Silicon Carbide Power Electronics for Electric Vehicles

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***Abstract*—The success of electric vehicle drives heavily depends on the maximization of energy conversion efficiency. Losses in power electronic converters increase system size, weight and cost, raise energy demand and limit the operating distance range. Advances in semiconductor technology can remedy these problems and silicon carbide devices are of special interest in this context. This material enables manufacturing high-voltage devices with lower on-state voltage drop and shorter switching times, thus reducing both static and dynamic power loss. In this paper, recent achievements in silicon carbide technology as well as their applications in electrical vehicles have been reviewed.**

***Keywords*—power semiconductor devices, silicon carbide, electric vehicles**

I. Introduction

Power semiconductor devices are the basic components of power electronics. Their optimisation allows to fundamentally improve such important technical and economic indicators of power converters as efficiency, specific values of mass and volume, reliability or quality of output parameters. There is a trend of increasing conversion frequency of electric power, related first of all to the aim of reducing size, weight, cost and power loss of passive components. The development of high-frequency power converters needs solving complex technical problems in converter design. However, the technical and economic effect obtained by moving to higher frequencies fully compensates the cost of research and development. Many fundamental limits of power semiconductor devices in this respect are related to limitations in material properties. Therefore, although silicon (Si) is still most widely used in this area, thanks to its technology maturity and low cost, it is not necessarily the best option and new materials are being proposed. Among prospective solutions, silicon carbide (SiC) is especially promising.

II. Effects of Semiconductor Material Properties on Power Device Operation

One of the major constraints for power semiconductor devices is their operating voltage which results from the critical electric field E_{crit} at which avalanche breakdown occurs. For silicon, this value is relatively low. The electric field E of a reverse-biased PN junction follows the Poisson's law [1]

$$\mathrm{d}E/\mathrm{d}x = e\,N\,/\,\varepsilon \qquad (1)$$

where e is the elementary charge, N is the dopant concentration, and ε is the permittivity. The resulting distribution is shown in Fig. 1. The breakdown voltage is by definition equal to the area under the critical electric field distribution:

$$V_{br} = \int E\,\mathrm{d}x = (E_{crit}\,W)\,/\,2. \qquad (3)$$

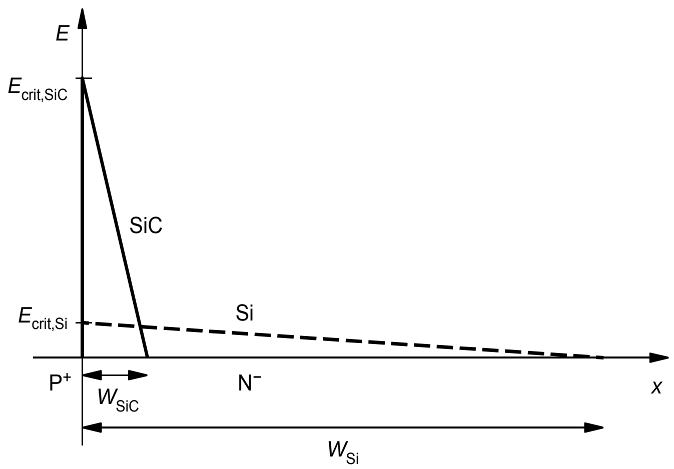

Fig. 1: Electric field distribution at a reverse-biased PN junction in a silicon (Si) and a silicon carbide (SiC) high-voltage power semiconductor device having the same voltage blocking capability

Thus, with low critical field, the lightly doped layer width W must be important to obtain high voltage capability. Based on (1) and (2), it can be found that

$$W = \sqrt{\frac{2\varepsilon V_{br}}{eN}} \, . \qquad (3)$$

This means that additionally, the dopant concentration must be low, which has negative consequences for the forward bias. With unipolar conduction, the on-state resistance is given by [2]

$$R_{on} = W / (e \mu N A) \qquad (4)$$

where μ is the carrier mobility and A is the device cross-section area. It is therefore high for low E_{crit}. Consequently, manufacturing high-voltage unipolar devices (Schottky diodes, MOSFETs, JFETs) from silicon is not profitable.

