GaN Technology,
What the Power Designer Needs to Know

PSMA PTRM 2013

July 12, 2012

Carl Blake, VP Marketing

transphorm

Company

Offices and labs

Fab

- Founded in 2007
- Goleta, CA
  - Daily temp 64°C to 74°C year round
- 100+ employees
- $63 M raised capital
- 150+ years of combined GaN experience

luxcapital

Foundation CAPITAL

Google ventures

Soros Fund Management

KPCB

Outline

1. Why are power devices with GaN needed?
2. What does the system designer need to know?
    1. GaN comes in two flavors
        1. normally on (d-mode)
        2. normally off (e-mode)
3. How has GaN technology changed recently

4. Today both are available and offer different trade offs for the designer

5. There are both low voltage and high voltage devices available, I will show some test results about the high voltage devices and discuss cascode connection versus a single e-mode type device.

Disclaimer – although I will focus on Transphorm GaN device test results, I believe all other companies will go through similar process steps as we are all striving for the same goal. The difference will simply be the sequence of product timing

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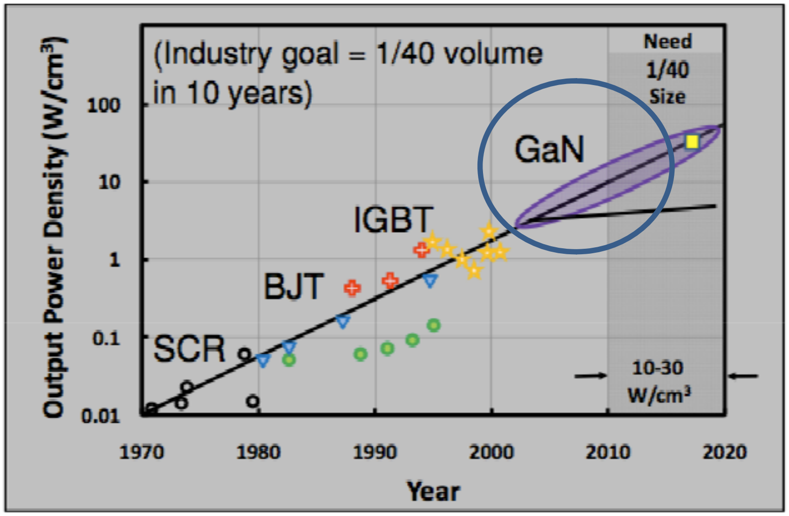
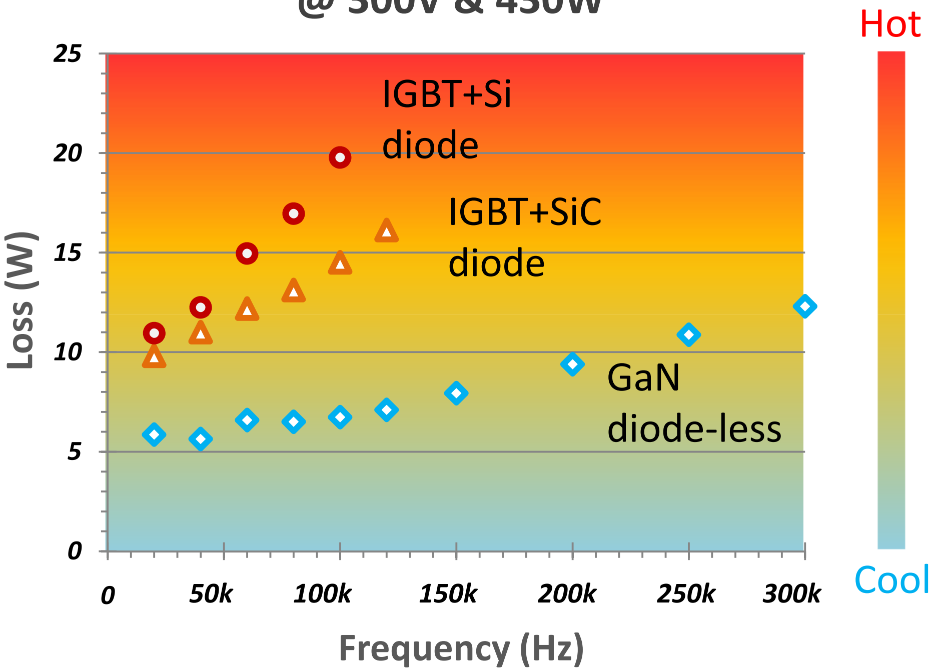
GaN solutions enables continuation of the “Moore’s” law of power electronics – density doubles every 4 years

Industry Power Density Roadmap for PS and MD



- Density in power electronics has doubled every 4 years
- Efficiency must improve to achieve the smaller size
- Silicon technology can not meet the density roadmap

Measured performance vs. frequency @ 300V & 430W



- >600 V devices are needed to continue this roadmap
- **Existing 600 V GaN device performance is enabling this roadmap today**

Compare e-mode and d-mode (cascode)

E-mode

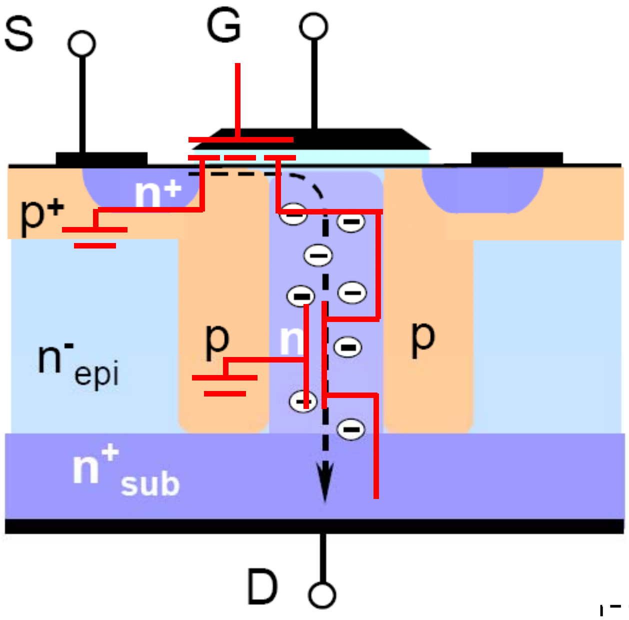
- GaN chip is lateral
- Single chip
- Lower V_{th},
- Gate will rupture at + 6 V
- Need special driver
- More desirable at low V
- More difficult at high V
- Can build multiple transistors on single chip

Cascode using d-mode

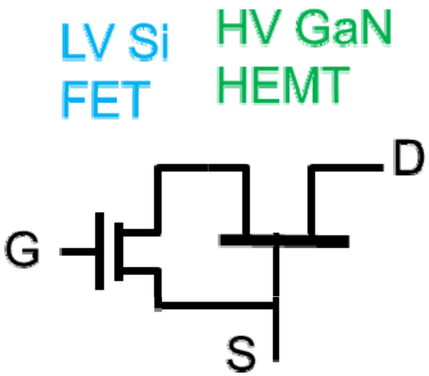
- GaN chip is lateral
- Two chip in package
- Higher stable V_{th}
- Gate ruggedness to + 30 V
- Works with existing drivers
- More desirable at high V
- Simpler to achieve at high V
- Multiple devices each need LV Si device
- Faster time to market
- Earlier experience with GaN

Another way to look at the operation Principles of Power HV FETs

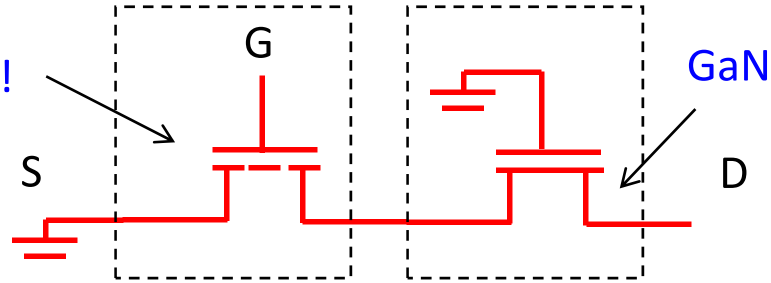
CoolMOS



Cascode-HEMT



Si is the best choice!



GaN is the best choice!

Current Controller

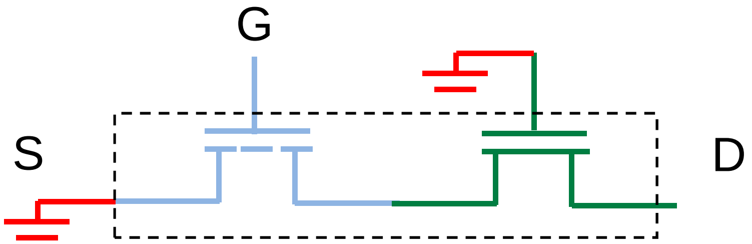
Voltage Blocker

Normally-Off FET

Normally-On FET: conduction modulated by the output of the current controller

The Cascode solution

Combine the "best" current Controller with the best voltage blocker



Current Controller	Voltage Blocker
Si MOSFET	**GaN HEMT**
Robust Normally-Off (+/- 20 or 30 V gate)	Gate limited to + 6 V
Stable Threshold	High Speed (lower capacitance)
Available at Low Cost	Higher voltage / mm
	Lower Ron

Take full advantage of what mother nature gave us
(rather than fight against the nature)
Let each semiconductor do what it does best…….

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Some basic information for the designer or retracing the evolution of GaN devices

- Blocking voltage
  - Reached 1,000 volts in 2000, similar device could switch in 2005
  - Leakage current – mA / mm is a research term, total current is a product value.
- Low Rds(on) – for what volt device?
  - ohm / mm under what condition? (static or dynamic)
- Switching speed
  - 200 volts or 10 amps per nanosecond (conditions)
    - Defines the need for low inductance layout requirements
- Does the same device do all three?
- Will it survive in a real application?
  - Spikes, layout,
- Will it last?

