B. The operating boundary of the compressor will be greatly expanded

1) Stronger low-speed control capability. Stronger low-speed operation capability of E-compressor can bring significant benefits to the air-conditioning system regarding system energy efficiency and compressor endurance capability optimization [32]. The current observer-based speed sensorless control used by E-compressor inverter requires accurate output voltage estimation, especially in low-speed ranges [33]. Compared with the silicon IGBTs, the SiC MOSFET solution shows significant advantages in low-speed control capabilities. In low-speed conditions, the effect of the saturation voltage drops and dead time introduced by the traditional IGBT scheme causes nonlinear voltage vector errors, which may even exceed the fundamental output voltage [34]. By modelling the error voltage vector in Fig. 11 introduced by the on-state voltage drop and dead time, it is possible to obtain:

$$u_{err} = (u_{th} + u_d)(sign(i_a) + e^{j\frac{2\pi}{3}} sign(i_b) + e^{-j\frac{2\pi}{3}} sign(i_c)) \quad (2)$$

$$u_d = \frac{u_{dc} t_d}{T_{PWM}} \quad (3)$$

where u_{th} is the IGBT conduction voltage drop, i_a, i_b, i_c is the three-phase current, and u_d is the voltage error due to dead time. To solve the problem, the conventional approach is to counterbalance the influence of nonlinear factors by additional compensation or by adding a nonlinear model to the motor control algorithm [35], which can reduce the influence but cannot eliminate it. Once the compensation for IGBT is inaccurate, it could cause compressor system start-up failure or system instability. This will cause a significant increase in the product parts-per-million (PPM) for E-compressor products.

The SiC MOSFET solution is a more advantageous option than the silicon IGBT solution, particularly regarding low-speed control performance. With SiC MOSFETs, the on-state voltage drop at zero current is almost non-existent, and the dead time is minimal due to their high switching speed. Even with twice the switching frequency of IGBT solutions, the output voltage error due to dead time is only one-fifth of that of IGBT solutions. The nonlinearity of the SiC MOSFET inverter is much lower than that of the IGBT scheme [36], resulting in significantly better low-speed performance without compensation. Furthermore, the high switching frequency of SiC MOSFETs can effectively reduce switching ripple, which reduces motor torque pulsation. In addition, increasing control frequency can improve control stability and bandwidth under load disturbance, ultimately playing a crucial role in enhancing low-speed performance and control stability of E-compressors.

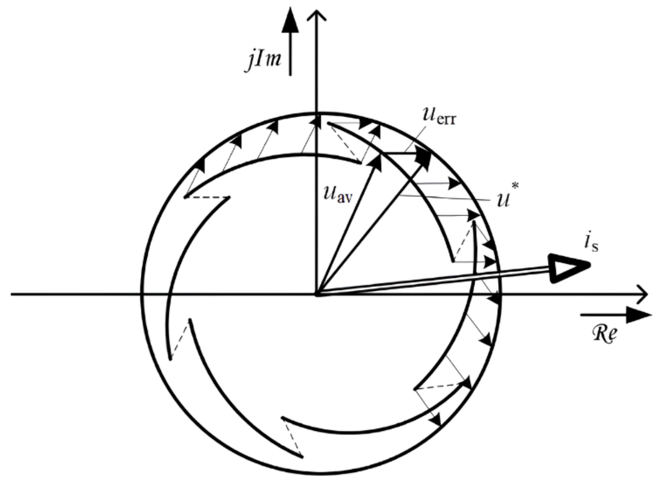


Fig. 11. Modelling of error voltage vector

2) Stronger start-up & operation capability under high-temperature heavy load conditions. For the supercharging conditions of the 800V battery electric vehicle, the E-compressor needs to have a more vital ability to start with a heavy load and high-temperature environment. Imagine the following scenario: A hot summer day with an ambient temperature of 42°C, no wind around, and a temperature of 85°C inside the compressor compartment after direct sunlight, when the suction and discharge pressure of the electric compressor is relatively high, and the electric vehicle needs to be charged at the supercharging station with 360kW power and nearly 500Arms. In this case, the air conditioning compressor needs peak power output to get enough cooling capacity to cool the battery pack and the cabin. This scenario is highly harsh to the E-compressor, especially for the traditional IGBT solution: The compressor needs to run for several seconds in a high-temperature initial environment for a high-torque start-up without heat dissipation taken by the refrigerant, since the initial flow is slow, and needs to rely on the thermal capacity of the heat sink base plate to absorb the power device losses. Because of its high losses, the IGBT can easily cause the power device junction temperature to exceed its maximum permissible range, resulting in start-up failure, and even causing IGBT destruction. However, SiC MOSFETs have much lower losses than IGBTs. The chips can operate at higher junction temperatures, supporting more extended periods until the compressor system builds up cooling capability.

Table. 4 below shows the comparison test results between Si-IGBT and SiC MOSFET-based E-compressors in super-

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

TABLE IV
TEST RESULTS BETWEEN IGBT AND SIC E-COMPRESSORS

Solution	Working conditions	Switching frequency	Device case temp.
IGBT solution	1. Supercharging; 2. Ambient temperature at 49°C, with direct sunlight and no wind; 3. 720V DC Link voltage;	10kHz, with audible EM noise	110°C
SiC solution		20kHz, with no audible noise	65°C

charging operation during the summer test. Compared with the traditional IGBT solution, adopting SiC MOSFET-based solution for the E-compressor can not only decrease the power device case temperature from 110°C to 65°C and thus decrease power device overheat failure risk but also eliminate audible electromagnetic noise by using 20kHz switching frequency.

3) More suitable for ultra-low temperature heat pump working conditions. An ultra-low temperature heat pump can effectively improve the energy efficiency of electric vehicles in winter heating, thus further improving the mileage of the car, which is the future development direction. In ultra-low temperature heat pump operating conditions, the suction pressure is generally above 0.5, and the discharge pressure is around 2.3 when the suction temperature is as high as 60°C, the E-compressor works as a PTC heater which is well known as "triangle loop" [37], as shown in Fig. 13. In this mode, the heating energy comes from the input DC power of the E-compressor. This places higher demands on the power consumption of the air conditioning compressor inverter: It needs to maintain a high torque output capability at a higher refrigerant temperature, and the low loss and high operating junction temperature capability of SiC MOSFET devices are very suitable for these conditions.

The figure below presents a comparative analysis of the operational boundaries of a 45cc E-compressor, comparing SiC MOSFET and IGBT solutions. It is evident that the maximum outlet pressure supported by the SiC MOSFET-based E-compressor is 0.1 to 0.2 MPa higher than that of the IGBT-based E-compressor, which indicates a wider operation boundary for the SiC MOSFET solution.

