Integrated Power Conversion and Power Management
Next generation technology for emerging business opportunities

A User's Perspective on GaN and Silicon Power Devices for Integrated / Miniaturized Power Management

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Acknowledgements

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- Ahsan Zaman, Aleks Radic, and Behzad Mahdavikhah

From Point the Power

- Alex Avron

Valuable material from

- Texas Instruments and Infineon, APEC 2016
- MIT, Powersoc 2014
- Transphorm, ExxonMobil, TI, EETimes online material

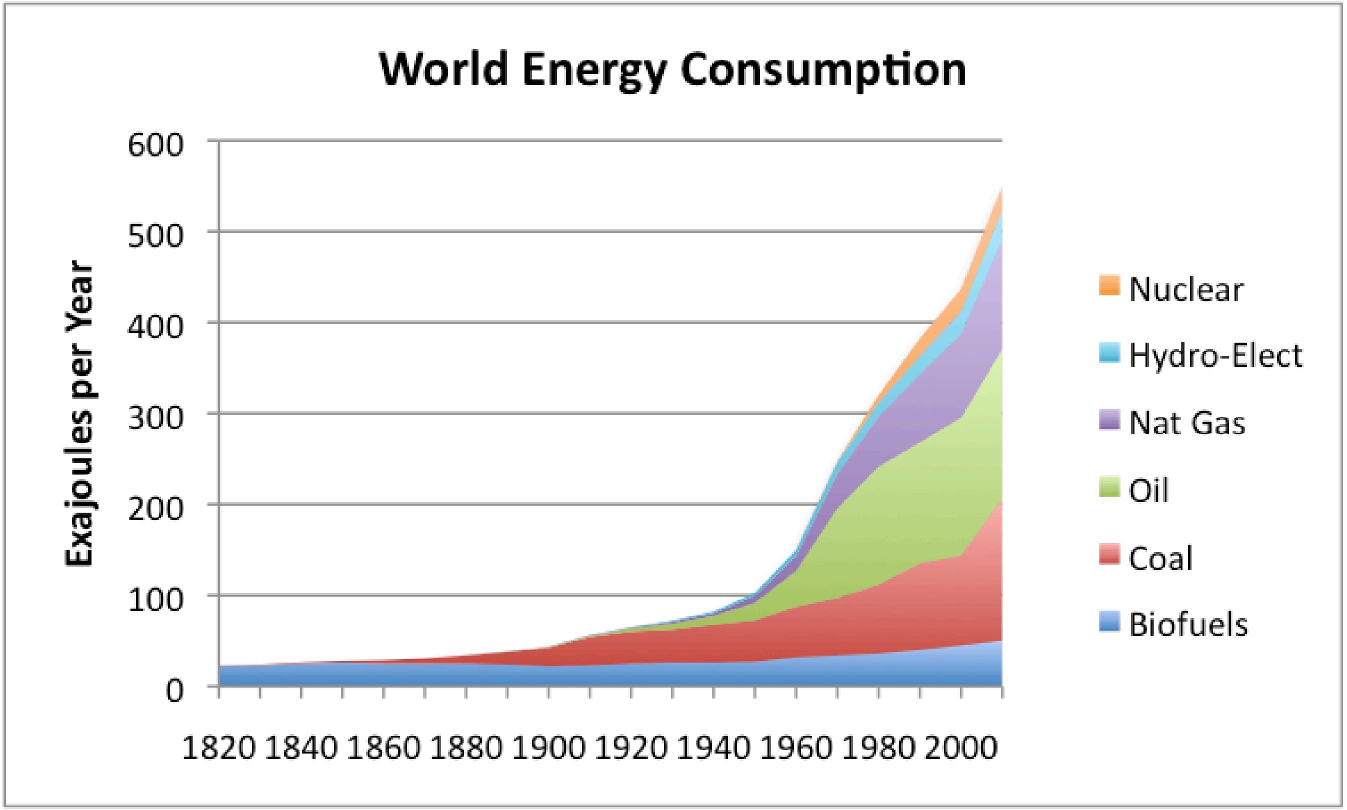
Appulse Power Inc.

www.appulsepower.com
www.appulsepower.com/careers
www.linkedin.com/appulsepower

- Founded by PhDs from the U of Toronto in January 2015
  - *'UofT Laboratory for Power Management and Integrated Switch-Mode Power Supplies.'*
- Develops ICs, reference designs, and adapters
- Disruptive innovations in:
  - Power conversion topology
  - Control
  - Semiconductors
- Achieves the thinnest form factor for ac/dc converters and highest efficiency across load range
- Supports programmable output without compromising efficiency

The Need For Power

- We have entered an era of never-ending need for energy



Ourfiniteworld.com

World Energy Consumption by Source, Based on Vaclav Smil estimates from Energy Transitions: History, Requirements and Prospects together with BP Statistical Data for 1965 and subsequent

The Need For Power

Thomas Edison probably could not have envisioned all the ways people would use electricity in the 21st century.

