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A STUDY ON WIDE BANDGAP SEMICONDUCTORS IN POWER CONVERTER

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Abstract: The development of new power plants is based on semiconductor materials such as silicon which are widely used in power converters. Wide bandgap, (WBG), semiconductors are very different from regular semiconductors as they have a larger bandgap. Larger distances allow more bandgap semiconductor power devices to operate at higher voltages, temperatures, and waves. In this study paper advantages of two WBG semiconductors SiC and GaN in power converters are discussed.

***Index Terms* – SiC (Silicon Carbide), GaN (Gallium Nitride), WBG (Wide band gap), Power converter**

I. INTRODUCTION

Wide bandgap, (WBG), semiconductors differ significantly from conventional semiconductors since they have a larger bandgap. A bandgap refers to the energy difference in between the top of the valence band and the bottom of the conduction band. The larger distance allow the power devices to operate at higher voltages, temperatures, and frequencies. Ordinary semiconductor like silicon have a bandgap in the range of 1 - 1.5 electronvolt (eV), while the wide-bandgap materials have bandgaps in the range above 2 eV. Semiconductors are an important component used to make green and blue LEDs and lasers, and are used in radio frequency applications, notably military radars. Their internal qualities make them suitable for a wide range of other applications, and they are some of the leading competitors for next-generation devices for general semiconductor use. Tolerance to high temperatures also means that these materials can be used at very high-power levels under normal conditions with the order of 300 °C. This makes them very attractive for military applications, where they have seen a right amount of use. Additionally, most wide-bandgap materials also have a much higher critical electrical field density, on the order of ten times that of conventional semiconductors. Combined, these properties allow them to operate at much higher voltages and currents, which makes them highly valuable in military, radio, and power conversion applications.

Specifically, with the latest developments in wide-band gap semiconductor devices, the SiC MOSFET has become an ideal alternative due to its fast-switching speed, lower switching loss, higher thermal conductivity and high voltage blocking voltages compared with Silicon based devices. Since the transition time of SiC MOSFETs can be reduced, they are suitable for nanosecond pulsed generation applications [2].

A power electronic technology capable of operating in harsh environment and especially at high temperature (>300 ◦C) is particularly important mainly in the fields of drilling, transports and aerospace. Current solutions based on the silicon technology are limited at temperature above than 200 ◦C.

This is due to the low silicon bandgap (1.12 eV) which is responsible for the rapid increase in leakage currents by temperature. A solution is the use of technology based on Wide Bandgap semiconductor such as silicon carbide (SiC). The NASA has tested a 4H-SiC circuit based on JFETs up to 961 ◦C [4]. Other technologies as BJT and CMOS have respectively operated at 500 ◦C. The main advantage of SiC devices is drift region had very low resistance due to which they are fabricated for high voltage application.

As a result of the low operating and switching losses, as well as higher thermal conductivity and operating temperatures, SiC devices can use smaller heatsinks to improve power density. [8]

In a Hybrid SiC power module, the anti-parallel diode is replaced by a SiC Schottky Barrier Diode (SBD). High speed switching is possible with Hybrid – SiC module. Every SiC power module has a SiC MOSFET with SiC SBD connected in anti-parallel [9]. Particularly due to the high structural properties of GaN material and AlGaN/GaN heterostructures, AlGaN/GaN High Electron Mobility Transistors (HEMTs) are widely selected as the key switches in various forms of power converters.[16]

Gallium Nitride enhancement-mode high electron mobility transistors (GaN E-HEMTs) have significant advantages over Si MOSFETs, such as the zero reverse recovery loss, low capacitive loss, excellent transconductance to reduce the rise/falling time during switching transitions, and good paralleling capability, etc. These benefits make GaN HEMTs promising candidates to seek high switching frequency, high conversion efficiency, and high-power density.[17]. In this study paper the uses and advantages of SiC and GaN in different power applications specifically discussed from different literature review.

