Whitepaper
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A full-GaN solution for high power density chargers and adapters

Using GaN HEMTs in USB-C PD synchronous rectifiers: Methodology & design guidelines

Abstract

Due to the continuous demand for high power density, USB-C fast chargers' switching frequencies need to be increased to reduce the size of the transformers and the filter components. Emerging technologies based on Wide Band Gap (WBG) semiconductor materials enable new approaches to increase power density. At high switching frequencies, GaN HEMTs for synchronous rectifier (SR) switches have the advantages of lower charges and faster switching transitions. In addition, the size of a GaN HEMT is smaller than that of a Silicon (Si) MOSFET for the same voltage rating and on-resistance. Despite these clear advantages, state-of-the-art systems still use MOSFET SR. But what is the reason behind this?

The relatively high third quadrant (body diode) mode voltage drop of GaN compared to MOSFETs introduces higher conduction losses during turn-on/-off delay times. These "dead-time" losses increase with higher switching frequencies. To minimize these losses, the controller circuit must be GaN-optimized to shorten the delay for turn-on and turn-off gate biasing. State-of-the-art SR controllers have delay times on the order of tens to hundreds of nanoseconds. This introduces significant losses in topologies like LLC, Active Clamp Flyback (ACF), and especially in the Quasi-Resonant (QR) Flyback. Even with a well-optimized controller, the delay times could be quite long, still in the order of tens of nanoseconds, due to PCB layout parasitics that affect the accuracy of drain-source voltage (VDS) sensing and reaction time of the SR controller. However, by addressing the issues during the design process, the full potential of GaN in SR applications can be realized.

This paper presents the methodology of using GaN HEMTs for SR in USB-C PD charger and adapter designs. First, we provide an overview and comparison of the most common charger & adapter topologies used in the market. Then synchronous rectification characteristics are discussed, and design tips for using GaN HEMT as SR are provided. Finally, we introduce Infineon's 65 W Full Gan ACF converter Evaluation Board.

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1 GaN HEMTs in high power density chargers and adapters

In recent years, the ever-growing usage of mobile electronic devices has led to increased electronic waste due to the wide range of charger/adapter types with different power levels. In order to reduce e-waste and improve user experience, there is currently a joint effort from associations and the European Union towards the standardization of charging ports for most electronic devices. In that case, it is not only the demand for higher power density greater than 20 W/in³ in charger/adapter designs but also the demand for various power levels, starting from tens of Watts, including 65 W, and reaching possibly hundreds of Watts in the near future. Higher power density in power electronics is possible mainly by increasing the switching frequency, which results in smaller magnetics and filter components. However, efficiency should also be increased accordingly as the charger/adapter case temperature is typically limited to a certain value (e.g., 60ºC), and with more compact designs, the available area to dissipate the losses reduces.

Higher efficiency at higher frequencies is only possible by selecting the proper topology with an optimum design using the right components. So far, silicon MOSFET technology has been a popular choice for both primary and secondary sides. GaN HEMTs are beginning to be used on the primary side due to lower gate charge, and device output charge values an order of magnitude lower than superjunction (SJ) MOSFETs. This opens a way to apply them in higher switching frequencies with an easier implementation of zero voltage switching (ZVS) [1]. As shown in Figure 1, the GaN HEMT stores much less output charge than SJ MOSFET. This is a critical parameter in soft switching, especially in high line where the amount of charge to be removed increases significantly. Faster switching times with lower gate and output charge, lower on-resistance, no reverse recovery, and smaller packages with system-on-chip (SoC) solutions make GaN-based primary switching attractive for future charger designs.

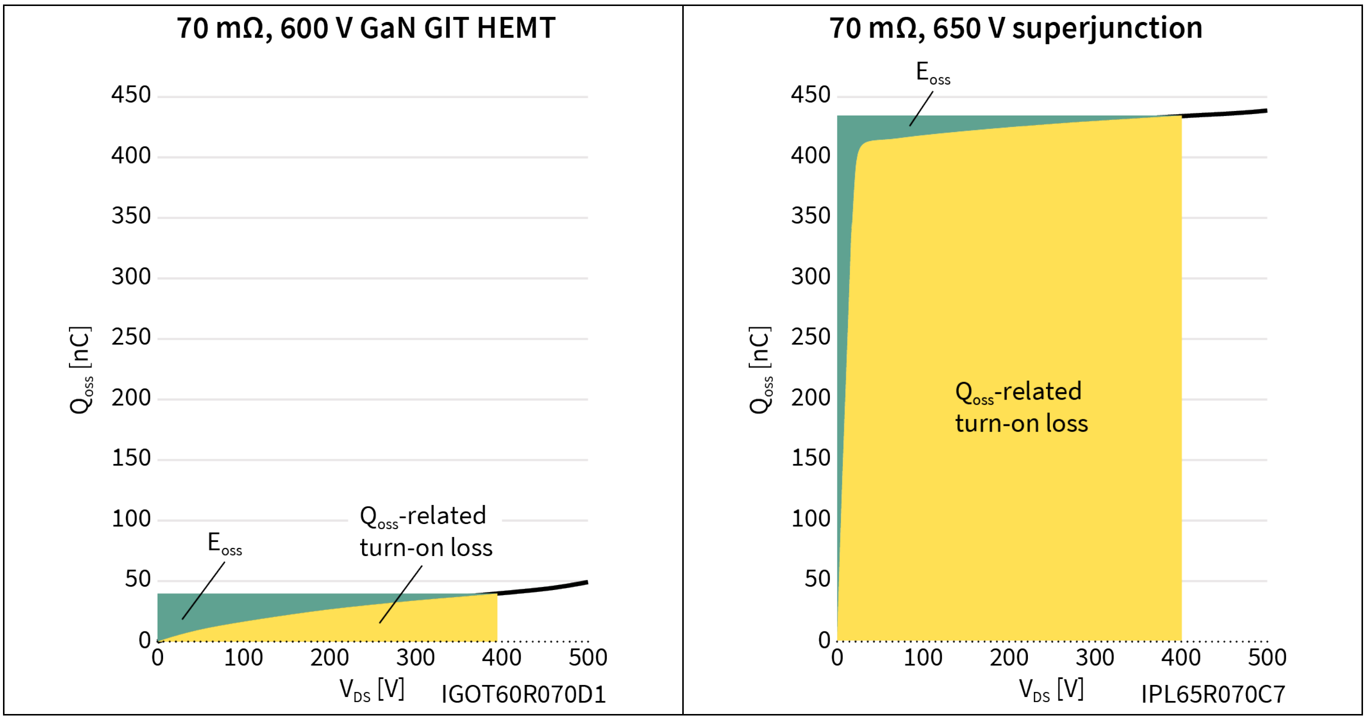

Figure 1 GaN HEMT vs. silicon superjunction (SJ) MOSFET. Stored energy and Q_{OSS}-related loss

Regarding the secondary side, until now, silicon MOSFETs have been used in almost every charger design regardless of the preferred topology and switching frequency. Although GaN HEMTs have significant advantages over silicon MOSFETs, they have typically not been preferred as a synchronous rectifier (SR) for chargers. This is mainly because GaN-based SR designs need special attention for the topology selection, turn-on/-off delay times, and PCB layout. Considering higher current levels on the secondary side for the same power level, compared to the primary side GaN HEMT usage, "body diode" mode conduction (source-drain conduction without gate triggering) losses are more severe. This affects the high-frequency performance of GaN HEMT SR, which is expected to be high due to the low gate charge and output charge.

2 Overview of topologies for charger designs

Various topologies have been preferred in charger/adapter designs depending on price, simplicity, and higher demand for power density. Figure 2 shows the wide range of Infineon's system solutions for charger/adapter applications [5]. If the required power level is lower than 65 W, a single-stage flyback converter-based design is almost always the case since no PFC pre-regulation is necessary up to this power level. However, above 65 W grid compliance is required, which increases the complexity of the design as well as the price and overall size due to the inclusion of the PFC stage.

