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# Gallium nitride technology in adapter and charger applications

## The promise of GaN in light of future requirements for power electronics

## Abstract

This paper will discuss the benefits of e-mode GaN HEMTs in low power applications such as USB-PD adapters and mobile device chargers. In comparison to the next best silicon alternative, this paper will show quantitatively how much better systems being built with GaN devices will be. It will also provide further insight into corresponding topologies, choice of magnetics and switching frequencies to take the full benefit of the next generation of power devices.

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# 1 Introduction

The commercial availability of wide bandgap power semiconductors with their significantly better figures of merit raises some fundamental questions on the agenda of many customers: how much better are system solutions based on these wide bandgap components in terms of density and efficiency? To what extent can silicon based solutions follow at the potential expense of more complex topologies and control schemes?

This paper tries to give answers to these questions for two application fields, adapters and compact chargers.

GaN HEMTs as lateral power devices have an order of magnitude lower gate charge and output charge compared to their silicon counterparts. Combined with virtually zero reverse recovery charge it enables hard commutation of reverse conducting devices. Thus, GaN supports simpler topologies and an optimization of control methods seamlessly changing between soft switching and (partial) hard switching. Even though hard commutation is acceptable for silicon based power devices in low and medium voltage classes, Superjunction devices as prominent technology in the 600V class prevent any such operation due to losses and voltage overshoots. The designer of AC-DC applications has three choices as next best alternatives to the use of wide bandgap devices: single-ended topologies such as boost converter as a power factor correction stage, strict avoidance of hard commutation through corresponding control methods such as triangular current mode (TCM) operation in totem pole PFC, or the use of cascaded converter architecture where the voltage stress is distributed to several series connected converter stages.

While single-ended topologies may not comply with efficiency targets, alternative solutions such as the dual boost may not comply with space or cost targets. Even though cascaded solutions have demonstrated their ability to reach both efficiency and density targets [1], control efforts remain challenging and may limit the use of this concept to the high power segment only.

The design options for compact chargers are significantly narrowing down when trying to overcome density targets of 20 W/in$^3$ for a 65 W adapter. The need to recuperate the energy in the leakage inductance and to provide zero voltage switching in most or all operation conditions rules out much of the single-ended topology choices.

This paper explores the value of GaN HEMTs in comparison to next best silicon alternatives.

## 2 Device concepts

As the race is set between GaN HEMTs versus their silicon counterpart, Superjunction devices being evidently the best alternative, let’s start with a brief review of the latest technology achievements.

Superjunction devices have pushed for more than a decade towards ever lower on-state resistance [2], which in turn reduces the device capacitances and makes the devices inherently faster switching. Figure 1 shows the output capacitance characteristics of three subsequent generations of Superjunction transistors versus an e-mode GaN HEMT. Figure 2 shows the energy stored in the output capacitance.

