# Gallium Nitride (GaN) Enables Next-Generation High-Frequency Circuits

**By Tom Ribarich, Sr. Director Strategic Marketing at Navitas Semiconductor**

The key to improved power density is increased switching frequency to minimize passive components such as transformers, EMI filters, bulk and output capacitors, while simultaneously maintaining or improving efficiency. Over the years, high-speed topologies such as the active-clamp flyback (ACF) have been proposed by academics since 1996[i] but were frustrated by silicon's poor switching ($Q_{GD}$, $T_{rr}$, $C_{OSS}$) performance[ii] plus complexity and system cost.

Gallium nitride (GaN)[iii] is a 'wide band-gap' material because it offers an electron band-gap that is 3x larger than silicon, which means GaN can handle 10x stronger electric fields and deliver high power with dramatically smaller chips. With much smaller transistors and shorter current paths, ultra-low resistance ($R_{DS(ON)}$) & capacitance ($Q_{GD}$, $C_{OSS}$, zero $T_{rr}$) are achieved, enabling up to 100x faster switching speeds. To deliver actual performance to match GaN's promise, GaN power ICs[iv] monolithically-integrate GaN power (FET) and drive, plus control and protection to control and protect the GaN power switch at high speeds.

Three new topologies are presented: 50W pulsed-ACF, 300W CrCM totem-pole PFC, and 1kW half-bridge LLC.

## Pulsed-ACF: electrolytic bulk-capacitor elimination

Bulk capacitor reduction - or complete removal - has been an elusive topology for many years, with little to no success. Bulk capacitor rating (uF) is determined by the required output power, AC line voltage and AC line frequency. The rating is a balancing act between charging the capacitor each AC line cycle and discharging it to provide the necessary output power, all while maintaining a minimum DC hold-up voltage level (~400V) necessary for providing a constant DC output voltage. Increasing the switching frequency of the power conversion stage itself has no effect on the size of the bulk capacitor, so it does not benefit from the same frequency-to-size reduction that we get with magnetics. Even if the switching frequency is increased high enough such that the magnetics shrink down to PCB-based 'air cores', the bulk capacitor voltage must still be replenished by the AC line voltage at the ultra-low AC line frequency (50/60Hz) so the rating – and physical size - remain unchanged.

However, if we change the output requirements of the converter from, say, a tightly regulated DC voltage to a rectified AC voltage, then we can change the rules of the game. With a pulsed output, we can have a rectified AC bulk capacitor voltage which allows for the bulk capacitor capacitance value to be greatly reduced and the DC bus voltage can follow the rectified AC line voltage directly. For smartphone fast chargers, a pulsed current is acceptable, especially if the phone's battery charging algorithms are slightly modified to accept the pulsed voltage waveform.

To achieve the new pulsed output voltage requirement, the active clamp flyback (ACF) topology can efficiently convert the rectified AC bus voltage into a pulsed DC output voltage. Traditional QR flyback is simple and low cost but 'hard-switches' during high line conditions. Resonant LLC topologies deliver ZVS operation over the entire load range but depend on a limited-range DC bus voltage.



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The ACF topology offers the best of both worlds by enabling ZVS operation over the entire line and wide load and voltage range. Compared to the traditional QR flyback, the ACF topology includes an additional high-side switch and capacitor to slew the switched-node voltage ($V_{SW}$) to the opposite rail during the dead-time and achieve ZVS. MHz-ACF using GaN power ICs was demonstrated academically in 2016[v] and available for industry since the 2018 introduction of TI's UCC2878x ACF PWM controller. GaN enables high frequency ACF operation and results in a dramatic size reduction of the transformer, for example from a 22mm-high RM10 bobbin-based transformer at 50kHz to an 8mm-thin EI25 planar transformer at 500kHz, as shown in figure 1.

