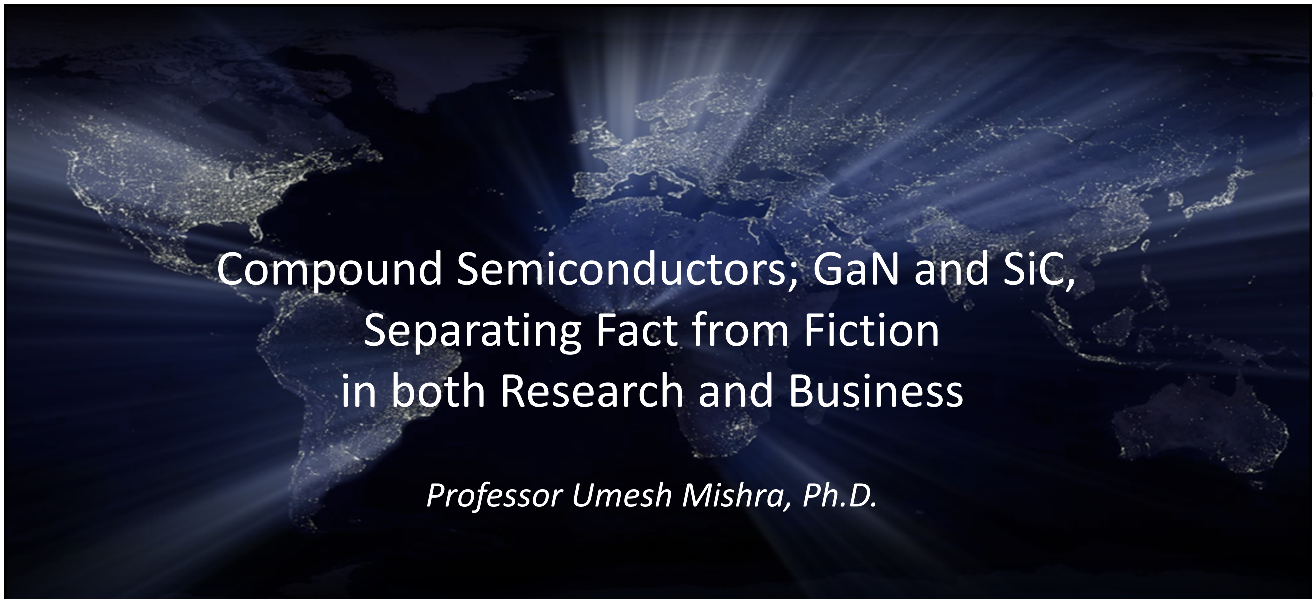

Compound Semiconductors; GaN and SiC, Separating Fact from Fiction in both Research and Business

Professor Umesh Mishra, Ph.D.

Redefining Energy Efficiency

APEC transphorm

Compound semiconductors – separating *Fact* from *Fiction*

- Why do we need a new technology?
- What technologies are possible?
- What are the relative merits of SiC and GaN?
- Performance of GaN vs. SiC

2

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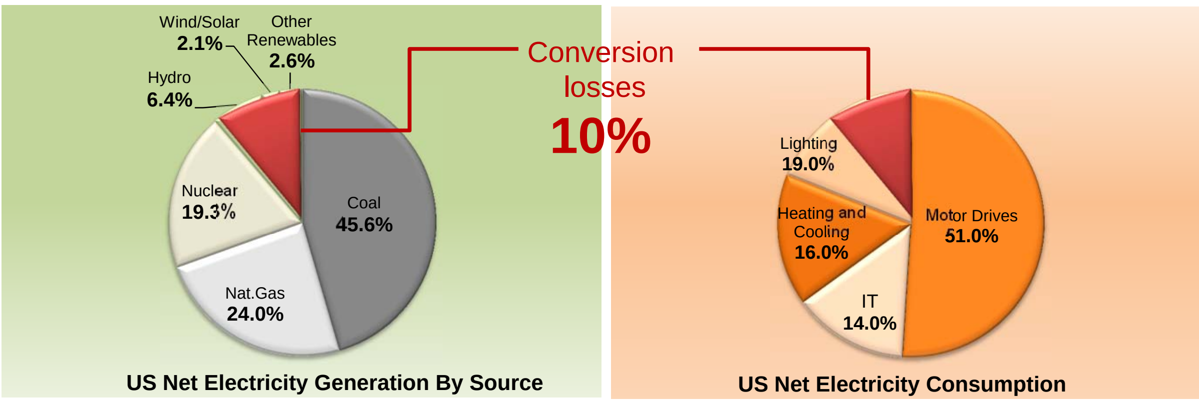
New Solutions Needed to Meet Growing Energy Demands

