Power Semiconductor Considerations for xEV applications

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Abstract

A major shift in the automotive market is underway due to the aggressive decarbonization and zero emissions targets issued by the federal government. Automakers around the globe are pivoting from internal combustion engine (ICE) technology towards EV technology. The rapid adoption of electric vehicles is driven by innovation in power semiconductor technology moving beyond the traditional silicon technologies to wide bandgap technologies (SiC and GaN) that enable the power electronic systems in automobiles achieve efficiencies and system solution size reduction that were beyond the reach of silicon power technology. In this paper, we give an overview of the three major subsystems – Traction inverters, On-board chargers (OBCs) and DC-DC converters – and discuss the tradeoffs of a choice between the types of power semiconductors Si IGBTs and MOSFETs, SiC MOSFETs and GaN HEMTs.

INTRODUCTION

With the aggressive roadmaps towards decarbonization and zero emissions, automakers around the globe are pivoting from internal combustion engine (ICE) technology towards EV technology. EVs have seen a rapid growth in demand in the last few years and by 2030, EVs could account for more than 60% of the new vehicles sold globally [1]. xEV technologies include hybrid electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs), in order of increasing electrical drivetrain contribution. The primary motivation for moving to BEVs is higher efficiency in addition to zero emissions and mechanical simplicity leading to better reliability. The shift to BEVs is currently constrained by the rather limited driving range, extended charging times and the manufacturing supply chain. Innovations in battery technology and power semiconductor technologies are facilitating highly efficient energy transfer from the battery to the traction drive system, regenerative braking, faster battery charging, and reduced form factors [2]. In this paper, we discuss the choice of power semiconductor devices from silicon technologies to state-of-the-art wide bandgap semiconductor technologies (SiC and GaN) for xEV applications. While high power density, small system solution size, and high efficiency are the primary requirements for a modern xEV, each of these technologies has its own place depending on the application under consideration. The choice of power semiconductors comes down to a trade-off between performance and system-level cost savings.

POWER ELECTRONICS IN XEVS

Power electronics in xEVs could be broadly classified in three different categories, each playing a different yet vital role in determining the efficiency and functionality:

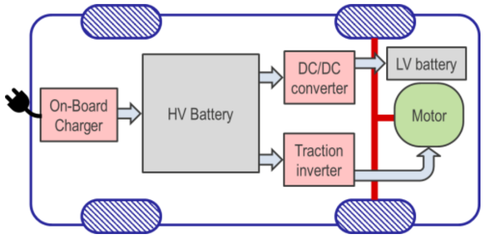

Fig. 1. System block diagram of a typical xEV showing the various power electronic components.

I. *Traction inverter*

The traction inverter forms the most critical power electronic component of an electric vehicle. The inverter converts the DC voltage from the battery pack to a variable frequency AC to power the traction motors. The DOE targets the inverter modules to support a power density of 100 kW/L at a cost of \$2.7/kW. and the whole inverter to reach 33 kW/L at a cost of \$6/kW [2]. The BEVs benefit from a reduced inverter module volume by increased battery size or cargo/passenger space. In addition, traction inverters need to ensure reliability up to 300,000 miles or 15 years [2]. The inverter is driven by applying pulse width modulated (PWM) voltage signals to the motor stator to develop three sinusoidal currents with 120^o phase shift. Modulation of the high-voltage input is typically achieved by using Si IGBTs and MOSFETs switching at frequencies ranging from 20 kHz to 100 kHz. The design challenge is to minimize energy loss during switching while maintaining safe timing. Gate drivers controlled by a microcontroller subsystem (MCU) determine the timing of the switching devices. At such frequencies, switching losses from the devices become important, especially because the mission profile may require the inverter to operate in light load for considerable periods of the time. A typical EV traction inverter spends only 5% of its time in acceleration (100% load) and 45% of its time with 10% load during city driving. Overall, during 95% of the driving time, it operates under 30% of its full load. At low loads, switching loss dominates over conduction loss. Higher frequency operation is desirable to reduce filter size and is enabled by WBG devices as discussed later. However, higher frequency operation also requires improvements in busbar design and reduction of parasitics, without compromising the thermal management [2].

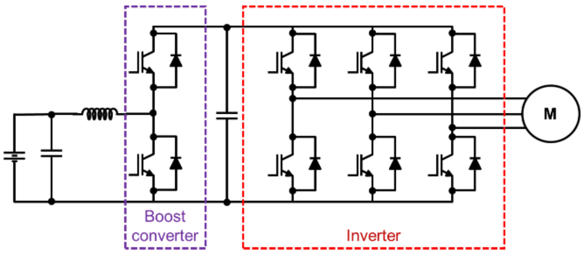

Fig. 2. A schematic of a traction inverter with a boost converter having IGBTs as switches.

