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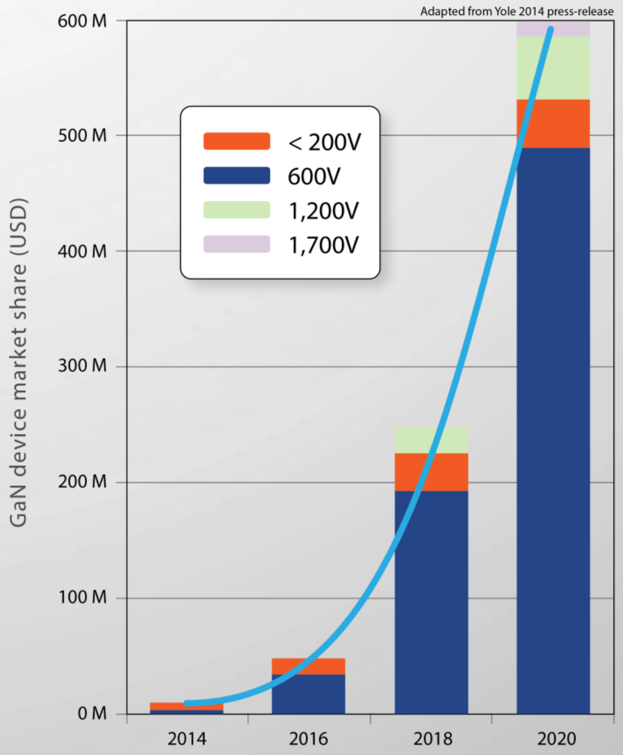
GaN Systems

Maximizing GaN Power Transistor Performance with Embedded Packaging

J. Roberts, CTO
GaN Systems, Inc.
1145 Innovation Drive, Ottawa, ON, Canada

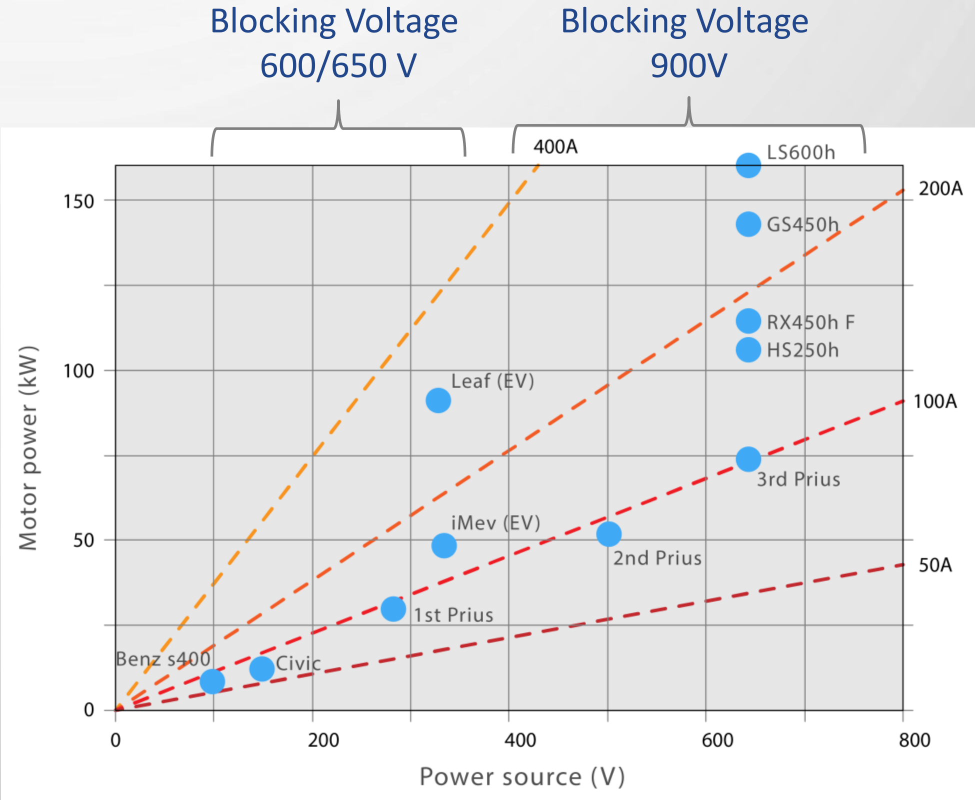
Market opportunities for GaN power transistors

- Very rapid sales growth is expected within the next five years leading to sales exceeding $500M by 2020
- Yole has published a market research report and press releases (June 2014) that identifies EV/HEV applications as being a key element of the market opportunity
- According to Yole the "*Ramp-up will be quite impressive starting in 2016, at an estimated 80% CAGR*"



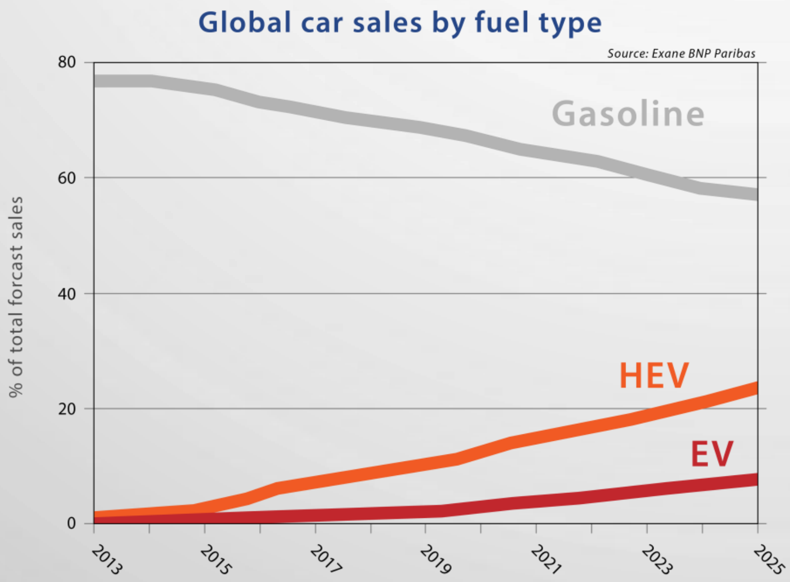
Motor power and source voltage for electric vehicles