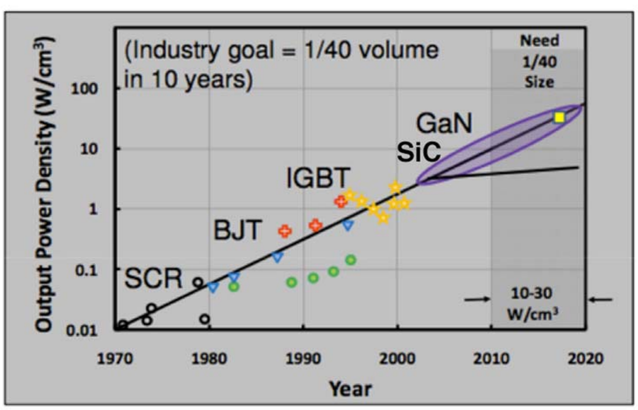


Source: EIA (Energy Information Administration)

Source: EPRI, E-Source and Exxon Mobile

So what is the issue with Silicon?

Industry Power Density Roadmap



- Silicon has provided us the pathway for power conversion solutions for several decades but has now reached its physical limits
- GaN and SiC open new possibilities

4

New material options to keep us on the power density roadmap

- **SiC -** established in the market as a high performance diode; released as JFETs and MOSFETs (target application space 1200V)
- **GaN on Si -** high performance solution with a roadmap to low cost for diodes and transistors
- **GaN on SiC -** higher cost solution for applications demanding higher performance with reduced sensitivity to cost
- **GaN on GaN -** early stage of development
- Gallium Oxide - very early stage
- Diamond - out there

APEC 5 transphorm

How can a new technology penetrate a market dominated by Silicon?

- Have material properties far superior to that of Silicon
  - Not just one product but providing a sustained roadmap to develop a new standard in power conversion
- Provide a solution in an existing market that Si cannot provide
  - Compound semiconductor devices
    - Diodes (SiC and GaN)
    - Transistor (SiC and GaN)
    - Novel transistor packaging (Quiet Tab™)
- Provide a cost advantage in an existing market
  - System solutions at cost parity or cheaper than Si-based solution
    - Reduced components (diode-free bridge operation)
    - Efficient high frequency operation
      - small mechanical and electrical size
- Create a new market

APEC 6 transphorm

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APEC 7 transphorm

Comparing Si, SiC & GaN Semiconductors

- GaN and SiC offer:
  - High breakdown field
- GaN offers:
  - High mobility
- SiC offers:
  - High thermal performance

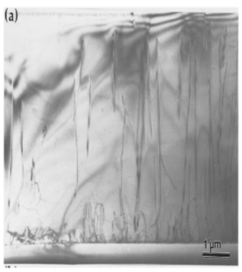
	Si	4H-SiC	GaN
E_g (eV)	1.1	3.2	3.4
E_{bk} (10^5 V/cm)	3	21	21
v_s (10^6cm/s)	6	9	12
μ (cm²/Vs)	1000	500*	2000
k (W/mºC)	150	450	130
$(E_{bk}v_s/\pi)^2$	1	110	140
μE_{bk}^2	1	25	98

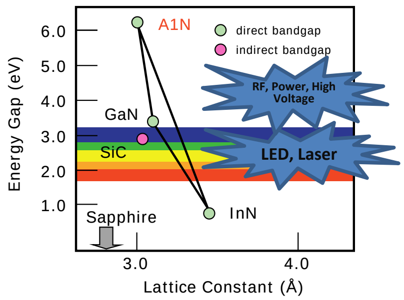
** Inversion layer: <100; drift 1000*

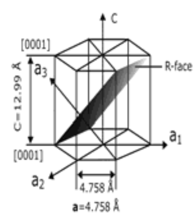
APEC 8 transphorm

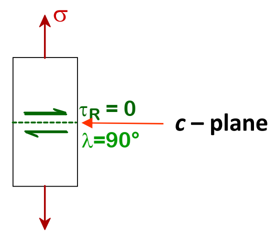
Why is GaN so remarkable?

- GaN is a direct bandgap material; It emits light from a dislocated material !
- Basis of a $10B LED industry today **(who would have thought?!!)**
- GaN is the wide band gap solution for next generation RF wireless base stations and military RADAR ; chosen over dislocation free SiC MESFETS **(who would have thought?!!)**
- The tight lattice and no shear stress to move the dislocations makes GaN almost insensitive to dislocations compared to SiC and other compound semiconductors









NO shear stress exists for *c*-GaN !