Bipolar devices (PIN diodes, IGBTs, thyristors) rely on the introduction of minority carriers into the lightly doped layer. In this case, excess carriers of both types (electrons and holes) are present, so carrier concentrations are much higher than the dopant concentration N and they are increasing functions of current density [1]. As a result, the on-state resistance is lower than with unipolar conduction and it decreases with current. This way, bipolar devices provide low on-state resistance and voltage drop which are almost independent of doping and current, as Fig. 2 demonstrates. Unfortunately, the resistance still depends on the layer width, so it increases with voltage capability. However, the most important disadvantage of bipolar devices is their long switching time resulting from the need to introduce or to remove the excess carriers. Combined with high transitory currents or voltages related to these processes, this leads to elevated dynamic power loss. The number of excess carriers must increase with the lightly doped layer width, so this loss increases with voltage capability. As the dynamic power loss is proportional to frequency, the latter becomes considerably limited [2]. A low switching frequency necessitates larger and more lossy passive components, thus reducing system efficiency and increasing its cost.

III. Advantages of Silicon Carbide for Power Electronics

The disadvantages of silicon resulted in the search for alternative materials among which silicon carbide (SiC) has received much attention. Its band gap is wider, so its critical field is higher. This is because carriers must be accelerated to a higher speed to reach the kinetic energy necessary to overcome the gap.

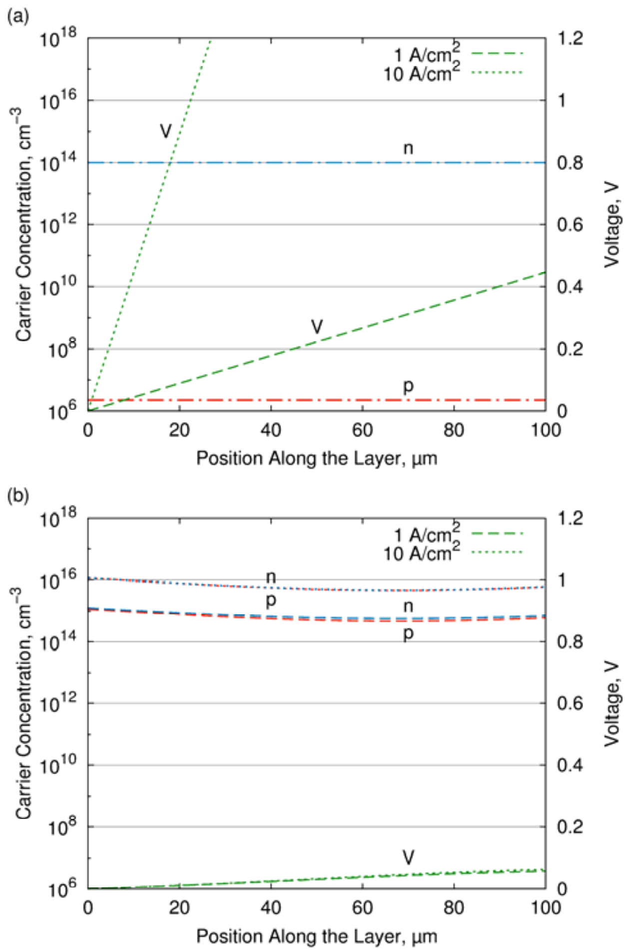

Fig. 2: Electron concentration n, hole concentration p and voltage drop V along a lightly doped n-type semiconductor layer (W = 100 µm, $N = 10^{14}$ cm^{-3}) for two current density values: (a) unipolar conduction, (b) bipolar conduction

