Performance Evaluation of Wide Bandgap Semiconductor Technologies in Automotive Applications

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***Abstract*—This paper evaluates the commercially available semiconductor switch technologies for automotive applications. For this purpose, conventional Silicon (Si) Insulated Gate Bipolar Transistor (IGBT) is compared with wide bandgap Gallium Nitride (GaN) and Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET). Various design aspects of commercially available wide bandgap switches are introduced. Afterwards, experimental efficiency measurements for SRM drive systems using different semiconductor technologies are performed. Methods to improve performance of the automotive drive system are introduced.**

I. Introduction

In order to cope with the increasing demand for more efficient and compact Hybrid Electric Vehicles (HEV), integration of wide bandgap semiconductor technologies in automotive drive system is of interest. Low switching and conduction losses of these semiconductor technologies result in higher efficiencies for the motor drive system. Moreover, due to the lower losses, smaller cooling systems are required.

Preliminary comparisons between the wide bandgap technologies and Si-IGBTs suggest an order of magnitude reduction in the semiconductor power losses in single switch converters [1]. SiC and GaN technologies can provide low On-state resistances at higher break-down voltages compared to similar Si switches. Therefore, unlike conventional Si technology that migrates to IGBTs in high voltage applications, FETs are ideal solution for wide bandgap converters. This will in turn lead to lower switching losses and higher efficiencies.

Recent developments in semiconductor technologies has resulted in low cost GaN on Si High Electron Mobility Transistors (HEMT) [2]. Compatible manufacturing process has enabled GaN on Si to commercially compete with conventional Si transistors. Moreover, this technology has the lowest On-resistance (i.e. $R_{ds_{on}}$) among the power switches [3]–[6]. For this reason, GaN HEMTs will not only reduce the power losses, but also relax the requirements for the cooling system. Therefore, wide bandgap technologies will result in low cost automotive drive systems with minimal real estate requirements.

On the other hand, traction drive systems capable of operating reliably at high-temperature environments are demanded by the automotive industry. In these vehicles, the temperature of the coolant can increase to $105°\mathrm{C}$. Therefore, semiconductor technologies that can operate reliably under this condition are of interest. It has been shown that SiC-JFETs are capable of operating at temperatures up to $400°\mathrm{C}$ [7]. Hence, wide bandgap technologies can provide solutions for converters operating in harsh environments.

Recent studies show that Double Stator Switched Reluctance Machines (DSSRM) provide higher power densities compared to the conventional Switched Reluctance Machines (SRM) [8]. Therefore, these machines can be the driving force for the new generation of HEVs.

This article presents an experimental study of the application of wide bandgap semiconductor technologies mainly in DSSRM traction systems. For this purpose, fundamental design considerations using wide bandgap technologies will be introduced. Afterwards, a comparative study between three semiconductor technologies will be experimentally performed.

II. Comparative Study Between Wide Bandgap Technologies

Recent advancements in semiconductor technology have led to commercially available SiC and GaN switches. SiC technology has a high cost of manufacturing. For this reason, economic considerations do not allow for integration of SiC MOSFETs in HEVs unless the required characteristics cannot be delivered with GaN switches. One of these characteristics is operation at very high temperatures. Although SiC MOSFETs are not capable of operating at high temperatures due to intrinsic characteristics of their oxide interface, SiC JFETs has been successfully tested at $400°\mathrm{C}$ [7].

SiC MOSFETs are commercially available in medium voltage levels (i.e. > 1200 V). Therefore, high frequency switching at high voltages with low conduction losses is provided with this technology. In the near future, high voltage SiC switches will introduce applications of wide bandgap technologies to marine and submarine traction systems.

On the other hand, GaN on Si has low cost of manufacturing due to its compatibility with conventional Si fabrication equipment. Moreover, GaN on Si transistors have better switching

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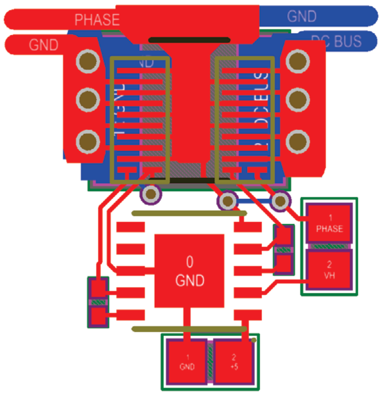

Fig. 1. Single sided inverter leg PCB using LGA packaging.