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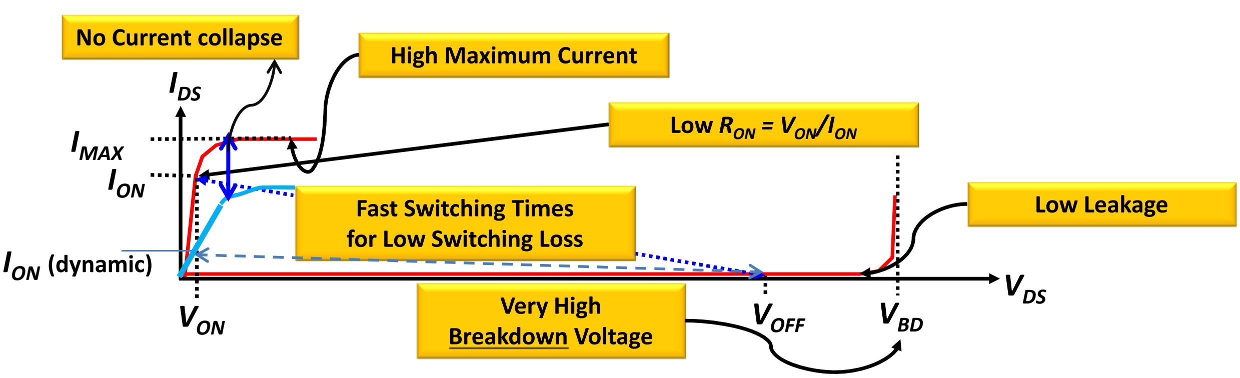
The heart of all power conversion unit is a "SWITCH"



Total Loss of a switch= conduction loss + switching loss

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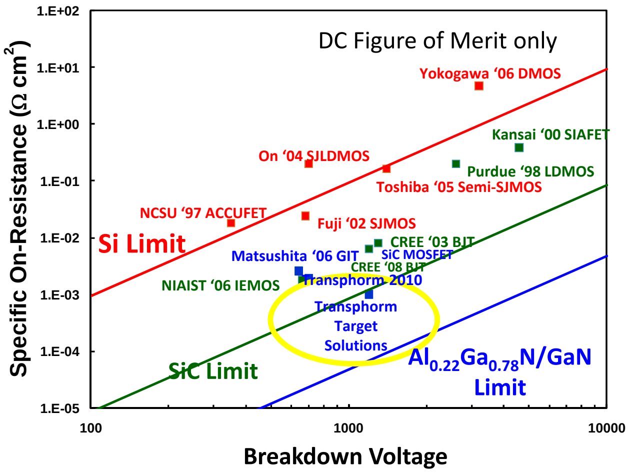
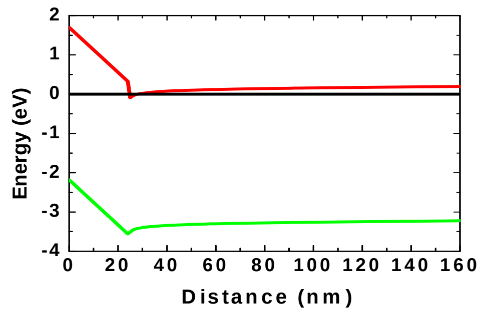
GaN –Switch gives the lowest conduction loss

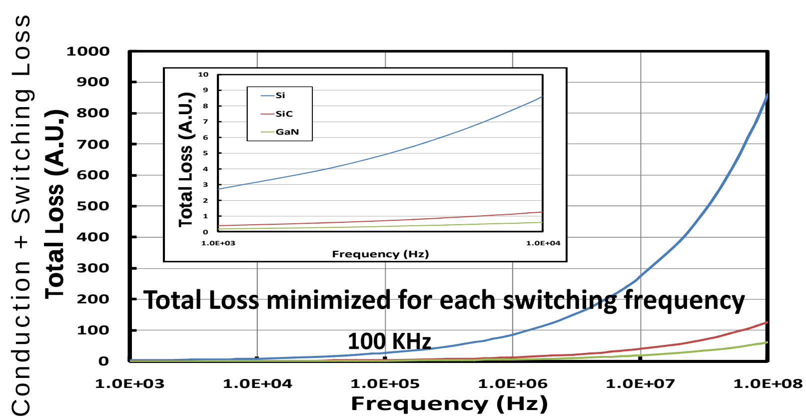




Channel with High $n_{s,}$ m → Low R_{on} → Low conduction loss
Wide band-gap → High Critical Field, High Breakdown Voltage, High Temperature Stability