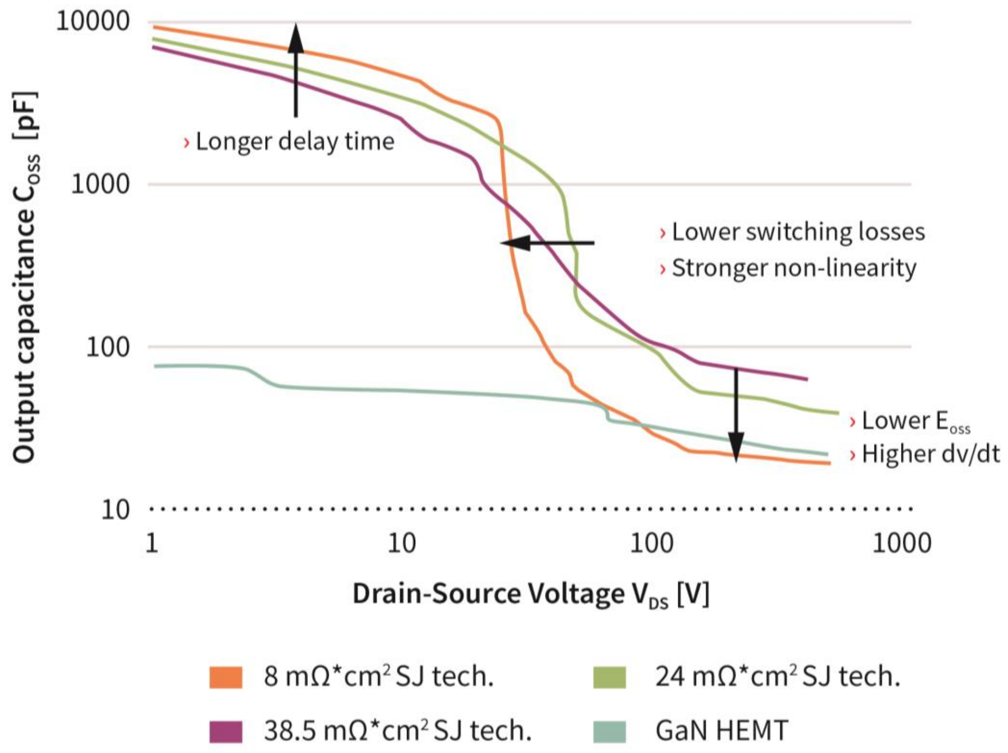

**Figure 1** **Development of the characteristic output capacitance of three consecutive technology nodes of Superjunction device in comparison to an e-mode GaN HEMT**

