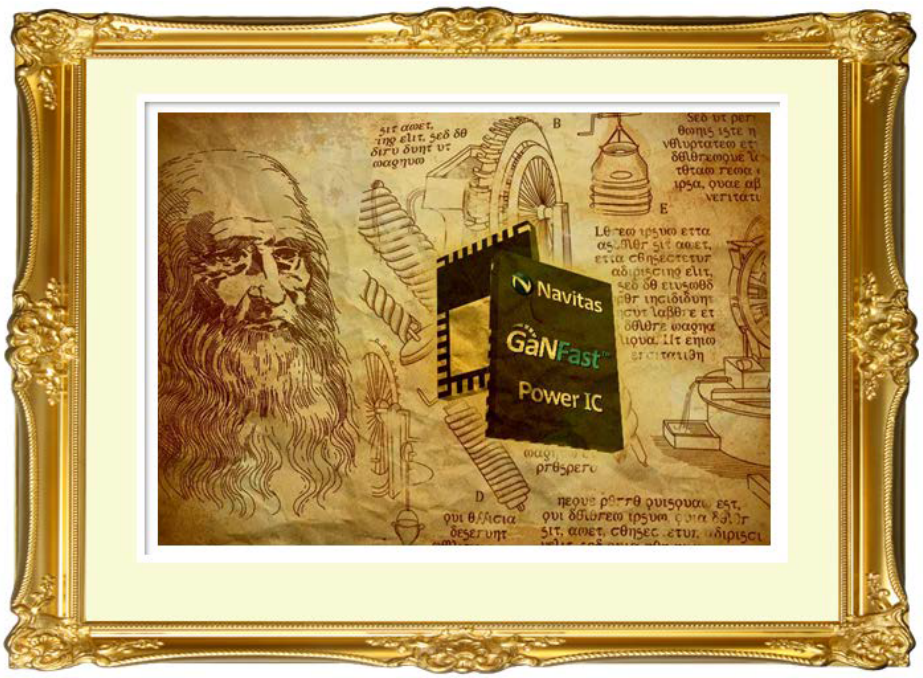
Gallium Nitride (GaN) Power ICs: Turning Academic Dreams into Industry Reality

by Stephen Oliver and Tom Ribarich

Like Leonardo da Vinci (1452-1519) and his amazing inventions, including the 'helicopter' and 'robotic knight', electronics academics have long been frustrated that their ideas cannot become reality due to the limited materials available at the time. Leonardo would be amazed at today's lightweight alloys and tiny, high-speed electric stepper motors compared to his rudimentary ironwork and waterpower. Now, old, slow, lossy silicon chips are consigned to history, as new, fast, efficient gallium nitride (GaN) power ICs turn academic dreams into industrial reality from mobile fast chargers to data center power supplies.



Gallium Nitride[i]: High-Speed Enabler

High-speed – or rather – high-frequency power topologies mean smaller and smaller passive components, to the extreme case that in a 40MHz phi-2 converter at Stanford University[ii], the ferrite material completely disappears in an 'air-core' inductor.

The flyback converter has had several proposed improvements, such as the high-frequency quasi-resonant (HFQR) from Professor Fred Lee at Virginia Polytechnic (VPT) in 1988[iii], and R. Watson's active-clamp flyback (ACF), also from VPT in 1996[iv] which eliminated snubber loss. However, in each case, the output capacitance (C_{OSS}) of the silicon MOSFET created such high switching losses[v] that implementation was not feasible – so no commercial control ICs would be financially viable.

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Twenty years later, in 2016, a prototype 25W[vi] ACF switching at 1MHz was designed by Xiucheng Huang at VPT using Navitas GaNFast power ICs and a TI DSP controller (C2000). Further MHz work using a GaNFast half-bridge power IC was completed at Zhejiang University in 2019[vii]. Though tiny designs, the DSP is designed for high-power industrial applications, and has a relatively high leakage current. As a result, the designs couldn't meet US DoE Level VI[viii] low-power standby requirements – in effect from February 2016 – so were not commercially practical.

GaNFast power ICs were the enabler for high-frequency systems, based on a) GaN's physical advantages over silicon, and b) robust[ix] performance and ease-of-use resulting from monolithic integration of GaN power (FET) and driver, plus protection and control. Since mass production release, GaNFast power ICs have been rated at 2MHz which is 20x faster than typical converter switching frequency of 50-60kHz.