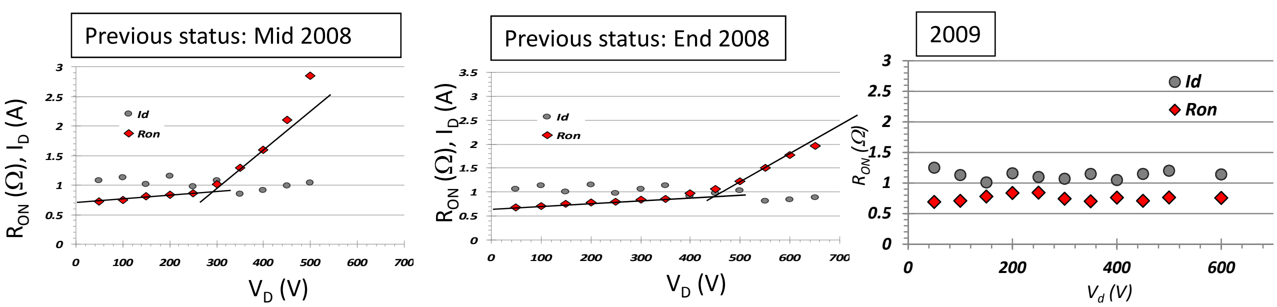
GaN enables high frequency operation with low switching loss

- 2x advantage over SiC
- 14x advantage over Si
- 5x advantage over Si Superjunction



Transphorm Improvements in Dynamic Performance of GaN

- Direct relation to performance in real world applications
- Major benchmark for success in GaN power devices
- Extracted from converter circuit



How can a new technology penetrate a market dominated by Silicon?

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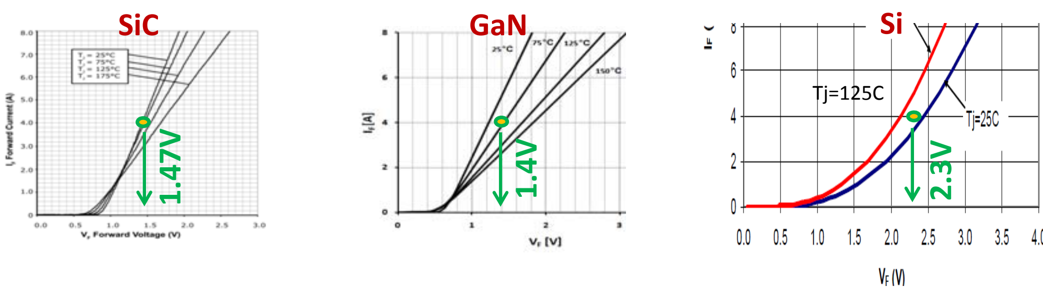
GaN-on-Si and SiC 600V Diodes Outperform Silicon

- 4A Diode Example
  - Both GaN and SiC diode have lower VF than silicon.
    - Less conduction loss
  - Both GaN and SiC diode has zero minority charge: 0 vs. 62nC (Si)
    - Less spike & stable high temp operation
  - GaN diode can be built on Si substrate



15

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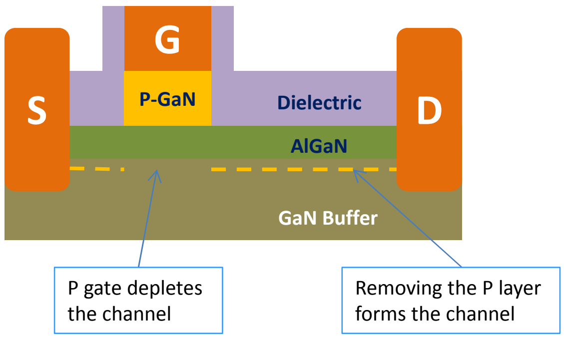
16

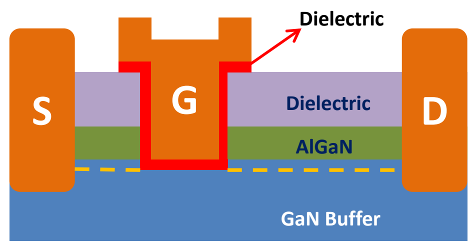
Normally –off HEMTs designs

Junction-gated HEMTs



Advantage: *Single chip normally off transistor*
Disadvantage: Low threshold voltage

Channel etch-through MOSFET



Advantage: *Single chip normally off transistor*
Disadvantage: Device/ Dielectric not qualified

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Cascode HEMT implementation

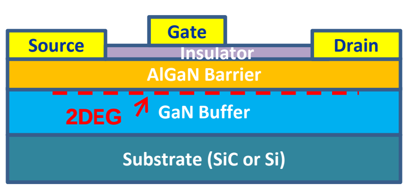
Advantage:

