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Wide Band Gap Materials: Revolution in Automotive Power Electronics

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ABSTRACT: The number of Electric and Hybrid vehicles on the roads is increasing year over year. The role of power electronics is of paramount importance to improve their efficiency, keeping lighter and smaller systems. In this paper, the authors will specifically cover the use of Wide Band Gap (WBG) materials in Electric and Hybrid vehicles. It will be shown how SiC MOSFETs bring significant benefits compared to standard IGBTs silicon technology, in both efficiency and form factor. Comparison of the main electrical characteristics, between SiC-based and IGBT module, were simulated and validated by experimental tests in a real automotive environment.

KEY WORDS: SiC, Wide Band Gap, IGBT, Power Module

1. INTRODUCTION

Nowadays, an increased efficiency demand is required in power electronics applications to have lighter and smaller systems and to improve the range of new Electric (EV) and Hybrid vehicles (HEV). There is an on-going revolution in the electronics of these cars, considering a) new voltage classes never seen before (up to 1,200 Volts), b) power of hundreds of Kilowatts, c) high temperature environment and huge thermal power cycling stresses, d) mechatronics integration and complexity requiring new cooling techniques, e) new functional safety boundaries, not really covered by previous mission profiles and, on top of all, f) the necessity to keep it within an affordable cost.

The power semiconductor represents a central challenge for EV & HEV applications, to address the mentioned points a) to f), because they must be optimized to increase power handlings, switching frequencies, efficiency, and, in the same time, keep power losses, size ,weight as low as possible, and always with an optimized overall system cost. Fig. 1 graphically shows the power semiconductor challenges for EV and HEV.

When considering power transistors in the high voltage range (above 600V), SiC MOSFETs are an excellent alternative to the standard silicon devices: they guarantee lower RON*Area values compared to the latest silicon-based Super-Junction MOSFETs, especially in high temperature environment (1). Additionally, SiC devices replace also the latest cutting edge technology for IGBTs, because of reduced switching losses and/or higher operating point (2). This allows very significant reduction of bulky and expensive inductances, making final systems lighter and less expensive. Furthermore, when considering three phase bridge topologies largely utilized in inverters for Hybrid and Electric Vehicle, SiC MOSFETs allow great advantages in terms of efficiency thanks to the excellent performances of its intrinsic body diode and low power losses at high temperature, up to 200°C, allowing significant reduction of power electronics and cooling mechanism. All these advantages bring, at the end, an improvement of the battery range of modern electric vehicles.

The purpose of this work is to highlight and verify, by a simulation and experiments, the higher SiC MOSFET performances. For this reason, STMicroelectronics has designed a specific SiC high power module and compared with a correspondent IGBT-based module. After, an experimental test has been carried out on a boost converter.

This paper is structured as follows: after the Introduction, the Section 2 describes the Wide Band Gap characteristics. Section 3 introduces some information of the SiC technology presence in the market. Section 4 is dedicated to the Material and Methods, together with the Simulation results of the 60kW module; the Section 5 follows, with the experimental results on the boost converter. Finally, the Conclusions summarize the paper, with considerations on future works.

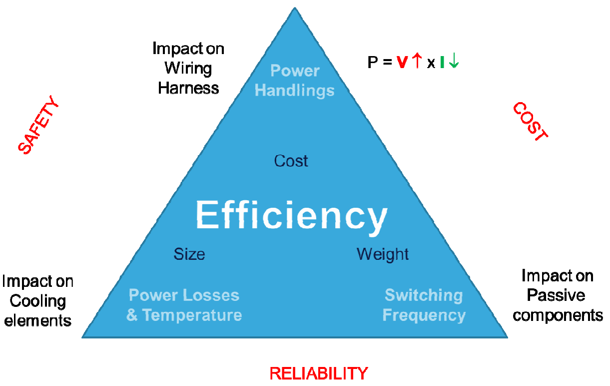

Fig. 1 Power semiconductor challenges for EV and HEV

2. WIDE BAND GAP CHARACTERISTICS

Table 1 compares the main intrinsic characterisics of the WBG, in this case GaN and 4H-SiC, and Si materials.

The first line shows that the band gap of WBG materials is around three times the one of Si materials: a wider band gap is responsible of keeping the main device parameters less dependent on the temperature and withstanding higher breakdown voltages. The second line represents the electron saturation velocity and it is related, on the final component, to the switching performance: higher is this parameter, higher is the maximum switching frequency and consequently smaller are the switching losses. It is immediate to notice that GaN material presents the higher value of electron saturation velocity, and this is the reason why it is widely used in applications where the switching frequency can reach, for example, few MHz, such as audio amplifiers and miniaturized Switching Mode Power Suppliers (SMPS). A higher Ec allows for higher breakdown voltages without compromising on-resistance, explaining why SiC devices are suitable, for example, in applications like rail traction or smart power grid (Fig. 2). When accounting for better thermal conductivity k, WBG power switches allow much higher temperatures to be reached in a saferer manner than silicon semiconductors.