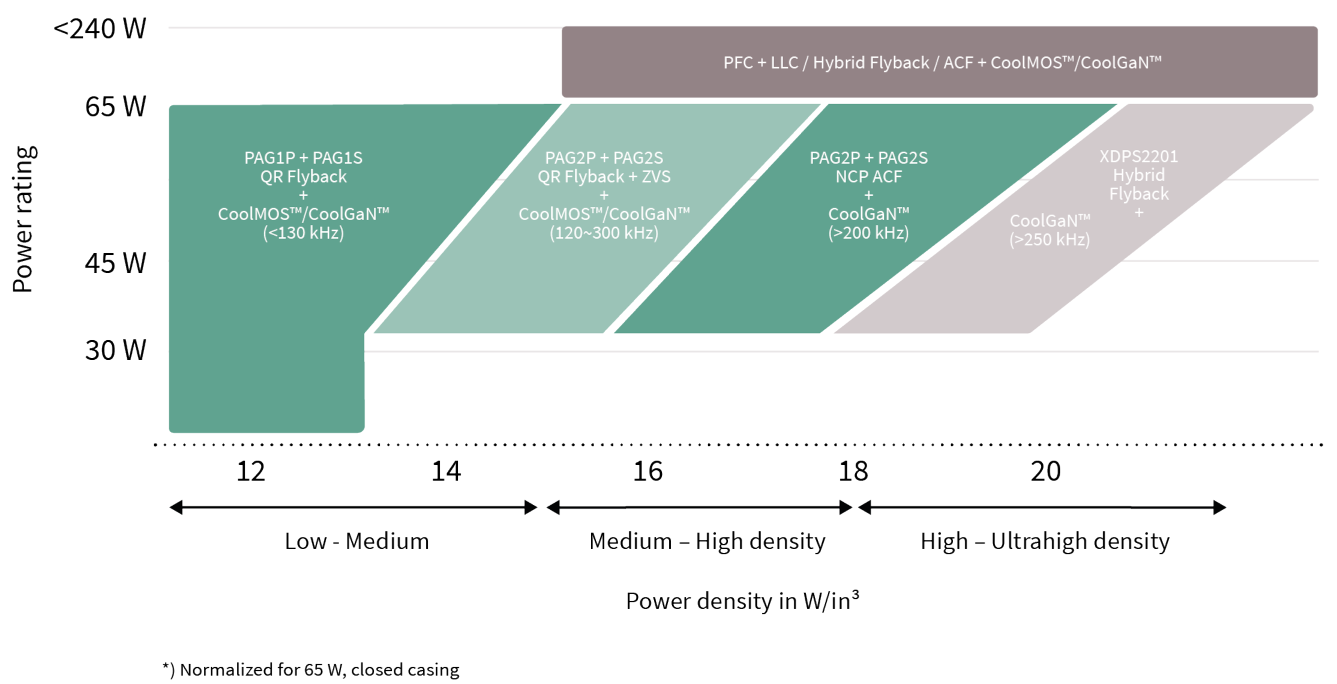

Figure 2 Infineon's system solutions for chargers and adapters [5]

Despite being the simplest and lowest-cost solution of all isolated topologies, conventional flyback has some shortcomings. These are related to the following:

- Primary FET voltage stress during turn-off,
- Hard turn-on of the primary FET,
- Energy trapped in the leakage inductance being dissipated as heat,
- High RMS currents both in primary and secondary sides,
- Partial utilization of transformer.

Different variations of the flyback topology have been introduced to overcome some of these disadvantages. However, improvements in topology and control result in increased complexity and cost. For instance, it is possible to relieve the primary FET voltage stress by clamping its V_{DS} to a capacitor with the help of another FET, as in the Active Clamp Flyback (ACF) topology, which will be explained later.

It is also possible to further reduce the primary FET voltage stress using the Hybrid Flyback (HFB) topology, which employs a dedicated controller [4]. If the additional high-side FET needs to be avoided for simplicity or lower cost, the quasi-resonant (QR) flyback topology is recommended, reducing turn-on losses through the valley switching method. A complete ZVS is achievable with ZVS QR Flyback by injecting extra energy into the transformer to force ZVS event.

Table 1 Comparison of topologies for charger/adapter designs

	QR flyback	ZVS QR flyback	Active clamp flyback (ACF)		Hybrid flyback (HFB)
			Complementary (CP)	Non-complementary (NCP)	
Full-load efficiency (low line)	✓	✓	✓✓✓	✓✓	✓✓✓
Full-load efficiency (high line)	✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Light-load efficiency (due to circulating energy)	✓✓✓	✓✓✓	✓	✓✓✓	✓
Cost	✓✓✓✓	✓✓✓	✓	✓✓	✓
Leakage energy	Lost	Lost	Recuperated	Recuperated	Recuperated
ZVS switching	Partially	Almost	Full	Almost	Full

2.1 Quasi-resonant (QR) flyback

The QR flyback topology is commonly preferred in charger/adapter applications due to its simplicity and low cost, in addition to easier control and better transient response. It utilizes the valley-switching operation, which reduces the turn-on losses significantly. However, these losses partially remain, especially in the high line where the input voltage exceeds 220 VAC. On the other hand, QR flyback has high efficiency in light load, which is an important parameter in charger/adapter designs. However, the operation of QR flyback is only possible in discontinuous conduction mode (DCM), and the transformer leakage energy is clamped through an RCD snubber. This implies high peak and RMS currents in QR Flyback compared to resonant-type converters with a sinusoidal current shape.

Another important detail is the variable frequency operation of the QR flyback, which requires special attention in EMI filter design. Apart from this, there is the ZVS QR flyback, which ensures lossless turn-on of the primary side switch, significantly improving efficiency, especially at the high line, compared to the QR flyback. Reaching frequencies up to 300 kHz with enhanced efficiency and higher power density is also possible.

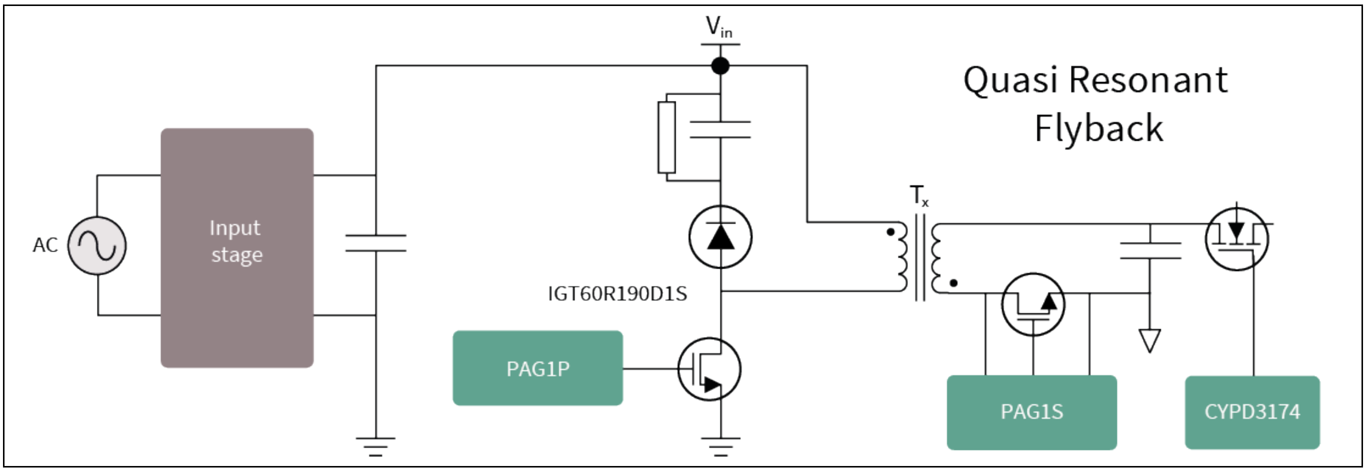

Figure 3 Quasi-resonant (QR) flyback converter

2.2 Active-clamp flyback (ACF)

A popular flyback topology that offers ZVS for the FETs is the Active Clamp Flyback (ACF) converter. This topology is suitable for higher frequency operation than the QR flyback due to the ZVS operation and complete recovery of the energy in transformer leakage inductance which is dissipated in the QR flyback RCD clamp. ACF also has good EMI performance regarding ZVS operation and clamping of the primary FET voltage through the clamp capacitor.