II. *On-board charger*

On-board chargers (OBCs) allow charging the EV battery directly from an AC grid. Many OBC implementations have bidirectionality, allowing the EV battery to relay power back to the grid during peak demand and to other vehicles or loads [3]. The OBC operation power is in the low-medium range of 3 kW to 22 kW [5]. A high efficiency of 98%, power density of 4.6 kW/L and cost of $35/kW is targeted by the DOE for 2025 [2]. The design complexity for OBCs arises from multiple components required for AC/DC conversion, power factor correction, DC/DC conversion, isolation and different topologies used for obtaining high efficiency [4]. High frequency switching is highly desirable for reducing the system size, and along with efficient devices and advanced packaging, the power density targets could be met.

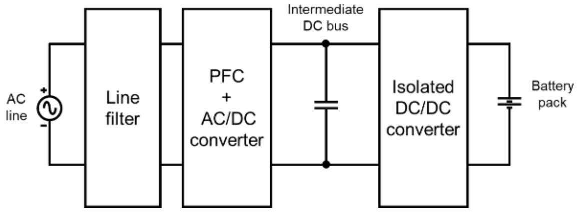

Fig. 3. Block diagram of an on-board charger (OBC) system.

III. *DC/DC converter*

The high voltage battery pack is also responsible for powering components for safety, functionality and comfort, such as sensors, cameras, navigation and computers [2]. DC/DC converters are needed to step down the battery voltage to ~12-14 V to power these accessories. With the increasing electrification, driver assistance and autonomous driving, the power requirements are expected to increase up to 5 kW by 2025 [5]. Like the OBC, a high efficiency of 98% and a power density of 4.6 kW/L are targeted by the DOE at a cost of $30/kW. In addition to this step-down converter, DC/DC converters may also be needed in the electric traction drive system to provide the bus voltage to the inverter stage, and in the OBC system to match the battery voltage [6]. Most of the design considerations for DC/DC converters are similar, i.e., high frequency, high efficiency operation to meet the power density targets. At Renesas, we recently announced a GaN-based 12 V/48 V DC-DC converter for mild hybrid vehicles and electic motorcycles (Fig.4). Renesas portfolio offers all the power electronics IC products including the power stage, MCU, PMIC and Gate Drivers. A SiC/GDU optimized inverter reference system complete with a system-level model development environment is shown in (Fig.5).

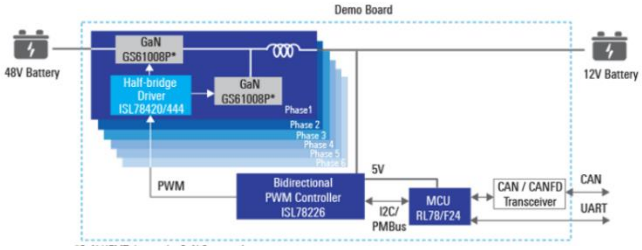

Fig. 4. Renesas' GaN-based DC-DC 12 V /48 V converter.

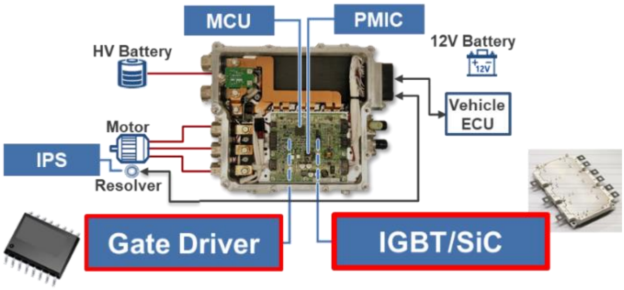

Fig 5. POWER SEMICONDUCTOR DEVICE TECHNOLOGIES

These power electronic systems described above can be constructed with a variety of switches (and rectifiers), depending on the topologies used. In the following section, we discuss the various candidates, viz. Si IGBTs, SiC MOSFETs, GaN HEMTs, and their suitability to the xEV applications.

I. *Si IGBTs*

Si IGBTs have been the traditional choice for traction invertors for electric vehicles for up to ~400 V applications. The main advantage of Si IGBTs is the very low cost, wide availability, proven reliability and maturity of technology which makes them attractive to many OEM manufacturers [7]. IGBTs are more robust to short-circuit and overcurrent stresses due to larger die sizes, compared to the WBG options. However, being bipolar devices, they suffer from higher switching losses, as well as a lower maximum junction temperature, typically 125 °C, which limits the current rating and requires bulky thermal management solutions. The high switching losses limit the maximum operation frequency to ~10-20 kHz and constraint the filter size. The increase in the overall system size when IGBTs are employed results in an undesirable volume and mass overhead and lower power density [7]. However, IGBTs usually perform better at high currents because of conductivity modulation compared to their unipolar counterparts. It has been demonstrated that Si IGBTs decrease the efficiency of inverters in the range of ~2-5% depending on the operation conditions [8]. Further, as the focus shifts to a higher battery voltage of 800 V to reduce copper losses and system weight, the voltage rating increases to 1200 V, and WBG devices emerge as clear winners in terms of performance and efficiency [9].

