



Power Accelerated

GaN Power IC Technology

Past, Present, and Future

The 29th International Symposium on Power Semiconductor Devices and ICs
Plenary Session

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May 29, 2017

GaN Power IC Technology

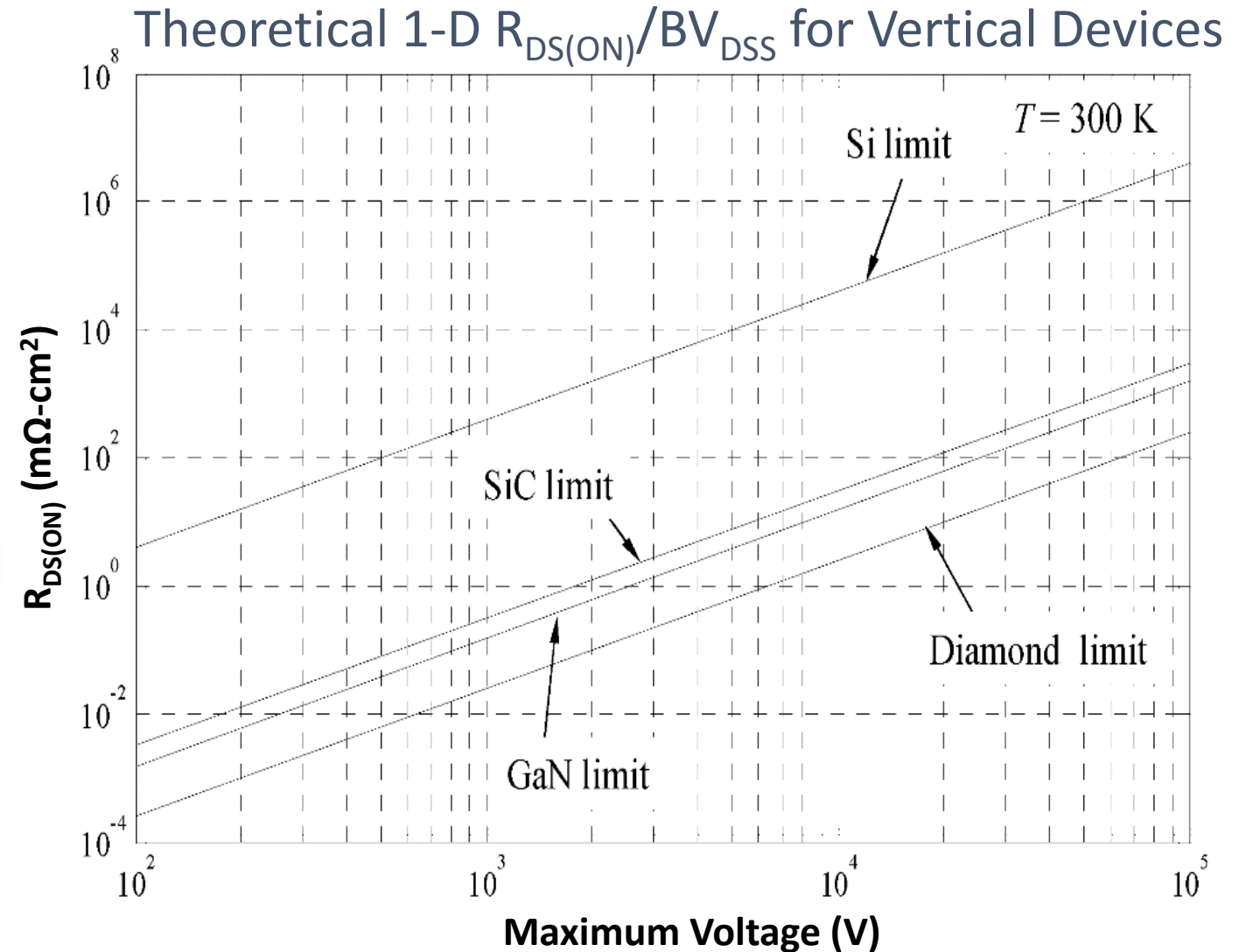
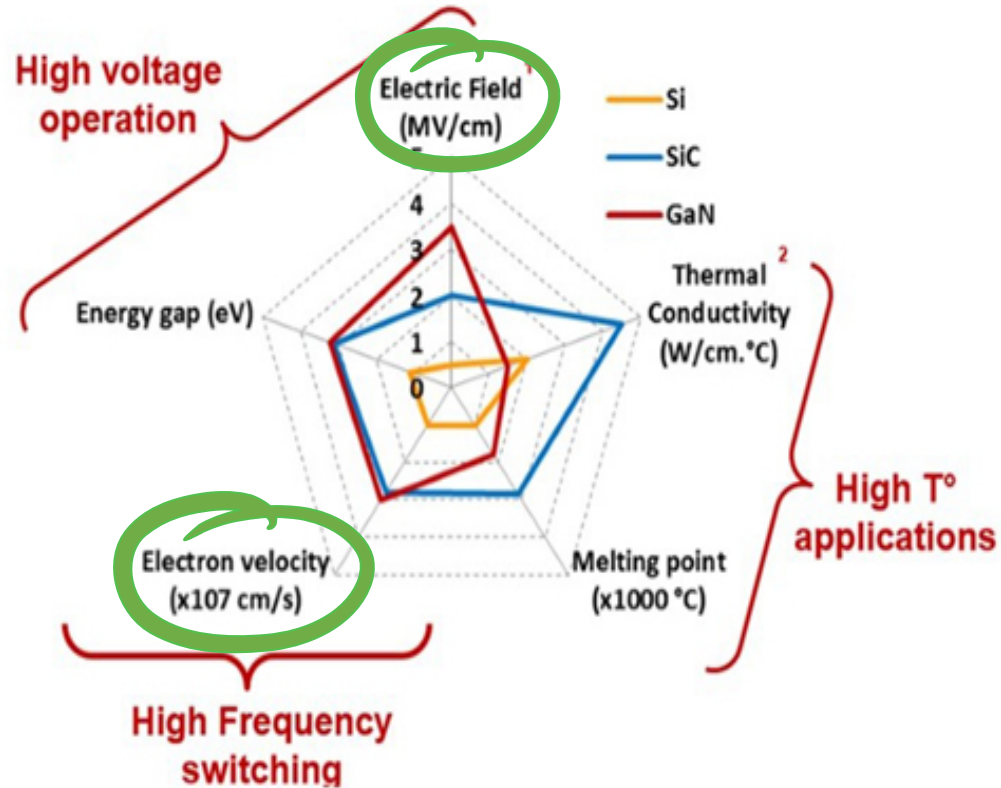
- Why GaN on Silicon?
- GaN IC Development History
- Navitas AllGaN™ Power ICs
- Application examples
- Future directions
- Summary

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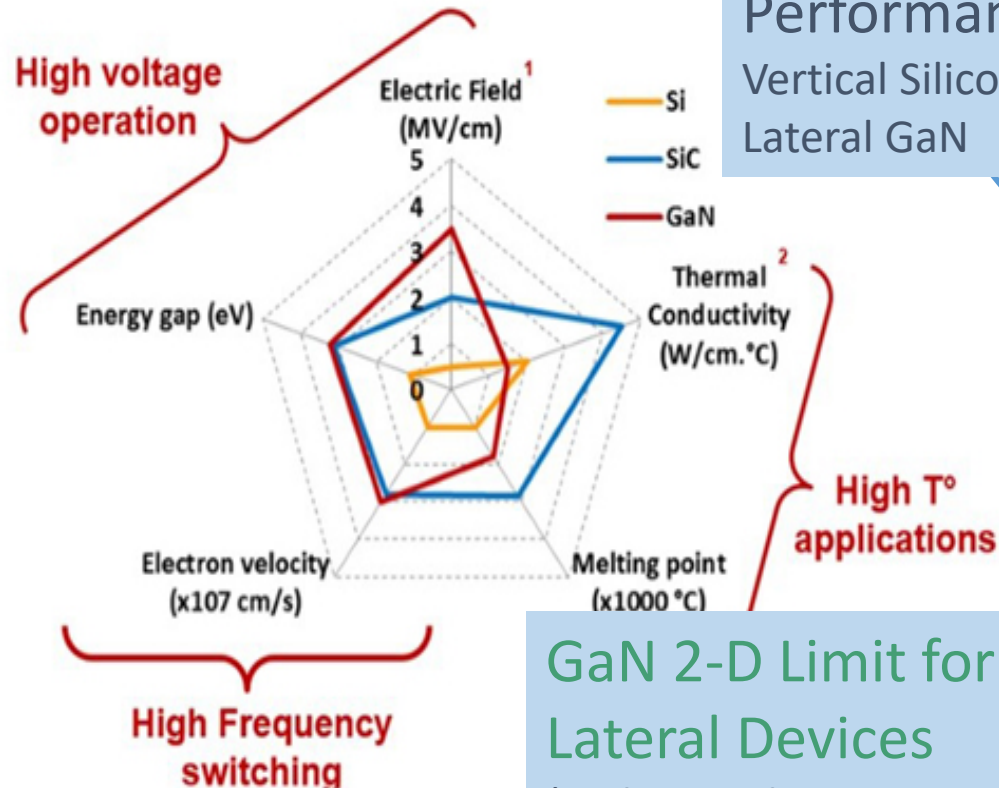
Performance Limits of Power Semi Materials

Important material attributes



Performance Limits of Power Semi Materials

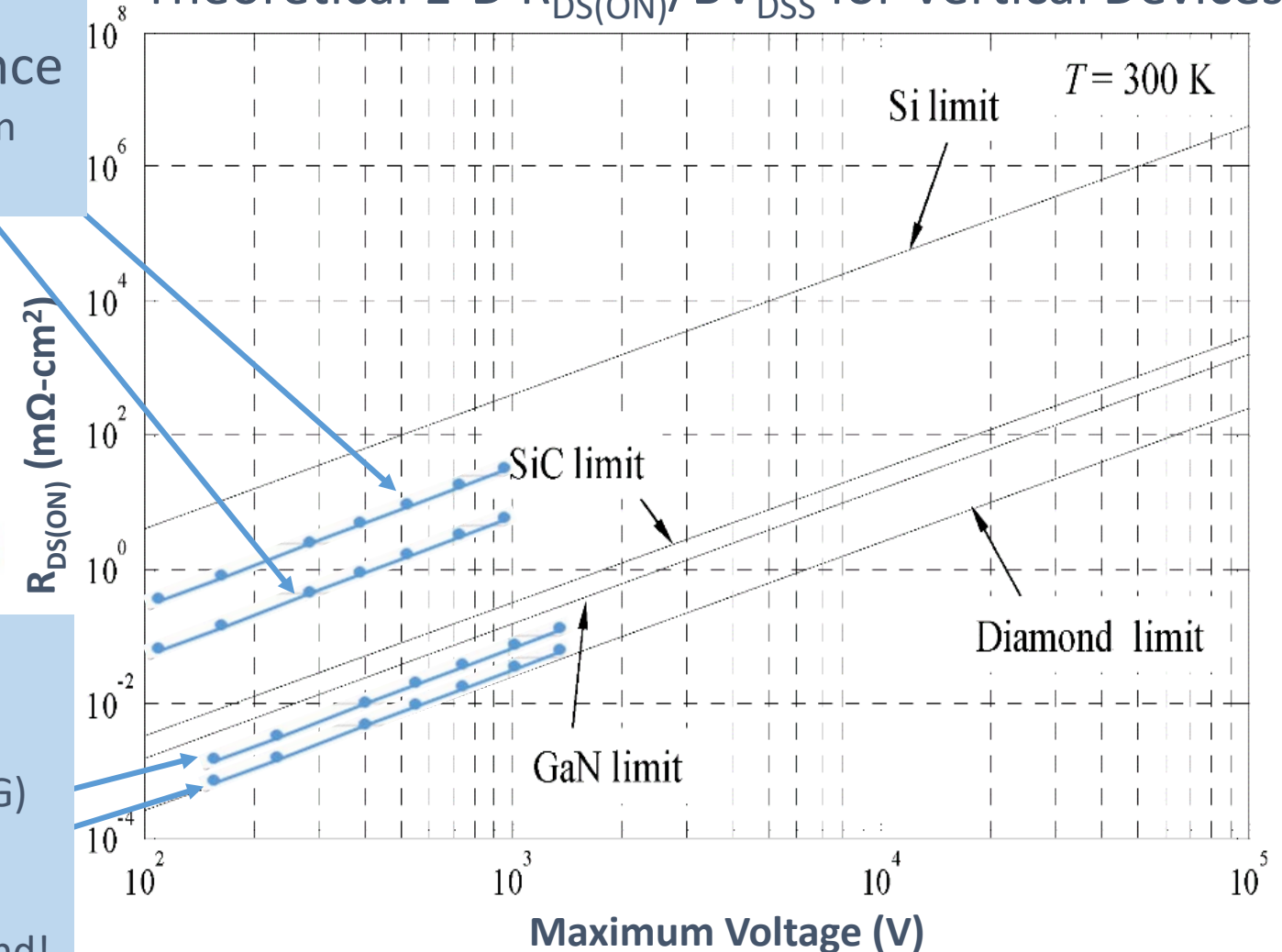
Important material attributes



Current Performance
Vertical Silicon
Lateral GaN

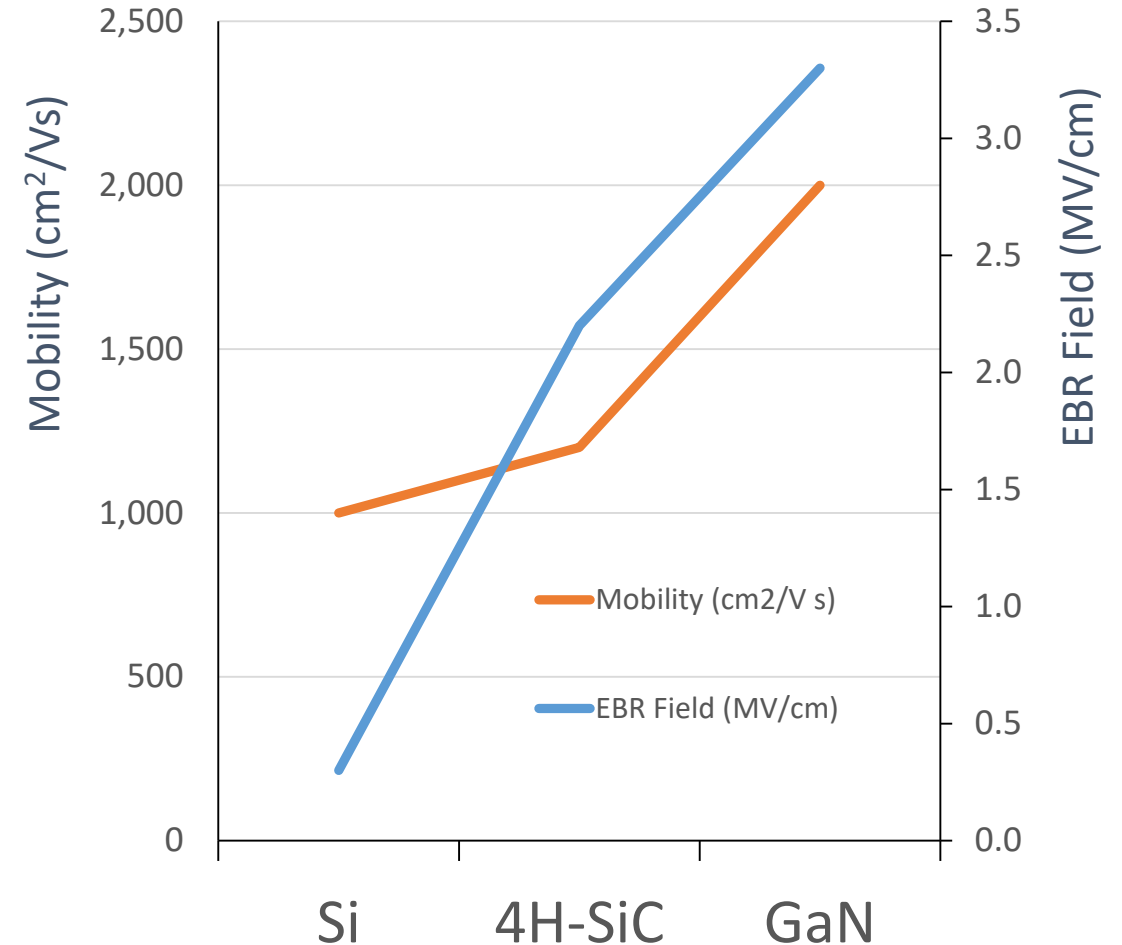
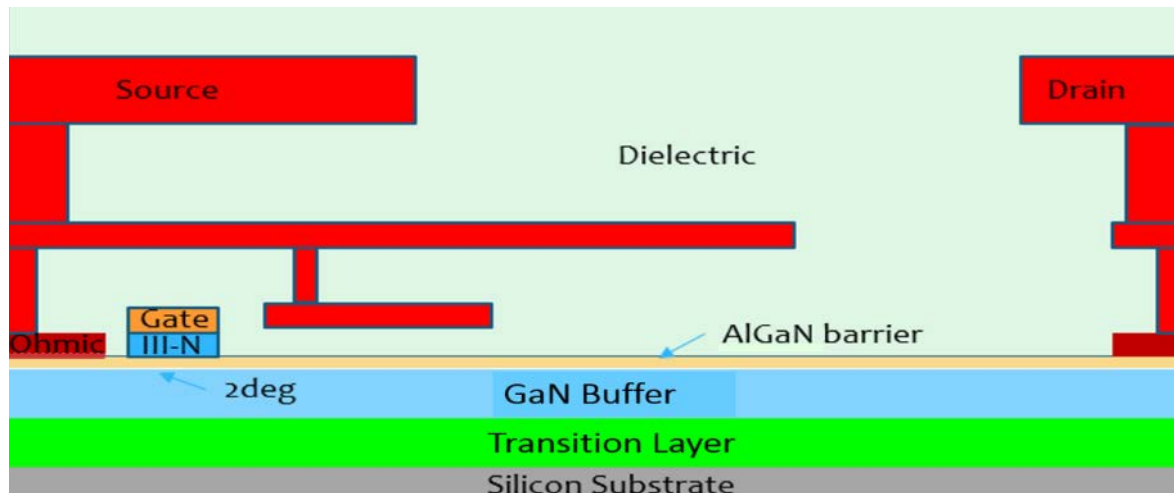
GaN 2-D Limit for Lateral Devices
(with 400 ohm-sq 2-DEG)
2.5 MV/cm
3.5 MV/cm
Almost matches Diamond!

