NC STATE UNIVERSITY

materials SCIENCE & ENGINEERING

Semiconductor Materials and Structures for Power Electronics

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→ New: ARPA-E (Feb 2010)

NSF

arpa·e

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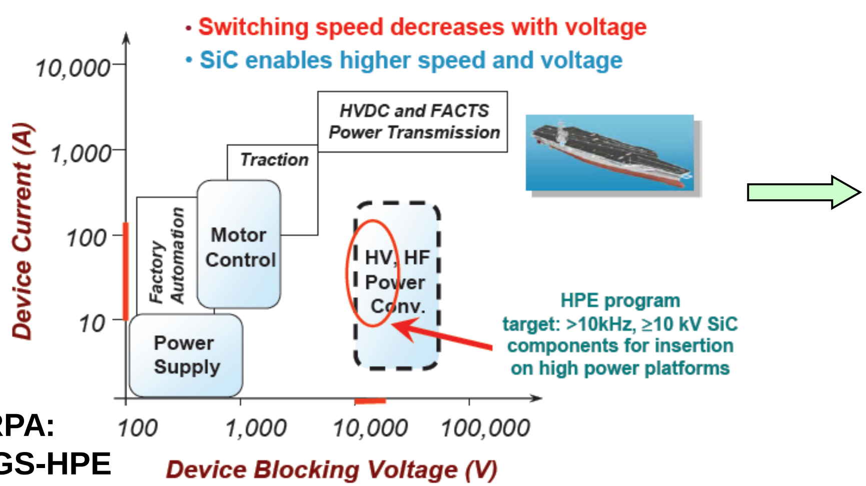
Overview

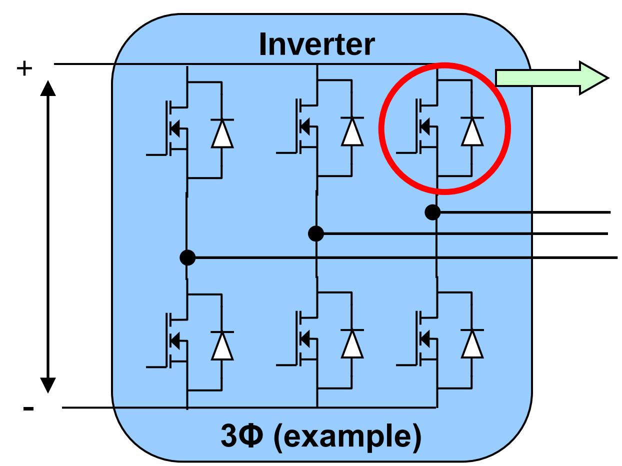
I. Background on Emerging Systems for Power Electronic Devices
II. Materials for Power Electronics
III. Epitaxial Dielectrics on GaN for FETs
IV. Summary

Motivating System Needs For Power Electronics

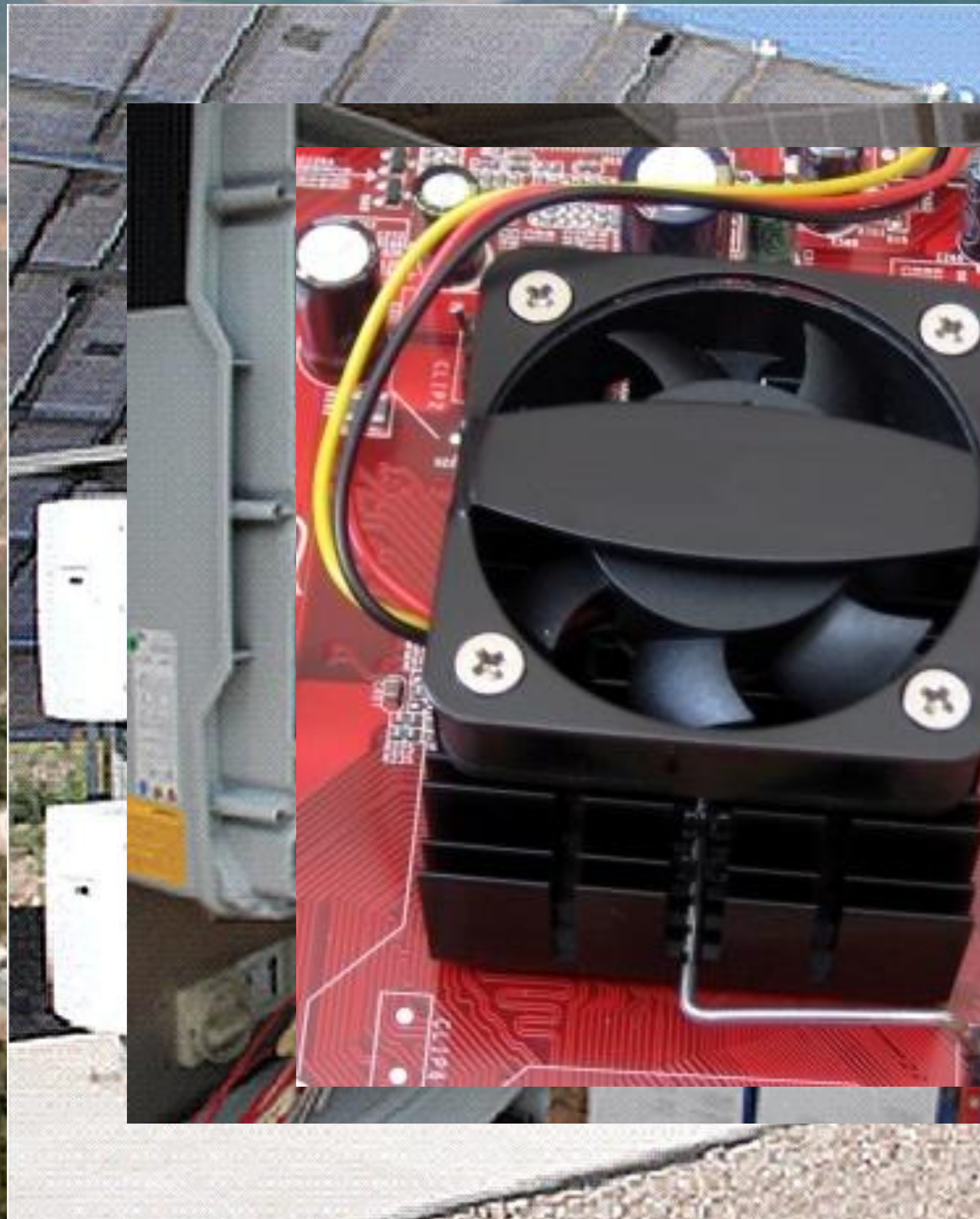
- Greater Efficiency with reduced Size, Cost and Weight
- Applications Segmented By Voltage and Current Ratings
- Small Scale Power Supplies (man) to Vehicle Traction (air, sea or land) to Power Distribution Systems (grid)
- At Core: Systems Need Switches (transistors) and flyback Diodes (fast)



DARPA: WBGS-HPE



Si ?
SiC ?
GaN ?



