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Measurement of WBG-based power supplies

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Keywords

Efficiency, power supply, wide bandgap, Gallium Nitride (GaN)

Abstract

This paper discusses different measurement methods to evaluate the efficiency of WBG-based power supply solutions, including electrical measurement methods and their verification with calorimetric methods, and compares the performance of Si-based and GaN-based chargers. The efficiency of chargers was measured at different load conditions, and it was observed that the maximum efficiency occurred generally at higher powers. GaN-based solutions outperformed Si-based chargers at higher power levels, leading to significant energy savings. The paper suggests that regulations for efficiency can be tighten and different voltage modes shall be included to ensure further energy savings. The benefits of using WBG devices are more evident in terms of power density, which could lead to their wider adoption in other power electronic applications.

I. Introduction

Power electronic devices incorporating wide-band-gap (WBG) technologies are maturing rapidly and offer enormous opportunities for improved energy efficiency. The introduction of WBG-based switched-mode power supply (SMPS) has marked a significant development in the market. These products boast high efficiency, although their cost remains relatively high. It is essential to demonstrate the potential for energy savings through a concrete use case in an appliance area that raises public awareness. The emergence of new WBG-based power electronic solutions has created an opportunity to establish internationally accepted approaches that support the adoption and promotion of WBG-based power electronics, and to foster a better understanding of the technology and drive actions among governments and policymakers, which are the goals of Power Electronic Conversion Technology Annex (PECTA) [1].

The focus of this paper is to analyze existing WBG-based power electronic solutions, in comparison to conventional Si-based technology. It is important to consider that factors other than the WBG-technology itself may contribute to efficiency differences, necessitating an examination of the topology and other relevant aspects. The energy efficiency potential will be elaborated, which can suggest further regulations for efficiency. Since April 1st, 2020, according to the EU Commission [2], the average active efficiency of external power supplies must exceed certain determined values, which are summarized in Fig. 1.

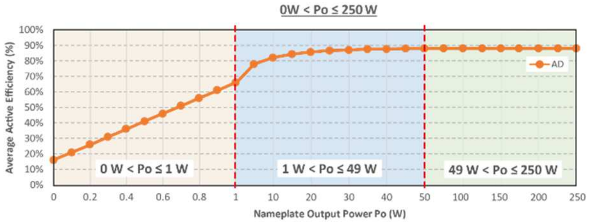
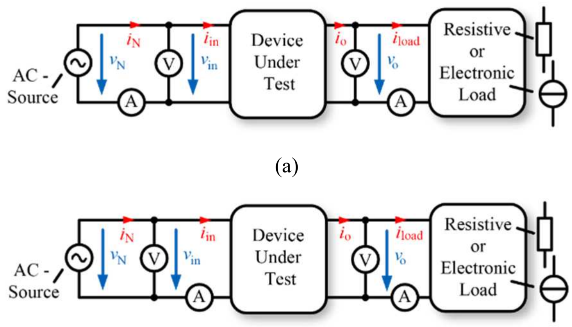


Fig. 1: Minimum limit of average active efficiency for external power supplies for a nameplate output power in the range of 0 W < Po ⩽ 250 W AC-DC external power supplies (AD).

In order to measure the electrical efficiency, both the input and the output power of the DUT shall be determined. Therefore, input voltage, input current, output voltage and output current must be measured as accurately as possible. For the active AC power, fundamental and harmonics with resistive content must be considered. The nature of measuring voltage and current simultaneously requires positioning one of both measurements closer to the DUT compared to the residual one. For both, input and output power evaluation, two different options are feasible – either voltage or current probe directly attached to the input/output terminals. Thus, four different solutions exist. The two most common versions are illustrated in Fig. 2 (a) and (b).



(a)

(b)

Fig. 2: (a) Measurement setup 1: voltage and current probe arrangement for a DUT (AC/DC converter) supplied from an AC-source for high power loads. (b) Measurement setup 2: Voltage and current probe arrangement for a DUT (AC/DC converter) supplied from an AC-source for low power loads.

The setup for the DUT electrical efficiency measurement should be chosen according to the respective power rating and internal resistive values of the current and voltage sensor. For high power measurements setup 1 (as shown in Fig. 2 (a)) is recommended, while setup 2 is recommended for low power measurements.

In the following sections, we will discuss the experimental setups for evaluating the efficiency of WBG- and Si-based power supplies. A selection of Si-based and GaN-based chargers in the market are investigated to showcase the measurement process, and to compare and better understand their performance.