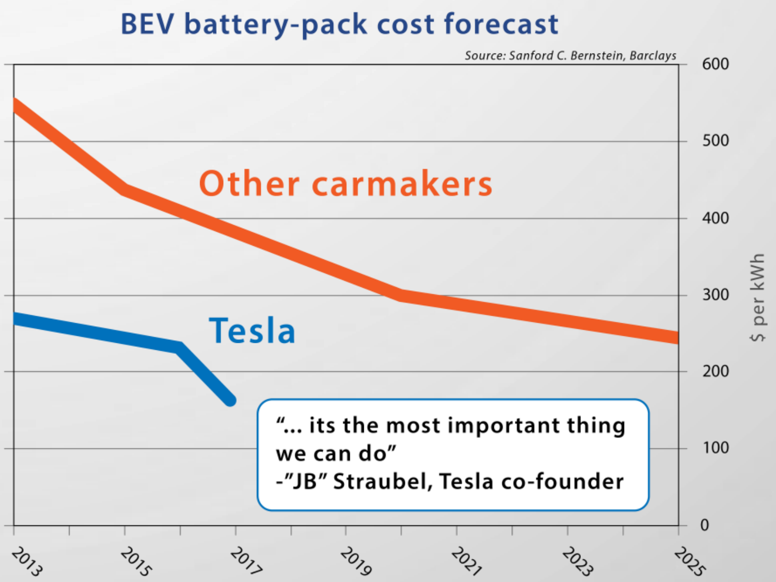
- 650 and 900 V devices are required by 2 level inverters
- IGBT devices currently used
- SiC and GaN are regarded as potential replacements
- 650 V GaN – 3 level inverter, high performance, low-cost, the best choice for 900 V operation at present
- 900 V SiC MOSFETs will be expensive and are difficult to protect and drive
- IGBTs too inefficient



T. Kachi, et al "GaN Power device and Reliability for Automotive Applications" Reliability physics Symposium (iRPS) 2012.J.

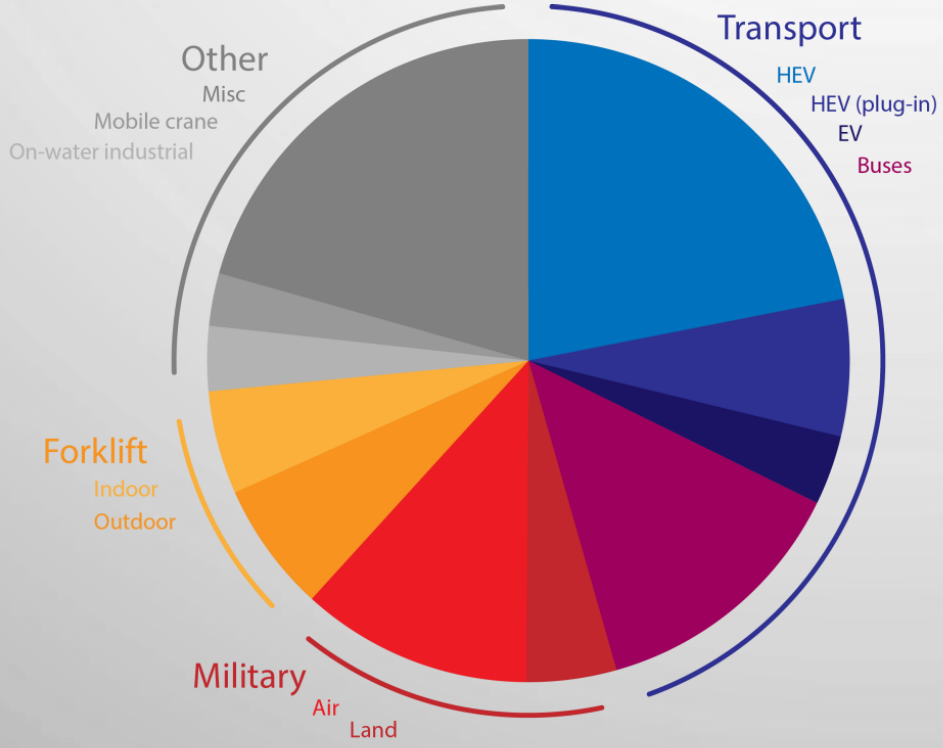
Annual Production 30 Million EV/HEV Cars by 2025





- Battery costs determine EV/HEV sales and the growth potential
- High volume production allows price to fall below 400 USD/kWh
- EV/HEV combined sales predicted to reach 30 % of market by 2025
- Result – production exceeds 30 Million EV/HEV cars per annum by 2025!?

Relative value of EVs in 2014 by application sector



- Light EV/HEV vehicles will constitute 32% of the market by 2025
- Other ‘electric vehicle’ markets are also expected to be substantial, but diverse
    - Busses: 13%
    - Military: 16%
    - Forklift: 15%

Adapted from IDTechEx

Fleet Emission Demands

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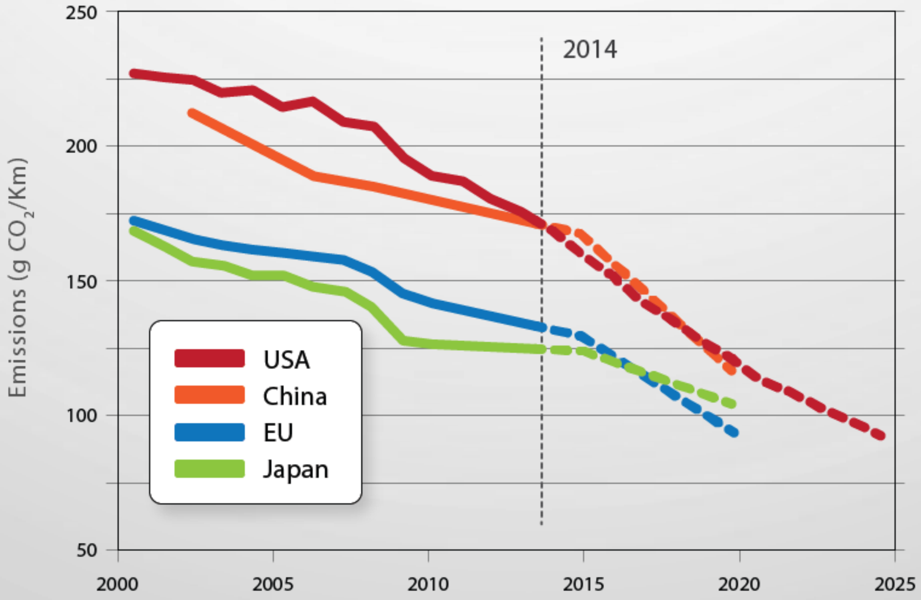
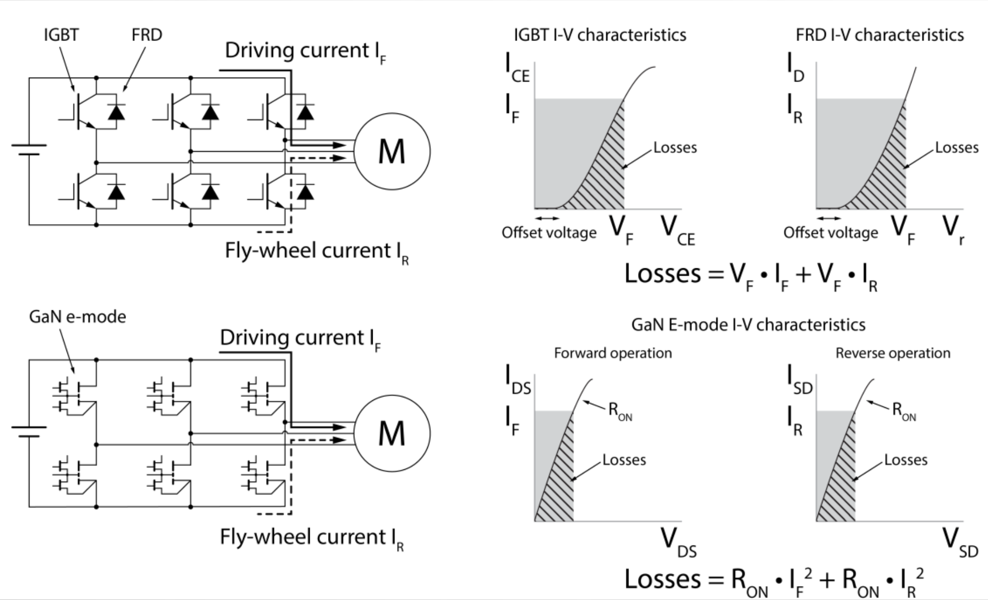
Adopted from: S. Araujo, et al. P1033, PCIM Europe 2014