System Efficiency Losses

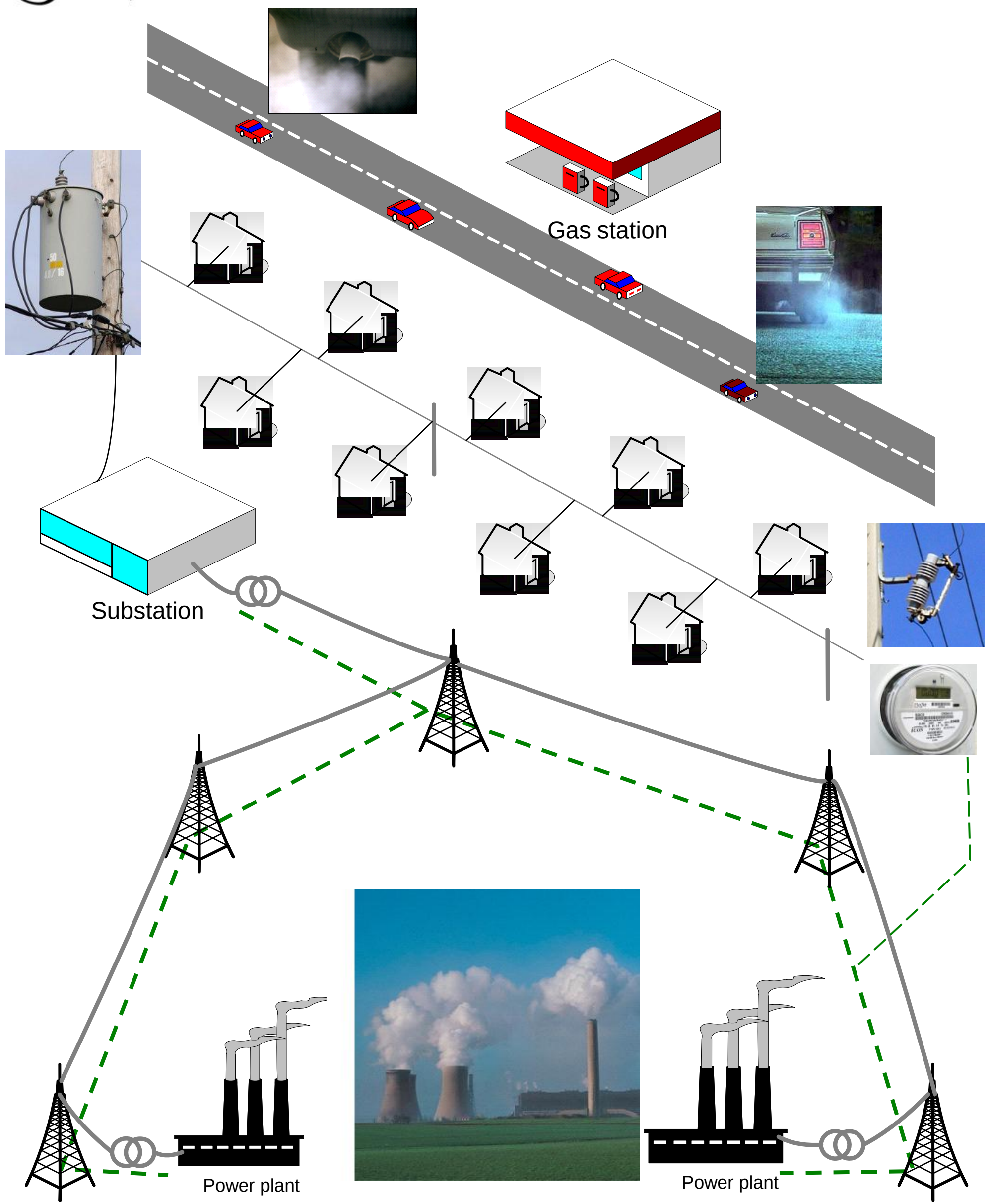
60W inverter losses on a 1200W solar array is equivalent to 19% vs 20% efficiency

Inverter Resistive and Switching Losses:
Normally-off Transistor
Fast Recovery Diode

Energy for Cooling:
High Temperature Operation

Storage:
Round-trip Losses

Today's Power Grid



Problems:

- Not user friendly
  - No plug-and-play interface
  - Large-scale integration of Distributed Renewable Energy Resource (DRER) would cause system collapse due to:
  - Lack of management system
  - Lack of energy storage

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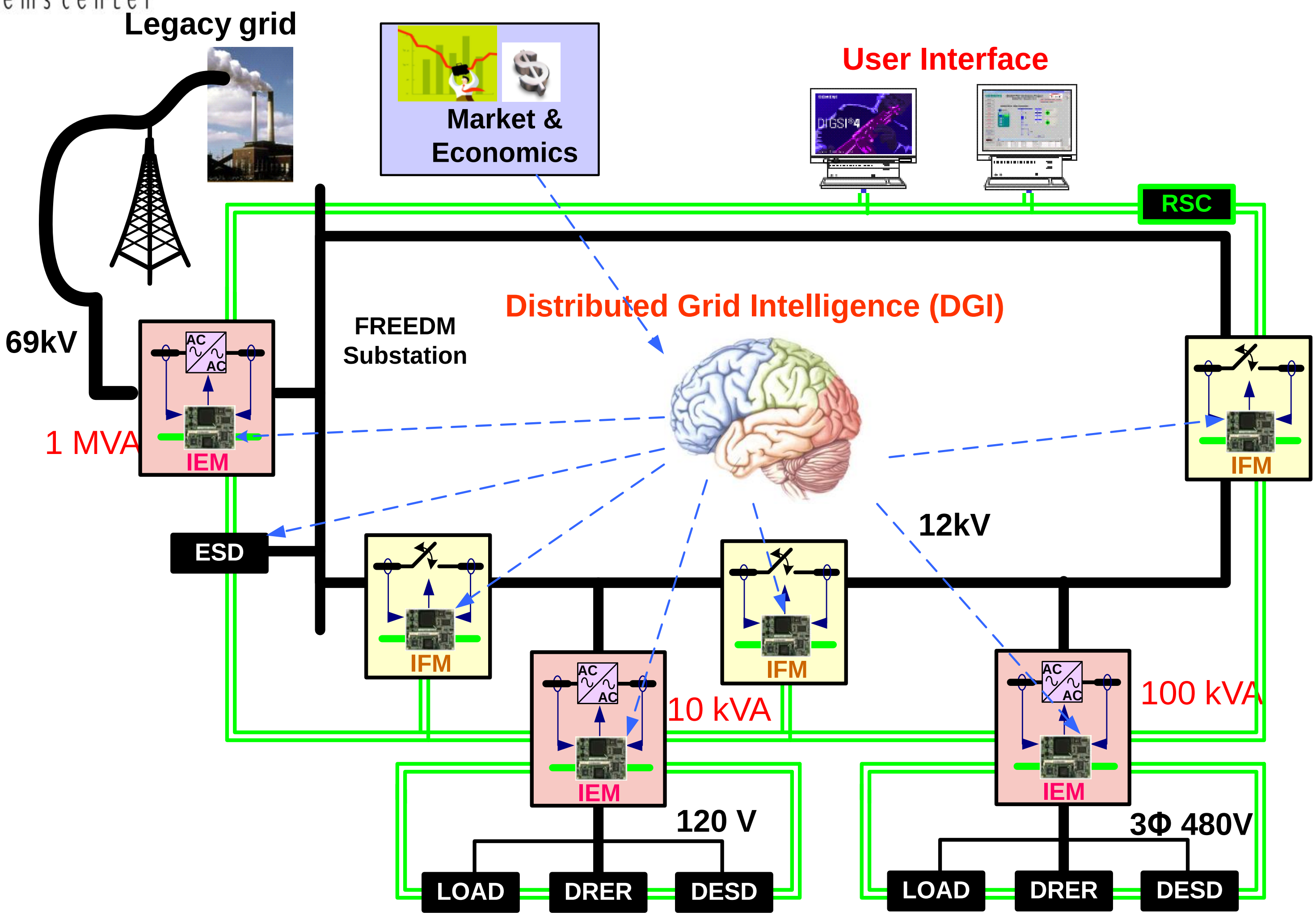
Notional Distribution System