II. Measurements with Power Analyzer Setup

A. Test Setup

Modern low-wattage cell phone or laptop power supplies can change their output voltage from 5 V to 20 V, which depends on the target device to be charged. For example, a 60 W DC-charger generally allows 5 different voltage configurations at the output (5 V, 9 V, 12 V, 15 V, 20 V) and the full output power of 60 W can only be delivered during a 20 V loading scenario. Hence, the charger requires a communication interface between the charger itself and the device to be charged, in order to set the correct output voltage before the charging process is going to be initiated. In order to verify the electrical efficiency for all different operating points (5 V – 20 V; 0 W – 60 W), the test setup requires an additional communication board which allows to set the different voltage and loading scenarios manually. Examples of such communication boards are the Infineon/Cypress CY4533 EZ-PD or the TI TIDA-050012.

An example of a test setup including current and voltage sensors, a power analyzer, a communication board, and an electrical load is shown in Fig. 3.

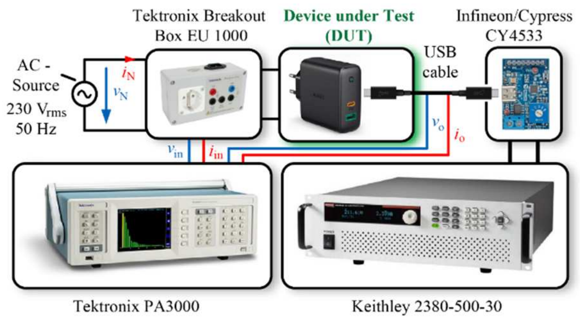


Fig. 3: Test setup including measurement devices, source, load and power analyzer.

The test equipment consists of the following products and devices:

- Power analyzer: Tektronix PA3000
    - Integrated 1 A shunt: for input current measurements

- Integrated 30 A shunt: for output current measurements

- Tektronix break-out box: BB1000-EU (240 V)

- PD Communication Kit (Eval board): Infineon/Cypress CY4533 EZ-PD

- Current Sink: Keithley 2380-500-30

B. Measurement Results

Results for two chargers will be detailed (one GaN-based, another one Si-based) and results from more chargers will be summarized.

a. GaN-based power supply A

The GaN A is a power supply which comes with 2 different charging outputs:

- PD (power delivery) 3.0 – USB type - C: 60 W, 5 V/3 A, 9 V/3 A, 12 V/3 A, 15 V/3 A, 20 V/3 A

- QC (quick charging) – USB type - A: standard 5 V/2.4 A

The GaN A PD and QC power supply is based on a standard rectifier bridge, followed by a QR flyback converter operating in discontinuous mode (Fig. 4). The flyback primary side semiconductor is based on GaN technology, whereas both the paralleled rectifier input stages and the synchronous rectifying MOSFET on the secondary side is based on silicon MOSFET and diodes. Furthermore, an additional Si-based DC/DC Buck converter with CC/CV control, directly connected after the PD output capacitors to generate the 5V QC port. Therefore, it can be concluded that the GaN A power supply is not solely based on GaN power semiconductor devices but incorporating both Si and GaN transistor technology.

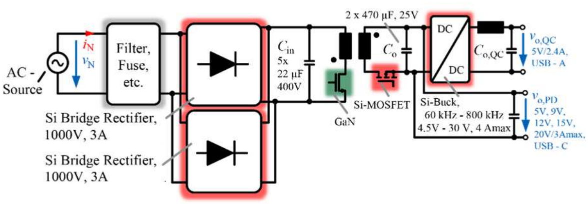


Fig. 4: Basic schematic of the GaN A power supply with PD and QC port.

The switching frequency of the flyback converter is changing for different outpower values. While operating in 20 V charging mode the switching frequency shows its maximum at around 55 kHz, as shown in Fig. 5, it is non-linearly decreasing for smaller loads and even reaches values of approximately 0.6 kHz during 5 V PD no-load operation.

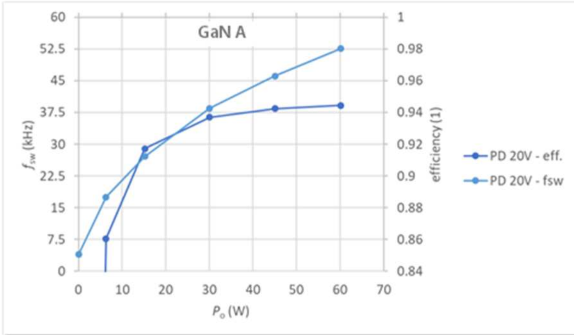


Fig. 5: GaN A port electrical efficiency and DC/DC flyback converter switching frequency of dedicated primary-side GaN transistor for different load conditions (0 W – 60 W) and a charging voltage of 20 V.