Thus, high-voltage SiC devices have low on-state resistance, so they can be unipolar with the ability of fast switching. With low resistance, cross-section area can be small. This fact provides the additional benefit of small parasitic MOS capacitances that limit the switching speed of field-effect transistors. On the other hand, if the control circuit is ignored, the unipolar device switching time is the time needed for the carriers to be swept away by the developing electric field. The latter is normally high enough to cause carrier velocity saturation at some value v_{sat}. Then, the switching time is simply [2]

$$t_{sw} = W / v_{sat} \, . \qquad (5)$$

Although there are about 200 known crystal polytypes of silicon carbide, only three of them are suitable for mass production of electron devices: 3C, 4H and 6H [3]. Each polytype has distinct electrical, mechanical and thermal properties. There are no 3C-SiC wafers commercially available yet. Due to the greater electron mobility, 4H-SiC is preferred over 6H-SiC for power appplications.

Other compound semiconductors interesting for application in power electronics include gallium arsenide (GaAs) and gallium nitride (GaN). A comparison of selected material parameters is presented in Table 1. Additionally, Table 2 shows unipolar device parameters for a voltage capability of 1000 V and a device cross-section of 1 cm^2, calculated using (2) to (5). Based on these data, SiC has several further advantages (than just the high critical field) for power electronics [3, 4]:

- High theoretical maximum operating temperature (about 1000 °C) that follows from the increase of the intrinsic carrier concentration with temperature. It concerns electron-hole pairs, so when it becomes higher than doping, PN junctions disappear; concurrently, leakage currents become important. With a wider band gap, the intrinsic concentration is lower, because more energy is needed to create a free carrier pair. The high maximum temperature enables high power loss and thus high operating current and voltage.
- High Debye temperature, at which elastic lattice vibrations occur with a maximum frequency. It is the limit of thermal stability: when exceeded, oscillations can become non-elastic and lead to material destruction.
- High thermal conductivity (at the level of copper for polycrystalline SiC), which facilitates heat removal and thus enables higher power loss even under the same (low) junction temperature as for silicon.
- High saturation velocity of carriers, which results in short switching times but also in a low resistivity under high electric field, when carrier velocity saturates, so conductivity depends on v_{sat} instead of the low-field mobility μ.
- Easy formation of insulating silicon oxide (SiO_2) thanks to silicon atoms being present in the lattice, which simplifies the technological process and lowers the production cost. For example, oxide can be produced by placing the wafer in an atmosphere rich in oxygen under high temperature (thermal oxidation) or by implanting oxygen ions.
- High threshold energy for defect formation due to radiation, resulting from the low lattice constant. This makes SiC suitable for space applications.

TABLE 1: POWER SEMICONDUCTOR MATERIAL PARAMETERS AT 300 K [3, 5]

	Si	**4H-SiC**	**GaAs**	**GaN**
Bandgap (eV)	1.1	3.3	1.4	3.4
Relative dielectric constant	11.8	10.0	12.8	9.0
Breakdown electric field (10^6 V/cm)	0.3	3.0	0.4	3.0
Electron mobility (cm^2/(Vs))	1500	1000	8500	1200
Saturation electron velocity (10^7 cm/s)	1.0	2.0	2.0	2.5
Intrinsic carrier concentration (cm^{-3})	10^{10}	10^{-7}	10^6	10^{-9}
Thermal conductivity (W/(cm K))	1.5	4.9	0.5	2.1
Defect threshold energy (eV)	9	153	13	131

TABLE 2: IDEAL UNIPOLAR POWER DEVICE PARMETERS (FOR V_{BR} = 1000 V AND A = 1 CM^2)

	Si	**4H-SiC**	**GaAs**	**GaN**
Dopant concentration (10^{14} cm^{-3})	2.9	250	5.7	220
Layer width (µm)	66.7	6.7	50.0	6.7
On-state resistance (mΩ)	94.5	0.2	6.5	0.2
Unipolar switching time (ns)	0.67	0.03	0.25	0.03