There are two types of ACF control schemes, complementary (CP) mode and Non-Complementary mode (NCP). In CP mode, the main Flyback switch and Clamp switch are turned on/off alternatively to complement each other in every switching cycle, and the transformer current waveform is similar to a sinusoidal shape. Both the main Flyback switch and Clamp switch are under ZVS switching. With CP mode, the switching frequency keeps on rising with load decrease. This may have an impact on light load and standby efficiency as well as EMI. Additionally, the full resonant current in the resonant tank increases the conduction loss in the transformer.

To overcome the increased conduction loss and improve the light-load efficiency, NCP ACF is used. NCP ACF operates the active clamp FET so that it only turns on to accumulate enough magnetic energy to ensure the main FET ZVS operation. This way, the circulating clamp capacitor currents are mitigated.

A few analog ACF controllers exist in the market. Some of them can only support either CP or NCP, but not both types of operation.

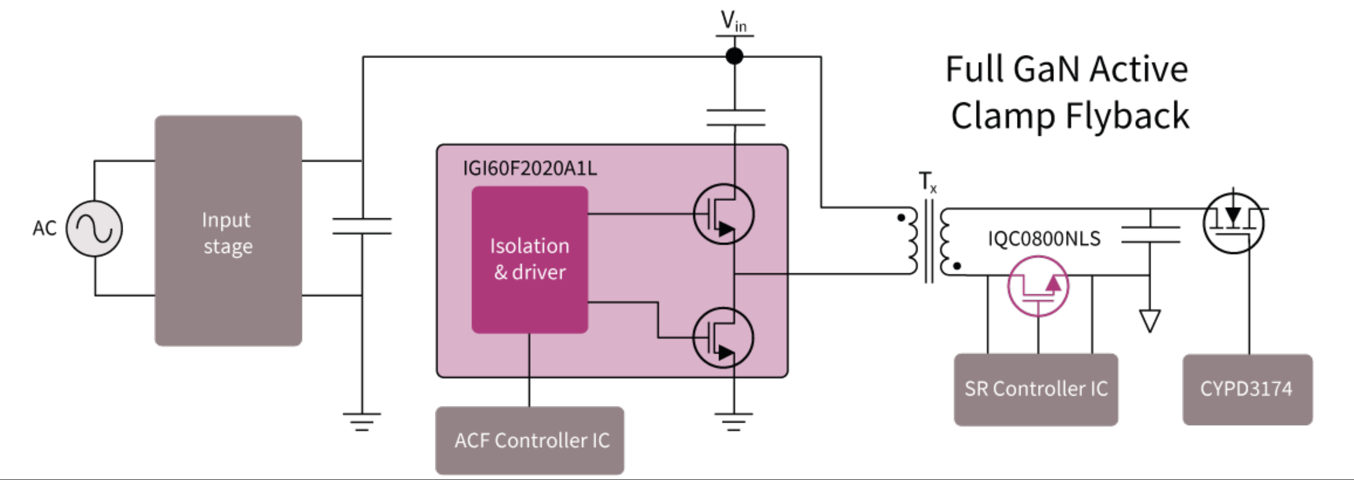

Figure 4 Active-clamp flyback (ACF) converter

2.3 Hybrid flyback (HFB)

Another resonant topology with ZVS and ZCS operation is Hybrid Flyback (HFB) converter. The primary side circuit is similar to the LLC converter, which is based on the resonant operation. Similar to ACF, using HFB, high-frequency operation with high efficiency is possible due to ZVS operation and lower RMS currents, thanks to the resonant type current waveforms. In addition, transformer energy storage of HFB is less since the resonant capacitor helps in energy storage. This opens the way to reduce the transformer size compared to the other pure flyback-based topologies and other flyback-type topologies. The voltage stress over the FETs is even better than ACF, thanks to the half-bridge structure with a self-voltage clamp to V_{bus} on the primary side. HFB has an additional FET on the primary side compared to QR flyback which requires special care for the light-load efficiency due to the circulating currents of the resonant type operation. Also, special design effort is needed for the universal input specifications. Control complexity is higher in HFB than in QR flyback; however, Infineon's XDPS2201 [4] solves the control challenges through a dedicated control algorithm.

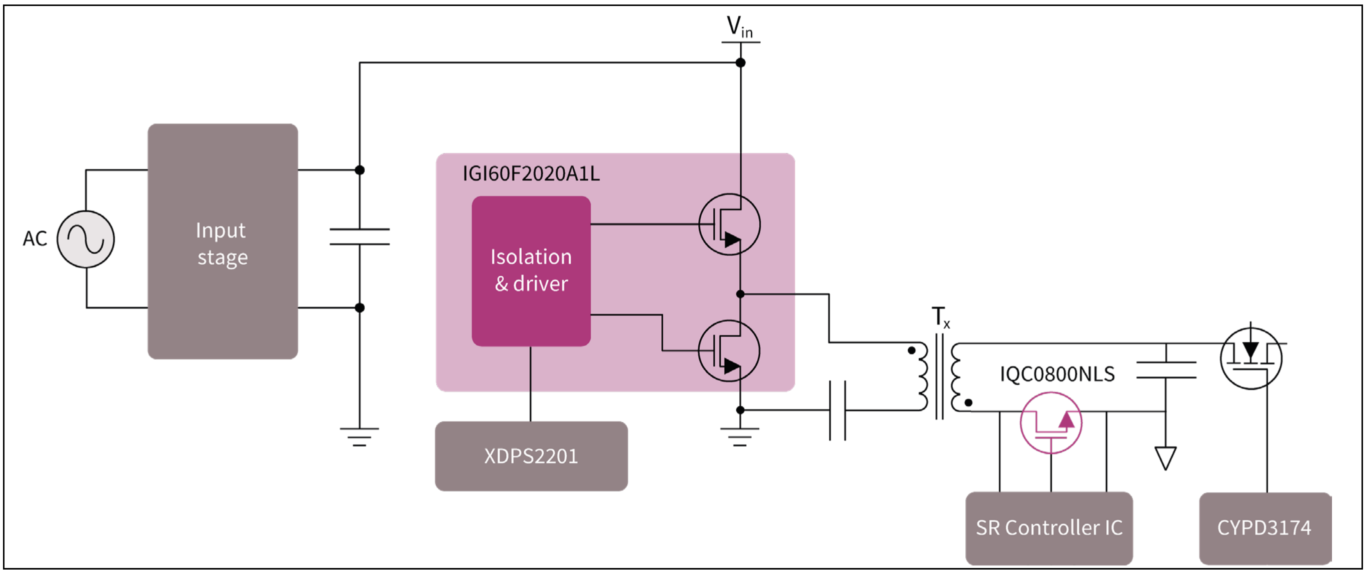

Figure 5 Hybrid flyback (HFB) converter

3 Characteristics of a synchronous rectifier (SR)

The aforementioned modern charger topologies have an SR switch instead of a diode. In this section, SR characteristics will be analyzed to make the correct positioning of GaN HEMTs. Using a GaN HEMT as SR requires special attention regarding the device properties, topology selection, and layout. In order to utilize the advantages of GaN HEMT used as SR, especially in high switching frequencies where GaN HEMTs are superior considering gate charge and output charge, certain design effort is required regarding turn-on/-off delay times as well as the PCB layout.
Losses of an SR are mainly composed of three components:

- $P_{cond} = R_{DS(on)} \times I_{SRrms}^2$
- $P_{delay} = T_{delay} \times V_{sd} \times I_{SR} \times F_{sw}$
- $P_{gate} = Q_g \times V_{gate} \times F_{sw}$

Conduction loss (P_{cond}) is proportional to the square of the SR RMS current (I_{SRrms}) and the on-resistance ($R_{DS(on)}$) of the SR FET. Here, the temperature dependency of the $R_{DS(on)}$ should be considered, as well as the current waveshape, which is highly dependent on the selected topology. An important loss contributor, especially for GaN HEMT, is the "body diode" mode conduction loss (P_{delay}) which is proportional to the voltage drop as well as the turn-on/-off delay times. In reality, the "body diode" mechanism of GaN HEMTs differs from the one in MOSFETs. There is no PN junction, so the "body diode" of GaN HEMTs has no reverse recovery. On the other hand, the V_{sd} voltage drop is around three times higher than MOSFET, which needs special attention when used as an SR switch.