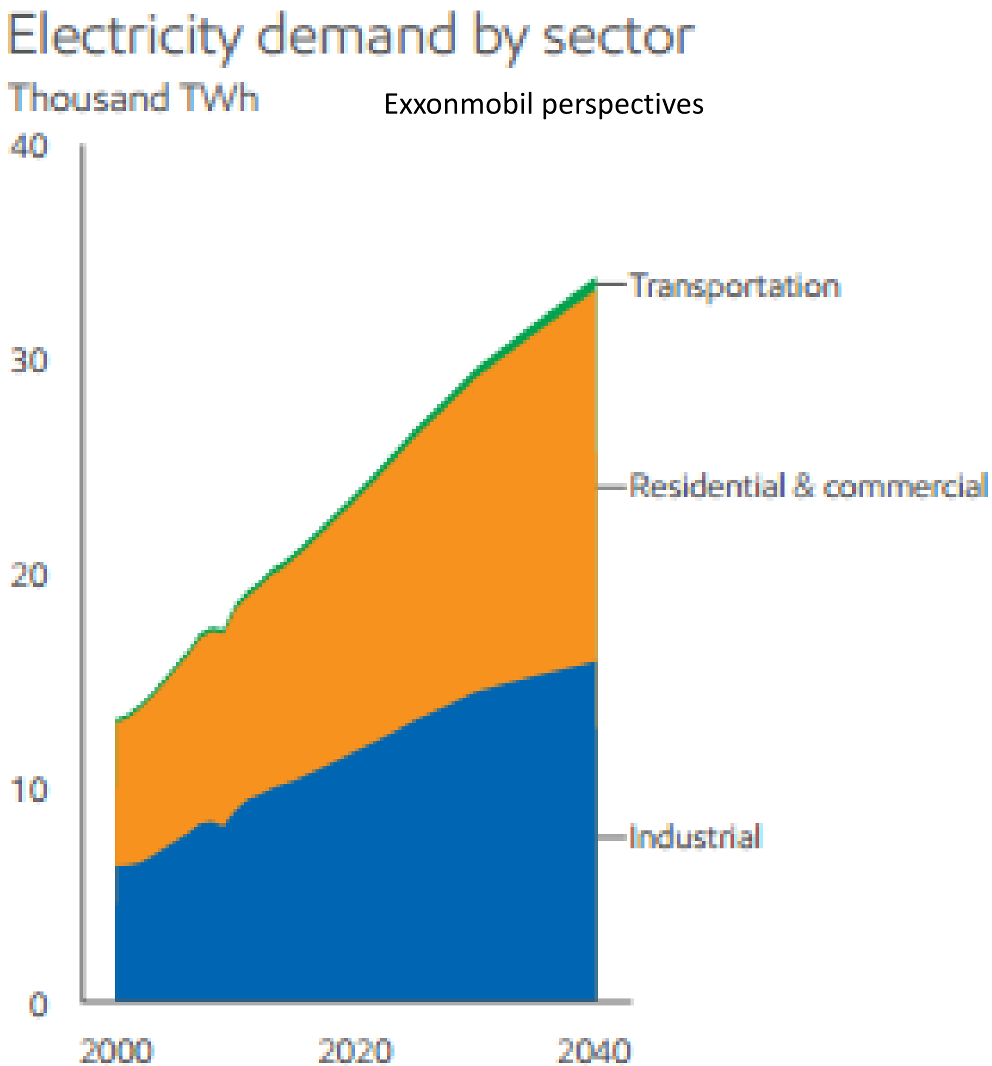
- Electricity powers the factories that make the world's goods. It provides light, heat and air conditioning for homes and commercial buildings.

- **Electricity runs the Internet and everything that connects to it.**

- Global demand for electricity is expected to rise by 65 percent from 2014 to 2040.

Exxonmobil perspectives

The Need For Power



- Demand for electricity to more than double by 2040 !
- Residential & commercial use comparable to industrial use, both growing rapidly.
- Quite possibly a major under estimation
  - It is hard to predict what IoT will look like in 2040

Fundamental Properties of Power Semiconductors

Device property	Si	GaN
Band gap energy, Eg (eV)	1.1	3.42
Electric breakdown field, E_{crit} (10^6 V/cm)	0.3	2 (epi) 3.3 (bulk)
Relative dielectric constant, ε_r	11.9	9
Thermal conductivity, k (W/K·cm)	1.5	1.3 (epi) 2.3 (bulk)
Electron mobility, μ_e (cm^2/V·s)	1350	1150 2000 for 2DEG
Saturation velocity, v_{sat} (10^7 cm/s)	1	3

- GaN outperforms Si in almost every metric for a power device

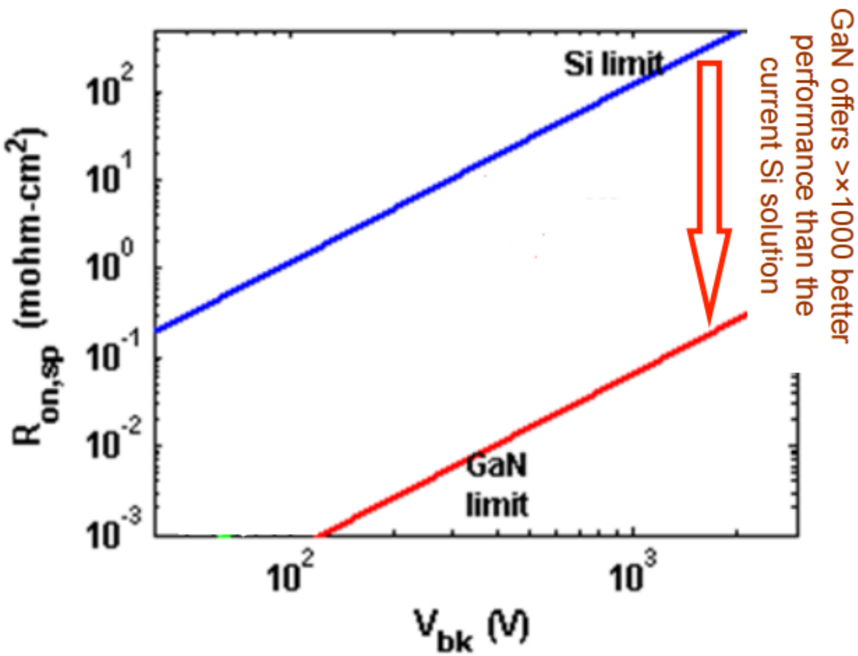
Fundamental Properties of Power Semiconductors

GaN for Power Electronics

Main parameters in power electronics:

- Breakdown voltage
- Specific On-resistance

} Efficiency and size



GaN vs Si

For the same breakdown voltage…

~1000 better resistance …

~Much higher frequency …

T_{max} ~ 175C: Reduced cooling requirements

Much smaller size and higher efficiency than traditional power electronics!!