The main advantages of GaAs are its high mobility and saturation velocity, both resulting in low resistivity. Alloys of GaAs using Al, P, Sb or In have characteristics that complement those of GaAs, allowing some flexibility. On the other hand, GaN merits are wide bandgap, high saturation velocity, high thermal conductivity, and radiation resistance. The most significant barrier for gallium compounds is the high cost of single-crystal substrates as gallium is an element rarer than gold [6]; arsenic is not rare, but it is poisonous. Another significant drawback is the absence of a natural insulating oxide. Due to the narrow bandgap, the critical field of GaAs is similar to that of Si, resulting in important on-state resistance, switching time and intrinsic concentration. Moreover, GaAs has very low thermal conductivity; GaN has higher thermal conductivity than Si and GaAs, but it is still lower than for SiC.

Finally, it should be noted that the use of any material in electronics requires the ability to manufacture substrates and layers of high purity and which can be doped in a controlled manner. It is difficult to achieve the values listed in Tables 1 and 2 with a yield high enough for commercial success. Therefore, reliable conclusions on final device characteristics cannot be drawn from material properties alone; device manufacturing technology must be taken into account as well. The development of a reliable technology is long and costly, which results in a high device cost at the initial stage.

Thus, silicon carbide has some serious drawbacks, too. A major one is the high wafer cost; nevertheless, it is constantly decreasing as the technology is becoming more established and its market is expanding. Another one is hardness: SiC is nearly as hard as diamond, which makes it suitable for cutting tools, but slicing SiC crystals into wafers is troublesome. Moreover, the pronounced anisotropy of SiC parameters complicates substrate manufacturing.

IV. RECENT ADVANCES IN SILICON CARBIDE TECHNOLOGY

Silicon carbide became regarded as a material for power electronic devices before the 1990s. However its successful introduction to mass production only became possible in the 2000s thanks to the development of a technology advanced enough to produce crystals of required size and in adequate quantities [7].

At present, for power electronic applications SiC Schottky diodes (including Junction Barrier Schottky and Merged PIN-Schottky) are already widespread on the market; JFETs and MOSFETs are also available. At the same time, companies are working on the improvement of SiC BJTs, IGBTs and GTOs to enable making the step to the market [8]. From November 2010, GeneSiC company offers world's first commercially available SiC thyristors which are single-chip devices with ratings reaching 6.5 kV, 80 A, 200 ºC and 200 kHz. They are not mass-produced, but their production can be ordered, if necessary, directly from the developer [9].

The first power module with all SiC components ready for high-volume manufacturing, rated for 1200 V and 100 A, was presented by Cree in November 2012 [10]. This MOSFET module can switch at frequencies up to 100 kHz, which is beyond what is customarily associated with silicon IGBT-based modules with similar ratings. The use of SiC components in power modules increases the efficiency of the whole system, still with the same circuit design [11].

Implementation of integrated circuits using silicon carbide looks attractive in view of the properties of this material. In the future, these integrated circuits would have a number of significant advantages over widespread silicon ICs, including exceptional resistance to errors caused by radiation as well as to high temperatures [12]. Integrated circuits based on silicon carbide are currently under development and research. There are no such devices available on the market yet.

To make full use of the advantageous characteristics of SiC, there are many problems that need to be solved, such as obtaining reliable electric contacts. This is due to the fact that at temperatures above 500 °C contact metallization becomes severely degraded due to inter-diffusion between layers, contact oxidation as well as compositional and microstructural changes at the metal-semiconductor interface. This leads to device failure. Vacuuming of the semiconductor in a special facility is applied but this multiplies its cost, size and weight. One solution to this problem is the use of a multilayer metallization. The use of a three-layer Ti/TaSi2/Pt metallization allowed to achieve the temperature stability of current-voltage characteristics and ohmic contact resistance in the air for more than 600 hours at 500 °C [13]. The peculiarity of this contact is that the initial oxidation of silicon creates a critical mechanism of diffusion barrier that prevents further penetration of oxygen into the metallization layer. It offers the prospect of creating high-temperature semiconductor devices in more efficient housings or without housing.

