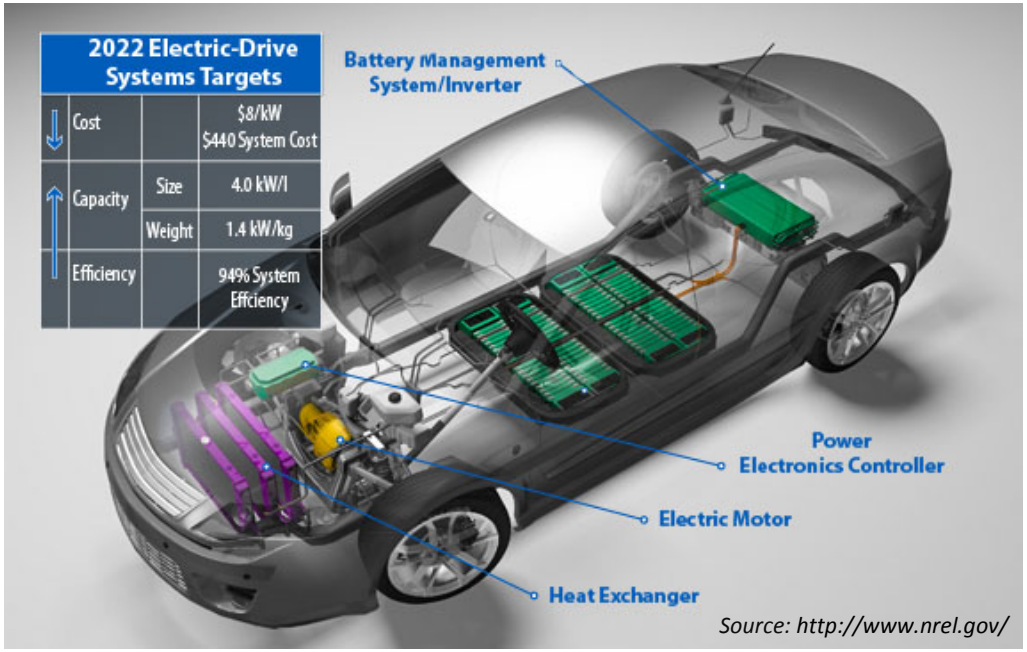
High-Power Devices, High-Temperature Materials and Packaging for Electric Cars

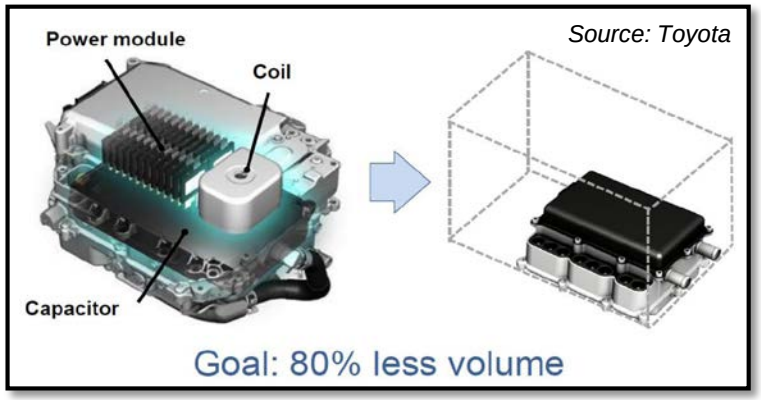
Georgia Tech Packaging Research Center

PROGRAM OBJECTIVES

- Design and demonstrate ultra-miniaturized, high-efficiency and high-reliability 1-50kW power modules for automotive with:
  - Vertical-conduction GaN bipolar devices
  - New packaging structures, materials and processes for high-frequency (0.5-1MHz) and high-temperature (250ºC) operations
  - Improved thermal efficiency at increased power density