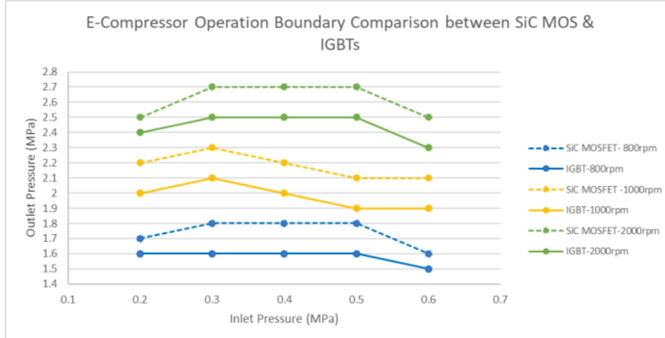


Fig. 12. Comparison of E-compressor operation boundary between SiC MOSFET and IGBT solutions

C. SiC MOSFET Solutions can Deliver NVH Performance Improvements

The NVH problem of the E-compressor system is more

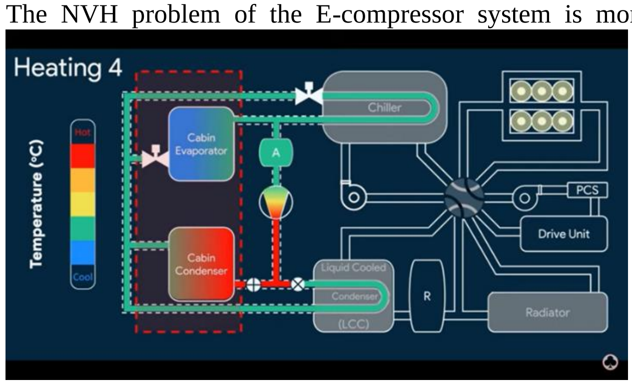


Fig. 13. Ultra-low temperature heat pump operation condition in Tesla Model Y [56]

prominent at low speeds for electric vehicles, mainly because there is no masking effect of the background noise vibration of

TABLE V
SIC SOLUTION AND ITS EFFECT ON NVH PROBLEM

Number	Noise Type	Noise order	Response	Improvement effect
1	Electromagnetic noise caused by high frequency switching	Times of switching frequency	Increase the switching frequency to avoid the range of human ear perception (see Fig. 16)	Improved
2	Torque pulsation caused by time harmonics generated by PWM modulation	Times of switching frequency	Increase the switching frequency to decrease time harmonic	Improved
3	Torque pulsation caused by space harmonics because of the motor structure	Times of fundamental frequency	NA	No effect
4	Unbalanced inertia forces introduced by the scroll structure	Fundamental frequency	Increase the switching frequency to proceed torque compensating strategy	Improved

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

the conventional internal combustion engine (refer to Fig. 14).

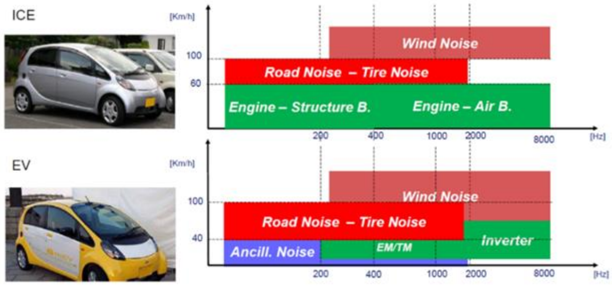


Fig.14. NVH performance comparison between fuel vehicle and electric vehicle [57]

The NVH analysis of E-compressors generally follows the "excitation source-transmission path-receiver" model [38], and the solutions are generally addressed from the source of the excitation or transmission path.

The transmission path aspects are mainly considered from the mechanical structure, such as the modal and order optimization design of the compressor structure, the use of optimized vibration damping structure and bracket design, the use of various types of plugs, vibration damping pad, rubber pad and other measures [39].

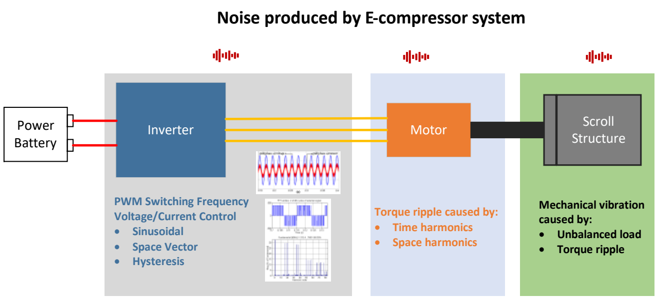


Fig.15. Noise produced by E-compressor system

While the excitation source part mainly consists of the following three categories as shown in Fig. 15 [40]:

1) ***Inverter + cable + motor***: electromagnetic noise caused by high-frequency current switching due to PWM modulation and high-frequency current harmonics.

2) ***Inverter + motor:*** motor torque pulsation by time harmonics (caused by PWM modulation) and space harmonics (caused by motor winding structure, gear structure, etc.) assembly.

3) ***Scroll mechanical structure***: As the compressor's dynamic and static scroll disk in operation will produce an unbalanced rotational inertia force, this periodic unbalance force can easily excite the compressor's high-frequency vibration.

The SiC MOSFET solution can significantly reduce the noise in Table 5 for the above noise excitation sources.

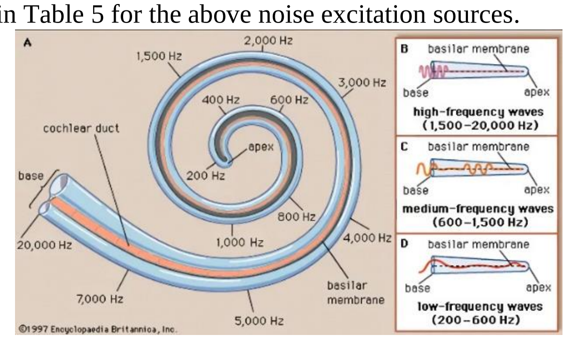


Fig.16. The range of noise spectrum perceptible to the human ear [58]

D. Promoting the Miniaturization of E-compressor

The miniaturization of E-compressor systems has always been a massive hit in the industry: It can facilitate the arrangement of E-compressor, save space for the front compartment, shorten the length of the compressor harness, and help reduce the vehicle weight. The development of the miniaturization of E-compressor systems is similar to that of the powertrain: To increase the motor speed and thus reduce the size of the motor and compressor while maintaining the same output power. In this case, the fundamental frequency of the inverter output will increase significantly. Moreover, the inverter's switching frequency must increase further to maintain the same current harmonic component [41], which is more challenging for traditional IGBT devices.

With the significantly reduced outer diameter of the high-speed E-compressor, the inverter is axially mounted on the housing shell of the compressor. The mounting size of the compressor inverter will be proportionally limited. The low cooling requirements of SiC MOSFET power devices and the more minor footprint requirements of the chip allow the integration of the power devices and driving circuit together into a miniaturized power module (i.e. intelligent power module, IPM), resulting in a significant reduction in the size of the power circuitry section and ultimately the miniaturization of E-compressor systems [42].

The following table and figure showed comparison results between a 1200V SiC MOSFET IPM and 1200V IGBT IPM with similar voltage & current ratings.

