Silicon carbide power device characteristics, applications and challenges: an overview

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ABSTRACT
Silicon (Si) based power devices have been employed in most high power applications since decades ago. However, nowadays, most major applications demand higher efficiency and power density due to various reasons. The previously well-known Si devices, unfortunately, have reached their performance limitation to cover all those requirements. Therefore, Silicon Carbide (SiC) with its unique and astonishing characteristic has gained huge attention, particularly in the power electronics field. Comparing both, SiC presents a remarkable ability to enhance overall system performance and the transition from Si to SiC is crucial. With regard to its importance, this paper provides an overview of the characteristics, advantages, and outstanding capabilities in various application for SiC devices. Furthermore, it is also important to disclose the system design challenges, which are discussed at the end of the paper.

Keywords:
Silicon carbide power device
Silicon power device
Power device material

1. INTRODUCTION
In recent decades, power electronics have gained high interest due to new materials invented for the new power devices. Ever since the silicon (Si) based device was created, the innovation in power device materials has been evolved to meet the application requirement and performance needs in various fields[1]. Up till now, the advancement is predominantly driven by the Si power devices such as an insulated-gate bipolar transistor (IGBT) for high voltage, high power, and low-frequency application, and power metal-oxide-field-effect transistor (MOSFET) which are particularly targeted for low voltage, low power, and high-frequency application. While MOSFET which is based on the trench gate structure dominates the global market for applications below 600 V, its super junction version (SJ-MOSFET) and IGBT based on field stop and injection enhancement concept have secured the market shares for application in the range from 600 V to 6.5 kV. Even with these advancements, the Si power device has reached its performance limitation. To date, the most high-end Si IGBT breakdown voltage capability is only 6.5 kV with limited switching performance. Furthermore, there is no Si device could operate above 200°C[2].

Owning these restrictions, power converter efficiency is reduced severely which leads to the needs of a complex cooling system and expensive passive components. As a result, an upgraded material power

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device is expected. The exploration of the solution to the silicon limitation leads to the investigation of a wide bandgap (WBG) semiconductor materials. The advancement in WBG semiconductor material has made it possible to improve the efficiency of electric energy transformation. Having a trade-off between process/manufacturing maturity, theoretical characteristics, and commercial marketability, Silicon Carbide (SiC) and Gallium Nitride (GaN) are becoming perfect semiconductor material candidates for the next generation of power devices. Despite offering decent high-frequency and high-voltage performance, GaN comes with inferior thermal conductivity and a lack of good-quality bulk substrates required for vertical devices. Consequently, it makes SiC become a better option for power device material [3], [4]. Nevertheless, GaN-based power devices are still being used and play a major role in other specific applications.

Therefore, due to the interesting features of the SiC power device, this paper presents an overview of the SiC power device and its contribution to the improvement in the state-of-the-art selected applications. SiC properties and their characteristics are presented in section 2. Adaptation in applications and their contribution to enhancing the overall system performance is discussed and summarized in section 3. In addition, the system design challenges of SiC are summarized in section 4.

2. THE CHARACTERISTICS

Recent trend discloses that Silicon Carbide (SiC) based power device has established its popularity among power electronics practitioners in modern applications. Since Infineon introduced SiC Schottky diode back in 2001, the SiC-based power device has kept its momentum in technology development and market growth as projected by [3] depicted in Figure 1. This is due to the fact that the properties and characteristics are well suited to solve innumerable power electronics-related problems and performance demands. From the application perspectives, the most advantageous features of SiC, compared to Si are the breakdown field, its higher conductivity, and its wide bandgaps as tabulated in Table 1.