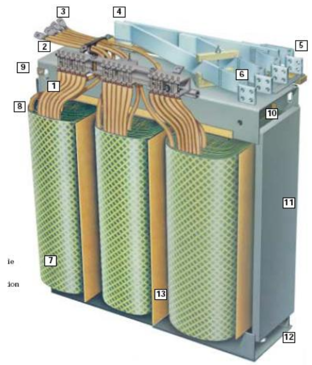
IEM: Intelligent Energy Management

IFM: Intelligent Fault Management

DRER: Distributed Renewable Energy Resource

DESD: Distributed Energy Storage Device

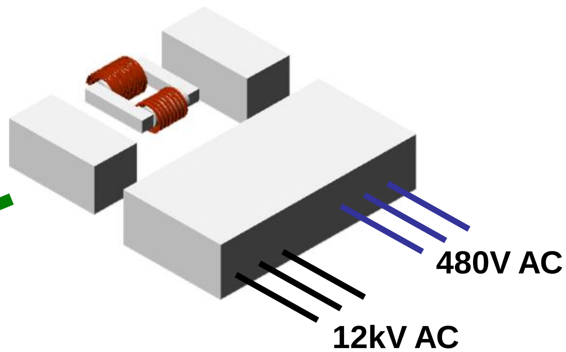
Technology Path

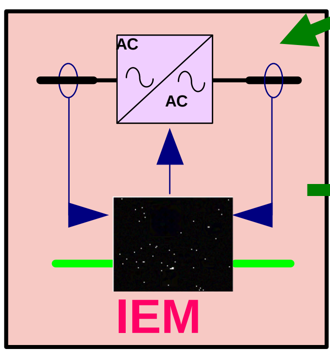


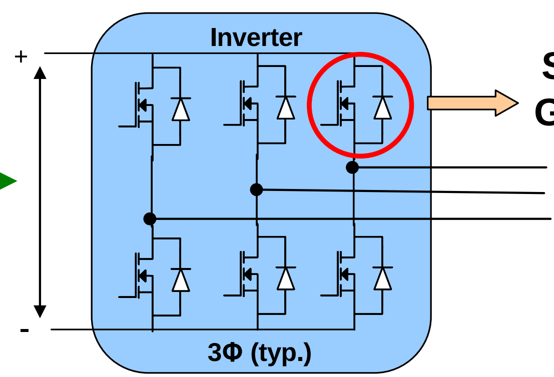
Conventional Transformer
[60Hz]

5 X size reduction
10 X weight reduction

Solid State Transformer (SST)
[10-15 kHz]







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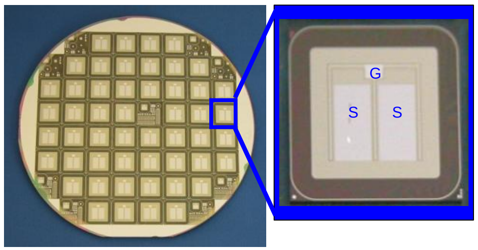
SiC ?
GaN ?



Leverage
SiC MOSFET
Technology

- John Palmour in Breakout -

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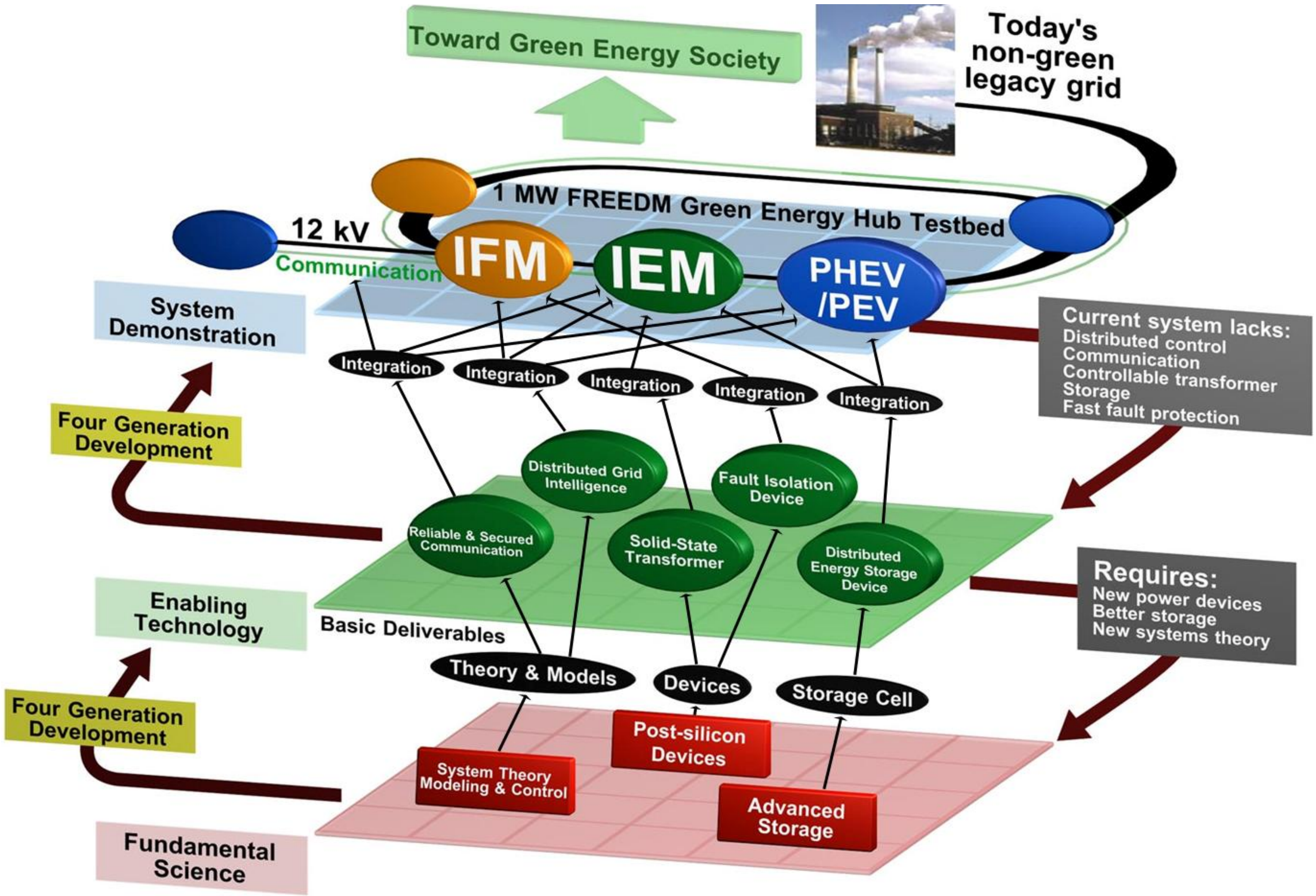
Technical Development Program Linkages