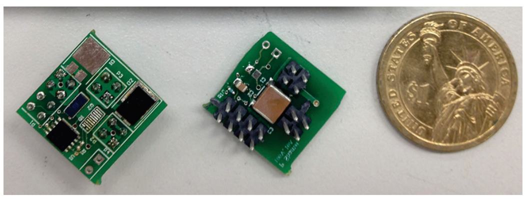

Fig. 2. Single sided asymmetric bridge with eGaN switches.

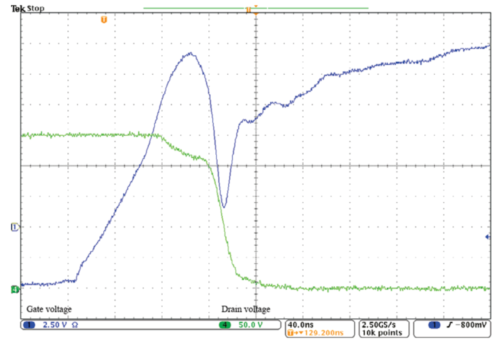

Fig. 3. Faulty turn-on due to large gate resistance.

performances in comparison with SiC MOSFETs. GaN on SiC switches are capable of operating at Extremely High Frequencies (EHF). However, the price of this technology is extremely higher than GaN on Si. Therefore, GaN on Si is an ideal choice for switching applications. Commercial GaN switches are available up to 600 V and experimental switches up to 900 V have been reported [9]. Therefore, SiC MOSFETs are the only available wide bandgap options at higher voltages ($>$ 1200V).

Commercial GaN switches are mostly available in cascode and enhancement-mode FET configurations. Cascode configuration utilizes a GaN JFET cascaded with a Si MOSFET. GaN switch will tolerate the drain-source voltage while the Si MSOFET provides turn-off functionality at zero gate voltage. The gate resistance of cascode switches cannot be tuned to control Electro-Magnetic Interferences (EMI). Enhancement-mode GaNs (eGaN) are similar to conventional enhancement Si MOSFETs. Moreover, eGaNs demonstrate better performances compared to cascode GaNs.

A. Packaging

Available SiC MOSFETs use conventional Transistor Packages (TO). In order to minimize over-voltages due to parasitic inductances of the lead wires, eGaN FETs are introduced in Line Grid Array (LGA) packages. LGA packages can be integrated in an optimal dc bus structure for minimum stray inductances. An example of an optimal dc bus structure for an inverter leg is shown in Fig. 1. Using this structure, asymmetric bridges have been designed for experimental analysis. The developed circuit is shown in Figure 2.

B. Gate Driver

The required on-state voltage for commercially available SiC MOSFETs is 20 V. For this reason, modifications to conventional gate drive systems are required for proper operation of these switches. On the other hand, eGaN switches require 5 V as the recommended on-state gate voltage. Moreover, due to their fast switching times (i.e. $<$ 10 ns), conventional gate drivers cannot provide sufficient charge and discharge slew rates for maximum eGaN speed utilization. On the other hand, majority of the optocoupler-based gate drivers are not optimized for operation at high speeds. Therefore, non-isolated gate drivers are used for driving eGaN switches at high speeds. Moreover, turn-on and turn-off currents on these switches are not equal. A turn-off current sink of 5 A is recommended for short fall-time of the drain current.

Due to very short rise and fall times of wide bandgap semiconductor switches, the value of the gate resistance plays a significant role in switching losses. Large gate resistances can lead to high gate voltage ripples due to current of the miller capacitor (i.e. C_{gd}). Fig. 3 illustrates an example of gate voltage drop due to the capacitive current from the gate to drain through C_{gd} during turn-on process of a SiC MOSFET.