II. SILICON CARBIDE (SIC)

1. In this conference paper the author discussed the use of SiC in power control unit (PCU) in electric vehicle. The PCU controls the current supply of the motor while the vehicle is operating. In present sitiuation, silicon-based power semiconductors no longer able to meet the needs of modern energy vehicles, so siliconized synthetic materials have become the developmental guideline. It is expected that silicon carbide power devices significantly reduce the size, weight, and energy savings of drive systems in electric vehicle inverters and DC-DC converters. The Toyota Central Research and Development Laboratory (CRDL) and the manufacturer of the well-known parts DENSO have been coproducing SiC semiconductor materials since 1980. In May 2015, Toyota Motor Corporation announced road test results for a hybrid vehicle (HEV) equipped with a SiC semiconductor power control unit (PCU). By improving the motion control, the goal of increasing fuel efficiency by 10% can be achieved compared to the initial improvement of 5%. At the same time, as the semiconductor device technology, it has reduced power control unit size by 80%. Therefore, the replacement of silicon-based IGBTs by SiC MOSFETs is an inevitable process in the development of electric drive systems.
2. In this paper compares Si and SiC MOSFET which shows that the SiC MOSFET has better electrical properties than Si MOSFET and it is preferable in the pulsed power converter. A 1200 V SiC MOSFET is proposed in a high-frequency series resonant pulsed power converter for the application of plasma generation. To increase the accuracy of predicting the behavior of the SiC MOSFET, the proposed analytical model involves all parasitic components in the converter, including the nonlinearity of the junction capacitances and transconductance, stray inductances from the package, printed circuit board (PCB) and transformer, parasitic capacitances from the transformer, and the capacitive load of plasma. The proposed model enables us to evaluate and optimize the switching solution of a SiC MOSFET for the pulsed power converter.
3. The power density and performance efficiency of the controlled rectifier circuits are sufficiently enhanced using the next level semiconductor switches like Silicon Carbide (SiC) MOSFET having wide band gap structure. Here the Author proposed a single-phase close loop control rectifier with switching device as SiC MOSFET and diodes as Schottky SiC diode is proposed which minimizes the reverse recovery losses of semiconductor switches. Proposed converter is designed for powering the high accuracy of Direct Current Current Transformer (DCCT) which operates on the Hall Effect principle for high DC current measurements of Kilo ampere range. The need of low switching losses and low reverse recovery losses in high power low voltage application has been achieved with this topology as low-speed switching Si based devices are replaced by the faster SiC devices.
4. This paper presented a comparative test of a softswitching inverter, i.e. the auxiliary resonant commutated pole inverter (ARCPI) using SiC MOSFETs or Si IGBTs. The results show that the ARCPI using SiC MOSFETs has better performance than that using Si IGBTs because of the shorter turn-off delay of SiC MOSFETs. The ARCPI using SiC MOSFETs makes complete ZVS (Zero voltage switching). Unlike Si IGBTs, SiC MOSFETs have no turn-off tail current and no forward voltage drop during switching transitions. Therefore there is almost no switching loss in the SiC MOSFETs. The switches in the ARCPI using SiC MOSFETs endures less current stress and less ripple current in the neutral point when compared to that of Si IGBTs. A 3.1% efficiency improvement can be achieved at 6 kW with SiC MOSFETs than those with Si IGBTs. However, the cost of the ARCPI using SiC MOSFETs is approximately 80% higher than that using Si IGBTs.
5. In this paper, a comparative efficiency analysis for silicon (Si), silicon carbide (SiC) MOSFETs and IGBT device-based DC–DC boost converter is performed. A 500 W boost converter for wide input voltage range (30–72 V) and 110 V output voltage is designed having a single gate driver circuit for Si, SiC MOSFETs and IGBT. A single gate driver provides the gate-source signal for all the devices which eliminates the use of separate gate driver circuit. Si MOSFET and IGBT are driven by 12 V gate-source voltage whereas SiC MOSFET is operated by 18 V gate-source voltage using the gate driver circuit for 20 and 50 kHz switching frequencies. It is found that SiC based converter provides highest efficiency ≈ 97.8%, while the lowest efficiency ≈ 94% is found for IGBT based converter at 20 kHz switching frequency. Apart from this, SiC application has another advantage such as low switching loss at higher frequency resulting compact converter size. However, use of IGBT at higher switching frequency results in higher switching losses, hence lower efficiency of the converter. It is concluded that the application of the combination of power semiconductor devices (SiC MOSFET+SiC Schottky diode) in DC–DC converter provides the highest efficiency as compared to Si and IGBT devices.
6. This paper development of HV(high voltage) SiC power semiconductors and the MV(medium voltage) power electronic equipment in distribution grids is summarized, and the role of SiC in these applications is analyzed. In the normal microgrid, the benefits of using HV SiC in DER converters can be obtained both at the converter and system levels. At the converter level, the SiC-based DER converter has significant weight and size advantages compared with its Si-based counterpart, e.g., an 82.9% weight reduction and 73.2% size reduction can be achieved for a 1 MW, 13.8 kV PV interface converter using HV SiC devices. The SiC-based DER converters can work with a higher switching frequency (e.g., 3 times that of Si-based), thus having a higher control bandwidth.
7. This paper illustrate the analytical model power loss analysis and efficiency of three-level neutral-pointclamped (3L-NPC) inverter that is widely used in solar photovoltaic energy conversion system. A silicon carbide (SiC) 3L-NPC inverter is developed by using wide bandgap semiconductor power devices, such as SiC MOSFET and SiC diode (SiC D). These devices are used due to their superior features over silicon (Si) semiconductor devices to reduce inverter power losses, and as a result, an improving efficiency at the high switching frequency. According to operating calculation, the results showed that the efficiency increases from 95.2% to 99.2% at a different output power of the inverter, and the highest efficiency is obtained when the DC input voltage is 800 V. Overall, it is obtained that the total power loss and output power of 3L NPC inverters can be improved by using SiC semiconductor device. Therefore, operating the 3L-NPC inverters using SiC MOSFET and high switching frequency SPWM strategy is a very efficient solution for grid-connected SiC PV inverter applications.
8. This paper introduced a design optimization tool that can optimize the volume or mass of a three-phase two-level dc–ac converter that uses SiC switching devices. Using SiC MOSFETs the design tool produced a converter with a power density of 3.503 kW/L that is 159.4% higher than Si IGBTs. The algorithm structure of the converter has been discussed and the methods that can be used to improve its computational efficiency.
9. SiC devices have higher critical breakdown strength, wider bandgap, thinner drift layer and better heat conductivity when compared to Si devices. A traction inverter using SiC devices will have low value of conductivity loss, lower values of