IFM Intelligent Fault Management

IEM Intelligent Energy Management

PHEV/PEV Plug-In Hybrid Electric Vehicle / Plug-In Electric Vehicle

NSF

Comparison of Power Densities

Hybrid Vehicle Inverter

20kW – 120 kW
< 0.1 m^3
Silicon IGBT Based
Currently Water Cooled

Power Distribution

Transformer

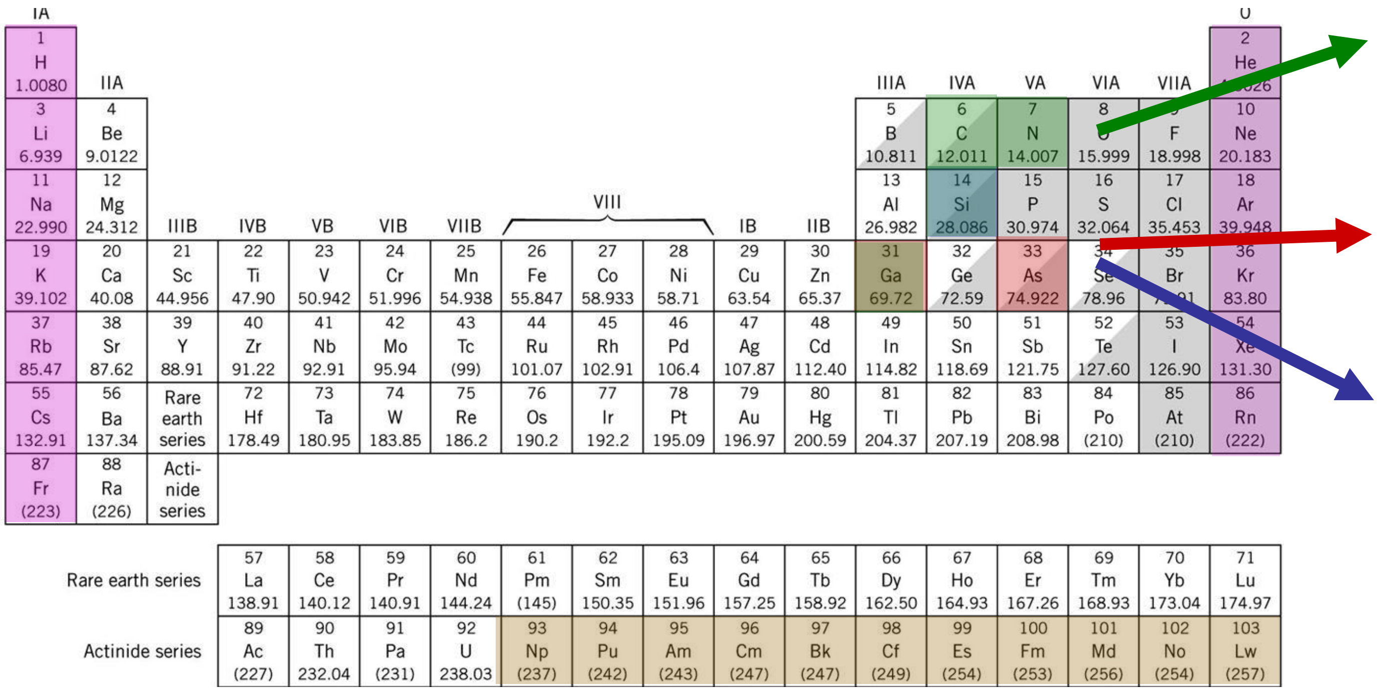
Breaker

20kVA – 120 kVA
~ 1 m^3
All Passive – No Communication, Control or Dispatch
Highly Efficient

Why Anything but Silicon?

- **Size**: Limit to Current Rating Leads to Large Area Devices, Lower Frequency and Overall Weight
- **Efficiency**: Resistive and Switching Losses Potentially Less with SiC or GaN Devices
- **Temperature:** Larger Bandgap Energy Allows Higher-Temperature Operation Leading to System Efficiency
- **Why Now?:** Emergence of SiC and GaN Materials for Optoelectronic Applications Provides Unique Opportunity for Advancement in Power Electronics
- **Gallium Nitride**: Direct Wide Bandgap; Wurtzite (polar) Crystal Structure, AlGaN/GaN Heterostructures, good Electronic Transport Properties, …

Periodic Table and Wide Bandgap Semiconductors

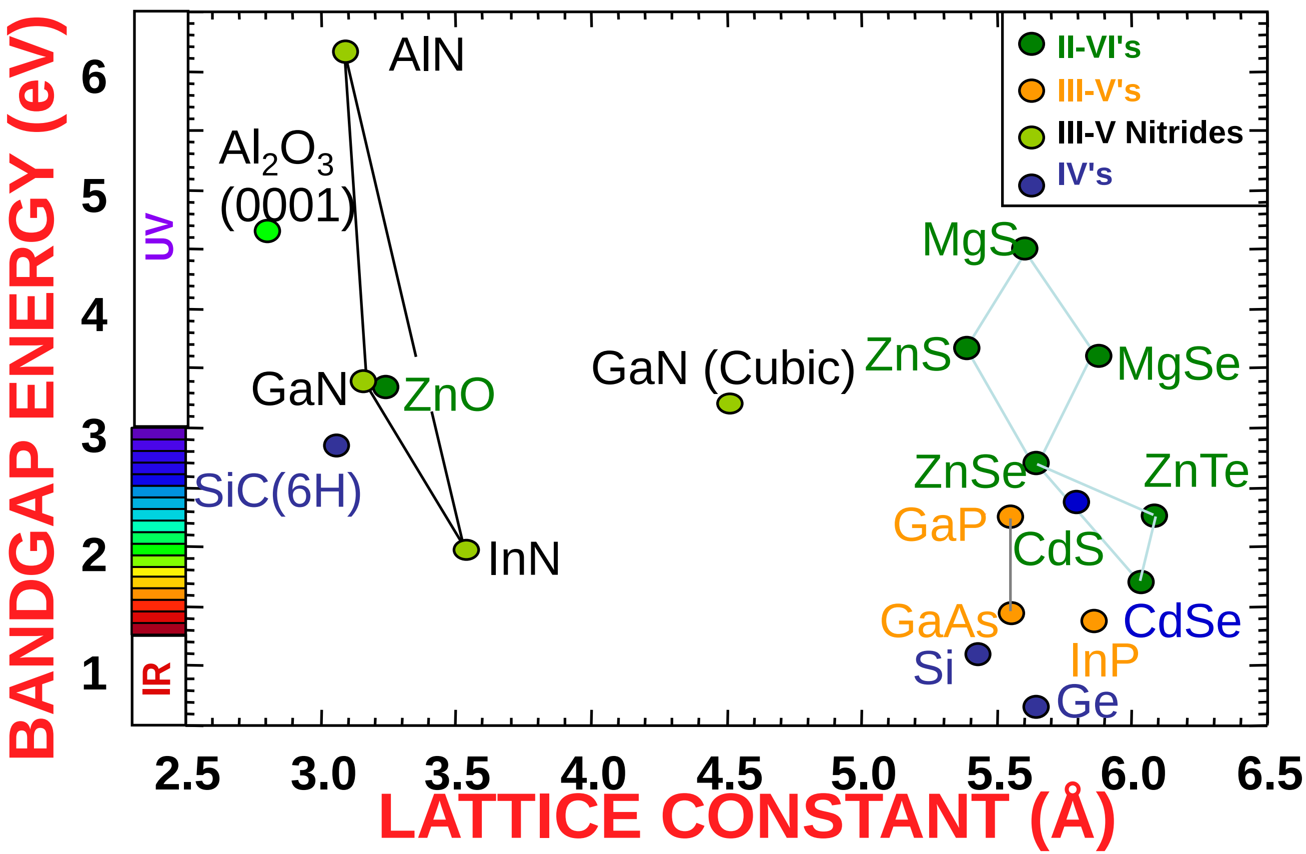


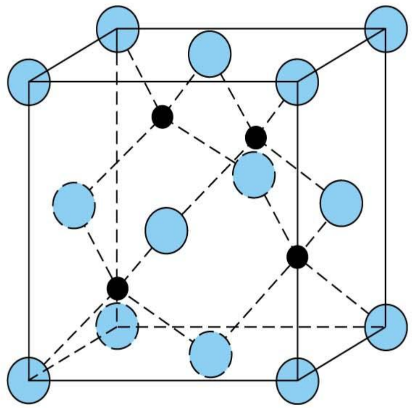
GaN & SiC
LEDs
Blue Lasers
Power Electronics

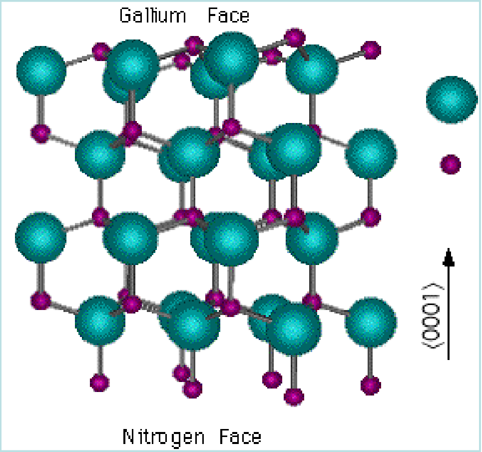
GaAs
Mobile Phones
Wireless

Silicon
Microprocessors
Moore's Law
Power Controllers

Silicon Carbide and Gallium Nitride Wide Bandgap Semiconductors







Most Wide Bandgap Semiconductors have a Hexagonal Structure
Most III-V Semiconductors have Zincblende Structure

Comparison of Semiconductor Materials

	Silicon	4H-SiC	GaN (Epitaxial)
Bandgap Energy (eV)	1.12	3.26	3.4
Dielectric Constant	11.9	10.1	9
Breakdown Field (MV/cm)	0.25	2.2	2.3
Electron Mobility (cm^2/Vs)	1500	1000	1250
Thermal Conductivity (W/mK)	150	490	130
Saturated Electron Velocity (cm/s)	$1.0x10^7$	$2.0x10^7$	$2.2x10^7$
Combined Figure of Merit $K_{th}\varepsilon\mu_e v_s E_c^2$	1	286	102

Problems:

1) What is Device Meaning of the Combined Figure of Merit ?
2) Evolution of Measured Material Properties with Advancement in Materials Technology (E_c, K_{th}, μ_e, …)

Ex: L. Tolbert, et.al. "Power Electronics for Distributed Energy Systems (ORLN/TM – 2005/230)

Figures of Merit

- Combined Figure of Merit (General Assessment)

  $$k_{th}\varepsilon\mu_e v_s E_c^2$$

- Keyes Figure of Merit (Power Density & Speed)

  $$k_{th}\sqrt{[c\, v_s / (4\pi\, \varepsilon_s)]}$$

- Baliga Figure of Merit (Resistive Losses)

  → $\varepsilon\mu_e E_c^3$

- Baliga High Frequency Figure of Merit

  → $\mu_e E_c^2$ (Switching Losses)

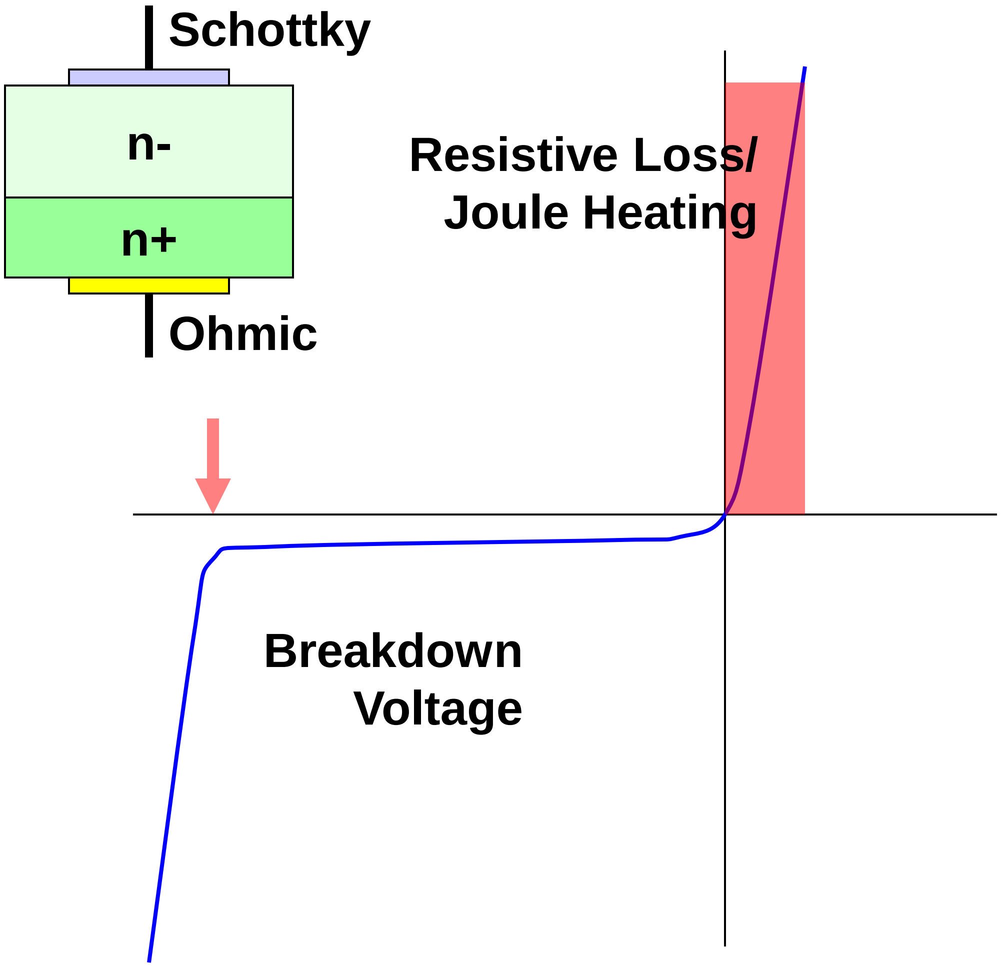
R. W. Keyes, "Figure of Merit for Semiconductors for High Speed Switches,"
Proc. IEEE, vol. 60, pp. 225-232, 1972
B. J. Baliga, "Semiconductors for High-Voltage, Vertical Channel Field-Effect Transistors,"
J.Appl.Phys., vol. 53, no. 3, pp. 1759-1764, 1982
B.J. Baliga, "Power semiconductor device figure of merit for high – frequency applications,"
IEEE Electron Device Lett., vol. 10, pp. 455-457, 1989.

Resistive Loss in Power Rectifiers

- Minimize Series Resistance Loss at Voltage Rating
- Assume Series Resistance Dominated by n- Drift Region (Low Contact Resistance)
- From Device Model

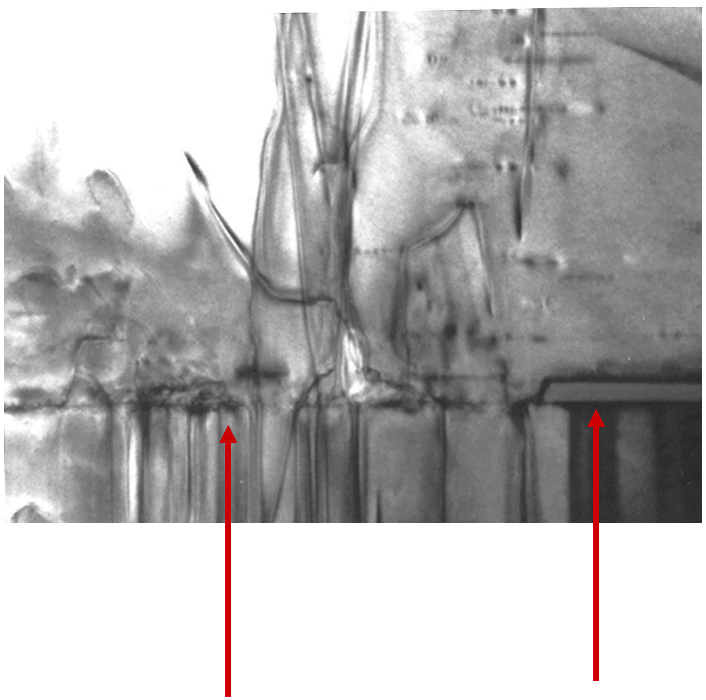
$$R_{on} = \frac{4 \cdot BV^2}{\varepsilon \cdot \mu_e \cdot E_c^3}$$

BFM



Mobility at Drift Region Doping Levels
NOT Values for Undoped Material

GaN Laser Diodes:
Lateral Growth Reduces Crystal Defects



UnMasked

Masked

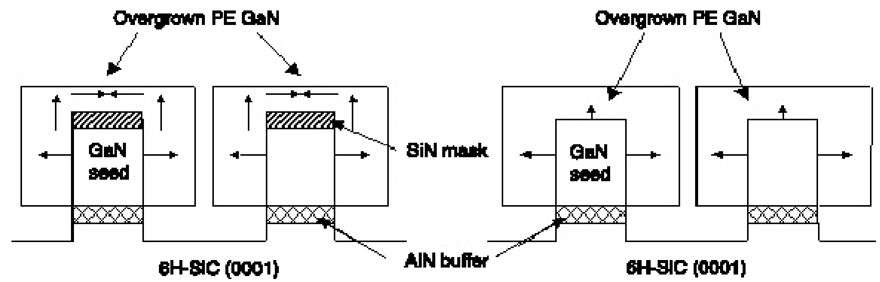


Fig. 1. Schematic of: (a) PE growth from GaN seed laterally off the sidewalls then vertically and laterally over the silicon nitride mask; (b) PE growth from GaN seed laterally off the sidewalls and vertically off the stripe.