The resulting WBG semiconductor power devices are thinner than their Si-based counterparts with smaller drift region resistances.

Table 1 Comparison between Si and WBG Materials

	Si	*GaN*	*4H-SiC*
E_g [eV] – Band gap	1.1	3.4	3.3
V_s [cm/s] – Electron saturation velocity	1×10^7	2.2×10^7	2×10^7
ε_r – dielectric constant	11.8	10	9.7
E_c [V/cm] – critical electric field	3×10^5	2.2×10^6	3×10^6
k [W/cm K] – thermal conductivity	1.5	1.7	5

It can be summarized that, thanks to higher critical electric field, better thermal conductivity and dielectric constant, SiC will provide low on-resistance, low leakage current even at higher temperatures and overall improved performance at high temperature environment. With reduced electron saturation velocity, GaN materials allow higher frequency operation, making both technologies co-exist for different market segments.

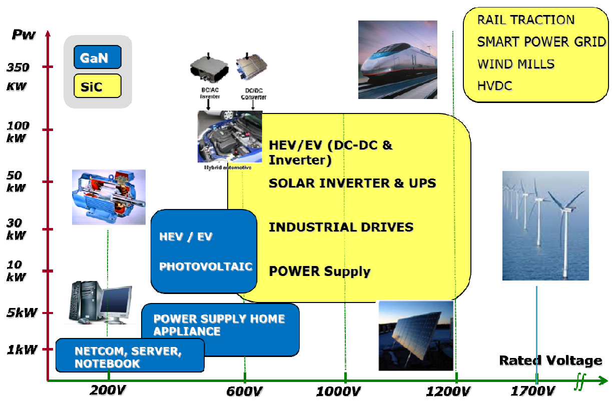

Fig. 2 SiC and GaN market positioning

3. STMICROELECTRONICS SiC COMPONENTS AND THEIR PRESENCE IN THE MARKET

For many years ST has been a worldwide leader in high voltage power devices dedicated to energy conversion. During the last decade, electronic systems have followed a continuous trend towards higher power density and more energy savings driven by governments' environmental awareness. Power supply designers are permanently confronted with efficiency regulations, such as Energy Star, 80Plus, European Efficiency, and so on. The designers are forced to consider the use of new power converter topologies and more efficient electronic components such as high-voltage silicon-carbide (SiC) Schottky rectifiers and transistors. Actually, for the reasons explained in the Session 2, Wide Band Gap (WBG) devices offer some advantages over silicon in the voltage range of 600V, up to 1700V, representing a solution to the quest for increased power density, safer thermal operation, better efficiency and reduced system form factor (1). For example, in hard-switching applications such as high end server and telecom power supplies, materials such as SiC and GaN show significant power losses reduction and are commonly used. A growing use of those materials is also recorded in solar inverters, motor drives, UPS and EV applications. In particular, in the automotive ecosystem, WBG materials can significantly help reducing fuel consumption, mitigating cooling requirements and minimizing environment impact.

To assist the designers facing the mentioned challenges, since 2008, ST has been developing 600V SiC diodes. In 2013, to further help designers in their quest for more current density and helping them to reduce cost, STMicroelectronics developed a second generation of SiC Schottky rectifiers. The design of these new diodes provides increased robustness while not impacting their performance and blocks the effect of the positive thermal coefficient of the silicon carbide material; furthermore, the peak reverse voltage was increased to 650 V in order to ensure a safer operation in certain designs (3). Lastly, in 2014 ST released its first 1200V SiC MOSFET, the only in the market to reach the junction temperature of 200 degC, thanks to a new proprietary package HiP247TM. This easy-to-drive device can operate at several times the switching frequency of similar-rated IGBTs and results in more compact, reliable and efficient designs in applications such as solar inverters, high-voltage power supplies and high-efficiency drives.

To complete the ecosystem of WBG portfolio, STMicroelectronics released, in 2015, a dedicated isolated driver for SiC MOSFET, GAPDRIVE1S, with positive gate driver capability up to 36V, an extended negative driver capability down to -10V, together with a 1500V of voltage rail (4).