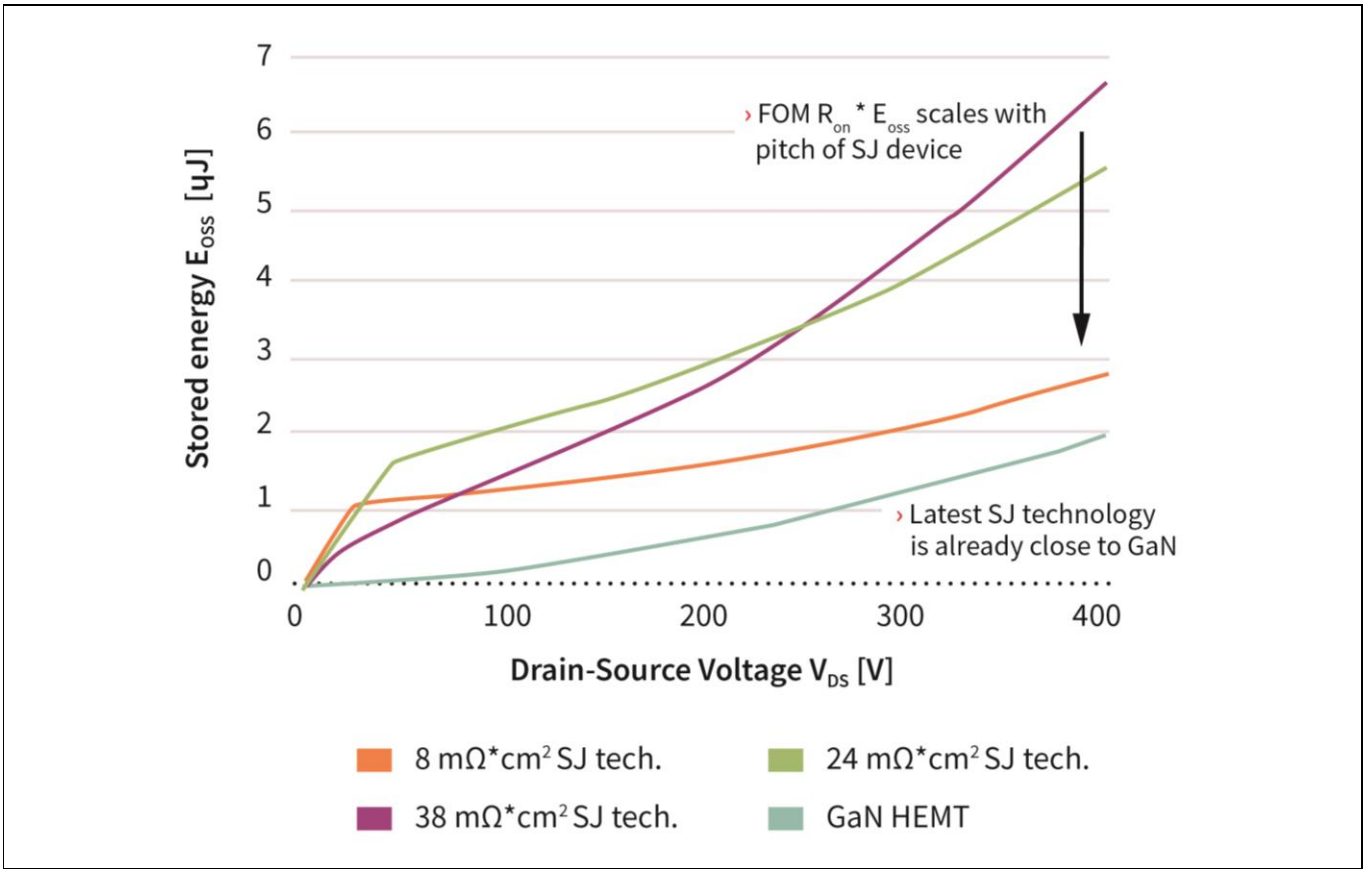

**Figure 2** **Trend for the energy stored in the output capacitance across three consecutive generations of Superjunction devices in comparison to GaN HEMTs**

Even though the output capacitance of GaN is significantly lower in the low voltage range, the energy stored in the output capacitance is comparatively close to the values achieved by Superjunction devices. Since this energy is dissipated as heat in every switching cycle during hard switching transients, it is already obvious from this graph that the true value of GaN will be in half bridge based circuits and will be limited in single-ended topologies.

Figure 3 shows a comparison of the charge stored in the output capacitance as one of the key parameter for soft switching transitions.

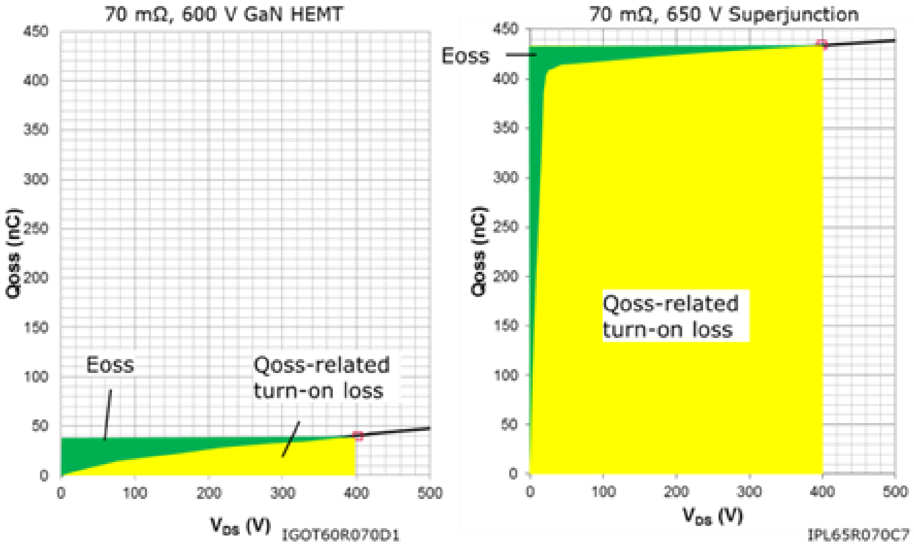

**Figure 3** **Comparison of $Q_{OSS}$ versus voltage for an e-mode GaN HEMT (left) to an advanced Superjunction device (right)**

Whereas in single-ended topologies the $E_{OSS}$ parameter is governing loss mechanisms, in half bridge based circuits the charge stored in the output capacitance [3] and the reverse recovery charge is commanding the losses. While Superjunction devices are optimized for an extremely low $E_{OSS}$ figure of merit, GaN HEMTs offer a much more favorable $Q_{OSS}$ figure of merit, with the first generation already being one order of magnitude better than their silicon counterparts.

