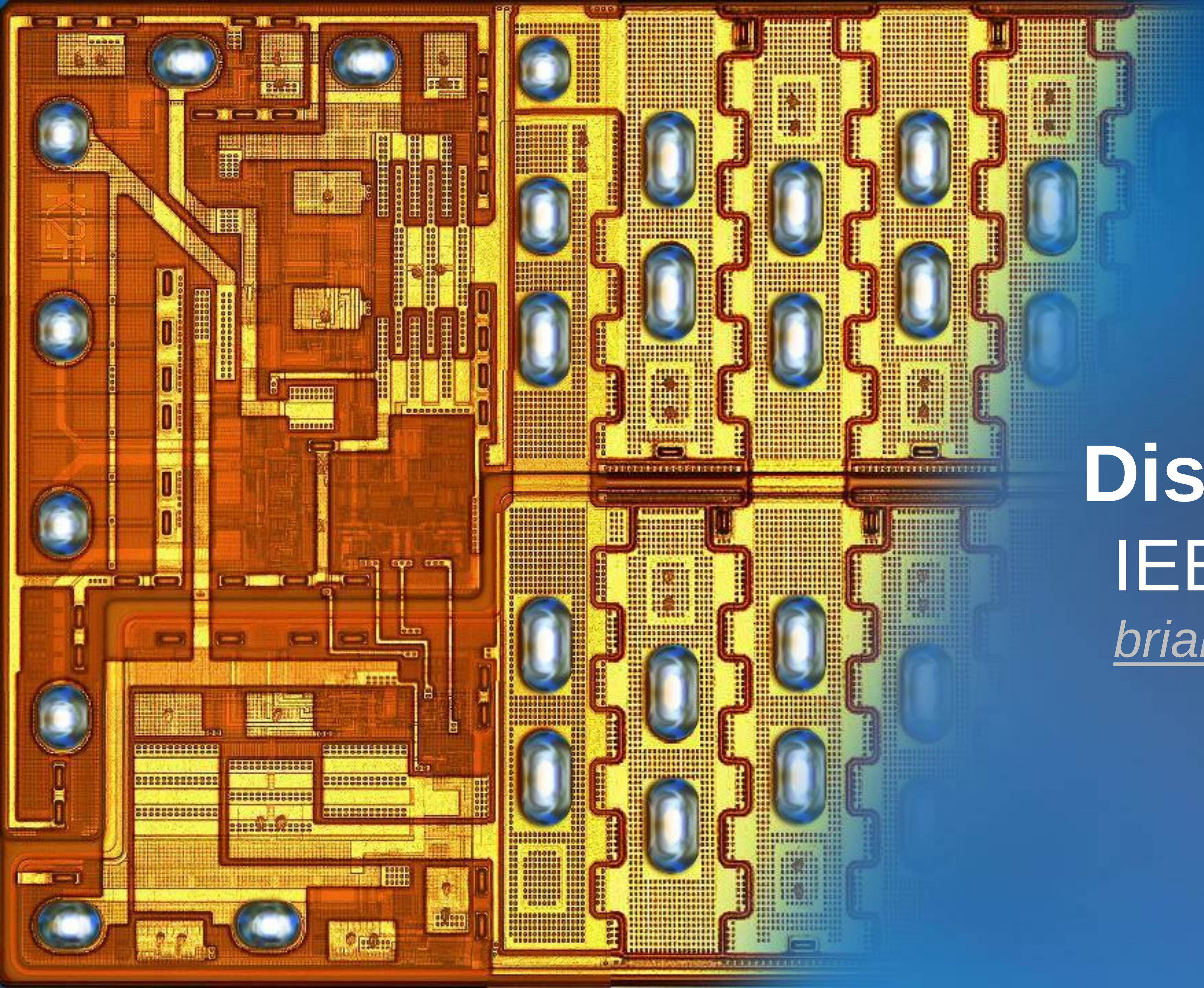


GaN FETs: Discrete vs. ICs

IEEE-Long Island

brian.miller@epc-co.com

EFFICIENT POWER CONVERSION

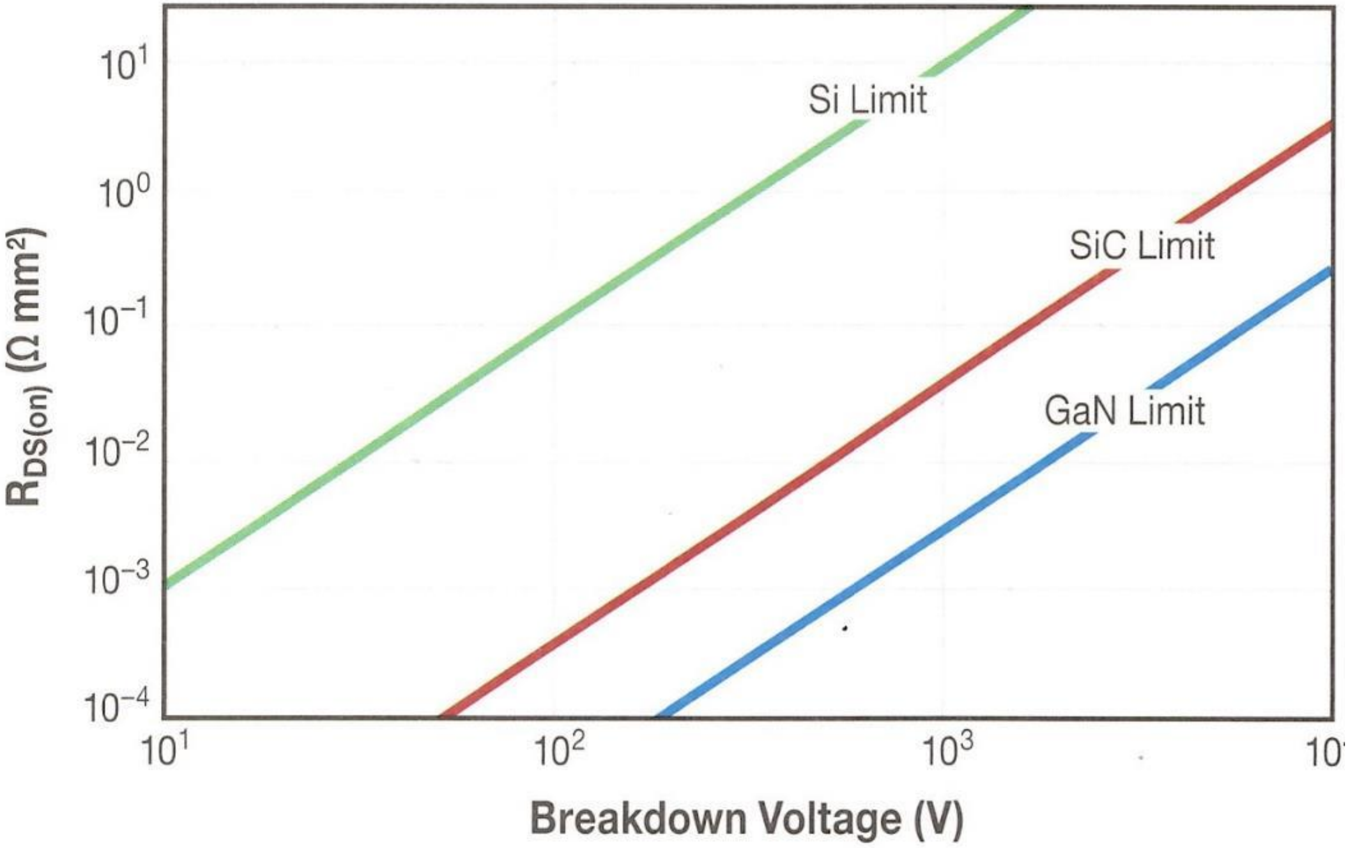
Agenda

- Introduction and Review of GaN Power Devices
- Discrete GaN FETs
- GaN modules
- GaN power ICs
- Comparison – Advantages and Disadvantages
- Summary
- Bonus Topics
  - Motor Drive & GaN FETs
  - Bi-directional Blocking FET

Motivation for Wide Band Gap Devices

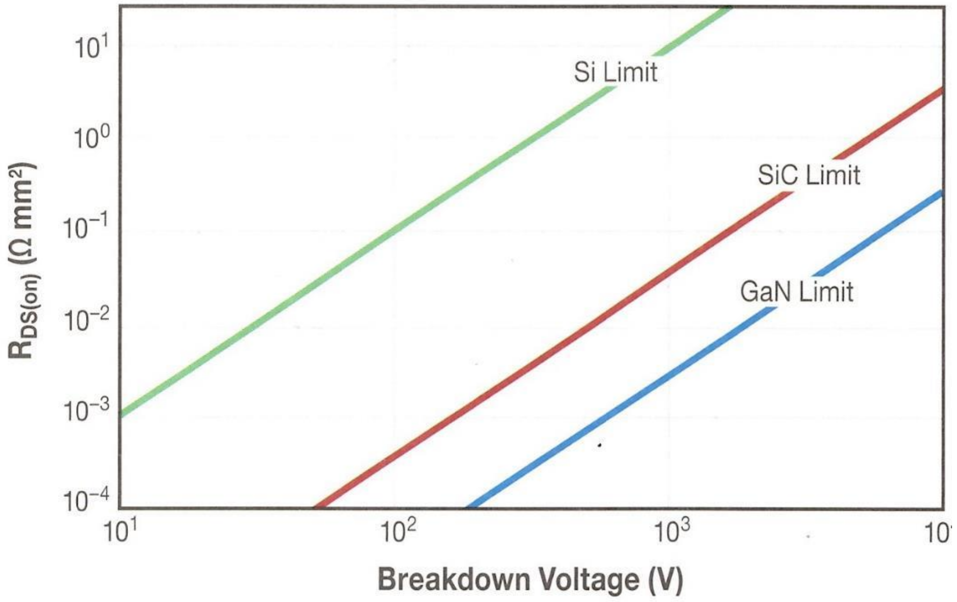
The potential of wide band gap

- SiC and GaN: theoretical much smaller size for a given Rds(on)
- Can this potential be realized?
  - Silicon MOSFETs **have** reached their potential. Real-world devices match the green line
  - What about GaN FETs? What advancement is seen?



Why use GaN FETs?