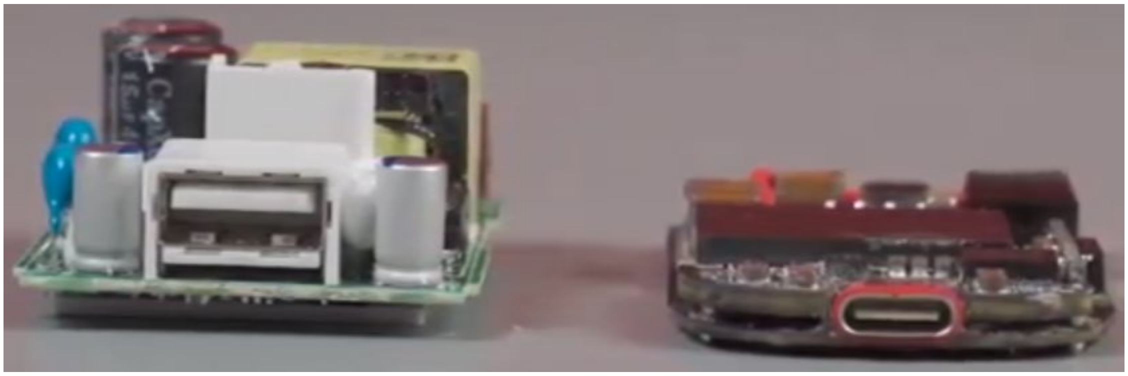

*Fig. 1: How high frequency drives smaller passive components, 50W fast-charger example. On the left, ~100 kHz traditional bobbin (22 mm high), on the right, ~500 kHz planar transformer (8 mm).*

Size reduction by increased frequency and pulsed operation (bulk capacitor elimination) led to the introduction of OPPO's ultra-thin 50W 'Cookie' GaN-power-IC-based fast charger in 2020. This was a perfect example of combining GaN with some novel system partitioning to reduce the converter size and profile and ultimately creating a new and unique out-of-the-box user experience.

### High-frequency PFC, without the bridge

Conventional PFC topologies for mid-power (100-500W) applications include an input bridge rectifier followed by a traditional boost converter. As the boost switch is turned on and off at a given switching frequency, the switch on and off times are controlled such that the AC line input current follows the same shape and phase as the AC line voltage and the DC bus output voltage is maintained at a constant level. During $90V_{AC}$ input and full-load conditions, this circuit can reach efficiencies of about 96%. The boost converter itself can be made very efficient but the AC input-bridge losses are very high, causing severe thermal extremes and poor overall efficiency.

Enter the 'bridgeless totem-pole' PFC topology.

In conventional PFC circuits with a standard AC rectifier, at any point in time, two diodes of the input bridge are always conducting and generate > 50% of the total PFC circuit losses. Many bridgeless PFC circuits have been investigated over the past few decades in attempts to eliminate the input bridge rectifier and boost system efficiency but few have made it out of the lab and into the mainstream market mainly due to higher complexity and cost. These topologies include classic bridgeless, semi-bridgeless, bi-directional bridgeless, and bridgeless totem-pole. Each of these topologies has their own set of pros and cons but none of them are the perfect solution.



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While microcontroller-based designs have been implemented for multi-kW datacenter SMPS, standby losses have been too high to meet consumer market requirements like DoE Level IV and Euro CoC Tier 2.