Theoretical 1-D $R_{DS(ON)}/BV_{DSS}$ for Vertical Devices

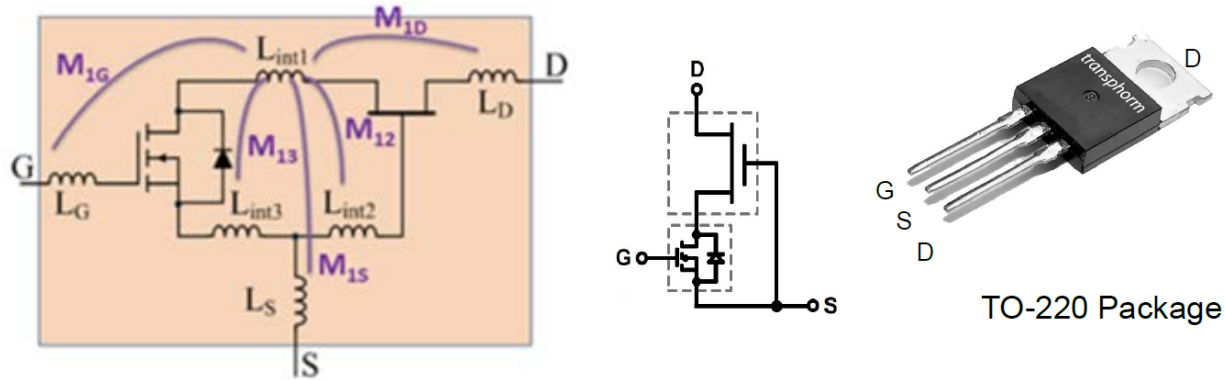


Lateral GaN Advantage for Off-line Applications

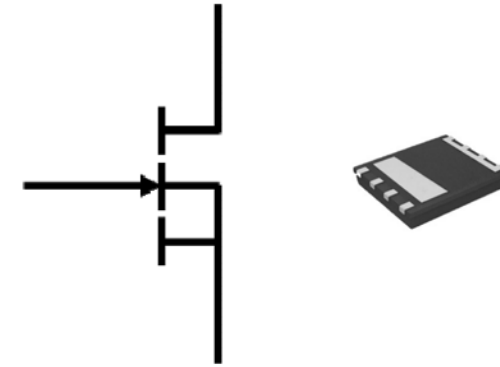
- WBG GaN material allows high electric fields so high carrier density can be achieved
- Two-dimensional electron gas with AlGa_N/Ga_N heteroepitaxy structure gives very high mobility in the channel and drain drift region
- Lateral device structure achieves extremely low Q_g and Q_{oss} and allows integration
- Integration on silicon substrates means mature low cost wafer fabrication is available



Comparison of Different GaN Technologies



- Cascode GaN Switch
 - Relatively easy to control gate
 - Traditional packages
 - Large package inductance
 - Prone to oscillation
 - No dV/dt control
 - Complicated multi-die package

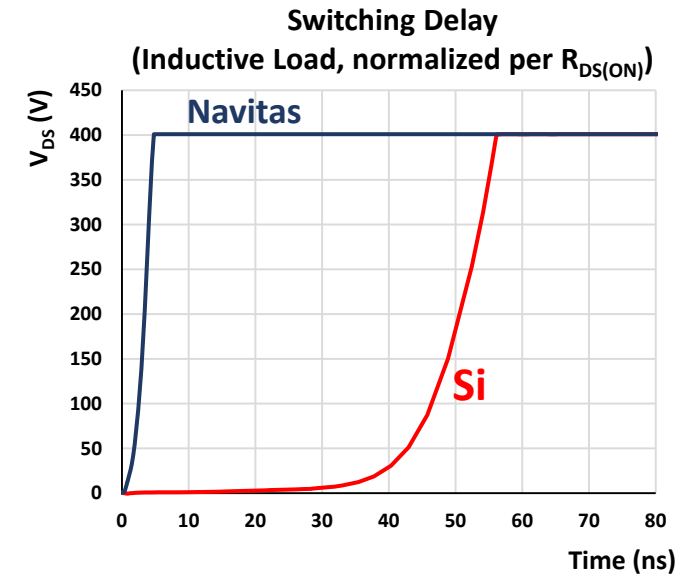
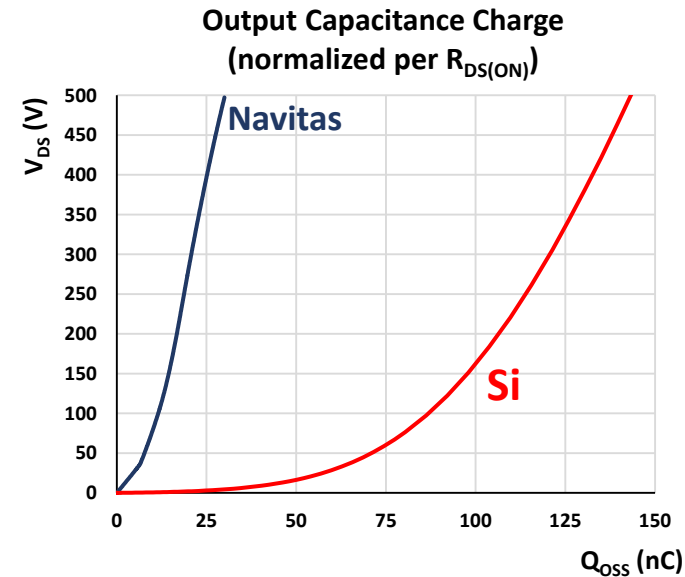
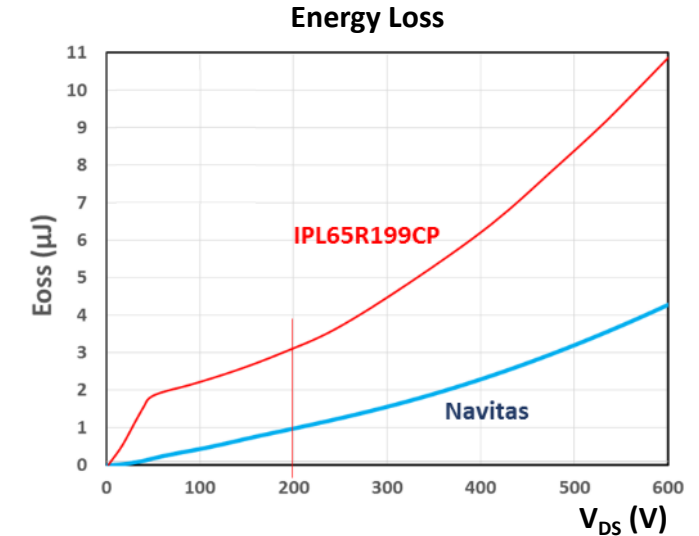
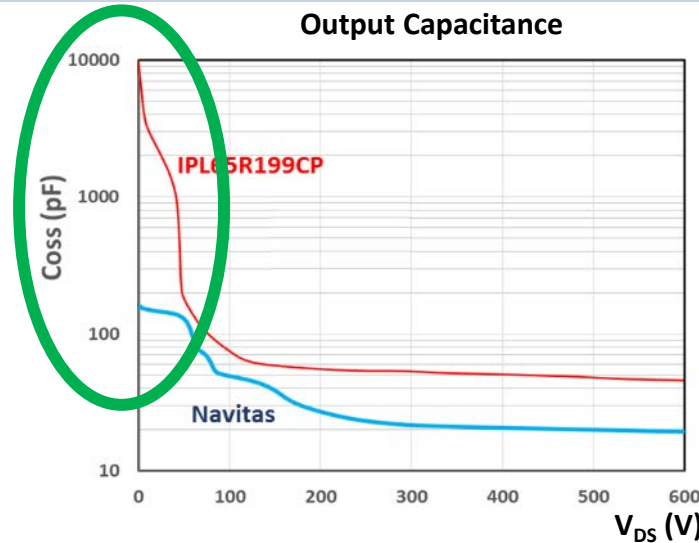


- E-mode GaN Switch
 - Extremely low gate charge
 - No reverse recovery loss
 - Easy to package
 - Low package inductance
 - Can control dV/dt
 - Hard to control gate

GaN vs Silicon Output Characteristics

- Switching loss:

$$P_{LOSS} = E_{OSS} (V_{DS}) * F_{SW}$$
- $C_{OSS} \rightarrow$ Delay (limits F_{SW})
- Too slow $\rightarrow$ partial ZVS $\rightarrow E_{OSS}$ loss
- Si C_{OSS} is 50x-100x higher than GaN at $V_{DS} < 30V$
- Si P_{LOSS} is 3x higher than GaN at 200V (partial ZVS)
- Big effect at full or light load condition
- Further information: “ C_{OSS} Hysteresis in Advanced Superjunction MOSFETs”, Harrison, APEC 2016



Hard-Switch → Soft-Switch with GaN Power IC

Primary Switch Power Loss:

$$P_{FET} = P_{COND} \overset{\text{Minimized}}{\circledast} \overset{\text{Minimized}}{k} + P_{DIODE} + P_{T-ON} + P_{T-OFF} + P_{DR} + P_{QRR} + P_{QOSS}$$

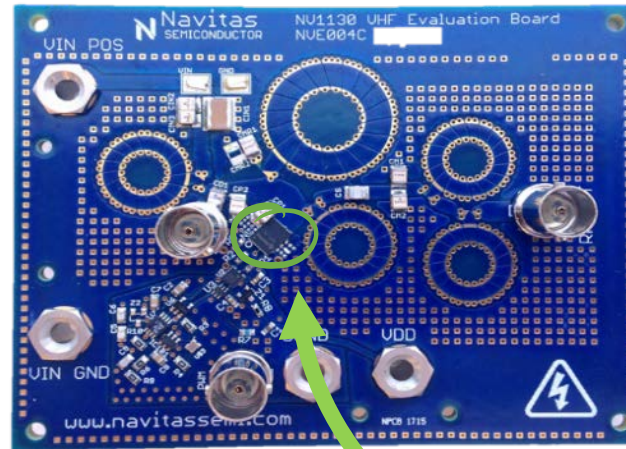
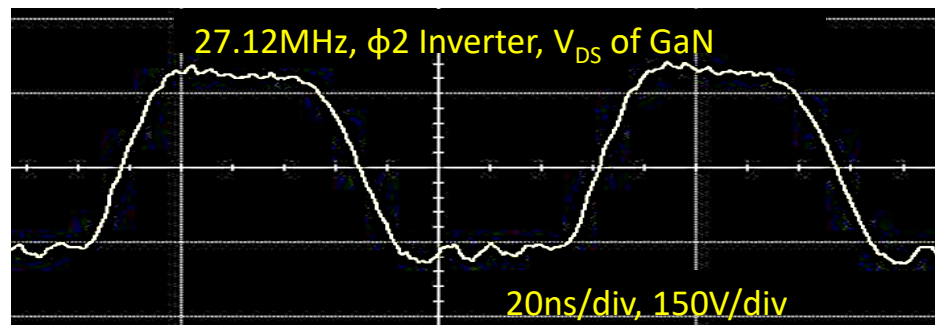
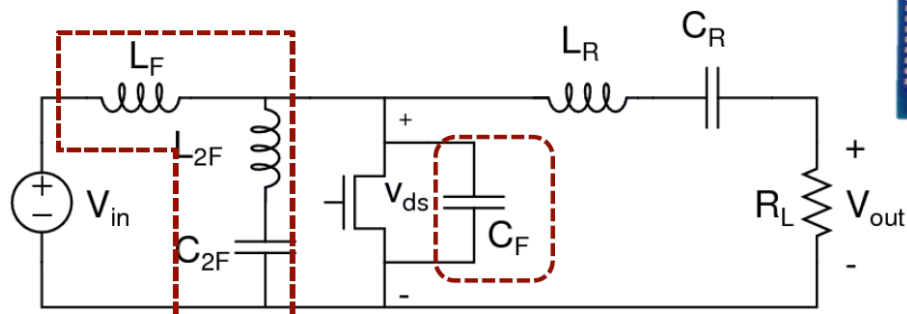
- k-factor >1 due to increased circulating current, duty cycle loss
- P_{T-On} = 0 (soft-switch)
- P_{Qoss} ↓ 10x 2-3x (GaN C_{OSS} charging/discharging loss negligible up to 2MHz)
- P_{DRIVER} ↓ 10x (GaN P_{DR} negligible up to 2MHz)
- P_{QRR} = 0
- P_{DIODE} ↓ 3x 2x (synchronous rectification with improved dead-time control)
- P_{T-OFF} = 0 Reduced (near-zero drive loop impedance with integration)

>10x frequency increase possible with higher efficiencies

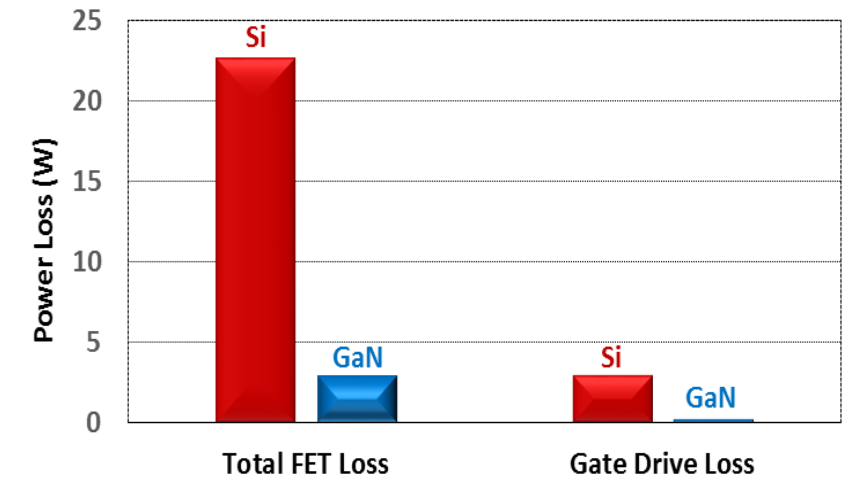
27 MHz, 40 MHz...