TABLE VI
COMPARISON BETWEEN ZINSIGHT SIC MOSFET IPM AND ONSEMI SI IGBT IPM WITH SIMILAR RATINGS

Items	SiC MOSFET IPM	Si IGBT IPM
Manufacturer	Zinsight Technology	Onsemi
Voltage/Current rating	1200V/40A	1200V/35A
Footprint	44*26*4.5 mm	80*33*8.0 mm

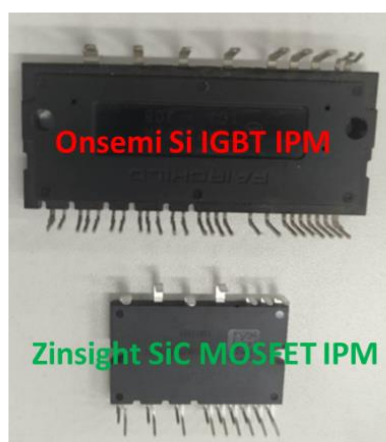


Fig.17. Appearance comparison between SiC MOSFET IPM and IGBT IPM with similar ratings

E. Summary of the advantages

According to our analysis, applying SiC MOSFETs in an E-compressor inverter will:

1. Improve the inverter efficiency under light load conditions by up to 25%. If considering the additional motor efficiency increase with higher switching frequency and the additional compounding effect caused by compressor loss reduction, the COP of the compressor will be increased even more than 2 times.
2. Extend E-compressor's working speed range under heavy load conditions from 800~8500 rpm to 400~12000 rpm due to significantly reduced dead time and increased switching frequency. In addition, applying SiC MOSFETs in an E-compressor can support supercharging in extremely high-temperature environments and ultra-low-temperature heat pump working conditions.
3. Greatly enhance NVH performance of the E-compressor by eliminating electromagnetic noise audible to the human ear and reducing torque pulsation caused by time harmonics generated by PWM modulation with higher switching frequency.
4. Reduce the inverter size by up to 50%, and save up to 1kg weight for the E-compressor. Which will further standardize and platform the compressor system, thus reducing development and manufacturing cost.

Table VII compares the SiC MOSFET solution with the Si IGBT solution for an 800V, 45cc compressor. Based on the results, it may be inferred that the SiC MOSFET has the potential to replace the traditional Si IGBT in the forthcoming years.

III. Cost Reduction Potential of SiC MOSFETs

While the initial cost of SiC MOSFET devices may currently exceed that of equivalently rated IGBTs, it's important to note that SiC MOSFETs possess a substantial potential for cost reduction that surpasses traditional IGBTs.

The following describes SiC MOSFETs from the development of large-size wafers, the breakthrough of SiC single crystal growth and substrate processing and cutting technology, the improvement of the yield rate of each link in the SiC MOSFET industry chain, and the optimization of the manufacturing process and device structure design to prove that there is enormous cost reduction potential for MOSFET power devices.

TABLE VII
COMPARISON RESULTS BETWEEN SiC MOSFET SOLUTION AND Si IGBT SOLUTION FOR AN 800V 45CC COMPRESSOR

Comparison Items	SiC MOSFET Solution	Si IGBT Solution
COP under typical operation condition	2.5	2
Size Reduction	50%	0%
Weight	6.5kg	7.5kg
Max. case temp. under supercharging conditions	65°C	110°C
NVH Performance	No audible electromagnetic noise	With audible electromagnetic noise

A. Development of large-size wafers

The SiC MOSFET device industry chain includes substrate, epitaxy, and device design and manufacturing, of which the substrate accounts for about 46% of the cost in the value chain and is the core link, so it is crucial to reduce the cost of the substrate. Now the wafer size of the SiC MOSFET substrate is still 6 inches (150 mm) as the mainstream, but with the arrival of 8 inches (200 mm) SiC MOSFET wafer, the chip cost can be reduced to a large extent [43], as depicted in Fig. 18.

From the 6-inch wafer to the 8-inch wafer size upgrade, the growth of the single substrate area is conducive to the decline in manufacturing costs [44]. At the same time, the substrate edge waste will also decline. For a 32 mm² die, a 6-inch SiC MOSFET substrate can produce 448 pieces with 14% edge loss; while an 8-inch SiC MOSFET substrate can produce 845 pieces with edge loss down to 7% and higher substrate utilization.

In the past two years, major international manufacturers have actively promoted the development of SiC to 8 inches. Wolfspeed aims to commence production at its 8-inch SiC wafer plant by 2024 [45]. In April 2022, II-VI projected a 5 to 10-fold increase in SiC substrate production capacity over the next five years, encompassing mass production of 8-inch diameter substrates [46].

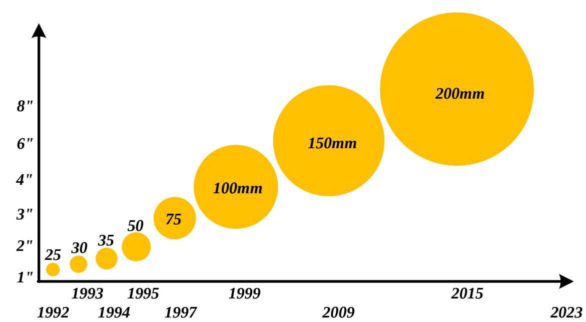


Fig. 18. SiC MOSFET Wafer Size Evolution [43]

B. Breakthrough in single crystal growth and substrate cutting technology

As mentioned earlier, the high cost of SiC MOSFET ingots is an important factor restricting the large-scale application and development of various SiC MOSFET power semiconductor devices. To reduce the cost of SiC MOSFET single crystal, in addition to expanding its diameter, increasing the growth rate of SiC MOSFET single crystal, increasing the thickness of SiC MOSFET crystal ingot, and improving the substrate cutting and processing technology are all effective and essential methods.

Firstly, to address the challenges posed by the slow growth rate, high defect density, and difficulty in diameter expansion associated with the PVT sublimation method [47], some companies have begun developing solution-based SiC MOSFET single crystal growth techniques which enable the growth of SiC MOSFET single crystals under conditions

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

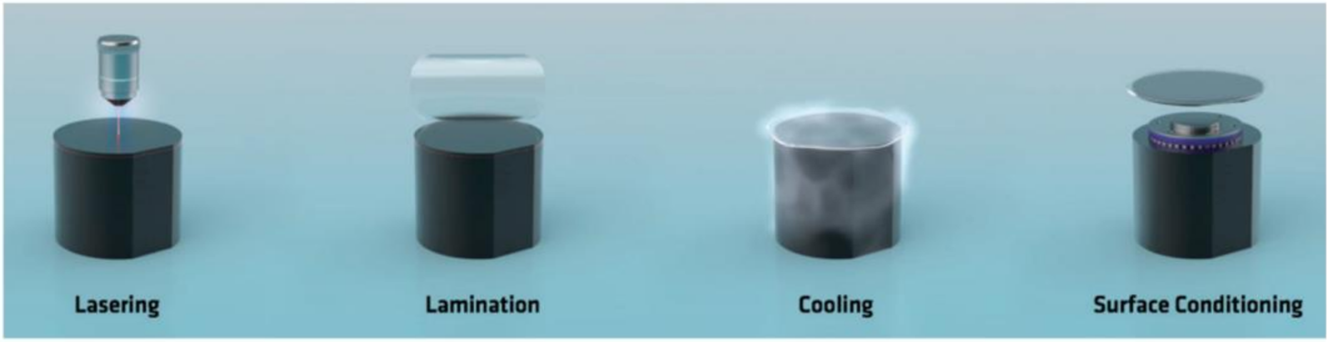


Fig. 19. Siltectra's COLD SPLIT technology [52]

approaching thermodynamic equilibrium at lower temperatures (below 2000 °C). Sumitomo Corporation of Japan has announced the successful growth of nearly defect-free 6-inch SiC MOSFET substrates using the solution method, achieving usable areas of over 99% [48].