The efficiency curves at different output voltage modes for GaN A are shown in Fig. 6.

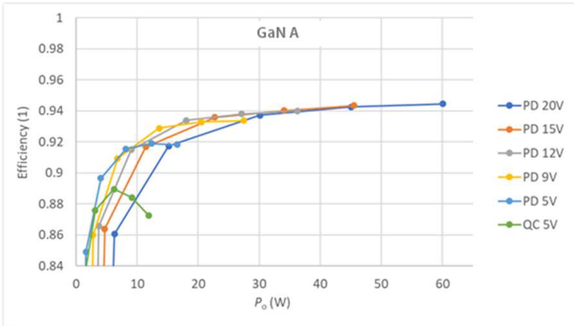


Fig. 6: Efficiency over output power curves of GaN A charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

b. Si-based power supply B

The Si B power supply is based on a standard rectifier bridge, followed by a flyback converter. To generate the PD output a USB PCB is utilized. All semiconductors utilized in this power supply are based on silicon technology.

The switching frequency of the flyback converter is changing for different outpower values, as shown in Fig. 8. While operating in 20 V charging mode the switching frequency shows its maximum at around 65 kHz, it is non-linearly decreasing for smaller loads and even reaches values of approximately 22 kHz during 5 V PD no-load operation.

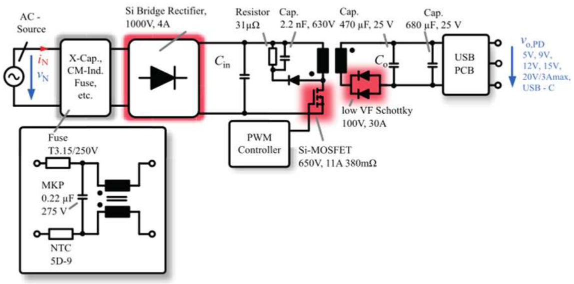


Fig. 7: Basic schematic of the Si B power supply.

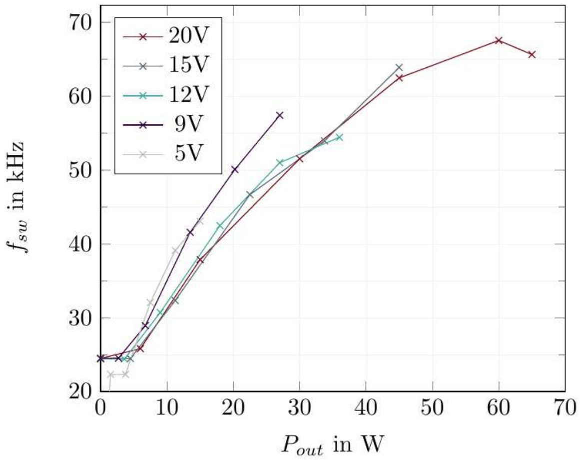


Fig. 8: DC/DC flyback converter transistor switching frequency of Si B for different load conditions (0 W – 60 W) and charging voltage levels (5 V – 20 V).

The efficiency curves at different output voltage modes for Si B are shown in Fig. 9.

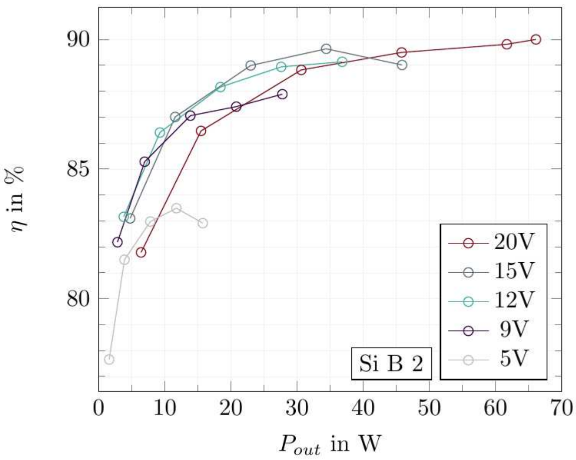


Fig. 9: Efficiency over output power curves of Si B 65W charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

c. Comparisons in Efficiency and Power Density

Two other GaN- and Si-based chargers from different manufacturers are also tested and results from all different chargers are compared in Fig. 10 for efficiency and for power density in Fig. 11. It can be seen that GaN-based chargers provide higher efficiencies and higher power density compared to Si counterparts.