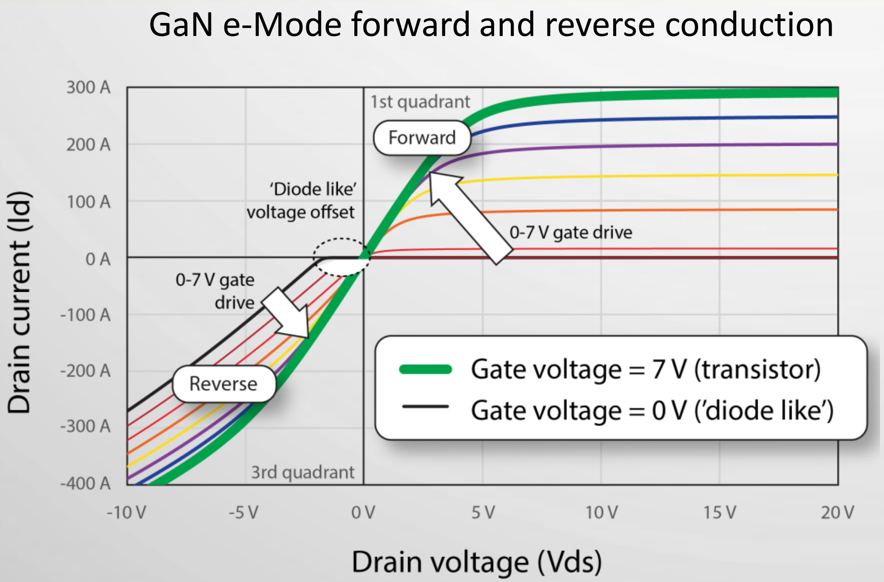
- Strict CO_2 fleet emission pressures are being placed up on the automotive industry
- Critical need to reach 95 gCO_2/km by 2020/2025
- Move to introduce EV/HEV models more rapid than expected

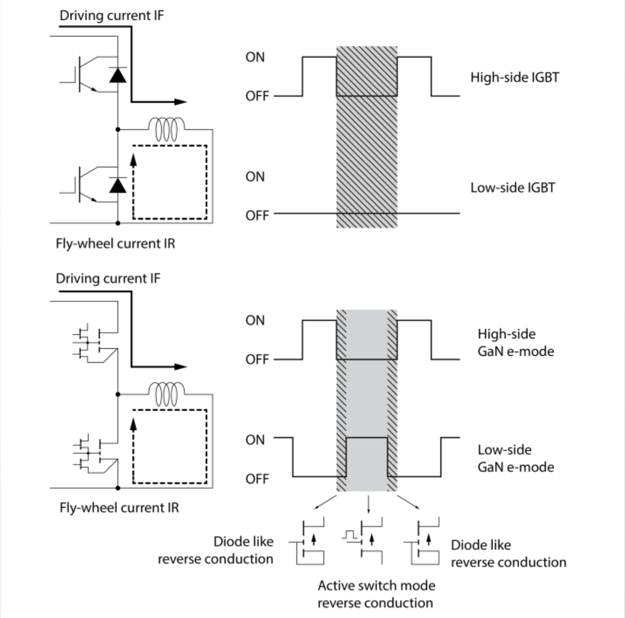
Traction Inverter: GaN e-Mode vs. FRD - IGBT



- Traction Inverter Semiconductor Modules account for 30% of total cost of the unit - the Inverter is the second most expensive component after the battery pack
- GaN e-Mode has lower losses due to the absence of the Offset Voltages of the Fast Recovery Diodes and IGBTs
- Lower losses lead to reduced cooling system costs
- GaN e-Mode system allows smaller battery packs to be used

GaN e-Mode Reverse Conduction Advantage





- Reverse conduction is an intrinsic operational capability of an GaN e-Mode – no Fast Recovery Diodes are required
- When the GaN e-Mode active switch mode is used, as shown, very low losses are achieved because the 'diode like' offsets are eliminated

IGBT vs. GaN Loss Simulation 600/650V – 100A/400A

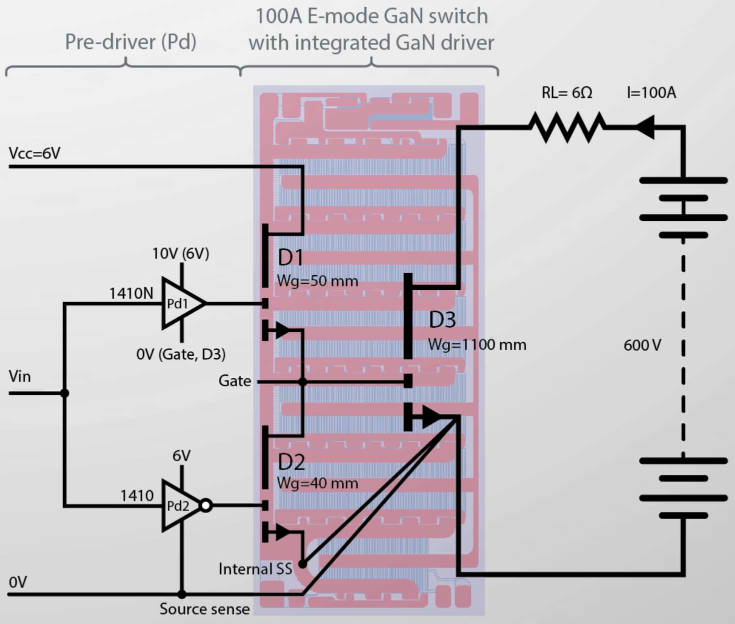
Adopted from: C. Assad, et al. CIPS 2012