Secondly, by improving the thermal field of SiC MOSFET single crystal growth equipment and other technologies, its thickness can be effectively increased, significantly reducing the cost of SiC MOSFET substrates [49]. Recently, the Advanced Semiconductor Research Institute of the International Science and Technology Innovation Center of Zhejiang University-Qianjing Semiconductor Joint Laboratory successfully grew a 6-inch SiC MOSFET single crystal with a thickness of 50 mm [50].

Furthermore, in the substrate processing process, breakthroughs in cutting technology can significantly reduce the waste of SiC MOSFET crystal ingots, effectively increase the number of sliced wafers, and considerably reduce the cost of SiC MOSFET substrates. DISCO's new laser slicing technology KABRA can substantially shorten the processing time of SiC MOSFET [51]. Infineon's acquisition of its subsidiary Siltectra's cold cutting technology (COLD SPLIT) has the potential to enhance the yield of SiC MOSFET substrates by up to 90%, effectively increasing the number of substrates that can be obtained from SiC MOSFET ingots [52].

C. Continuous improvement in yield rate

From substrate epitaxy to manufacturing of SiC MOSFET devices, the yield rate of each link is low, and the loss of yield rate dramatically affects the final cost of SiC MOSFET devices.

For the SiC MOSFET substrate, due to its harsh production environment, immature production process, high difficulty in material processing, and slow growth rate of the crystal ingot, at the same time, there are more than 200 crystal forms of SiC MOSFET. All these factors lead to a shallow yield rate of SiC MOSFET substrates [53].

According to the data from the System Plus department of Yole, in the front-end process of 1200V SiC MOSFET from epitaxy to device manufacturing (as shown in Fig. 20), the device manufacturing yield rate is only 58.5%. The loss cost due to the yield rate accounts for 42% of the total cost of the chip, which is almost equivalent to the cost of the epitaxial wafer (including the substrate) [54].

It can be predicted that with the maturity of technologies such as substrate growth, cutting, high-temperature ion implantation and high-temperature annealing, and gate oxidation to reduce the interface state density, the yield rate of substrate and device manufacturing will climb steadily, while the cost of SiC MOSFET devices with the improvement of yield rate, it will be significantly reduced.

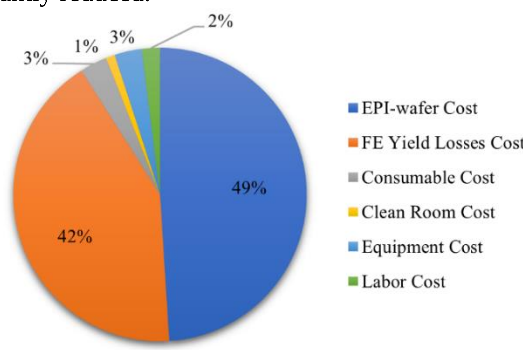


Fig. 20. SiC MOSFET device front-end process cost ratio

D. Optimization of the manufacturing process and chip structure

As the manufacturing process is refined and structural design undergoes iterative optimization, the chip area of SiC MOSFETs is steadily decreasing. This reduction in chip area translates to the ability to produce a more significant number of chips on a single-size wafer. Simultaneously, the reduction in wafer edge waste contributes to significant cost savings.

With the reduction in cell pitch of SiC MOSFETs, the specific on-resistance of the chips diminishes, resulting in an amplified power capacity within the same area. Wolfspeed's second-generation SiC MOSFET occupies an area 35% smaller than its first-generation CMF series counterpart. Furthermore, the evolution of SiC MOSFETs from a planar to a trench structure by manufacturers like Rohm and Infineon has significantly reduced chip area [55]. For instance, considering a 1200V 30mΩ SiC MOSFET, the chip area with the trench process is merely 9 mm², whereas the planar process occupies 15mm² – signifying a substantial 40% difference in area.

IV. Gate Oxiode Reliability Issues of SiC Mosfets

SiC MOSFETs outperform IGBT devices in 800V electrical vehicle E-compressor applications in many aspects as described

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

above. However, reliability of SiC MOSFETs is still big concern for their widespread applications in automotive E-compressor applications [59][65].

The reliability of gate oxide quality significantly impedes the advancement of SiC MOSFETs, primarily due to three pivotal factors. Firstly, the process of thermal oxidation of SiC, accompanied by the presence of carbon atoms and defects formation, leads to an exceptionally high density of interface traps. During the oxidation process that forms the gate dielectric, these conditions foster the creation of high-density electrically active interfacial defects. The density of charged interface defects and interface states in SiC/SiO_2 structures is estimated to be roughly two orders of magnitude greater than those observed at Si/SiO_2 interfaces, which significantly contributes to the reliability issues and compromises the ruggedness of SiC MOSFETs[62][63].

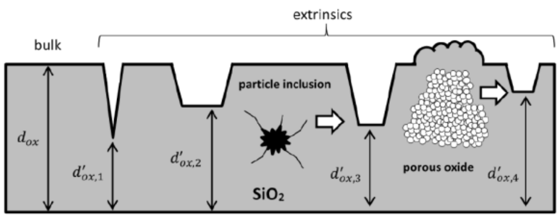


Fig. 21. Schematic representation of extrinsic defects in SiO_2 [62]

Secondly, the energy band offsets between the SiC semiconductor and the SiO_2 are notably small. The gate tunnelling barrier with SiO_2 stands at only 2.7 eV, which is 0.4 eV lower than that observed with Si/SiO_2 interfaces [60]. As a result, under identical electric field conditions, the gate tunnelling current in SiC MOSFETs substantially exceeds that of Si-based devices. Furthermore, the effective barrier height at the SiC/SiO_2 interface markedly decreases as the temperature increases, thereby exacerbating the unreliability of the device under high-temperature conditions.

Thirdly, the critical electric field for SiC devices is approximately an order of magnitude higher than that for Si devices due to much thinner gate oxide. This significant difference poses a heightened risk of gate oxide failure in the reverse bias state of SiC MOSFETs.

Collectively, these factors delineate the critical challenges that must be addressed to enhance the reliability of SiC MOSFETs in EV E-compressor applications.

Over the past decade, significant advancements in gate-oxide reliability for silicon carbide (SiC) MOSFETs have paved the way for their commercialization. These improvements stem from a deeper understanding of SiC material properties and enhanced processing techniques. Innovations such as improved substrate purity and advanced oxidation techniques have been pivotal in reducing defect densities within the gate oxide layer. Additionally, the implementation of novel design strategies like the incorporation of field plates and optimized gate geometries has been instrumental in mitigating electric field concentration, thereby enhancing device robustness and operational reliability[61].