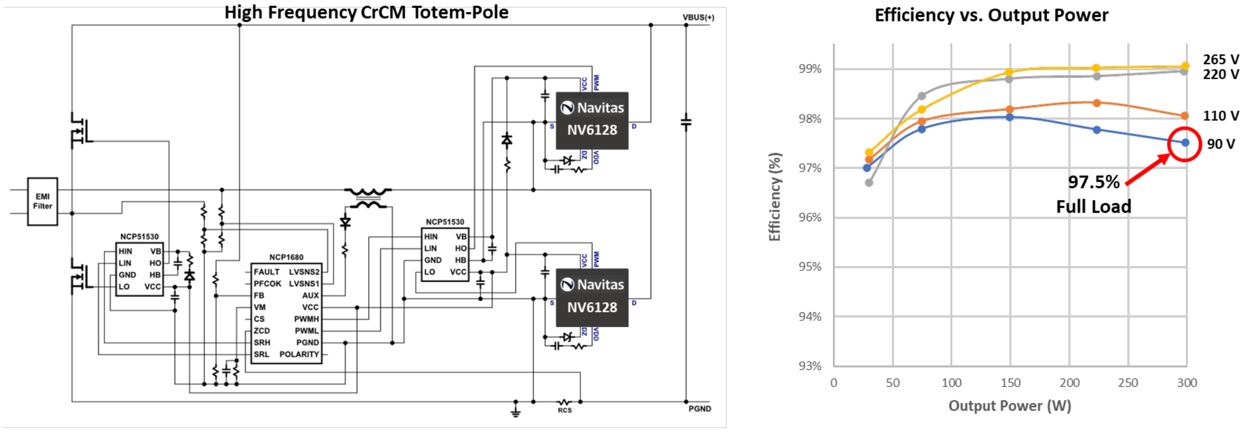



*Figure 2: 300W CrCM totem-pole PFC schematic and efficiency data.*

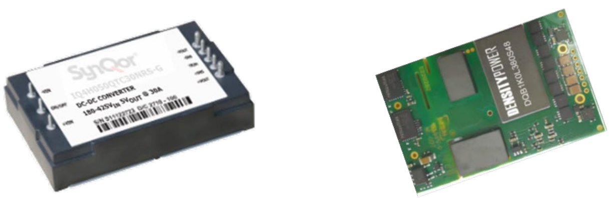
With the emergence of new controllers in 2021, the high-frequency CrCM bridgeless totem-pole is emerging as a popular topology due to low EMI, plus simplified voltage and current sensing by the controller. Switching speeds can be increased up to 10x, from fixed-frequency 50kHz CCM to 200-500kHz for CrCM totem-pole operation, and GaN's low output capacitance ($C_{OSS}$) delivers a cool, high-efficiency result.

## High-frequency DC-DC: 6x the power with GaN

For fixed-output voltage converters in the 100W-3000W power range, the downstream DC-DC converter choice is typically an LLC resonant stage with ~400$V_{DC}$ input. The 400V bus can come from an upstream PFC stage within an encased AC-DC SMPS, or can be the main distribution rail in a HVDC installation.

The LLC topology has several benefits that include ZVS operation, high efficiency and high power density, and the ZVS operation makes this converter an ideal platform for increasing the switching frequency and reducing the size of the magnetics using a high-speed powertrain.

In the industry-standard (DOSA) quarter-brick form-factor, best-in-class silicon-based designs reach 150W. By using GaN power ICs and increasing the DC-DC switching frequency 3x from 275kHz to 830kHz, the power rating can be increased up to 6x to 1kW.



Best-in-class Si
150W, 90-92%, 275 kHz

GaNFast Power ICs
1kW, 97.0-97.7%, 850 kHz

*Figure 3. 400V input DOSA quarter-brick DC-DC converters. On the left, best-in-class Si-based, 275kHz, 150W, and right GaN-based 830kHz reaching 1kW (Density Power).*



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## High-speed GaN enables high-frequency applications

These are only a few of the vast opportunities in power electronics to be revolutionized by gallium nitride power ICs. As operating frequencies are increased and magnetic sizes decreased, the entire eco-system will continue to evolve, including upgraded magnetic materials, new planar transformer designs, smaller capacitor technologies, new circuit topologies, improved thermal materials. The results are higher efficiencies, improved robustness, new power adapter form-factors and ultimately, lower costs.

For More Information:

[i] R. Watson, F. C. Lee and G. C. Hua, "Utilization of an active-clamp circuit to achieve soft switching in flyback converters," in IEEE Transactions on Power Electronics, vol. 11, no. 1, pp. 162-169, Jan. 1996, doi:10.1109/63.484429.

[ii] D. Kinzer, Navitas "Welcome to the Post-Silicon World: Wide Bandgap Powers Ahead", keynote PCIM 2016.

[iii] Gallium nitride (GaN) overview at https://www.navitassemi.com/gallium-nitride-the-next-generation-of-power/

[iv] D. Kinzer and S. Oliver, "Monolithic HV GaN Power ICs: Performance and application," in IEEE Power Electronics Magazine, vol. 3, no. 3, pp. 14-21, Sept. 2016, doi: 10.1109/MPEL.2016.2585474.

[v] S. Oliver, T. Ribarich, "State-of-the-Art Mobile Charging: Topologies, Technologies and Performance", APEC 2017 , Industrial Session IS05, https://www.navitassemi.com/download/state-of-the-art-mobile-charging%ef%bf%bdtopologies-technologies-and-performance/?wpdmdl=36540&ind=1561120266242





22 Fitzwilliam Square South, Saint Peter's, Dublin, D02 FH68, Republic of Ireland

www.navitassemi.com
www.ganfast.com

Tel.: ThinkGaNIC +1 (844-654-2642)
Info@NavitasSemi.com



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