25°C, 400A Typ. values	IGBT	GaN/Si Sim.	
V_{on} (V)	1.45	0.4	Voltage drop at full load 400A
P_{on} (W)	580	160	Conduction loss at full load
E_{off} (mJ)	13	0.25	Switching off energy
E_{on} (mJ)	2.9	0.42	Switching on energy
V_F (V)	1.55	0.4	Forward voltage drop (reverse current)
P_{VF} (W)	620	160	Reverse conduction loss
E_{REC} (mJ)	3.6	0.9	Reverse recovery loss
V_{on}@ 100A (V)	1.0	0.1	Voltage @ 25% load
P_{on} @ 100A (W)	100	10	Conduction loss @ 25% load

- IGBT/FRD offset voltage greatly effects losses achieved at typical 100A running current
- Four parallel connected GaN e-Mode devices each 650V/4mΩ provides a 1mΩ on resistance a 10 to 1 improvement in power loss

GaN transistor with on-chip driver

- The GaN device can be built as a very large integrated single structure whereas the IGBTs usually are paralleled devices within a module which uses an external driver
- The GaN device shown is a 100 A/650 V design that includes an on-chip driver and it includes a yield enhancement scheme
- This device is a first step towards a totally integrated very large 400 A integrated GaN structure



Embedded GaN-on-Si Devices

The laminate packaged device shown is a 650 V - 50 mΩ GaN-on-Si e-mode transistor.

The embedded lateral GaN devices have the smallest parasitic elements and the package interconnect significantly supplements the current carrying capacity of the GaN die.

Device design strategies

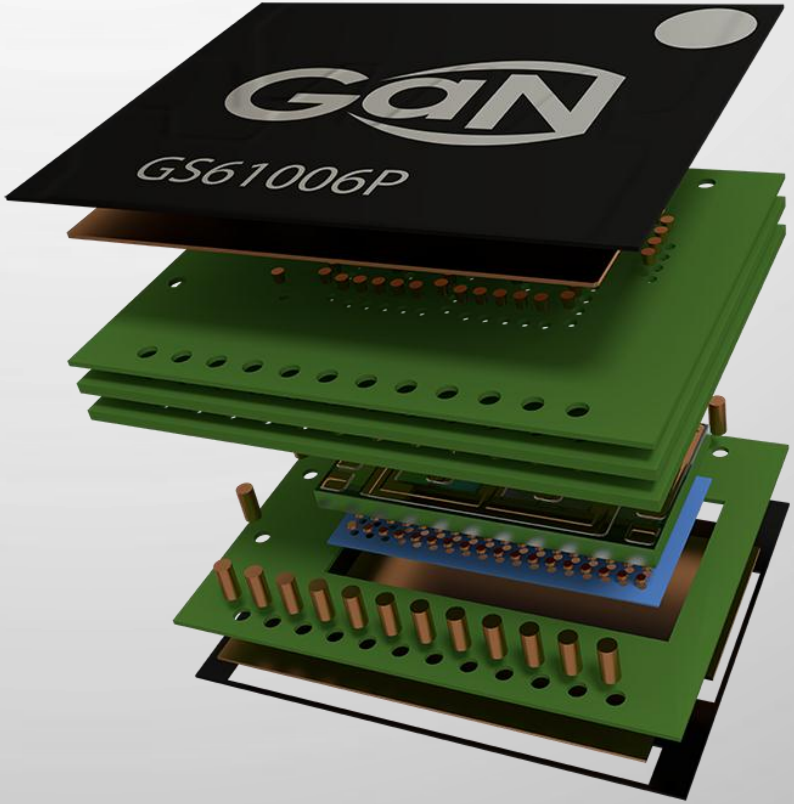
GaN*PX* embedded packaging cross-section

Superior inductance, current handling, and thermal performance

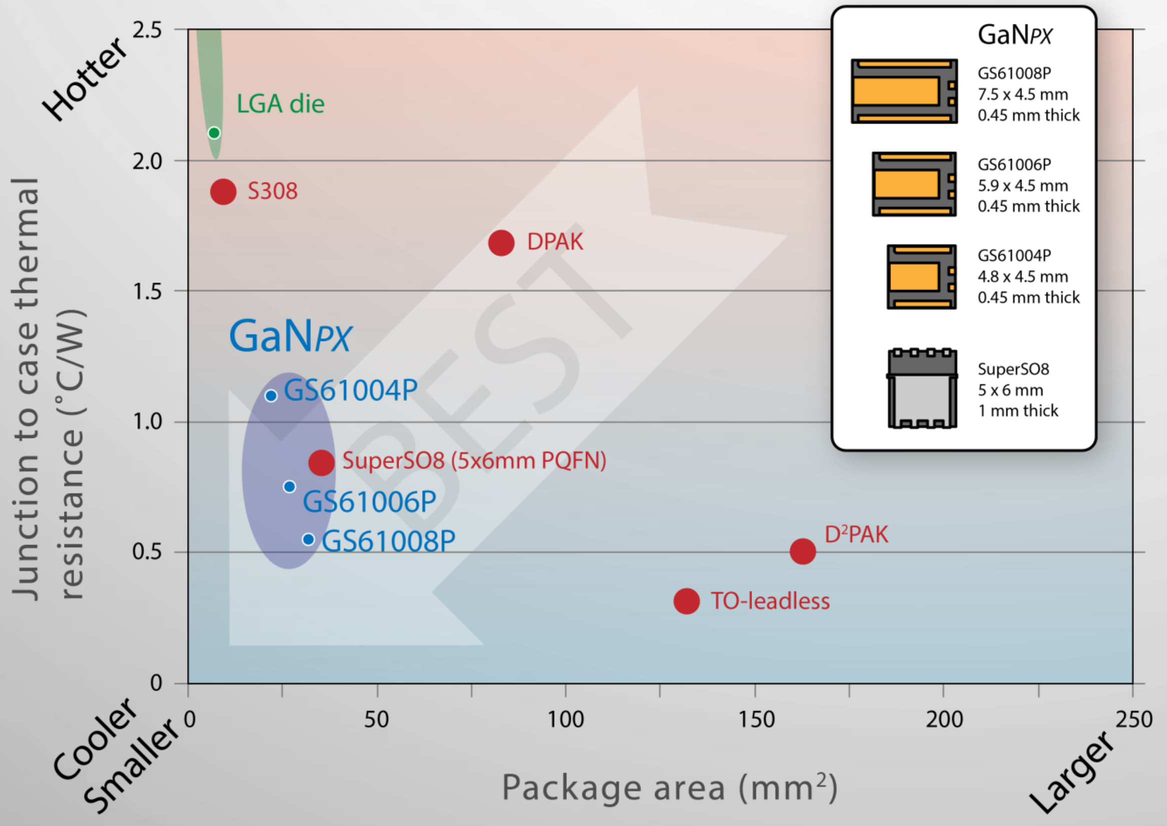
Embedded device structure

- The embedding technique has completely removed any electromigration concerns because the package metal augments the RDL and on-chip metal.