In principle, the SiC scored a breakdown field ten times higher compared to what Si has. Therefore, the thinner drift layer and higher doping concentration can be used on the SiC power devices at the same blocking voltage. As depicted in Figure 2, SiC power devices such as Unipolar Schottky diodes and MOSFET would have lower specific on-resistance compared to Si counterpart by having thinner blocking layer and higher doping concentration [5]. As a WBG material, it offers other incredible material properties that are attractive to power device design and development. WBG semiconductor material such as SiC, in particular, has advantages of operating in higher temperatures and greater radiation hardening. Theoretically, the thermal energy of the electron valance band is directly proportional to the temperature. As such, it has enough energy to propagate to the conduction band at a certain temperature. But, this uncontrolled conduction event must be avoided. For Si-based material, this could occur around 150°C [6], [7]. In contrast, bandgap energy is higher in WBG semiconductor material, as such, more thermal energy is required by the valence electron to travel to the conduction band. Remarkably, for SiC this intrinsic temperature is about 900°C. The aforementioned argument is also valid for radiation hardening. Radiation energy likewise can stimulate an electron like the thermal energy and make it travel to the conduction band. Consequently, devices developed based on WBG material such as SiC can endure more in extreme heat and radiation without sacrificing its delightful characteristic [11].
In principle, as the drift velocity of the semiconductor increases, the switching frequency capability is also increased. The drift velocities of SiC semiconductor material are more than twice the velocity of Si as shown in Table 1. Higher drift velocity permits the minority carriers to be removed faster from the depletion region at the moment of turn-off transient. As such the SiC’s switching speed is faster due to the higher electron saturated drift velocity. Additionally, the increased switching frequency is also contributed by the lower on-resistance at the same breakdown voltage of the SiC semiconductor material. The junction capacitance of the SiC devices e.g. MOSFET is lower than the Si devices, taking into account trade-offs between thinner drift regions and smaller dice size [12]. Furthermore, numbers of Coss and Qg of SiC material are lower compared to in the Si, which makes SiC device able to switch at much higher dv/dt. Figure 3 depicts high-frequency switching produced by SiC MOSFET compared to Si IGBT, which offers low switching loss and thus enhancing the converter power density and efficiency [13].

3. SiC APPLICATIONS

3.1. Electric vehicle/hybrid electric vehicle

At the beginning of 2013, the electric vehicle (EV) market shares cover 0.02% of the total passenger car segment [14]. However, it is projected that there will be over 600 million cars will be on the road due to strong policies worldwide, and by 2030, it is estimated that passenger EV will secure 50% of market shares [15], [16]. 32% reduction in size and 40% of reduction in weight and loss of the EV electronics circuit is expected as per an announcement made by The EV Everywhere Challenge in 2013. This will be only possible with the deployment of SiC devices in the circuit design [17]. Numerous research and development activities have been conducted globally. For instance, in Japan, Denso Corporation has developed 100A SiC-MOSFET with the SiC-Schottky Barrier Diode (SiC- SBD) inverter module back in 2007. Later in 2008, NISSAN has introduced to the market an inverter with SiC diode for fuel cell vehicle (FCV). ROHM in collaboration with Honda also developed a 1200V 230A high power inverter module. SiC-SBD and SiC-MOSFET have been adopted by them in the design with an integrated three-phase inverter and one phase converter module. As a result, a 25% reduction of switching loss can be offered compared to the Si version [18]. A year after that, Mitsubishi Electric has introduced 11kW inverter. The inverter module comes with SiC-MOSFET and SiC-SBD on-board and produces 70% and 75% loss and volume reduction, respectively [19]. The race of research and development of SiC power devices for EV application continues as demand increases, not only by introducing new devices but also in improving the quality and reliability of existing technology. This is true when Toyota Corporation has put SiC power technology into trial on its hybrid Camry and fuel cell bus in 2015 [20]. Figure 4 shows the SiC power control unit developed by Toyota. Table 2 summarizes the research and development of SiC based power device and module for EV application.

![Figure 3: Si IGBT versus SiC MOSFET switching waveform](image-url)

### Table 1. Si and SiC properties comparison [9],[10]

| Properties                  | Si | 3H-SiC | 4H-SiC | 6H-SiC |
|-----------------------------|----|--------|--------|--------|
| Energy Gap, eV              | 1.12 | 2.4 | 3.26 | 3.03 |
| Electron Mobility, cm²/Vs   | 1400 | 800    | 900    | 370    |
| Hole Mobility, cm²/Vs       | 600 | 40     | 100    | 90     |
| Breakdown Field, V/cm·10⁶  | 0.3 | 4      | 3      | 3      |
| Thermal Conductivity, W/cm°C| 1.5 | 3.2    | 4.9    | 4.9    |
| Saturation Drift Velocity, cm/s | 1  | 2.5    | 2.7    | 2      |

In principle, as the drift velocity of the semiconductor increases, the switching frequency capability is also increased. The drift velocities of SiC semiconductor material are more than twice the velocity of Si as shown in Table 1. Higher drift velocity permits the minority carriers to be removed faster from the depletion region at the moment of turn-off transient. As such the SiC’s switching speed is faster due to the higher electron saturated drift velocity. Additionally, the increased switching frequency is also contributed by the lower on-resistance at the same breakdown voltage of the SiC semiconductor material. The junction capacitance of the SiC devices e.g. MOSFET is lower than the Si devices, taking into account trade-offs between thinner drift regions and smaller dice size [12]. Furthermore, numbers of Coss and Qg of SiC material are lower compared to in the Si, which makes SiC device able to switch at much higher dv/dt. Figure 3 depicts high-frequency switching produced by SiC MOSFET compared to Si IGBT, which offers low switching loss and thus enhancing the converter power density and efficiency [13].
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remarkably promising, estimated approaching 97% at 20 kHz switching frequency and 4.11 W/inch3, respectively. In 2019, Infineon Technologies has introduced in the market its EVAL-M5-E1B1245N evaluation board which is optimized for motor drive application. Table 3 tabulates a summary of other selected SiC power device contribution in a power drive application.