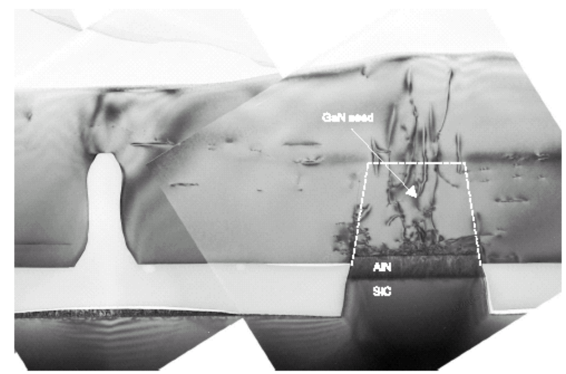


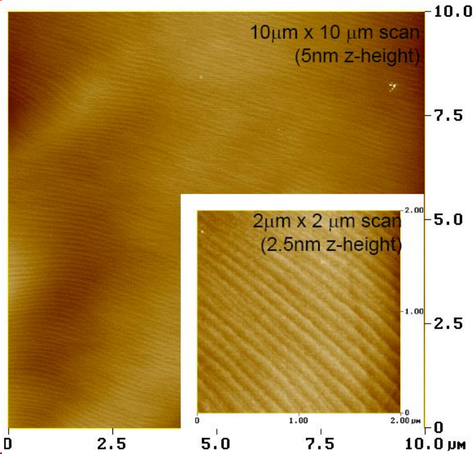
Fig. 2. Composite of cross-sectional TEM micrographs of a PE $Al_{0.1}Ga_{0.9}N$ film. Note the threading dislocations continue from the GaN stripes into the film.

Davis, et.al.

Laser Diode Lifetimes > 1000 hrs with Low Defect GaN

Micro-morphology and dislocation density

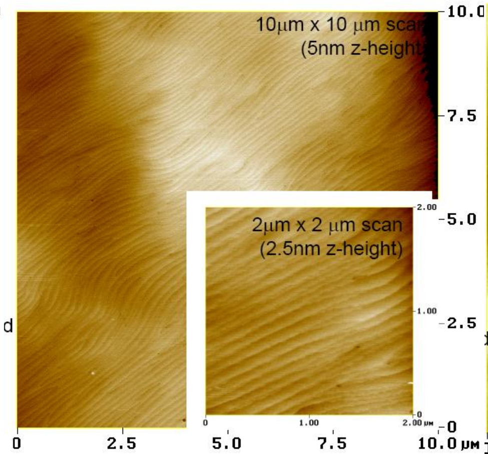
HVPE Ammonothermal High Pressure



$N_{dis}=2x10^7\ cm^{-2}$

250-µm-thick free-standing HVPE GaN

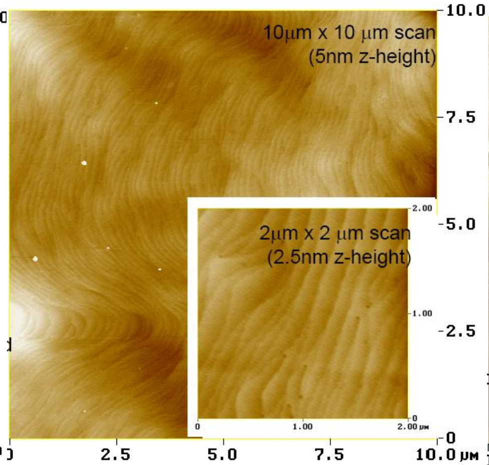
HVPE



$N_{dis}=2x10^8\ cm^{-2}$

10-µm-thick HVPE GaN
sapphire

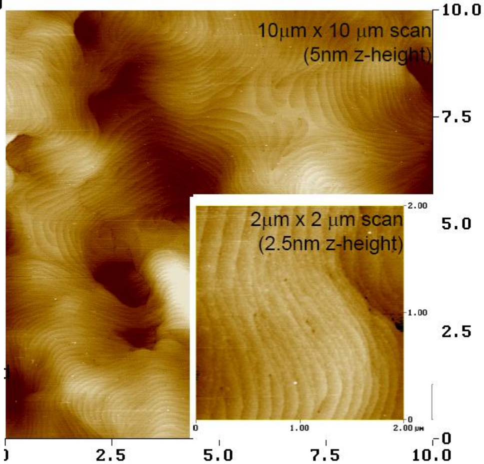
MOCVD



$N_{dis}=3x10^8\ cm^{-2}$

3-µm-thick
buffer
6H SiC

MOCVD

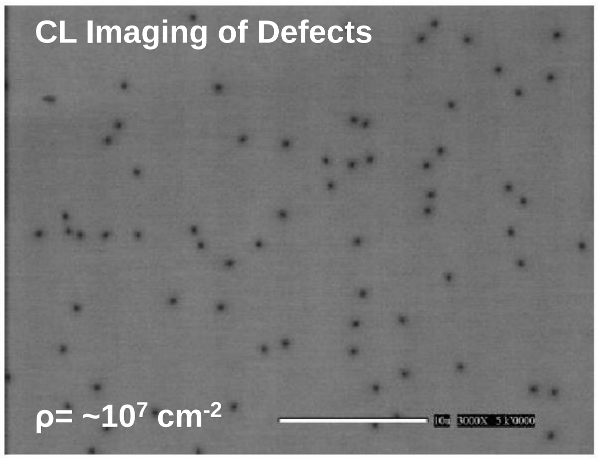


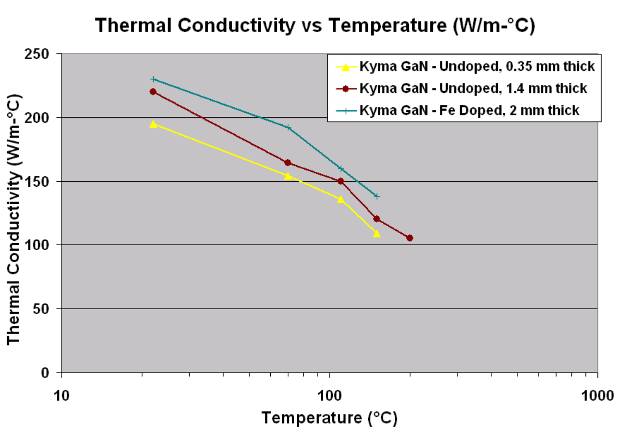
$N_{dis}=4x10^8\ cm^{-2}$

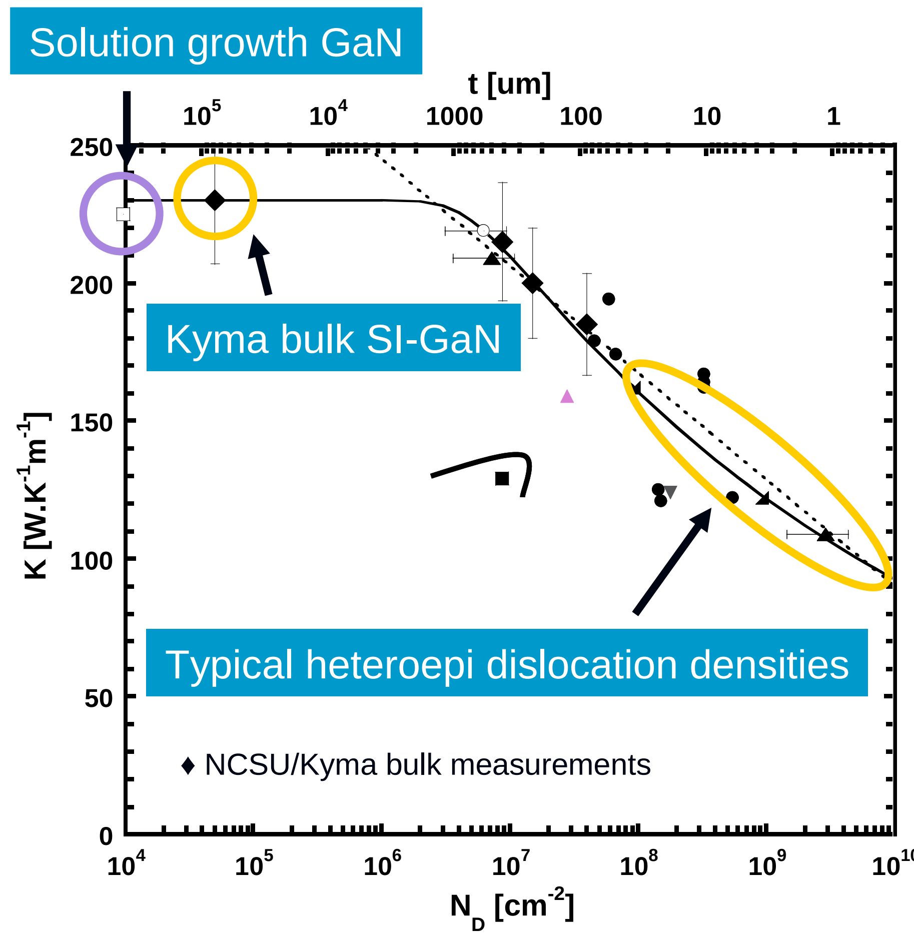
3-µm-thick
buffer
sapphire

G. Brandes, IS on Bulk Nitrides, Sept. 2005, Bremen, Germany

Thermal Conductivity of Low Defect Bulk GaN by 3-ω Method







C. Mion, NC State University (2005)

GaN for Power Electronics

GaN as material for high-speed and high-power applications

BFM – minimized resistive losses [$\varepsilon\mu E_c^3$]