switching and recovery losses, increased range in terms of switching frequency and temperature with better heat dissipation. The converter will be smaller and lighter due to less cooling requirements. A study was done on various options available. Efficiency was compared using an improved model of SiC MOSFET. Currently lowest possible losses in a traction inverter can be achieved only by using all – SiC power modules.

10. SiC devices are characterized by a low reverse recovery charge and high carrier saturation velocity, by which it is possible to work at high frequency, and high breakdown voltage. In this paper, power losses in Si and SiC devices are evaluated in simulation and compared to each other. To demonstrate significance of the SiC devices over the silicon ones for the highest frequencies, the converter used PWM control under different switching frequencies, up to 600 kHz. SiC devices offer better performances in terms of efficiency at the highest frequencies: from 20 kHz to 400 kHz.

III. GALLIUM NITRIDE (GAN)

1. GaN is preferred over other wide bandgap materials like SiC, GaAs and Diamond as it can deliver a 'cost effective 'revolutionary performance. For proving the benefits of GaN based power devices in a real converter, a high-frequency, hard-switching boost converter was constructed, emphasizing on efficiency and frequency. The used transistors are E-mode AlGaN/GaN/AlGaN double-heterostructure FETs as these have a great interest. The low dynamic on resistance and low gate charges of the components results in low transistor losses, enabling very high switching frequencies and a compact converter design. A high-power efficiency of 96% was reached at a frequency of 512 kHz at 100W output power.
2. This paper introduced a 4 kW GaN-based isolated bidirectional DC/DC converter intended to interconnect 400 V HV batteries with 48 V on-board power supply systems in electrical vehicles. A new, highly compact 3D setup has beeen developed, allowing not only the power switches, but also the magnetic components to be actively water cooled. The heat sink also acts as an EMI shield, protecting the boards against the transformers' magnetic fields. Finally, three 4 kW prototypes with integrated magnetics have been built in order to validate the feasibility of the topology and of the electrical and thermal behaviors of the GaN switches.
3. Electric vehicles and hybrid electric vehicles are widely used and these vehicles are all equipped with DC/DC converters to charge lead-acid batteries from high-voltage storage batteries. This paper describes a DC/DC converter that has been downsized by 50% compared to conventional ones by increasing the switching frequency from 100 kHz to 500 kHz using GaN devices. By increasing the switching frequency with GaN devices, the newly developed converter achieved an output density of 6 W/cc. The newly developed converter has a low-profile structure, 18.5 mm in height, so that it can be installed in the basement of vehicle. This allows a greater flexibility of installation, as compared with the existing products. With regards to power conversion efficiency and noise, being issues in a higher switching frequency converter, the newly developed converter achieved comparable or better performance.
4. The paper deals with the experimental analysis of the switching performance of selected GaN (Galium Nitride) power transistor, which has been used in bidirectional buck/boost DC-DC converter. The switching performance was evaluated through highly accurate and verified simulation models of GS61008P transistor from GaN systems. Over 95 % of efficiency was achieved for both buck and boost mode (125 W), even switching frequency was above 500 kHz. From the results of measurements of efficiency of the designed converter, it can be concluded that very high switching frequency of GaN power transistors has not affected the efficiency performance of the power converter stage. The maximum achieved efficiency was above 97.5 % at the 40 % of power delivery.
5. Gallium Nitride enhancement-mode high electron mobility transistors (GaN E-HEMTs) can achieve high frequency and high efficiency due to its excellent switching performance compared with conventional Si transistors. In this paper, the test setup and measurements on the dynamic RDS (on) of GaN E-HEMTs have been discussed. Specifically, the clamping circuit design for the on-state voltage measurement on both the HS and SR devices and the junction temperature measurement are presented. Two different test setups, i.e., the DPT-based pulse test with soak time control and the continuous Boost/Buck converter system test, have been conducted. Finally, the calculation and measurement results of junction temperature are compared to validate the proposed dynamic RDS(on) and power loss models. • The increase of RDS(on) is caused by both the heating and trapping effects which are separately quantified.