# 3 Application examples: universal mobile device charger

To evaluate, quantitatively, the performance improvements offered by wide bandgap power devices, multi-objective optimizations were performed for each application. This method allows us to consider all available degrees of freedom in the converter design such as various topologies, interleaving of stages, switching frequencies, and semiconductor usage, and yields as a result for each potential design efficiency and power density. Such an analysis reveals an envelope function with all Pareto optimal designs and allows an assessment of the trade-off between efficiency and density for an entire application [4].

## 3.1 Asymmetrical flyback converter

The growing popularity of mobile electronic devices such as laptop, mobile phones, tablets, e-book readers and smart watches has led to a wide range of different charger types. In order to reduce electronic waste and to simplify the user experience, the need for a universal adapter with high efficiency and high power density has become evident. For this purpose the USB-PD standard has been introduced which supports a wide range of output voltages (5 V to 20 V) with power levels up to 65 W.

To identify the most suitable topology for a high density USB-PD adapter, several topology options have been evaluated by means of multi-objective optimizations.  The considered topologies include: PFC flyback with secondary side power pulsation buffer, flyback converter with a fixed (high) output voltage and subsequent buck converter, flyback converter with wide output voltage range, cascaded asymmetrical PWM flyback converter where the primary side consists of two cascaded half-bridges, and asymmetrical PWM flyback converter. The optimization results are showed in Figure 4 for full load operation at worst case input voltage ($V_{in}$ = 90 V) and highest output current ($I_{out}$ = 4 A). In addition, the thermal limit line is showed, which defines the minimum efficiency required for a given power density in order to keep the surface temperature of the adapter below 70 °C. Only designs above this line possess the necessary efficiency required to dissipate the generated heat passively (i.e., natural convection and radiation) without exceeding the thermal limit of the case. This clearly shows that the target of highest power density is inevitably linked to highest conversion efficiency, underlining the necessity of a comprehensive multi-objective optimization approach.