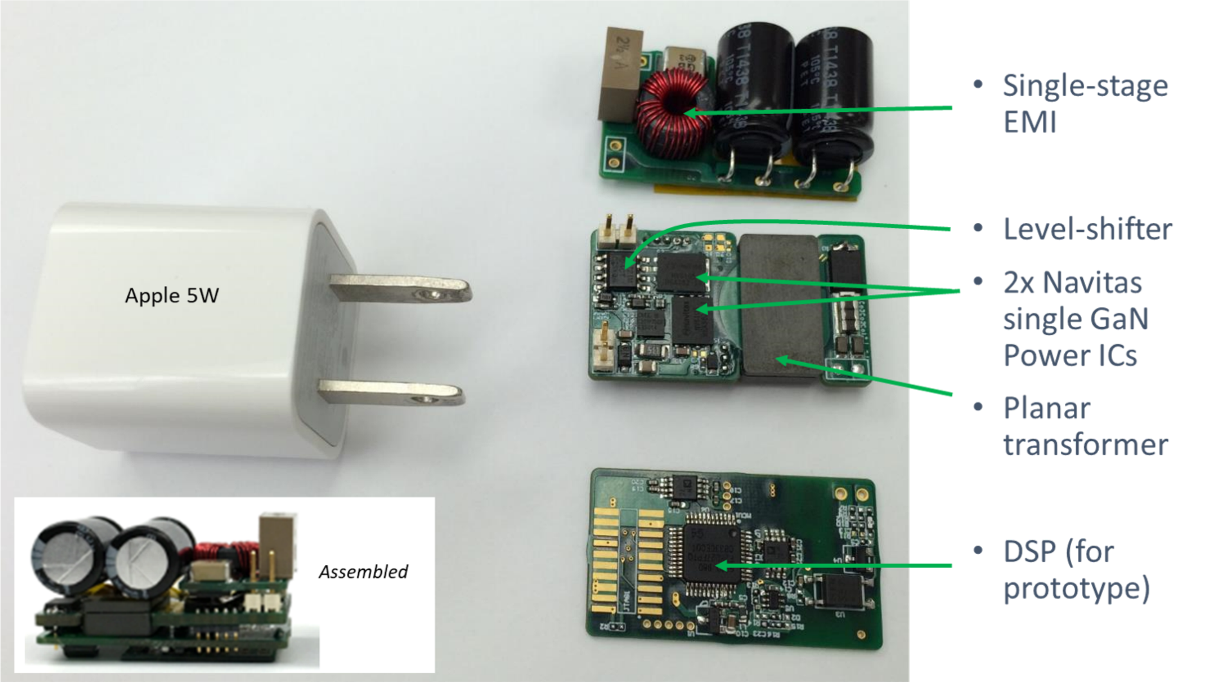

Figure 1: Left: High-performance, high-frequency 1MHz 25W activeclamp flyback (ACF) prototype from CPES (Virginia Polytechnic), using Navitas gallium nitride (GaN) power ICs, planar transformer and C2000 DSP. Prototype achieved 17W/in^3 (estimate, cased).

A reliable, high-performance, high-speed GaN powertrain meant that control IC companies could confidently invest time and resources to design and release speed-optimized ASICs which met DoE Level VI requirements and be part of cost-effective system bills of material (BoMs). The first Level VI-compatible high-frequency controller was the TI UCC28780 with a headline peak frequency of 1MHz for ACF, which was used in the world's first, and thinnest 45W USB-C fast charger – the Mu One[x].

This was quickly followed by the HFQR NCP1342 from On Semi, which increased switching frequency 4x from 50kHz to 200kHz, ending a frustrating 30-year wait.

A recent upgrade to ACF has been the 'Pulsed-ACF'[xi], as used in OPPO's 50W Mini "Cookie" charger, which achieves another 'vanishing act'. The electrolytic 'bulk cap' can occupy 40% of the total charger size but a proprietary innovation creates the world's first charger using 'pulsed' power conversion.

This eliminates the electrolytic bulk capacitor, and the rectified 100Hz pulsating DC feeds directly into the high-frequency ACF circuit which can maintain a smooth output to charge the phone's battery, even when the input voltage range is wide. A follow-on benefit is that OPPO-proprietary 'direct-charge' approach means that during each pulse gap, the polarization effect in the phone battery is eliminated so reducing wear-out mechanisms and extending battery life.

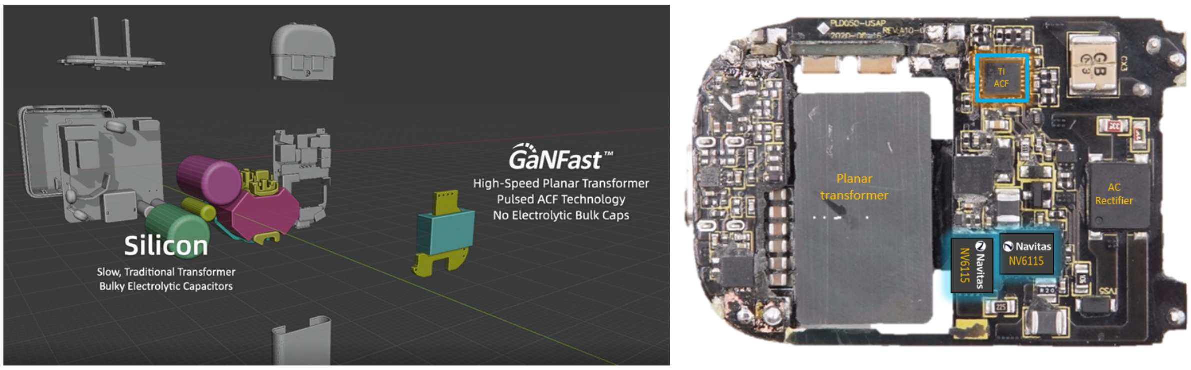

Figure 2: OPPO 50W Mini "Cookie" charger, showing high-frequency planar magnetics and elimination of electrolytic bulk capacitor.