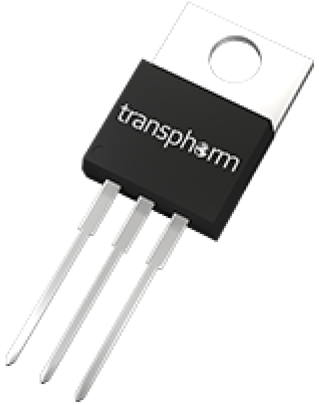
- From the previous graph:
  - Smaller
  - Lower On Resistance
- Faster – lower switching loss
- Lower System Cost – higher freq. → smaller L, C
- Reliability



GaN FETs:
Discrete, Module, & IC

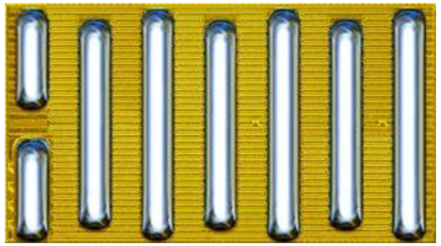
GaN FETs – Discrete

- Discrete GaN FETs: no integrated features (i.e. no gate driver)
- From 15 V to >1 kV
- Packaged or Chip Scale



- Example 650 V FETs:
  - Transphorm, GaN Systems / Infineon, etc.

- Example 100 V and 200 V FETs:



- The largest size difference is at higher voltages. But even at lower voltages (next page)

200 V GaN vs. Si Devices

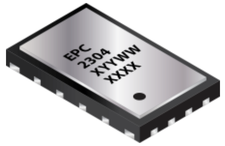
Si MOSFET Benchmark

9.9 x 11.7 mm

eGaN FET

4.6 x 1.6 mm

GaN FET



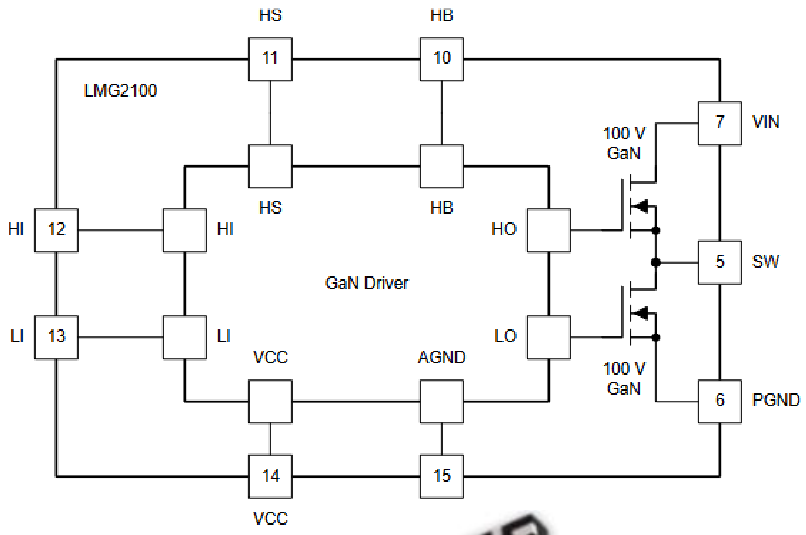
3 x 5 mm

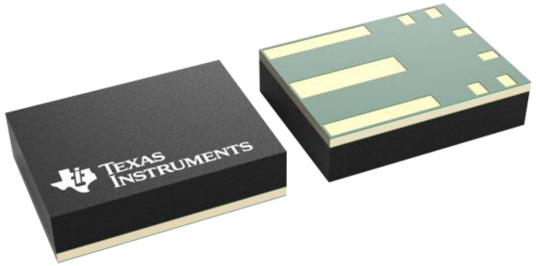
Parameter	IPT111N20NFD (@ 10 V_{GS})	EPC2215 (@ 5 V_{GS})	EPC2304 (@ 5 V_{GS})
$R_{DS(on)}$ typ	9 mΩ	6 mΩ	3.4 mΩ
$R_{DS(on)}$ max	11.1 mΩ	8 mΩ	5 mΩ
Q_G typ	65 nC	10 nC	20 nC
Q_{GD} typ	8 nC	1.6 nC	3.2 nC
Q_{OSS} typ	162 nC	68 nC	68 nC
Q_{RR} typ	309 nC	0 nC	0 nC
Device Size	115.83 mm^2	7.36 mm^2	15 mm^2

15x smaller, less losses, no reverse recovery, higher f_{SW}

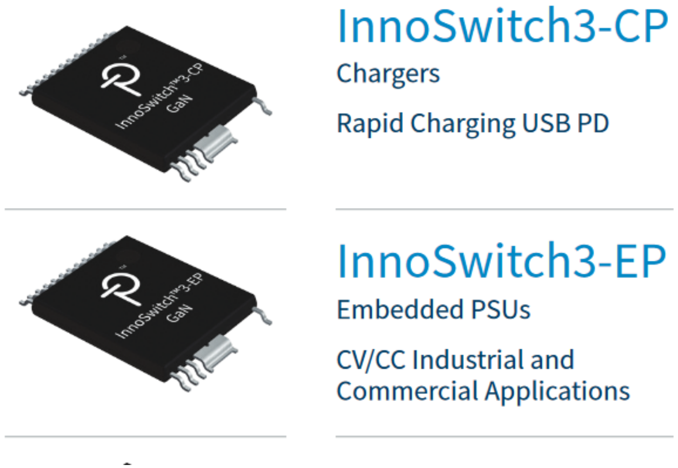
GaN FETs – Modules

- Modules have gate drivers (or controller) + GaN FET(s) in the same package
  - Examples:
  - TI's LMG5200: 100 V
  - TI's LMG2100: 100 V

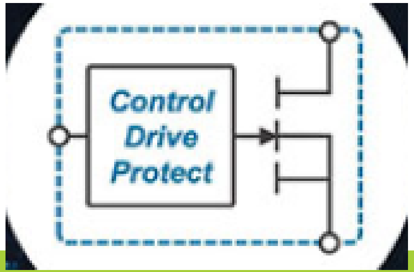




  - Power Integrations:
    - 750+ V
    - Off-line power conversion
    - InnoSwitchx-xx: Flyback module



  - Navitas

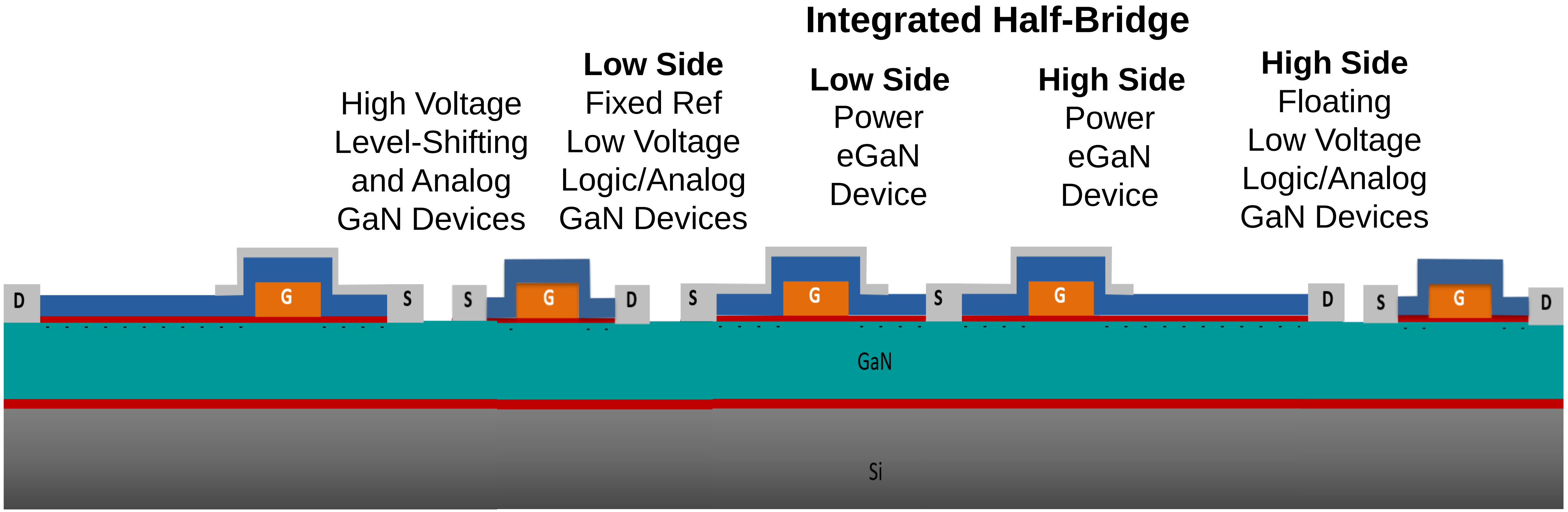


GaN FETs – Modules

- Example Result: Small AC Adapter
  - Small due to:
  - Small FET
  - Less heat
  - Higher frequency

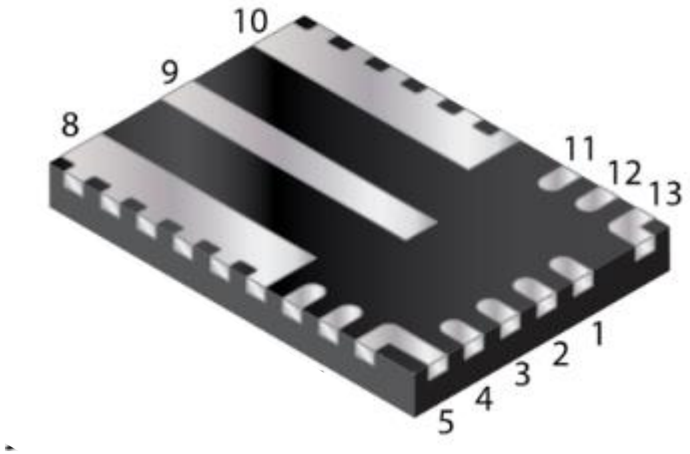
GaN FETs – ICs (Monolithic)

- Structure of GaN FET enables optimized IC
  - MOSFET: Vertical device, so all FETs the same voltage
  - GaN: Lateral device, so various voltage ratings on the same die



GaN IC example

- EPC23102:
  - Monolithic GaN IC
  - 100 V, 35 A
- Trade-offs
  - Small size: 3 x 5 mm
  - Very fast gate driver
  - But: not all features of all discrete
  - Efficient/optimized, high speed
  - But: limited choice of variations
    - Top FET & bottom FET the same
    - One variation: external bottom FET
  - Layout internal
  - But: quiescent current (operation)