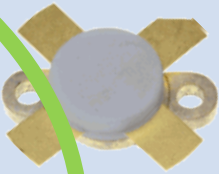
Class Phi-2 DC/AC converter

- 50% less loss than RF Si
- 16x smaller package
- Air-core inductors
- Minimal FET loss
- Negligible gate drive loss



Power Loss Breakdown (Active Components)



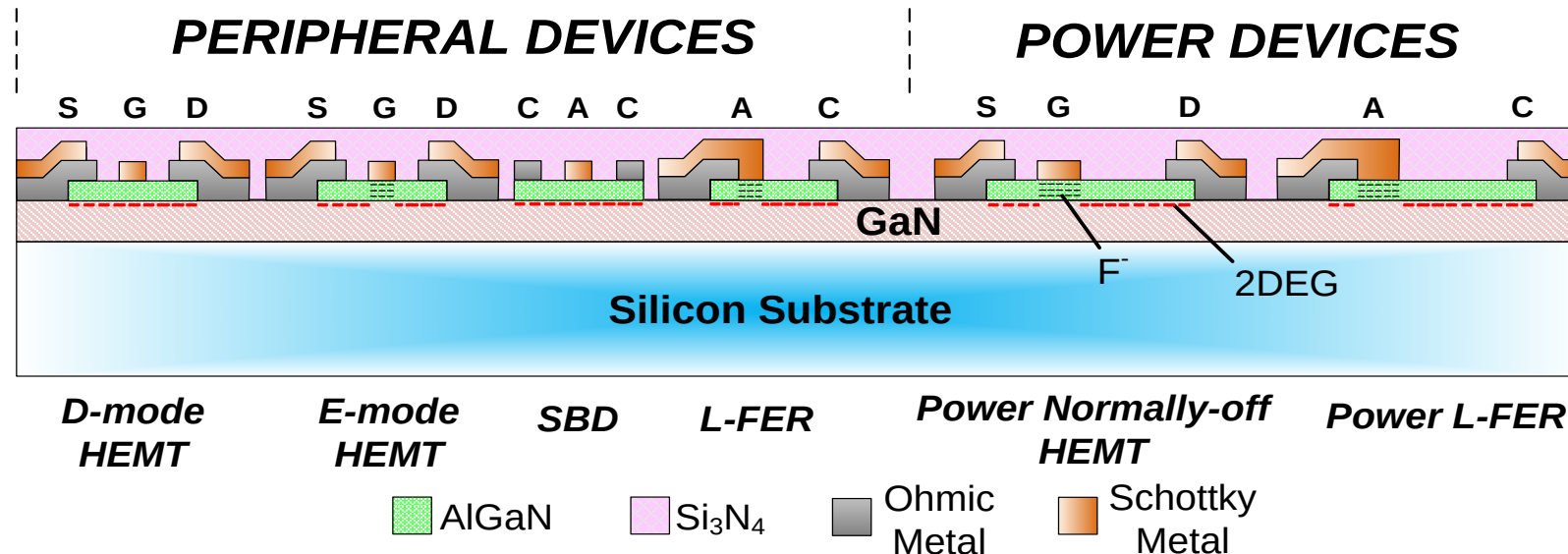
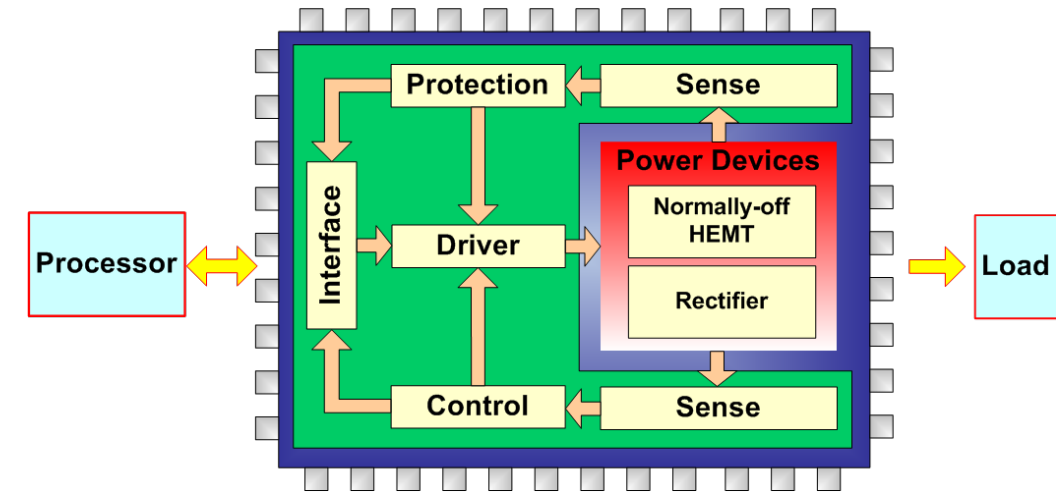
Technology	V	Pack (mm)	F _{sw} (MHz)	Eff. (%)	Power (W)
RF Si (ARF521) 	500	M174 22x22 	27.12	91%	150
	650	QFN 5x6 	27.12	96%	150
			40.00	93%	115

GaN Power IC Technology

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- **GaN IC Development History**
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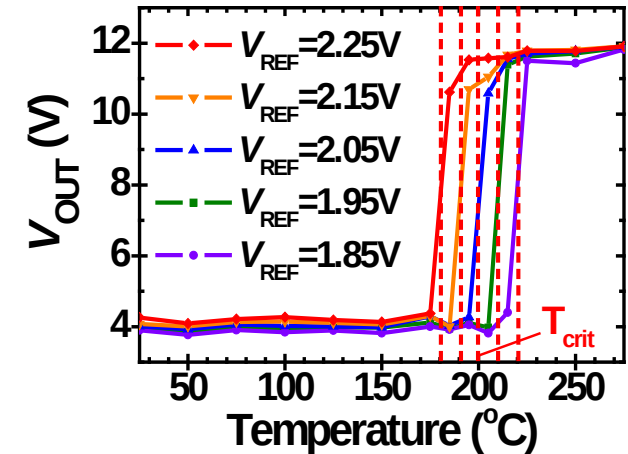
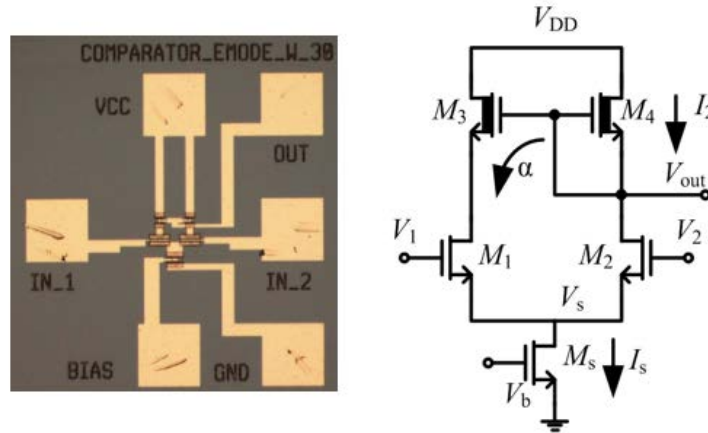
Early years of GaN Power IC Technology

- Concept of GaN power ICs developed as potential of GaN for power widely explored
- Ideal device has simple digital I/O, and all necessary functions to manage a load, such as gate drive, sensing, protection, & control
- Integrated dMode & eMode small signal HEMT, Schottky, Power HEMT, and power rectifier were proposed and demonstrated
- Threshold shift into positive range used F- implant, with some stability issues

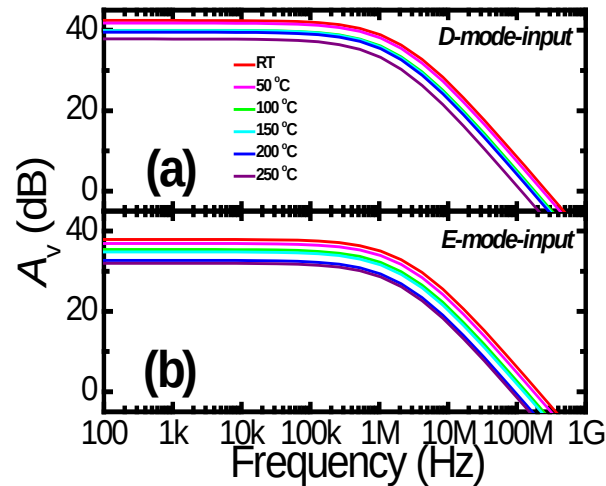


Developing Fundamental Analog Blocks in GaN

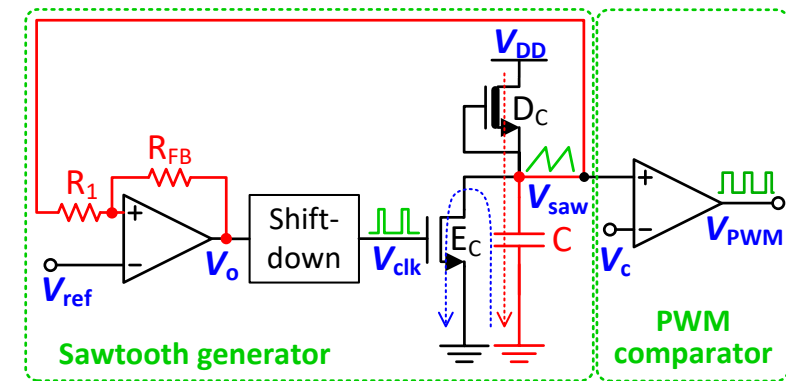
- Since then, a variety of circuit blocks and functions have been reported:
- Comparator, with both eMode and dMode input pairs
- Temperature sensors and references
- Integrated controller functions such as sawtooth generator and PWM comparator



A. M. H. Kwan, Y. Guan, X. Liu, and K. J. Chen, "Integrated over-temperature protection circuit for GaN smart power ICs," Jpn. J. Appl. Phys., 52, 08JN15, 2013



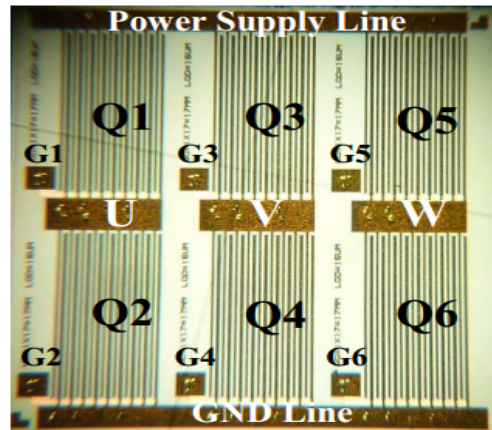
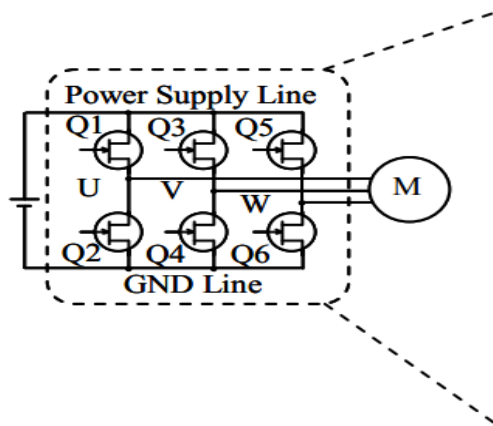
X. Liu and K. J. Chen, "GaN Single-Polarity Power Supply Bootstrapped Comparator for High Temperature Electronics," IEEE Electron Device Letters, vol. 32, No. 1, pp. 27-29, Jan. 2011



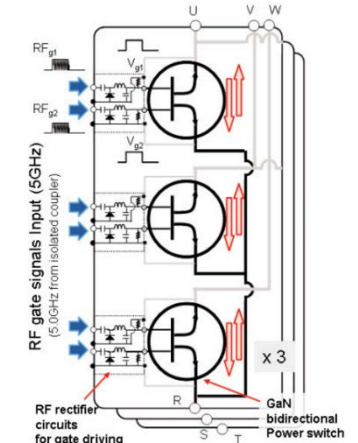
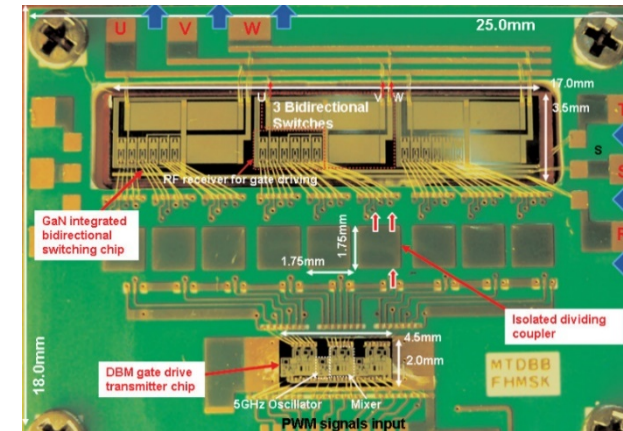
H. Wang, A. M. H. Kwan, Q. Jiang, and K. J. Chen, "A GaN Pulse Width Modulation Integrated Circuit," ISPSD2014, Waikoloa, Hawaii, USA, June 15-19, 2014

Multiple Power Devices on Chip

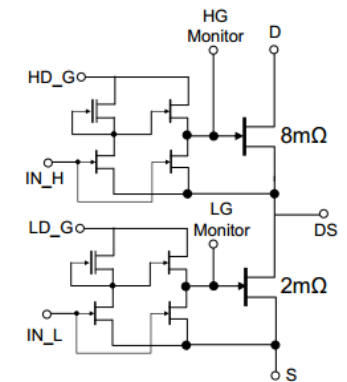
- One reported 3-phase inverter intended for medium voltage motor driver
- A novel integration of 9 bidirectional switches in AC/AC 3-phase to 3 phase matrix converter
 - Gate drive function is by eighteen rectifier circuits that receive 5 GHz pulse trains during Intended on periods
- A low voltage assymmetric synchronous buck circuit for point-of-load converter
 - An early demonstration of an integrated output buffer stage to provide a gate drive output buffer function



Y. Uemoto, T. Morita, A. Ikoshi, H. Umeda, H. Matsuo, J. Shimizu, M. Hikita, M. Yanagihara, T. Ueda, T. Tanaka, D. Ueda, "GaN Monolithic Inverter IC Using Mornallu-off Gate Injection Transistors with Planar Isolation on Si Substrate," 2009 IEDM, Dec 2009



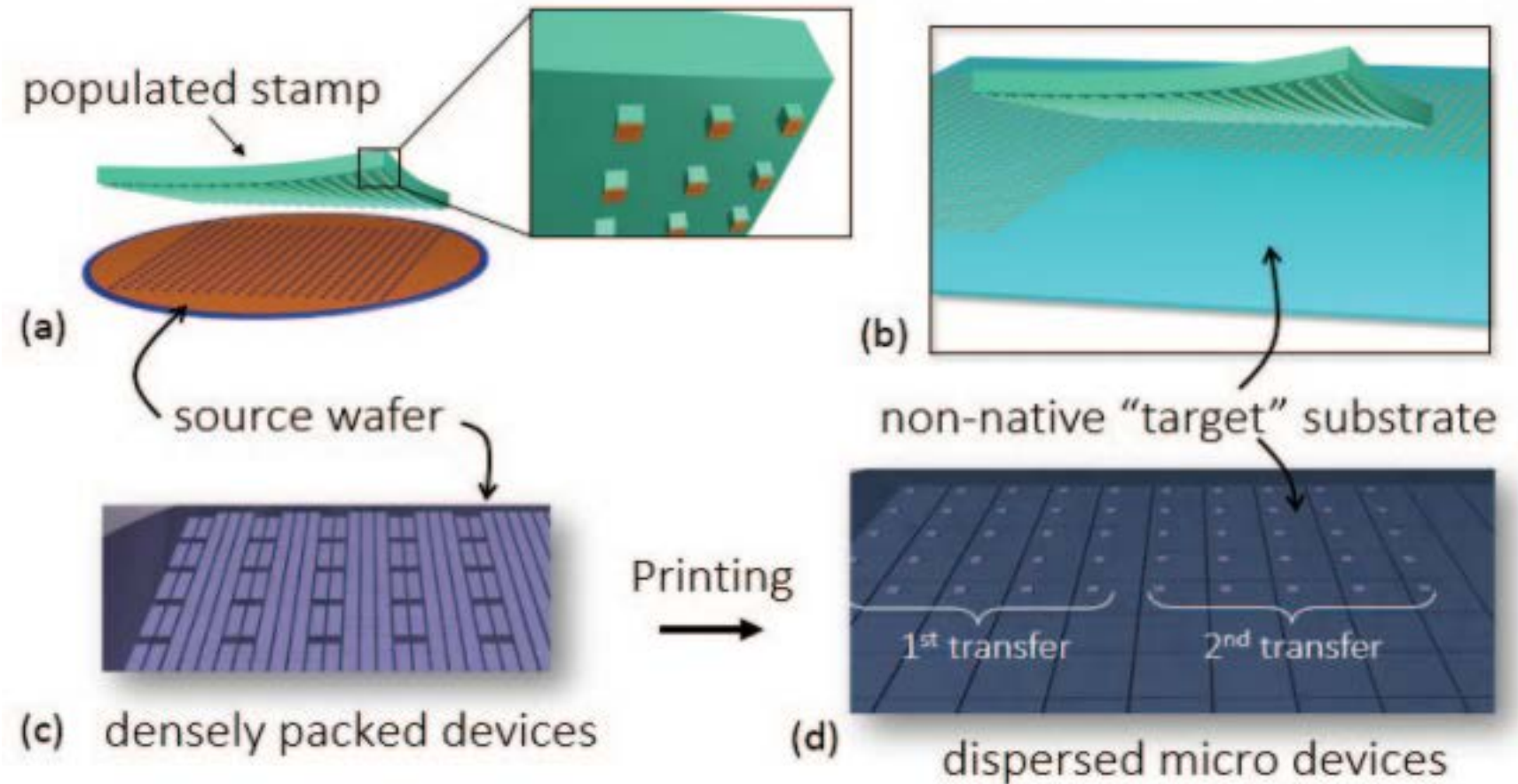
S. Nagai, Y. Yamada, N. Negoro, H. Handa, Y. Kudoh, H. Ueno, M. Ishida, N. Otuska, D. Ueda, "A GaN 3x3 Matrix Converter Chipset with Drive-by-Microwave Technologies, Intl. Solid State Circuits Conf. 2014



S. Ujita, Y. Kinoshita, H. Umeda, T. Morita, S. Tamura, M. Ishida, T. Ueda, "A Compact GaN-based DC-DC Converter IC with High-Speed Gate Drivers Enabling High Efficiencies," ISPSD2014, Waikoloa, Hawaii, USA, June 15-19, 2014

Hybrid Integration: Chip-on-Chip Bonding

- An alternative to full monolithic power IC integration:
- Select GaN transistors from a source wafer to provide high voltage and/or high frequency capability
- Using a designed stamp, pick the devices on an interval that matches the size of the target IC.
- Transfer and release to form the power GaN on CMOS chip on chip