In addition, the converter topology plays an important role due to the SR current waveshape difference between topologies. For instance, Figure 6 shows a typical SR current waveshape of a QR flyback converter together with V_{DS} and V_{GS} voltages where a triangular-shaped current is observed due to the discontinuous nature of the QR flyback operation. This results in a significant current flow during the turn-on delay time of the SR FET while the gate is not triggered.

The duration of the body diode conduction mode depends on the controller sensing scheme, signal propagation delay, and C_{OSS} behavior. MOSFETs have a non-linear C_{OSS} showing higher capacitance at lower V_{DS} voltages, which reduces the body diode conduction time for a MOSFET SR by delaying the start of it before the SR turn-on. This reduces the effect of the increased losses caused by the SR controller IC's delay on the turn-on of the SR as it gives the SR controller IC more time to react. On the other hand, due to the smaller and more linear C_{OSS} of GaN HEMTs compared to MOSFETs, C_{OSS} discharging will be faster during the V_{DS} falling edge. With a fixed SR controller delay for both cases, body diode conduction will have a longer duration for a HEMT than for a MOSFET, as shown in Figure 7. This figure shows that for the same SR controller IC, GaN HEMT SR has more than double the "body-diode" conduction time compared to MOSFET SR. Therefore, to take full advantage of the GaN HEMTs, minimizing these losses by reducing the SR controller delay is crucial.

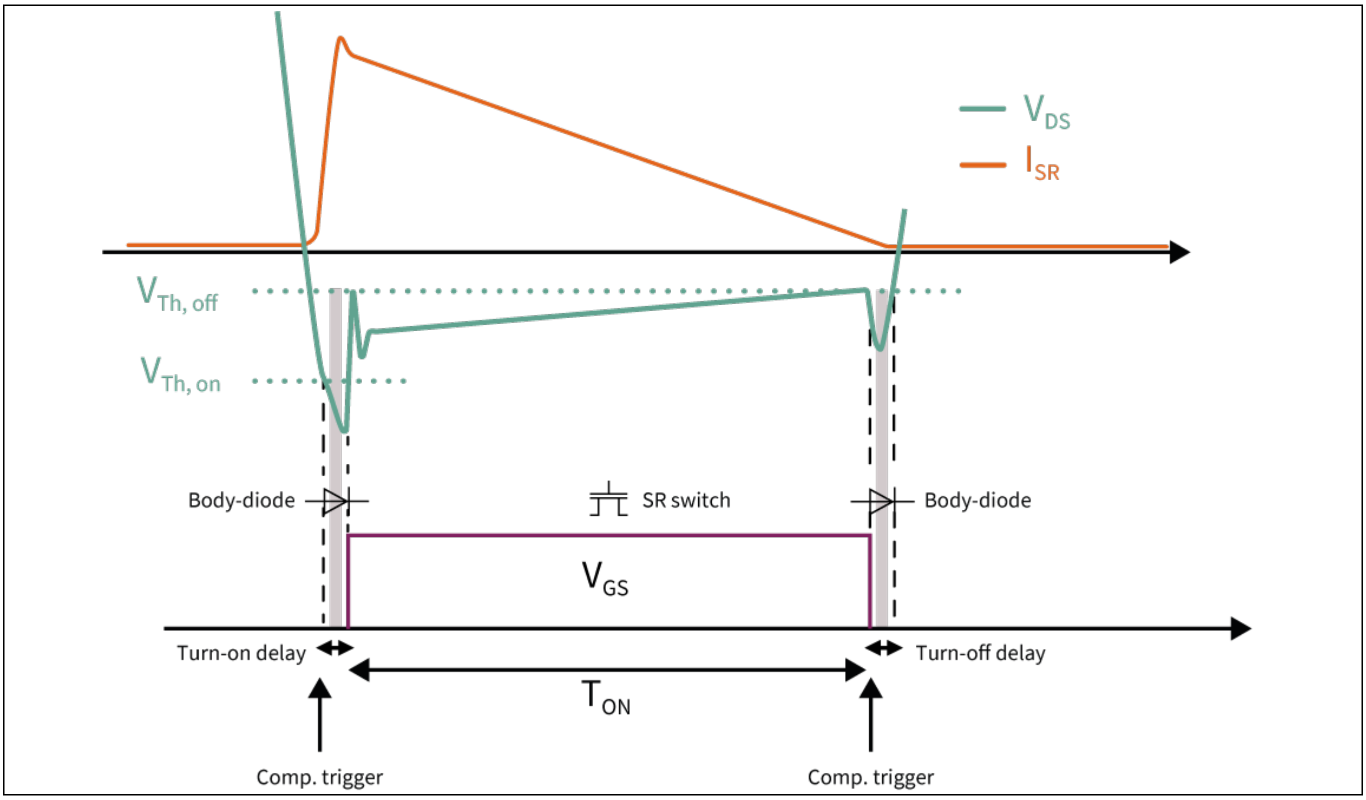

Figure 6 QR flyback SR waveforms and turn-on/-off timing

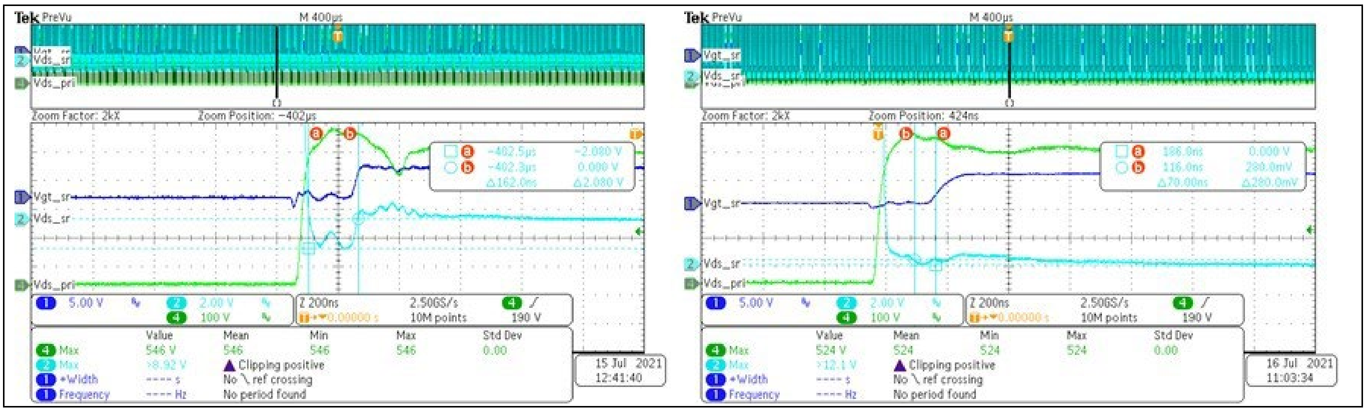

Figure 7 GaN HEMT (left) vs. MOSFET (right) turn-on instants of QR flyback SR.

Some flyback topologies that operate similarly to resonant converters, such as ACF and HFB, have sinusoidal current waveforms, as depicted in Figure 8. Compared to the QR Flyback, the instantaneous current passing through the body diode of the SR FET during SR turn-on/-off delay is lower in the ACF and HFB because of their sinusoidal SR current waveshape. As a result, the effect of the “body diode” loss during SR turn-on/-off delay will not be so severe with GaN HEMT SR in ACF or HFB compared to QR Flyback. This implies that, with the proper topology selection, it is possible to reduce the negative effect of turn-on/-off delay times for GaN HEMT SR.