Comparisons

GaN discrete FETs vs. GaN power ICs vs. GaN modules

Efficiency – Comparison

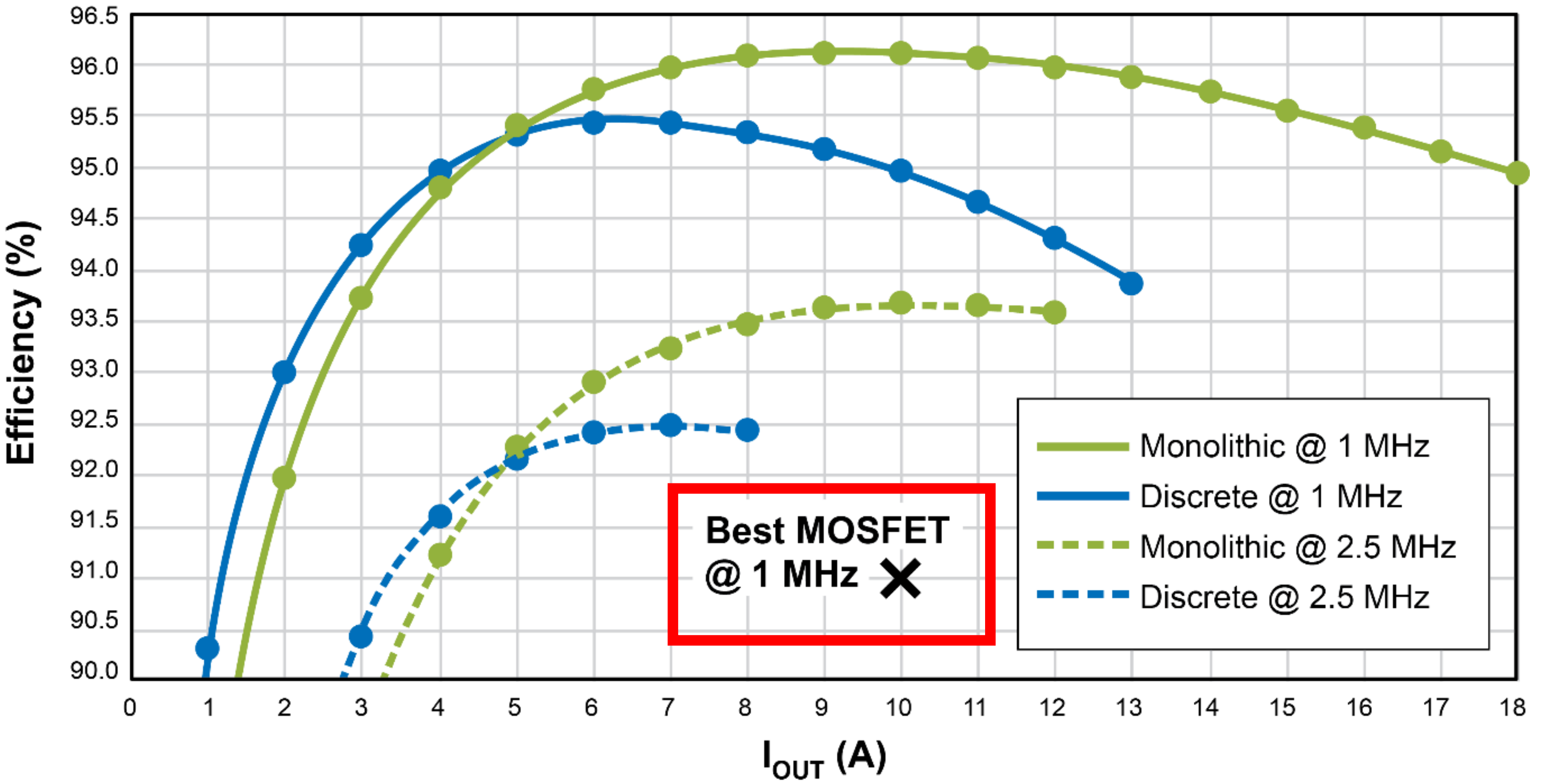
GaN from EPC

- **Green line** = monolithic GaN IC
- **Blue line** = discrete GaN FETs

- So, GaN IC is best?
- Not always…
- Depends on conditions

48 V – 12 V Buck Converter Topology

L= 2.2 μH, Air Flow = 800 LFM



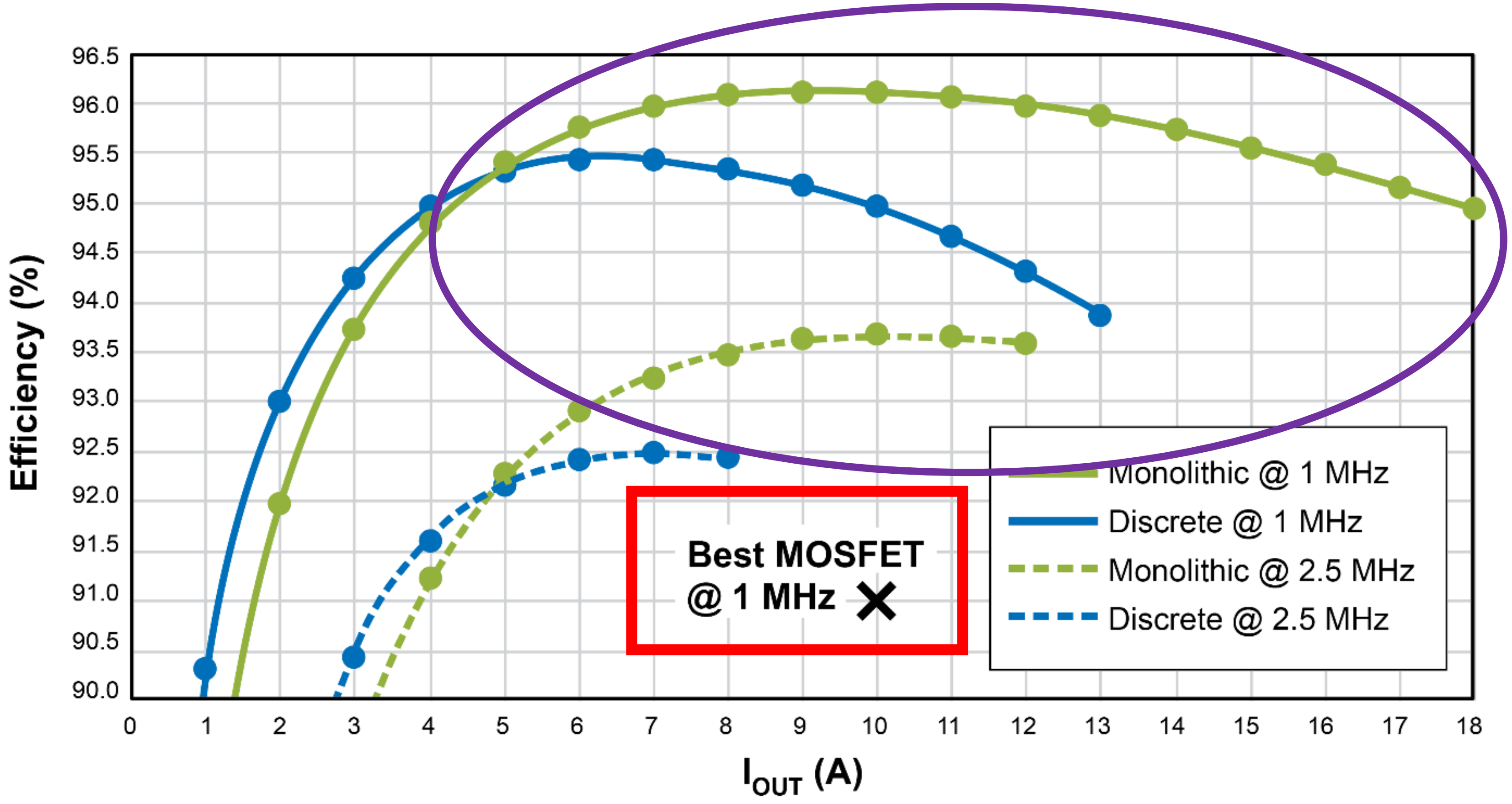
Efficiency – max load

Max load: GaN power ICs win (**Green line**)

- Why? Several factors:
  - ICs have internal layout
  - Gate driver (optimized)
  - Inductances:
    - Detail, next page
  - Result: better than expected efficiency