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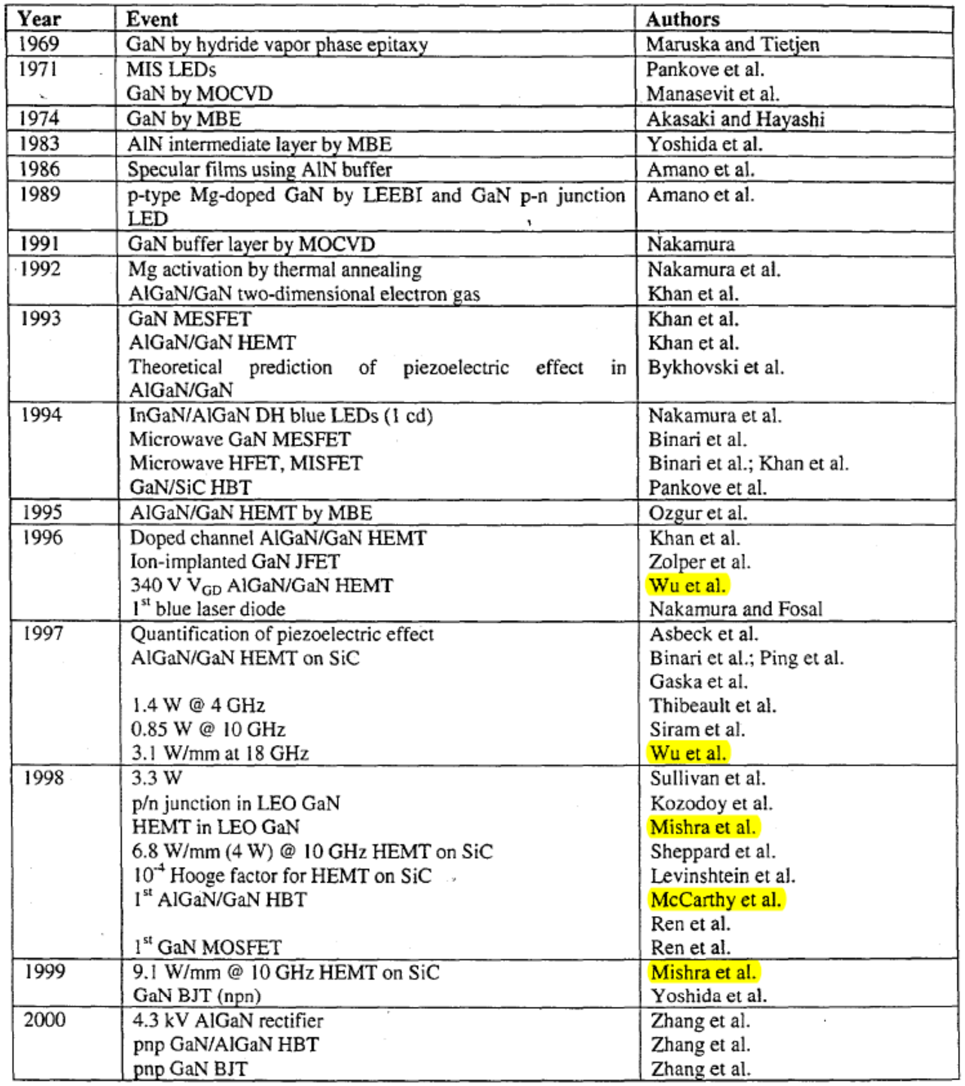
Earlier history of GaN and AlGaN/GaN development leading toward power devices

Table I. Historical development of GaN-based electronics.



Year	Event	Authors
1969	GaN by hydride vapor phase epitaxy	Maruska and Tietjen
1971	MIS LEDs	Pankove et al.
	GaN by MOCVD	Manasevit et al.
1974	GaN by MBE	Akasaki and Hayashi
1983	AlN intermediate layer by MBE	Yoshida et al.
1986	Specular films using AlN buffer	Amano et al.
1989	p-type Mg-doped GaN by LEEBI and GaN p-n junction LED	Amano et al.
1991	GaN buffer layer by MOCVD	Nakamura
1992	Mg activation by thermal annealing	Nakamura et al.
	AlGaN/GaN two-dimensional electron gas	Khan et al.
1993	GaN MESFET	Khan et al.
	AlGaN/GaN HEMT	Khan et al.
	Theoretical prediction of piezoelectric effect in AlGaN/GaN	Bykhovski et al.
1994	InGaN/AlGaN DH blue LEDs (1 cd)	Nakamura et al.
	Microwave GaN MESFET	Binari et al.
	Microwave HFET, MISFET	Binari et al.; Khan et al.
	GaN/SiC HBT	Pankove et al.
1995	AlGaN/GaN HEMT by MBE	Ozgur et al.
1996	Doped channel AlGaN/GaN HEMT	Khan et al.
	Ion-implanted GaN JFET	Zolper et al.
	340 V V_{GD} AlGaN/GaN HEMT	Wu et al.
	1st blue laser diode	Nakamura and Fosal
1997	Quantification of piezoelectric effect	Asbeck et al.
	AlGaN/GaN HEMT on SiC	Binari et al.; Ping et al.
		Gaska et al.
	1.4 W @ 4 GHz	Thibeault et al.
	0.85 W @ 10 GHz	Siram et al.
	3.1 W/mm at 18 GHz	Wu et al.
1998	3.3 W	Sullivan et al.
	p/n junction in LEO GaN	Kozodoy et al.
	HEMT in LEO GaN	Mishra et al.
	6.8 W/mm (4 W) @ 10 GHz HEMT on SiC	Sheppard et al.
	10^{-4} Hooge factor for HEMT on SiC	Levinshtein et al.
	1st AlGaN/GaN HBT	McCarthy et al.
		Ren et al.
	1st GaN MOSFET	Ren et al.
1999	9.1 W/mm @ 10 GHz HEMT on SiC	Mishra et al.
	GaN BJT (npn)	Yoshida et al.
2000	4.3 kV AlGaN rectifier	Zhang et al.
	pnp GaN/AlGaN HBT	Zhang et al.
	pnp GaN BJT	Zhang et al.

The purpose of including this historical perspective is to show that GaN development is not new and that Power Devices are simply the latest market segment following

1. LED
   Low voltage (<50 V) , small diode devices
2. RF transistors and amplifiers
   Low voltage (<150 V) slightly larger transistor devices
3. Power devices
   1. First device 30 V, larger than RF
      d-mode
   2. Reached 200 V in 2010
      e-mode
   3. Reached 600 V in 2012
      d-mode, cascode

Extract from DOE report in 2000 on GaN
SAND2000-1869C

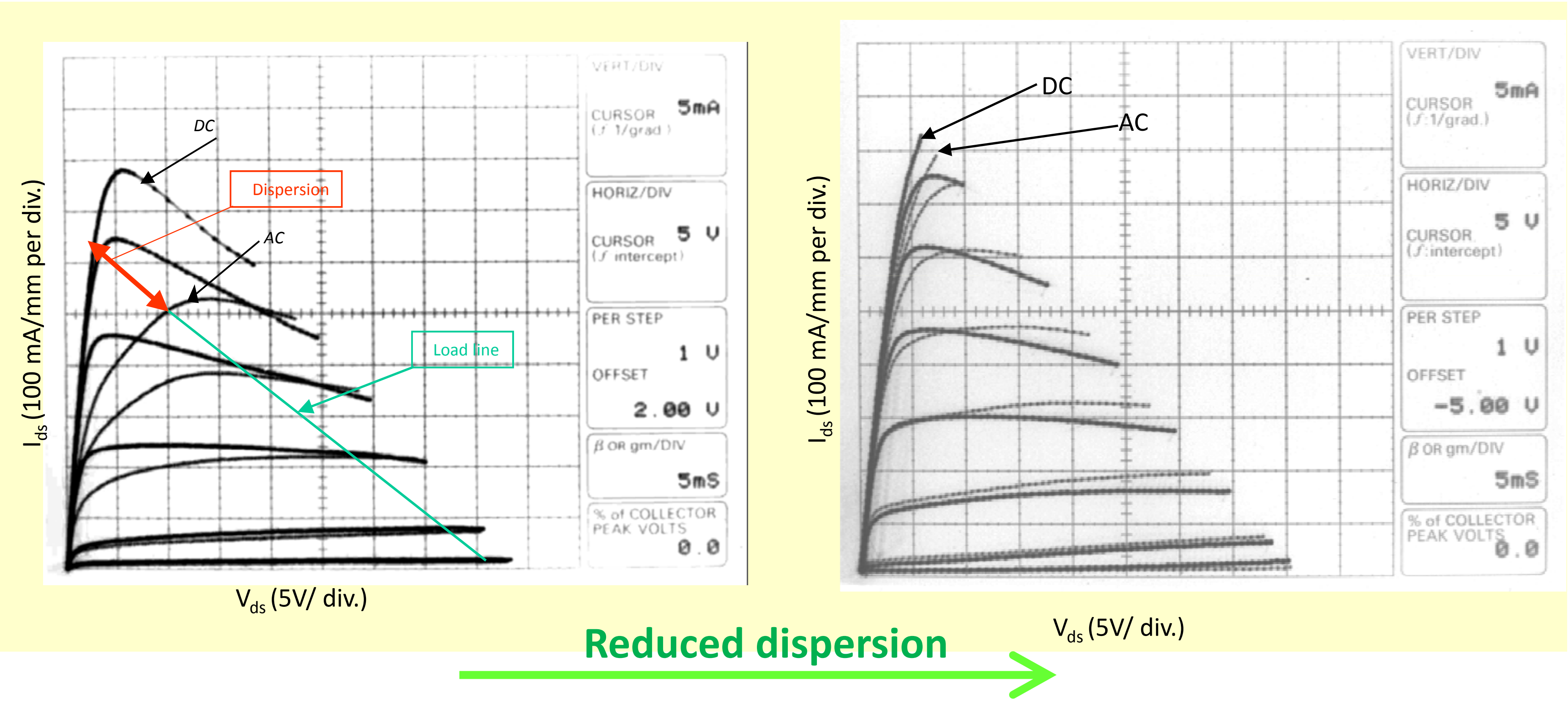
Recent History of power Gallium Nitride

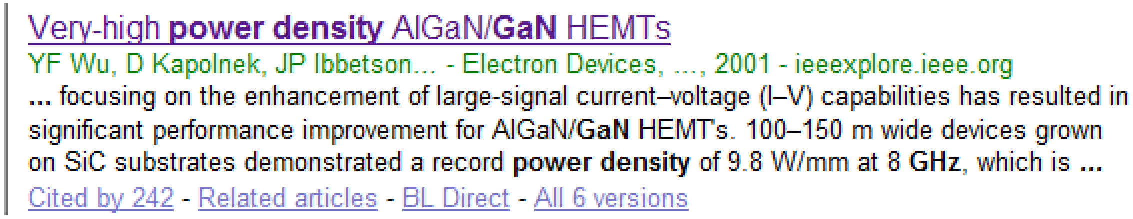
First switching RF HEMT	**1996**
First GaN EPI on Si (for transistors)	1999
First AlGaN/GaN kv class HEMT	2000
First switching AlGaN/GaN kv class HEMT	**2005**
First normally-off pGaN/AlGaN/AlN/GaN JFET	2006
Transphorm Incorporated	2007
First Current Apertured Vertical Electron Power Transistor in GaN	2008
First commercial e-mode GaN – 200 V – EPC	2009
First commercial low voltage GaN HEMT- IR	2010
1st high efficiency power conversion with 600 v Total GaN	2011
1st high efficiency power conversion with HV Total GaN on Si	**2012**

* People or product at Transphorm

Earlier Findings in RF Devices-Dispersion
The Mystery behind RF-DC discrepancy

Dispersion---trapping effect





Very-high **power density** AlGaN/**GaN** HEMTs

YF Wu, D Kapolnek, JP Ibbetson... - Electron Devices, ..., 2001 - ieeexplore.ieee.org

... focusing on the enhancement of large-signal current–voltage (I–V) capabilities has resulted in significant performance improvement for AlGaN/**GaN** HEMTs. 100–150 m wide devices grown on SiC substrates demonstrated a record **power density** of 9.8 W/mm at 8 **GHz**, which is ...