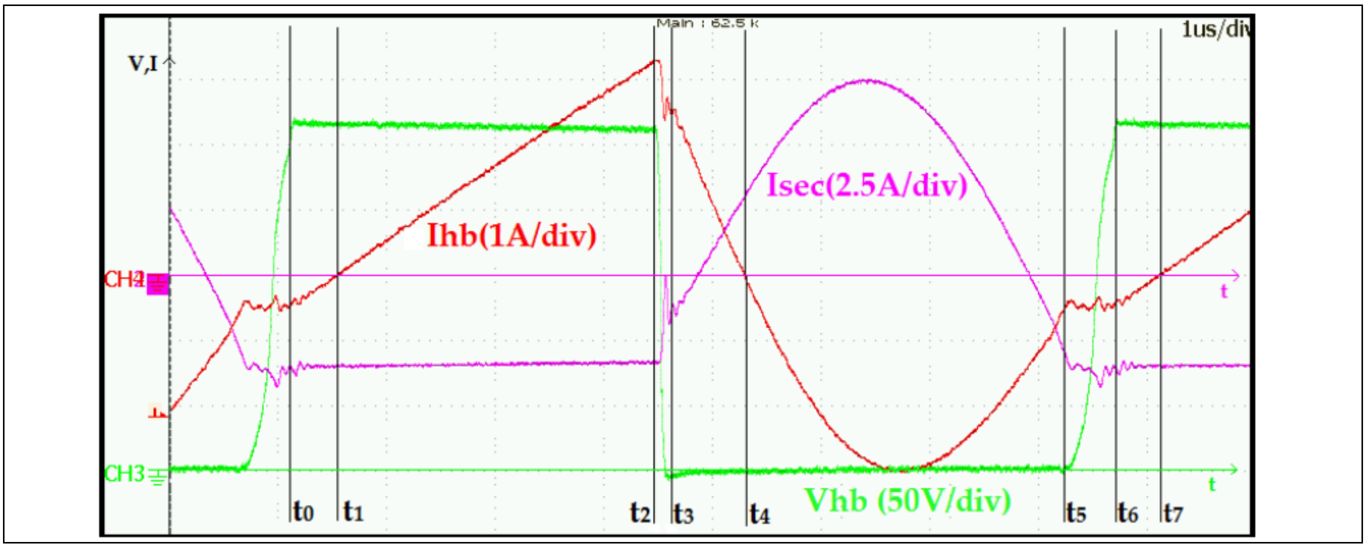

Figure 8 Hybrid flyback waveforms. I_{hb}: tank current, V_{hb}: half-bridge middle point voltage, I_{sec}: SR current [3]

Another frequency-related loss contributor for SR FETs is the gate drive loss. Here, GaN HEMTs have a clear advantage over MOSFETs since the gate charge is significantly lower. Infineon Technologies CoolGaN™ SG HEMT 100 V IQC0800NLS is driven with 5 V and has a 10 nC total gate charge, which is up to seven times lower than a MOSFET with a similar $R_{DS(on)}$ value. Due to the dependence on the frequency, the contribution to the overall SR loss will be more significant in higher frequencies, as shown in Figure 9.

This graph compares a 100 V CoolGaN™ SG HEMT and a MOSFET with a similar $R_{DS(on)}$ value for a 65 W ACF charger with 20 V output. Here a constant 50 ns delay time has been assumed for both cases. The MOSFET is assumed to be driven with 10 V gate voltage to ensure the datasheet $R_{DS(on)}$ value, whereas the GaN HEMT is driven with 5 V. It can be observed that frequency-related losses dominate the MOSFET SR losses, becoming even more significant in higher frequencies. Based on Figure 9, we can conclude that GaN HEMTs have a visible advantage at higher frequencies as long as the turn-on/-off delay times are kept small. This is mainly due to the lower device charge value of GaN HEMTs compared to MOSFETs with similar $R_{DS(on)}$.

Figure 10 shows the loss distribution of both SR devices for the same 65 W ACF charger at 300 kHz full load, where the output delivers 3.25 A at 20 V. It can be concluded that GaN HEMTs have a beneficial potential in high switching frequency chargers as long as the turn-on/-off delay times are minimized. It is important to note that BSC35N10NS5 is selected for device comparison, with a similar $R_{DS(on)}$ value as the IQC0800NLS. However, it can be observed in Figure 10 that gate charge-related losses significantly dominate the MOSFET SR losses due to higher gate drive voltage which also increases the total gate charge value. This implies that a logic-level MOSFET would be a good candidate at higher switching frequencies for a fair comparison.

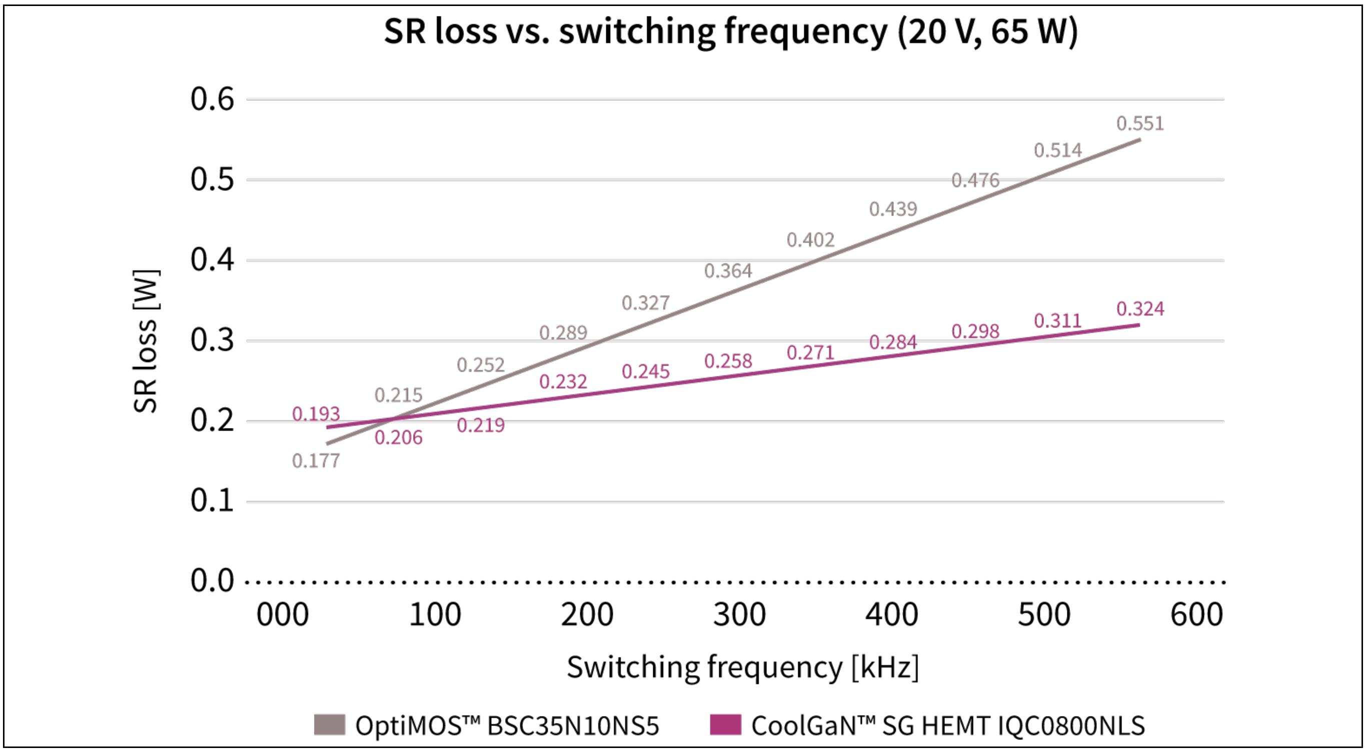

Figure 9 **SR loss vs. switching frequency for CoolGaN™ SG HEMT 100 V IQC0800NLS and BSC035N10NS5 MOSFET for a 65 W ACF charger**