4. 60kW MODULE FOR AUTOMOTIVE

In a previous paper, STMicroelectronics introduced the exercise done in simulating a 60kW inverter for driving an electric motor present in an electric vehicle, comparing the results using a full SiC module and a full IGBT module (5). The simulated inverter includes a three phase bridge, where each switch is implemented by SiC MOSFETs or IGBTs in parallel without freewheeling diodes, a gate resistor of 4.7 Ω for each SiC MOSFET (to compensate the possible gate voltage thresholds' mismatches) and six 1200V diodes to implement the desaturation protection for the inverter.

We have simulated, using Matlab, operative conditions as follows: switching frequency = 20 KHz, sinusoidal modulation with carrier frequency = 400 Hz, PF = 0.8, peak current = 250 A and a bus voltage Vdc = 900 V.

To be more specific, the IGBT module consists of Trench Field-stop IGBT switch with 2 devices in parallel, each one rated at 1,200V, 140A, while the SiC module is composed by 8 SiC MOSFETs rated at 1,200V, 30A each.

The selected SiC MOSFET from STMicroelectronics, has the following main characteristics: BV > 1,200 V; In = 45 A @ 25 °C; Ron 80 mΩ typical; Qg(typ) < 105nC; Gate Driving Voltage = +20/-5 V.

The simulation results based on comparison of SiC MOSFETs versus the state-of-the-art Trench Field-stop IGBTs are reported on the Table 2.

Table 2 Comparison between IGBT and SiC solutions

	Si-IGBT solution	*Full SiC solution*
Total chip area per switch [mm^2]	300	168
Conduction losses [W]	125	55
Turn-on losses [W]	280	90
Turn-off losses [W]	246	40
Body diode conduction losses [W]	NA	12.3
Diode conduction losses [W]	5	NA
Diode Q_{rr} losses [W]	260	5.3
Total losses [W]	**916**	**203**

The simulation of the SiC module results in power losses reduction about 75% compared to IGBT, with final module dimensions of the full SiC module of 100 mm x 170 mm x 14 mm, which is smaller by a factor 25% compared with an IGBT-based module. Further optimization can be made possible thanks to larger die size limiting paralleling, integration of Rg into SiC MOSFET structure and optimized module structure.

5. 4kW BOOST CONVERTER

This session reports the performance comparison test between SiC MOSFET and Si IGBT on a 4kW DC/DC boost converter. In particular, the goal is to demonstrate that a solution based on SiC can achieve the same electrical performance of the solutions based on IGBT, with a switching frequency of 4 times higher, thus reducing the cost of the overall system.

Fig. 3 4kW DC/DC boost converter developed in our laboratory

Fig.3 shows the picture of the 4kW board used for this experiment (5). For the purpose of the performance comparison test, two DC/DC Converters with output power up to 4 kW have been used. The first board has been modified and tuned for the IGBT as main switch, while the second for the SiC MOSFET. Both boards are equipped with 1200 V SiC boost diodes. The main features of the proposed boost converter are: input voltage Vinmin=400 V and Vinmax=600 V; output voltage Vout=800 V; maximum power Pmax=4 kW. The board has also over temperature, inrush, under voltage input protections.

The simplified block diagram is showed in Fig. 4.

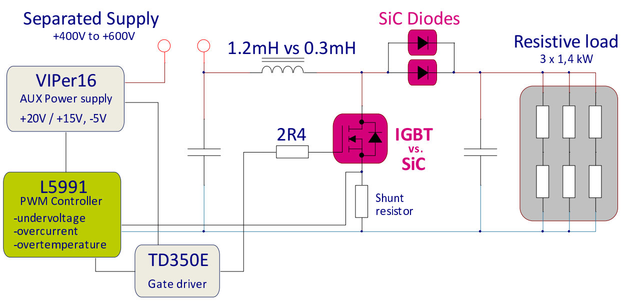

Fig. 4 4kW DC/DC boost converter developed in our laboratory

Table 3 shows the components and settings of the boards with the different transistors. It is possible to notice that we have used two boost inductors to optimize the switching frequencies.

Both the DC/DC converters have been tested with 3 different loads: 1.3 kW, 2.6 kW and 4 kW. Three temperatures - ambient temperature, heat-sink temperature and transistor case temperature) – have been measured by thermocouples with FLUKE 189, while the input/output voltage and input/output power by the power analyzer LEM NORMA 4000. All the measurements have been performed in steady-state after 45 minutes from the power-on.

The results are summarized in Fig. 5.