Palacios, PowerSOC 2014

In terms of fundamental limits, GaN is orders of magnitude better than Si

Fundamental Properties of Power Semiconductors

transphorm

Highest Performance, Highest Reliability GaN

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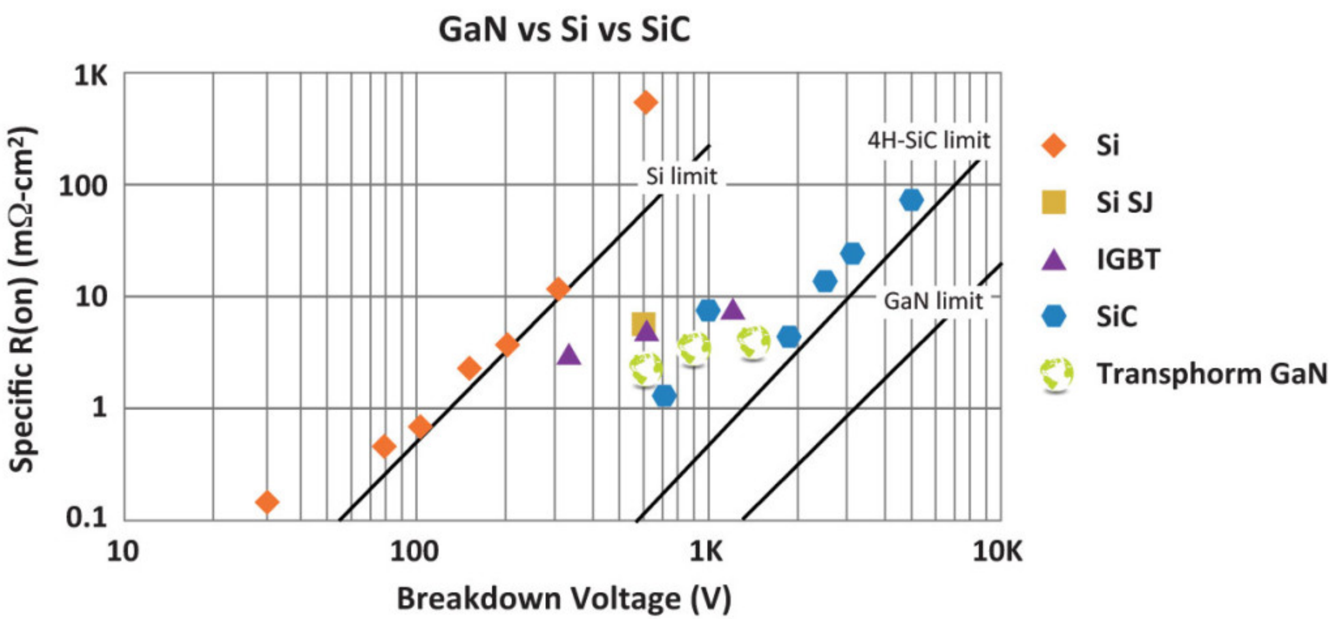
Why GaN-on-Si?

Silicon-based power transistors are reaching limits of operating frequency, breakdown voltage and power density in the power electronics industry and GaN's performance is beginning to shine. By no means is silicon going extinct, but energy requirements are continuing to increase, thereby requiring new methods and materials to be investigated/used to meet these demands.



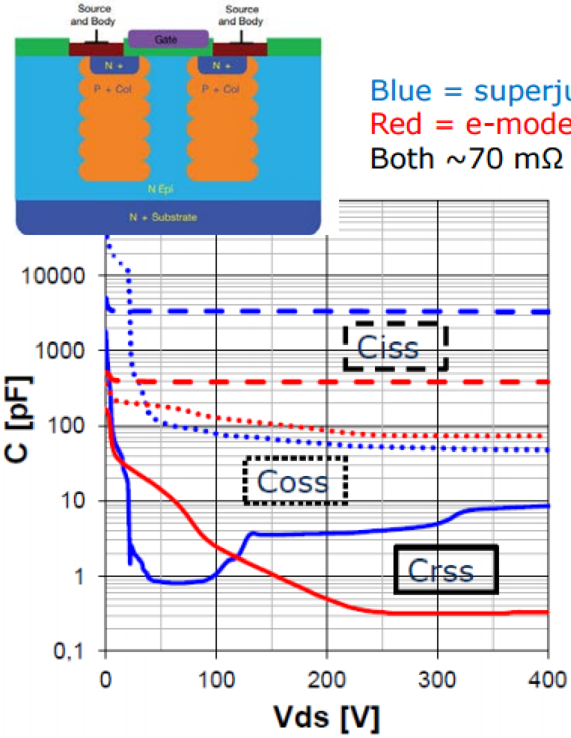
Comparison of 600V E-mode GaN and SJ-MOSFETs

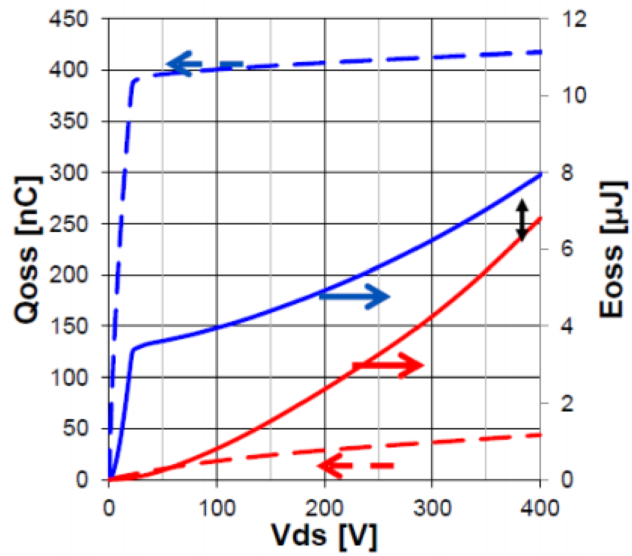
Parameter	E – Mode GaN	SJ-MOSFET	Comments
Vdss	600 V	600 V	
Rdson	52 mΩ	52 mΩ	
R Θ JC (C/W)	1.0	0.77	Package dependent
Tk Rdson (150C/25C)	1.8	2.37	
Qg	6 nC	68 nC	10x lower gate charge
Qrr (Qoss)	44nC	6000 nC	100x lower
Co	110 pF	1050 pF	10x lower
Eoss	7 uJ	8 uJ	Near parity hard switching performance