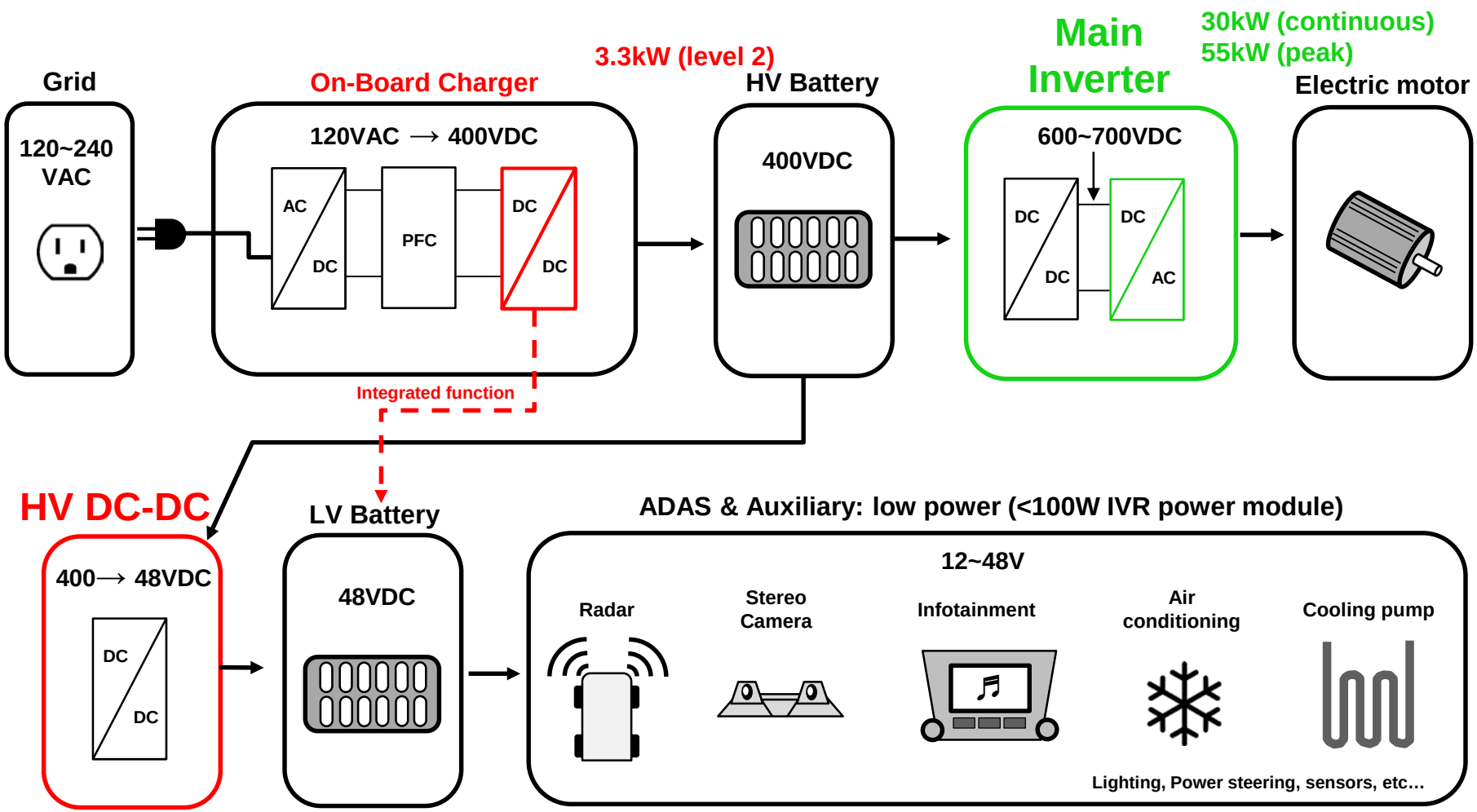


Source: http://www.nrel.gov/

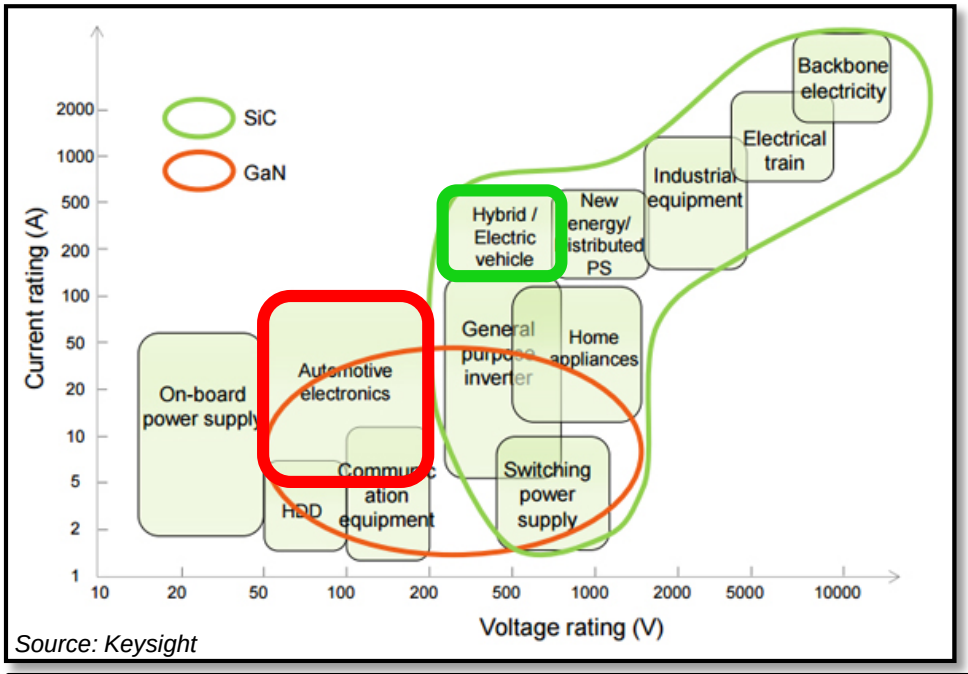


Source: Toyota

POWER FLOW IN ELECTRIC VEHICLES

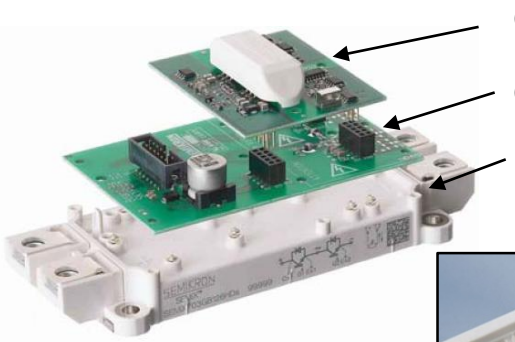


PRIOR ART – THE ONGOING WBG REVOLUTION SiC IN POWER TRAIN