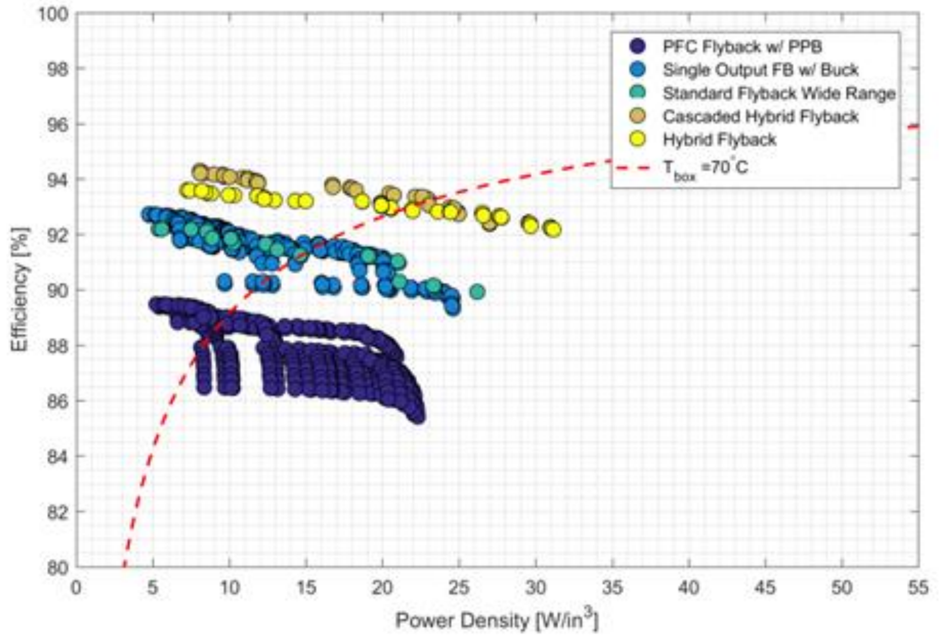

**Figure 4** **Multi-objective optimization results of several different adaptor concepts for full load ($P_{out}$ = 65 W), $V_{out}$ = 20 V, and low line ($V_{in}$ = 90 V) operation**

The optimization results reveal the asymmetrical flyback (see Figure 5) is the best suited topology among the considered candidates for highly compact chargers since it offers the highest efficiency. This topology features ZVS of the primary side half bridge by utilizing the magnetization current, and ZCS of the synchronous rectification switch, laying the foundation for highest conversion efficiency. The converter is operated with a fixed on-time of the low-side switch of the primary half-bridge, which is determined by the resonance frequency, and a varying on-time of the high-side switch, which depends on the output voltage [5]. This results in a varying switching frequency.

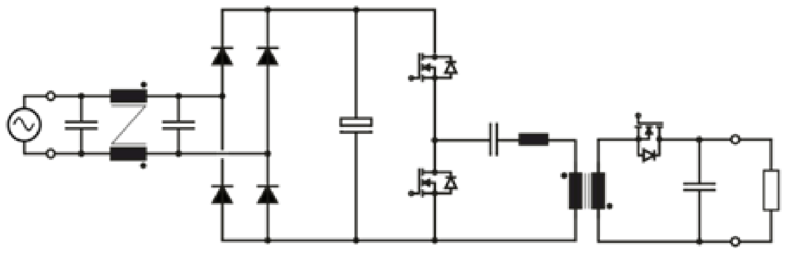

**Figure 5** **Asymmetrical PWM flyback with synchronous rectification**

Based on the optimization results, a 65 W prototype employing 500 V/140 mΩ MOSFETs has been developed (see Figure 6) [6]. It supports USB-PD with different output voltage profiles ranging from 5 V / 3 A to 20 V/ 3.25 A. The operation frequency varies from 100 kHz to 220 kHz depending on the input and output voltages. The prototype achieves a maximum efficiency of 94.8 percent, while the lowest full-load efficiency at $V_{in}$ = 90 V is 93 percent as showed in Figure 9.