- Robust
- High performance
- Compatible with Si drivers

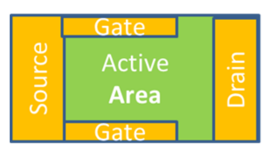
Disadvantage

- Two-chip solution

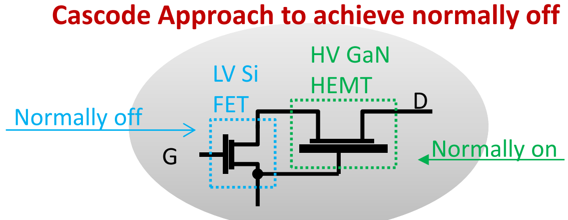
Device Cell Cross-section



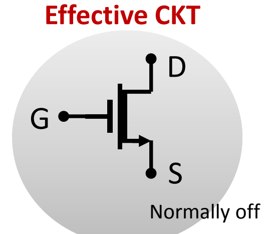
Device Layout



Cascode Approach to achieve normally off



Effective CKT



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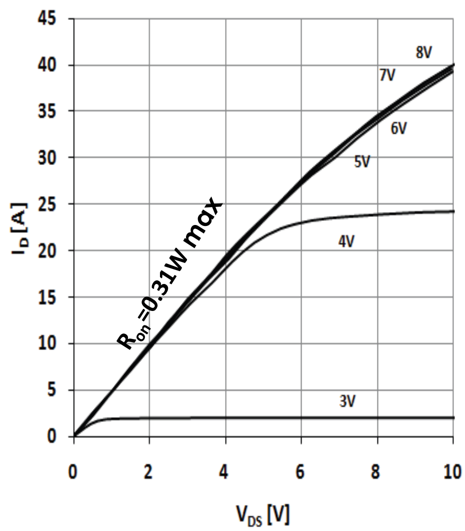
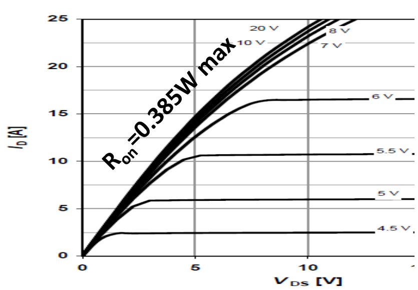
Gen-1 GaN HEMT vs. Si Super Junction MOSFET



GaN HEMT



Si CoolMOS (Super junction MOSFET)

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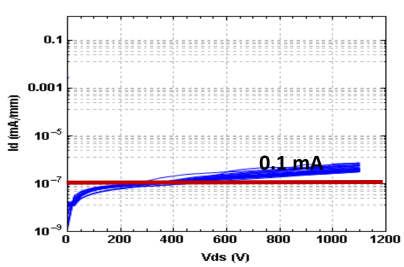
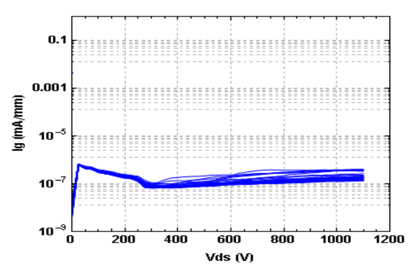
GaN HEMT on Si vs. GaN HEMT on SiC

- V_{BD} > 1100 V on Si and SiC substrates
- Similar leakage with both GaN on SiC and GaN on Silicon
- 1 nA/mm at >1kV !
- < 10% change in Ron under switching



GaN-on-SiC



GaN-on-Si

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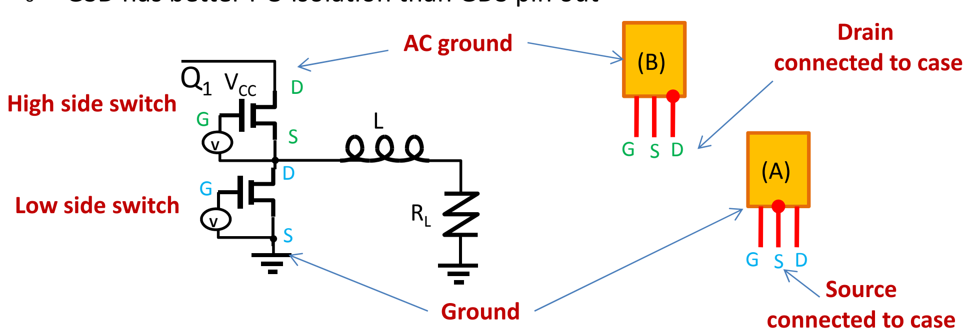
APEC 21 transphorm

Quiet Tab™ package made possible by lateral GaN devices

- Source connected to case for low side switch (A)
- Drain connected to case for high side switch (B)
  - Package body (large capacitor) is always at a DC potential; no switching
  - Reduced charging capacitance: lowering charging loss and CM EMI
  - GSD has better I-O isolation than GDS pin out