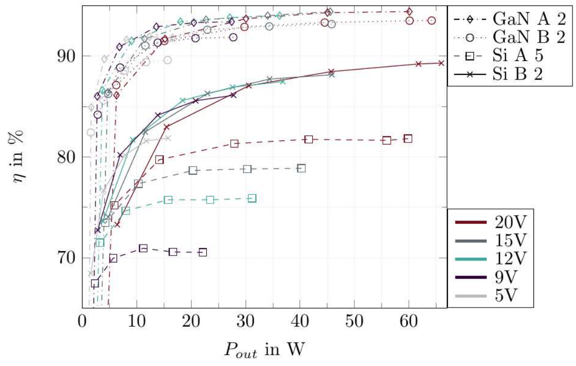


Fig. 10: Output power and efficiency of the different chargers.

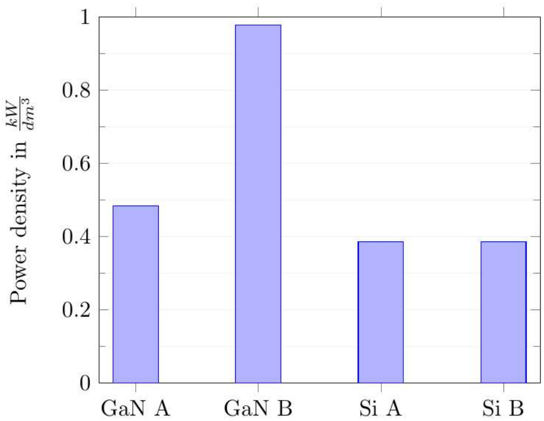


Fig. 11: Power density of the different chargers

III. Measurements with Power Analyzer Setup

A. Test Setup and Verification with Calorimetric Method

As an alternative to the power analyzer setup, oscilloscope with high precision voltage and current probes can also be used for efficiency measurements of power supplies after careful calibration.

The test equipment used consists of the following products and devices:

- Oscilloscope: Tektronix 1 GHz MSO68B
- Current probes: Tektronix 30A AC/DC Current Probe TCP0030A (bandwidth 120 MHz)

- Voltage probes: Tektronix High-voltage Differential Probe THDP0200 (bandwidth 200 MHz)

The oscilloscope measurement setup was first verified with a novel dual-chamber calorimeter proposed in [3], as shown in Fig. 12. Calorimetric systems directly measure the losses thermally and provide a measurement which is independent from the operation frequency of the DUT.

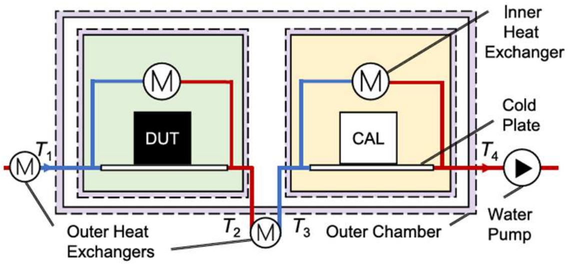


Fig. 12: Schematic view of the calorimeter.

The proposed calorimeter enables geometry-independent loss measurements by transferring the heat to the water through heat exchangers (convection) and cold plates (conduction). Two identical heat-insulated chambers are placed inside an outer chamber that isolates the calorimeter from the ambient. The water at the ambient temperature flows through the DUT chamber and after absorbing the heat generated by the DUT, gets cooled down to the ambient temperature using an external heat exchanger. The liquid then flows through the calibration (CAL) chamber and heats up with its dissipated power (P_{CAL}). After the calibration chamber, another external heat exchanger cools down the liquid to the ambient temperature. The entire heat-transfer cycle is repeated until the temperatures reach a steady state. Such a closed loop for the coolant ensures a constant flow in both chambers and eliminates the need for precise flow measurements. Temperature gradients $T_4 - T_3$ and $T_2 - T_1$ are measured and compared constantly, and a proportional-integral (PI) regulator adjusts P_{CAL} such that both chambers have equal steady-state temperature gradients.

The calorimetric system was used to measure the losses of a high-frequency inductor when excited by a 277-kHz source (fundamental) [4], and compared with measurements by the oscilloscope setup, which confirmed its accuracy.