C. Reverse Conduction

SiC MOSFETs are integrated with a low speed reverse diode. The forward voltage of this diode is designed to be close to 3.5 V. Hence a schottky diode can be paralleled with the switch to prevent reverse recovery losses on the internal diode. Fast or schottky diodes using GaN technologies are not commercially available. eGaN switches do not have an integrated diode. However, if a reverse voltage is applied to the switch, source-drain conduction provides the required freewheeling operation. For this purpose, the voltage of the drain has to reach the threshold voltage of the gate-drain ($\sim$2.5 V). Therefore, during the reverse conduction, a voltage drop equivalent to the threshold voltage is observed across the switch. It should be noted that if the turn-off voltage of the switch is below zero (i.e. $V_{gs} < 0$), the reverse conduction voltage will increase accordingly.

In order to minimize the reverse conduction losses in an eGaN switch, synchronous control of the gates can be imple-

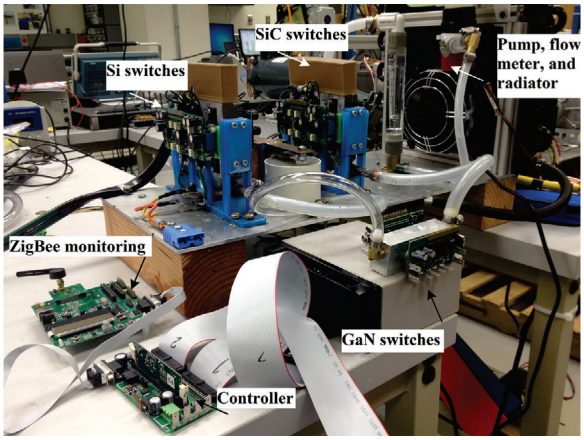

Fig. 4. Water cooled SRM drive systems.

TABLE I
EXPERIMENTAL EFFICIENCY MEASUREMENTS.

Technology	Coolant temperature rise	Efficiency
Si-IGBT	0.5°C	95%
SiC-MOSFET	0.3°C	97%
e-GaN FET	0.1°C	99%

mented. For this purpose, if a reverse conduction is required, the gate can be turned on to allow a minimum voltage drop across the switch. This procedure is experimentally studied in the following section.

III. Automotive Drive Systems Using Wide Bandgap Technologies

In order to experimentally measure performance criteria for various switch technologies, shared switch and SBSC SRM drive systems have been designed and developed [10]. The test setup is illustrated in Fig. 4. The developed drive system has a 4 kW converter using Si technology, a 4 kW converter using SiC technology, and a 1.5 kW converter using enhancement-mode GaN FETs. Moreover, each converter is water cooled. Therefore, an accurate experimental measurement of the power losses for each converter can be performed. Temperature sensors measure the temperature of the input and output water to each converter. Moreover, a water pump regulates the flow of water. Therefore, the thermal energy absorbed by the coolant can be estimated.

A. *Efficiency Measurements*

The eGaN based converter in Fig. 4 has low voltage switches (<100 V). The maximum voltage of the converter is restricted by availability of the commercial switches. Therefore, in order to have a comparative study, a SRM has been tested at low speed operation. The total mechanical power delivered by the SRM in this test is set to 150 W at a regulated speed. Moreover, the water flow is regulated at 0.1 GPM. The results from this test are shown in Table I. It can be observed that GaN technology has the highest efficiency. This is due to the very low switching losses, low conduction losses, and non-existent reverse recovery losses. It should be noted that high efficiency schottky diodes have not been paralleled with SiC MOSFETs. Hence, the efficiency of the SiC based converter can further be improved. However, the purpose of this paper is to study the best technology for automotive applications. GaN has the highest efficiency, lowest real estate requirements, and is available at low costs. Therefore, this technology presents the ideal solution for automotive applications.

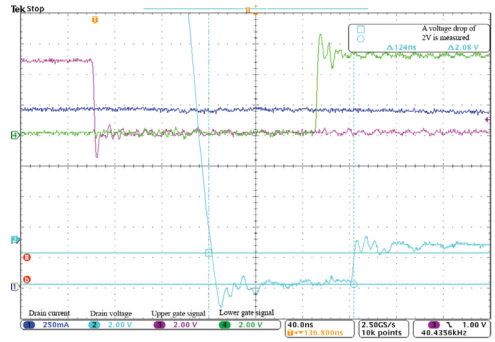

Fig. 5. Turn off signals for a GaN inverter leg.