II. SiC MOSFETs

SiC, being a WBG material has many favorable properties for use in power semiconductor devices [10]. SiC MOSFETs outperform Si IGBTs in terms of switching losses while having comparable conduction performance. The low switching losses are enabled by a smaller die size and unipolar device operation. Further, due to the wide bandgap of SiC and higher intrinsic temperature, high junction temperatures are possible [3]. SiC MOSFETs also have a lower thermal resistance, allowing them to dissipate more power for a given junction temperature. The temperature derating of resistance is lower in SiC MOSFETs than Si which reduces the degradation in device performance at elevated temperatures [3]. These factors result in reduced cooling requirements and savings in mass and volume of the system, which can result in easier integration with HEVs and help extending the range of BEVs. High frequency operation of such MOSFET based inverters has been demonstrated by many groups [7], [8] for different topologies.

Despite the various advantages of SiC MOSFETs, there are certain challenges. The poorer quality of oxide, compared to silicon MOSFETs results in charge trapping effects and threshold voltage shifts due to bias temperature instabilities [11]. Because of smaller die sizes, the short circuit current density is high in SiC MOSFETs and it can lead to lower short circuit withstand times. High dv/dt and high di/dt switching conditions can couple with the parasitics resulting in overshoots and EMI. These issues make SiC based inverters design more challenging compared to Si IGBT based inverters [3]. In addition to traction inverter applications, owing to the high frequency operation, SiC based MOSFETs can find applications in OBCs and DC/DC converters [4]. It is expected that SiC technology would become cost competitive as manufacturing volume and suppliers increase.

III. GaN HEMTs

GaN-on-Si HEMTs have shown immense promise for lateral low voltage applications owing to high breakdown field of GaN and the high mobility of the 2-DEG at the heterointerface [12]. Because of the reduced die size, GaN HEMTs have very low capacitances and have very low switching losses. GaN HEMT switching up to the ~MHz range in various applications has been demonstrated [14]. For low voltages up to 650 V, GaN devices show a great promise as they outperform Si and SiC based devices for low power applications such as DC/DC converters and OBCs. One distinct advantage of GaN devices is that they obviate the requirement of a flyback diode, thereby reducing the number of parts in a module and reverse recovery associated losses [14].

Because of the lateral structure and relatively higher thermal impedance, the current rating of GaN devices is typically modest and applications in inverters are rare. Parallelization of devices and gate drive can be challenging [14], [15]. Owing to the low capacitances and fast slew rates, GaN devices are prone to overshoots. Integrated GaN technologies have emerged to allow faster operation and suppressing the parasitics [12]. A major drawback of HEMTs is destructive breakdown due to the lack of UIS capability, and therefore, they need to be overdesigned. A voltage derating of 100% is not uncommon for GaN HEMTs [14]. From a reliability point of view, understanding failure mechanisms and devising mitigation solutions are still work in progress. This is where SiC technology has an advantage as reliability has been proven in field applications, high volume and over time. The lateral structure of GaN devices also limits their benefit as the voltage is increased. Therefore, they are not expected to be very attractive for 1200 V node (800 V bus).

As discussed above, WBG technologies have a clear advantage over silicon for all the power electronic applications in xEVs. Hybrid device configurations such as Si IGBTs with GaN HEMTs [16] or SiC Schottky diodes [17], are also being explored for reducing the cost and achieving higher efficiency while evading the limitations of individual technologies. It is expected that for 800 V bus SiC MOSFETs would be the dominant devices, but for 400 V bus, GaN HEMTs could be preferred in low- to mid-power applications. The use of Si IGBTs and MOSFETs is expected to decline but may hold for longer time due to the very low cost and streamlined supply chain. As for the choice between GaN and SiC, the 650 V node applications area is a battle ground (OBC chargers) but GaN shines best in mid- to low voltage range (48 V to 650 V). Automotive customers tend to prefer SiC technology over GaN because of its maturity and manufacturing experience. The reliability issues for GaN such as dynamic $R_{DS(on)}$, low headroom for voltage spikes, no UIS and poor short-circuit withstand capability are the factors that are still being resolved. Table I compares the GaN and SiC technologies.

CONCLUSION

In this paper, we have discussed the choices of power semiconductors for automotive subsystem applications. While WBG technologies have a clear advantage over silicon for all the power electronic applications in xEVs, silicon IGBTs and MOSFETs still have a place depending on the application. The choice of a type of power semiconductor comes down to performance and cost savings at a system level. For 800 V bus SiC MOSFETs would be the dominant devices, but for 400 V bus, GaN HEMTs could find their place in many applications.

TABLE I

Comparison of key characteristics of GaN and SiC technologies.

	GaN	SiC
Substrate+epi	GaN on Si epi, complex	SiC single crystal, slow growth rate
Wafer cost (substrate+epi)	0.8-0.9x	1x
Vertical structure	No, lateral HEMTs	Yes
$R_{DS(on)}$×A FOM	Excellent	Good
Normalized switching loss	Excellent	Good
High-temperature capability	Good	Excellent
Power density	Good	Excellent
Avalanche capability	No	Yes
Short-circuit capability	Poor	Good
Voltage node sweet spot	48 V to 650 V	1200 V and above
Reliability	Good for industrial, automotive not yet	High, proven in high volume
Paralleling of devices	Challenging	Relatively straightforward
Gate drive	Needs special gate driver design	Similar to IGBT gate drivers
Process maturity	Emerging technology	Mature, 10-year advantage over GaN

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