Higher Power, Higher Speeds

As we move to higher powers (>75W), power factor correction (PFC) is required, and we also face the perennial problem of the lossy diode bridge rectifier.

Traditional PFC has been constant current (CCM) or discontinuous conduction mode (DCM) boost with a main switch and diode. GaN's wide band-gap sibling – silicon carbide (SiC) – has helped to minimize diode drop and reverse-recovery losses. However, silicon's switching losses (specifically C_{OSS}) continued to limit frequency to around 50-60kHz[xii].

In a similar story to the ACF, the introduction of GaN power ICs spurred new PWM controllers. One example chip-set was the NCP1631 interleaved CrCM boost, NCP13992 LLC, and NCP4305/43080 SR PWM controllers as used in the world's smallest 300W reference design by Ongineer[xiii]. This was the inspiration for the Asus / NVIDIA AC-48V 300W laptop charger using GaN power ICs[xiv].

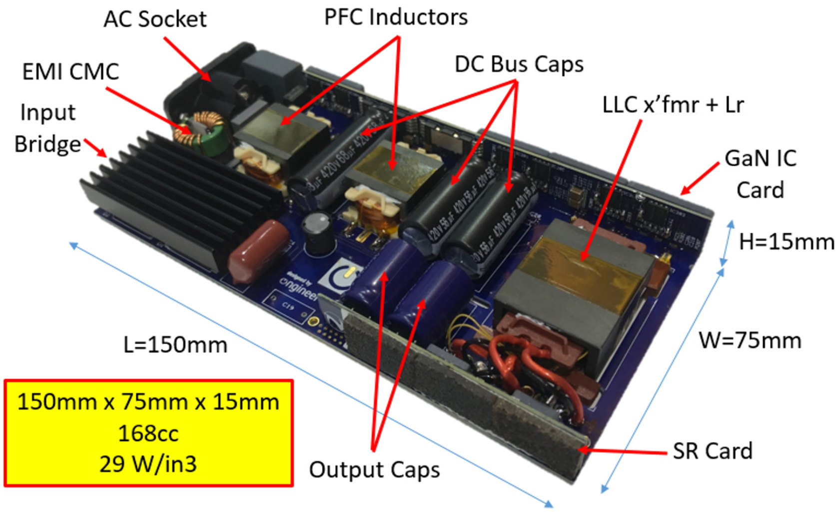

Figure 3: 300W AC-19 V_{DC} reference design using GaN power ICs: Interleaved CrCM/DCM Boost using NCP1632 (with frequency-foldback function to reduce power consumption), minimum 200kHz (90 VAC, peak-of-line) to maximum 450kHz. LLC using NCP13992 (with adaptive dead-time features, soft-start, comprehensive protection and HV start-up) and NCP4305/NCP43080 (SR), 500kHz normal operation (with higher frequency during load / start-up burst conditions).

The next architectural advance was the 'bridge-less' boost PFC from Milan Jovanovic[xv] which combined the AC bridge rectifier plus PFC circuit, and used two switches for AC-rectification and two more switches for the PFC function. This was described in 2008 and was used in high-power server AC-48V and AC-12V power supplies but remained low-frequency due to hard-switching silicon FETs, so had a small increase in efficiency but no change in power density.

A later development was the 'totem-pole' variant[xvi] but still only 50kHz. With gallium nitride, the frequency-related limits of silicon are overcome, and high-frequency CrCM 'totem-pole' PFC becomes a reality.

For a 300W laptop adapter, the upgrade from AC-bridge plus 50kHz boost PFC, to 200-500kHz CrCM totem-pole using a new Level VI-compliant PWM controller and new GaN power ICs like the NV6128[xvii] achieves power density over 1.1 W/cc. This is 3x smaller and lighter than current tier-1 OEM designs.

Moving up in power and frequency, a prototype 3.2kW AC-54 V data center power supply was built at the University of Texas, Austin using a 100% gallium nitride powertrain with an interleaved CrCM totempole PFC running from 350kHz to 1.5MHz (sweep using CrCM)[xviii].

650V GaN power ICs were used on all legs of the totem-pole and primary LLC, with 80V GaN FETs on the secondary rectification side. Both PFC and DC-DC stages used planar magnetics and the C2000 DSP for control. As a data center SMPS is not classified as an 'external supply', the Level VI standby loss requirement does apply so in this case, the PWM controller was ready, waiting for gallium nitride to full the academic's needs, achieving 4.4W/cc (73W/in^3).

Gallium Nitride: Living the Dream

Even in the renaissance period, the rate of technological innovation could not keep up with Leonardo's dreams. Today, gallium nitride – in the form of the GaN power IC – delivers efficient, high-speed performance that has ended decades-long frustration; to fulfil academics' dreams and advance them to industry-proven realities.

For More Information:

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

[vi] S. Oliver, T. Ribarich, "State-of-the-Art Mobile Charging: Topologies, Technologies and Performance", APEC 2017, Industrial Session IS05, https://www.navitassemi.com/articles/

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