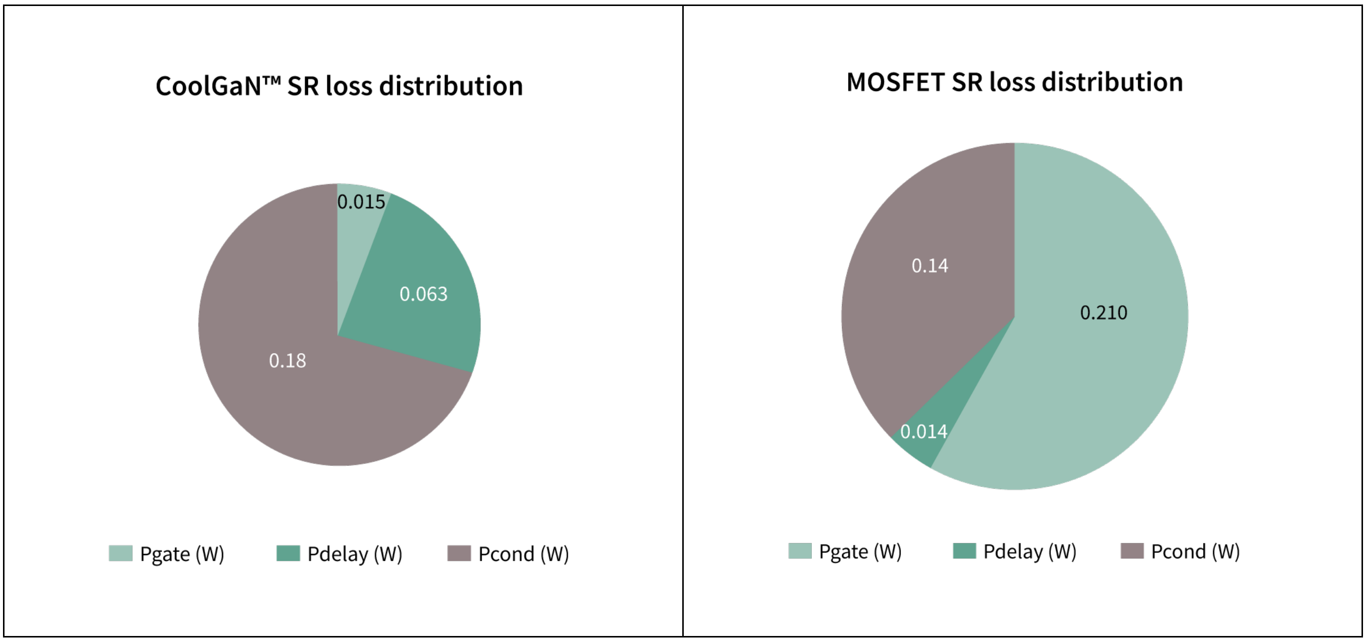

Figure 10 **SR Loss (W) distribution of CoolGaN™ SG HEMT IQC0800NLS (left) vs. BSC35N10NS5 MOSFET (right) as SR at 300 kHz F_{SW}**

An important detail in minimizing the GaN SR “body diode” losses due to turn-on/-off delays are related to the inductances due to the PCB layout and device package. Similar to the common-source inductance effect that changes the gate voltage due to the inductive voltage drop on the source pin, the V_{DS} sensing of the SR controller may also be affected due to the inductive voltage drop, especially at higher frequencies resulting in a phase shift in the sensed signal. Given a threshold-based secondary SR control, this phase shift could introduce an error in the turn-off delay time, leading to increased conduction time of the FET body diode. Figure 11 shows a simulation result with different drain (L_d) and source (L_s) inductances where a sinusoidal current flows through the SR FET at 500 kHz with a 50 percent duty cycle. It can be observed that, at these frequencies, sensed V_{DS} voltage waveform is modified significantly with the package and layout-related inductances, even if the values are below 1 nH.

The phase shift effect shown in Figure 11 may significantly change the turn-off and turn-on times of the SR switch depending on the switching frequency. It can be concluded that using an SR switch with a package inductance of more than an nH may result in up to hundreds of nanoseconds of earlier SR turn-off. In turn, this will result in a significant amount of current flowing through its body diode instead of its channel at frequencies close to 500 kHz and higher. In this case, a good V_{DS} measurement layout will not be enough to minimize this effect. Infineon's CoolGaN™ SG HEMT 100 V IQC0800NLS has a package with extremely small inductance, significantly improving this drawback.

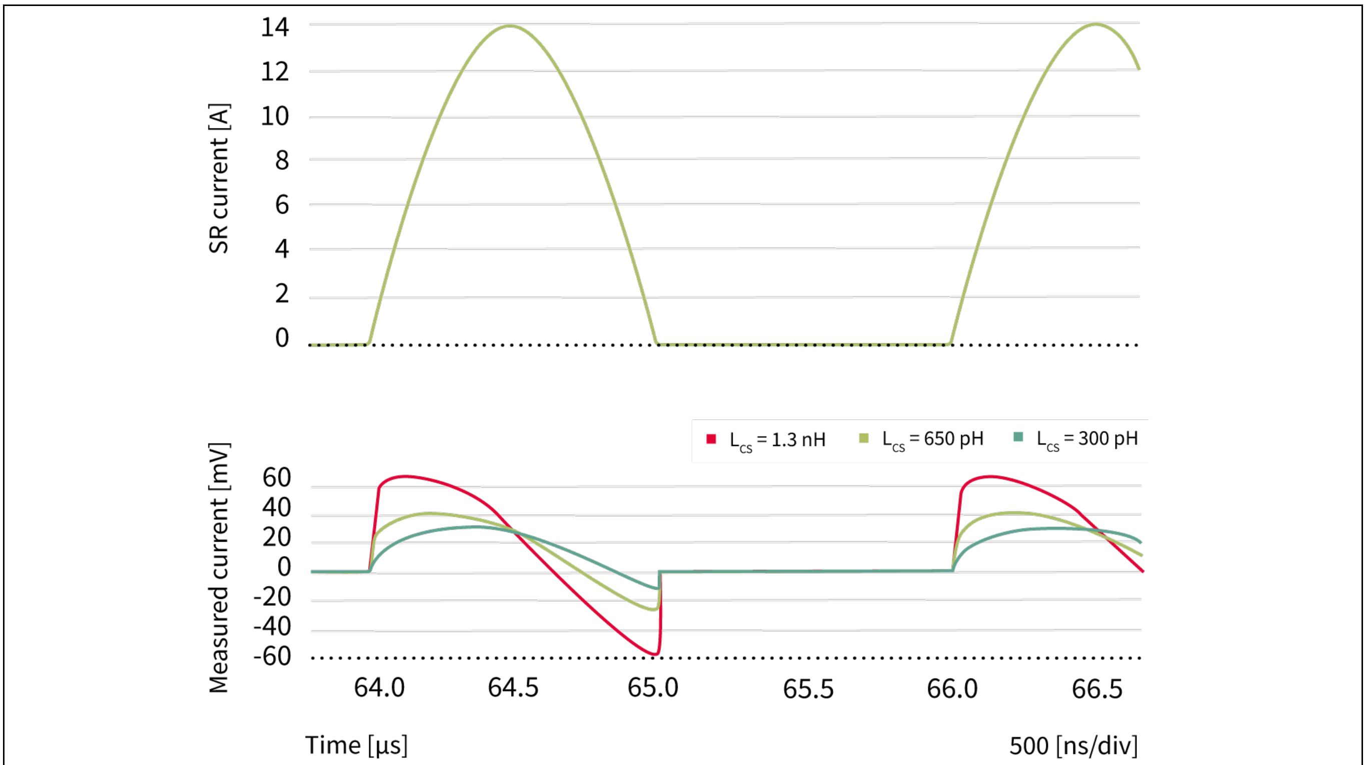

Figure 11 V_{DS} **sensing phase shift effect in high frequencies due to common source inductance (**L_{CS}**)**

Careful PCB layout is crucial in high-frequency circuit design. This is also well-known to SMPS designers since FET dv/dt and di/dt values determine EMI performance as well as switching losses. When a GaN HEMT is used, the PCB layout becomes even more critical since dv/dt and di/dt values become even higher, and the need for a thorough design increases for higher switching frequencies.