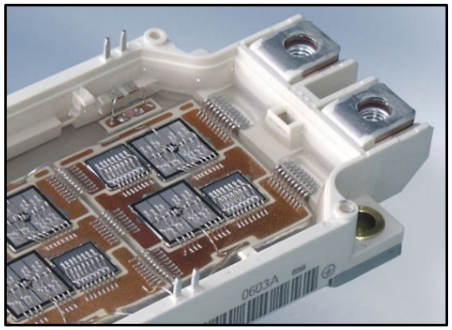
Source: Keysight

Conventional Si IGBT inverter package



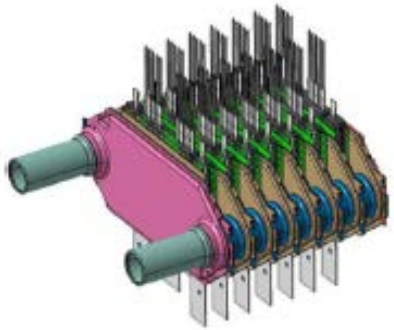
Source: Semikron

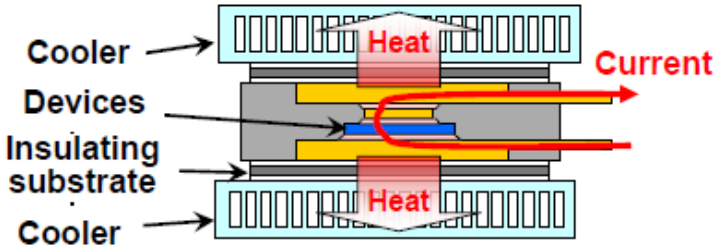
Multi-chip module on DBC substrate with bond wires