Under high-temperature operation, thermo-mechanical stress can cause cracking and, ultimately, device failure, because of different thermal expansion coefficients [14]. To reduce the thermo-mechanical stress induced in a package, metal-matrix composites with low thermal expansion are typically used and to ensure SiC device working safely, it must be mounted mechanically onto a cold plate which provides coolant flowing paths. In this assembly, the necessary thermal terminal interface material such as thermal grease significantly affects the cooling efficiency. The base plate can be replaced with a cold-base plate, which is directly bonded to the power stage by solder [15]. The advantage of commonly used composites such as copper molybdenum, copper tungsten, copper graphite, aluminium graphite and aluminium silicon carbide is that their thermal expansion coefficients can be adjusted to match the rest of the package assembly while retaining acceptably high thermal conductivity [16].

Another issue hindering high-temperature applications is that lifetime under thermal cycles is estimated to reduce by a factor of 50 when the operating temperature is increased from 150 °C to 200 °C. Novel advanced bonding methods will probably allow to cope with these conditions [17]. Additionally, temperature limitations also concern other components at the system level, such as capacitors and gate drivers. Because of the harsh environment of high-temperature applications, potting, encapsulation, and case materials must withstand these temperatures while providing sufficient electric insulation and protection from the environment. To prevent arcing within a package, gels have traditionally been used as the encapsulation materials in power modules.

A significant problem in the manufacturing of silicon carbide wafers are crystallographic defects. They include micropipes, carrots, triangular defects, threading screw dislocations (TSDs), threading edge dislocations (TEDs) and basal plane dislocations (BPDs) in SiC bulk substrates and epitaxial layers. High power semiconductor device quality was degraded under the forward bias conditions due to the presence of such defects because electron-hole recombination introduces stacking faults leading to an increase in the voltage drop [18]. This resulted in a significant decrease in the operational lifetime and deviations in device characteristics. In order to overcome these degradations, various approaches have been taken over the last decade [19]. In the case of BPD concentration, the most common solution is to turn these defects located in substrates into TEDs located at the substrate/epitaxial layer interface. This can be achieved by different techniques such as modification of epitaxial growth conditions like the carbon/silicon ratio and temperature [18].

Initially, the principal constraint to the commercial sustainability of SiC as a power semiconductor material was the high density of micropipes [3]. It has been widely discussed till now and there are many opinions about the mechanisms involved in their formation. A better understanding of these mechanisms, together with detailed experimental studies and modelling of the crystal growth process have enabled significant improvements to the technology through successful control of micropipe formation. There has been a steady decreasing trend in micropipe density. At present, for 150 mm wafers available on the market, the lowest guaranteed micropipe density is 0.2 cm^{-2} [9] (see Table 3).

The on-state resistance is one of the crucial characteristics of unipolar power transistors. It can be therefore regarded as a good indicator of the overall effect of technology progress on the final products. Fig. 3 shows its evolution over time for devices that have been successfully introduced to the market by various manufacturers until present. To enable comparison, only 1200 V devices have been considered, which is the current standard for SiC transistor voltage rating. Constant improvement can be observed for JFETs whereas 80 mΩ remains the limit for most MOSFET technologies. Nevertheless, by introducing in June 2014 a commercially available 1200 V MOSFET with an on-resistance as low as 25 mΩ, Cree confirmed its leader position in SiC power devices and seems to have set new standards in this field [20].

As it has already been noted, an important problem on the way to a wide implementation of any new semiconductor material is the wafer cost and size. The wafer size for SiC has grown over the years, reaching 150 mm of diameter recently [8], [21] (see Table 3). The technology has developed over the last decade so that now much larger wafers with lower defect density are reducing the effective cost per single device.