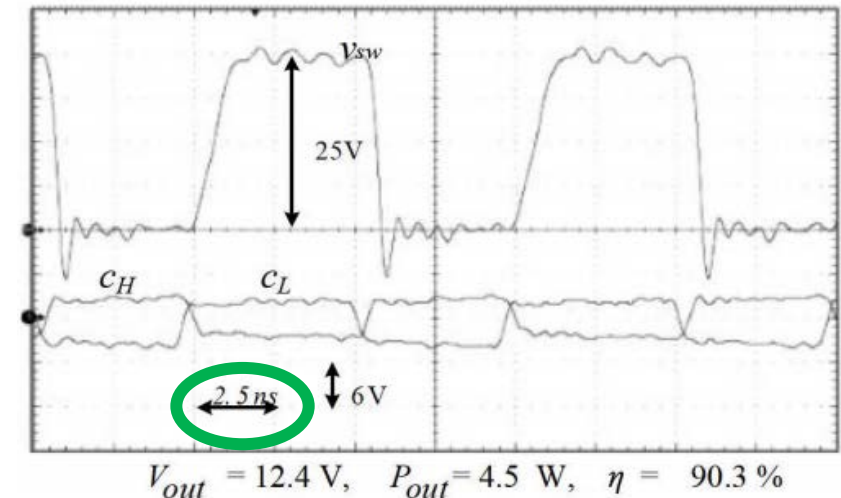
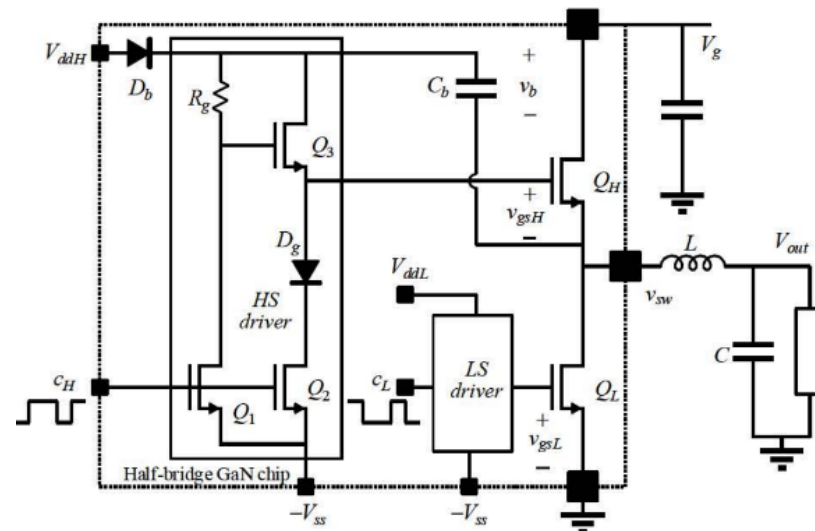
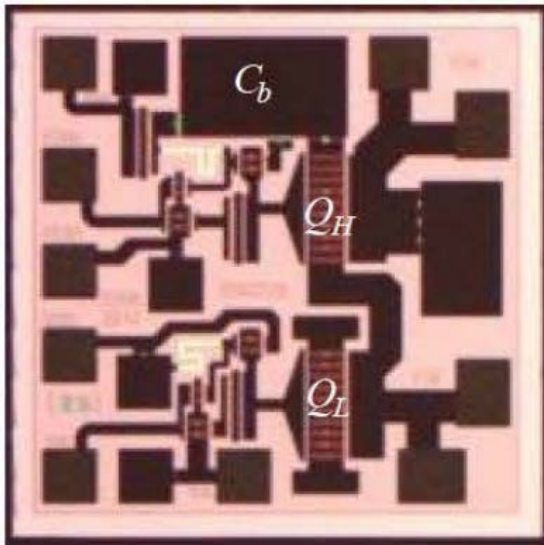


R. Lerner, S. Eisenbrandt, C. Bower, S. Bonafede, A. Fecioru, R. Reiner, P. Waltereit, "Integration of GaNHEMTs onto Silicon CMOS by Micro Transfer Printing," ISPSD2016, Prague, Czech Republic, May, 2016

Pushing GaN Power IC Technology >100 MHz

- This monolithic GaN buck converter example is showing operation with near 90% total efficiency up to 100MHz and 45V input.
- At these frequencies, high Q RF compatible air core magnetics and low ESR ceramic capacitors are essential

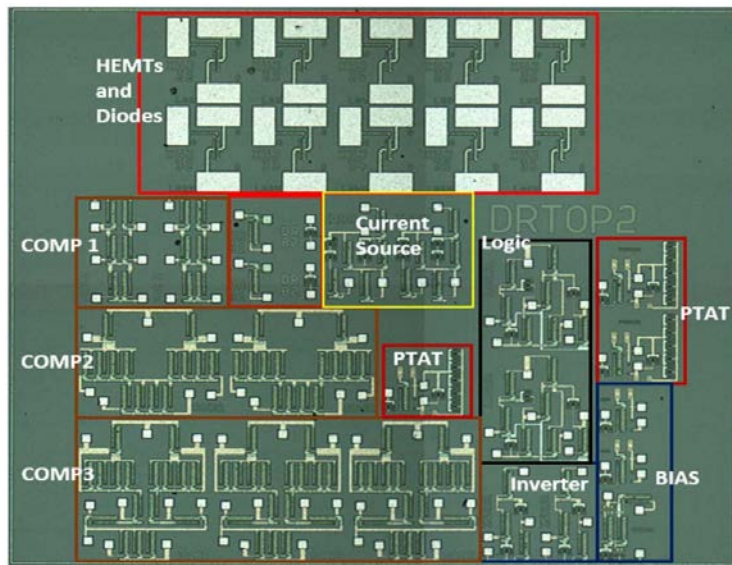
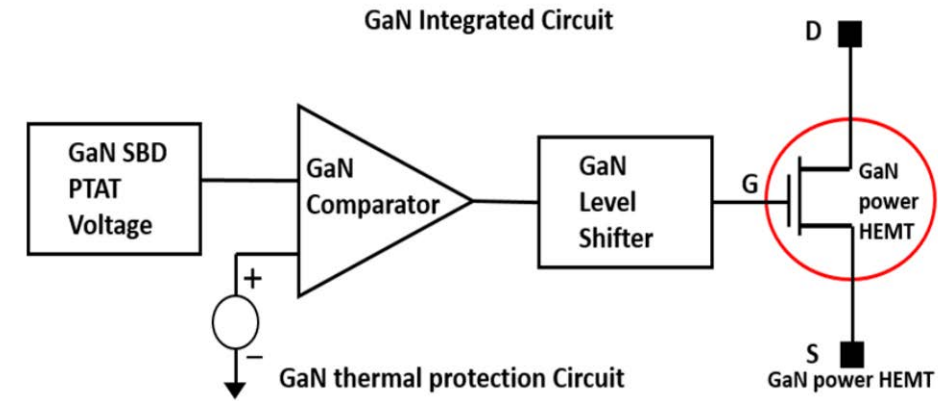
Switching frequency, f_s [MHz]	20	50	100	200	400	100
Input voltage [V]	25	25	25	25	20	45
Maximum output power [W]	16.0	10.1	7.1	3.4	5.0	6.0
Peak power stage efficiency [%]	95.0	94.2	93.2	86.5	72.5	91.7
Peak total efficiency [%]	92.5	91.7	89.2	82.0	67.0	90.2
Inductance (L) [nH]	160	90	47	22	12.5	90
Duty cycle (D) [%]	75	75	75	75	50	50



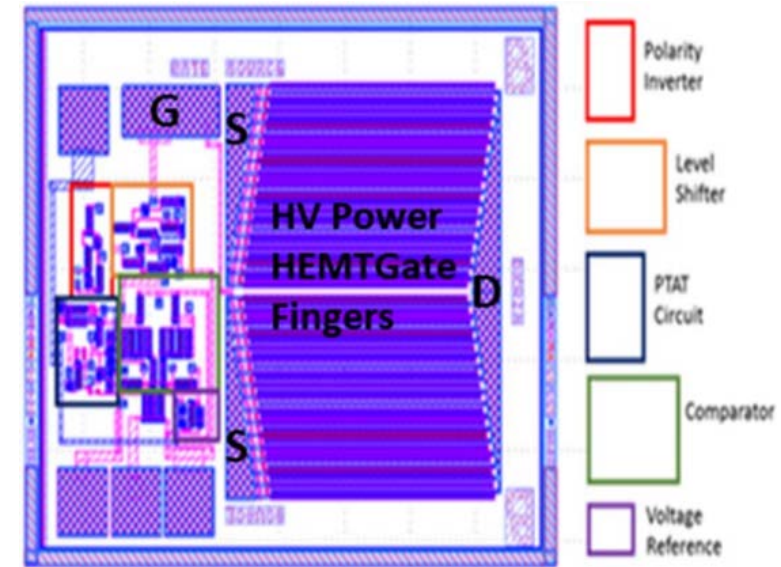
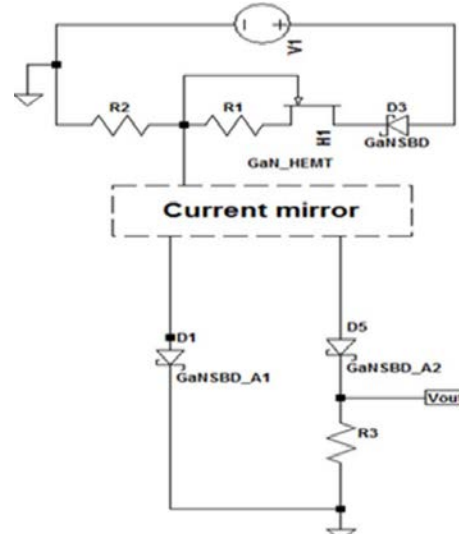
Alihossein Sepahvand, Yuanzhe Zhang, Dragan Maksimovic, "High Efficiency 20-400 MHz PWM Converters using Air-Core Inductors and Monolithic Power Stages in a Normally-Off GaN Process," APEC 2016 March 21, 2016, Long Beach, Ca. USA

Recent Cell Library Development and Application

- A cell library includes current sources, comparators, bias and logic circuitry, a PTAT generator, and a reference
- All of this is integrated in the example to provide a high voltage GaN single transistor Power IC with thermal protection

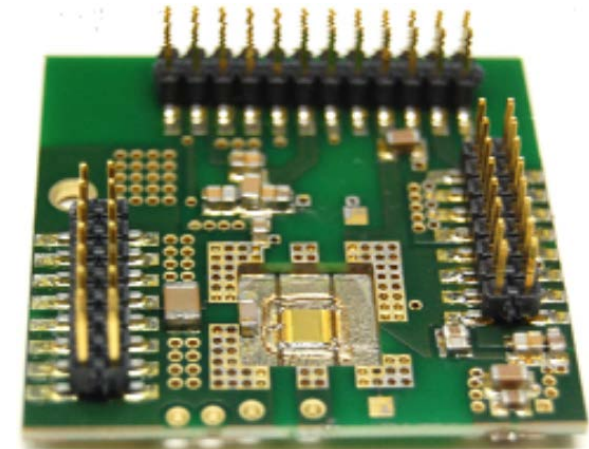
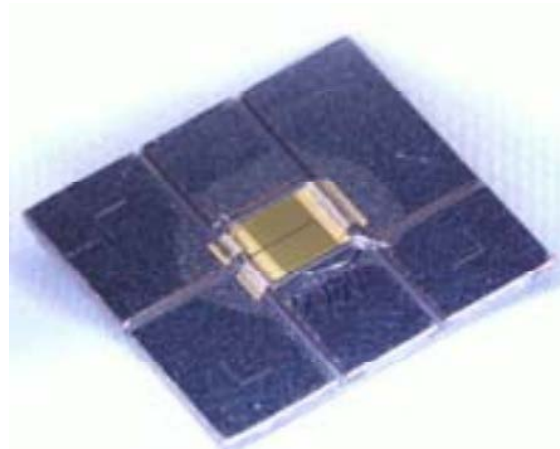
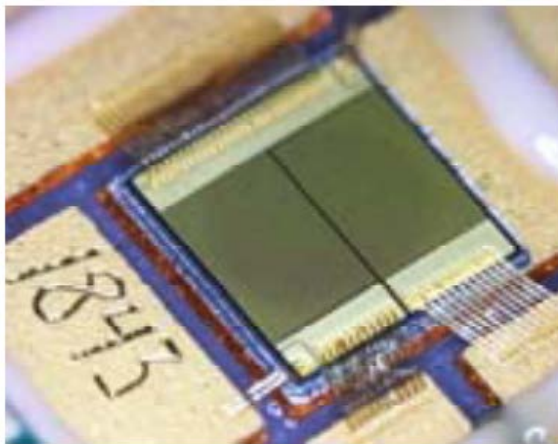
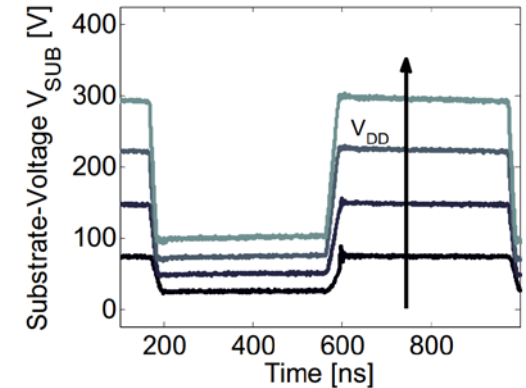
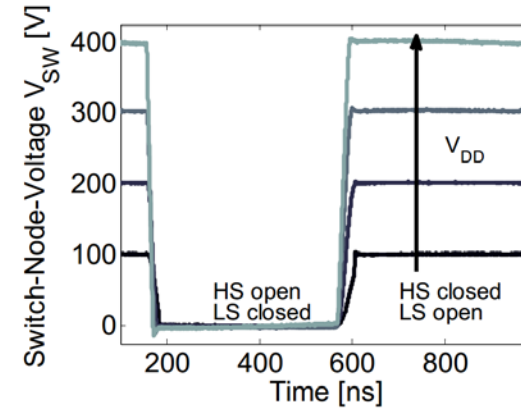
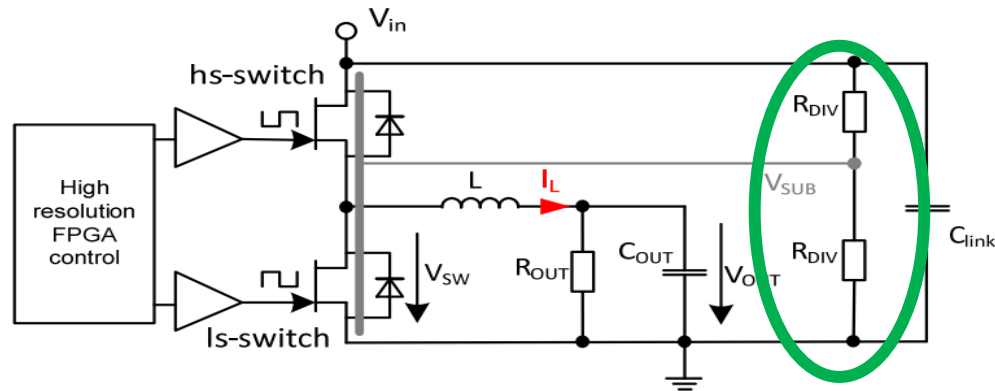


PTAT Voltage Generator



A Demonstration of Half Bridge Integration

- In order to suppress current collapse, the chip substrate is connected to a passive network formed by the R_{DIV} divider and the chip capacitance that causes it to closely follow the switch node.