SiC devices have been deployed, investigated, and analyzed in different inverters by numerous researchers. For instance, a group of researchers in the United States [33],[34] have been working on a solar inverter that based on SiC Schottky diode which demonstrated the improvement of inverter’s efficiency above 96% and reduced reverse recovery losses.

Figure 5: 7.5 kW EVAL-M5-E1B1245N-SiC motor driver [35]

| Commercial or R&D Year | Developer/Researcher | Specification/Performance | Approach |
|------------------------|-----------------------|---------------------------|----------|
| 2007 [36]              | Tiefu Zhao, North Carolina State University | At 10 kHz switching frequency, 68% conduction loss reduction, 78% switching loss reduction loss, 99.1% system efficiency, and 75% heat sink size reduction. | 1200V SiC MOSFET, 1200V/ 20A SiC Schottky diode |
| 2014 [37]              | J. Colmenares et.al, KTH Royal Institute of Technology, Sweden | 99.3% inverter efficiency at 20 kHz switching frequency over the entire load range. | 1200 V/ 168A SiC MOSFET |
| 2015 [38]              | Firus Zare et.al, Danfoss Drives, Denmark | 3% efficiency improvement across wide power range (6-17 kW) compared to Si IGBT and 18.5 kW power at 16 kHz switching frequency | SiC MOSFET and SBD |
| 2016 [39]              | Qin Hahong et.al, Nanjing University of Science and Technology | 50% power loss reduction, system efficiency increased by 1% compared to Si-based system, and heat sink temperature reduction by 3°C | 1200 V/ 24A SiC MOSFET |
| 2016 [40]              | S. Tiwari et.al, Norwegian University of Science and Technology | System efficiency 98.7% at 20kHz switching frequency, and 71% switching losses reduction. | 1200V/ 50A SiC MOSFET |
| 2018 [41]              | A. Kempitita et.al, Infineon Technologies America Corp. | Semiconductor power loss reduction up to 30% | 1200 V SiC MOSFET |
| 2019 [42]              | O. Sivkov et.al, Czech Technical University | Switching slew rate two times higher compared to Si IGBT’s. | 1200 V/ 50A SiC MOSFET |
| 2019 [43]              | J. Loncarski et.al, Upsala University, Sweden | 27% conduction loss reduction at 60 kHz switching frequency and overvoltage peak reduction by 71% | 1200 V SiC MOSFET |

3.3. Solar inverter

With the remarkable performance of the SiC power device, it is the best candidate in the applications where efficiency, power density, cost, and speed are the ultimate concern. One of them is the solar inverter. The capability to reach higher efficiency in the energy conversion process is directly proportional to the cost reduction i.e. reduced solar panel area, simpler circuitry/topology, and even lower installation fee [7], [44]. Furthermore, in the past few years, a group of GE’s researchers and engineers have been working on a single-stage megawatt level solar inverter [45]. The inverter integrates an advanced SiC MOSFET module with an innovative system engineering design. As a result, at 900V dc input, the California
energy commission (CEC) efficiency of the inverter is reaching close to 99%. Figure 6 and Figure 7 illustrate the efficiency of GE SiC megawatt solar inverter and GE’s LV5+ SiC-based solar inverter, respectively. Table 4 summarizes several selected researches works on SiC devices in the emerging solar inverter applications for the past few years.

![Figure 6: Efficiency of GE SiC megawatt solar inverter](image1)

![Figure 7: GE’s LV5+ SiC-based solar inverter](image2)

Table 4: Summary of related research/development of SiC devices in solar inverter applications