B. Efficiency Comparisons of Si-Based and GaN-Based Chargers

In order to make a fair comparison of the efficiencies of Si-based and GaN-based power solutions, only the chargers with the same power rating and the same output voltage mode are compared. Fig. 13 compares the efficiency of two 30 W Si-based and GaN-based chargers at 15 V mode and 20 V mode, both of which are able to reach the rated maximum power. For these two 30 W chargers, they show similar performance and the difference in efficiency is around 1% at full power.

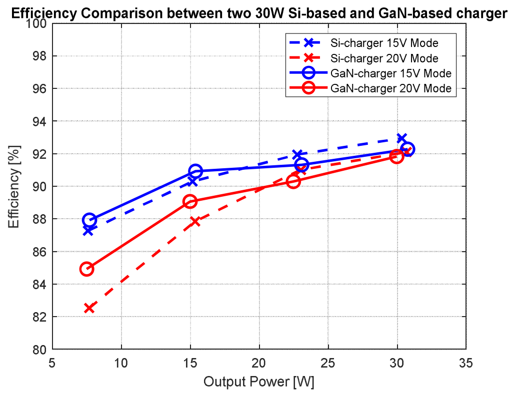


Fig. 13: Efficiency Comparison between two 30W Si-based and GaN-based chargers.

Fig.14 shows the efficiency curves of two 60 W GaN- and Si-based charger. The efficiencies of the GaN charger which is always higher than the Si-based one across the whole power range with a difference of more than 2%. This will translate into a difference in losses of about 1.4 W at an output power of 60 W. It is clear that at higher power, the GaN-based solution shows better performance in terms of efficiency and losses saved.

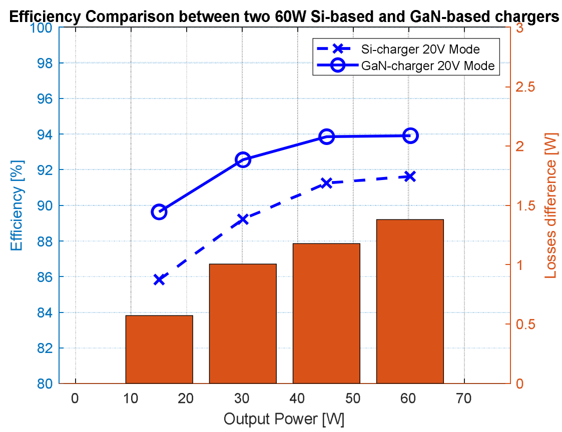


Fig. 14: Efficiency Comparison between two 60W Si-based and GaN-based chargers.

To obtain an overall picture of the performance of all the chargers investigated, the efficiency results at the maximum power allowed at different voltage modes are set out in Fig. 15, as these chargers are usually used at full power at a certain output voltage. In general, GaN-based chargers outperform Si-based ones in the power range above 30 W, by an increase of about 2-3% in efficiency. In terms of reduced losses, this will become more significant especially when the output power is higher.

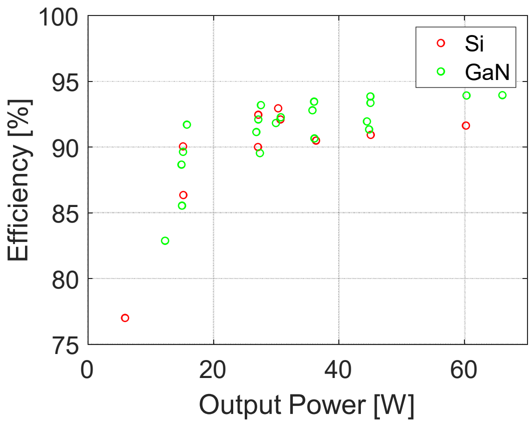


Fig. 15: Full power efficiency comparison of all investigated chargers.

C. Power Density Comparisons

Another important metric to evaluate the performance of Si-based and GaN-based chargers is the power density since a well-known benefit of using WBG devices is the higher switching frequency to shrink the passive component volumes. The gain is straightforward as shown in Fig. 16.

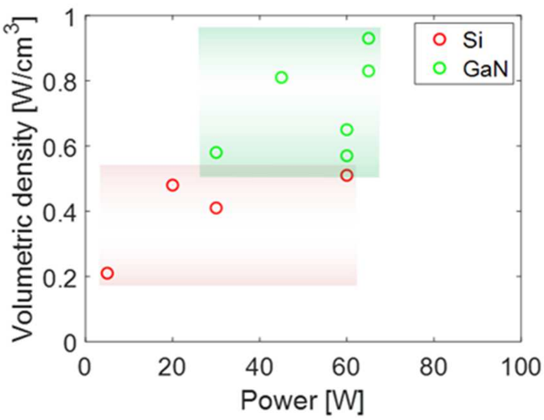


Fig. 16: Comparison of power densities of the investigated chargers.