"GaN in a Silicon world: competition or coexistence?" Tim McDonald, Infineon, APEC 2016, Long Beach, California

Fundamental Properties of Power Semiconductors

Blue = superjunction
Red = e-mode HEMT
Both ~70 mΩ max $R_{DS(on)}$





- Superjunction capacitances are much higher when compared to GaN
- Superjunction C_{oss} and C_{rss} behave very nonlinearly with voltage

- Output charge difference is very large (up to 10x at 100 V) between superjunction and GaN
- But gap in E_{oss} is much smaller (eg: 20% at 400 V)

Co(tr) of GaN device is ~10x lower than SJ FET; this benefit can be leveraged in ZVS applications where it can result in lower power losses

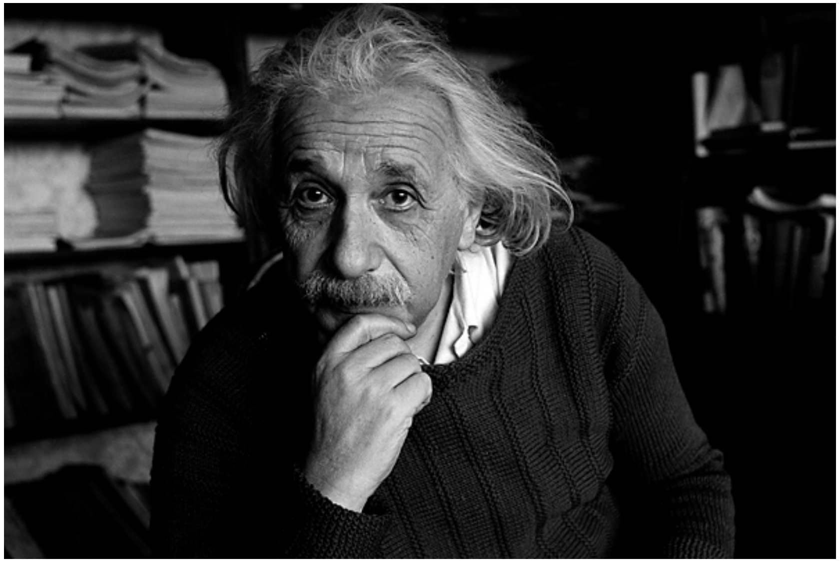
Qrr >100x lower for GaN devices: this can be leveraged in choice of topology and application

“GaN in a Silicon world: competition or coexistence?” Tim McDonald, Infineon, APEC 2016, Long Beach, California

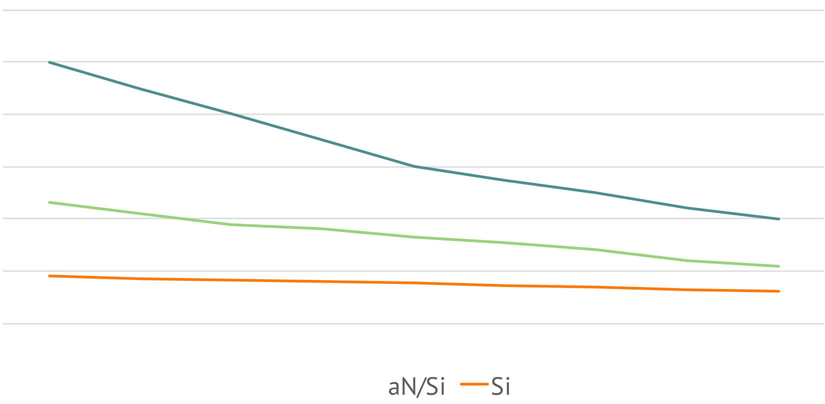
What is limiting GaN Adoption?

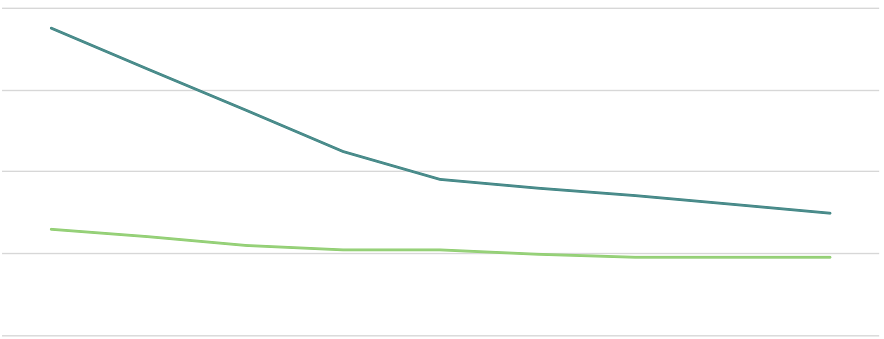
If GaN significantly outperforms Si as a power device,
Why does it not have widespread adoption already?

- Cost?
- Reliability / usability?
- Availability?
- Something else?



Cost Estimate At 600V





- Adoption of GaN process and high volume manufacturing will drive cost erosion
  - TSMC now fully part of the GaN manufacturing supply-chain.