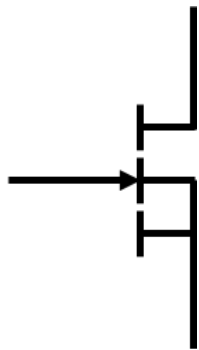
B. Weiss, R. Reiner, P. Waltereit, R. Quay, O. Ambacher, A. Sepahvand, D. Maksimovic, "Soft-Switching 3MHz Converter based on Monolithically Integrated Half-Bridge GaN-Chip," WiPDA, Nov 7-9, 2016, Fayetteville, Ar, USA

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Navitas AllGaN™ Power ICs

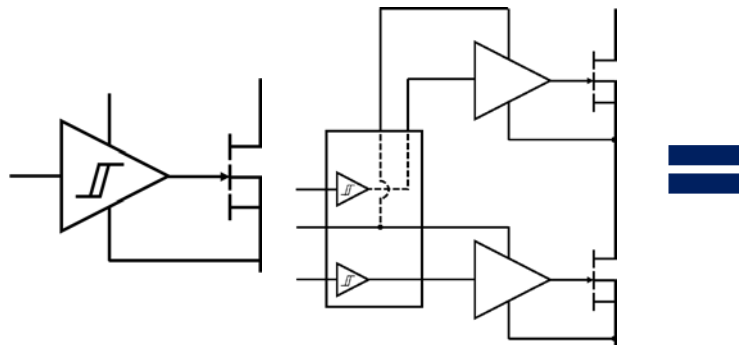
Fastest, most efficient
GaN Power FETs



>20x faster than silicon
>5x faster than cascoded GaN
Proprietary design



iDrive First & Fastest
Integrated GaN Gate Drivers



>3x faster than any other gate driver
Proprietary design
30+ patents granted/applied



World's First
AllGaN™ Power IC

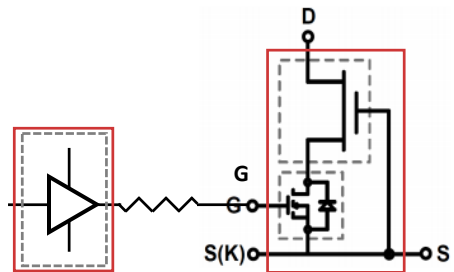


Up to 40MHz switching, 5x higher density & 20% lower system cost

Multiple Discretes → Monolithic Integration

Normally-ON
(dMode)

Co-pack Cascode FET
Discrete, External Driver
Multiple Chips, Two Packages



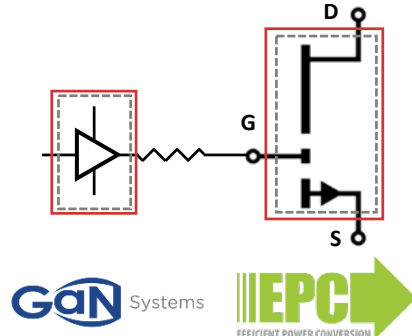
transphorm



ON Semiconductor

Normally-OFF
(eMode)

Discrete
External Custom Driver
Two Chips, Two Packages



GaN Systems

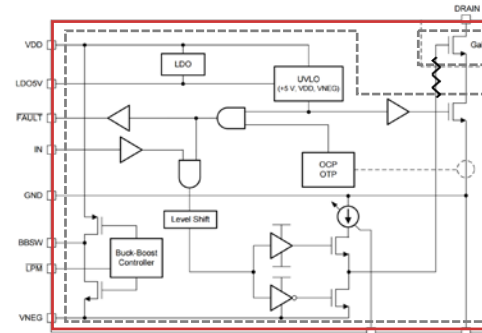


Panasonic



Normally-ON
(dMode)

Co-pack Cascode FET & Driver IC
Charge Pump Negative Rail
Two Die, One Package

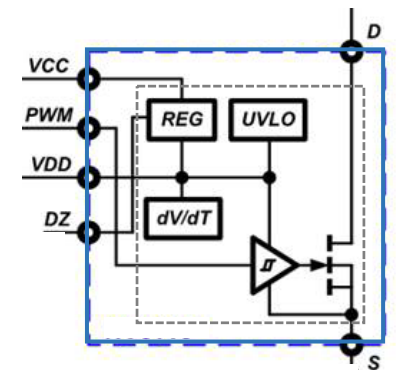


TEXAS
INSTRUMENTS



Normally-OFF
(eMode)

GaN Power IC
1 Die, 1 Package



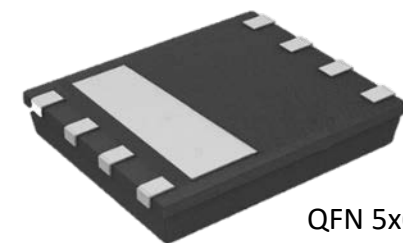
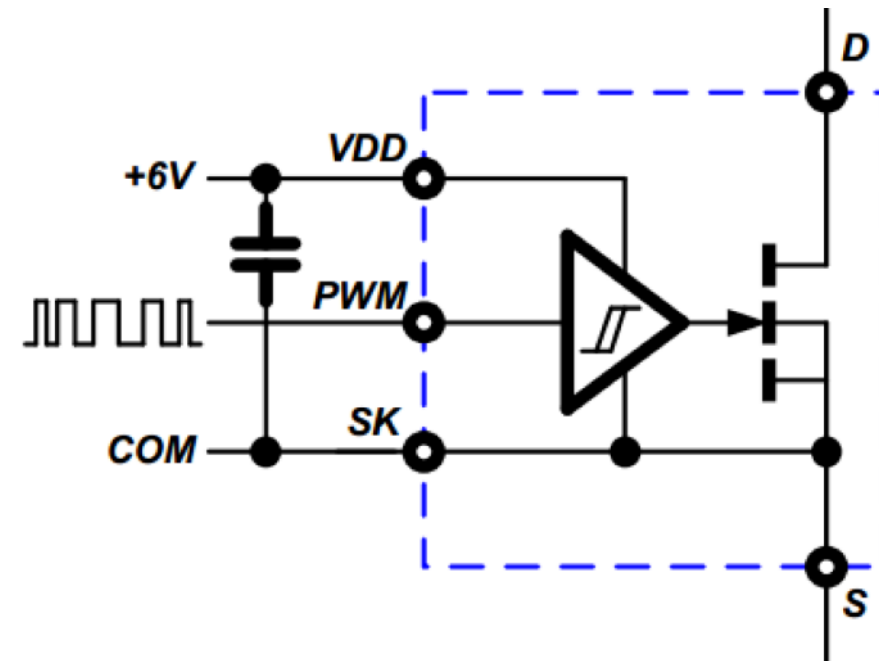
Navitas



Fast, Easy, Low Cost

Navitas GaN Power IC

- Monolithic integration
- 10X lower drive loss than silicon
- Driver impedance matched to power device
- Short prop delay (10ns)
- Zero inductance turn-off loop
- Digital input (hysteretic)
- Rail-rail drive output
- Reduces layout sensitivity



QFN 5x6mm

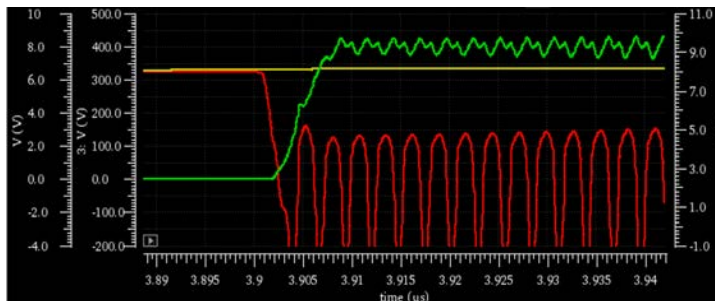
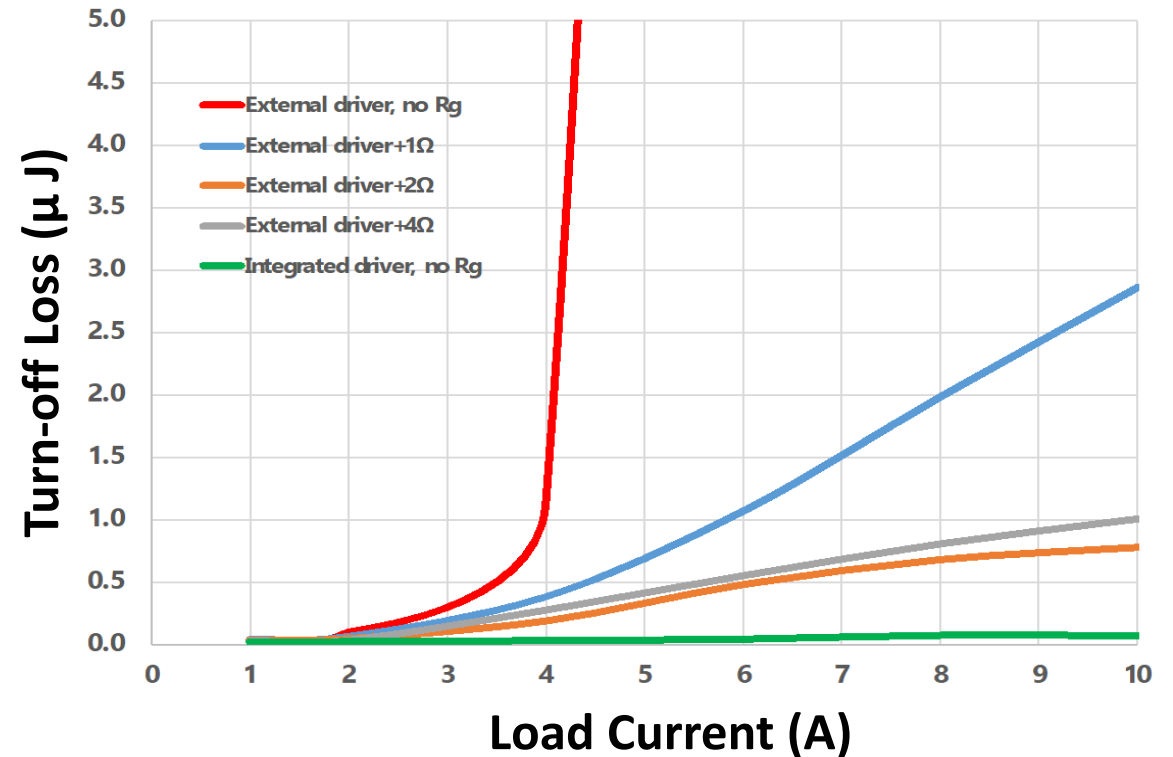
Speed & Integration → Eliminate Turn-off Losses

External drivers

- Just 1-2 nH of gate loop inductance can cause unintended turn-on
- Gate resistors reduce spikes but create additional losses

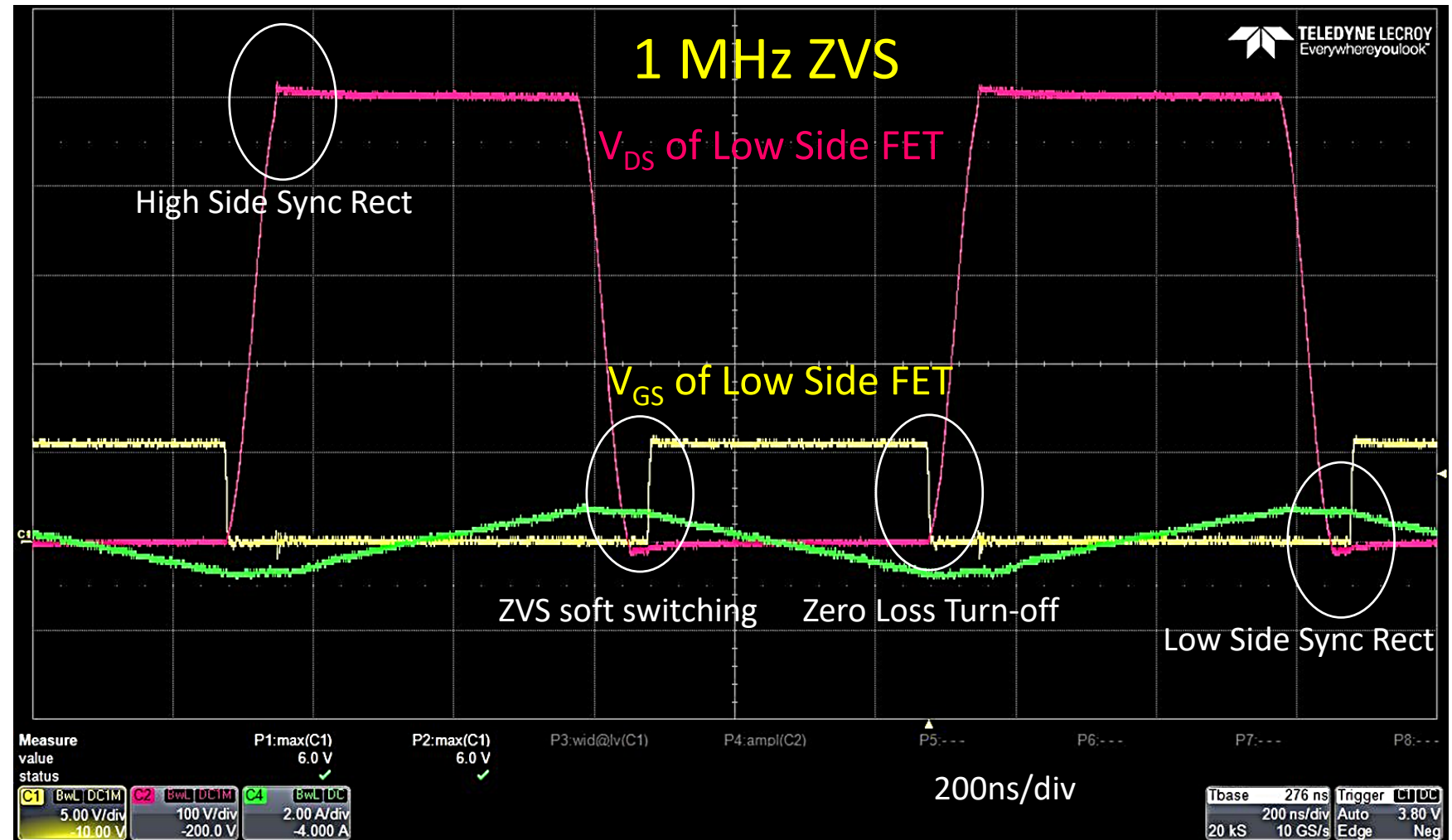
Integrated GaN drivers (iDrive™)

- Eliminate the problem
- Negligible turn-off losses



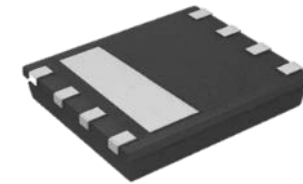
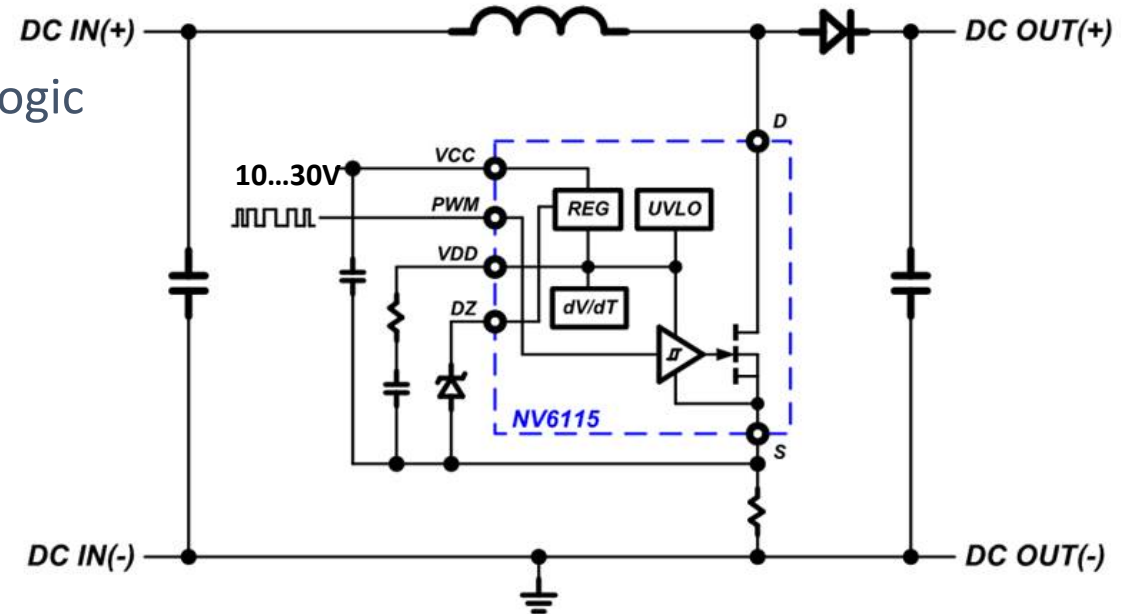
GaN Power IC – *Fast & Efficient*

- 500 V Switching
- No overshoot / spike
- No oscillations
- ‘S-curve’ transitions
- Zero Loss Turn-on
- Zero Loss Turn-off
- Sync Rectification
- High frequency
- Small, low cost magnetics