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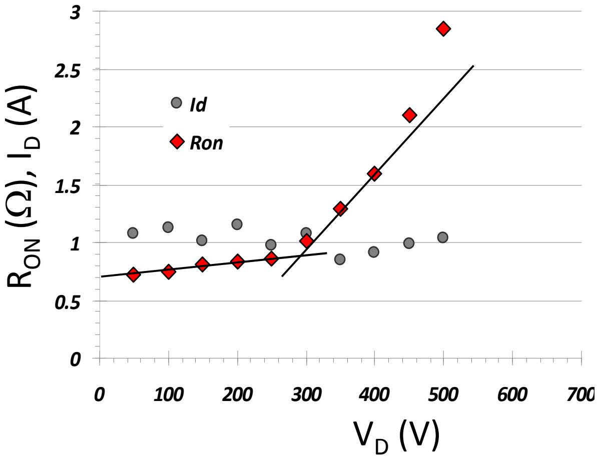
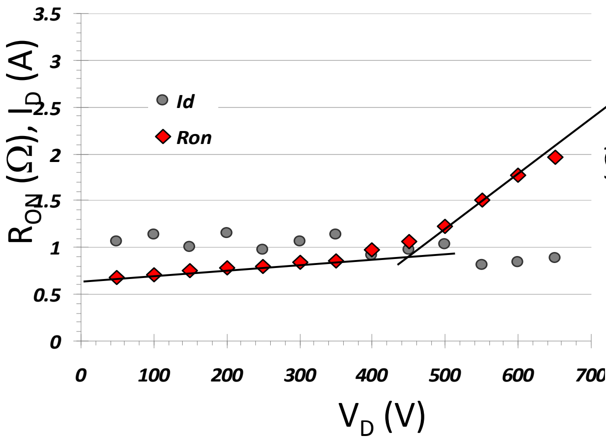
1st solution of the current collapse issue at 600 volts achieved in early 2009, 2nd company in 2011, others following

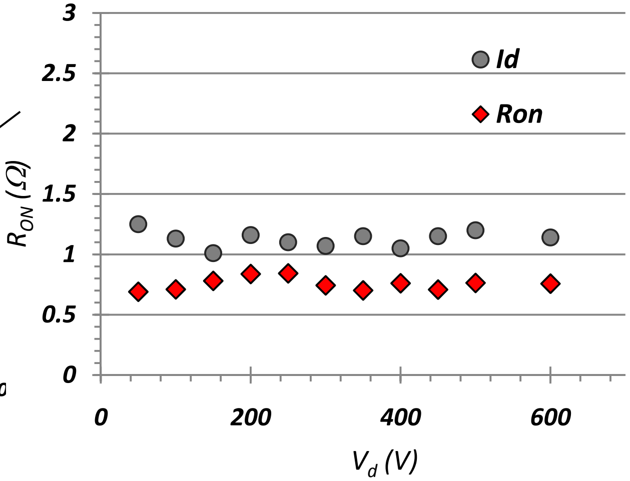
Previous status: Mid 2008



Previous status: End 2008

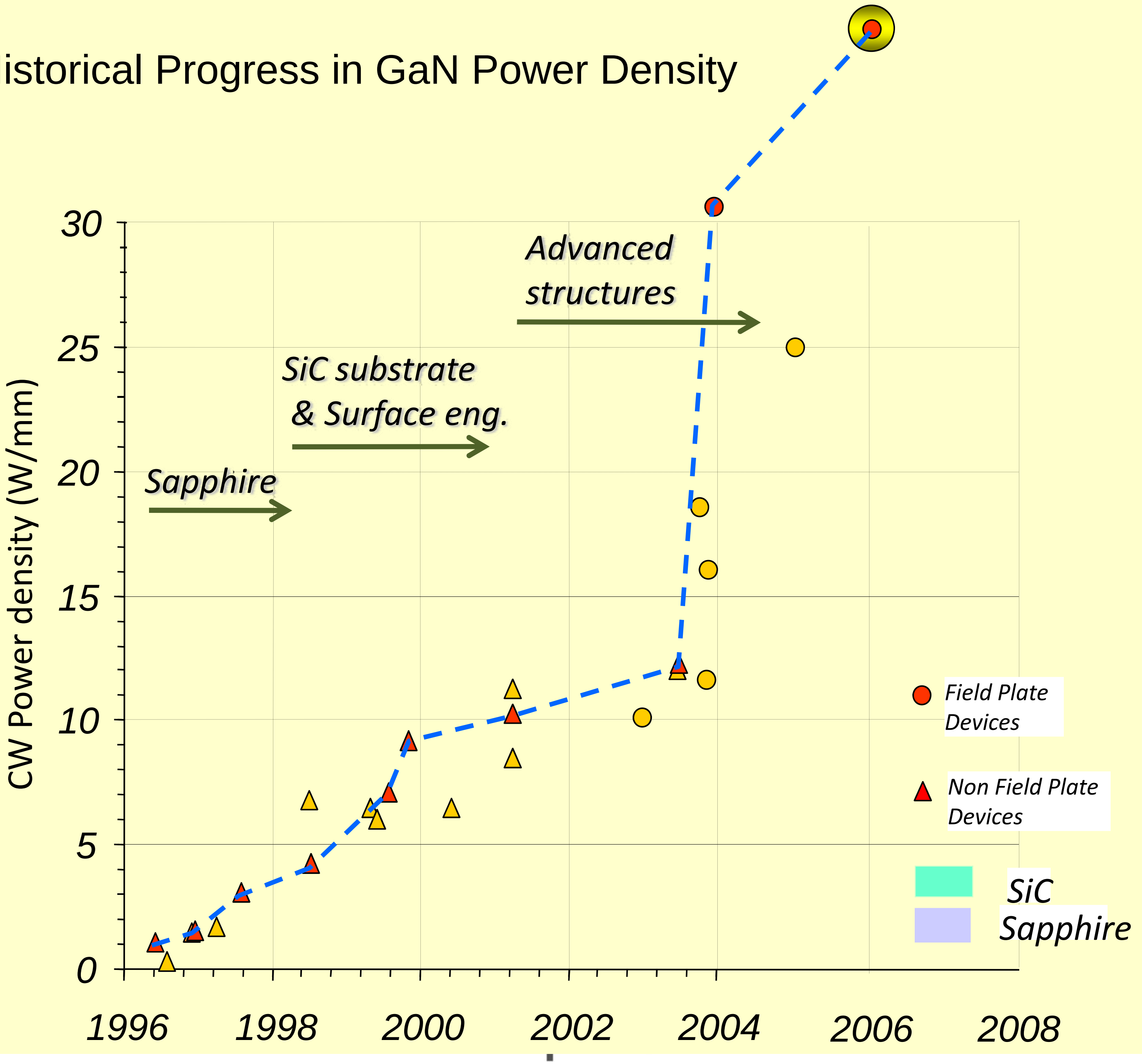


2009: No current collapse

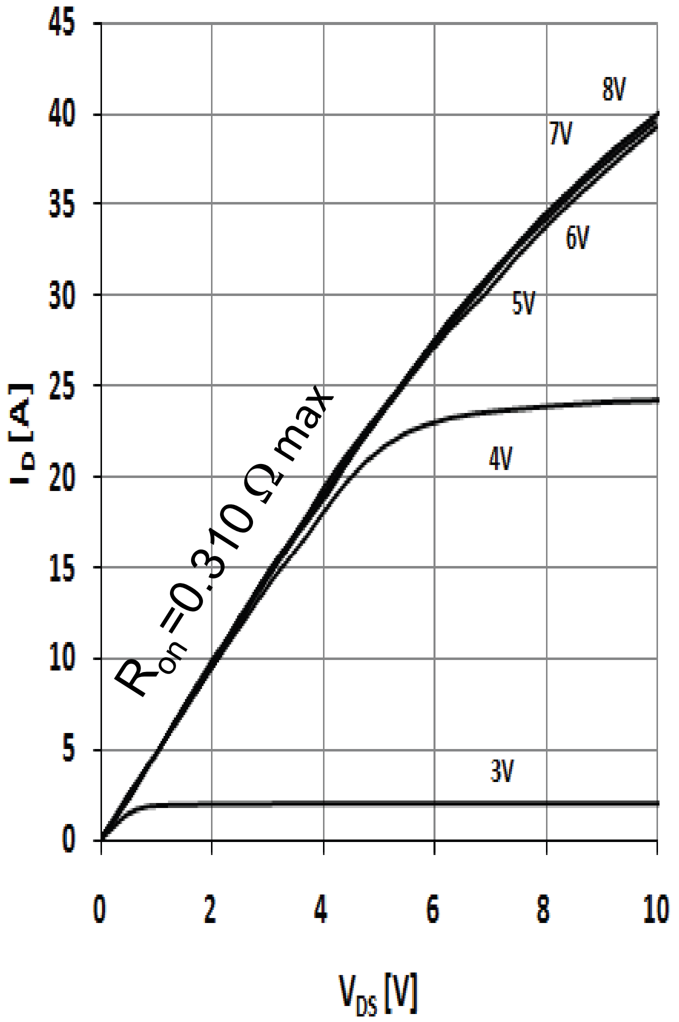


- Resistance (R_{on}) is the measure of current collapse: Resistance (loss) should not increase with higher operating voltage, otherwise it is a sign of current collapse
- Direct relation to performance in real world applications
- Major benchmark for success in GaN power devices: **Low dynamic on resistance at 600 Volts in demonstrated in 2009**

Historical Progress in GaN Power Density

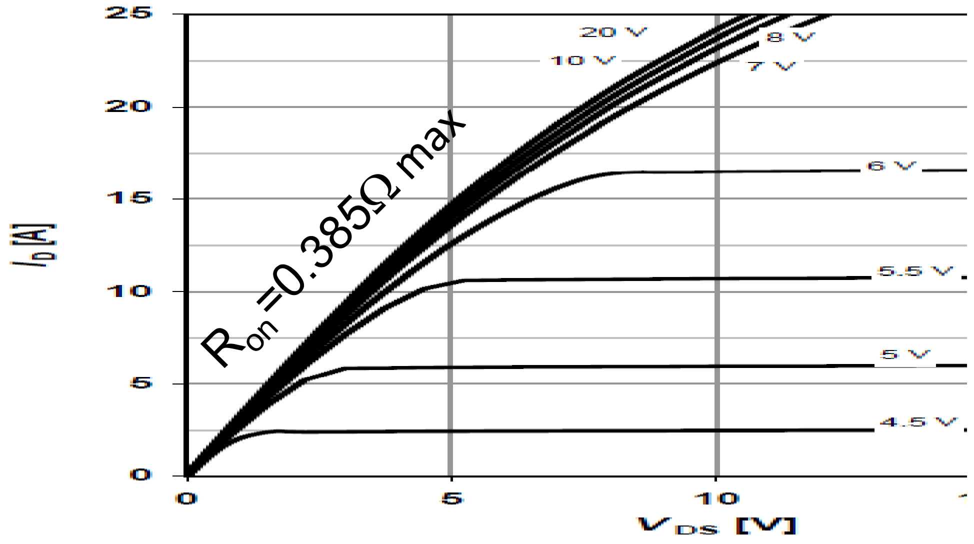


Gen-1 GaN HEMT Offers Lower Ron & High Current Than Competing Si Super Junction MOSFET