Through improved material handling and refined production processes, industrial SiC MOSFETs have begun to successfully penetrate the mass market, demonstrating reliability levels comparable to Si devices. These technological advances not only enhance overall gate-oxide integrity but also significantly reduce the likelihood of early failures through stricter quality control and advanced screening techniques. For instance, the introduction of the "marathon stress test" has been a pivotal development[61][62]. This test method stresses devices under extended operating conditions to identify and mitigate early failures, thereby ensuring enhanced long-term stability and reliability of the gate oxide.

Literature [64][66] investigates the efficacy of burn-in processes to enhance gate oxide reliability in SiC MOSFETs, such as high-temperature reverse bias (HTRB) tests, to identify and eliminate potentially unreliable SiC MOSFETs. These methods effectively reduce the likelihood of field failures by ensuring that devices with extrinsic defects are removed before deployment. The results indicate that optimized burn-in conditions significantly reduce early failures and improve the long-term reliability of devices without degrading performance, thereby demonstrating a successful balance between screening efficiency and device integrity.

In summary, the developments in gate-oxide reliability for SiC MOSFETs highlight a transition from early reliability issues to their current capability to meet stringent industrial demands. Ongoing research will continue to push the boundaries in this field, aiming for even more efficient and reliable semiconductor devices.

IV. Conclusion

In conclusion, the efficiency of compressors poses a significant challenge in the advancement of EVs and HEVs. The emergence of 800V systems in the battery industry has highlighted the need for improved air conditioning compressors. Compared to Si IGBT, this study has demonstrated that SiC MOSFETs offer distinct advantages for electric vehicle 800V air conditioning compressors.

Through a systematic comparison, this research has shown that SiC MOSFETs exhibit superior system energy efficiency, expanded compressor operation boundaries, enhanced NVH performance, and potential for miniaturization. These benefits make SiC MOSFETs a favourable choice for achieving higher

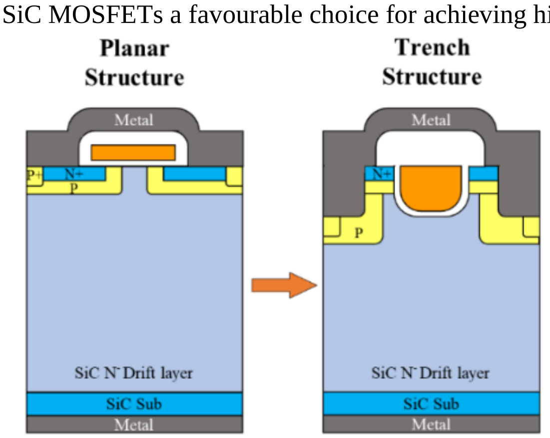


Fig. 22. Planar MOSFETs to Trench MOSFETs

performance and efficiency in electric vehicle air conditioning systems.

Furthermore, the discussion has also shed light on the challenges associated with cost reduction and gate oxide reliability issues for SiC MOSFETs, acknowledging the importance of addressing this aspect for widespread adoption. Nevertheless, the potential advantages and advancements offered by SiC MOSFETs make them a promising technology for enhancing the overall efficiency and performance of electric vehicle air conditioning compressors in the future.

Overall, this research emphasizes the significance of selecting the appropriate power devices, such as SiC MOSFETs, for improving the efficiency of air conditioning compressors in electric vehicles. By leveraging the advantages of WBG devices, the development of 800V systems can contribute to overcoming the efficiency limitations and accelerating the progress of electric vehicle and hybrid vehicle technologies.

REFERENCES

[1] U.S. Department of Energy, "Electrical and Electronics Technical Team Roadmap," *U.S. DRIVE Partnership*, Oct. 2017.

[2] Tesla, "Model 3," 2018. [Online]. Available: https://www.tesla.com/model3.

[3] Y. Takatsuka, H. Hara, K. Yamada, A. Maemura, and T. Kume, "A wide speed range high efficiency EV drive system using winding changeover technique and SiC devices," *in Int. Power Electron. Conf. (IPEC)*, May 2014, pp. 1898–1903.

[4] C. N.-M. Ho, H. Breuninger, S. Pettersson, G. Escobar, and F. Canales, "A Comparative Performance Study of an Interleaved Boost Converter Using Commercial Si and SiC Diodes for PV Applications," *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 289–299, Jan. 2013.

[5] D. Ramadan, M. Aly, and E. M. Ahmed, "Practical Performance Analysis and Device Selection for Photovoltaic Multilevel Inverters Installations," in *Int. Conf. Innovative Trends Comput. Eng. (ITCE)*, Feb. 2019, pp. 559–563.

[6] B. Stevanović, E. Serban, S. Cóbreces, P. Alou, M. Ordonez, and M. Vasić, "DC/DC Stage Contribution to Bus Voltage in 1000- and 1500-V Grid-Connected Solar Inverters," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 10, no. 5, pp. 6252–6265, Oct. 2022.

[7] R. S. Krishna Moorthy et al., "Estimation, Minimization, and Validation of Commutation Loop Inductance for a 135-kW SiC EV Traction Inverter," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 1, pp. 286–297, Mar. 2020.

[8] Q. Zhang, H. Zhang, S. Mao, J. Li, Z. Hu, and L. Xu, "A high-speed air compressor controller for vehicle used fuel cell systems," in *IEEE Veh. Power Propuls. Conf.*, Oct. 2021, pp. 1–4.

[9] H. Zhu, N. Fujishima, Y. Onozawa, and S. Hu, "Study the Thermal Performance of the CLLC Transformer in the OBC Designed Using SiC MOSFETs," in *Int. Power Electron. Conf. (IPEC)*, May 2022, pp. 1783–1788.

[10] A. Khaligh and M. D'Antonio, "Global Trends in High-Power On-Board Chargers for Electric Vehicles," *IEEE Trans. Veh. Technol.*, vol. 68, no. 4, pp. 3306–3324, Apr. 2019.

[11] H. V. Nguyen, D.-C. Lee, and F. Blaabjerg, "A Novel SiC-Based Multifunctional Onboard Battery Charger for Plug-In Electric Vehicles," *IEEE Trans. Power Electron.*, vol. 36, no. 5, pp. 5635–5646, May 2021.

[12] S. K. Mazumder, K. Acharya, and C. Ming Tan, "Design of an All-SiC Parallel DC/DC Weinberg Converter Unit Using RF Control," *IEEE Trans. Power Electron.*, vol. 23, no. 6, pp. 2893–2904, Nov. 2008.

[13] D. Han, J. Noppakunkajorn, and B. Sarlioglu, "Comprehensive Efficiency, Weight, and Volume Comparison of SiC- and Si-Based Bidirectional DC–DC Converters for Hybrid Electric Vehicles," *IEEE Trans. Veh. Technol.*, vol. 63, no. 7, pp. 3001-3010, Sep. 2014.

[14] X. Ding et al., "Analytical and Experimental Evaluation of SiC-Inverter Nonlinearities for Traction Drives Used in Electric Vehicles," *IEEE Trans. Veh. Technol.*, vol. 67, no. 1, pp. 146–159, Jan. 2018.

[15] E. Trushliakov, M. Radchenko, A. Radchenko, S. Kantor, and Y. Zongming, "Statistical Approach to Improve the Efficiency of Air Conditioning System Performance in Changeable Climatic Conditions," in *5th Int. Conf. Syst. & Inform. (ICSAI)*, Nov. 2018, pp. 256–260.