APEC 22 transphorm

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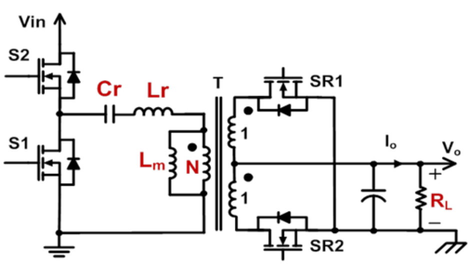
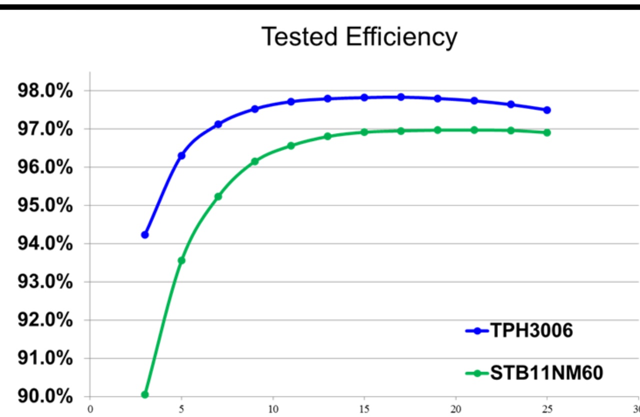
23

LLC DC converter's improved performance with GaN at 500 kHz



Parameters	Value	Parameter	Value
Vin(V)	400	$V_o(V)/Io_{max}(A)$	12/25
Lm(uH)	100	Lr(uH)	5.05
Cr(nF)	15	Fr(kHz)	530
Td(ns)	120	Fs(kHz)	470

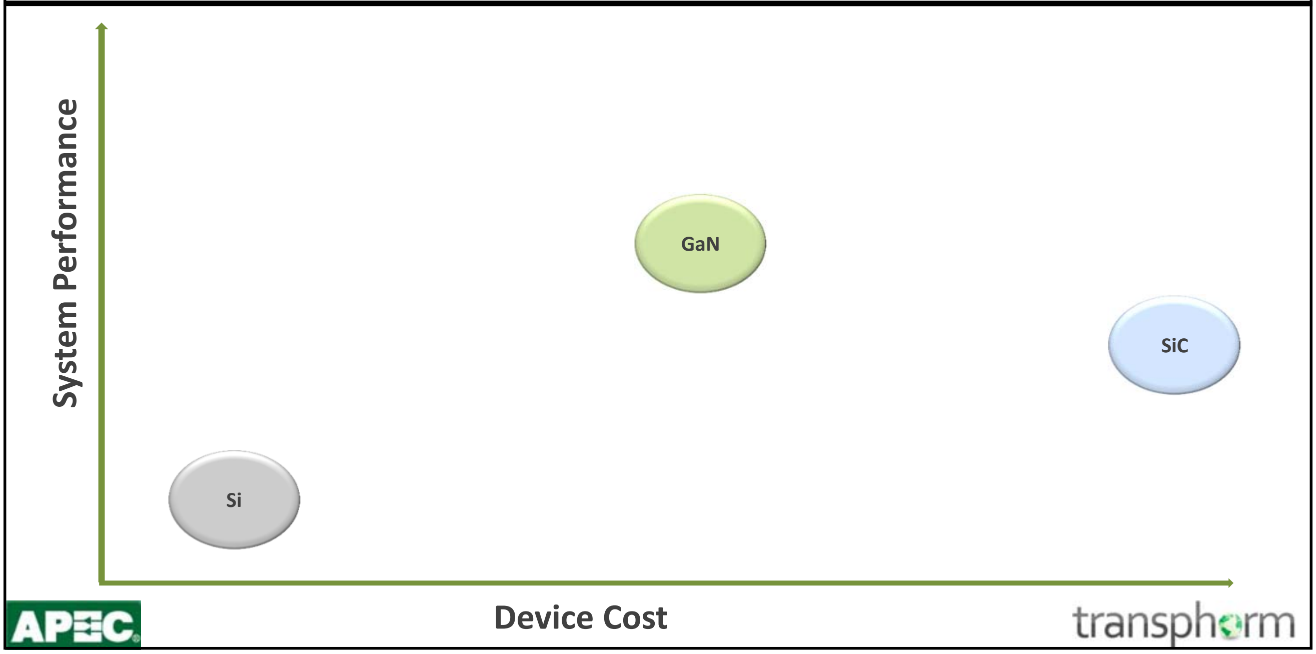
Courtesy: Work done by CPES at Virginia Tech.