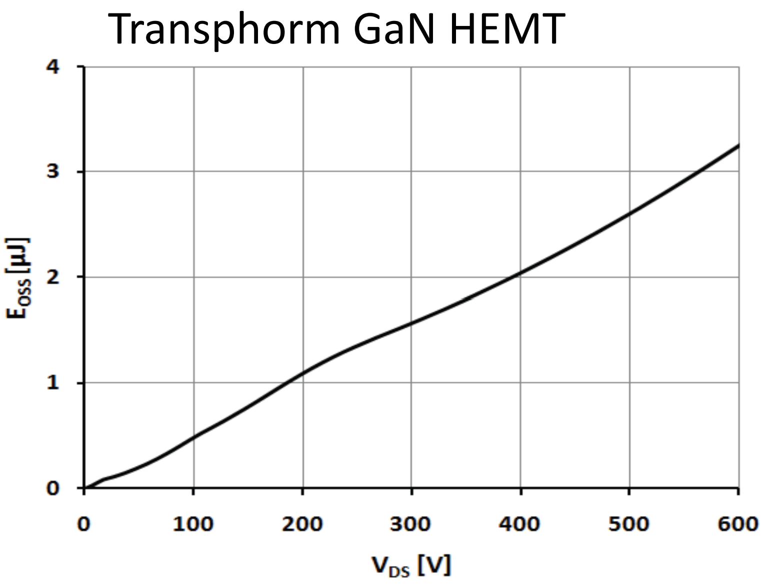


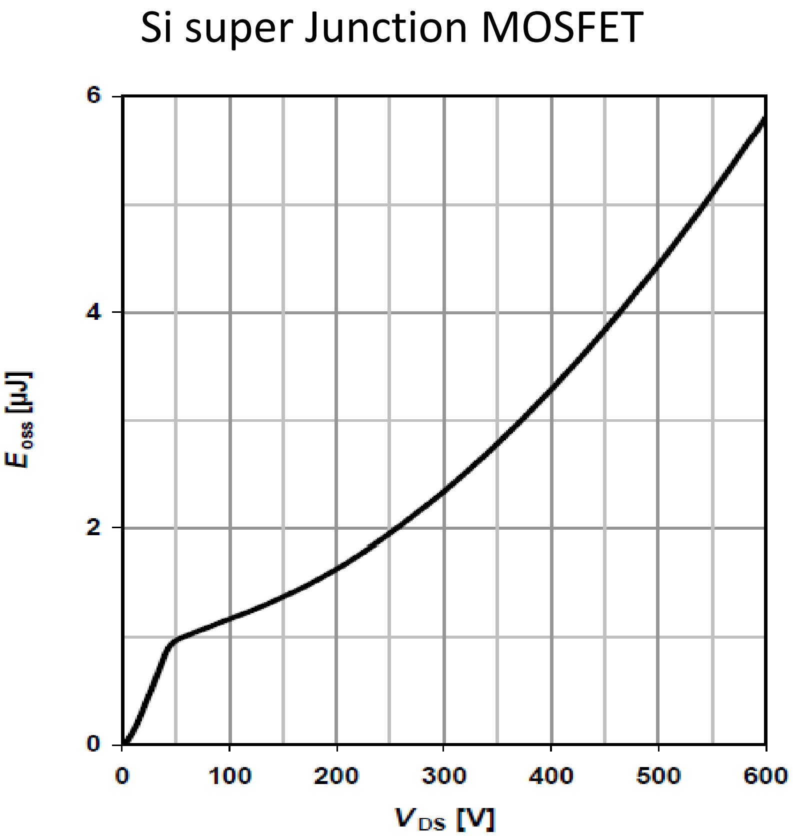
GaN HEMT

Si CoolMos
(Super junction
MOSFET)



Early Gen 600 V GaN HEMT Offers Less Qg & Qo,er for Same on Resistance as Competing Si Super Junction MOSFET

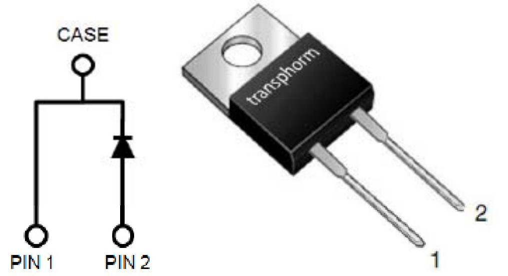




Q_g ~ 1/3 of Si
$Q_{o,er}$ ~ 1/2 of Si

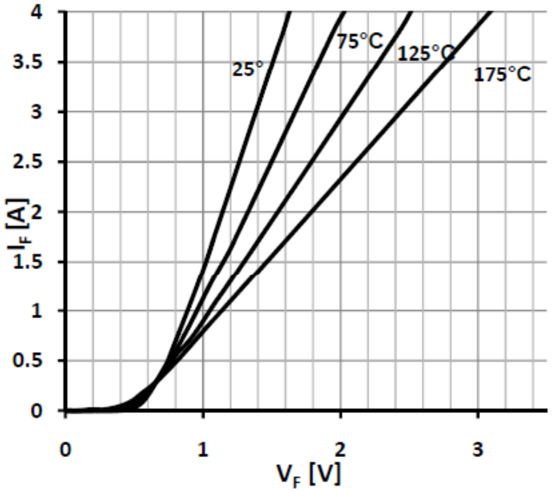
Early 600 V GaN Diode vs. Competing SiC Diodes

GaN Schottky Diode



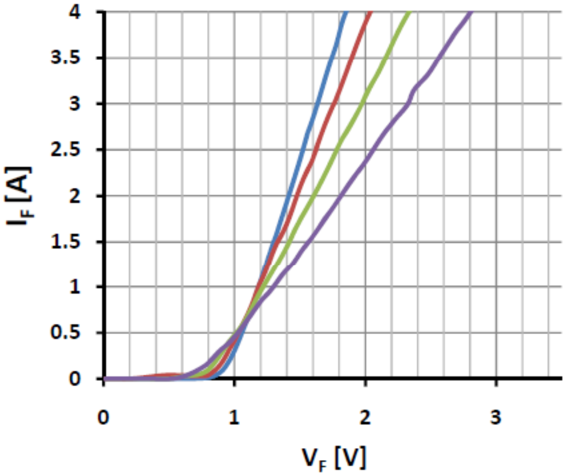
TO220 Package

GaN



TPS2012PK

SiC



C3D02060A

Vf at If=2A

Temp.(C)	25	75	125	175
TPS2012PK	1.15V	1.3V	1.55V	1.8V
C3D02060A	1.4V	1.45V	1.6V	1.8V

- **GaN Diode has lower V_F over most of operating temperature range**
- **In-circuit efficiency matches latest SiC diodes**

What does the GaN on Si future hold?

- Future goal for everyone is e-mode technology that covers LV to some high voltage level above 600 volts
  - To achieve this, various companies will take different paths
- Key parameters
  - Cost will decline rapidly versus silicon
    - Wafer size will move from 6” in 2012 to 8” by 2014
    - EPI growth time will decrease, equipment will become more automated
    - Fab uniformity will improve yields and reduce spec margins = smaller die
  - Drain voltage rating will increase
    - 600 v devices are already qualified on SiC substrate 1st half 2012
    - Expect same to be qualified on Si substrate 2nd half 2012
  - Temperature rating of devices
    - Tj = 175 C in 2012, 200* C in 2014, 250* C in 2016
  - Positive voltage Gate rating will increase enabling robust e-mode HEMT
    - 6 v in 2012, 12 v in 2014, 15 v in 2016
  - Current rating will increase with process uniformity

* New package materials needed

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GaN Roadmap

	2012			2013			2015			2018		
	LE	P	E	LE	P	E	LE	P	E	LE	P	E
Max Vdss	1200	600				600	1700		1200		1700	
Max I_D @ 200 v	50				50			100				
Max I_D @ 600 v	50	20		100	50	20		100	50			100
Max I_D @ 1200 v	25			50	25		100	50			100	
Typ Ron @ 150 v (mΩ) 5 x 6 PQFN	14						2					
Typ Ron @ 600 v (mΩ) TO-220	120	150		55		150		35			22	
Typ Ron @1200 v (mΩ) TO-247	120			75	120		55		120	35		75

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GaN reliability issues (excerpted from IR APEC seminar 2010) that were resolved over the past 3 years by more than 1 company

- Gate Lag / current collapse – solved by several companies
  - Constant Current Test
  - Dynamic Switching waveforms

- Reverse Bias Lifetime, Stability: High Temperature Reverse Bias (HTRB)
  - Trapped charge and field management are critical in GaN devices and must be resolved to pass both HTRB and current collapse. Process uniformity is critical to pass this test

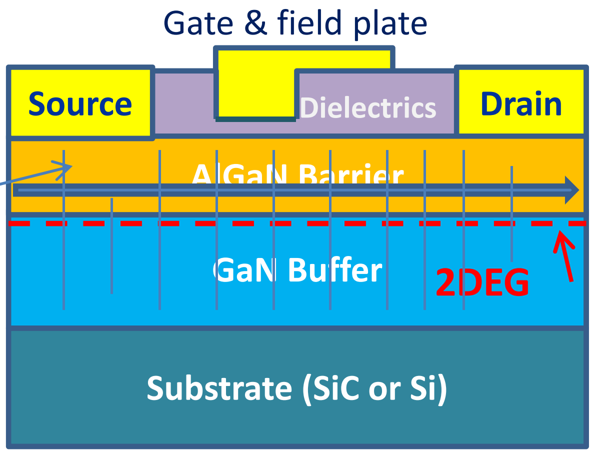
- Gate Structure Lifetime, Reliability: High Temperature Gate Bias (HTGB)
  - For insulated gates, the integrity of the gate insulation is a critical issue, not as difficult as the gate oxide issues encountered with SiC devices.

- Inverse Piezoelectric effect
  - Field management issue reported by some in 2008

- Electromigration -
  - Small die, small pads, large current makes this more of a problem at lower voltages at the present time

- Operating Life – not an issue up to 200C

Dislocation density for GaN (on Silicon or SiC substrate) may be in the 10^8-10^9/cm^2
Myth- GaN devices will not be reliable
Answer: Does not matter in lateral, uni-polar GaN devices (e.g. GaN HEMTs)



Dislocations Are Vertical

Current Flow for today's GaN devices is lateral and thus decoupled from dislocations

- Dislocations arise due to the growth of dissimilar materials, such as Gan on Si or SiC

- **But dislocations do not equate to failure points, otherwise no GaN devices would have performed or shown stable operation at high voltage**
  - **No one would have been able to show 1000 hours HTOL, qualified, or reliable devices or lifetime in any area - RF or Power**

- **Well-designed GaN 600V power devices have similar electric fields as 100V RF GaN devices which have been shown to be reliable by multiple suppliers and are military qualified for reliability**
  - **Current density for power typically lower than RF devices due to nature of power applications**

EZ-GaN™ Diode and HEMT Qualification in 2012

- HTRB: Qual lots completed 1,000 hrs at T_J = 150°C,
  - Median leakage current reduced from 19 to 8 microamperes with time.
- HAST: Qual lots passed 96 hrs,
  - No leakage increase
- TC: Passed 1000 cycles on Qual lots
  - On resistance changed by less than 5%
- Power cycling (IOL): Qual lots passed 5,000 cycles with a ΔT of 125°C (25°C to 150°C)
- HTOL: Qual lots passed 1000 hours at T_J = 175°C

What was learnt during the multiple attempts to pass JEDEC 1,000 hour Qual?