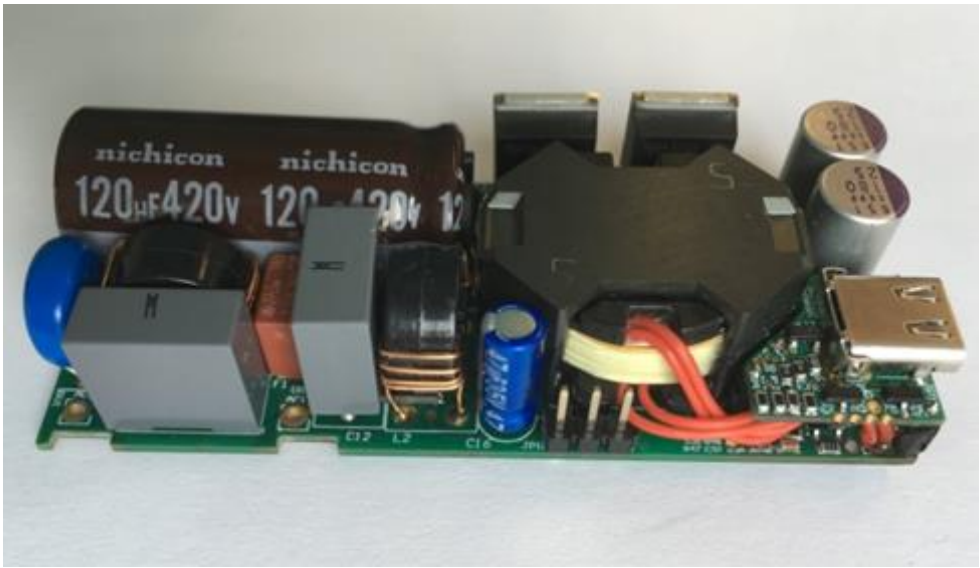

**Figure 6** **Prototype of the 65 W USB-PD adapter based on the asymmetrical PWM flyback topology. The prototype features a power density of 27 W/in$^3$ (cased: 20 W/in$^3$).**

## 3.2 Modes of operation

The operation of the asymmetrical PWM flyback converter can be explained by using four phases as showed in Figure 7:

- Phase 1: energy storage phase
- Phase 2: dead time 1
- Phase 3: energy transfer phase
- Phase 4: dead time 2

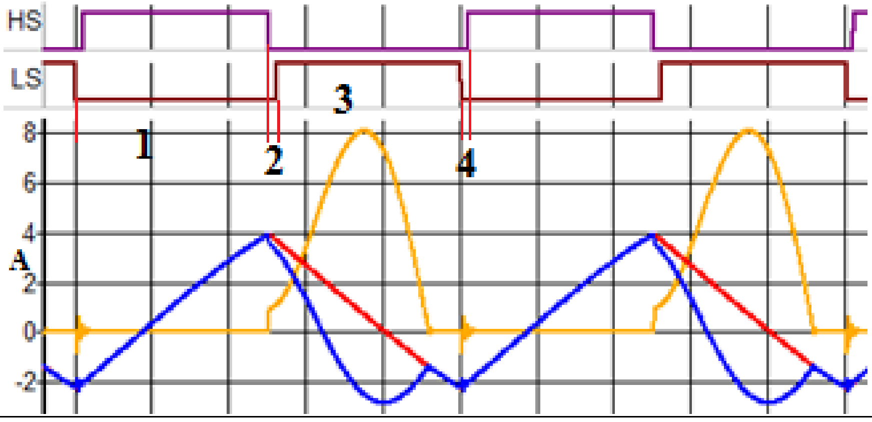

**Figure 7** **Typical waveform of the Asymmetrical PWM fly-back (blue: LC tank current, red: magnetizing current, yellow: secondary current)**

Phase 1:

During this first phase the high-side switch is turned on and the low side switch is turned off. The transformer current increases and resonant capacitor $C_r$ gets charged. The secondary diode is not conducting. No energy is transmitted to the secondary side.

Phase 2:

In this phase both switches are turned off. The current in the transformer will force the half bridge middle point to drop until the body diode of the lower MOSFET clamps the voltage.

Phase 3:

During the so called energy transfer phase, the low-side switch is turned on under ZVS condition. The high side switch remains turned off. The voltage in the transformer has reversed; therefore, the secondary diode starts to conduct. The energy stored in the transformer and the resonant capacitor is transferred to the output. The secondary side current is sinusoidal with a resonant frequency which is defined by the resonant capacitor and the leakage inductance of the transformer. For reduced conduction losses on the secondary side, a synchronous rectification MOSFET is used.

Phase 4:

In this last phase both transistors are turned off again. The current in the transformer will now force the half bridge middle point to increase its voltage. That will lead to turning on the high side switch under with ZVS condition.

In a standard flyback converter or in an active clamp flyback converter the transformer always has to store all the needed energy. This can lead to a non-optimized transformer size because of the required input voltage range.

In the asymmetrical flyback converter the energy storage, as well as the energy transfer from the primary to the secondary side, is shared between the resonant capacitor and the transformer. Therefore, the size of the transformer can be reduced significantly.

As showed in Figure 8 the amount of transferred energy from the transformer and the resonant capacitor depends on the input voltage. The higher the input voltage the more energy is transferred from the transformer to the output.