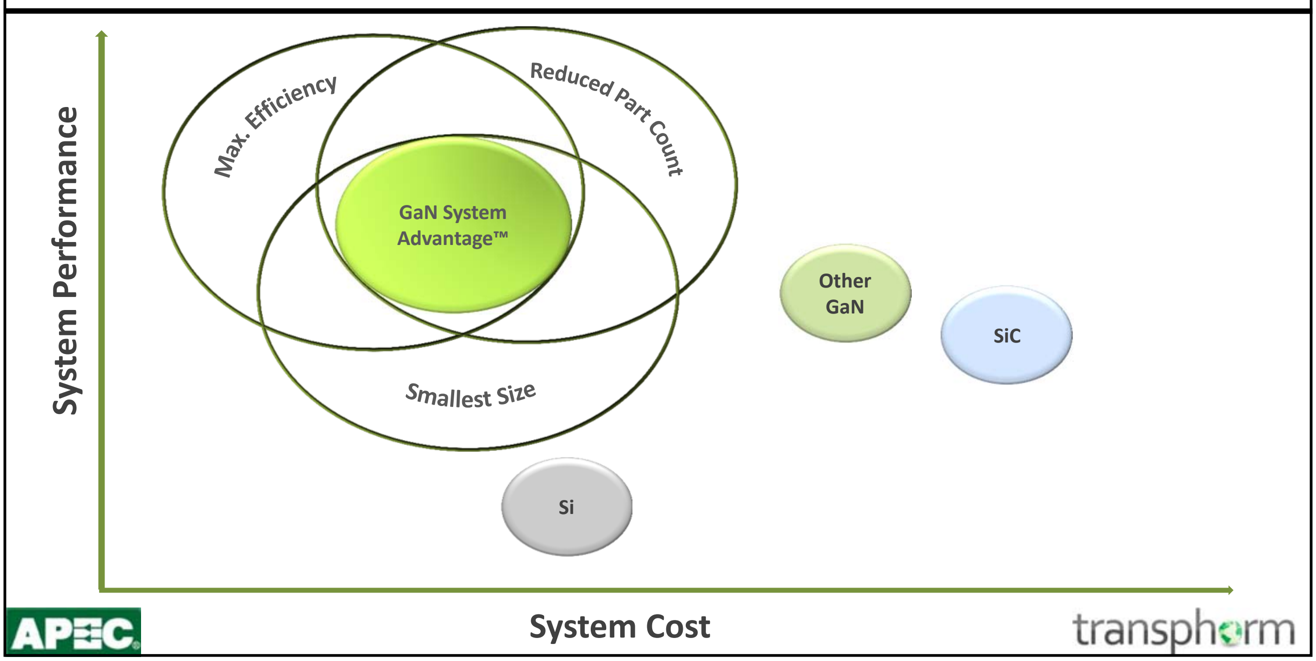
- 500kHz for compact power supply design.
- Peak efficiency gain by GaN is ~ 1%.
- Low-load efficiency gain (2-3%)

24

Performance / Price Comparison



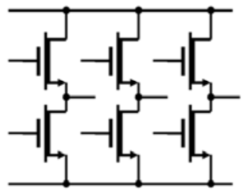
Transphorm uniquely enables superior performance at lower cost



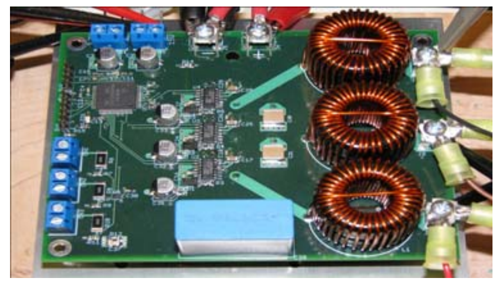
3-Phase GaN module & high frequency inverter (motor drive or PV)

- High frequency design (100kHz-300kHz) enables compact filter (Lower cost)
- Diode-free Bridge (Lower cost and loss)

Module



Inverter

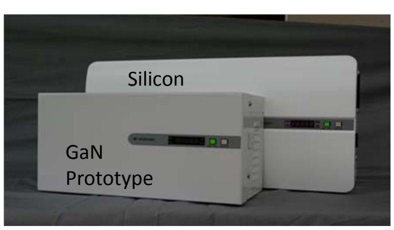


27

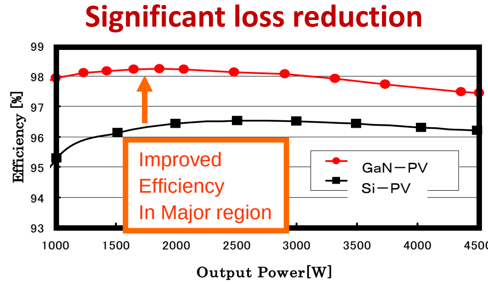
Yaskawa PV converter GaN prototype

- Output power 4.5kw (Single Phase 200V)
- Input voltage 60-400V
- Maximum Power Efficiency > 98% (vs. >96.5% with Silicon)
- Volume about 10L <18L (existing Silicon based)