- Good Parts (that pass 1,000 hours)
  - Continue to show stable operation out past 3,000 hours and going
  - When the d-mode parts switch, they are very stable
    - Unlike SiC, the dislocations are stable and do not move
  - e-mode gates add significant level of complexity
    - GaN gates are not rugged (limit is +6 volts, no spike)
    - Gate leakage current is a failure mechanism
  - Traditional indicators of weak silicon parts do not correlate to weak GaN parts
    - Higher leakage is not a predictor of early life test failures
    - GaN devices do not have Avalanche capability
      - Missing the body drain diode (no zener type BV curve)
      - But they work in the circuit

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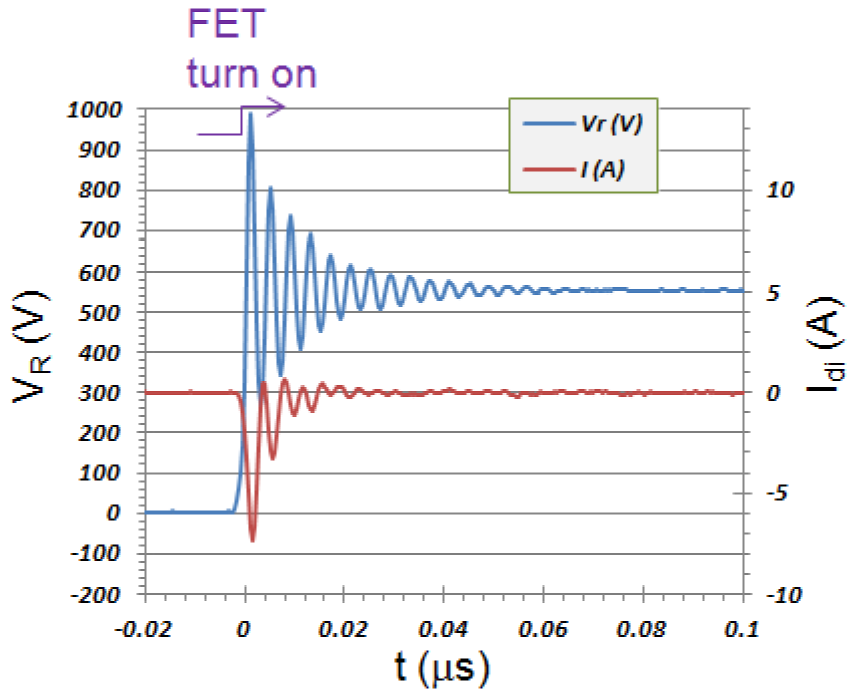
Some 600 V-rated GaN diodes and HEMTs sustain high spikes (>900V) as well as high-voltage/current Transients without issue

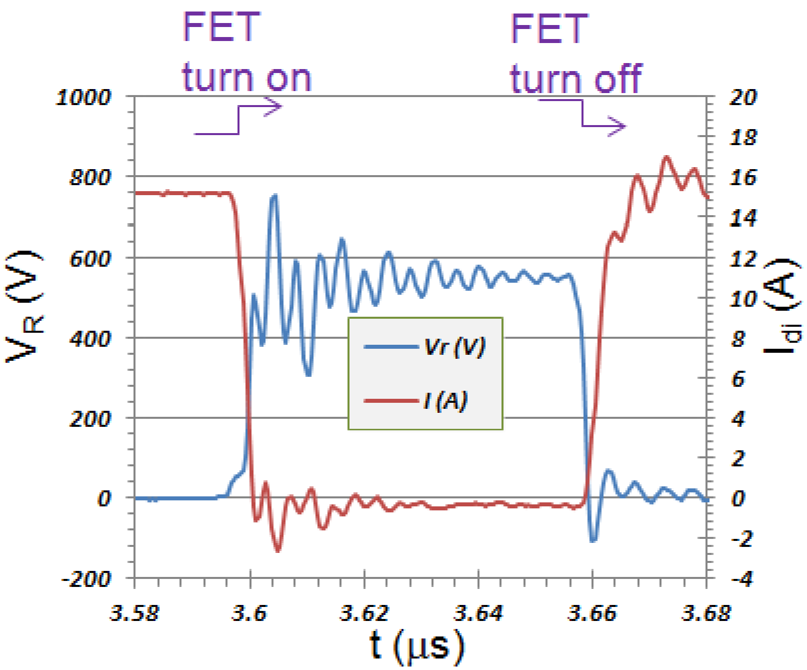
A wire loop of 2cm^2 was inserted in a standard boost circuit to cause spikes

Bus voltage Vdc = 560 V

Inductor current at 0

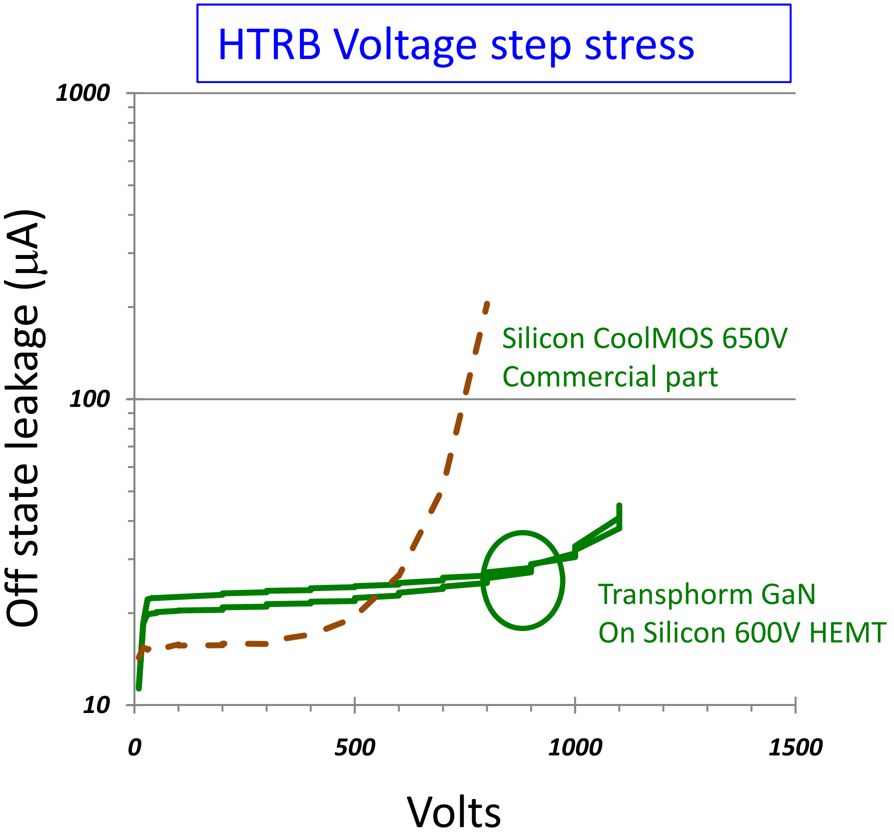


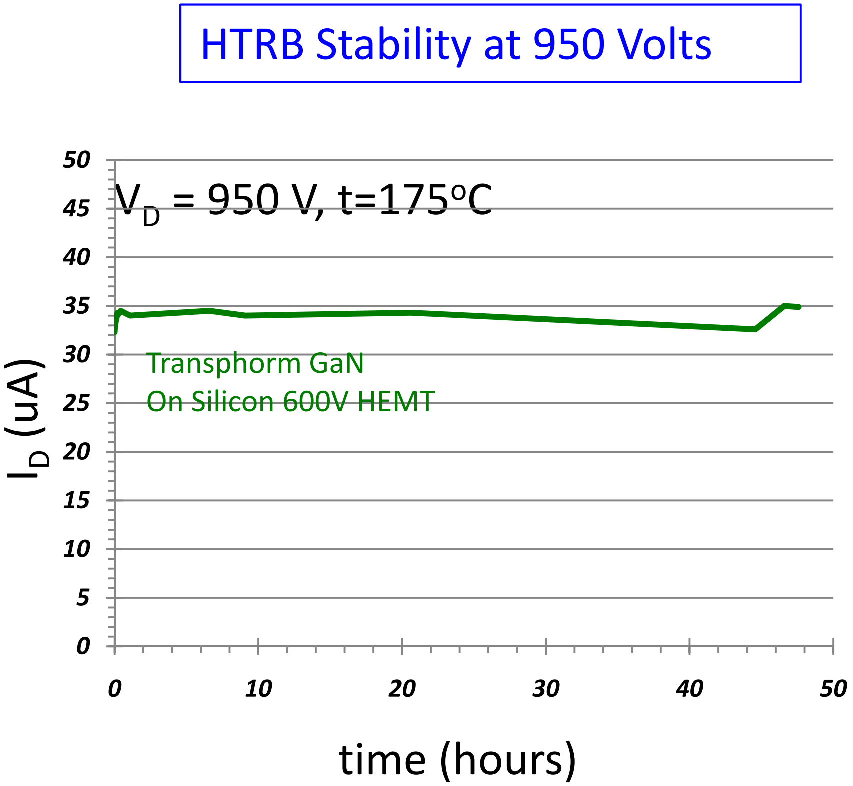
Inductor current at 15A



- Voltage overshoot up to 450 V, spike of 990V at 0A, Vdc=560 V
- Device has no functionality change after 100,000 shots of 990 V spikes
- GaN stable at dV/dt = 660 V/ns and dI/dt = 5500 A/us

GaN on silicon HEMT designs are robust:
Stable operation and lower high-voltage leakage than silicon CoolMOS at 175°C





- 600 V GaN on Si HEMT device designs are proven to be robust
  - Can be taken to >1000 volts (overdesigned for Gen-1 to ensure reliability)
    - Proof that dislocations are not an issue