BHFFM – minimized switching losses (μE_c^2]

JFM – minimized switching delay [$(v_{sat}E_c)^2$]

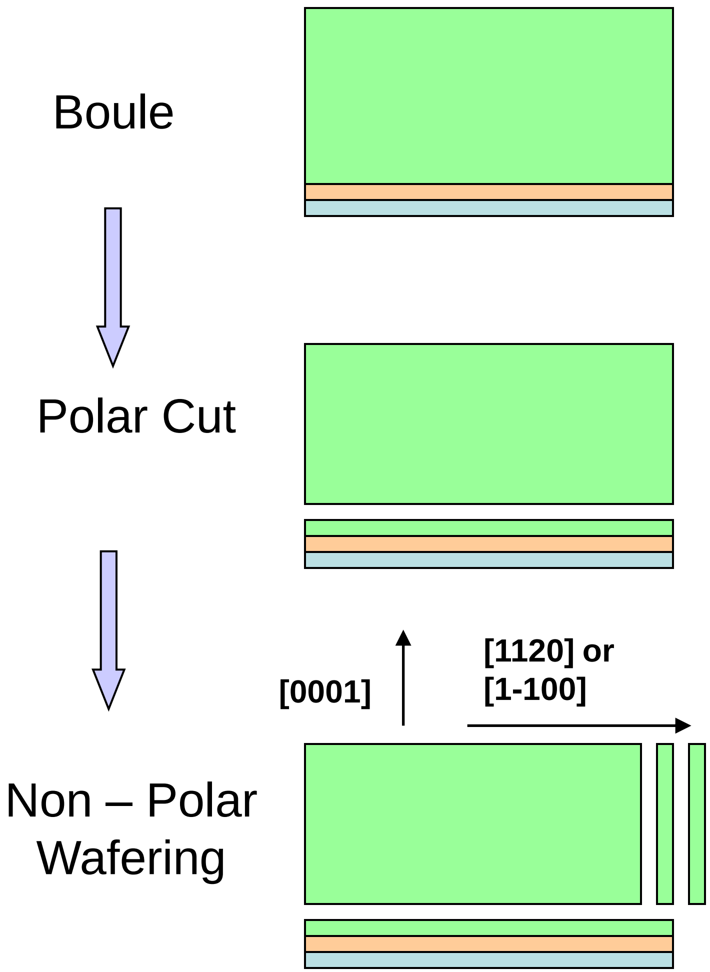
	Silicon	4H-SiC	GaN (epi)	GaN (bulk)
E_g (eV)	1.12	3.26	3.4	3.4
Diel. Constant	11.9	10.1	9	9
K_{th} (W/mK)	150	490	130	230
E_c (MV/cm)	0.3	2.2	2	3.3 2.7 (exp)
v_{sat} (x1E7 cm/s)	1	2	3	3
mobility (cm^2/Vs)	1350	900	1150	1150
BFM (rel)	1	223	190	850
BHFFM (rel)	1	45	36	98
JFM (rel)	1	215	400	1090

Low Resistive Loss

Low Switching Loss

Metamorphic Quasi-Bulk GaN

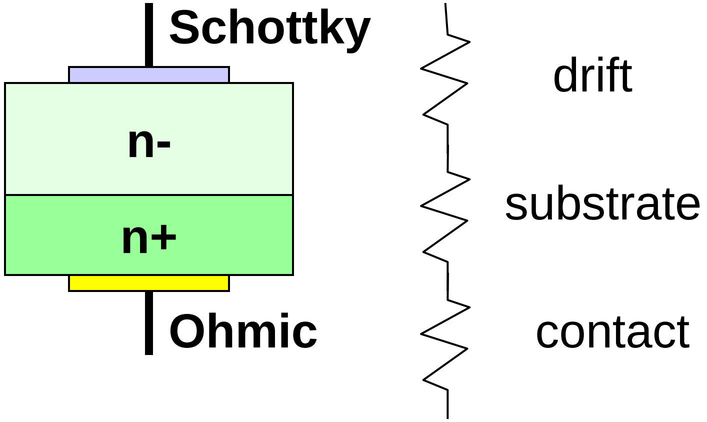
- HVPE for GaN Boule Synthesis: NH_3, Ga, HCl
- Wafering by slicing and polishing
- Defect density reduction with increased thickness: as low as mid-$10^5/cm^2$
- Orientation controlled by wafering direction



kyma the new wave in nitrides

Substrate Series Conductivity

- **n-ohmic** ~10^{-6} Ωcm^2
- **Drift** <10^{-3} Ωcm^2 @ 1kV
- **substrate** 100 μm
  (target) 2×10^{18} cm^{-3} n-type
  500 cm^2/Vs mobility
  6×10^{-5} Ωcm^2