- The total metal thickness exceeds 30 microns and the critical width is more than 5 times larger.



Performance comparison



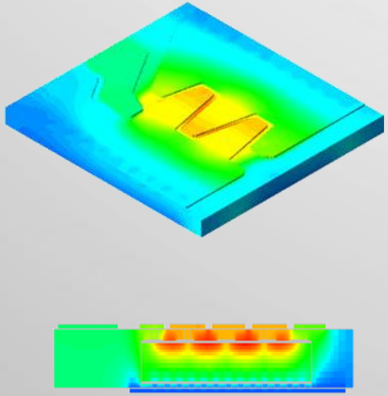
Benefits of GaN*PX* packaging

- Superior in terms of area and thermal resistance
- Best package figure of merit (°C/W * mm^2)
- Less than half the volume of the SuperSO8

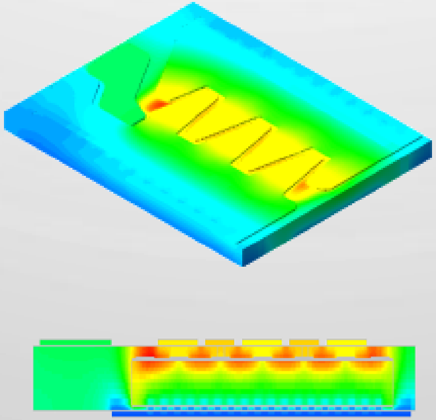
Smaller and provides excellent thermal performance