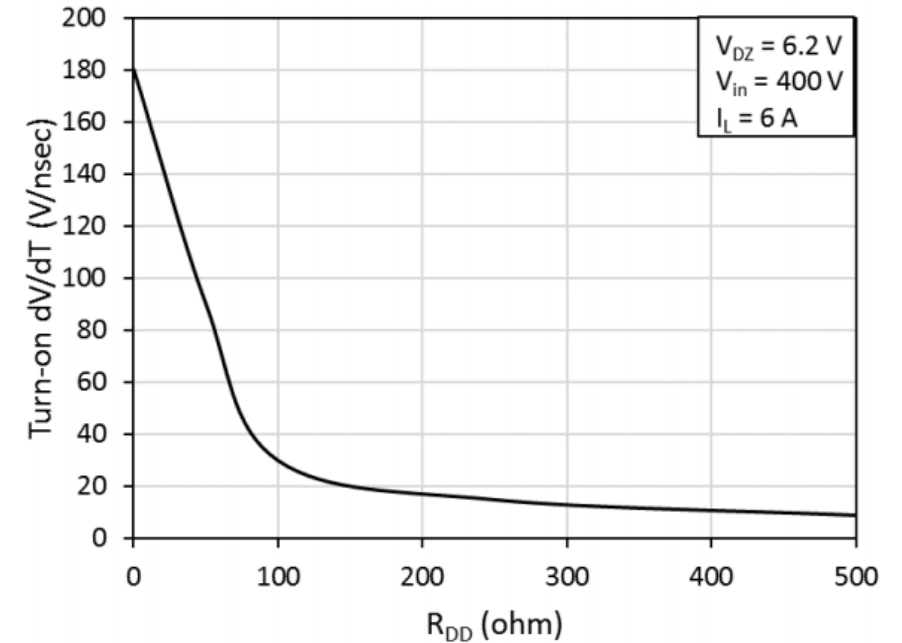
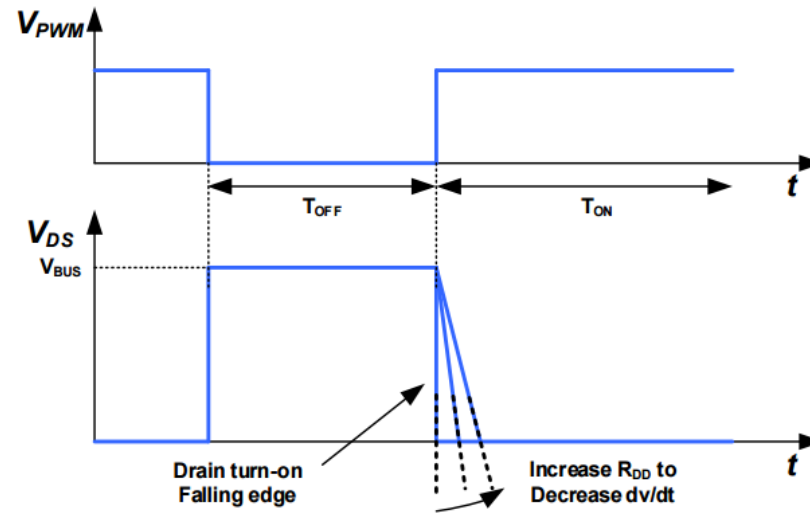
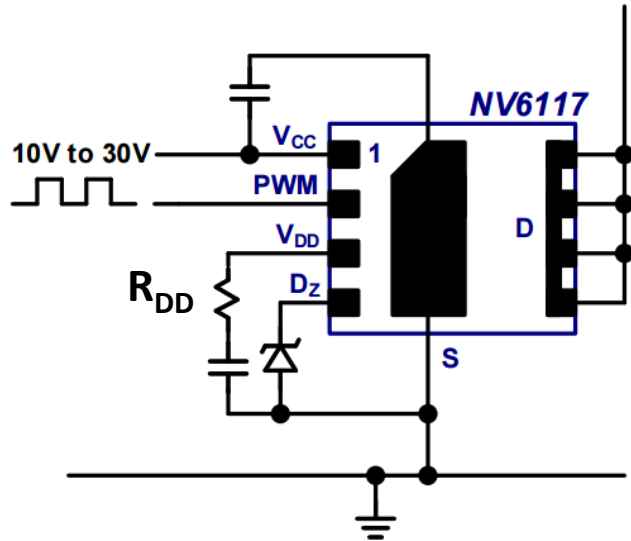
GaN Power IC: High-Speed FET, Drivers & More

- Monolithic integration of GaN FET, GaN Driver, GaN Logic
- 650 V eMode power device
- 10x lower drive loss than silicon (<35 mW at 1 MHz)
- Driver impedance matched to power device
- Very fast (prop delay including turn-on/off 10ns)
- Zero inductance turn-off loop
- High dV/dt immunity (200 V/ns)
- Regulated gate voltage
- Controllable turn-on dV/dt
- Digital input



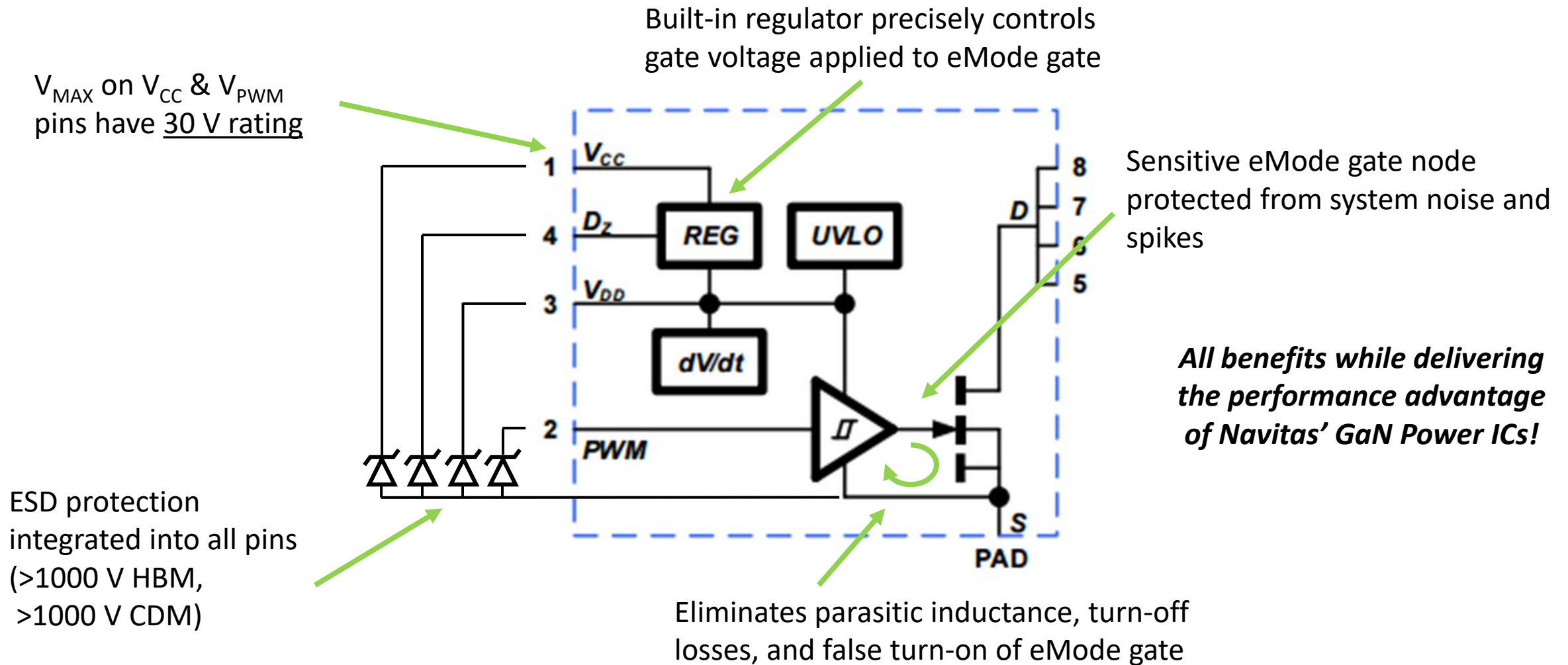
QFN 5x6mm

GaN Power IC – Voltage Slew Rate Control



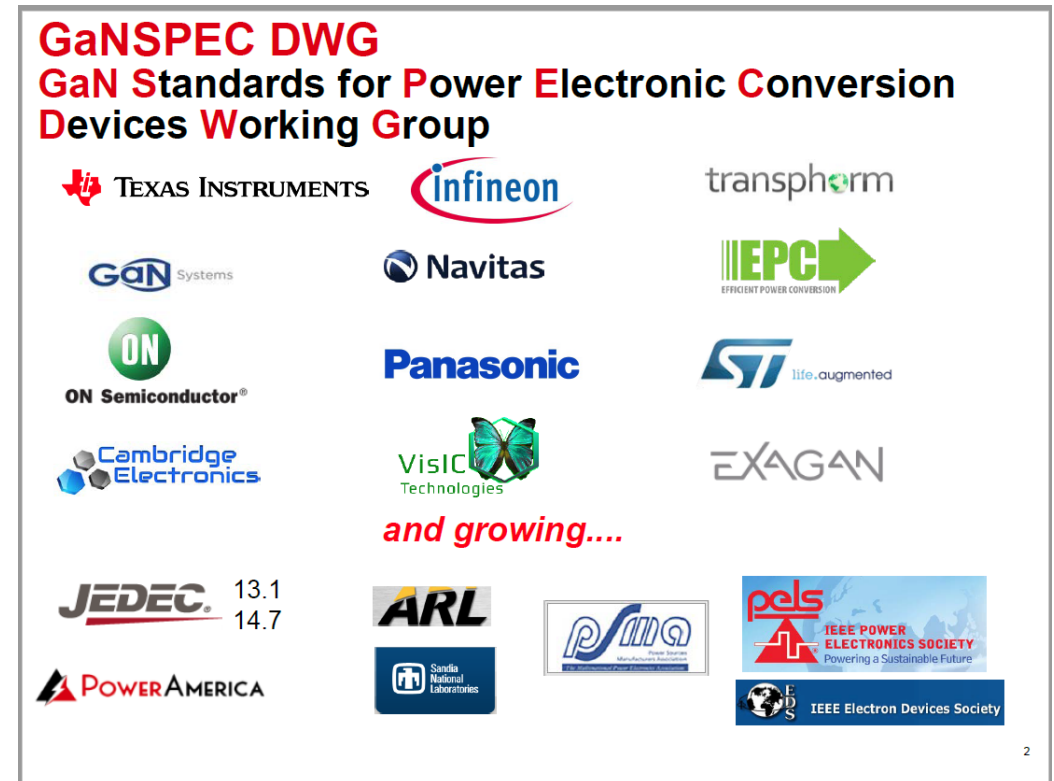
- dV/dt controllable from 180 V/ns to 10 V/ns for EMI optimization

Reliability Benefits of GaN Power IC



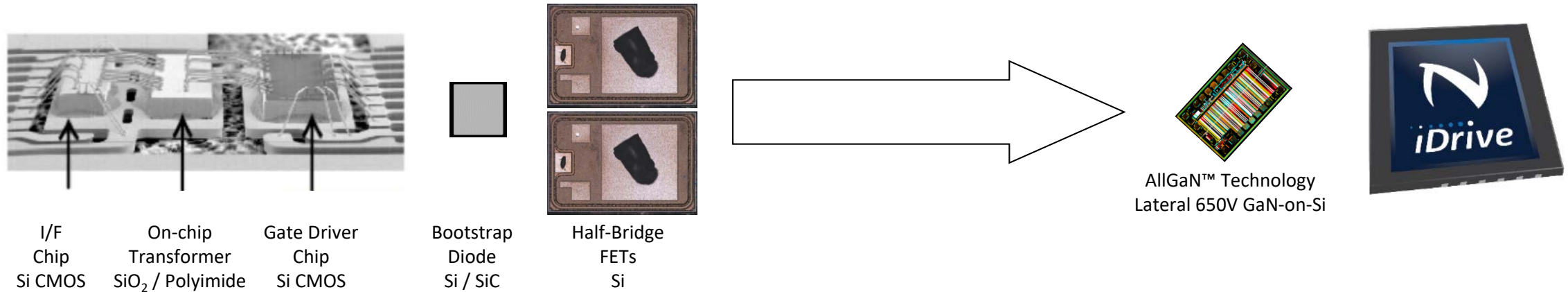
Taking GaN Beyond JEDEC & Industry Norms

- GaNSPEC DWG
 - GaN Standards for Power Electronic Conversion Devices Working Group
- Broad industry cooperation
- Defining new standards and guidelines for GaN quality & reliability
 - Test methods
 - Reliability & qualification procedures
 - Datasheet parameters



APEC 2017 Industry Presentation

High-Frequency Half-Bridge Integration



Disparate technologies:

Hybrid isolator, discrete driver, discrete power, bootstrap diode

High Loss

- 1) Driver loss, R_G loss
- 2) Bootstrap diode Q_{rr} , V_f
- 3) Pulsed high current level shifter power

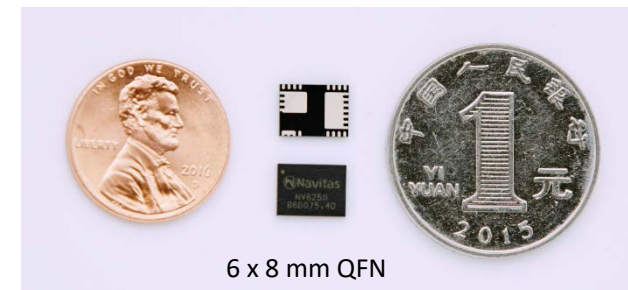
Monolithic platform:

Lateral GaN-on-Si, Half-Bridge GaN Power IC

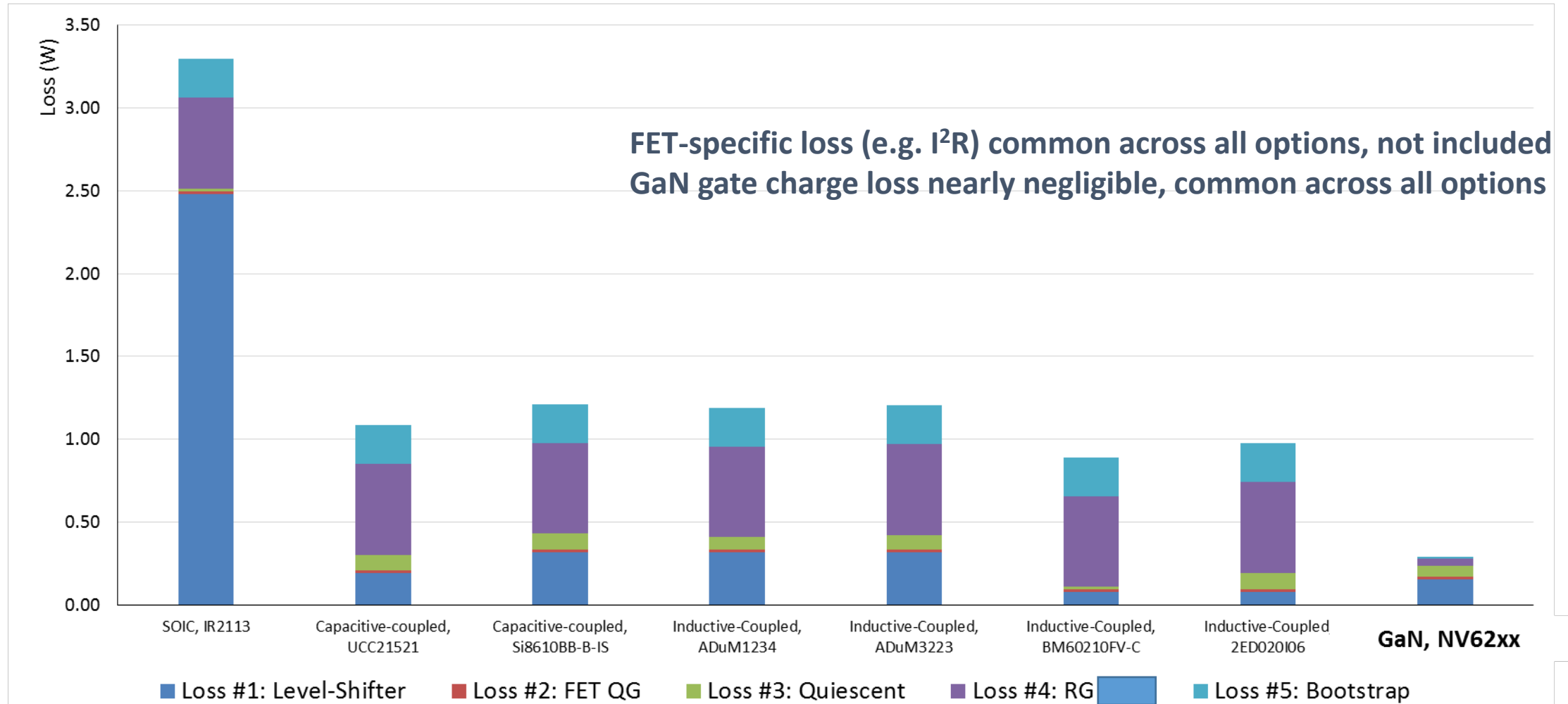
Low Loss

- 1) No gate driver loop parasitics, matched driver-FET capability, negligible loss vs frequency
- 2) Zero Q_{rr} , low $V_{DS(on)}$ in synchronous charging
- 3) Extremely fast, low-power level shifter, multi-MHz operation, short propagation delay