Recent trends: SiC power devices, double-sided cooling, power embedding

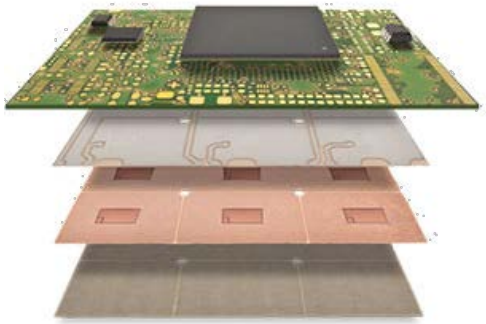
Double-sided cooling





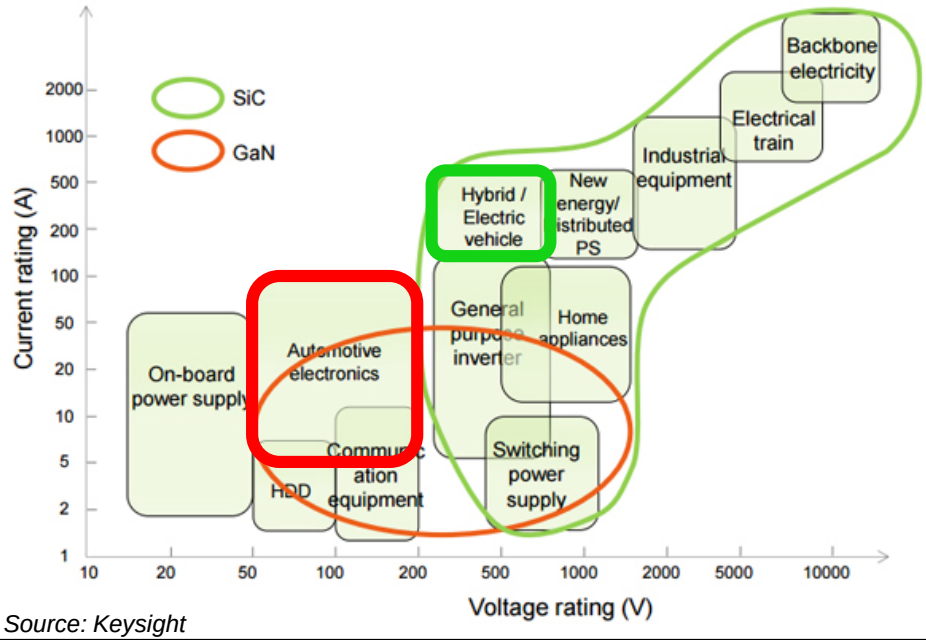
Toyota 4th generation Prius with molded leadframe all-SiC power card

Power embedding



Schweizer p² Pack

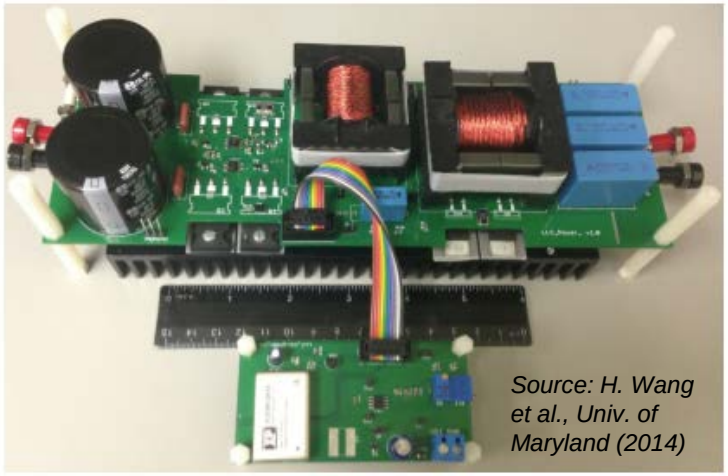
PRIOR ART – THE ONGOING WBG REVOLUTION
GaN IN ON-BOARD CHARGERS & POWER SUPPLIES



Source: Keysight

HV isolated DC-DC converter with Si power MOSFETs

200kHz 1kW isolated DC-DC converter

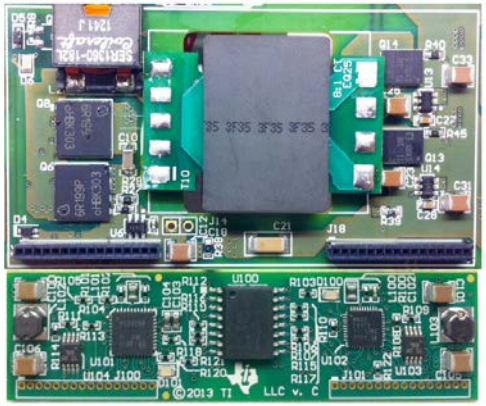


Source: H. Wang et al., Univ. of Maryland (2014)