Thermal simulation: Junction-to-case thermal resistance

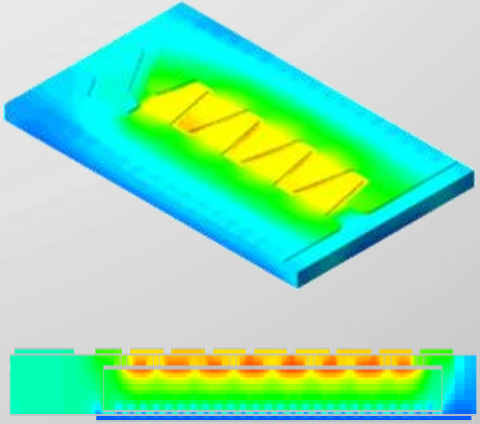
Bottom-side cooled package comparison



1.1 °C/W

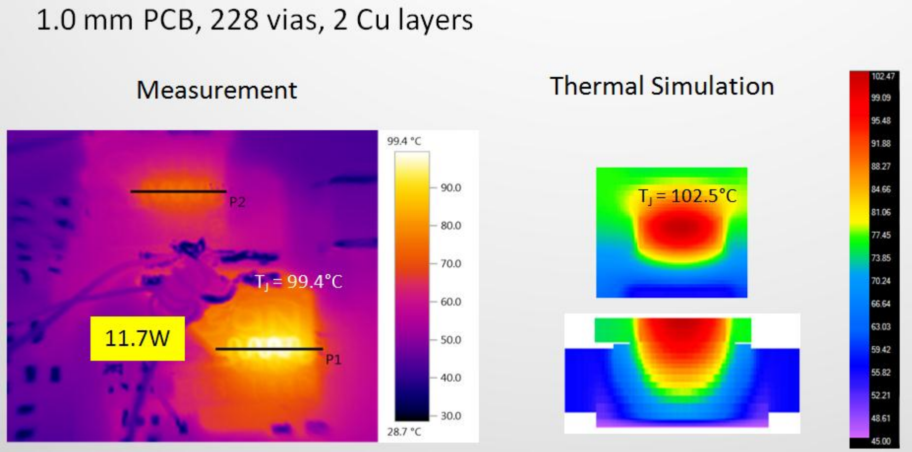


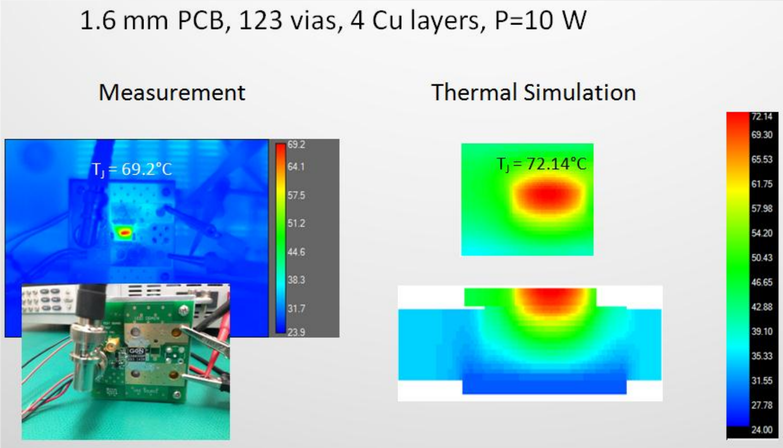
0.75 °C/W



0.55 °C/W

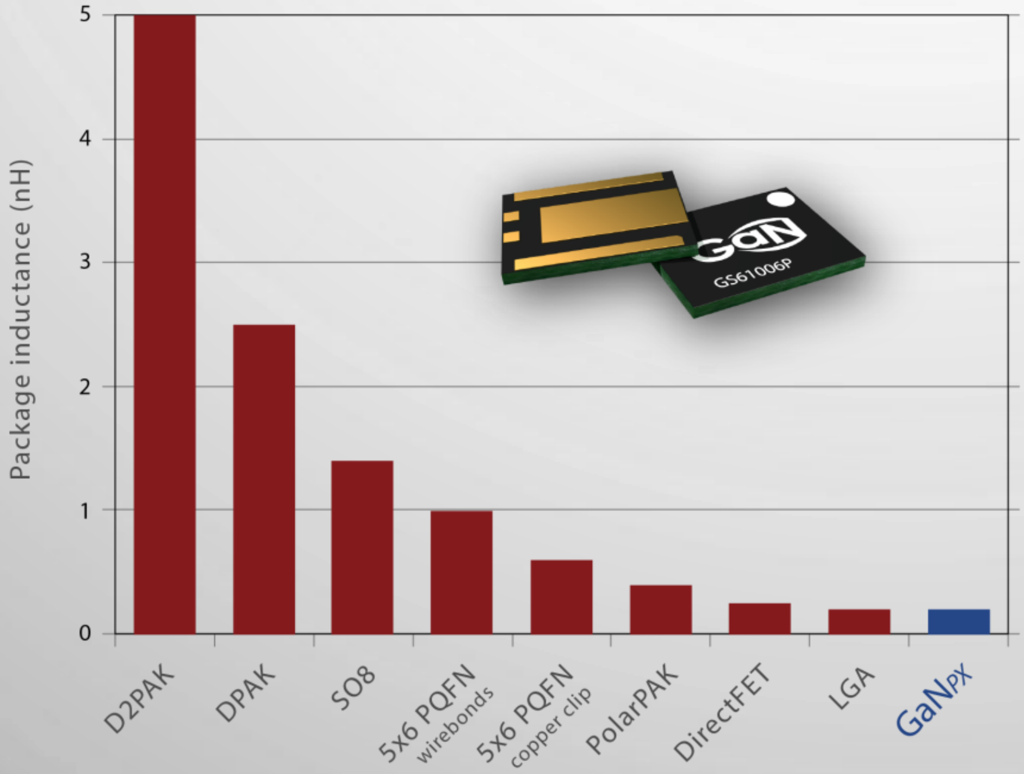
Measurement and Thermal Simulation Results Comparison





- Good agreements between the measurement and the thermal simulation results were obtained
- Thermal simulation predicts slightly higher junction temperature (~4%)
- The thermal camera measures the average temperature, the temperature from thermal simulation is maximum temperature

Performance comparison – Package inductance



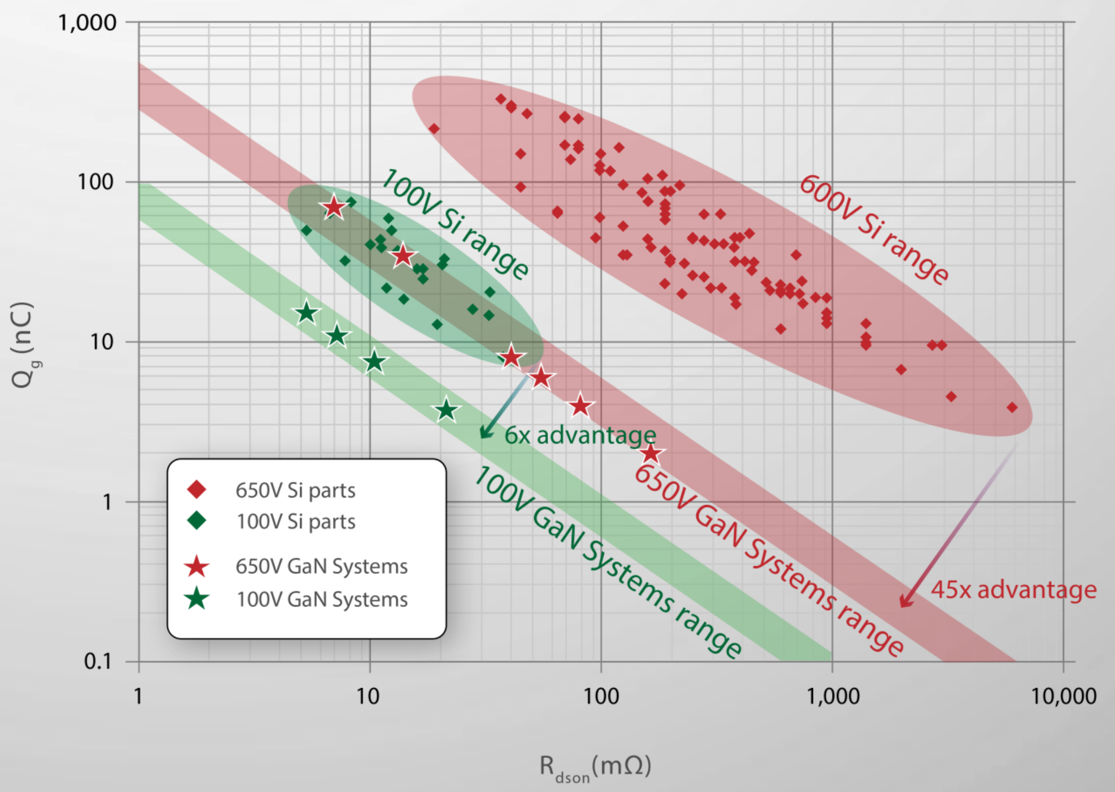
Benefits of low inductance packaging

- Vital requirement for lowest losses
- Lowest EMI
- Minimal voltage overshoot
- Simplifies gate drive
- Faster operation

GaNPX inductance is as low as an unpackaged part (LGA)

Performance comparison: R_{ON} & Q_G

- GaN transistors have lower switching charge requirements than SJ MOSFETs for a given specified on-resistance and blocking voltage
- Cascodes and SiC devices have lower performance
- Embedded E-mode devices have superior R_{ON} & Q_G performance