40% volume reduction



Significant loss reduction

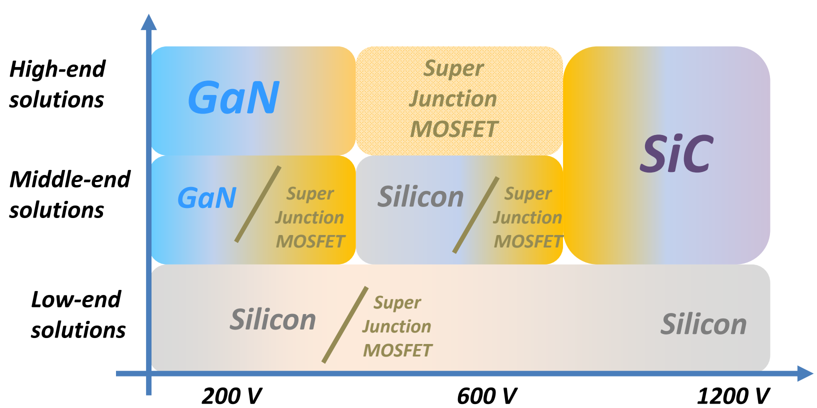


28

So where does this position GaN and SiC?

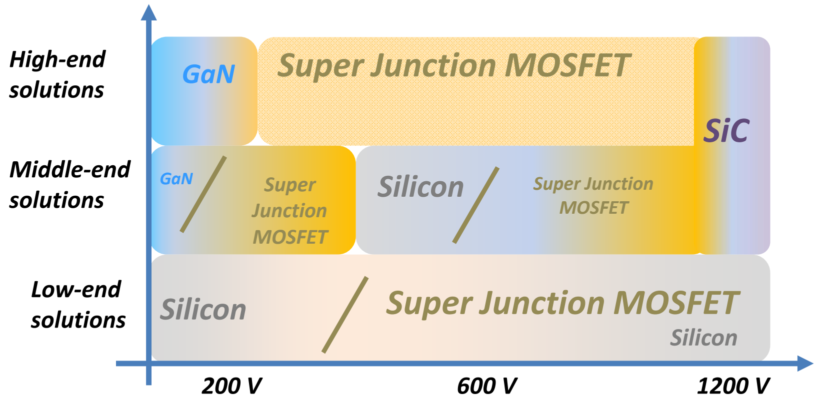
The view of the future depends upon your point of view

Market perspective



What Yole Developement showed in 2011 as future view

Market perspective



A Super Junction supplier's view of future

31

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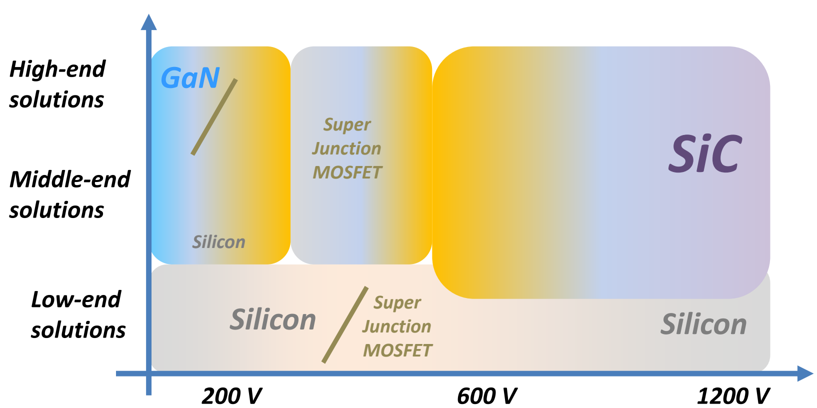
Market perspective

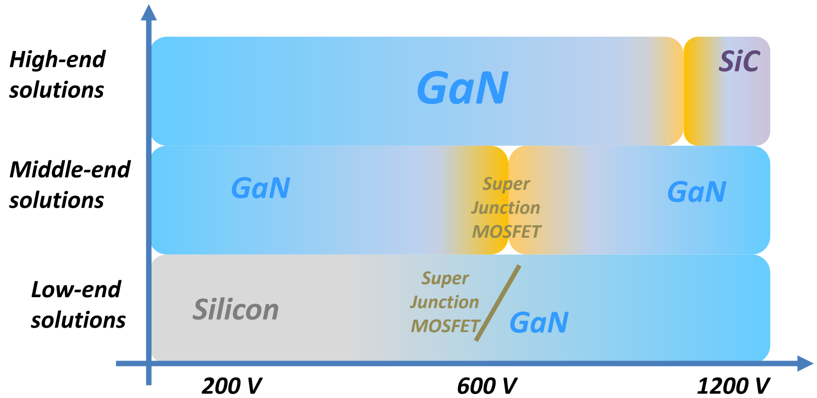


A SiC supplier's view of future

32

APEC transphorm

Market perspective



Now that 600 V GaN on Silicon is Qualified, a GaN solution supplier's view for future