Table 3 Component and settings of the 4kW DC/DC boards

	IGBT	*SiC MOSFET*
Transistor type	STGW25H120DF2 1200V, 25A, V_{CESAT}= 2.1 V	SCT30N120 1200 V, 45 A, R_{DSON}=90 mΩ
AUX power supply (gate voltages) [V]	+15V, -5V	+20V, -5V
Gate resistance [Ω]	2.4	2.4
Switching frequency [kHz]	25	100
Power inductor	1.2 mH / 25 kHz	0.3 mH / 100 kHz

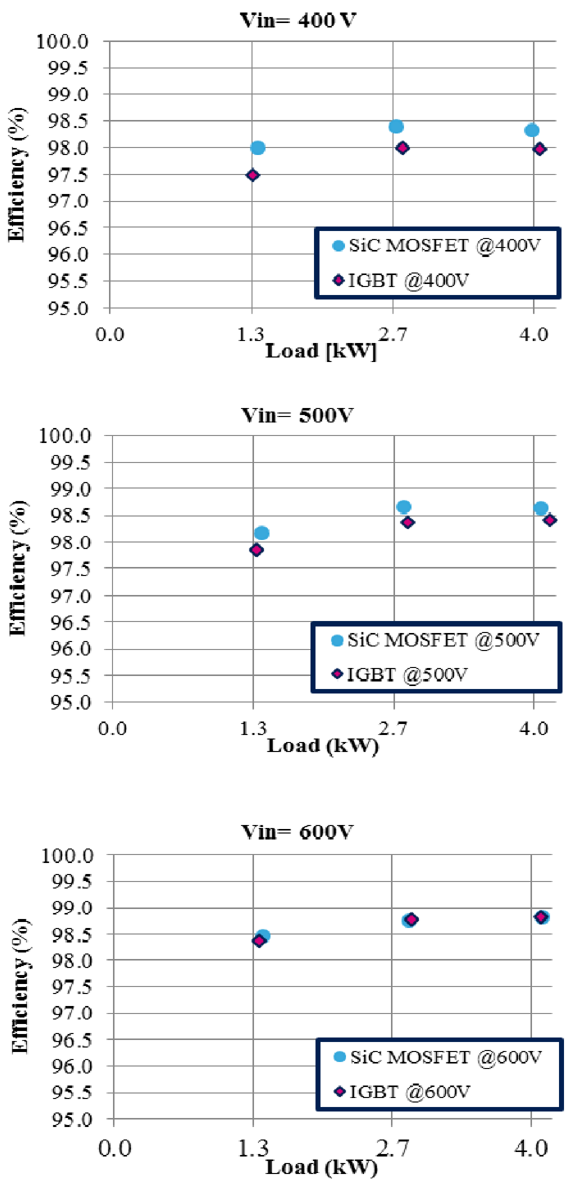

Fig. 5 Efficiency vs. load for input voltages Vin= 400 V, 500 V, 600 V

The results clearly show that the DC/DC converters with SiC switching at 100kHz and IGBT switching at 25kHz have the same performance of efficiency. In (6) it was demonstrated that the cost of the boost inductor and heat-sink can be actually reduced with SiC solution, bringing at the conclusion that SiC MOSFET has to be preferred over an IGBT based solution whenever the highest possible efficiency with lower cost have to be achieved.

3. CONCLUSIONS

In this papers, the authors showed different advantages of the usage of SiC devices compared with the standard Si technology. In particular, it was presented a simulation of a 60kW inverter and a real set of measurements of a 4kW DC/DC converter. Both the topologies are very common in electric cars applications, respectively for the traction and for the on board charger. It is interesting to notice that the WBG materials do not bring only a terrific advantage in term of efficiency and temperature performance, but also in term of costs. Future analysis will include the investigation of limitations of very high frequencies in those topologies, in addition to simulations and test verifications on different promising topologies in automotive, like bridgeless power factor correctors or bidirectional DC/DC converter for battery charger.

REFERENCES

(1) Fei Shang “A comprehensive evaluation of SiC devices in traction applications”, Proceedings of IEEE Transportation Electrification Conference and Expo (ITEC), pp. 1-5 (2014)

(2) L. Abbatelli, M. Macauda, G. Catalisano, A. Boscarato and D. Kohout “Cost Benefit on High Frequency Converter System based on SiC MOSFET approach”, Proceedings of PCIM Europe 2014; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, 1 - 5 (2014).

(3) STMicroelectronics, “New generation of 650V SiC diodes”, AN4242, (2013).

(4) STMicroelectronics, “How to fine tune your SiC MOSFET gate driver to minimize losses”, AN4671, (2015).

(5) Filippo Di Giovanni “Wide Bandgap Semiconductors: A New Approach to Automotive Power Electronics”, Technical Paper SIA edition, (2013)

(6) L. Abbatelli, M. Macauda and G. Catalisano, “Fully SiC based High Efficiency Boost Converter”, Applied Power Electronics Conference and Exposition (APEC), 2014 Twenty-Ninth Annual IEEE, 1835 - 1837 (2014).