[16] C.-Q. Su, Z.-Z. Wang, X. Liu, X. Xiong, T. Jiang, and Y.-P. Wang, "Research on thermal comfort of commercial vehicle and economy of localized air conditioning system with thermoelectric coolers," *Energy Rep.*, vol. 8, pp. 795–803, Nov. 2022.

[17] J. Ko, K. Thu, and T. Miyazaki, "Transient analysis of an electric vehicle air-conditioning system using CO2 for start-up and cabin pull-down operations," *Appl. Therm. Eng.*, vol. 190, p. 116825, May 2021.

[18] N. V. Burnete, F. Mariasiu, C. Depcik, I. Barabas, and D. Moldovanu, "Review of thermoelectric generation for internal combustion engine waste heat recovery," *Prog. Energy Combust. Sci.*, vol. 91, p. 101009, Jul. 2022.

[19] H. A. Ahmed, T. F. Megahed, S. Mori, S. Nada, and H. Hassan, "Performance investigation of new design thermoelectric air conditioning system for electric vehicles," *Int. J. Therm. Sci.*, vol. 191, p. 108356, Sep. 2023.

[20] S. Singh, A. Namboodiri, and M. P. Selvan, "Agent-based system to control the air-conditioner and EV charging for residents in smart cities," *IET Smart Cities*, vol. 1, no. 2, pp. 71–80, 2019.

[21] X. Pei et al., "Field-Line-Circuit Coupling Based Method for Predicting Radiated Electromagnetic Emission of IGBT-PMSM Drive System," *Chinese J. Electron.*, vol. 30, no. 3, pp. 561–569, 2021.

[22] J. Aurich, "Comparison and Evaluation of different A/C Compressor Concepts for Electric Vehicles," *Proc. Int. Compres. Eng. Conf.*, 2018, pp. 1434-1443.

[23] P. McGuthrie, "Tesla Model Y Cold Weather Range Testing in Colorado," Tesla North, Nov. 16, 2020. [Online]. Available: https://teslanorth.com/2020/11/16/tesla-model-y-cold-weather-range-testing-in-colorado

[24] Y. Liu, Z.X. Wu, H. Zhou, et al., "Development of China Light-duty Vehicle Test Cycle," *Int. J. Automot. Technol.*, vol. 21, no. 5, pp. 1233–1246, 2020.

[25] "CCRT management regulation", Feb. 17, 2023. [Online]. Available: https://www.cpqs.org.cn/ (only available in Chinese)

[26] R. F. Atallah, C. M. Assi, W. Fawaz, et al., "Optimal Supercharge Scheduling of Electric Vehicles: Centralized Versus Decentralized Methods," *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 7896–7909, Sep. 2018.

[27] X. Liu, G. Liu, and B. Han, "A Loss Separation Method of a High-Speed Magnetic Levitated PMSM Based on Drag System Experiment Without Torque Meter," *IEEE Trans. Ind. Electron.*, vol. 66, no. 4, pp. 2976–2986, Apr. 2019.

[28] M. Preindl and S. Bolognani, "Model Predictive Direct Torque Control With Finite Control Set for PMSM Drive Systems, Part 1: Maximum Torque Per Ampere Operation," *IEEE Trans. Ind. Inform.*, vol. 9, no. 4, pp. 1912–1921, Nov. 2013.

[29] A. Balamurali, A. Kundu, Z. Li, et al., "Improved Harmonic Iron Loss and Stator Current Vector Determination for Maximum Efficiency Control of PMSM in EV Applications," *IEEE Trans. Ind. Appl.*, vol. 57, no. 1, pp. 363–373, Jan. 2021.

[30] M. Verma, D. Phares, I. Grinbaum, and J. Nanney, "Cooling Systems of Large-Capacity Adjustable-Speed Drive Systems," *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 148–158, Jan. 2015.

[31] M. Noguchi, Y. Okazaki, T. Takazawa, T. Okamura, and N. Hirano, "Study of Refrigerant Circulation System and Cryofan for Cooling High Temperature Superconducting Coil," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, pp. 1–4, Sep. 2022.

[32] J.-D. Zhang, F. Peng, Y.-K. Huang, Y. Yao, and Z.-C. Zhu, "A novel low control frequency control strategy of high switching frequency inverter for high speed PMSM current control," in *Int. Conf. Electr. Mach. (ICEM)*, Aug. 2020, pp. 2358–2364.

[33] E. Atam, D. Patteeuw, S. P. Antonov, and L. Helsen, "Optimal Control Approaches for Analysis of Energy Use Minimization of Hybrid Ground-Coupled Heat Pump Systems," *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 2, pp. 525–540, Mar. 2016.

[34] J. Chen, J. Yang, S. Yang, S. L. Ho, and Z. Ren, "A 2-D Nonlinear Ambipolar Diffusion Equation Model of an IGBT and Its Numerical Solution Methodology," *IEEE Trans. Magn.*, vol. 54, no. 3, pp. 1–4, Mar. 2018.

[35] D. Salt, D. Drury, and D. Holliday, "The nonlinear voltage distortion effect of an extended IGBT turn-off time in sinusoidal PWM VSI applications," in *IEEE Int. Electr. Mach. & Drives Conf.*, May 2009, pp. 1497–1502.

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157

[36] P. Ning, T. Yuan, Y. Kang, et al., "Review of Si IGBT and SiC MOSFET based on hybrid switch," *Chinese J. Electr. Eng.*, vol. 5, no. 3, pp. 20–29, Sep. 2019.

[37] T. Reiners, M. Gross, L. Altieri, et al., "Heat pump efficiency in fifth generation ultra-low temperature district heating networks using a wastewater heat source," *Energy*, vol. 236, p. 121318, Dec. 2021.

[38] A. K. Putri, S. Rick, D. Franck, and K. Hameyer, "Application of Sinusoidal Field Pole in a Permanent-Magnet Synchronous Machine to Improve the NVH Behavior Considering the MTPA and MTPV Operation Area," *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2280–2288, May 2016.

[39] S.-K. Cho, K.-H. Jung, J.-Y. Choi, "Design Optimization of Interior Permanent Magnet Synchronous Motor for Electric Compressors of Air-Conditioning Systems Mounted on EVs and HEVs," *IEEE Trans. Magn.*, D. Peters, T. Aichinger, T. Basler, W. Bergner, D. Kueck and R. Esteve, "1200V SiC Trench-MOSFET optimized for high reliability and high performance," 2016 European Conference on Silicon Carbide & Related Materials (ECSCRM), Halkidiki, Greece, 2016, pp. 1-1, doi: 10.4028/www.scientific.net/MSF.897.489.vol. 54, no. 11, pp. 1–5, Nov. 2018.

[40] C. Gong, P. Zhang, S. He, and G. G S J, "E-motor NVH Analysis for PWM Induced Current Ripples in EV Applications," in *IEEE Energy Convers. Congr. & Expo. (ECCE)*, Oct. 2022, pp. 1–5.