Almost all existing producers of silicon power semiconductor devices are more or less active in the SiC area, but at much different stages. The SiC technology is surely becoming a reliable and relevant alternative to silicon and it is in power electronics that this can be seen most clearly [22]. Leading companies around the world have created specialized manufacturing facilities for SiC power semiconductor devices. Most of these companies also conduct active commercial and promotional activities in this area [23].

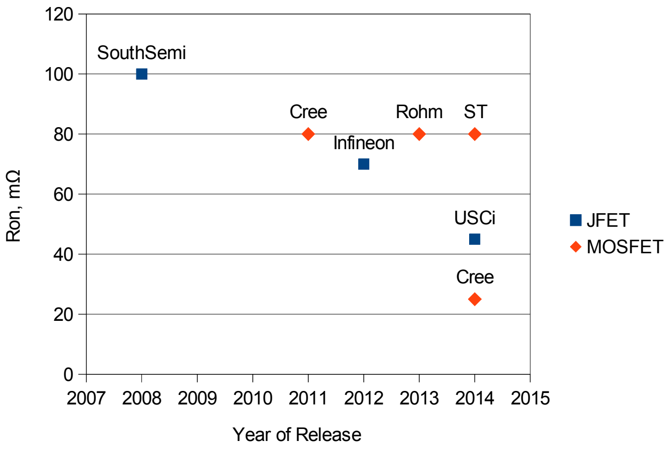

Fig. 3: Commercial silicon carbide transistor technology evolution [24-28]

TABLE 3: SIC WAFERS AVAILABLE ON THE MARKET [29-32]

Manufacturer	Product Line	Wafer Diameter	Micropipe Density (Max)
Cree	N-Type Very-Low Micropipe Density	150 mm	5 cm^{-2}
			1 cm^{-2}
Dow Corning	Prime Standard	100 mm	0.5 cm^{-2}
		150 mm	1 cm^{-2}
	Prime Select	100 mm	0.2 cm^{-2}
		150 mm	1 cm^{-2}
	Prime Ultra	100 mm	0.1 cm^{-2}
		150 mm	1 cm^{-2}
SiCrystal	Production Grade 2.3	100 mm	1 cm^{-2}

V. SILICON CARBIDE IN ELECTRIC VEHICLES

An ever-increasing role in the traffic belongs to road transport, which now makes up to 80% of the transportation volume of cargoes and up to 70% of passengers [33]. This makes it necessary to improve the structure of the road transport rolling stock in order to reduce transportation costs, save energy and preserve air quality. This is especially important when services in major cities are considered. Therefore, when solving environmental problems caused by the harmful effects of road transport, a complex approach is required. From the point of view of the energy source employed, electric vehicles have better prospects than combustion vehicles, as they consume electricity which can be easily obtained from solar or other forms of renewable energy. Due to this fact, the vast majority of automakers are now actively working on the creation of their own conceptual and serial electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV) [34].

The development and implementation of this type of vehicles require new approaches in the design of all their components. The crucial component of an electric vehicle is the electric motor power supply and control system (called the Power Control Unit, PCU) which is based on power electronics. In view of the different requirements that arise during operation and due to varying ambient conditions, the design of power electronics for electric vehicles requires careful attention. The success of electric vehicle drive technology heavily depends on maximization of electric energy conversion efficiency, while reducing operating costs and minimising any inconvenience caused to the user. Large power loss in power electronic circuits increases system size, weight and cost due to the necessary cooling components. It also raises energy demand both directly and indirectly through the cooling subsystem weight. This in turn leads to increased operating costs and limited operating distance range which is a serious hindrance for the user as a battery cannot be recharged as fast as a fuel tank can be refilled. These properties of power electronics are largely affected by the characteristics of semiconductor devices. In this respect, static and dynamic power losses are the key measures of their performance. Apart from device own properties, applied current and voltage levels have significant impact on both these components. Equally important is the effect of the switching method used [35].