4 Infineon's ACF full-GaN solution

Infineon Technologies offers a full-GaN ACF Charger Evaluation Board (EVB), which is shown in Figure 12. On the primary side, IGI60F2020A1L CoolGaN™ IPS half-bridge is used, and on the secondary side, IQC0800NLS CoolGaN™ SG HEMT is employed as an SR switch. The input voltage is 100-240 VAC and the output voltage is 20 V. The operating frequency is between 300-360 kHz, depending on the input voltage and load. The EMI results of the same design with the MOSFET SR switch are given in [6].

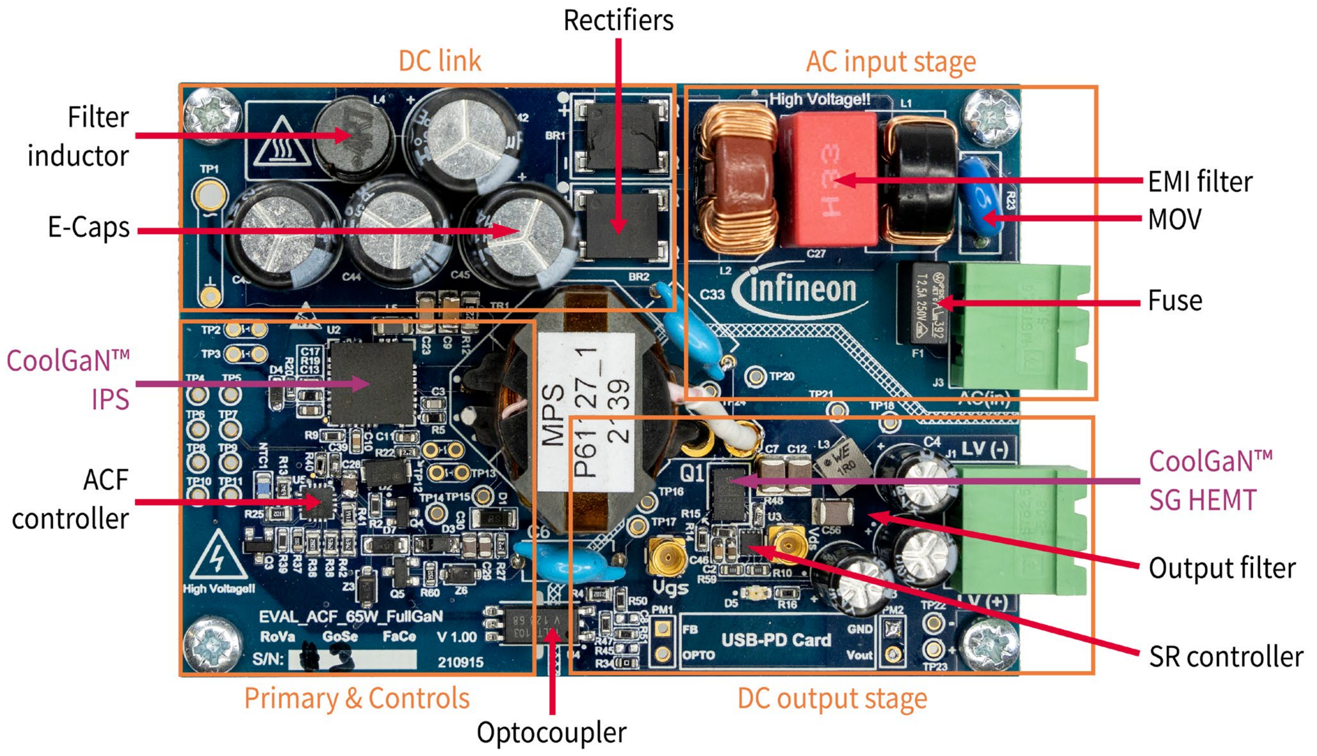

Figure 12 Infineon's ACF full-GaN evaluation board

Based on the evaluation board in Figure 12, experiments have been carried out with GaN HEMT and MOSFET mounted using an interposer. In order to make a fair comparison between CoolGaN™ SG HEMT IQC0800NLS vs. MOSFET, the gate charge-related figure of merit (FOM_G) needs to be considered. Table 2 shows such a comparison of various MOSFETs with CoolGaN™ SG HEMT IQC0800NLS. Here it can be seen that BSC034N10LS5 has better FOM_G than similar MOSFETs, which is why it has been selected in experimental comparison.

It should also be noted that devices can also be compared with a body diode-related figure of merit (FOM_{VSD}), which implies the effect of turn-on/-off delay losses if the delay times are not minimized. It should also be noted that when GaN-optimized standalone SR controllers are introduced to the market with reduced turn-on/-off delay times, further performance improvement will be observed with GaN SR compared to a MOSFET with similar $R_{DS(on)}$, as shown in the previous chapter.

Table 2 FOM comparison of various MOSFETs with CoolGaN™ SG HEMT IQC0800NLS

	$R_{DS(on),Typ}$ [mΩ]	$Q_{G,Typ}$ [nC]	$V_{SD,Typ}$ [V]	FOM_G [mΩ×nC]	FOM_{VSD} [mΩ×V]
IQC0800NLS	2.6	10	2.4	**26**	6.24
BSC093N15NS5	7.9	33	0.88	261	6.95
ISC0806NLS	6.5	20	0.89	130	5.79
BSC034N10LS5	3.5	37	0.85	130	2.98
BSC035N10NS5	3.5	70	0.88	245	3.08

Figure 13 shows the efficiency comparison at 120 VAC input between IQC0800NLS CoolGaN™ SG HEMT and BSC034N10LS5 MOSFET used as SR, which offers an improvement of up to 0.5 percent for the whole load range.