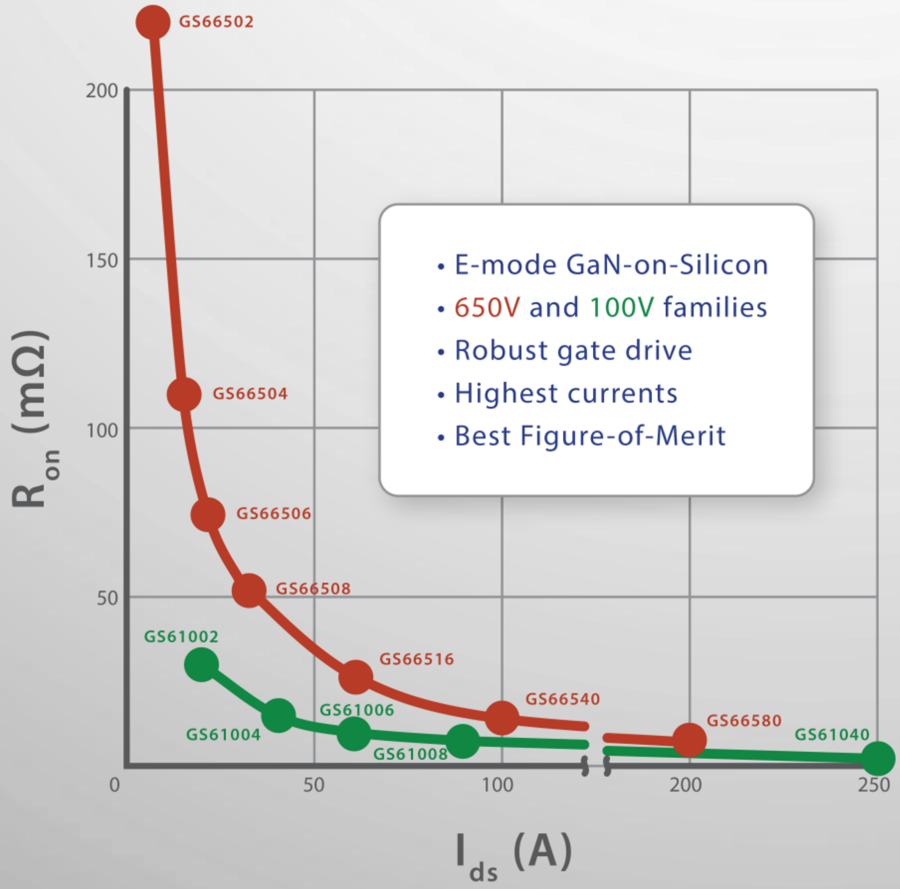
600/650V Device Comparison

Parameter	GaN e-Mode	GaN Cascode	Si MOSFET	Si/FRD IGBT
FOM: $Q_G \cdot R_{on}$ (pC·Ω)	375	1,400	10,000	17,000
FOM_{HS}: $(Q_{GD}+Q_{GS2}) \cdot R_{on}$ (pC·Ω)	185	550	4,400	7,300
$Q_{RR\ DIODE}$ (400A) (nC)	0	2,000	190,000	6,000

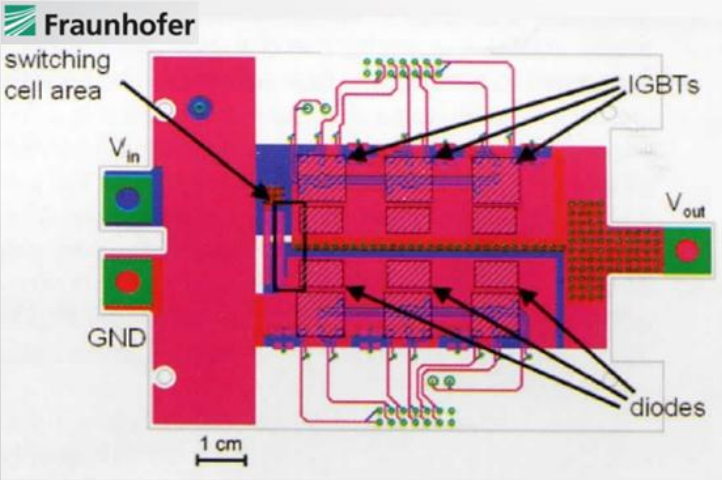
1. GaN e-Mode FOM is:
   - 3 - 4 times better than Cascode
   - 25 - 30 times better than MOSFET
   - 40 - 50 times better than FRD/IGBT
2. GaN e-Mode Hard Switching FOM is:
   - 2 - 3 times better than Cascode
   - 20 - 30 times better than MOSFET
   - 30 - 40 times better than FRD/IGBT
3. GaN e-Mode has no diode charge storage losses!

Power transistor product family

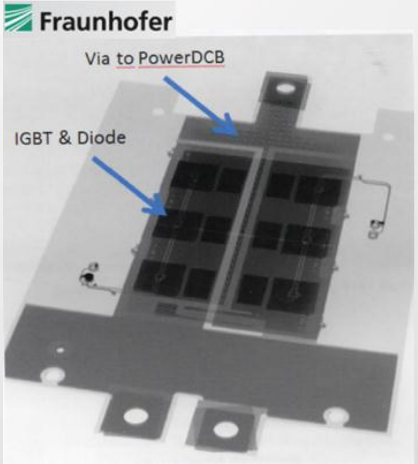
- E-mode GaN-on-Silicon
- 650V and 100V families
- Robust gate drive
- Highest currents
- Best Figure-of-Merit



System Embedding for Automotive Inverters



PCB layout 10kW system



X-ray picture of the 10kW module

- 10kW IGBT Embedded design has forced cooling
- 10kW GaN Embedded design can be finned HS cooled
- Future - Embedded 50kW module

Source: Advancing Microelectronics (IMAPS), JAN/FEB 2015, vol. 42, No.1

Conclusion

GaN Systems

- The embedded lateral GaN devices have the smallest parasitic elements and the package interconnect significantly supplements the current carrying capacity of the GaN die
- Superior in terms of area and thermal resistance
- Best package figure of merit (°C/W * mm^2)
- GaN*PX* inductance is as low as an unpackaged part (LGA)

Thank you for your attention

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1^{st} GEN. GaN e-Mode vs. 5^{th} GEN.IGBTs