48 V – 12 V Buck Converter Topology

L= 2.2 μH, Air Flow = 800 LFM



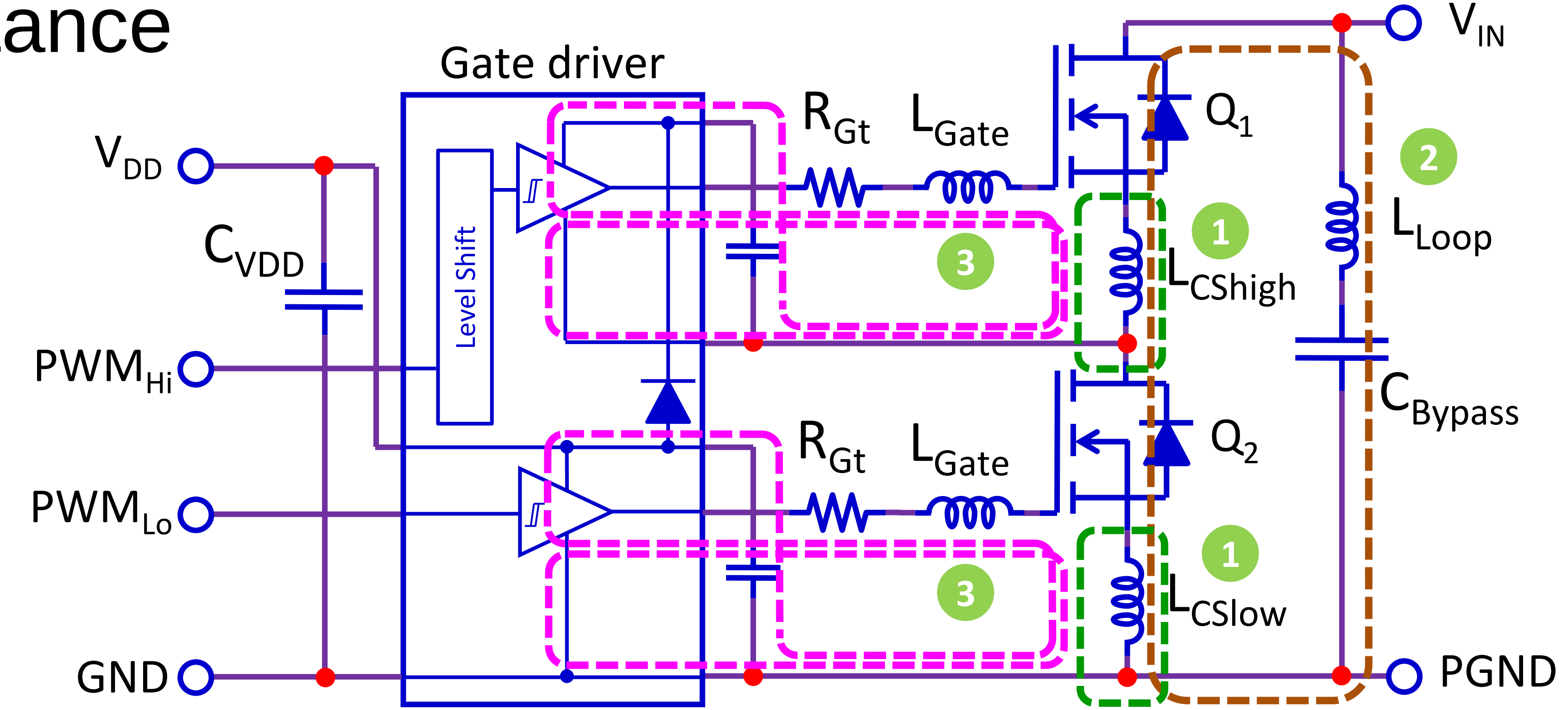
Parasitic inductances

1. Common source inductance
2. Power loop inductance
3. Gate loop inductance
   - Turn-on
   - Turn-off

WP010: Optimizing PCB Layout

How to GaN 05

How to GaN 05a

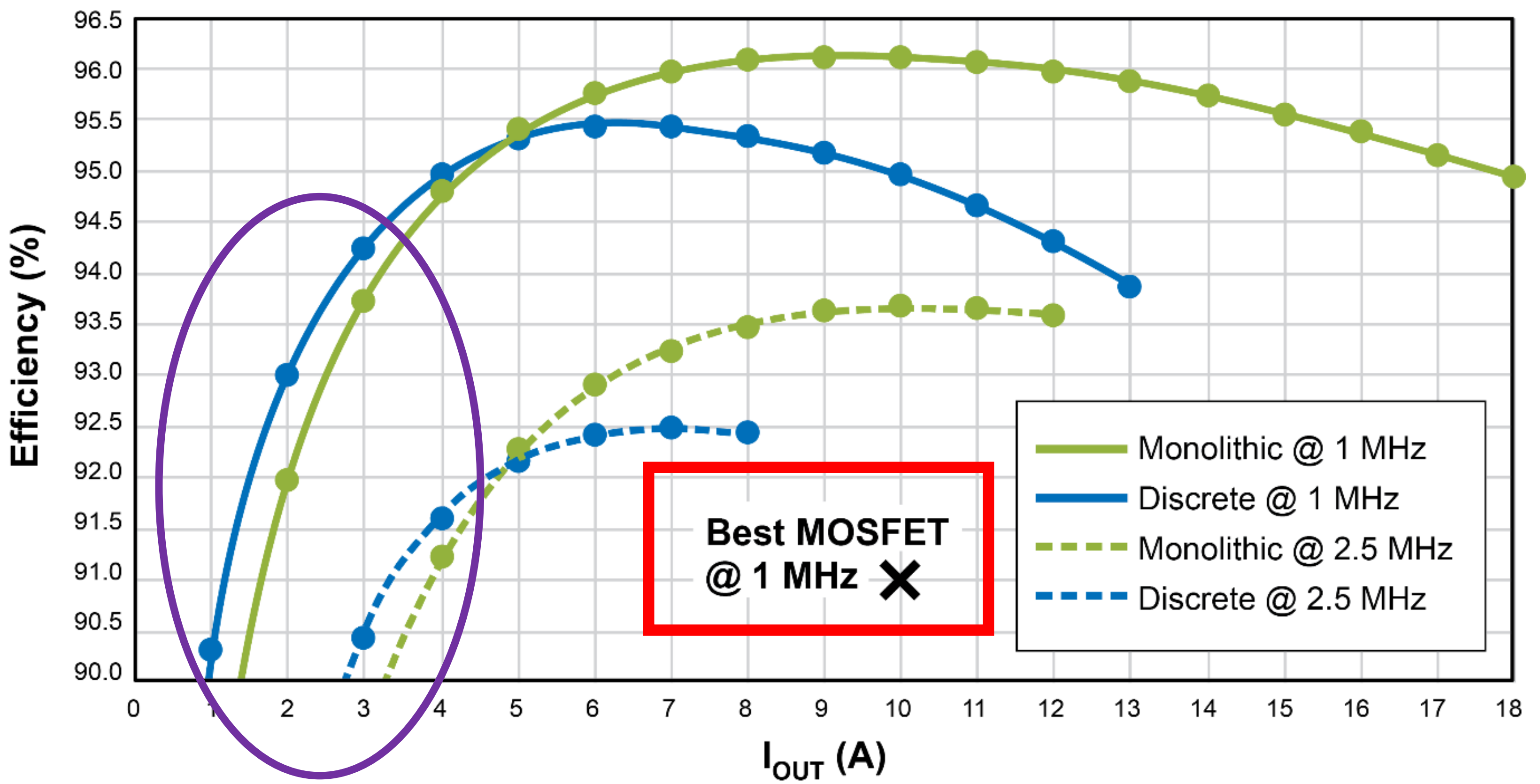


Efficiency – light load

Light load: GaN discretes win (**Blue line**)

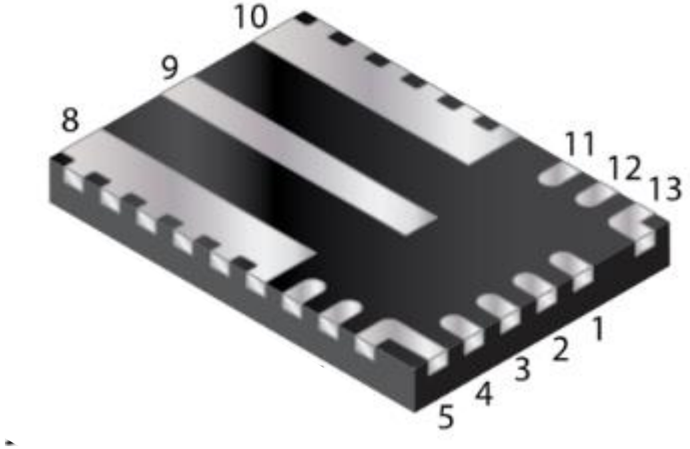
- Why? Quiescent current of IC
- GaN IC:
  - No P-channel FETs
  - So, N-FET logic
  - Thus, higher quiescent current
  - (insert example values)

48 V – 12 V Buck Converter Topology
L= 2.2 μH, Air Flow = 800 LFM

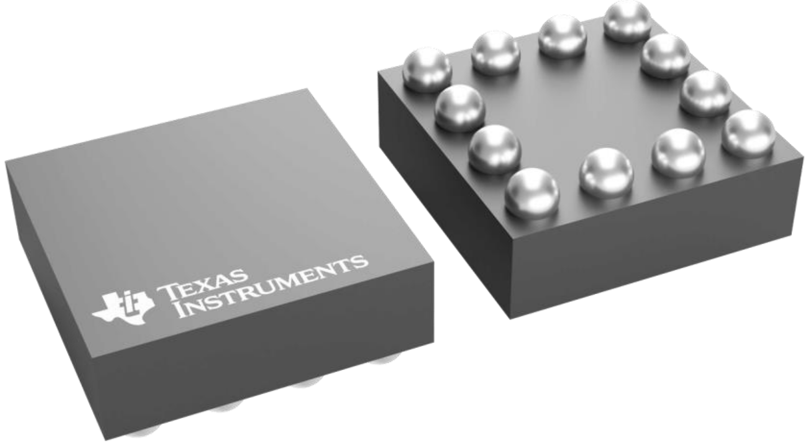


Efficiency – light load

- Quiescent Current: GaN ICs (integrated driver)
  - There are no P-FET, so no CMOS logic
  - Non-operating quiescent current, EPC23102: **10 mA**
  - However, a Standby function is added
  - Drops the current to approx. **0.1 mA**



- Quiescent Current: Discrete GaN + Driver
  - Function of the gate driver
  - May be in the range of **0.1 mA**



Voltage Ratings

Discrete GaN FETs:

- Very wide range
- 15 V to >1k V. For EPC, 15 to 350 V

Module GaN:

- Can be same as discrete FETs

Monolithic ICs (EPC):

- Half Bridges:
  - 100 V max, 120 V transient
  - Due to isolation rating
  - Top to bottom FET V
- Single FET + Driver:
  - Same as discrete FETs

Size

Discrete GaN FETs:

- FET + FET + gate driver
- Layout flexibility
- Total size likely larger

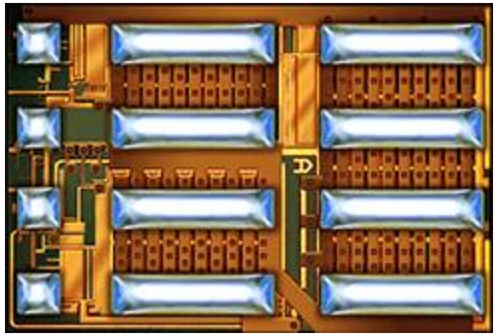
Monolithic ICs (EPC):

- Half Bridges: 10 sq. mm example
  - Just external decoupling caps (power + gate drive V)
- Single FET + Driver:
  - Just external gate cap

Module GaN:

- Typically larger vs. monolithic IC
- External adjustments (with some, not all)
- Example: TI's LMG2100

Driver: 2.5 sq. mm
FETs x 2: 7.5 sq. mm
total (without keep-out, external discrete passives): 10 sq. mm