Recent trends: GaN FETs, integrated magnetics for high-frequency designs

Monolithic integration of transformer and resonant inductor on single magnetic core

Source: G. Su et al., ORNL (2013)



Source: Michael D. Seeman et al., TI (2014)

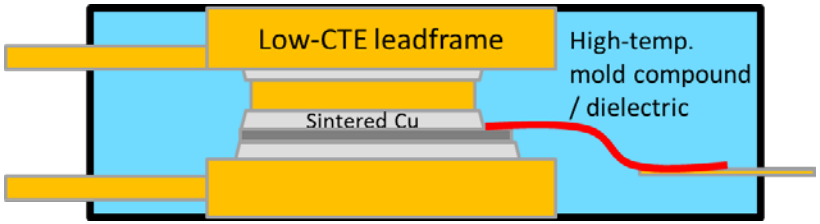
500W *400V/12V, 350kHz, planar magnetics, GaN,* ***308 W/in³***

- Need for high-frequency converter designs with low-inductance pkg and embedded magnetics

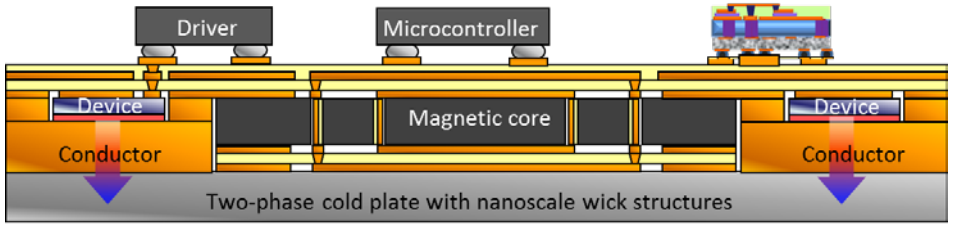
GT'S UNIQUE APPROACH & BASIC TECHNOLOGY FOCUS
From devices, components, materials, processes to system

- Vertical-conduction GaN power devices
- Materials for high-temperature and Hi-Rel packaging
- Low-cost high-power interconnections
- Magnetic component designs for high-frequency
- Power embedding with integrated control and drives
- Two-phase cold plates
- Reliability and condition monitoring

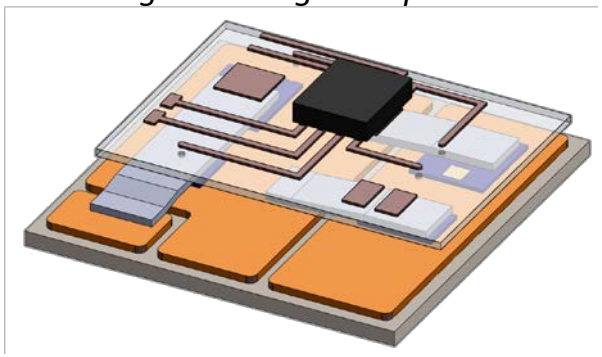
High-temperature Hi-Rel plastic package for double-sided cooling



3.3kW – 0.5-1MHz GaN LLC resonant converter with embedded magnetics, power density >200W/in^3 and efficiency >97%