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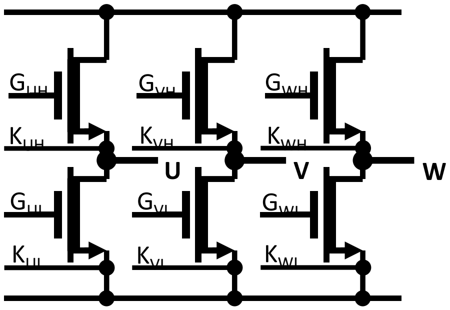
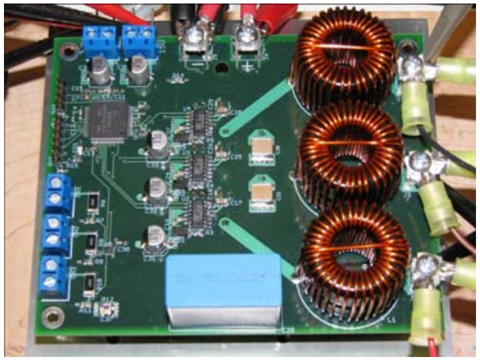
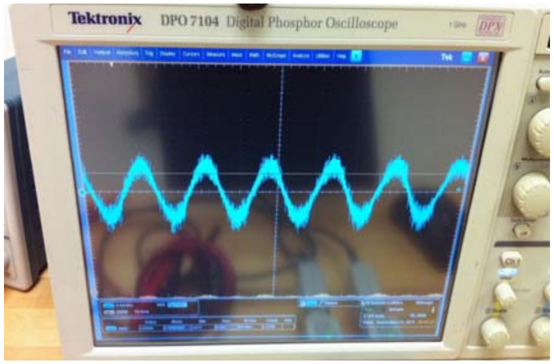
EZ GaN solution enables 5% benefit in electromechanical efficiency of 3-phase motor drive and motor system:



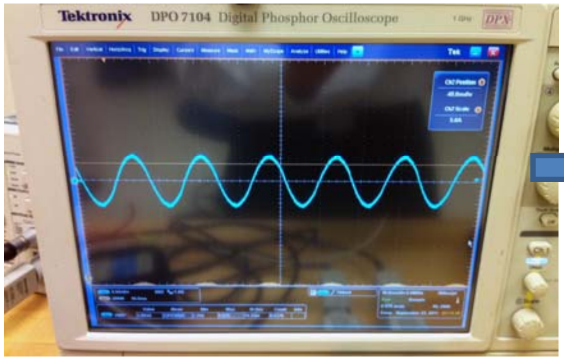


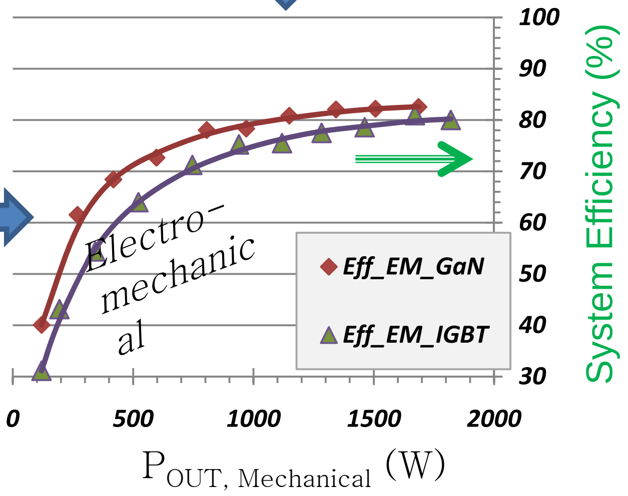
Measured at Yaskawa Electric America

IGBT Inverter



GaN Inverter

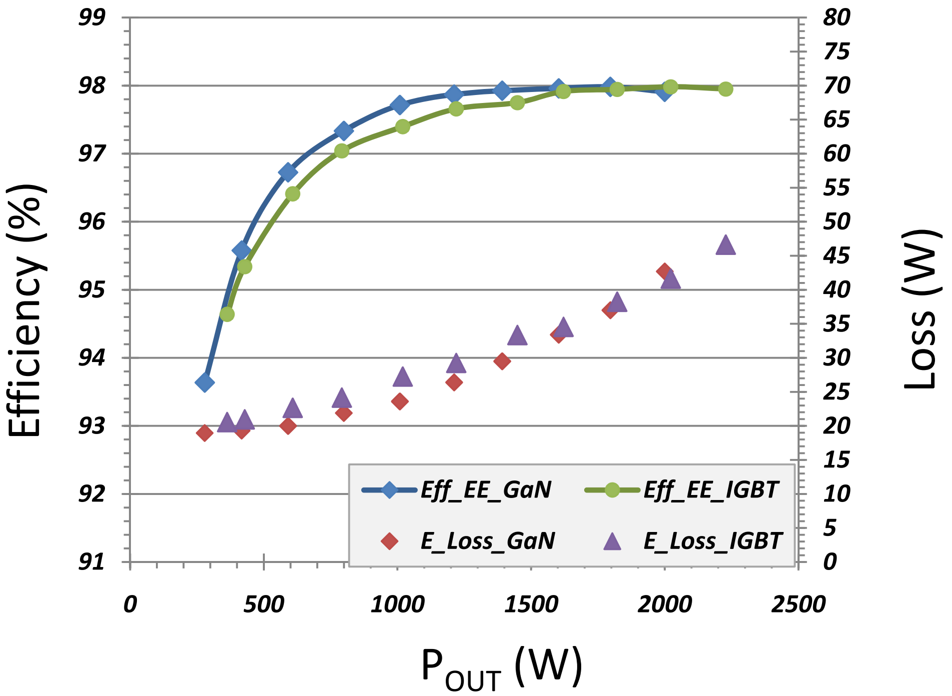




- GaN inverter operating at 100 kHz with compact filter & clean sine wave output
- IGBT inverter operating at only 15 kHz with PWM output
- GaN inverter output current is spike-free - ideal for motor drive

System value is key to early insertion of GaN in products

GaN Motor-drive at 100 kHz with Filter Vs. State-of-the-art IGBT at 15 kHz w/o Filter



- GaN Inverter efficiency exceeded IGBT:

  GaN: 100 kHz, include filter loss

  IGBT: 15 kHz, w/o filter loss
- Indicating superior device efficiency for GaN

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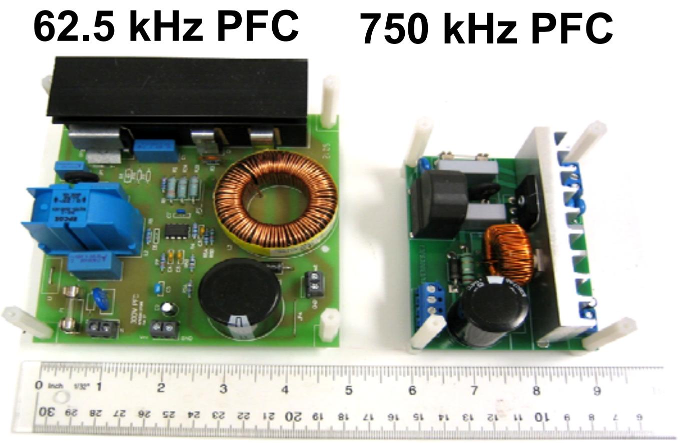
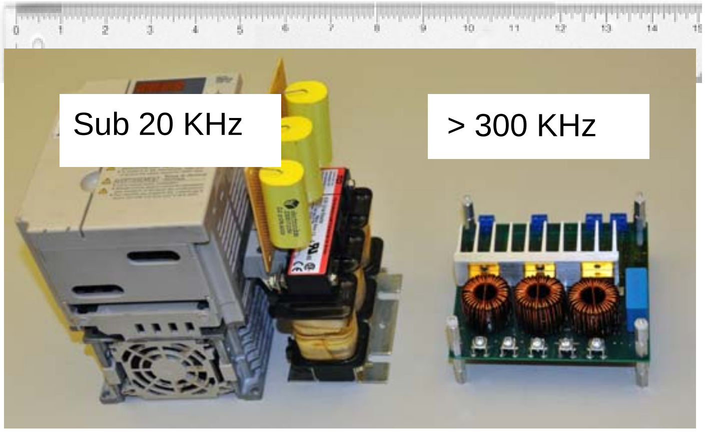
Application example: A complete GaN solution enables system level impact on efficiency, size and cost

Power Supply Solutions



Total GaN^{TM} (Transistor + Diode)

Motor Drive Solutions



Diode Free GaN^{TM} with integrated filter

Low loss by highest efficiency power devices

- Low cost by new circuits minimizing part count
- Eliminates unwanted snubbers and filters
- Small size by high frequency low EMI solutions

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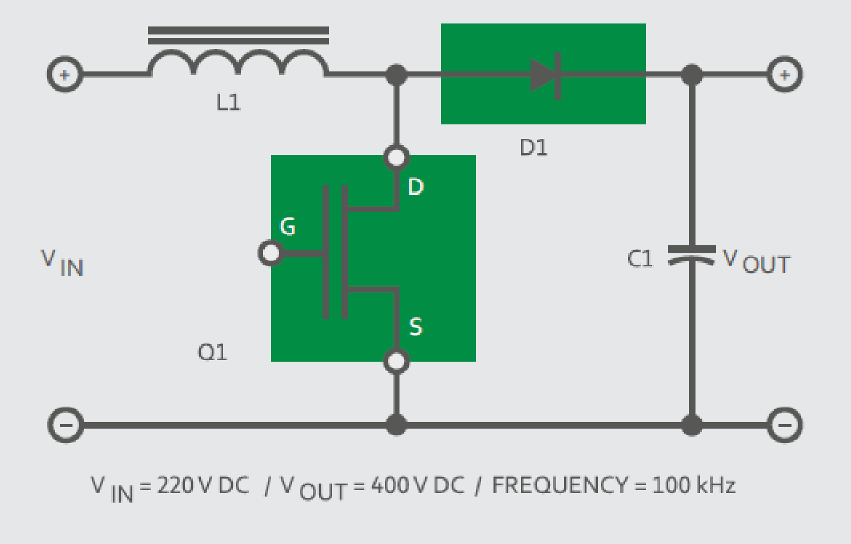
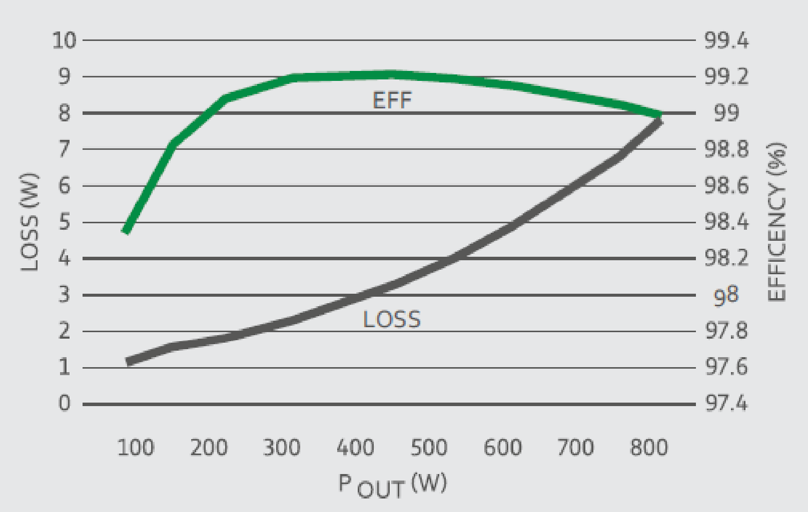
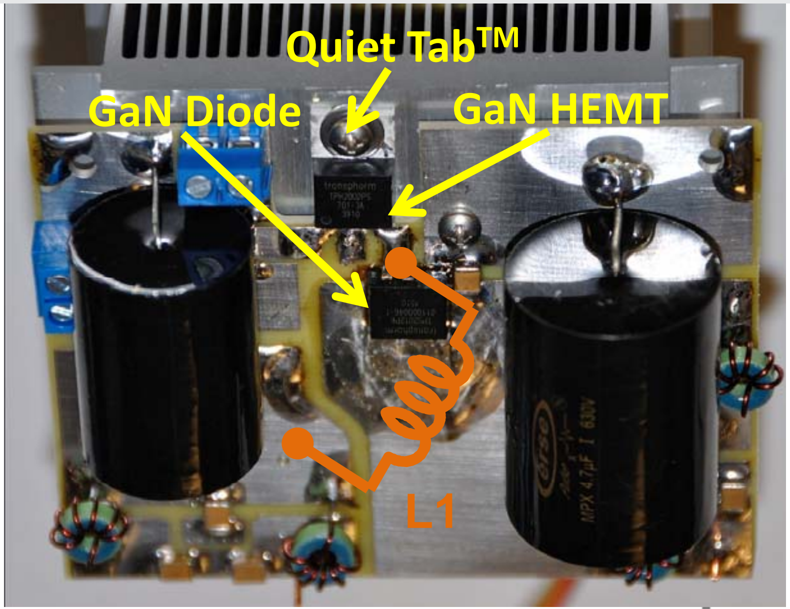
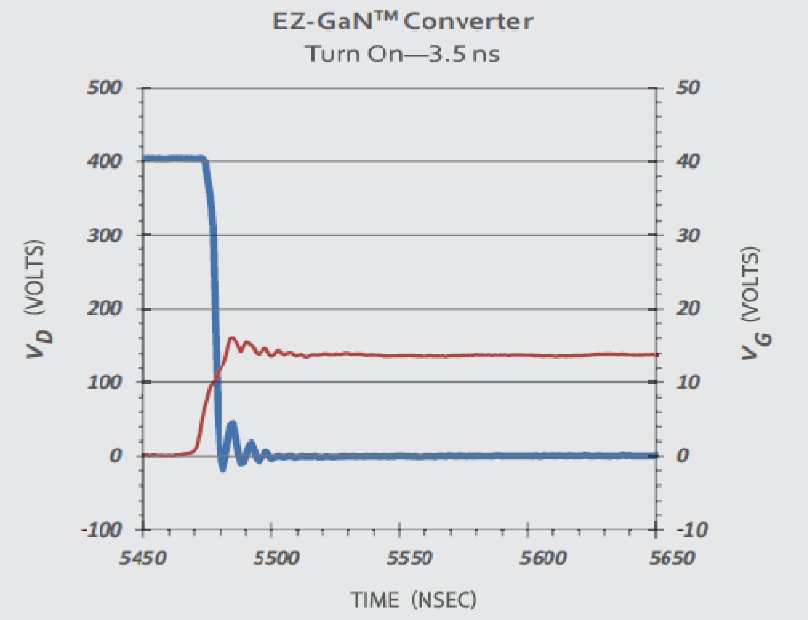
Total GaN Boost Converter illustrates all three are needed to achieve higher performance of GaN devices beyond best silicon devices