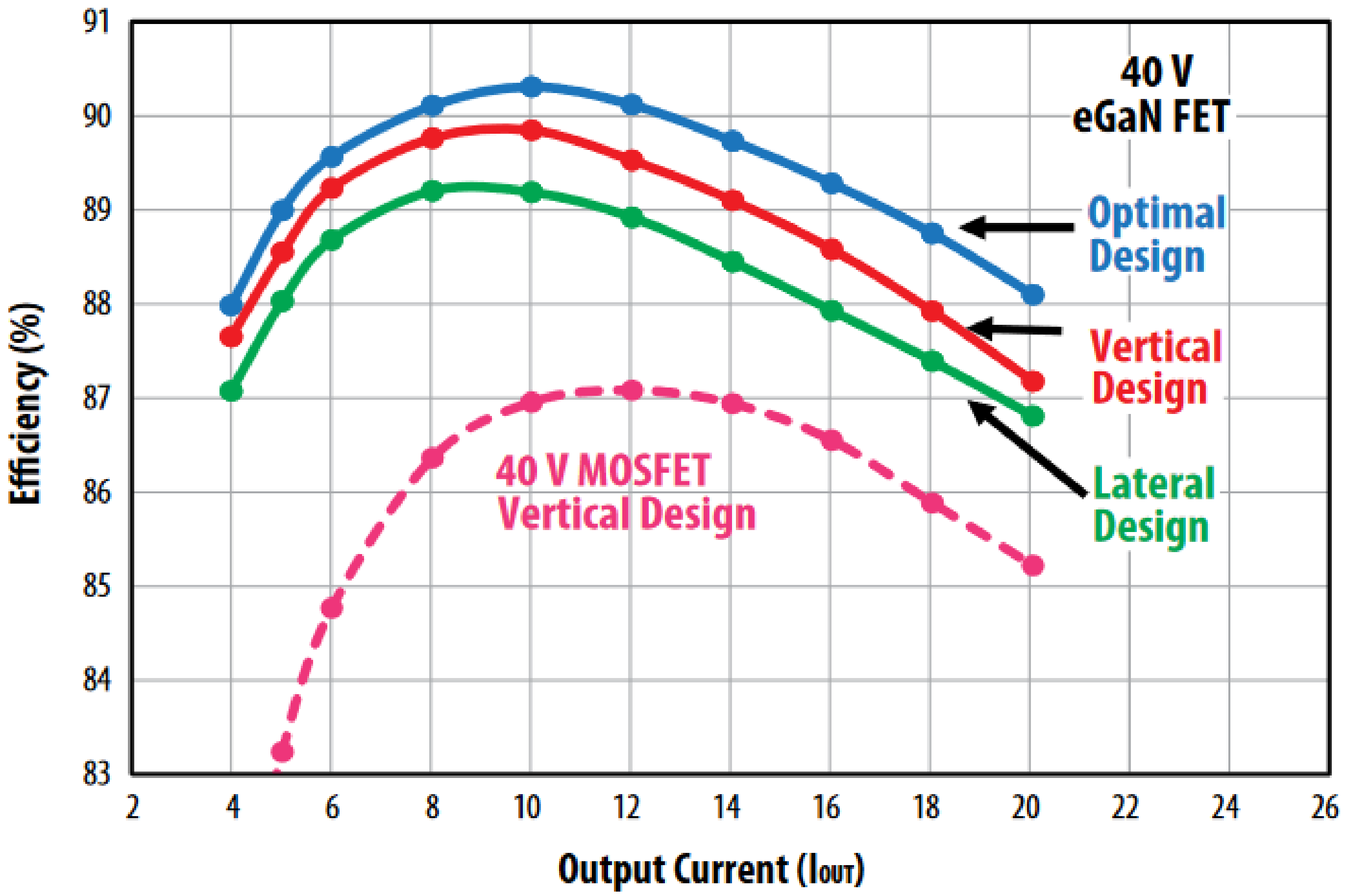
100 V, 15A
3.9 x 2.6 mm, 10 sq. mm

7 x 4.5 mm = 31.5 sq. mm

Layout - Efficiency

- Starting with results:
  - Solid lines: same EPC GaN FET

- Free efficiency improvement
  - Due to layout
  - Same schematic, same FETs

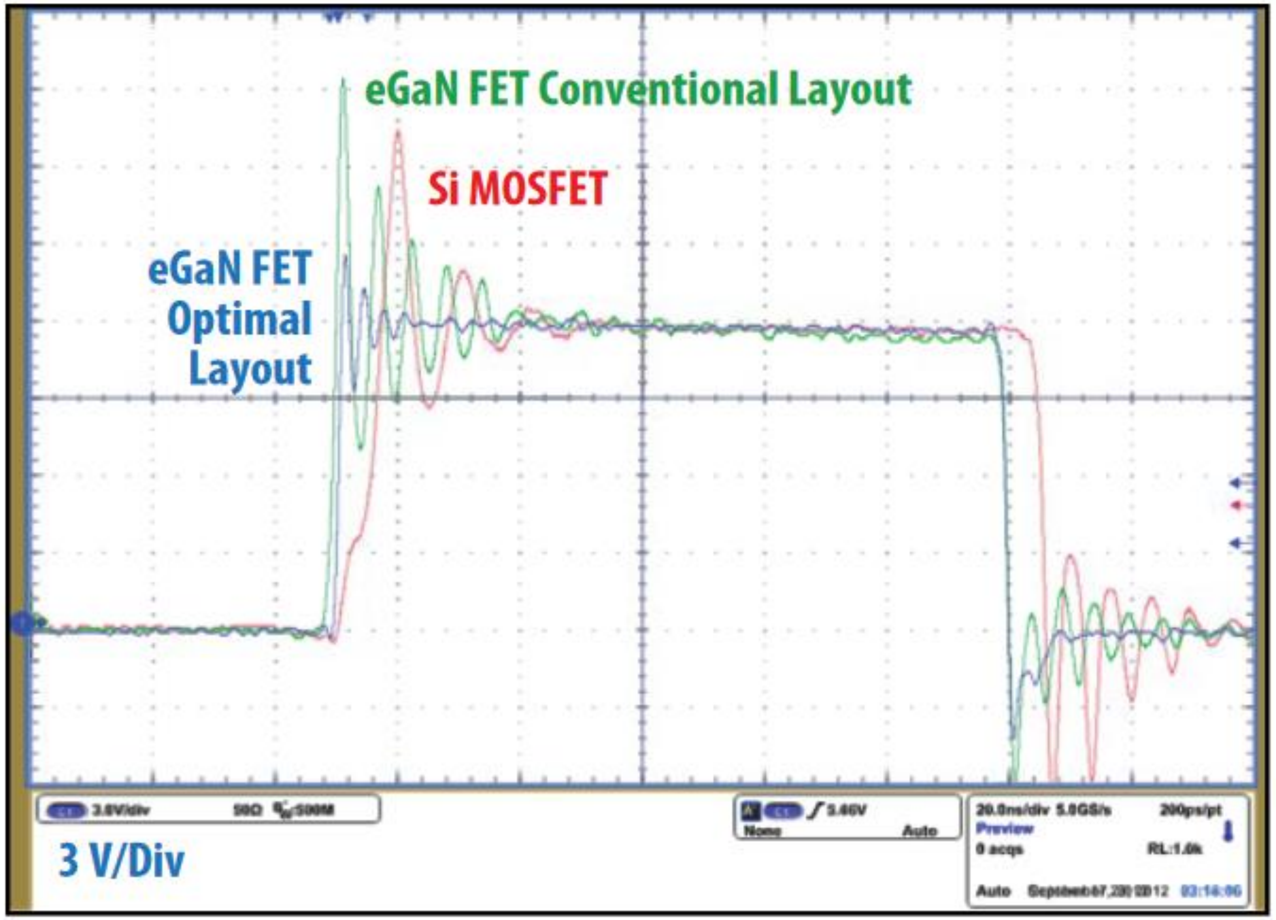


Buck converter, 1 MHz, 12 V to 1.2 V

App note link

Layout - Noise

- Starting with results:
  - Blue line and Green Line: same FETs, same schematic
  - EPC GaN FETs
- Free ringing improvement
  - Due to layout
  - MOSFETs don't benefit as much…

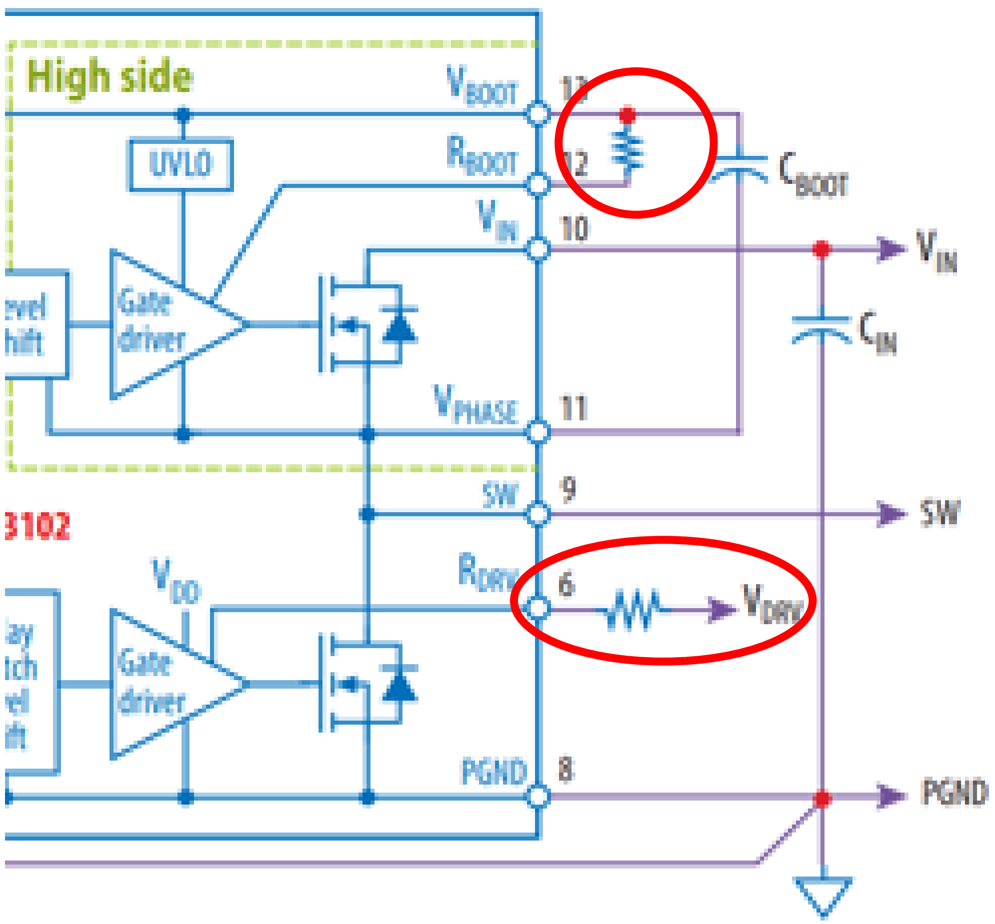


Buck converter, 1 MHz, 12 V to 1.2 V

[*App note link*]