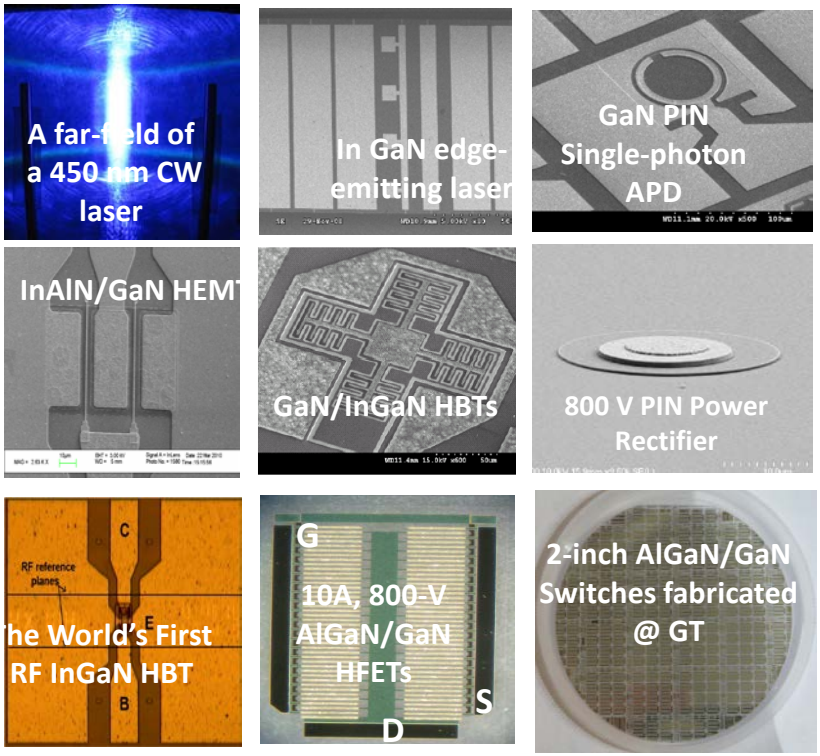


High-temperature power embedded package with glass as high-temp dielectric



GaN Technology at GT

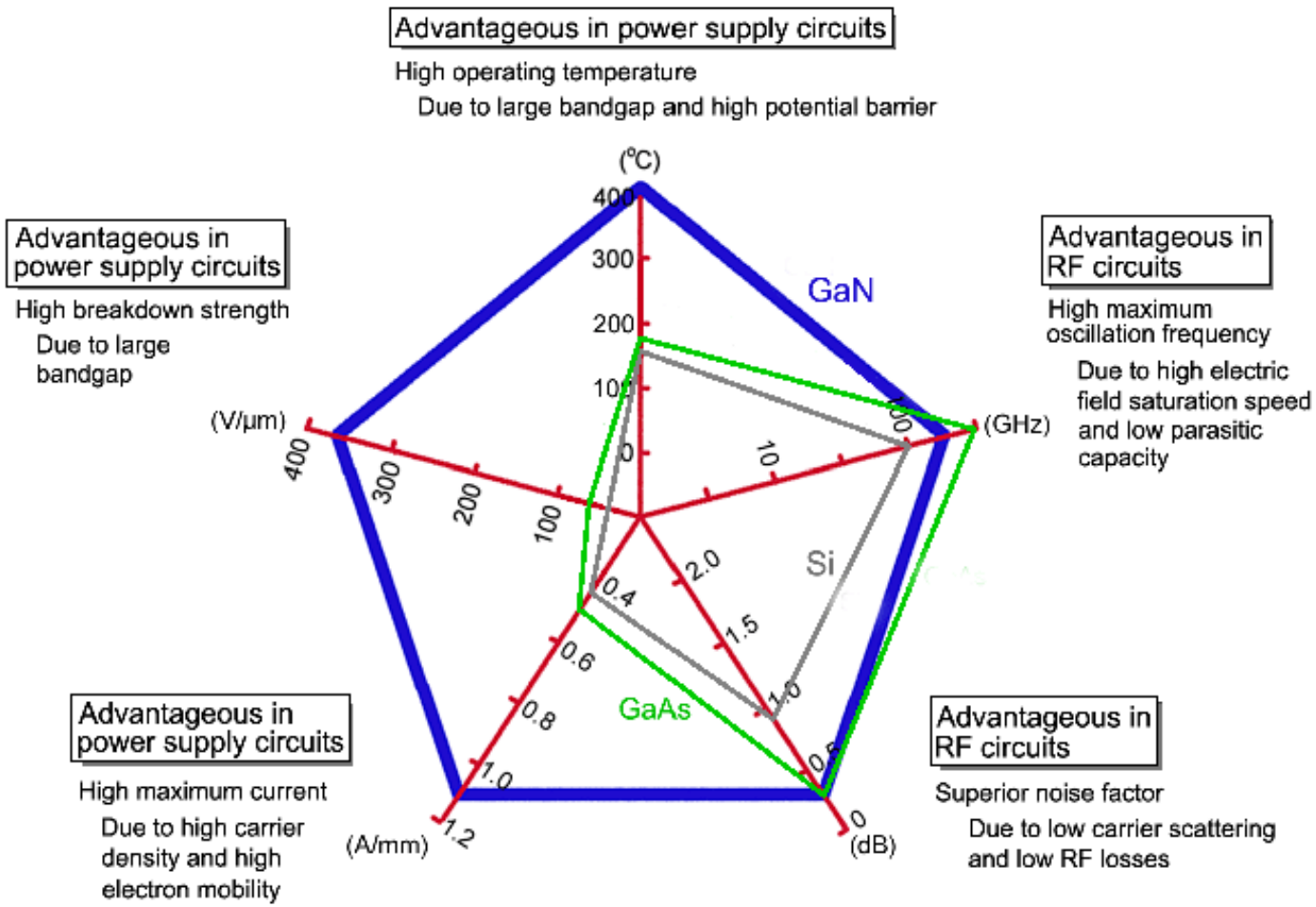
III-N DEVICE RESEARCH @ GT



- Center for Compound Semiconductors (CCS)
  - MOCVD epitaxial growth: Prof. Dupuis (CCS director)/AMDG
  - Simulation: Prof. Yoder
  - Device Fabrication & Circuits: Prof. Shen/SRL
- III-N Device Research Focus
  - InGaN/AlGaN UV/DUV Lasers
  - AlGaN/GaN UV/DUV Photodetectors
  - Al(In)GaN HFETs/MIS-HEMTs
  - InGaN HBTs
  - AlGaN/GaN power diodes

GaN for Power Electronic Devices

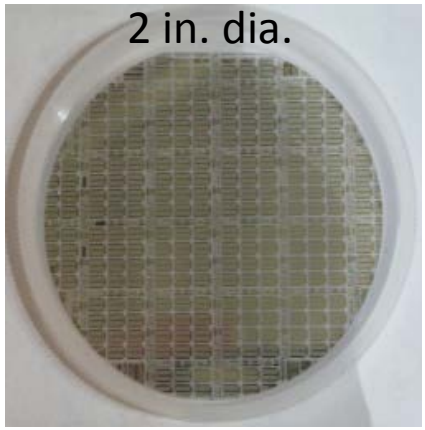