[41] C. Zwyssig, S. D. Round, and J. W. Kolar, "Power Electronics Interface for a 100W, 500000rpm Gas Turbine Portable Power Unit," in *Twenty-First Annual IEEE App. Power Electron. Conf. & Expo.*, 2006. APEC '06., USA: IEEE, 2006, pp. 283–289.

[42] X. Li et al., "High-Voltage Hybrid IGBT Power Modules for Miniaturization of Rolling Stock Traction Inverters," *IEEE Trans. Ind. Electron.*, vol. 69, no. 2, pp. 1266–1275, Feb. 2022.

[43] K. Nguyen. "200 mm Silicon Carbide Wafer - An Update," SEMI, March 11, 2021. [Online]. Available: https://semi.org/en/standards-watch-2021March/200-mm-SiC-wafer-spec-update

[44] N.V. STMicroelectronics, "STMicroelectronics Manufactures First 200 mm Silicon Carbide Wafers," Globe Newswire, July 27, 2021. [Online] . Available: https://www.globenewswire.com/news-release/2021/07/27/2269487/0/en/STMicroelectronics-Manufactures-First-200mm-Silicon-Carbide-Wafers.html

[45] N.C. Durham, "Wolfspeed Unveils World's Largest SiC Wafer Fab," Wolfspeed, April 25, 2022. [Online]. Available: https://www.wolfspeed.com/company/news-events/news/wolfspeed-opens-the-worlds-largest-200mm-silicon-carbide-fab-enabling-highly-anticipated-device-production/

[46] II-VI, "II-VI Incorporated Expands Silicon Carbide Manufacturing Footprint for Power Electronics in Electric Vehicles and Clean Energy Applications," Apr. 15, 2021. [Online]. Available: https://ii-vi.com/news/ii-vi-incorporated-expands-silicon-carbide-manufacturing-footprint-for-power-electronics-in-electric-vehicles-and-clean-energy-applications/

[47] X. Chen et al., "Research progress of large size SiC single crystal materials and devices," *Light Sci. Appl.*, vol. 12, no. 1, p. 28, Jan. 2023.

[48] Sumitomo Metal Industries, Ltd., "Sumitomo Metals Develops Technol ogy to Grow Silicon Carbide Single Crystal for Energy Saving Power D evices" Nippon Steel, Oct. 16, 2008. https://www.nipponsteel.com/en/news/old_smi/2008/news2008-10-16-01.html/

[49] S. Zhang, G. Fan, T. Li, and L. Zhao, "Optimization of thermal field of 150 mm SiC crystal growth by PVT method," RSC Adv., vol. 12, no. 31, pp. 19936–19945, 2022.

[50] ZJU-Hangzhou Global Scientific and Technological Innovation Center, "A research project of ZJU-Hangzhou Global Scientific and Technolog ical Innovation Center was selected into 'Lingyan' Plan of Zhejiang Pr ovince," Jan. 10, 2022. [Online]. Available: https://hic.zju.edu.cn/hiceenglish/2022/0114/c56814a2475543/page.htm

[51] Disco, "KABRA," 2021. [Online]. Available: https://www.disco.co.jp/kabra/index_eg.html

[52] Infineon, "SILTECTRA™ - Infineon Technologies," 2018. [Online]. A vailable: https://www.infineon.com/cms/en/about-infineon/company/siltectra/

[53] SICC, "Production Process of SiC Single Crystal," 2021. [Online]. Ava ilable: https://www.sicc.cc/en/Knowledgeen.html

[54] P. Waurzyniak, "Inspecting, Testing, And Measuring SiC," Semicondu ctor Engineering, Oct. 12, 2021. [Online]. Available: https://semiengineering.com/inspecting-testing-and-measuring-sic/

[55] M. Chaturvedi, S. Dimitrijev, D. Haasmann, et al., "Comparison of Commercial Planar and Trench SiC MOSFETs by Electrical Characterization of Performance-Degrading Near-Interface Traps," *IEEE Trans. Electron Devices*, vol. 69, no. 11, pp. 6225–6230, Nov. 2022.

[56] Untangle Club, "Tesla Model Y Thermal management system with OC TOVALVE & HEATPUMP," 2020. [Online]. Available: https://www.youtube.com/watch?v=kJJBmQ-5bNs&t=308s

[57] Siemens AG, "Vibro-acoustic engineering challenges in (hybrid and) el ectric vehicles," 2017. [Online]. Available: https://www.plm.automation.siemens.com/media/global/en/3_EV-HEV_Webinar_tcm27-2746.pdf

[58] M. Karam, F. A. Russo, C. Branje, et al., "Towards a model human cochlea: sensory substitution for crossmodal audio-tactile displays," *Graphics Interface*, 2008, pp. 267-274.

[59] Wang J, Jiang X. Review and analysis of SiC MOSFETs' ruggedness and reliability[J]. IET Power Electronics, 2020, 13(3): 445-455.

[60] Chbili, Z., Chbili, J., Campbell, J.P., et al.: 'Massively parallel TDDB testing: SiC power devices'. 2015 IEEE Int. Integrated Reliability Workshop (IIRW), South Lake Tahoe, CA, 2015, pp. 91–94

[61] D. Peters, T. Aichinger, T. Basler, W. Bergner, D. Kueck and R. Esteve, "1200V SiC Trench-MOSFET optimized for high reliability and high performance," 2016 European Conference on Silicon Carbide & Related Materials (ECSCRM), Halkidiki, Greece, 2016, pp. 1-1.

[62] T. Aichinger and M. Schmidt, "Gate-oxide reliability and failure-rate reduction of industrial SiC MOSFETs," 2020 IEEE International Reliability Physics Symposium (IRPS), Dallas, TX, USA, 2020, pp. 1-6.

[63] S. R. Stein, J. Kim, S. Das, D. J. Lichtenwalner and S. Ryu, "Characterization of Interface Trap Density in SiC MOSFETs Subjected to High Voltage Gate Stress," 2024 IEEE International Reliability Physics Symposium (IRPS), Grapevine, TX, USA, 2024, pp. 1-5.

[64] L. Shi et al., "Evaluation of Burn-in Technique on Gate Oxide Reliability in Commercial SiC MOSFETs," 2024 IEEE International Reliability Physics Symposium (IRPS), Grapevine, TX, USA, 2024, pp. 1-6.

[65] A. Marcuzzi, D. Favero, C. D. Santi, G. Meneghesso, E. Zanoni and M. Meneghini, "A Review of SiC Commercial Devices for Automotive: Properties and Challenges," 2023 AEIT International Conference on Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), Modena, Italy, 2023, pp. 1-6.

[66] P. Moens, F. Geenen, M. Avramenko, G. Gomez-Garcia and K. Matocha, "On the Intrinsic and Extrinsic Reliability Challenges of SiC MOSFETs," 2024 IEEE International Reliability Physics Symposium (IRPS), Grapevine, TX, USA, 2024, pp. 1-7

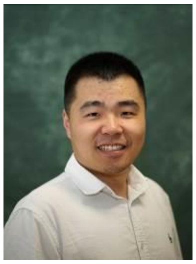
He Xu (Student Member, IEEE) was born in Shandong Province, China, in 1991. He received Dipl.Ing. degree in electrical engineering from the Technische Universität München, Munich, Germany in 2014. He has worked in Infineon AG (Munich), Global Research Center of General Electric (Munich & Shanghai) and Zinsight Ltd. (Shanghai). Now he is currently working toward the Ph.D. Degree in the College of Information Science & Electronic Engineering, Zhejiang University, China.