As demonstrated in Section II, the silicon technology is inherently limited in view of the demands of electric vehicles. Moving to the SiC technology allows reducing power electronics weight and power losses therein as well as raising the operating temperature limit. To investigate this approach, standard Si-based power semiconductor devices have been replaced with SiC MOSFETs and JBS diodes in the boost converter, the motor inverter and the generator inverter blocks of a third-generation Prius. It has been found that fuel economy is approximately 5% without greatly changing the controllers of the boost converter and the inverter [36]. An investigation of the impact of SiC power semiconductor devices in EVs through simulations shows that at a given switching frequency, the SiC technologies are able to outperform silicon ones by an almost 80% reduction in switching losses, 70% reduction in operating temperature and enhanced conversion efficiency. The simulation results have been confirmed through practical experiments and showed that SiC can enable lighter cooling systems and more compact power supplies [37].

The maximum operating temperature of SiC power devices is high enough to obviate the need for liquid cooling systems in hybrid and all-electric vehicles, which are one of their bulkiest components. The combustion engine of hybrid vehicles needs a cooling loop running at temperatures around 105 °C. However, the power electronics based on silicon stops performing above roughly 150 °C. Therefore, power electronics needs another cooling loop running colder than the engine loop, at about 70 °C due to some physical space existing between the electronics and the coolant. Using liquid cooling significantly increases the overall size of the engine. Moreover, power electronics can be destroyed in case the liquid leaks out [38]. Temperature limits and heat dissipation are among the main challenges in power semiconductor device application.

For cost optimisation, the cooling of power electronic devices in electric vehicles is combined with the engine cooling system that reaches temperatures of about 120 °C [4]. With increasing operating temperature of power electronic devices in electric vehicles, the choice has to be made between increasing the output current or decreasing the cooling costs. Cheaper cooling systems require high temperature device capabilities. At the same time, the increasing power electronics temperature can significantly affect all the other electronic subsystems located nearby. That is why effective management of heat generation should also consider the surroundings of the power module. The use of SiC power semiconductors and employing a Peltier cooler with active electronic control can help creating power electronic systems that can operate under a 120 °C ambient temperature [39].

The outstanding dynamic performance, high operating temperature and very low resistive power loss of SiC transistors bring power electronics to a new stage. For example, with the change of frequency from 100 kHz to 250 kHz, a SiC JFET/JBS power converter efficiency shows only a weak change, in contrast to the drop from 95% to 92.5% when using a Si CoolMOS and SiC JBS combination [40]. Increasing the switching frequency is advantageous from the point of view of inductive and capacitive circuit components which can be smaller, cheaper and introduce less power loss.

Electric traction drives already convert more than 85 percent of their power into usable mechanical energy, which is more than double the raw efficiency of a combustion engine. However, electronic converters, with their advantages, can be used not only for direct power supply to the engine from the battery, but also for battery charging and for auxiliary power supplies, as shown in Fig. 4.

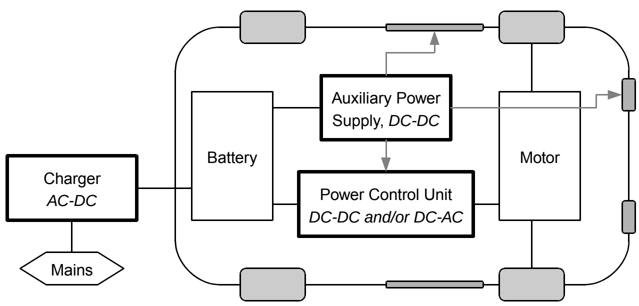

Fig. 4: Fields of SiC application in electric vehicles

These are two additional prospective areas of SiC application in electrical vehicles. For example, an SiC-based 750 V to 27 V power supply for the low voltage EV DC bus has been shown to increase efficiency from 88% to 96%, reduce size and weight by 25% and obviate the need for cooling fans compared to an Si-based solution [41].