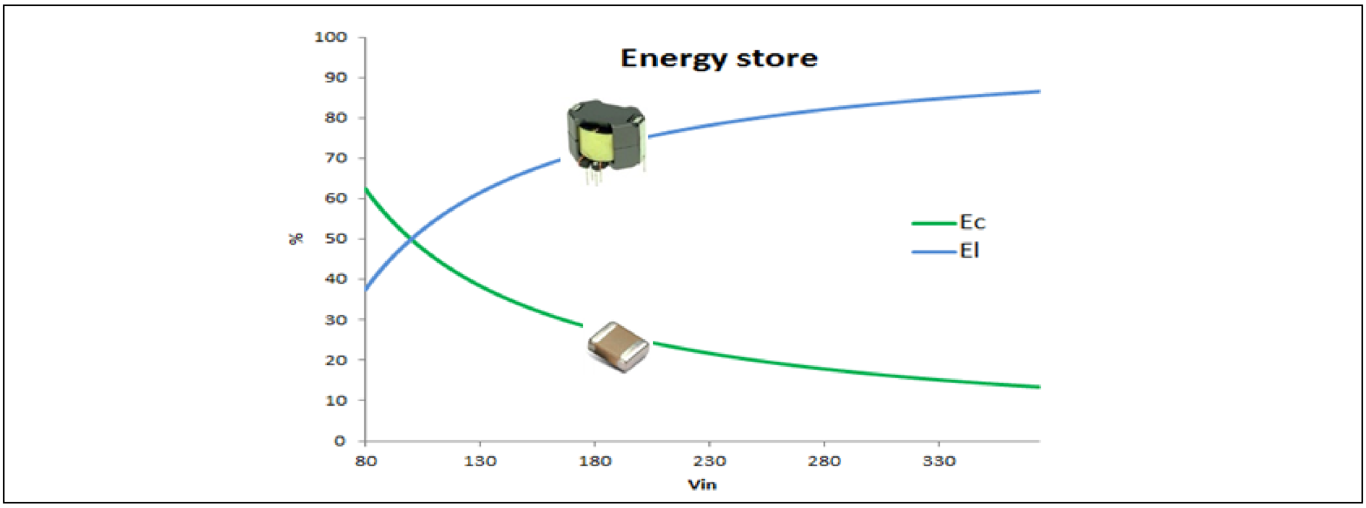

**Figure 8** **Energy sharing between transformer and resonant capacitor over input voltage**

To push the power density to even higher levels, the use of GaN HEMTs becomes mandatory, as they allow the efficiency of the converter to be increased, and thus to move away from the thermal limit. The first advantage of GaN is given by the greatly reduced $Q_{OSS}$ charge, which enables ZVS with lower magnetization current. Thus, the conduction losses in the switches, as well as the transformer can be reduced. Furthermore, due to the lower gate charge, the gate driving losses are reduced. Last but not least, the losses associated with the charging/discharging of $C_{OSS}$ capacitance of the switches during ZVS are also lower in GaN HEMTs than in Superjunction MOSFETs [7]. As a result, the efficiency of the entire system can be increased by around 0.4 percent at full load over the entire input voltage range, as depicted in Figure 9.