-

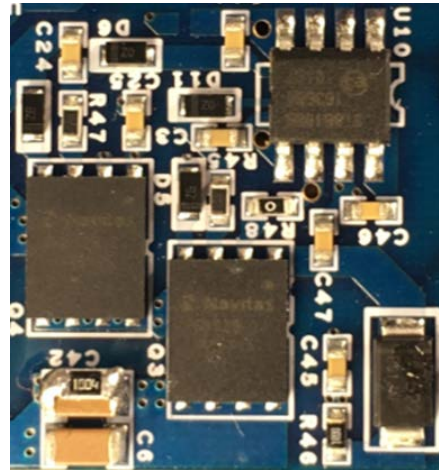


3x Lower Drive and Level Shift Loss at 1 MHz

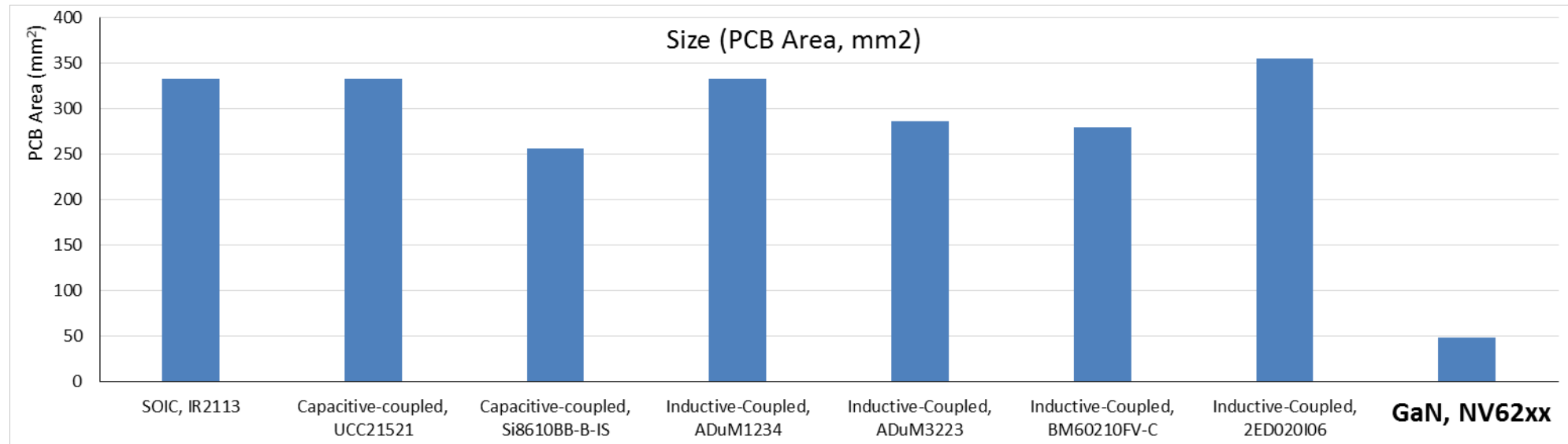


5x Smaller Footprint than Best Single GaN

Digital Isolator
2x Single GaN Power ICs
Bootstrap diode
Passives



Half Bridge
GaN Power ICs
5X smaller than
alternatives

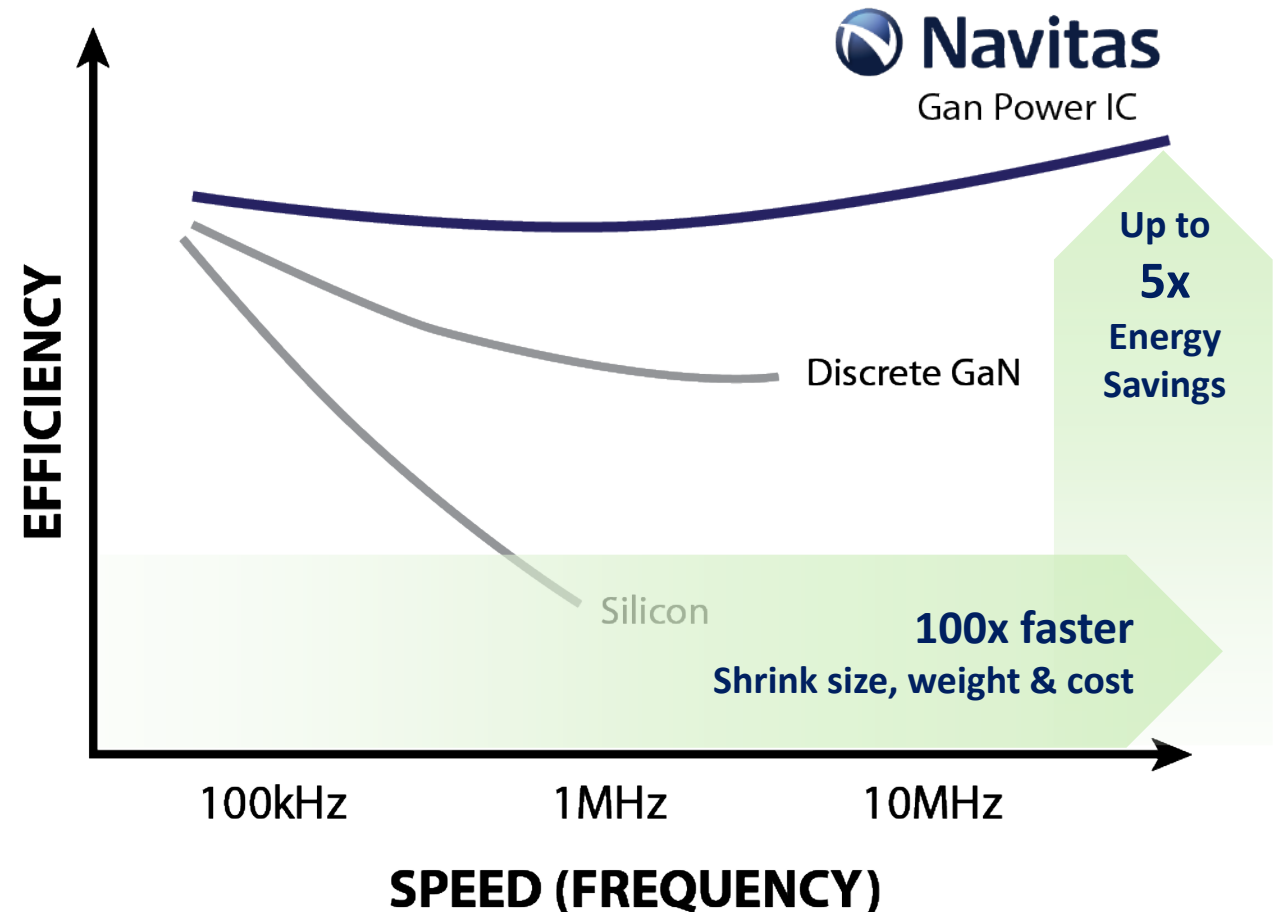


GaN Power IC Technology

- Why GaN on Silicon?
- GaN IC Development History
- Navitas AllGaN™ Power ICs
- **Application examples**
- Future directions
- Summary

Power Electronics: *Speed & Efficiency are Key*

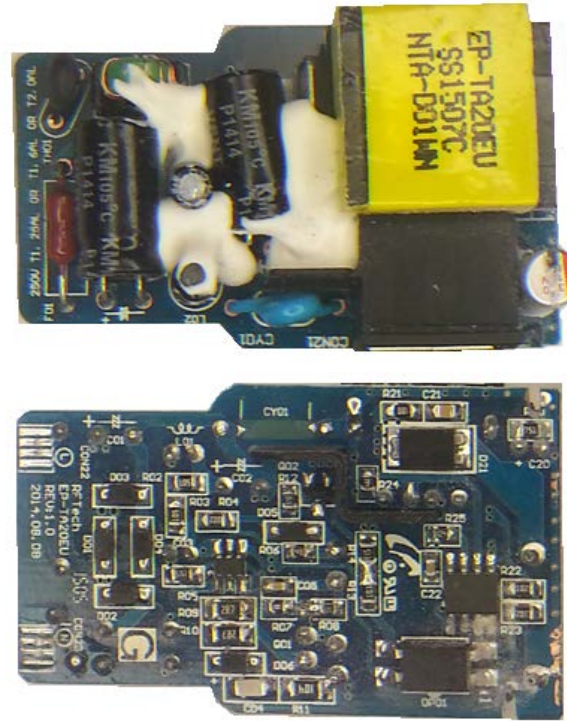
- **Speed** enables *small size, low-cost* and *faster charging*
- **Efficiency** enables *energy savings*
- With Silicon or Discrete GaN power devices, you can get one **or** the other
- With GaN power ICs, you get **both at the same time** with unequalled **Speed & Efficiency**



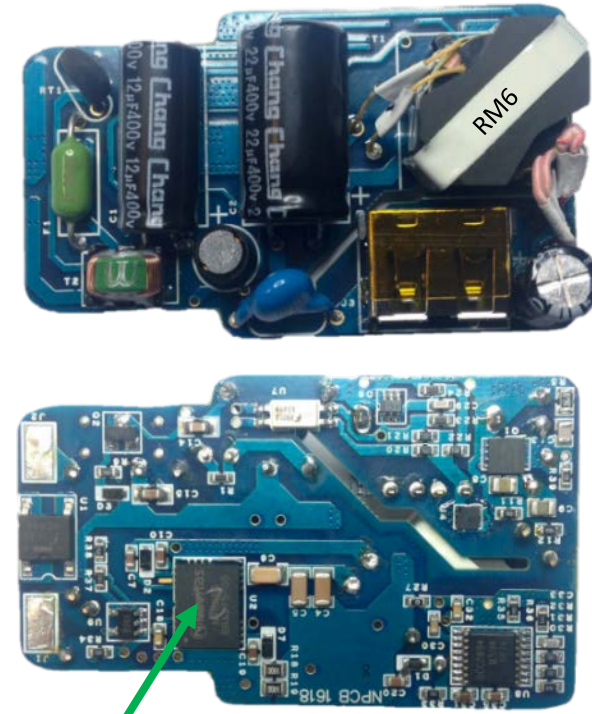
66% Higher Power with Half-Bridge GaN Power IC



Original 15 W AC/DC
charger case



Original 15 W, Si-based QR Flyback
~100 kHz, <90% efficient

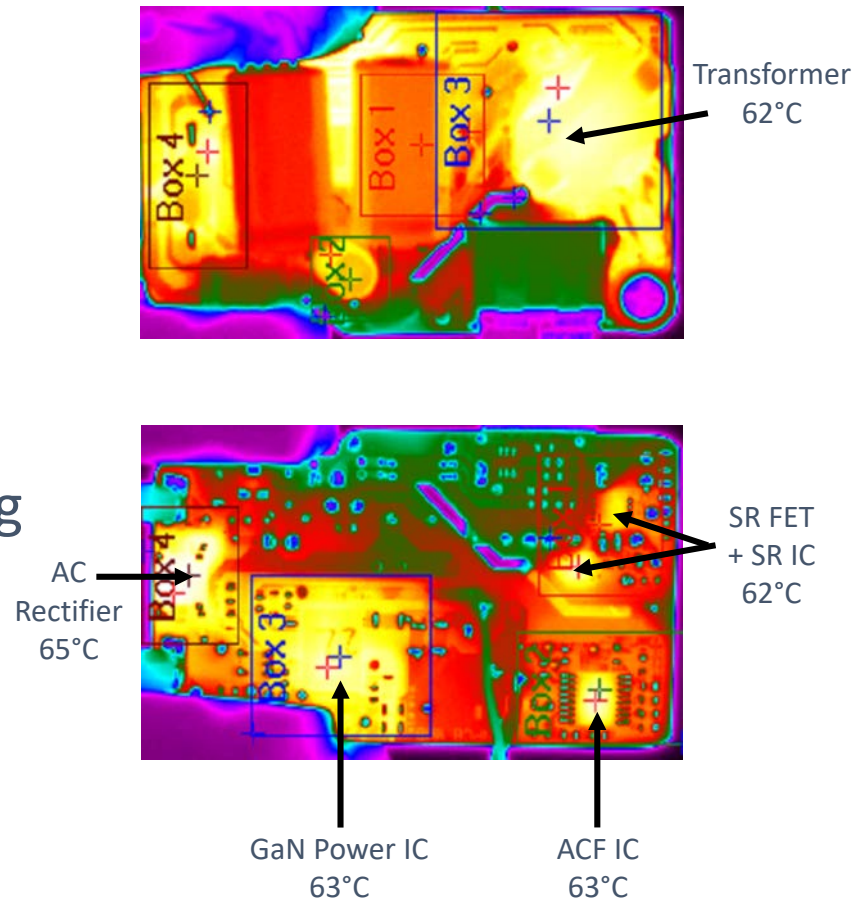


NV6250

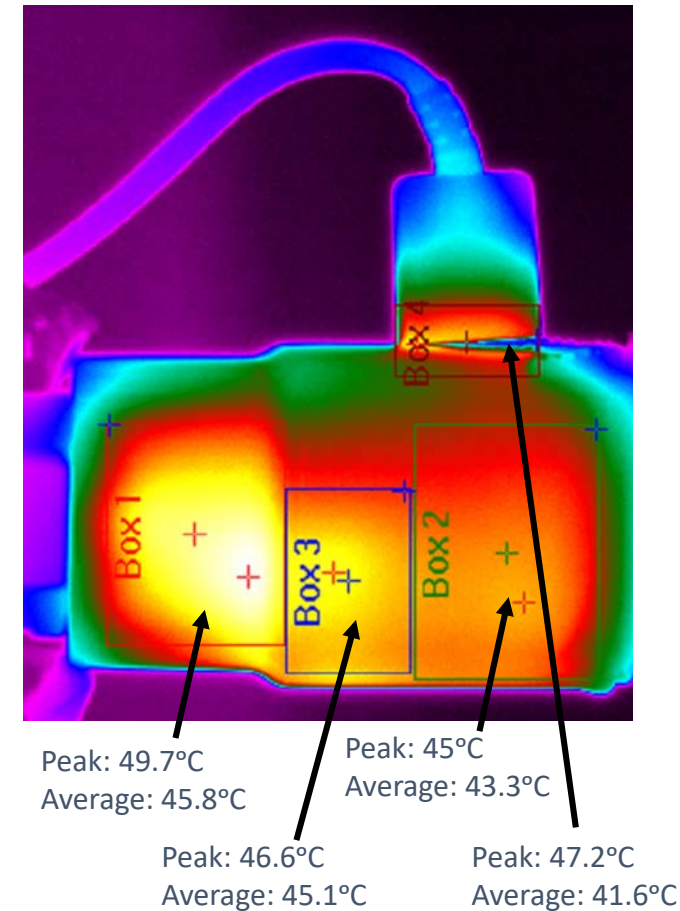
Upgraded 25 W Active Clamp Flyback
Half-Bridge GaN Power IC
~400 kHz, >94% efficient

25W Cool Thermals (12.5V, 2A)

25°C ambient
Full load
90 V_{AC} input
No heatsinking



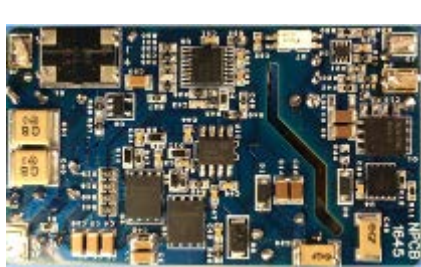
No case



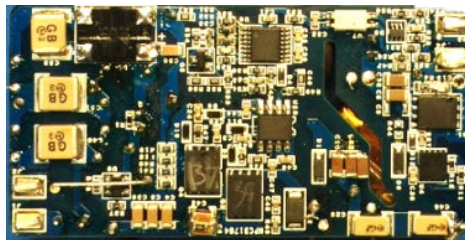
Cased

45W, 65W 24W/in³ ACF

45W = 59.1 x 33.5 x 15.7 mm = 24 W/in³ (uncased)
2x NV6115 (160mΩ)

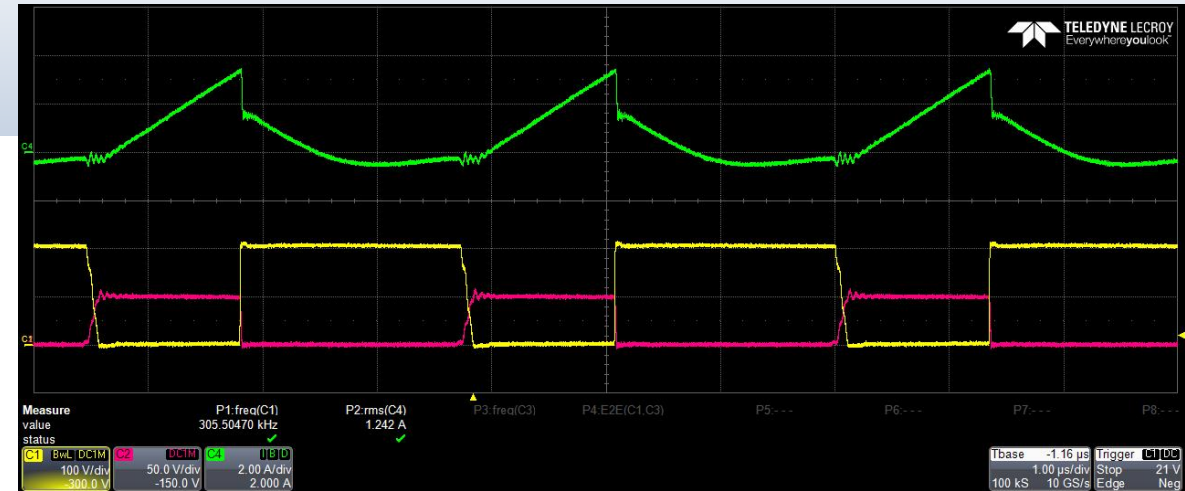
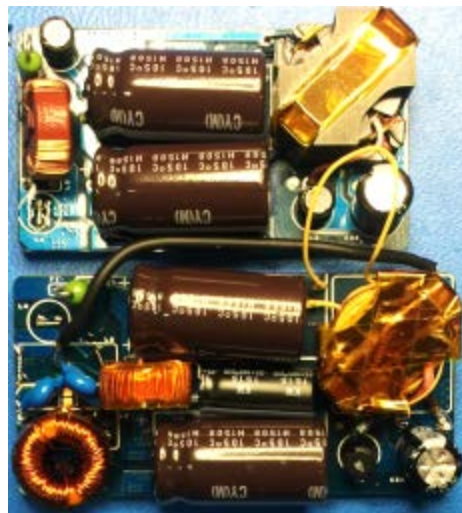