6. In this paper the impact of emerging 650/900 V cascade GaN devices on bidirectional dc–dc converters are investigated which are suitable for energy storage and distributed renewable energy systems. Dynamic features of Si, SiC, and cascade GaN power devices are examined through the double-pulse test (DPT) circuit at different gate resistance values, device currents, and DC bus voltages. The experimental results showed significant improvements in switching performance and energy efficiency from the emerging cascade GaN devices in the bidirectional converters. Compared to Si and SiC devices, the cascade GaN-FET showed outstanding switching features with significantly lower energy losses, which greatly improved the switching performance of the converter. Due to low on-state resistance and shorter switching times of the cascade GaN-FETs besides GaN's superior material properties, the GaN-based converter exhibited a major reduction in power losses, leading to highly improve the energy efficiency even at cruel operating conditions. Although GaN devices are expensive, the high price of GaN devices can be reasonably compensated by using smaller passive components and cooling systems in power converters.
7. In this paper, the GaN power IC platform is realized based on normally-OFF AlGaN/GaN MIS-HEMTs and the all GaN integrated DC-DC buck converter has been designed, fabricated and experimentally characterized. The fabricated converter IC realizes stable output at 10 V with constant output ripple and line input voltage ranging from 16 to 29 V. The converter can maintain stable output against input line voltage variations from 20 V to values of 16~29 V, or load variations from 500 Ω to values of 300~700 Ω. When subjected to over-current incident, the converter can be switched off within one duty cycle period. The proposed GaN power IC platform can be adopted and all GaN DC-DC converters is promising in power conversion applications.
8. Switched capacitor multilevel converters are good examples of topologies that can effectively reduce or eliminate passive components. Two GaN based device of three level topology, one for a low voltage (LV) 48 V server application and the other for a higher voltage (HV) 400 V power factor correction (PFC) circuit has been discussed in this paper. As a result of using lower figure-of-merit (FOM) devices, significant efficiency gains are observed for the LV and HV converters developed compared to a two-level topology. For the LV converter, a greater than 0.5% peak efficiency improvement is

observed, while a 2% peak efficiency improvement is observed for the HV converter. The LV converter is then cascaded with a high frequency buck converter to demonstrate the performance of the complete 48 V to 1 V POL system. It is seen that a three-level front end IBC cascaded with the high frequency buck provides the better solution, with an intermediate bus voltage of 6 V providing the better solution up to 12 A and 12 V being the better one beyond 12 A.

9. This paper presents a comprehensive study of GaN high electron mobility transistor (HEMT) based non-isolated point-of-load (POL) synchronous buck converter operating at 2.7 MHz with a high step-down ratio (24 V to 3.3 V). The characteristics and performance of GaN HEMT and three different Si devices are analytically investigated and the optimal operating point for GaN HEMT has been discussed. Zero-voltage switching (ZVS) is implemented to minimize switching loss in high switching frequency operation. It is found the high conduction loss due to the high inductor ripple current can be significantly minimized using GaN-based converter due to low on-resistance.
10. In this paper, a non-isolated bidirectional DC-DC converter equipped with Gallium Nitride (GaN) semiconductor transistors is presented. Here a high-frequency non-inverting Buck-Boost converter equipped with GaN devices is analyzed and designed. This converter is able to work in Buck, Boost and Buck-Boost modes depending on input and output voltages, therefore can achieve bidirectional operation. At the switching frequency of 10 MHz, the designed converter can achieve 94.4% efficiency, and the power density is 6.25W/cm3. A precise dead time control to minimize the conduction loss is important for efficiency improvement.