- **Need**: Thin, highly doped, highly conductive substrates

Nominal GaN MOS Power Transistor and Materials Development Issues

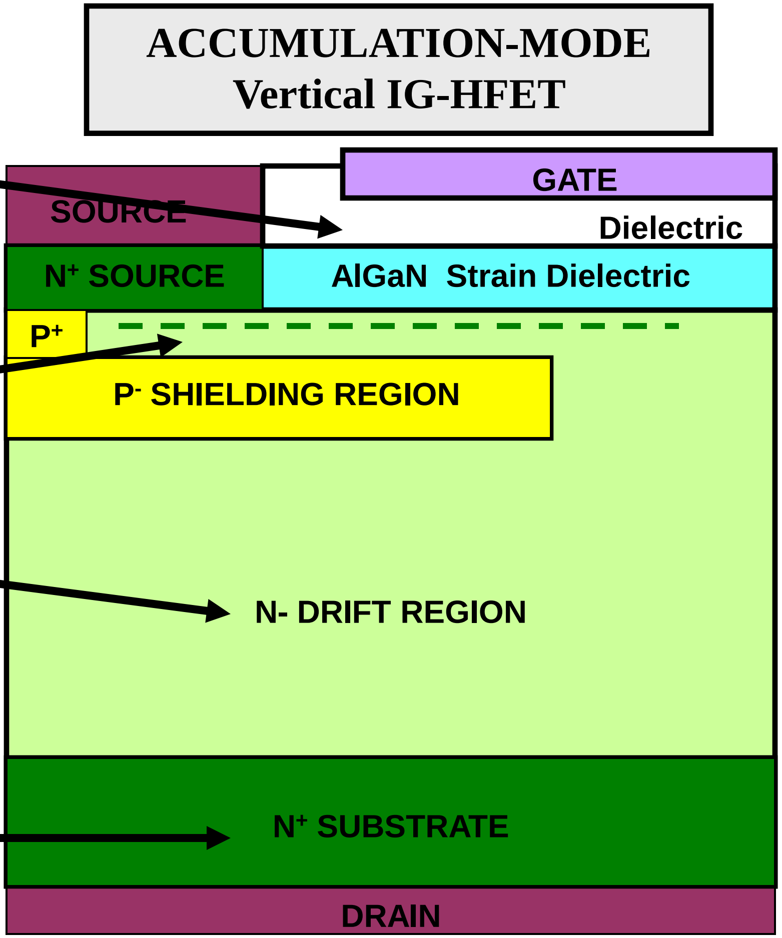
Materials Focus / Problem

III-N MOS Interface Structures

2DEG Fabrication & Epitaxy

Drift Region Power Limit

Low Defect GaN Substrate

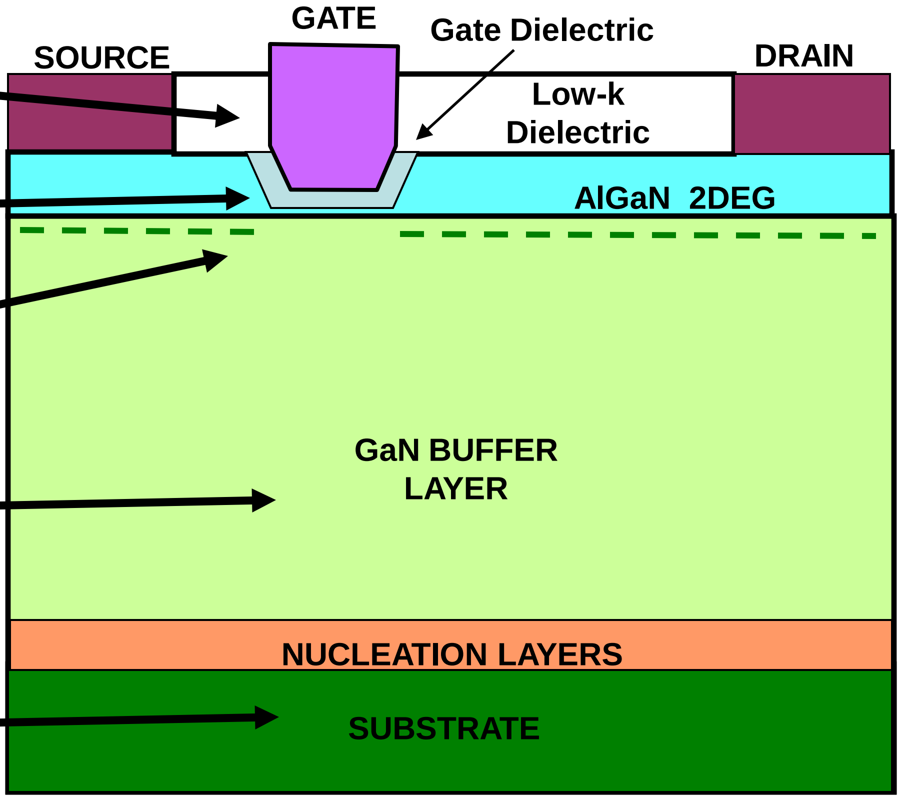


Lateral GaN MOS Power Transistor and Materials Development Issues

Enhancement-mode Lateral MOS-HFET

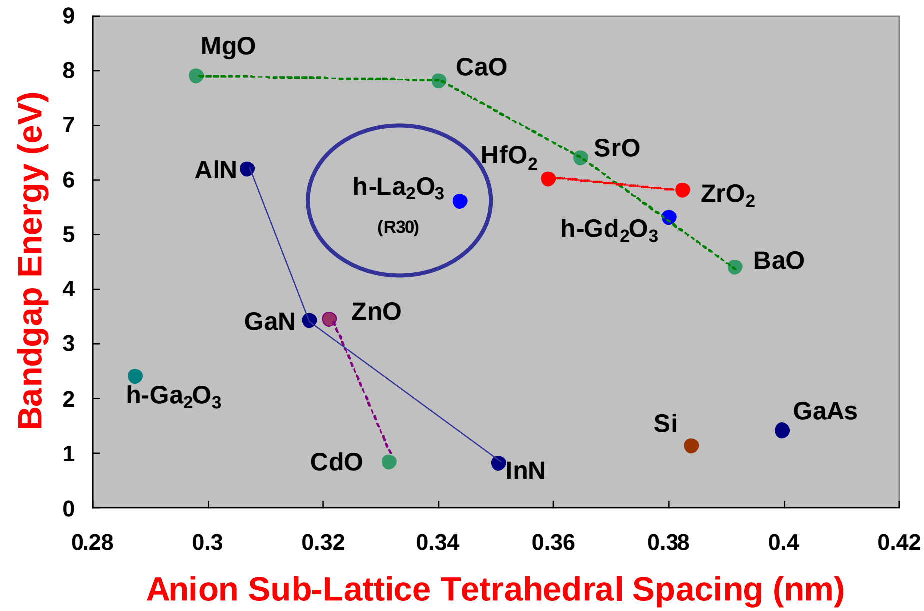
Materials Focus / Problem

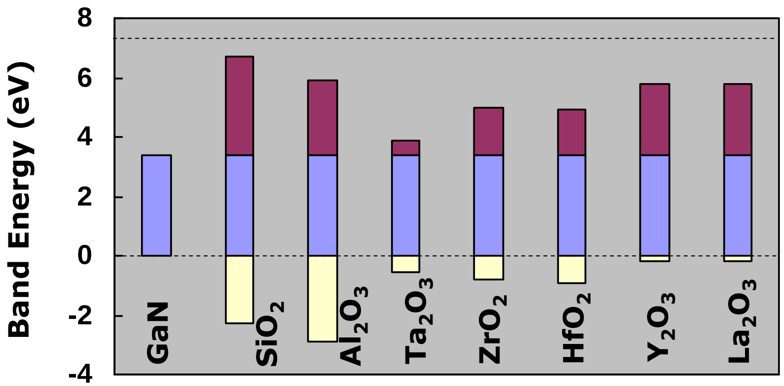
- MOS Interface & Structures
- Recess Etching
- 2DEG Fabrication & Epitaxy
- Buffer Layer Defects and Leakage
- Silicon, Silicon Carbide, Sapphire

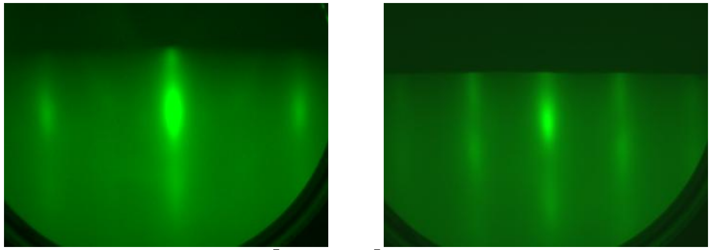


GaN Dielectric Interface – Fab Process

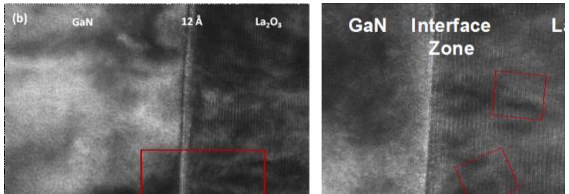
- **Deposition of GaN MOS Dielectric**
- **Consideration: Structure, Electron Energy and Thermal Stability**
- **Crystal Growth on III-Nitride Surface: Ga_2O_3 Interlayer**







La_2O_3 (MBE) on GaN



Summary

- Wide bandgap semiconductors opportunity in Power Systems

  - ‘Last mile’ of Electric Power Systems
  - High Voltage Transmission and Distribution
  - Renewable Energy Generation
  - Smarter Reactive & Resistive Loads

- Properties of WBGS advantageous in efficient power conversion

- Defect Density Key Issue in Wide Bandgap Semiconductors

- Gate Dielectrics for MOS applications

- Focus on GaN and SiC in Breakouts: John Palmour and Keith Evans

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- Thanks:

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N. Biswas, L. Ma, Y. Jin, Y. Saripalli, X-Q Liu, C. Vercellino, R. Fava, M. Veety, J-H Park, J. Muth, K. Evans, D. Hanser, E. Preble, T. Paskova, G. Mulholland, A. Huang, J. Baliga, S. Bhattacharya, H. Xu, Y. Wang, M. Park

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  - DARPA: Young Faculty Award
  - MDA, AFRL and ARO SBIR/STTR Programs

Questions?