Using SiC devices in charger converters softens commutation processes, thus enabling high current rate of rise. The generated electromagnetic disturbance stays low even under hard switching conditions [42]. Traditionally, battery or capacitor charging infrastructure for EV and PHEV is wired, but wireless vehicle-to-grid connection is another promising solution. Inductive power transfer is very suitable for the realisation of wireless charging infrastructure in the form of carports in private homes. Satisfying the main demands for such chargers, i.e. efficiency, compactness and light weight, is facilitated by SiC power semiconductor devices [43].

Table 4 summarizes the application examples cited above and illustrates the wide range of possible applications of SiC power semiconductor devices in the EV domain. It should be noted that the successful introduction of SiC devices can be exploited not only by the automotive industry. For example, U.S. Navy new DDG 1000 Zumwalt Class destroyer vessel is supplied with large amounts of electric power exceeding 78 MW at 4160 V (AC) using SiC technology. In the aircraft industry jet engines are still retained for propulsion, but electric power is used to significantly improve the serviceability of new, more-electric aircrafts by minimizing or eliminating the need for hydraulic or pneumatic accessory systems [34]. These components require providing electric power supply without significantly increasing the mass of the system.

In perspective, the use of silicon carbide power semiconductor devices will allow to largely reduce the size of electronic appliances and minimize energy losses, mainly due to the decreasing trend in SiC device manufacturing costs. Integration of power electronics with sources and loads becomes possible with the use of SiC devices thanks to their higher maximum operating temperature. A notable example is an integrated industrial servo drive where multiple supplies are integrated with motor and controller units [34]. It is capable of operating in hostile factory-floor conditions including water jet washdowns. It requires only 50% of the volume of a conventional servomotor with its separate controller. Such a solution facilitates the implementation of additional systems in electric vehicles, e.g. energy recuperation ones.

TABLE 4: SIC APPLICATION EXAMPLES IN ELECTRIC VEHICLES

Application Area	Converter Type	Device Type	Device Manufacturer	Device Rating	Ref.
PCU	DC-AC	MOSFET	Cree	1200 V	[35]
		BJT	Fairchild	1200 V	
		JFET	Infineon	1200 V	
		JBS	Infineon	1200 V	
PCU	DC-DC DC-AC	MOSFET	DENSO	1400 V 73 A	[36]
		JBS	DENSO	1400 V 200 A	
PCU	DC-AC	JBS	SemiSouth	46 A	[37]
		MOSFET	ROHM	22 A	
PCU, APS	DC-DC	JFET module	Teledyne	300 V	[38]
PCU	DC-AC	JFET	SemiSouth	1200 V	[39]
PCU	DC-DC	MOSFET	Cree	1200 V	[40]
		JFET	SemiSouth	1200 V	
		JBS	ST Micro	600 V	
APS	DC-DC	MOSFET	Cree	1200 V 20 A	[41]
Charger	AC-DC DC-AC	JFET	Infineon	1200 V	[42]
Charger	DC-AC	MOSFET	ROHM	1200 V 35 A	[43]

PCU = Power Control Unit; APS = Auxiliary Power Supply

VI. CONCLUSION

Silicon power semiconductor devices have serious disadvantages inherent to the physical properties of silicon. These properties make it impossible to manufacture high-voltage unipolar devices, thus considerably limiting the switching frequency. From several candidate replacement materials, silicon carbide seems the most promising. The feasibility of multiple SiC power devices has been demonstrated and some of them have been successfully marketed. Several works show that these devices have an application potential for electric vehicles. They offer low power loss, resulting in higher efficiency, lower battery power consumption and limited cooling requirements. Consequently, vehicle manufacturing and operating costs can be reduced and its operating distance extended, contributing to the attractiveness of electric vehicles.

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international cooperation of multiple disciplines such as physics, mathematics, electrical engineering, mechanical engineering and specialisms like control engineering and safety. By cooperation of these disciplines in a structured way, the ADEPT program provides a virtual research lab community from labs of European universities and industries [44].

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