IV. RESULTS AND DISCUSSION

This study paper focuses on two WBG semiconductors SiC and GaN. Some literature reviews of papers carried out in this study paper.

The study results of SiC are:

1. The replacement of silicon-based IGBTs by SiC MOSFETs is an inevitable trend in the development of electric drive systems.
2. SiC MOSFET has better electrical characteristics than Si MOSFET and it is preferable in the pulsed power converter.
3. The need of low switching losses and low reverse recovery losses in high power low voltage application is achieved with this topology as low-speed switching Si based devices are replaced by the fast acting SiC devices
4. The switches in the auxiliary resonant commutated pole inverter (ARCPI) using SiC MOSFETs endures less current stress and less ripple current in the neutral point when compared to that of Si IGBTs.
5. Application of the combination of power semiconductor devices (SiC MOSFET+SiC Schottky diode) in DC–DC converter provides the highest efficiency as compared to Si and IGBT devices.
6. The SiC-based DER converters can work with a higher switching frequency (e.g., 3 times that of Si-based), and therefore have a higher control bandwidth. Similar to the conventional microgrid, HV SiC devices can also benefit asynchronous microgrid PCS at both the converter and system levels.
7. The total power loss and output power of 3L NPC inverters can be improved by using SiC semiconductor device.
8. Using SiC MOSFETs the design tool produced for three-phase two-level dc–ac converter gives a power density of 3.503 kW/L that is 159.4% higher than one based on Si IGBTs.
9. Currently lowest possible losses in a traction inverter can be achieved only by using all – SiC power modules.
10. SiC devices offer better performances in terms of efficiency at the highest frequencies: from 20 kHz to 400 kHz approximately.

The study results of GaN are:

1. A high-power efficiency of 96% was reached at a frequency of 512 kHz at 100W output power.
2. Regarding power conversion efficiency and noise, being issues in a higher switching frequency converter, the newly developed GaN based converter achieved comparable or better performance than the competitor.
3. From the results of efficiency measurements of the designed converter, it can be concluded that very high switching frequency of GaN power transistors are not affecting the efficiency performance of the power converter stage.
4. Gallium Nitride enhancement-mode high electron mobility transistors (GaN E-HEMTs) can achieve high frequency and high efficiency due to its excellent switching performance compared with conventional Si transistors.
5. Compared to Si and SiC devices, the cascode GaN-FET exhibited outstanding switching characteristics with significantly lower energy losses, which greatly enhanced the switching performance of the converter.
6. It is found the high conduction loss due to the high inductor ripple current can be significantly minimized using GaN-based converter due to low on-resistance.
7. At the switching frequency of 10 MHz, the designed converter can achieve 94.4% efficiency, and the power density is 6.25W/cm3.

REFERENCES

[1] Jiangheng, Li. 2020. The Application of Silicon Carbide in PCU. Journal of Physics: Conference Series, 1676(1): p. 012074. IOP Publishing.

[2] Wu, Q., Wang, M., Zhou, W., Wang, X., Liu, G. and You, C., 2019. Analytical switching model of a 1200V SiC MOSFET in a high-frequency series resonant pulsed power converter for plasma generation. IEEE Access, 7, pp.99622-99632.

[3] Shaikh, A.M., Kulkarni, R.D., Sabnis, A., Bhaskar, M.S. and Subramaniam, U., 2020, June. Silicon Carbide (SiC) based Constant DC Current Source for DC Current Transformer Calibration. In 2020 International Conference for Emerging Technology (INCET) (pp. 1-6). IEEE.

[4] Zhou, W. and Yuan, X., 2020. Experimental Evaluation of SiC Mosfet s in Comparison to Si IGBTs in a Soft-Switching Converter. IEEE Transactions on Industry Applications, 56(5), pp.5108-5118.