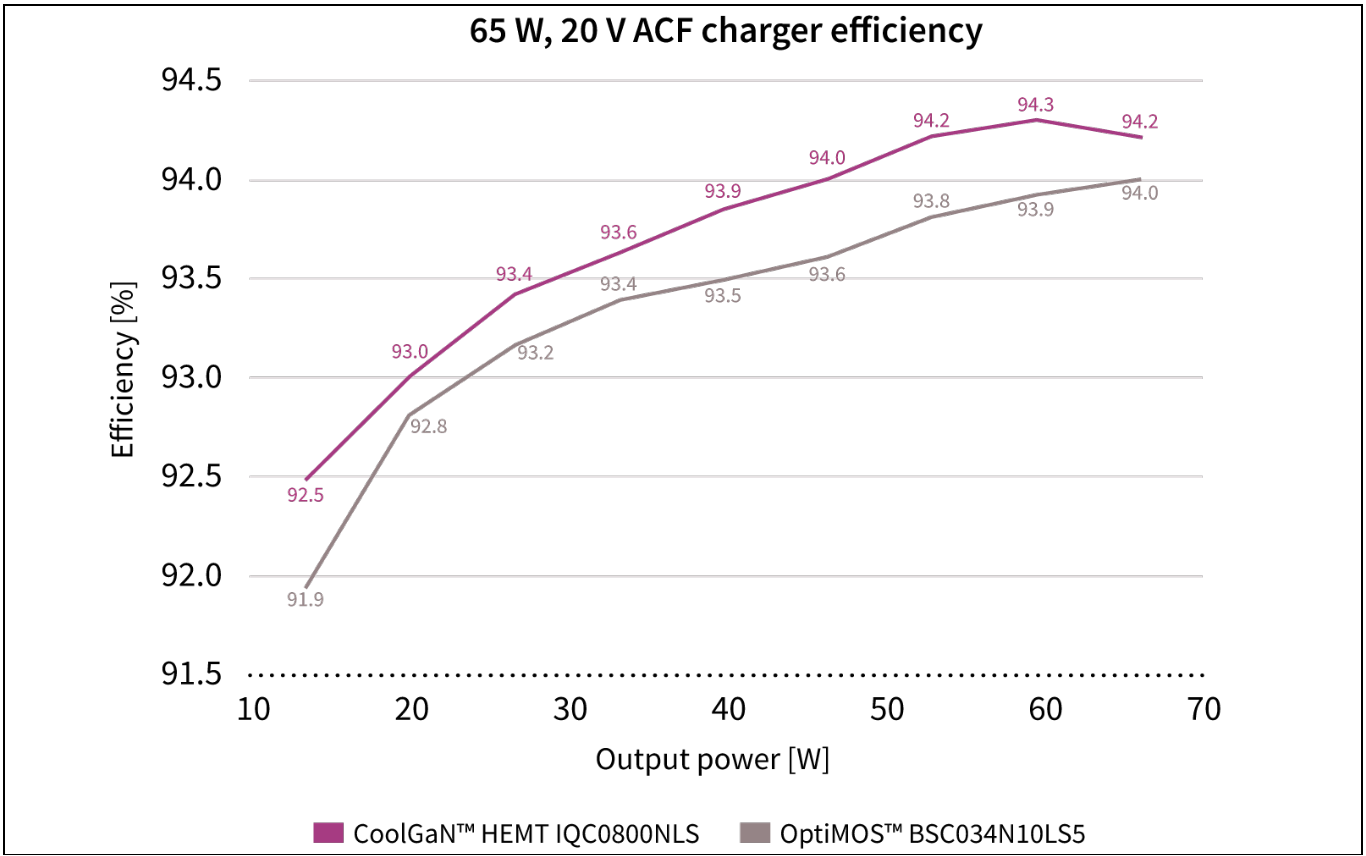

Figure 13 65 W Full GaN ACF Charger Evaluation Board – Efficiency Comparison – CoolGaN™ SG HEMT IQC0800NLS vs. MOSFET BSC034N10LS5 at 120 VAC input

Figure 14 shows a thermal image of two evaluation boards positioned side-by-side under test. The board on the left-hand side has CoolGaN™ SG HEMT IQC0800NLS as SR, and the board on the right-hand side has BSC034N10LS5 100 V MOSFET as SR, both boards having 120 VAC input at full load. The thermal picture was taken after the thermal steady state. Looking at the operating temperatures of both boards, 10 degrees of improvement in the SR switch and 15 degrees of improvement in the standalone SR controller can be observed. This can bring a clear advantage in charger designs since the temperature is the main limiter for higher power density.

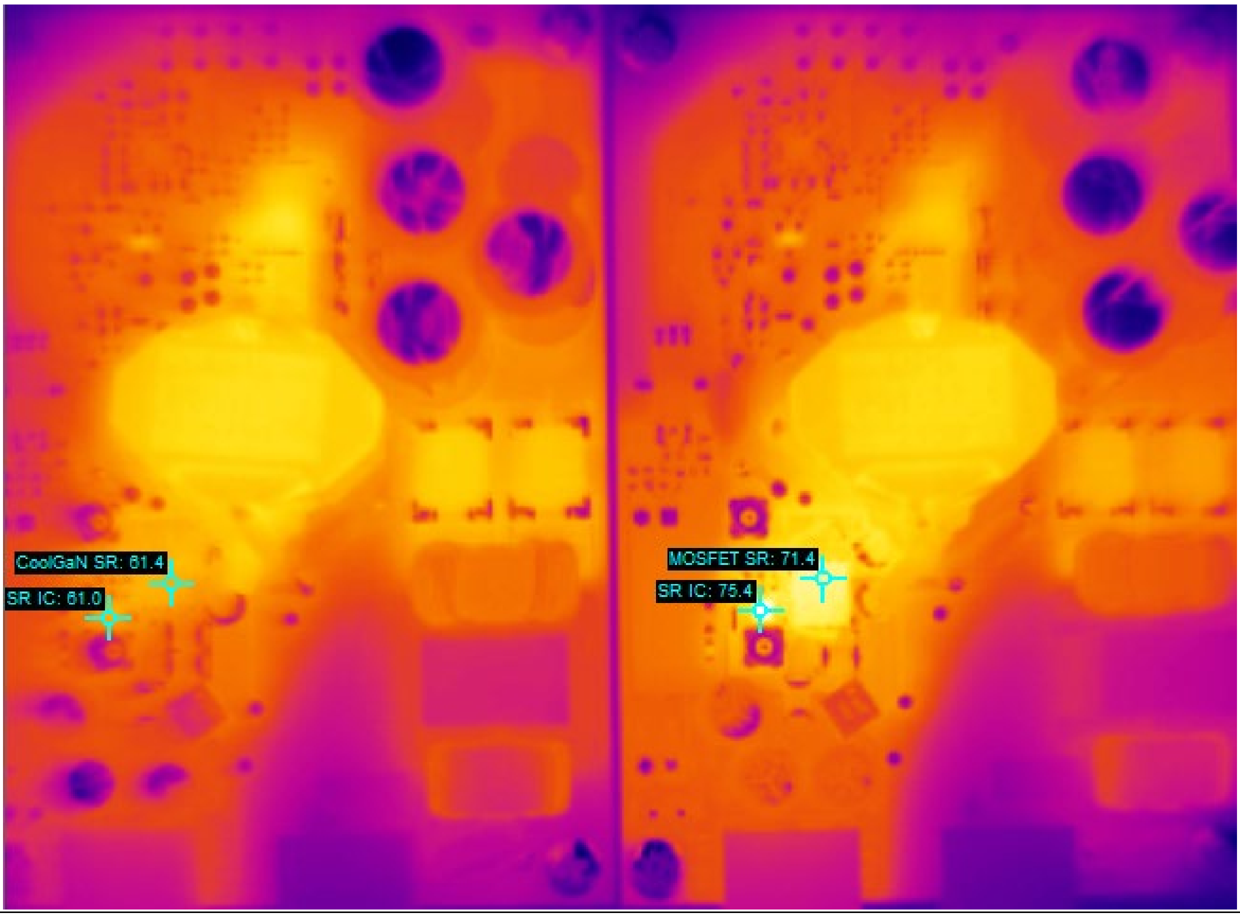

Figure 14 **Thermal images of the Full GaN ACF Evaluation Board at full load with 120 V CoolGaN™ SG HEMT IQC0800NLS (left) and MOSFET BSC034N10LS5 (right)**

In conclusion, GaN HEMTs have a high potential as SR in high-frequency, high power density chargers with a careful design using dedicated components and layout. Both efficiency measurements and thermal performance comparisons show that the gate charge advantage of CoolGaN™ SG HEMT IQC0800NLS is observed at high switching frequencies as long as losses due to turn-on/-off delay times are minimized. In addition, smaller package size is a plus in achieving higher-power-density charger designs.

5 Summary

High voltage GaN HEMTs used as primary side FETs have become popular in today's high power density charger and adapter applications. The main reason is that they can offer high-frequency switching due to their lower gate charge and reduced switching loss.

On the low voltage side, CoolGaN™ SG HEMT 100 V IQC0800NLS, used as Synchronous Rectifier (SR), also offers a significantly lower gate charge than a MOSFET with similar V_{DS} and $R_{DS(on)}$ values. This makes it a good candidate for high switching frequency, high power density charger, and adapter designs based on resonant topologies such as active clamp flyback (ACF), hybrid flyback (HFB), and LLC converter. In order to ensure the full performance of a GaN HEMT SR, special attention is needed to minimize turn-on/-off delay times together with a GaN-dedicated layout.

A full-GaN 65 W ACF converter evaluation board has been developed by Infineon Technologies to evaluate the CoolGaN™ SG HEMT IQC0800NLS as a secondary side synchronous rectifier, showing better efficiency figures and SR thermal performance compared to a MOSFET SR counterpart. In addition, a detailed discussion on how CoolGaN™ IPS can be used in high power density chargers and adapters is available in [7], which presents device features and benefits, application-specific topologies, key parameters, and evaluation results.

For more information about Infineon's CoolGaN™ product portfolio and comprehensive solutions, make sure to visit www.infineon.com/coolgan.

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Revision history

Document revision	Date	Description of changes
v1.1	2023.03.02	Figure 5 replacement

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