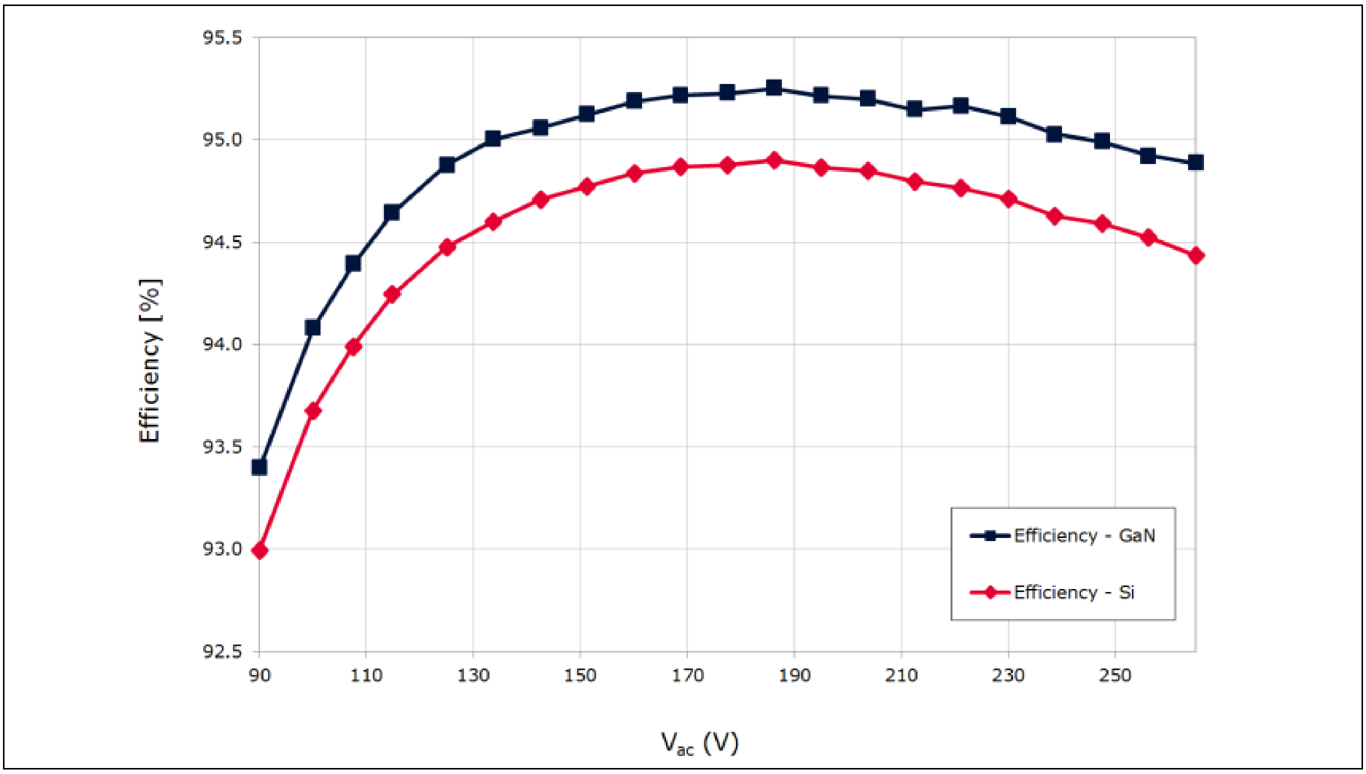

**Figure 9** Red curve: measured full load efficiency ($P_{out}$ = 65 W) of the prototype in dependency of the input voltage for an output voltage of $V_{out}$ = 20 V. Blue curve: efficiency improvements possibility with 600 V/190 mΩ GaN HEMTs instead of 500 V/140 mΩ Si MOSFETs.

# 4 Summary

The proposed resonant half bridge flyback converter has been identified as the most promising topology for highly efficient and compact USB-PD adaptors. This concept offers on one hand a very efficient operation due to ZVS and ZCS switching of the primary and secondary switches and on the other hand an easy controllability of the output voltage by adjusting the duty cycle.

The application studies performed show a clear value for e-mode GaN HEMTs in adapter and charger applications. GaN HEMTs allow us to push both efficiency and density frontiers.
For mobile applications GaN offers hitherto unachievable small form factors beyond 20 W/in$^3$ for 65 W USB-PD adapters.

For Infineon’s CoolGaN™ portfolio of switches and dedicated GaN EiceDRIVER™, please visit www.infineon.com/gan and www.infineon.com/gan-eicedriver.

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