[5] Alam, M., Kumar, K. and Dutta, V., 2019. Comparative efficiency analysis for silicon, silicon carbide MOSFETs and IGBT device for DC–DC boost converter. SN Applied Sciences, 1(12), pp.1-11.

[6] Wang, F. and Ji, S., 2021. Benefits of high-voltage SiC-based power electronics in medium-voltage power-distribution grids. Chinese Journal of Electrical Engineering, 7(1), pp.1-26.

[7] Ahmed, M.H., Wang, M., Hassan, M.A.S. and Ullah, I., 2019. Power loss model and efficiency analysis of three-phase inverter based on SiC MOSFETs for PV applications. IEEE Access, 7, pp.75768-75781.

[8] Laird, I., Yuan, X., Scoltock, J. and Forsyth, A.J., 2017. A design optimization tool for maximizing the power density of 3-phase DC–AC converters using silicon carbide (SiC) devices. IEEE Transactions on Power Electronics, 33(4), pp.2913-2932.

[9] Chakravarthy, B.K., 2019. All-Silicon Carbide Power Modules Based High Performance Inverter for Traction Applications. CVR Journal of Science and Technology, 16(1), pp.66-71.

[10] Pellitteri, F., Busacca, A., Martorana, C., Miceli, R., Stivala, S., Messina, A.A., Calabretta, M. and Vinciguerra, V., 2021, July. Power losses comparison between Silicon Carbide and Silicon devices for an isolated DC-DC converter. In 2021 IEEE 15th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG) (pp. 1-6). IEEE.

[12] Rothmund, D., Bortis, D. and Kolar, J.W., 2018. Highly compact isolated gate driver with ultrafast overcurrent protection for 10 kV SiC MOSFETs. CPSS Transactions on Power Electronics and Applications, 3(4), pp.278-291.

[13] Nakakohara, Y., Otake, H., Evans, T.M., Yoshida, T., Tsuruya, M. and Nakahara, K., 2015. Three-phase LLC series resonant DC/DC converter using SiC MOSFETs to realize high-voltage and high-frequency operation. IEEE Transactions on Industrial Electronics, 63(4), pp.2103-2110.

[14] de Oliveira, E.F., Sprunck, S., Pfeiffer, J. and Zacharias, P., 2020, September. A GaN-based DC/DC converter for e-vehicles applications. In 2020 22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe) (pp. P-1). IEEE.

[15] Tashiro, K., Okagawa, Y., Zhang, K., Yamada, Y., Tachizaki, S. and Takahashi, S., 2020. Downsizing of In-vehicle DC/DC Converters with GaN Devices. SEI Technicsal Review, (91), p.23.

[16] Frivaldsky, M., Morgos, J. and Zelnik, R., 2020. Evaluation of GaN Power Transistor Switching Performance on Characteristics of Bidirectional DC-DC Converter. 26(4), pp.18-24.

[17] Hou, R., Shen, Y., Zhao, H., Hu, H., Lu, J. and Long, T., 2020. Power loss characterization and modeling for GaN-based hard-switching half-bridges considering dynamic on-state resistance. IEEE Transactions on Transportation Electrification, 6(2), pp.540-553.

[18] Alharbi, S.S. and Matin, M., 2021. Experimental evaluation of medium-voltage cascade gallium nitride (GaN) devices for bidirectional DC-DC converters. CES Transactions on Electrical Machines and Systems, 5(3), pp.232-248.

[19] Sun, R., Liang, Y.C., Yeo, Y.C., Zhao, C., Chen, W. and Zhang, B., 2019, May. Development of GaN Power IC Platform and All GaN DC-DC Buck Converter IC. In 2019 31st International Symposium on Power Semiconductor Devices and ICs (ISPSD) (pp. 271-274). IEEE.

[20] Biswas, S. and Reusch, D., 2018, October. Evaluation of GaN based multilevel converters. In 2018 IEEE 6th Workshop on Wide Bandgap Power Devices and Applications (WiPDA) (pp. 212-217). IEEE.

[21] Lee, W., Han, D., Morris, C.T. and Sarlioglu, B., 2017. High-frequency GaN HEMTs based point-of-load synchronous buck converter with zero-voltage switching. Journal of Power Electronics, 17(3), pp.601-609.

[22] Kruse, K., Elbo, M. and Zhang, Z., 2017, March. GaN-based high efficiency bidirectional DC-DC converter with 10 MHz switching frequency. In 2017 IEEE Applied Power Electronics Conference and Exposition (APEC) (pp. 273-278). IEEE.