Although different chargers may have different available numbers of output voltage mode and therefore different design concerns, the results in Fig. 16 are based on the total output power capability at full load as indicated for each charger. It is clear that the GaN-based chargers offer higher power densities in general.

D. Discussion

The comparison of the efficiency between Si-based and GaN-based chargers of the same power level shows that the investigated chargers present a similar performance at power levels below 30 W. For example, for two chargers with a nominal maximum power of 30 W (Si-based 30 W and GaN-based 30 W), the average efficiency at the maximum power of four load conditions (25%, 50%, 75% and 100%) was similar, of around 90%. In the higher power range, GaN-based solutions outperform their Si counterparts for which the average efficiency was 92% for GaN-based 60 W and 90% for Si-based 60 W. Although these numbers are very close, the difference becomes much more considerable in terms of saved energy losses, especially at higher output powers. More investigations with a broader range of low-power Si-based and GaN-based chargers are needed to conclude in more details on the efficiency gain.

Furthermore, the chargers are not optimized in every voltage mode, and in general, the efficiency at lower voltage modes (for lower output power) is lower compared to higher voltage modes (for higher output power). This could result in significant power losses. For example, consider charging a phone battery of 4000 mAh and a battery voltage of 3.86 V with the Si-based 60 W charger and the GaN-based 60 W charger. The efficiency of 5 V mode in the 15 W level could be taken to calculate the energy loss of two different chargers (86.5% for Si solution and 91.5% for GaN power supply). According to Statista, the number of smartphone users reached 6.26 billion in 2021 globally [5]. The total energy lost during the charging process every year can be calculated as 6.26*10^9*(4Ah*3.86V)*(1/0.865-1)*365 = 5.5 TWh. This is equivalent to the total energy consumption of 1.56 million average EU households per year. An increase in efficiency to 91.5% (between Si- and GaN device) would lead to savings of 40% of the energy lost, or 2.2 TWh per year.

According to the EU commission regulation 2019/1782 for external power supplies [2], the average active efficiency for output powers higher than 49 W is 88%, which was met by mostly all chargers that have been tested. The GaN-based solutions in general showed better performance. Although all products came with different switching frequency and control strategy which also impacts the efficiency, the electrical efficiency regulation requirements could be increased to promote the adoption of WBG technologies and their implementation strategies aiming for higher efficiencies.

The results in this paper indicate additionally that the efficiency of the measured products is in particular cases even jeopardized by regulation policies. The reason for this lies in the following fact. In the current, above mentioned EU commission regulation 2019/1782, the efficiency requirements only apply to the lowest voltage mode if multiple output voltages are available for the nominal out-put power. For example, both 15V mode and 20V mode can access the nominal output power for the two investigated 30W chargers. Since the regulation only applies to the lowest voltage mode, i.e., 15V in this case, the measured efficiency of the 20V mode is lower than the 15V mode (see Fig. 13). This results in lower efficiencies at the higher voltage mode in the nominal output power for the same chargers, also at lower voltage modes for lower output powers since the converter design is only optimized at a certain voltage mode to meet the requirement. It is suggested that regulations for efficiency of different voltage modes shall be also included to ensure further energy saving.

The benefits of using WBG devices are more evident in terms of power density, with a reduction of about two-fold. Power density is currently a strong motivation for using GaN devices among manufacturers. As the power charger market was the first to experience the penetration of WBG devices, and the associated advantages have emerged, it can be foreseen that other power electronic applications will also benefit from their wider adoption, not only in terms of more material saved from high power density, but also from higher efficiencies.

E. Conclusion

To summarize, the measurements of different Si- and GaN-based power supplies show that power density and efficiency are the two main drivers for GaN. Industry works primarily towards higher power density, with less focus on exceeding the regulations in terms of efficiency. Efficiency does vary substantially among products, GaN-based solutions outperform Si ones for the power range of 60 W. Below 30 W, the efficiency difference between GaN and Si is small. The industry and policymakers should work closely on standardizations and regulations for both power density and efficiency to fully exploit the advantages of WBG devices and bring forward next-generation efficient power electronic solutions.

References

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