- Clear advantage for e-mode versus cascode when going to lower current.

GaN, SiC and Silicon price trends

Point the Power by Point the Gap

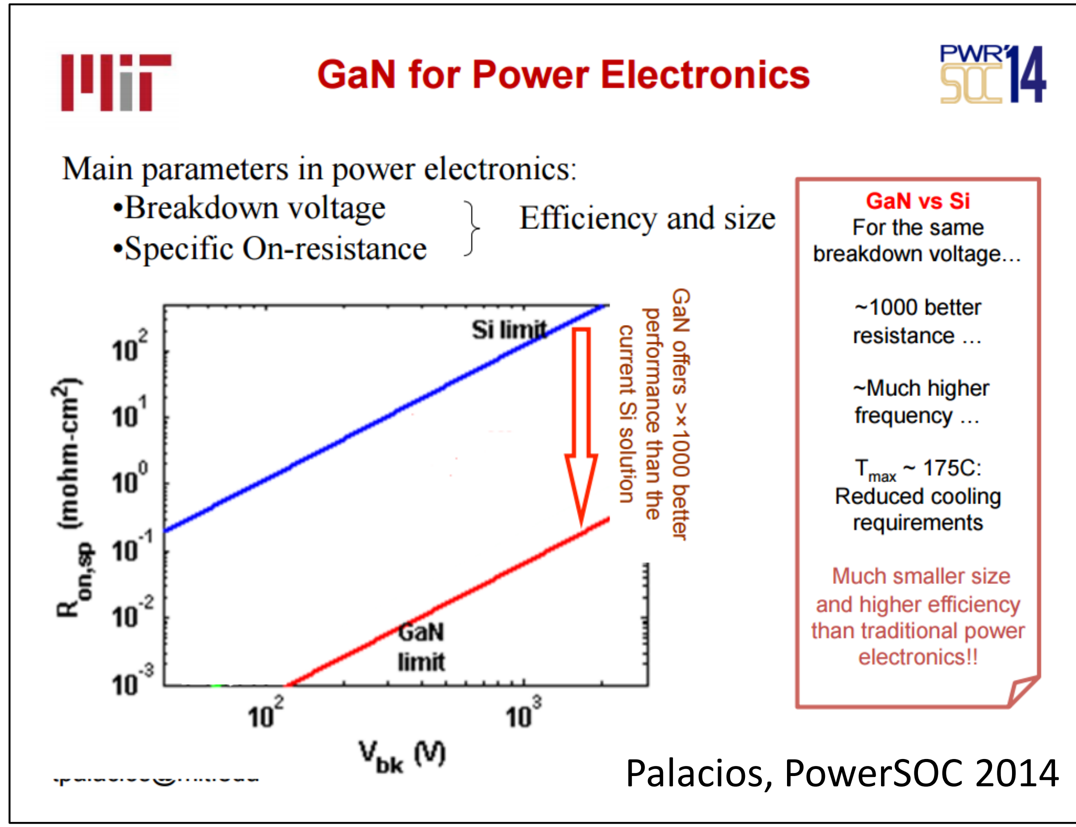
	Wafer size	Wafer cost	Processed Wafer Cost	Device Cost 600V/10A	Price evolution points ranking
Silicon SJ MOSFET	8”	200 USD - 250 USD	400 USD – 500 USD	0.8$	1. Process cost 2. Shrink of die size 3. Substrate cost
GaN HEMT	6”	400 USD – 500 USD	700 USD – 800 USD	1.6$	1. GaN Epi. Cost 2. Manufacturing Yield 3. GaN Epi. Yield 4. Package cost

- SiC cost is starting from very high and dropping faster. But we don’t expect to see it being in competition with GaN and Si on this voltage/current range. GaN will become affordable with production volume, but not directly competitive with Silicon based devices.
- Traction for GaN from Power electronics markets will come from systems designers which will make savings on passives.

A. Avron, Point the Power

Cost of Transistor vs Cost of System

- If a technology is 1000x better and 2x more expensive, cost can not be a barrier to its adoption
- eGan on Si wafers is not 1000x better than comparable Si transistors, but they are still much better
  - **The benefits are topology specific and requires innovation at the circuit level**

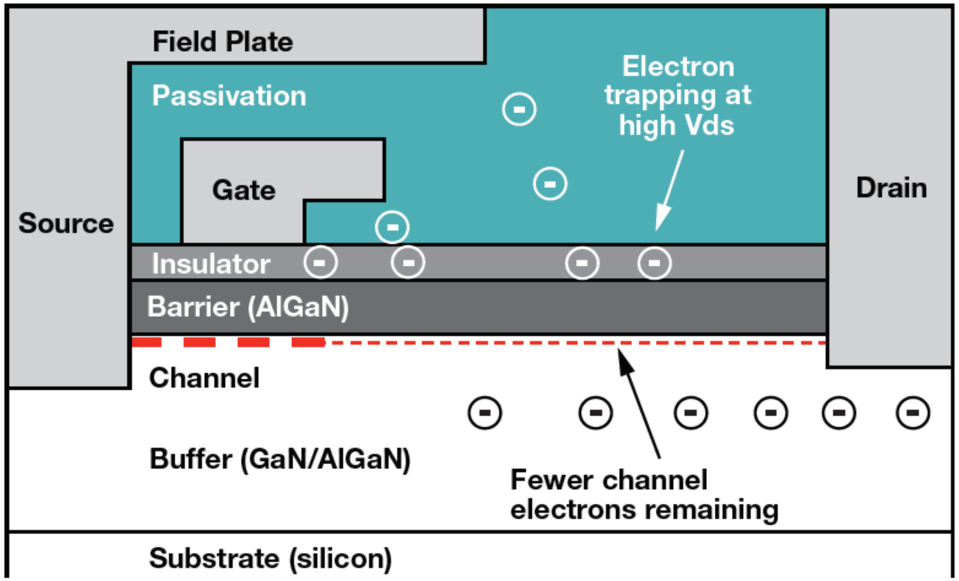


- Cost is one factor, but it should be easily absorbed in other savings at the system level

GaN Reliability – Device Specific

❖ GaN HEMTs can suffer from dynamic Rds-on increase aka “current-collapse”, caused by negative charge trapping in both the buffer and topside layers.