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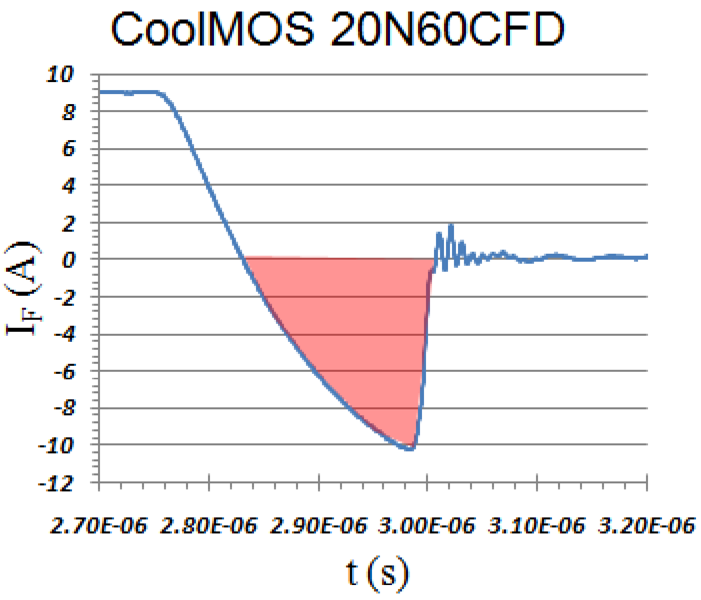
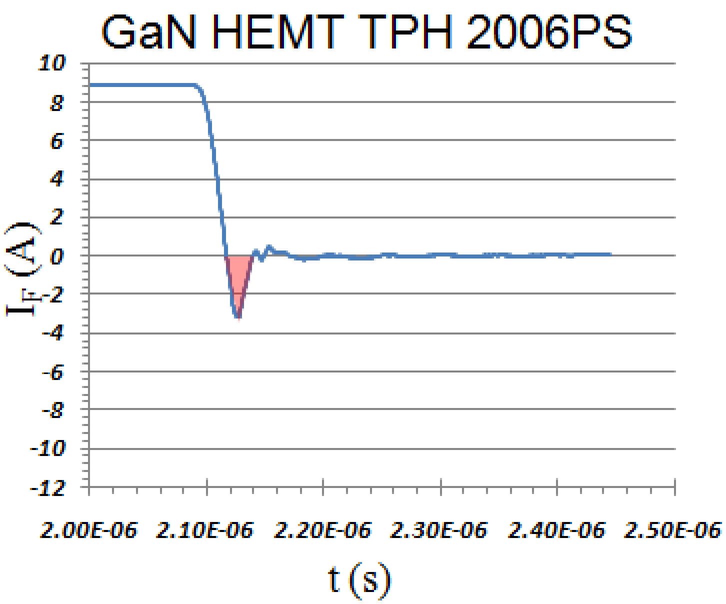
Qrr Measurement Confirms GaN HEMT’s 25x Advantage





Qrr=1000 nC at 9 A, 400 V

Qrr=40 nC at 9 A, 400 V

- Both measured in the same test board
- Transphorm GaN HEMT was tested at 450 A/µs with little ringing
- CoolMOS was not stable at 450 A/µs. dI/dt reduced to 100 A/µs for stability.
- GaN HEMT has Qrr of 25x less than CFD-type CoolMOS (Low Qrr design).

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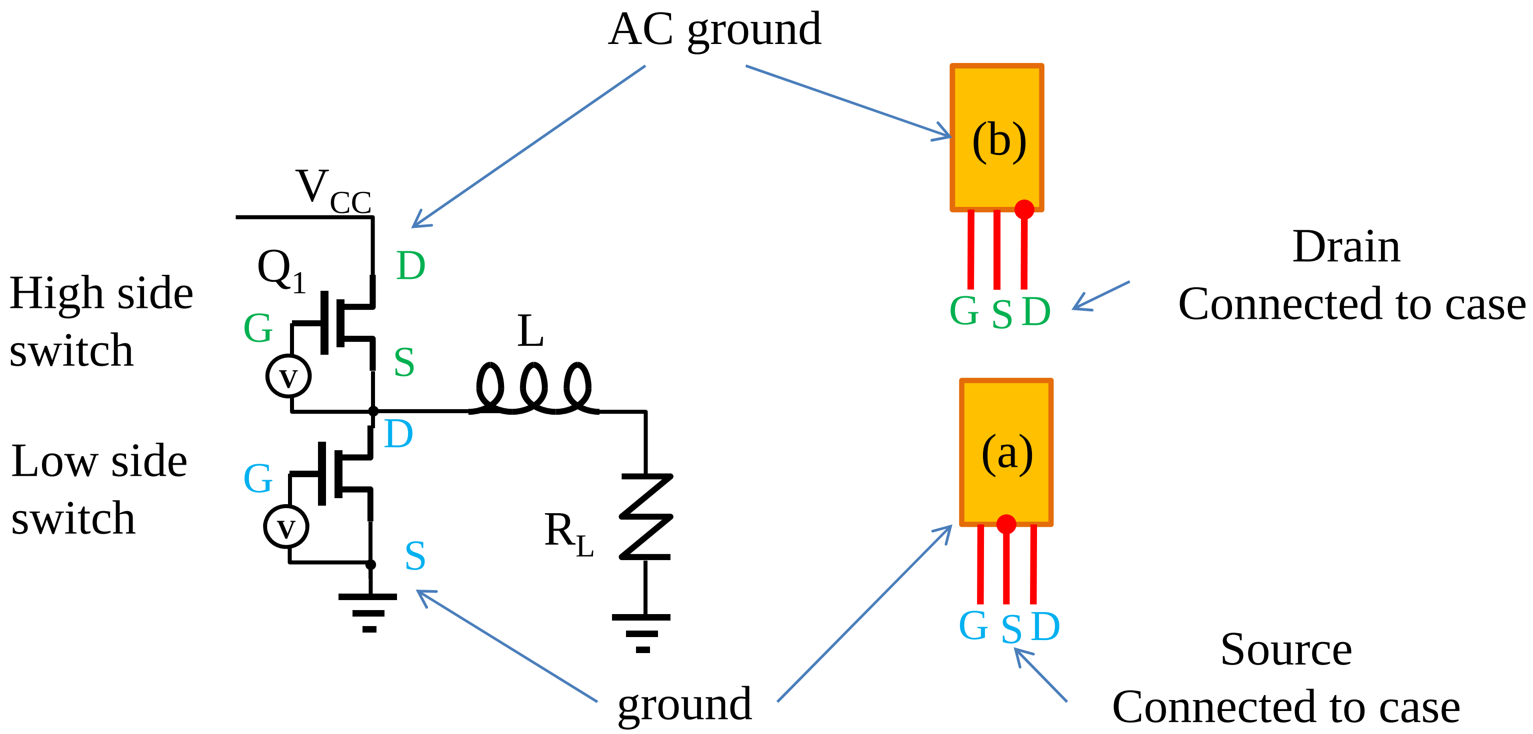
GaN HEMT Uses Quiet Tab$^{\text{TM}}$ Package Configurations for Friendly Circuit Implementation – new pin out enables TO-220 GaN