Layout – Efficiency & Noise

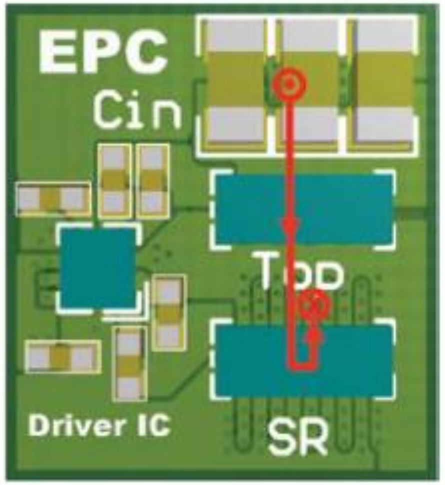
- Discrete
  - + adjust driver, gate resistor
  - - layout isn't as tight as module & IC
- Module
  - + tighter placement
  - - some don't have gate drive strength adjustment… for ringing adjustment
- IC
  - + layout all on one monolithic die
  - + drive strength adjustment pin (some ICs)
  - - limited choices, 100 V max (half bridge)



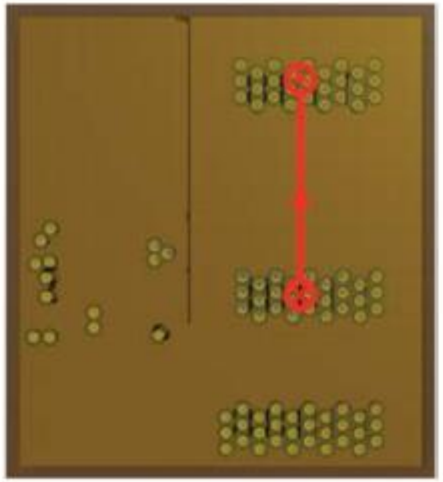
EPC2310x example

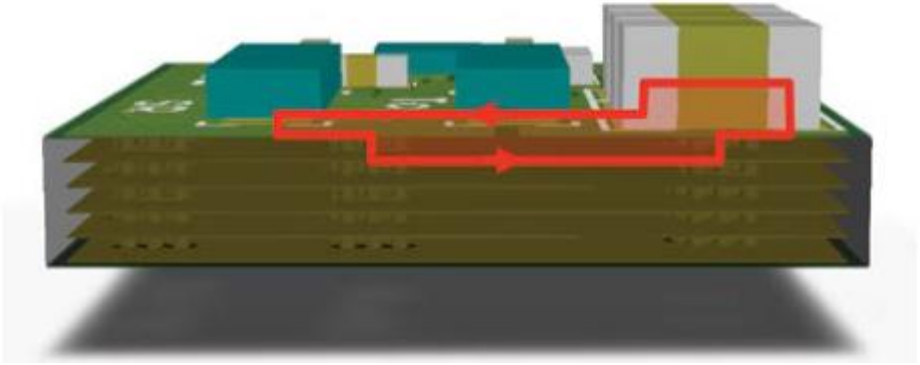
Layout – How?

- Layout options:
  - Optimal Power Loop
  - Top View, (a):
    - Current path is a straight line
    - But, what about return current?
  - First inner layer
    - Ground return
  - Side View:
    - Minimal loop lateral *and* vertical



(a)


(b)



app note link

Layout Comparison

Discrete GaN FETs:

- More difficult
- Power loop + gate drive loops
- Physical barriers to optimization

Monolithic ICs (EPC):

- Half Bridges:
  - Layout already done (internal)
  - Except decoupling caps (power + gate drive V)
- Single FET + Driver:
  - Gate drive loop internal

Module GaN:

- Between Discrete & IC
- Layout internal, but:
- Connections (bond wires, substrates, etc.)

Paralleling FETs Comparison

Discrete GaN FETs:

- Easy paralleling
- 1-2 series gate resistors per FET, at each FET

Monolithic ICs (EPC):

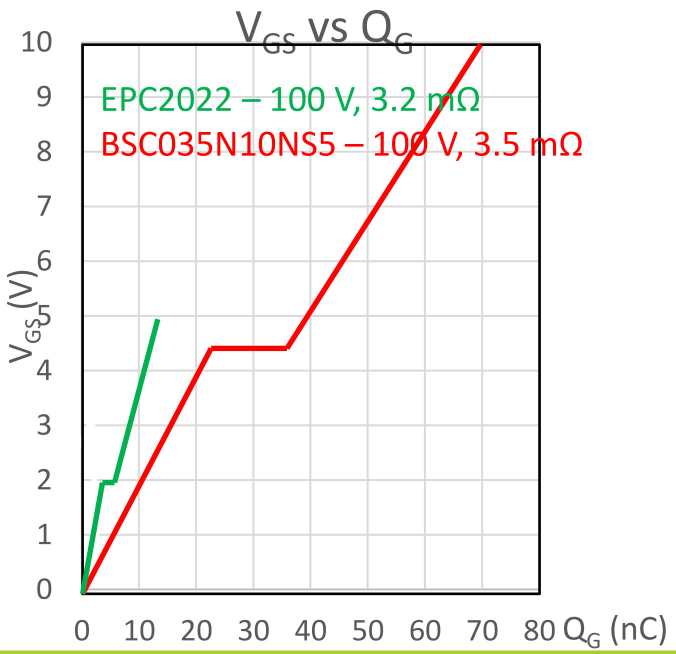
- Half Bridges:
  - Not recommended
  - Propagation differences
- Single FET + Driver:
  - Not recommended

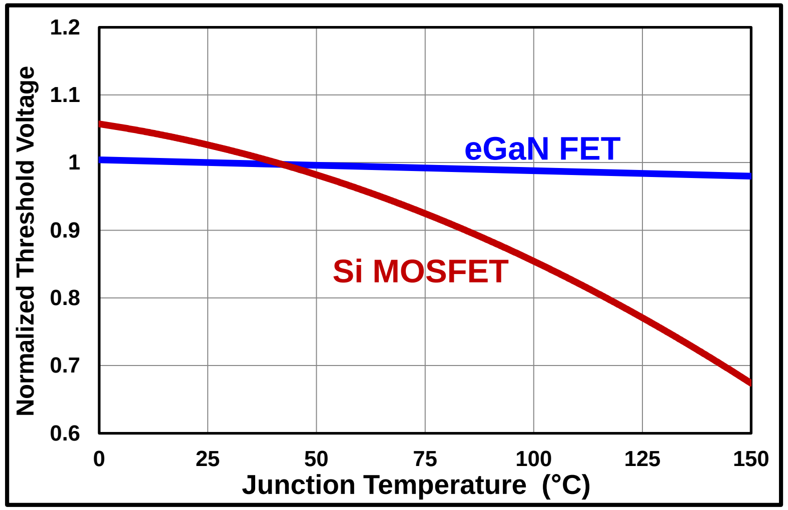
Module GaN:

- Paralleling in general not recommended
- See data sheet for each module

GaN FETs operate very well in Parallel

- Low gate charge: drive FETs in parallel from one gate driver
- Gate Threshold vs. Temperature: much better than MOSFETs
  - Hottest GaN FET does not turn on first; doesn't have more switching loss
  - App Note: AN020





Example: Motor Drive

GaN in motor drives: common myth

"There is no benefit to using GaN devices in BLDC Motor drives"

- GaN advantages in motor drives:
  - Smoother switching
  - Effect of the increase of PWM frequency
  - Effect of very small dead time
  - Application experimental results

GaN Benefits in BLDC Motor Drives

GaN FET/ICs switch fast with $Q_{RR} = 0$

Higher switching frequency

Electrolytic capacitor elimination
Reduced motor losses

Lower dead time

Higher torque per Ampere

Improves **inverter & motor** system **efficiency**
Reduces size & weight by integrating the inverter inside the motor

e-bike light load

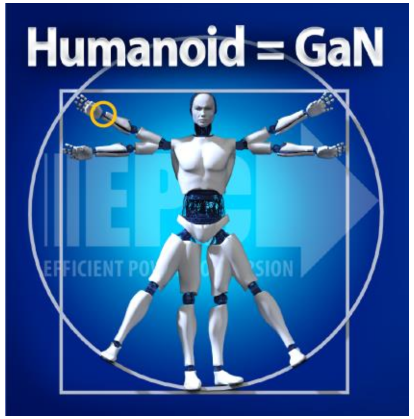
Setup	<u>MOSFET Inverter</u> 20 kHz, 500 ns dead time 400 RPM, 5 A_{RMS}	<u>GaN Inverter</u> 100 kHz,21 ns dead time 400 RPM, 5 A_{RMS}
Input Inductance	2.7 µH	None
Input capacitor	660 µF electrolytic	44 µF ceramic
P_{IN}	121.3 W	113.3 W
P_{OUT}	119.6 W	111.3 W
$\eta_{inverter}$	98.5 %	98.2%
Speed	42.25 rad/s	41.94 rad/s
Torque	1.876 N·m	1.940 N·m
Pmech	79.3 W	**81.36 W**
η_{motor}	66.3 %	73.1 %
η total efficiency	65.3 %	**71.8 %**

Example: Humanoid Robot

Usage Cases:

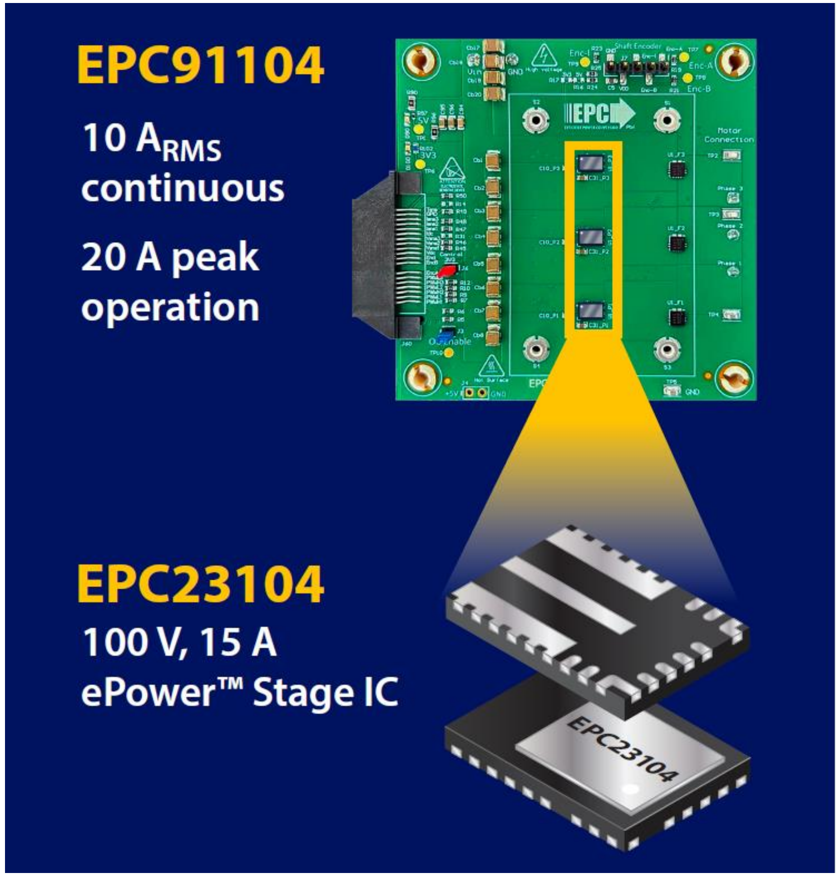
- Fingers
- Wrist
- Elbow, Knees
- Waist

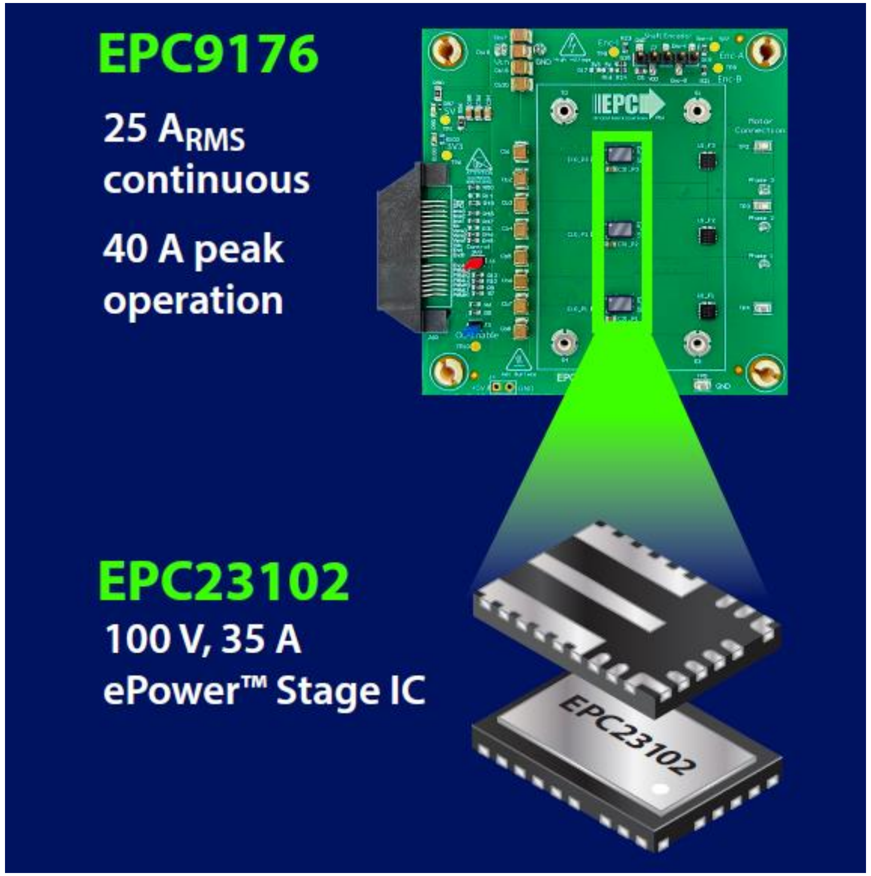
Humanoid Robots – lower power



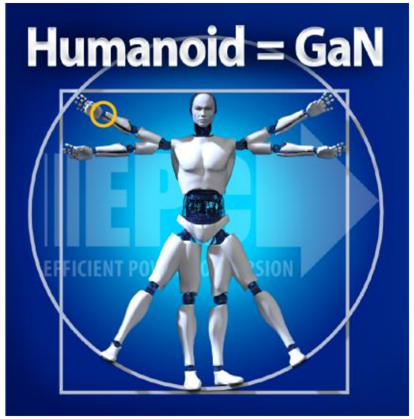
Usage Cases:

	Fingers	Wrist
	10 A rms	25 A rms





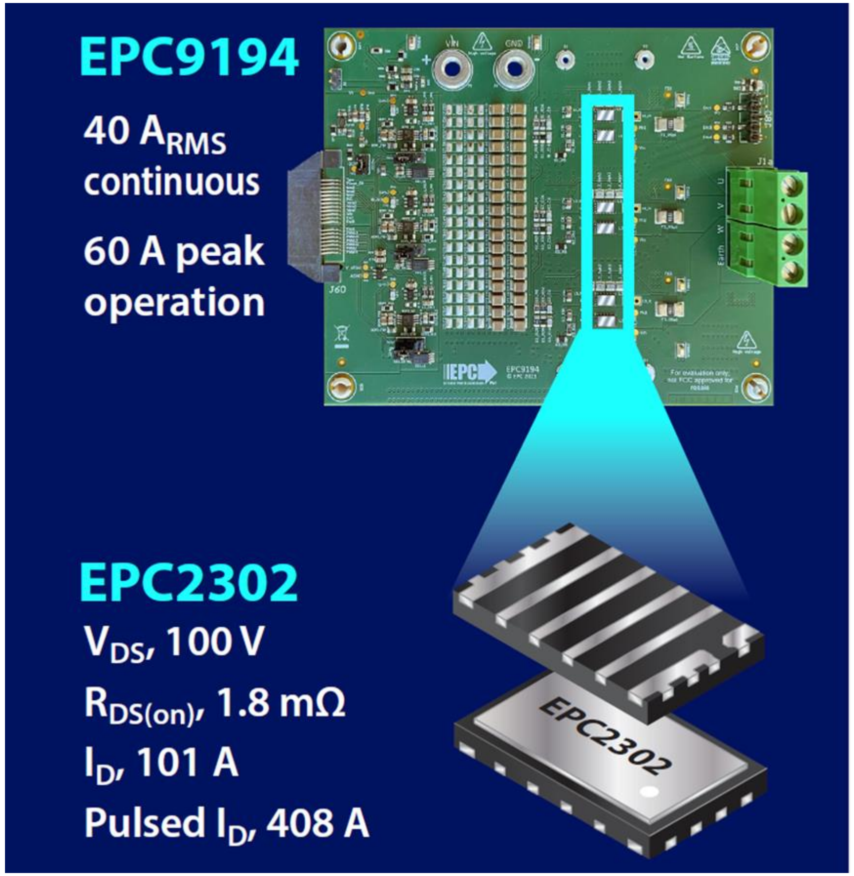
Humanoid Robots – higher power

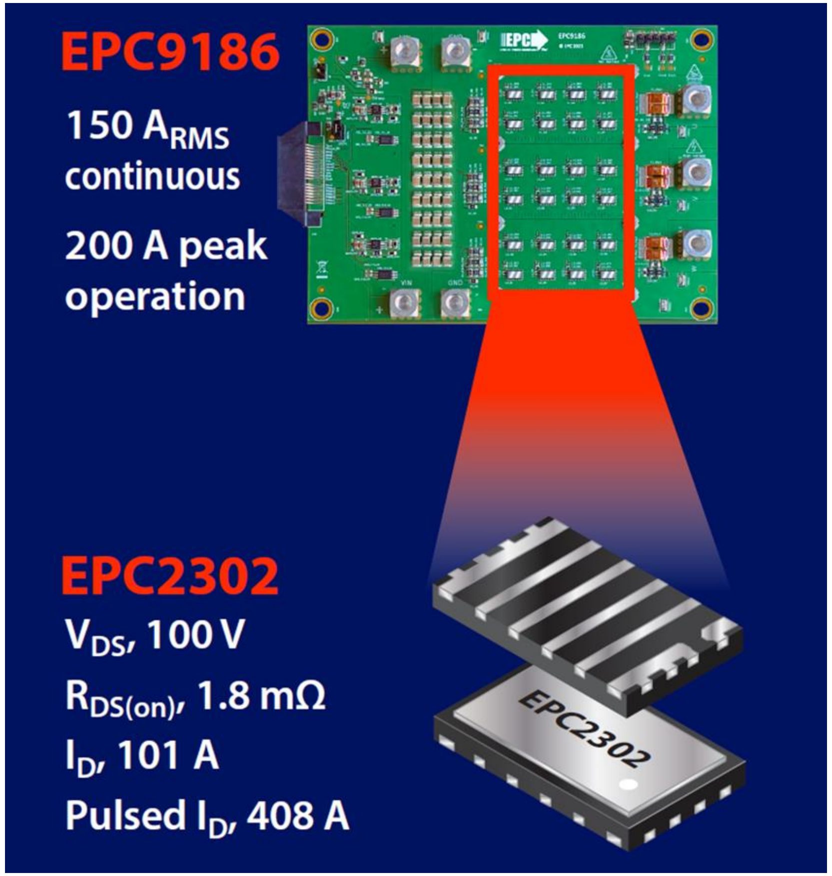


Usage Cases:

Elbow, Knees
40 A rms

Waist
150 A rms





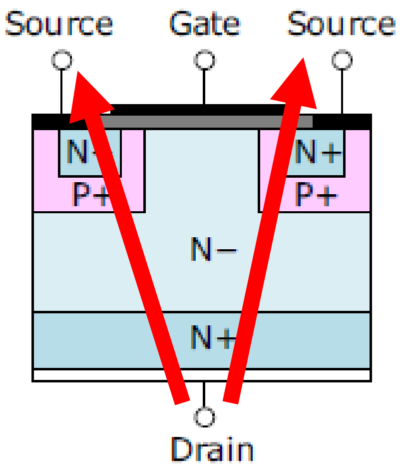
Extra: Bi-Directional Blocking GaN FET

IC in gate circuit…

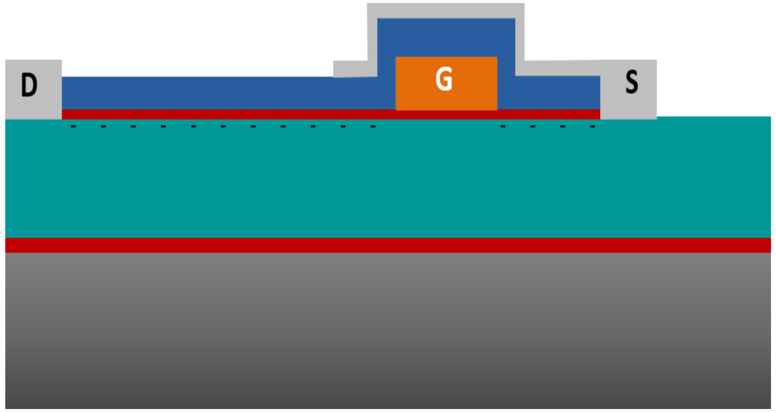
Bi-Directional Blocking GaN FET

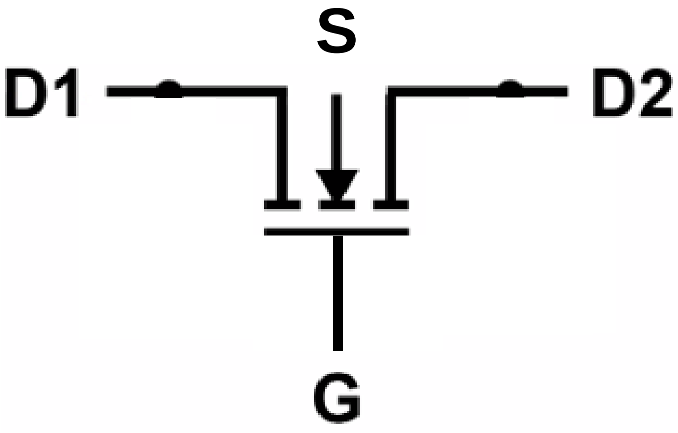
Back-to-back 100 V FETs:

- MOSFET: not easy…
  - Vertical current flow
  - Can't combine



- GaN FET: possible!



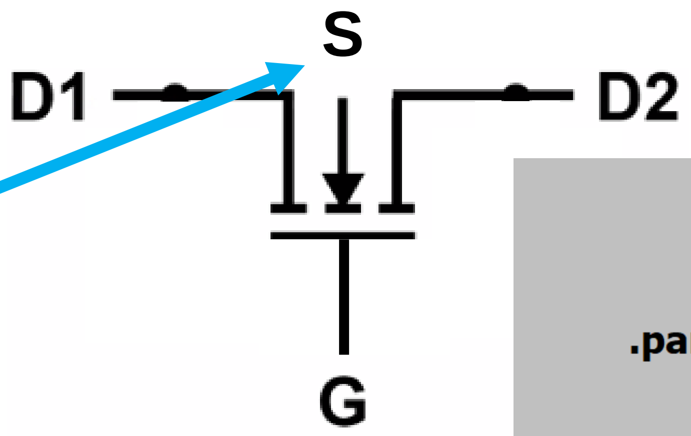


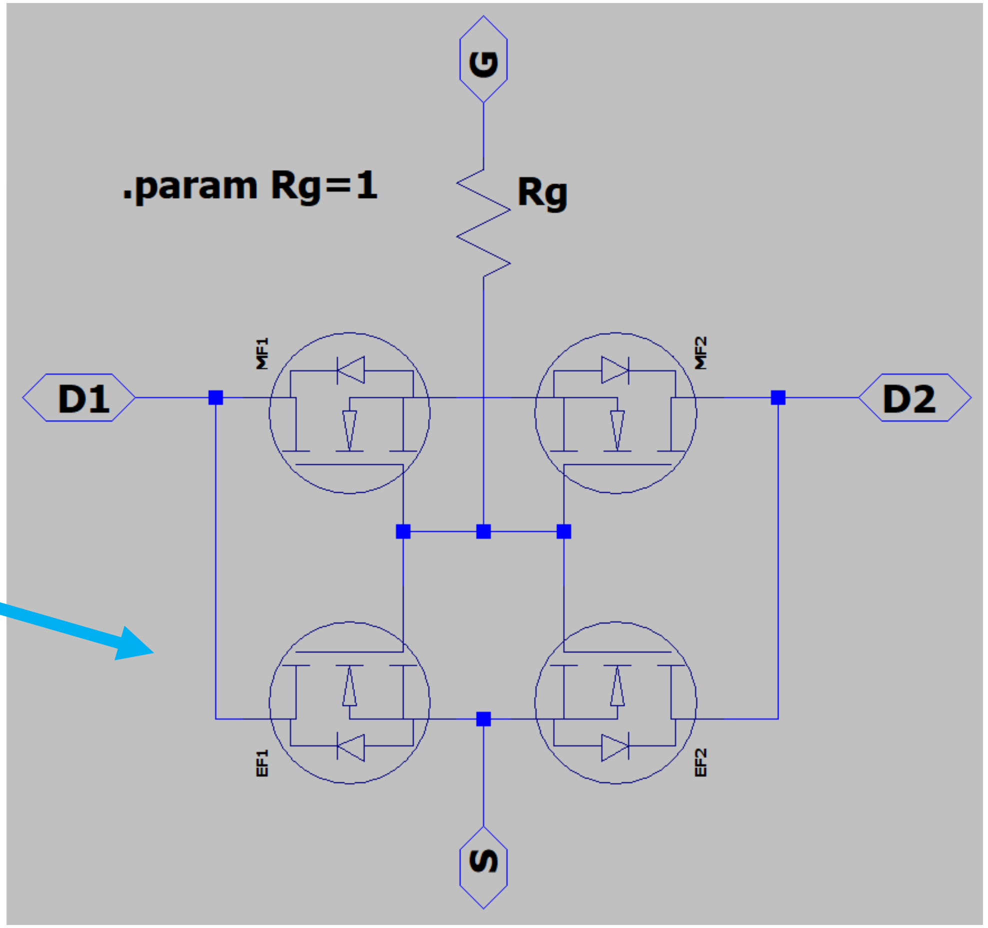
Bi-Directional Blocking GaN FET

Gate Return:

- Needed to drive
- “Source” = Gate Return
  - Not a power pin
- IC function used
  - Small FETs
  - to reference the “Source” to the lower-Drain
  - D1 or D2
  - (note: not 2 large FETs… model only)

- Reference: EPC2121



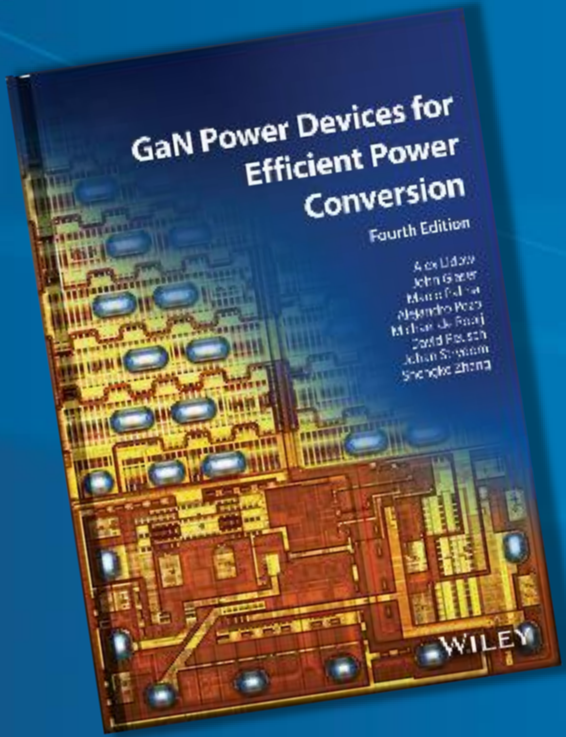


Summary

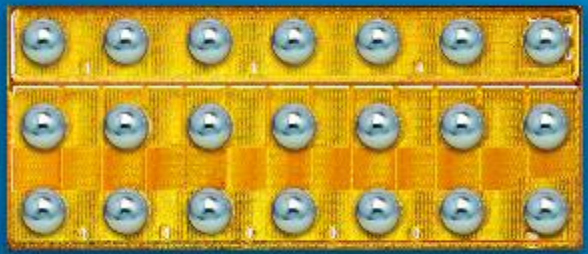
- GaN Technology has clear advantages for power electronics
- GaN available in a few forms
- Which is best? GaN ICs, GaN modules, or GaN discrete?
  - Application Dependent
  - Other factors: size, efficiency, cost, thermal, etc.
- Even a “discrete” bi-directional GaN FET benefits from IC technology
- Future: GaN ICs will continue to improve
  - FETs
  - Analog functions

Click on images to learn more

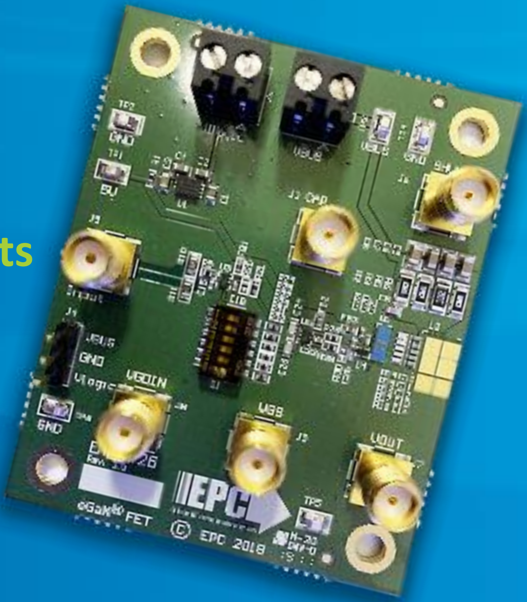
How To GaN Video Series



4th Edition Textbook



eGaN® FETs and ICs



Evaluation Kits

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