- Charge can be trapped when high-voltage is applied on the drain, and may not dissipate instantaneously when the device is turned on.
- The trapped negative charge repels electrons from the channel layer, and Rds-on increases (the number of electrons in the channel layer is reduced).



❖ Decreases efficiency and can cause the device to excessively self-heat and fail prematurely. The trap density can increase as the device ages, making the dynamic Rds-on effect worse.

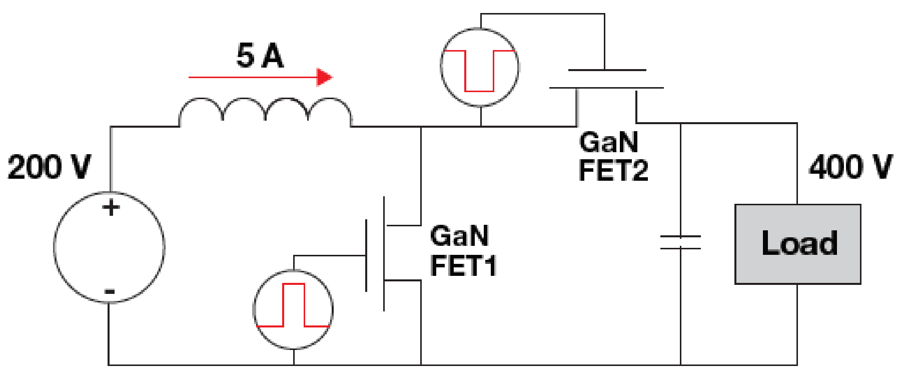
Sandeep R. Bahl, “**A comprehensive methodology to qualify the reliability of GaN products**” GaN Reliability, TI

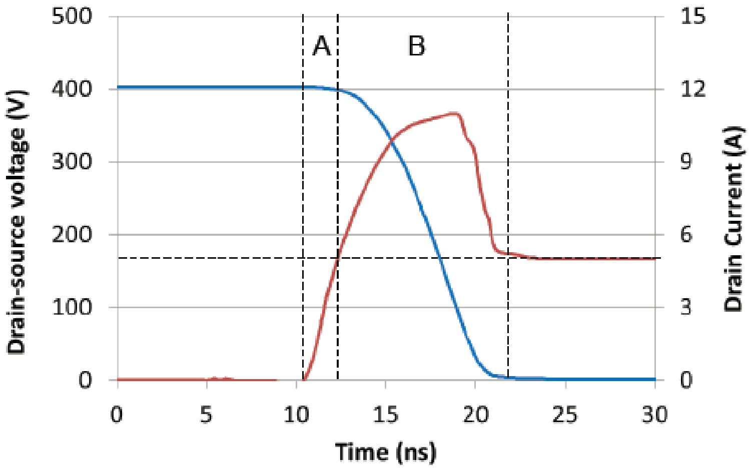
J. Joh, N. Tipirneni, S. Pendharkar, S. Krishnan, **“Current Collapse in GaN Heterojunction Field Effect Transistors for High-voltage Switching Applications**” International Reliability Physics Symposium (IRPS), p. 6C.5.1, 2014. O. Hilt, et. al, **“Impact of Buffer Composition on the Dynamic On-State Resistance of High-Voltage AlGaN/GaN HFETs,”** International Symposium on Power Semiconductor Devices and ICs, p. 345, 2012

GaN Reliability – Application Specific

- Simulation results of the hard-switching turn-on transition on the primary switch (FET1) are shown for a simple boost topology.

- The input voltage is 200V and the inductor current is 5A.





- When FET1 is off, its drain voltage is clamped at about 400V due to the conduction of the clamp FET (FET2).

- When FET1 turns on, it needs to sink the full inductor current before Vds starts dropping (A).

Sandeep R. Bahl, "**A comprehensive methodology to qualify the reliability of GaN products**" GaN Reliability, TI

GaN Reliability – Gate Drive

- Gate reliability of GaN often receives concern / attention

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Design How-To

Gate drive design for enhancement-mode GaN FETs

Steve Colino, Efficient Power Conversion, and Bob Bell & Youhao Xi, National Semiconductor

9/6/2011 08:54 PM EDT

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In recent years, enhancement mode Gallium-Nitride (eGaN$^{\text{Ò}}$) power transistors have emerged as promising next generation power switches for high power density switch mode power converters. Significantly higher conversion efficiencies can be realized when compared with standard Si MOSFETs in a number of topologies such as Buck, Boost, Forward, and Flyback. Given the same feature size, eGaN devices offer lower conduction resistance, smaller gate charge, and faster switching capability than comparable MOSFET devices. Being configured as enhancement mode, allows eGaN devices to operate similar to power MOSFETs, minimizing the learning curve for power converter designers. However, driving eGaN devices requires special considerations due to the low threshold voltage, fast switching speed and 6V gate-to-source maximum voltage rating. Fortunately, newly optimized gate drivers are now available that solves the challenges of driving eGaN devices, enabling industry

Driving eGaN devices requires special considerations due to the low threshold voltage, fast switching speed and 6V gate-to-source maximum voltage rating