His research interests include high power electronics, power module packaging and automotive industries.

Lianjie Wang (Student Member, IEEE) received the B.S degree in 2021 from the Zhejiang University – University of Illinois at Urbana-Champaign Institute, Haining, China, where he is currently working toward the master's degree all in electrical engineering.

His research interests include wide band gap device application, hybrid module parallel inverter and high-speed motor drive.

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2024.3467157



Chushan Li (Member, IEEE) received the B.E.E. degree and Ph.D. degree in electrical engineering from the Department of Electrical Engineering, Zhejiang University, Hangzhou, China, in 2008 and 2014, respectively. Currently, he is an assistant professor in Zhejiang University – University of Illinois at Urbana-Champaign Institute, Zhejiang, China.

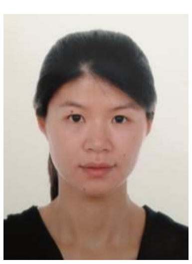
From April to September in 2008, he was an internship student with the Power Application Design Center in National Semiconductor (Hong Kong) Co.Ltd. From December 2010 to October 2011, he was a visiting scholar with the Freedm Center in North Carolina State University. From December 2013 to June 2014, he was a research assistant in Hong Kong Polytechnic University. From July 2014 to July 2017, he was a postdoctoral fellow in Department of Electrical and Computer Engineering, Ryerson University, Canada. His research interest includes high power density power converter design and Transportation Electrification.

Wuhua Li (Member, IEEE) received the B.Sc. and Ph.D. degree in Power Electronics and Electrical Engineering from Zhejiang University, Hangzhou, China, in 2002 and 2008, respectively.

From 2004 to 2005, he was a Research Intern, and from 2007 to 2008, a Research Assistant in GE Global Research Center, Shanghai, China. From 2008 to 2010, he joined the College of Electrical Engineering, Zhejiang University as a Post doctor. In 2010, he was promoted as an Associate Professor. Since 2013, he has been a Full Professor at Zhejiang University. From 2010 to 2011, he was a Ryerson University Postdoctoral Fellow with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON, Canada. He is currently the Executive Deputy Director of the National Specialty Laboratory for Power Electronics and the Vice Director of the Power Electronics Research Institute, Zhejiang University. His research interests include power devices, converter topologies and advanced controls for high power energy conversion systems. Dr. Li has published more than 300 peer-reviewed technical papers and holds over 50 issued/pending patents.

Due to his excellent teaching and research contributions, Dr. Li received the 2012 Delta Young Scholar from Delta Environmental & Educational Foundation, 2012 Outstanding Young Scholar from National Science Foundation of China (NSFC), 2013 Chief Youth Scientist of National 973 Program, 2014 Young Top-Notch Scholar of National Ten Thousand Talent Program, 2019 Distinguished Young Scholar from National Science Foundation of China. He serves as the Associated Editor of Journal of Emerging and Selected Topics in Power Electronics, IET Power Electronics, CSEE Journal of Power and Energy Systems, CPSS Transactions on Power Electronics and Applications, Proceedings of the Chinese Society for Electrical Engineering, Guest Editor of IET Renewable Power Generation for Special Issue “DC and HVDC system technologies”, Member of Editorial Board for Journal of Modern Power System and Clean Energy.

He received one National Natural Science Award and four Scientific and Technological Achievement Awards from Zhejiang Provincial Government and the State Educational Ministry of China. He was appointed as the Most Cited Chinese Researchers by Elsevier since 2014.



Menglian Zhao (Member, IEEE) received the M. S. degree in microelectronics and solid-state circuits and the Ph.D. degree in engineering circuits and systems from Zhejiang University, Hangzhou, China, in 2001 and 2004, respectively.

She joined the College of Electrical Engineering, Zhejiang University, in 2004. From 2005 to 2006, she was a Research Assistant in Department of Electronic and Computer Engineering, the Hong Kong University of Science and Technology, Hong Kong. She is currently an Associate Professor in the College of Information Science and Electronic Engineering, Zhejiang University. Her current interests include CMOS mixed-signal integrated circuit design, power management integrated circuit, and low-power techniques for integrated circuits and SoC.

Jingkui Shi received the B.S. and Ph.D. degrees from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2009 and 2022, respectively, both in power electronics. Since 2012, he has been with GE Global Research, Shanghai, China, as a Lead Engineer. Now he is the Founder and CEO of Zinsight Technology (Shanghai) Co., Ltd.

His research interests include the control and system design for high-power drives, renewable energy systems and SiC inverters.

Bo Qu was born in Shanghai, China, in 1982. He received Bachelor degree in electrical engineering from Shanghai Jiaotong University, China in 2004 and PhD degree in power electronics from Zhejiang University, China in 2010. He was Senior Engineer in Global Research Center of General Electric (Shanghai), focusing on medium voltage drives and SiC applications. Now he is CTO of Zinsight Technology (Shanghai) Co., Ltd.

His research interests include high power converters, machine control and SiC applications.

Li Xiang was born in Hunan Province, China, in 1988. He received Dipl.Ing. degree in electrical engineering from the Technische Universität Dresden, Dresden, Germany in 2015. He has worked in research and development department of Bosch AG (Lohr German, Xi’an & Wuxi China) and Zinsight Ltd. (Shanghai). Now he is currently working toward the Ph.D. Degree in the College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, China.

His research interests include power electronics, inverter, dc-dc converter and control technique of power systems.

Ying Mei (Student Member, IEEE) was born in Hubei, China, in 1986. He received the B.Sc. and M.Sc. degrees in 2008 and 2011, respectively from the College of Electrical Engineering, Zhejiang University, Hangzhou, China, where he is currently toward the Ph.D. degree. From 2011 to 2015, he was with the GE Global Research Center, Shanghai, China, as a Research Engineer, working on high power high frequency converter design for medical equipment. From 2015 to 2018, he was with the LG Electronics Shanghai R&D Center, Shanghai, China, as a Senior Engineer and Project Leader, working on high power density converter for e-mobility.

His current research interests include wireless power transfer, high power density converter and wide bandgap device-based power converter.

Yonghui Deng received B.Eng. degree in electrical engineering from Xi’an Jiaotong University, Xi’an, China in 2010, and the M.Sc degree in electrical engineering from Zhejiang University, Hangzhou, China in 2013. He has worked in Global Research and Development center (Shanghai) in General Electric, China Technology Center (Shanghai) from Valeo Automotive Co. Ltd. and Zinsight Ltd. (Shanghai). Now He is currently pursuing the Ph.D degree in electrical engineering from Zhejiang University, Hangzhou, China.

His research interests include high power electronics, power module packaging and silicon carbide power devices.

Huihui Xu was born in Anhui Province, China, in 1990. He received bachelor's degree in electrical engineering from Tsinghua University in 2013. He received Master’s degree in electrical engineering from the University of Chinese Academy of Sciences in 2016.

His research interests include high power electronics, power conversion control and automotive industries.