It has been shown that a single wide bandgap semiconductor switch has an order of magnitude lower losses compared to Si technology [1]. However, the results from Table I illustrate close to 3 to 5 times reduction in the power losses. This is due to increased losses in an inverter application. In a drive system, semiconductor switches often conduct in reverse direction. Therefore, losses due to the reverse conduction voltage drop and reverse recovery charger (in case of SiC) reduce the overall efficiency. In order to mitigate this problem, further improvements can be suggested.

B. *Improved Reverse Conduction*

In order to improve the efficiency of GaN converters, active reverse conduction can be integrated in the control strategy. For this purpose, asymmetric bridges are replaced with full inverter legs. Furthermore, active reverse conduction is enforced. This procedure is shown in Fig. 5. It can be observed that reverse conduction leads to a voltage drop equivalent to the threshold voltage of the switch across the source-drain. Therefore, activating the lower switch after a safe dead-time will eliminate the voltage drop across the switch. Hence, the overall efficiency of the system will improve. This voltage drop is illustrated in Fig. 5 and is close to 2 V.

C. *Electro-Magnetic Interferences and Noise*

Very small switching times lead to high frequency content on voltage and current signals. These high frequency harmonics can lead to EMI, common mode, and differential mode noise. These interferences can affect the gate signals as well as the analog signals used for measurements. For this reason, proper filtering and component placement is essential while utilizing wide bandgap technologies. Fig. 6 illustrates the interferences measured from the analog feedback signal of the phase current. The amplitude of the analog signal is

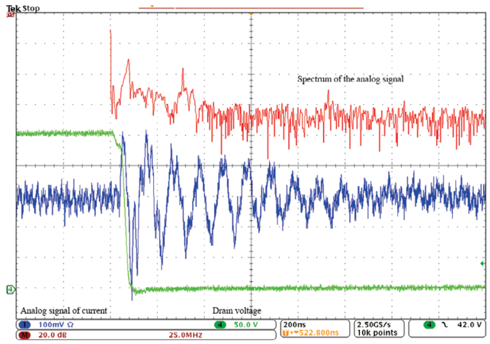

Fig. 6. Induced interferences on the analog current measurement signal.

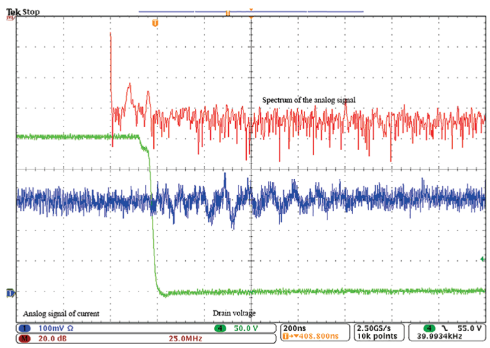

Fig. 7. Filtering the induced interferences on the analog current measurement signal.

very small due to the input-port requirements of analog-to-digital converters. Therefore, slight interferences induced by the switching function lead to wrong signal measurements. Due to added ground loops and common mode capacitance of the oscilloscopes and probes, accurate measurement of these interferences is very challenging. Fig. 6 presents an example of induced voltages on an analog signal.

In order to reduce this effect, low-pass analog filters can be utilized. It should be noted that if the pass-band of the filter is closed to the control band-width, the added phase shift by the filter can result in instabilities and overshoots. It can be observed that the induced voltages in Fig. 6 are at much higher frequencies than the control band-width. Hence, using RC filters at the analog inputs of the controller can reduce the amplitude of the induced noise. Fig. 7 illustrates the filtered analog signal.

IV. Conclusion

Experimental performance measurements for various semiconductor technologies were presented in this paper. Preliminary introduction of different design aspects using wide bandgap technologies were introduced. Afterwards, experimental efficiency measurements were illustrated. Further performance improvement methods were introduced. The conclusion of this research suggests that GaN semiconductor technology is an ideal solution for automotive drive systems.

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