TEXAS INSTRUMENTS — UCC27611
SLUSBA5C – DECEMBER 2012 – REVISED DECEMBER 2015

UCC27611 4-A and 6-A High-Speed 5-V Drive, Optimized Single-Gate Driver

1 Features

- Enhancement Mode Gallium Nitride FETs (eGANFETs)
- 4-V to 18-V Single Supply Range VDD Range
- Drive Voltage VREF Regulated to 5 V
- 4-A Peak Source and 6-A Peak Sink Drive Current
- 1-Ω and 0.35-Ω Pullup and Pulldown Resistance (Maximize High Slew-Rate dV and dt Immunity)
- Split Output Configuration (Allows Turnon and Turnoff Optimization for Individual FETs)
- Fast Propagation Delays (14-ns Typical)
- Fast Rise and Fall Times (9-ns and 5-ns Typical)
- TTL and CMOS Compatible Inputs (Independent

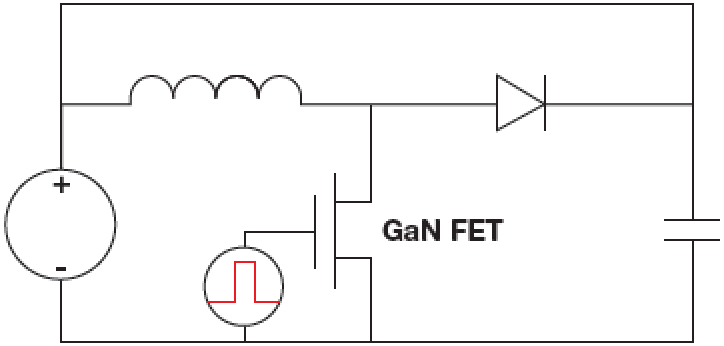
3 Description

The UCC27611 is a single-channel, high-speed, gate driver optimized for 5-V drive, specifically addressing enhancement mode GaN FETs. The drive voltage VREF is precisely controlled by internal linear regulator to 5 V. The UCC27611 offers asymmetrical rail-to-rail peak current drive capability with 4-A source and 6-A sink. Split output configuration allows individual turnon and turnoff time optimization depending on FET. Package and pinout with minimum parasitic inductances reduce the rise and fall time and limit the ringing. Additionally, the short propagation delay with minimized tolerances and variations allows efficient operation at high frequencies. The 1-Ω and 0.35-Ω resistance boosts immunity to hard switching with high slew rate dV and dt.

There are a number of driver ICs as well as options for co-packaging driver circuitry

GaN Reliability

- Device specific and application specific concerns
- Requires customized stress test and qualification

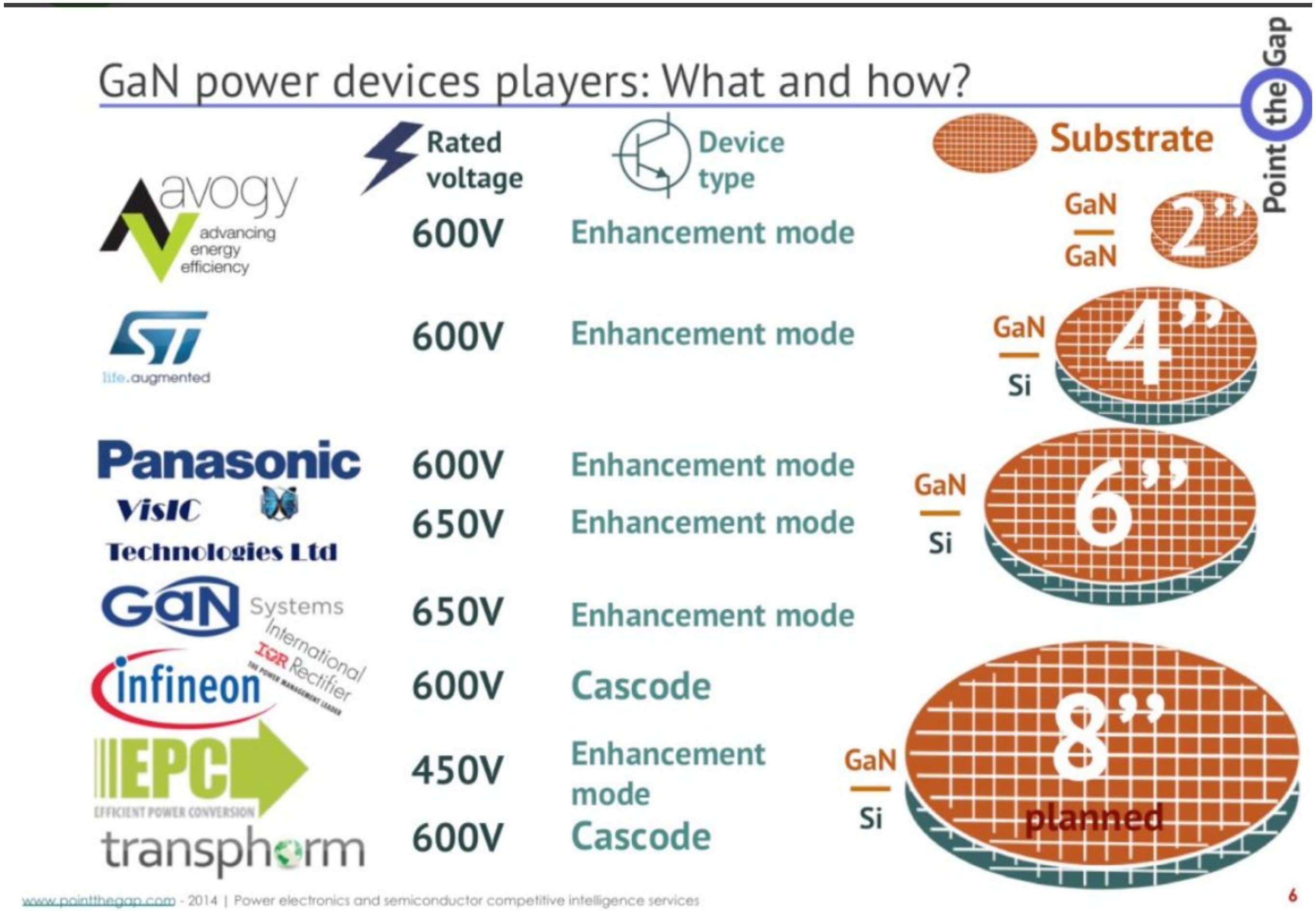


Test Vehicle for inductive switching application - TI

Sandeep R. Bahl, "**A comprehensive methodology to qualify the reliability of GaN products**" GaN Reliability, TI