45W

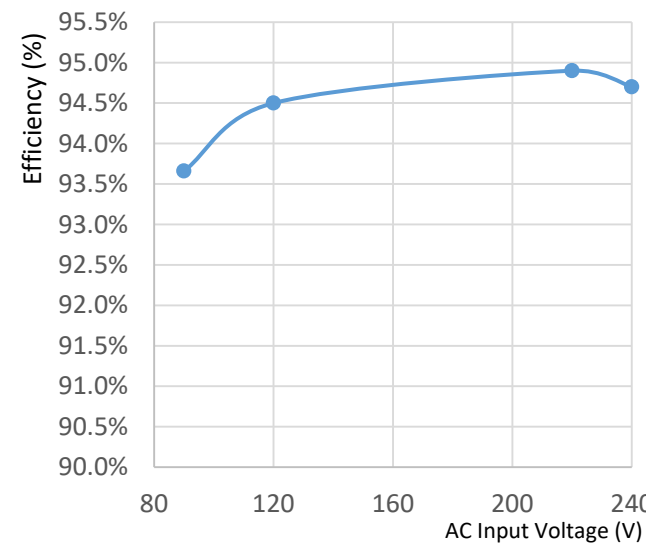


65W

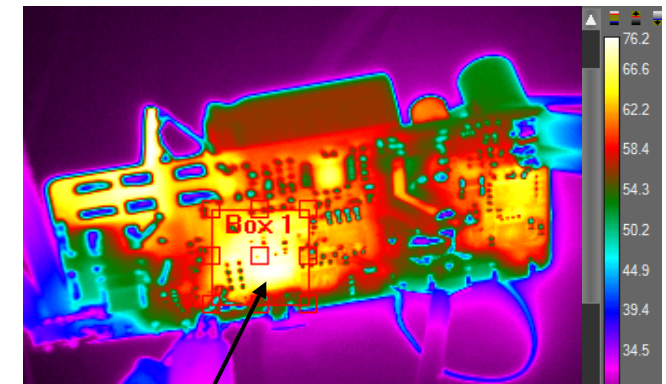
65W = 66.7 x 33.5 x 15.7 mm = 30 W/in³ (uncased)
1x NV6115 (160mΩ) + 1x NV6117 (110mΩ)



ACF switching waveforms, 300 kHz



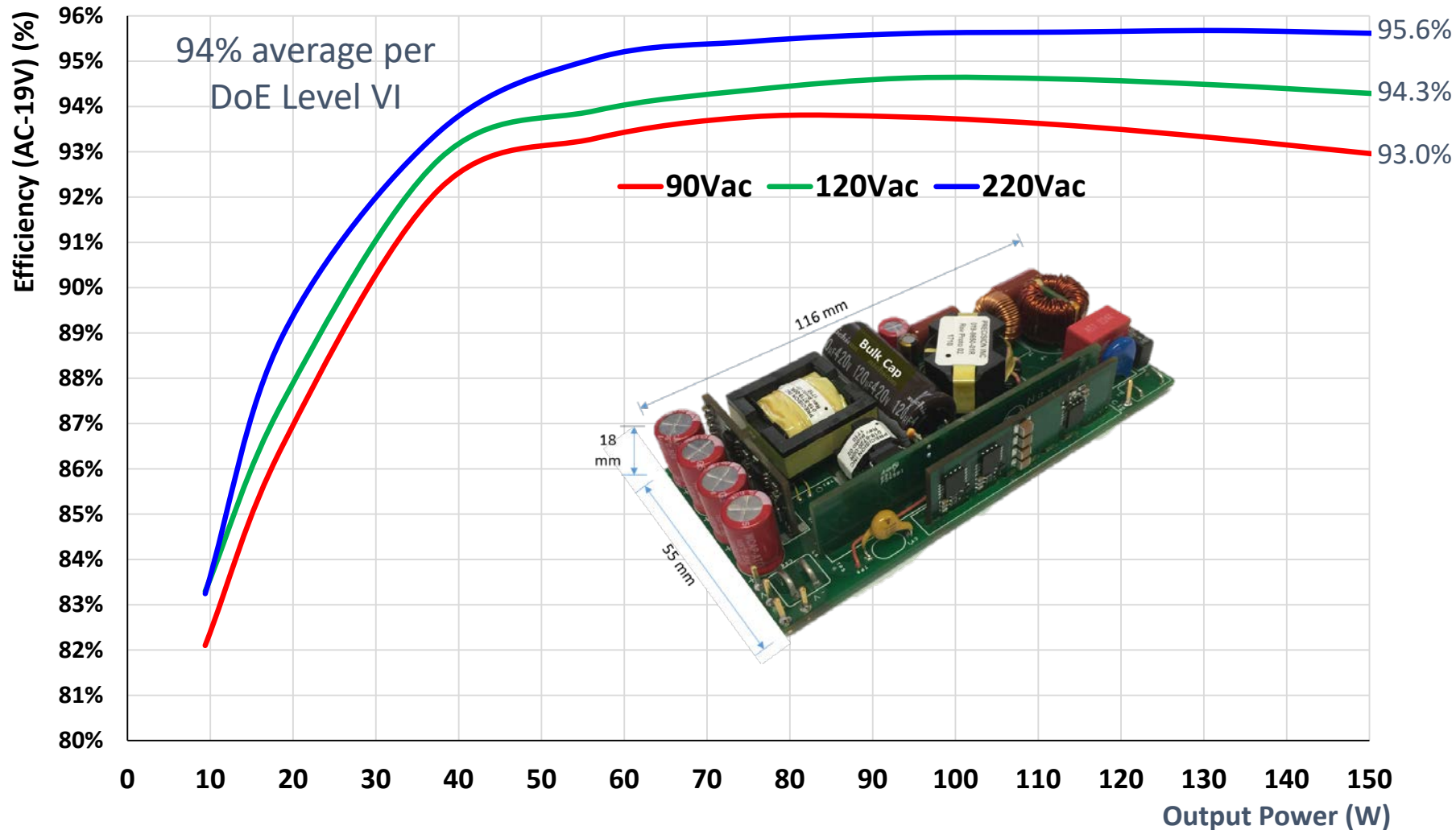
65W Efficiency vs. AC line
(25°C ambient, no airflow, full load)



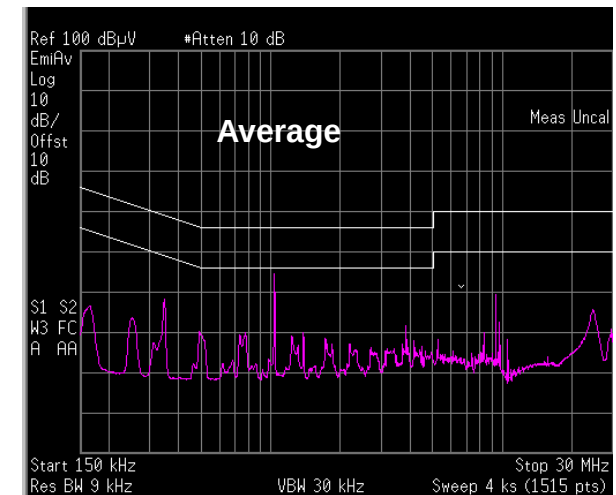
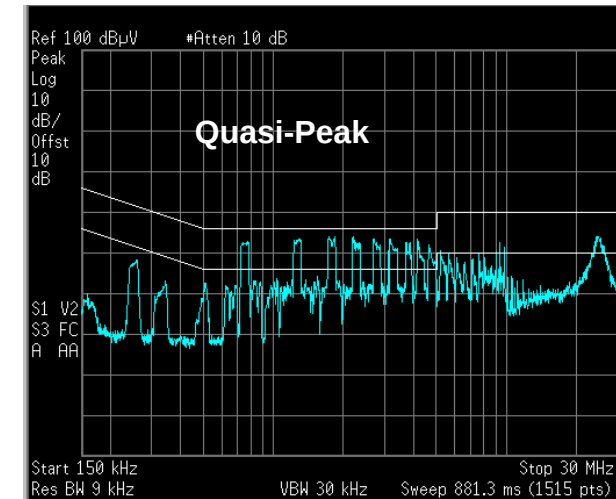
GaN Power IC ~76°C

65W Thermal Performance
(90V_{AC}, 25°C ambient, no airflow, full load)

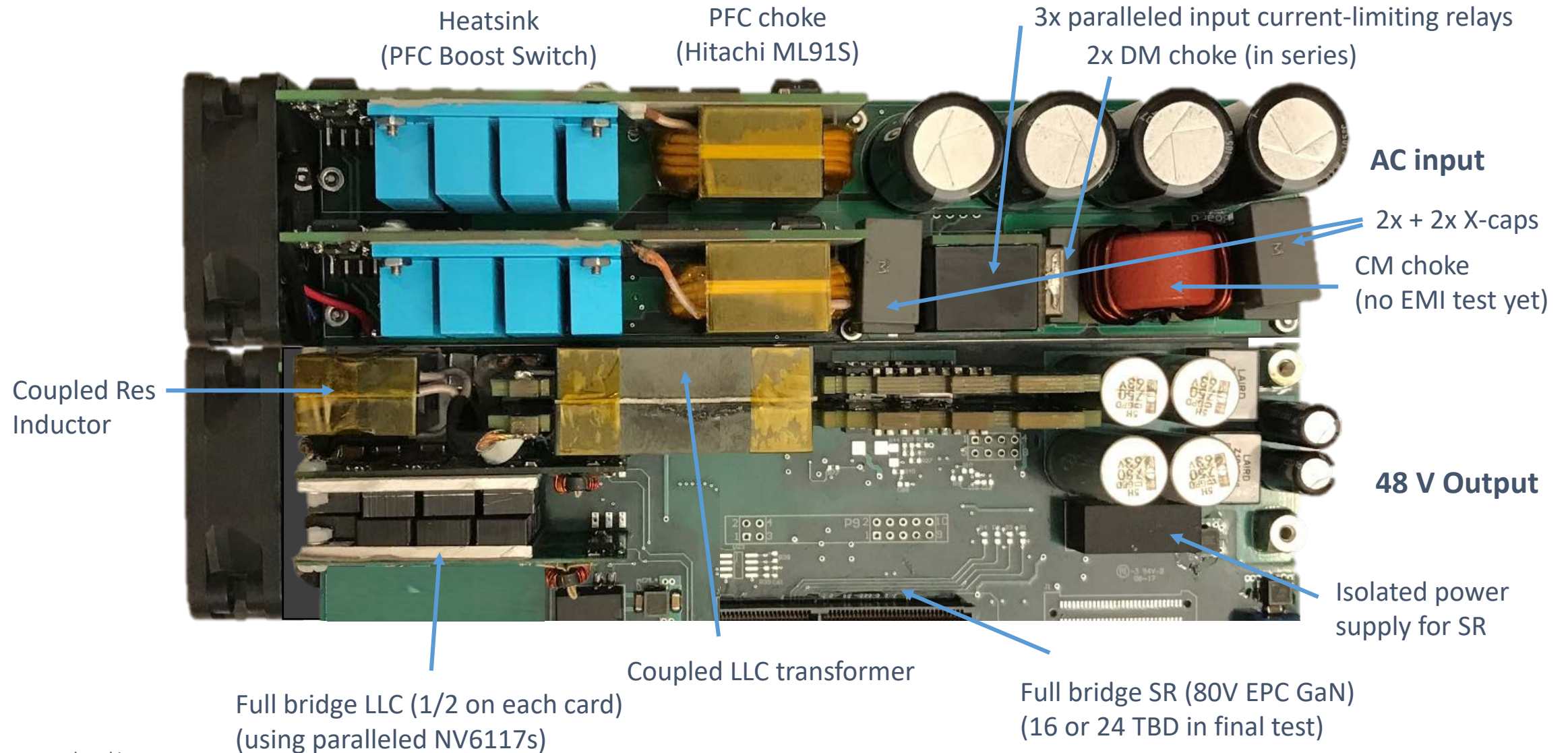
150W AC-19V, ~300 kHz, 21 W/in³



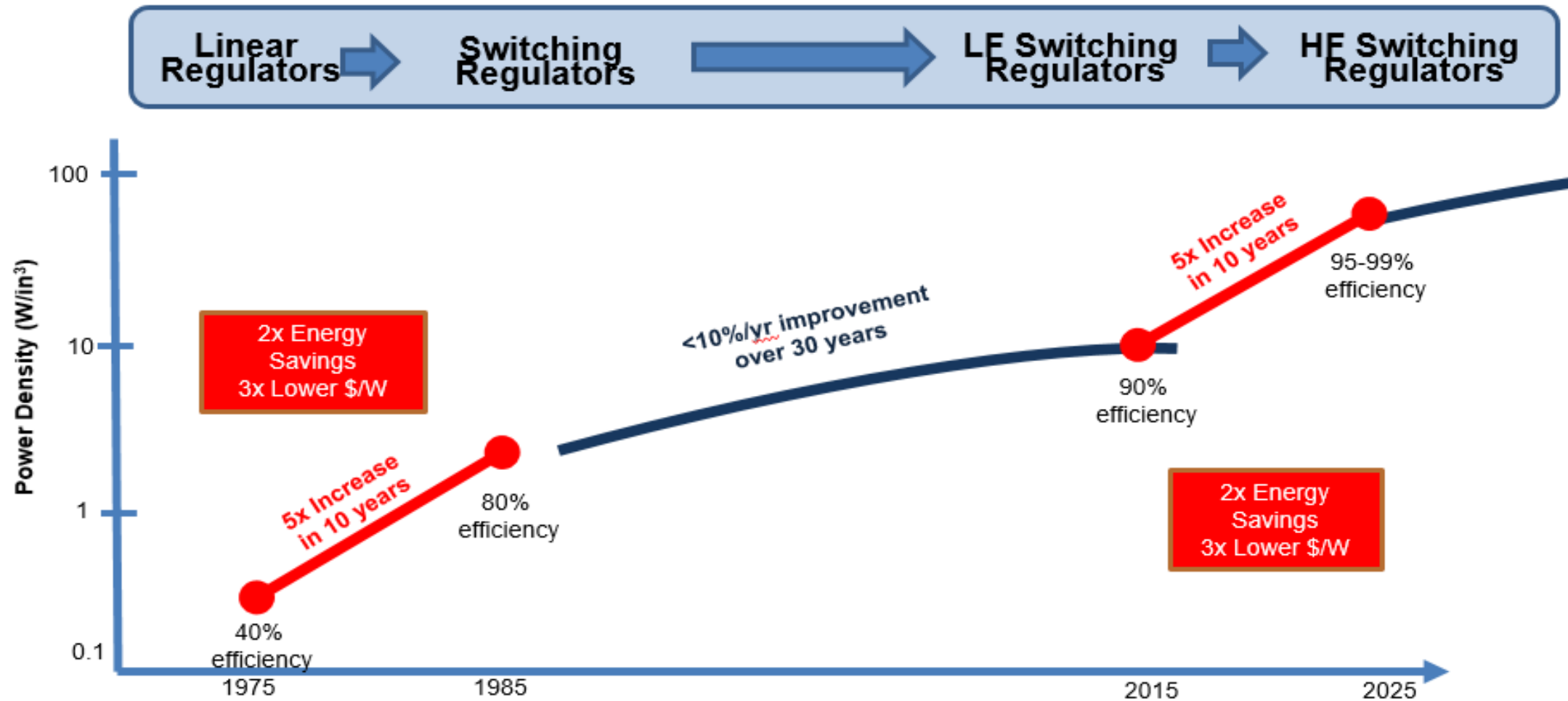
Conducted EMI



1 MHz, 3.2 kW 65W/in³ AlGaN™ AC/DC



GaN Power ICs Accelerate Change in Power Electronics



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GaN Power ICs: The Road Ahead



What's Left to Work on?

- A good P-channel for CMOS
- High density digital
- Memory (volatile, non-volatile, OTP, MTP, etc.)
- ICs rated for temperatures $> 150^{\circ}\text{C}$
- A full expansion of the cell library
- A process design kit

Summary

- GaN Power ICs set new standards for ease-of-use, speed, efficiency, density, & system cost
- Proven technology, ready for commercial use
- Best technology, for 90-305 V_{AC} off-line applications, 25W to 5kW
- GaN Power ICs + high-frequency magnetics + new controllers =
A bright future of rapid advancement in the power electronics industry!

Acknowledgements

- The entire team at Navitas
- Advisors in the preparation of the content
 - Prof. Kevin Chen, Hong Kong University of Science and Technology
 - Prof. Dragan Maksimovich, University of Colorado, Boulder
 - Dr. Tetsuzo Ueda and Dr. Yasuhiro Uemoto, both of Panasonic



GaN Power IC Technology

Past, Present, and Future

The 29th International Symposium on Power Semiconductor Devices and ICs

Plenary Session

Dan Kinzer, CTO/COO, dan.kinzer@navitassemi.com

May 29, 2017