(a) Source connected to case for low side switch

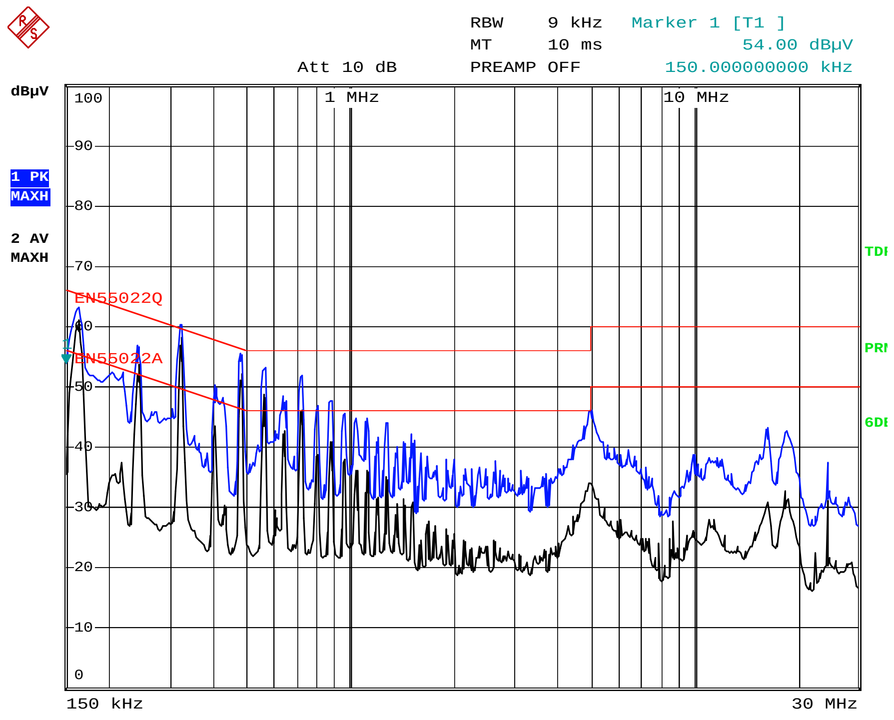
(b) Drain connected to case for high side switch

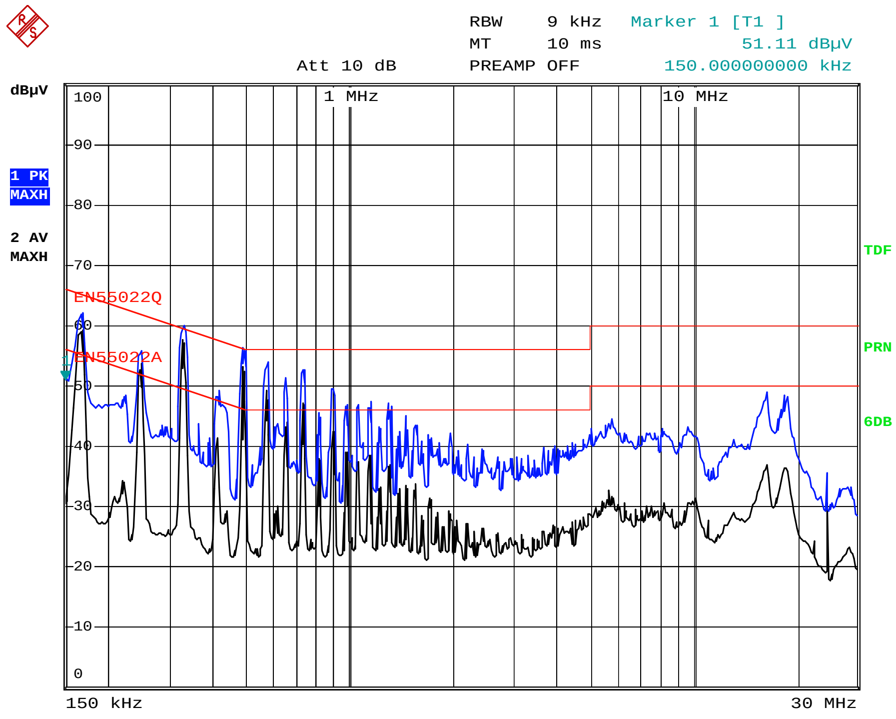
- Package body is electrically “cool”
- Reduced charging capacitance: lowering charging loss and CM EMI
- Lower thermal resistance than isolated package (by 1.5-2 °C/W)
- G-S-D has better I-O isolation than G-D-S pin out

Myth Buster:
Faster Switching ≠ Higher EMI*

*Courtesy of Fairchild Semiconductor company

Superjunction Silicon vs. GaN (TPH2002PS)





Peak

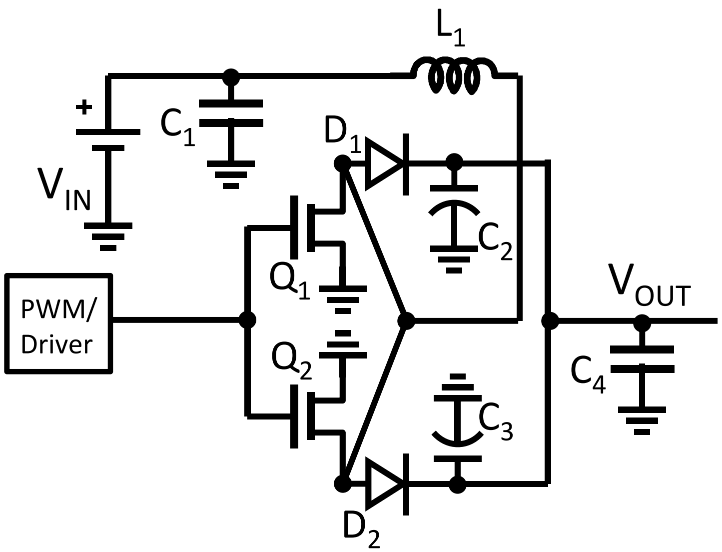
Average

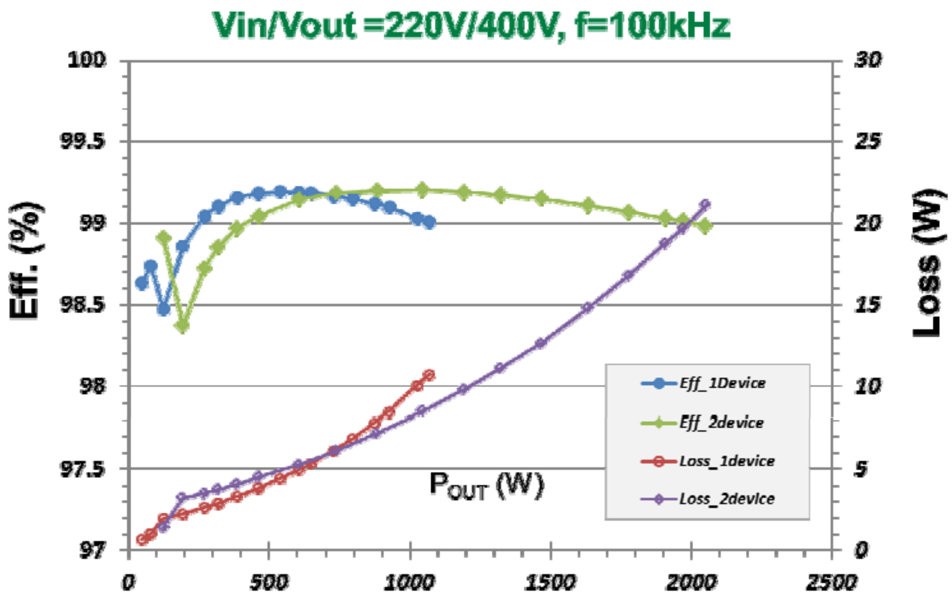
Conducted noise: Converter (PFC + Dual Flyback), 90 Watt, Vin = 230 Vac , Fsw = 60 kHz;

t_{on} & t_{off} of GaN is 0.33 t_{off} of Silicon, so the GaN is switching faster without increasing the EMI.

GaN Devices Paralleling:
Boost Converter with 2 Parallel HEMTs/Diodes

Circuit diagram





Design Target

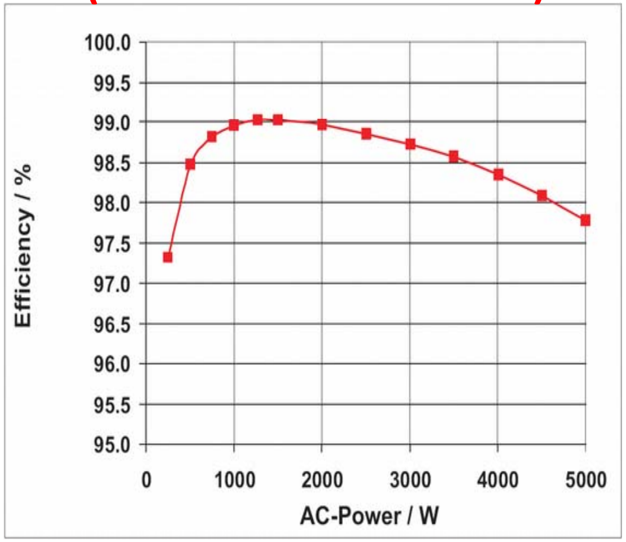
- Q1 & Q2: 600 V, 0.18 ohm GaN HEMTs.
- D1&D2: 4 A Schottky diodes.
- C2 & C3: SMD high-frequency bypass capacitors. Placed as close to cathodes of D1 & D2 as possible.
- C4: Storage capacitor.
- Omitting gate resistor to fully utilize the GaN switching speed (minimizing switching loss).

- Operation voltage: 400 V
- Operation current: 8A / device
- Same overshoot / undershoot as single device but with 2x current.
- Extending CW dc-dc converter output power to 2x.

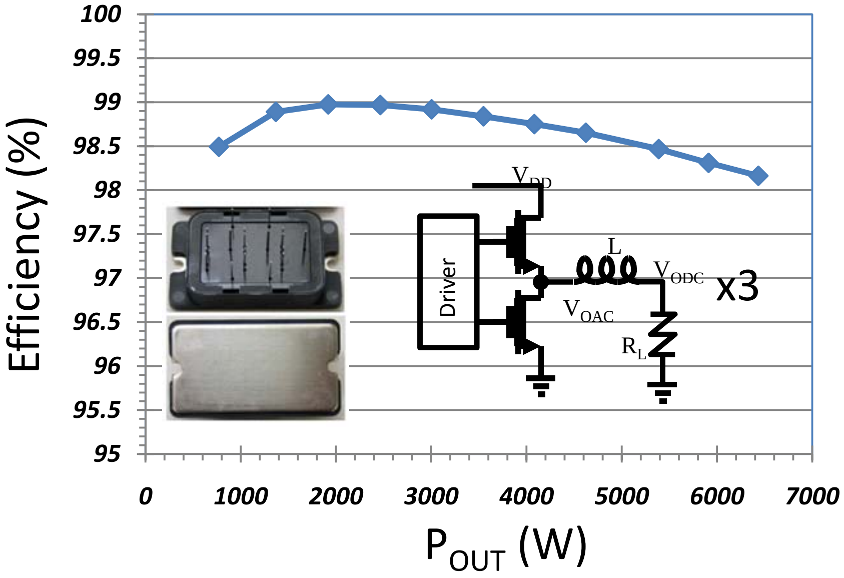
Comparing the Best Single-Phase SiC and GaN Inverters: GaN has demonstrated higher frequency operation with similar high efficiency

SiC: Fraunhofer ISE at 16 kHz

(Claimed World record)



GaN: inverter at 100 kHz



	Fraunhofer ISE	Transphorm
Power device	SiC J-FET (semi-south)	GaN HEMT (Transphorm)
PWM frequency	16 kHz	100 kHz
Peak efficiency	99% at 1.4 kW	99% at 2.2 kW
>98% efficiency power range	0.35-4.6 kW	0.3-6.5 kW

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Thank you