| Commercial or R&D Year | Developer/Researcher | Specification/performance | Approach |
|------------------------|----------------------|---------------------------|----------|
| 2014 [47]              | U. Schwarzer et.al, Infineon Technologies AG | 29.7% system power loss reduction for a 2-level inverter with 18% system cost-saving, and 47.9% system power loss reduction for a 3-level inverter with 20% system cost saving. | 1200V/45A SiC JFET, 1200V/60A SiC JFET, 600V SiC Diode |
| 2015 [48]              | K. Fuji et.al, Fuji Electric Co. Ltd | Switching slew rate reduced 10% compared to Si IGBT, current unbalance ratio is less than 7.5% of the nominal output current, and maximum efficiency is 98.08% with the EU average by 0.5% compared to conventional single-stage inverter. | 1200 V/100A SiC MOSFET & SBD |
| 2015 [49]              | A. Hensel et.al, Institute for Solar Energy System, Fraunhofer ISE | Inverter efficiency exceeds 98% at 48 kHz switching frequency | 1200V/55A and 1200V/24A SiC MOSFET |
| 2016 [50]              | A. Hatanaka et.al, Hitachi Ltd | Peak inverter efficiency exceeds 99.1% within a 30-60% load factor. 65% reduction in current deviation compared to Si IGBT | SiC MOSFET |
| 2016 [51]              | S. Wall et.al, Clenergy International Ltd | Inverter efficiency improved by 0.3% to 98% CEC weighted-average efficiency | 1200 V/200A SiC diode |
| 2017 [52]              | A. Anthon et.al, Technical University of Denmark | Semiconductor losses reduce by more than 50% converter efficiency increase by 1% at light load, over 60% reduction in cooling requirement at 192 kHz switching frequency | 1200V SiC MOSFET |
| 2017 [53]              | F. Remi et.al, Fraunhofer ISE | Peak efficiencies are 99.1% and 99.0% for booster stage and inverter stage, respectively, at 96 kHz and 48kHz switching frequency. Overall European average efficiency is 98.4 and reaches up to 98.07% at the peak. Improvement of power density up to 50% and 70% saving in-term of cost. | 1200V SiC MOSFET |
| 2019 [54]              | M. Ahmed et.al, Chongqing University | The efficiency increases to 99.2% from its initial 95.2% at a various output power | 1200V/19A SiC MOSFET and SBD diode |
| 2019 [55]              | Xu She et.al, United Technologies Corp | CEC average efficiency is more than 99% | 1200V SiC MOSFET |

4. CHALLENGES

Although comes to the market with the appealing characteristic and performance, there are still many challenges raised from the device and application point of views which require close attention from the developer as well as end-users [3].

The gate driver design is likely to be more challenging for SiC devices due to the occurrence of the positive counterfeit voltage gate [56]. This is due to the higher dv/dt of the SiC devices which imposes higher...
common mode current to be injected to the gate loop. Consideration to have an advanced gate driver with dv/dt and/or di/dt control is a must. Since SiC devices also hold a faster current rise during fault events, therefore a faster response protection requirement is indispensable. Nevertheless, timing mismatch caused by parallel or/and series also must be taken into consideration in the system design.

Some high voltage and high power applications that adopt SiC devices may face severe electromagnetic interference (EMI) noise because of the high dv/dt formed by the huge parasitic capacitance and fast switching speed. An appropriate EMI filter is necessary for motor drive applications to prevent the occurrence of voltage doubling effect caused by the high dv/dt. Similarly, extreme EMI conduction caused by high dv/dt will appear on the grid side in the grid-connected application. Therefore, the EMI filter is indispensable and advanced technology of EMI suppression method is also crucial to be investigated [57],[58].

Long term reliability of the SiC devices across all applications must vividly be demonstrated. This is vital for applications that are sensitive and extremely critical such as aviation, space program, and military [59]. The thermal ripple coming from the SiC-based converter is possibly larger than the Si converter due to its capability in providing a higher current rating. Consequently, a more rigid specification for package materials is compulsory as the SiC device operates at higher temperature conditions. Then again, due to SiC devices’ capability operates in high-temperature conditions, peripheral components associated with it become crucial, especially the capacitors because connectors linking high-temperature devices to the capacitor may further raise the capacitor’s temperature [60].

The full potential of the SiC device somehow cannot be achieved due to the packaging limitation [61]. As such it must be justified that the manufacturing for both front end and back-end processes must be improved to address the challenge. Since 2012, most major semiconductor and their silicon foundry companies have moved towards 150mm wafer fabrication which allows more dies to be planted. As such, lower cost per each device is achievable.

5. CONCLUSION
Silicon Carbide devices including MOSFET, diode, and other unipolar/bipolar switches are well accepted in the high-performance power electronics application. This due to its capability in yielding a remarkable benefit to at least in three following aspects; Noticeable reduction in power loss which leads to simplification of cooling requirement and poses higher system efficiency. Overall system improvement stimulated by high switching frequency and wide bandwidth control capability. Simplification and optimization of system circuitry and topology especially for converters.

However, SiC advancement characteristic brings several challenges to the device’s applications, including gate driver design, electromagnetic interference, reliability, and manufacturing/process. Some of the arguments presented in this paper are yet to be solved and active research is ongoing. No doubt that the continuous improvement of SiC technologies is crucial for it to be implemented in far-reaching applications.

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