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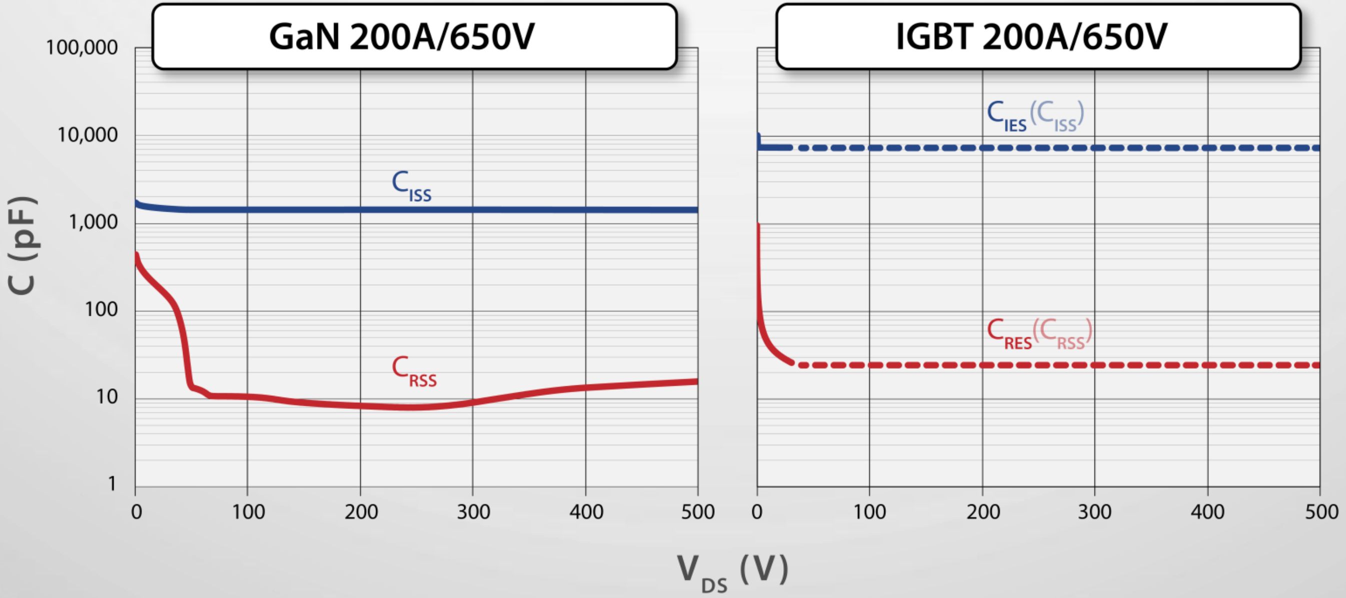
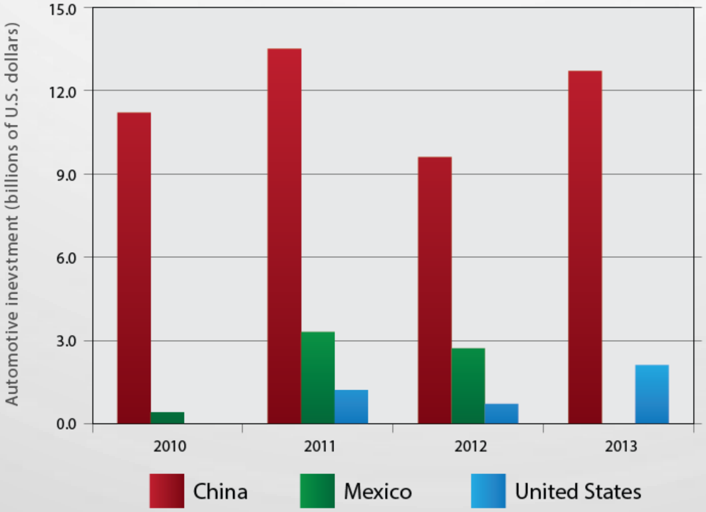


- Capacitances: C_{ISS} - 5 times lower , C_{RSS} - 2 times lower
- Total Gate Charge 40 vs. 300 nC
- Gate Voltage Swing 6 vs. 15 volts
- GaN device has integrated driver

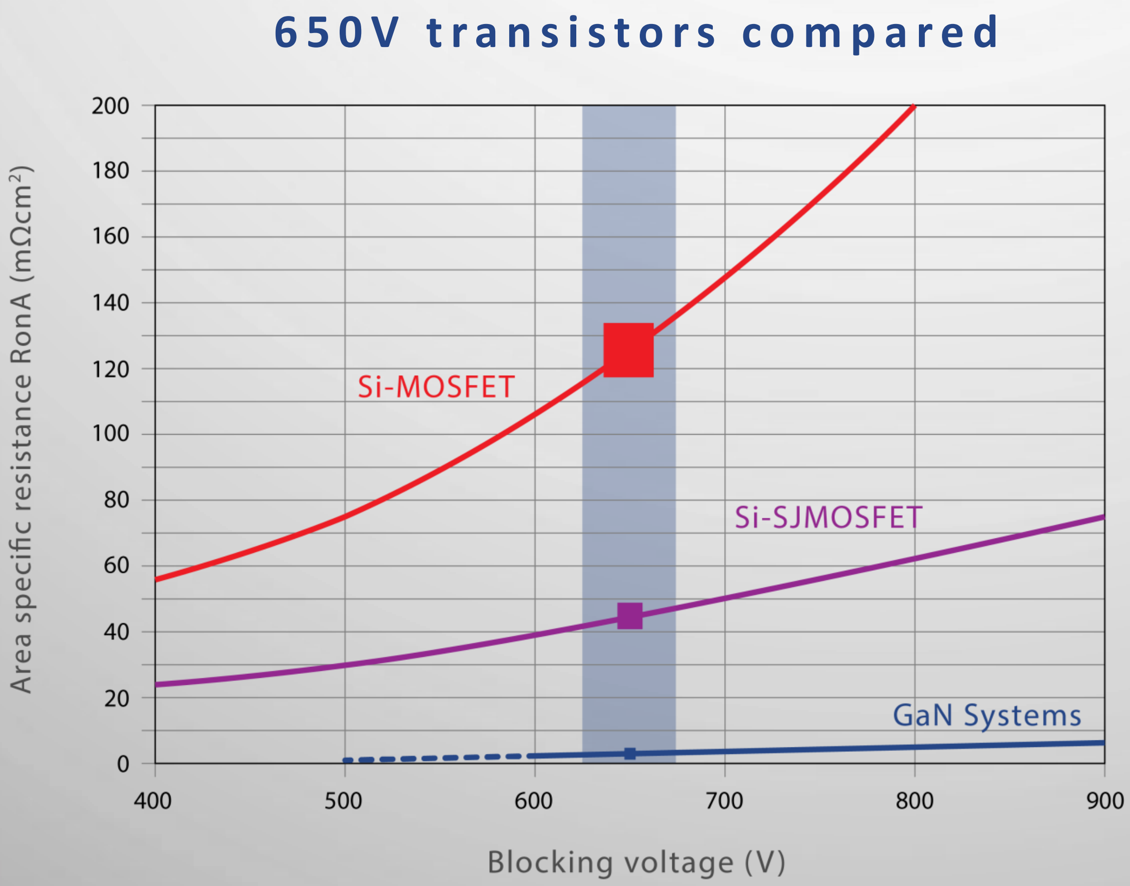
Automotive Investment

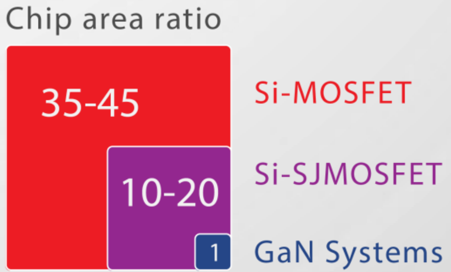
Data: Office of Automotive and Vehicle Research – Windsor U/G&M, April -2014



- Automaker spent $17.6 billion (US) around the world in 2013 to increase vehicle-making capacity
- In the past four years China spent $46.9 billion, Mexico spent $6.3 billion
- Even before 2010 transportation counted for 27% of total “end-use” energy and road vehicle CO_2 emission reached seven gigatons!!!

GaN - chip size advantages





- Chip area typically 40 times, and 15 times, smaller than Si-MOSFETS and Si-SJMOSFETS respectively for the same R_{ON}
- Smaller chip size reduces gate charge Q_G and capacitance