- Issues are very well understood and not new

GaN Availability



- It seems like everyone is making GaN

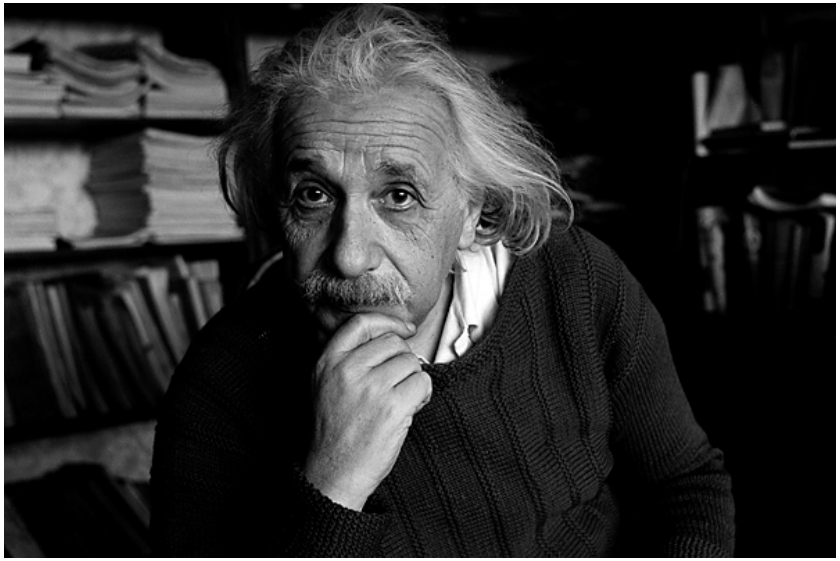
- Not all GaN are created equal

What is limiting GaN Adoption?

If GaN 1) significantly outperforms Si as a power device, 2) cost is manageable, 3) reliability issues are well understood and controlled, 4) and is widely available

Why does it not have widespread adoption already?

- Cost
- Reliability / usability
- Availability
- Something else



People / Talent

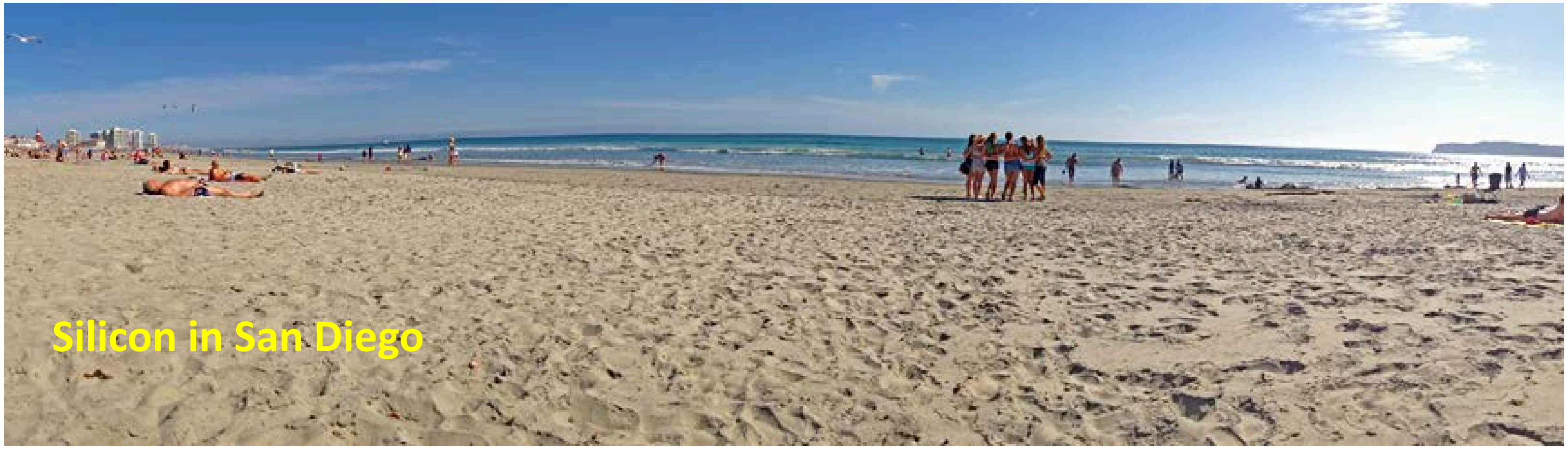
Appulse Power

Even before we talk about the adoption of a new semiconductor with unique reliability, tricky gate drive design, and cost sensitivity

- Power electronics engineers are hard to find
- Power electronics engineers with IC design skills are harder to find

How about change?

- Engineers take pride in doing more with less
- Would rather use a lower cost device that has proven the test of time and is in abundance



Change Does Not Happen Easily

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Once You Take The Leap

GaN has to potential for increasing power conversion efficiency:

- ❖ Reduced power losses & electricity
- ❖ Less materials such as plastic
- ❖ Reduced carbon foot print

GaN → GreeN

Summary

- Energy and electricity consumption is increasing in an unprecedented and unsustainable rate
- When realized in its full potential GaN is an enabler of very high efficiency power conversion
  - This requires the use of topologies that can fully leverage GaN's FOMs
- Cost, reliability, and availability are often cited barriers to GaN adoption
  - Increased awareness and education are needed
- High efficiency ac/dc conversion will help toward a greener future

Thank you.