- GaN performance exceeds Si and GaAs in many applications

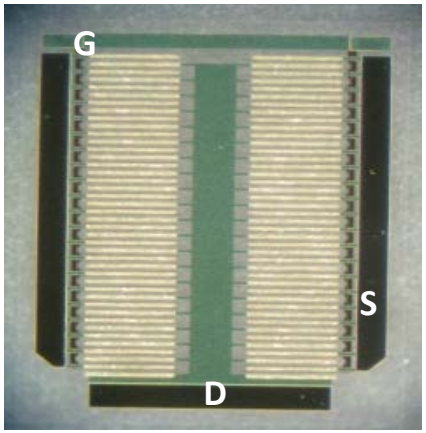


http://www.gansystems.com/why_gallium_nitride_new.php

HIGH-VOLTAGE III-N HEMTS – GAN ON SAPPHIRE

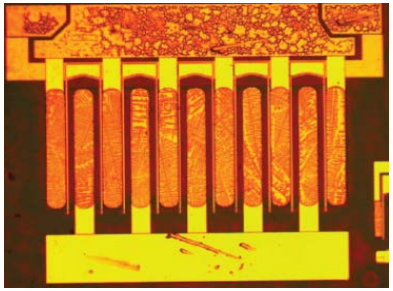
- GT device performance summary
  - **GaN/AlGaN HFET**
    - BV_{ds} > 1.4 kV, R_{dON} < 20 mΩ·cm^2 on 1 Amp power FETs
    - Gate leakage current < 10 μA/mm near device breakdown
  - **GaN/AlGaN lateral Schottky diode**
    - BV > 700, V_f = 1.3 V @ 2.5 A/cm^2
  - **10-A, 800-V power GaN FETs**
    - $R_{ds(ON)}$ = 0.8 Ω

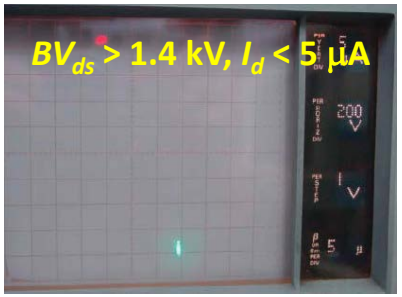


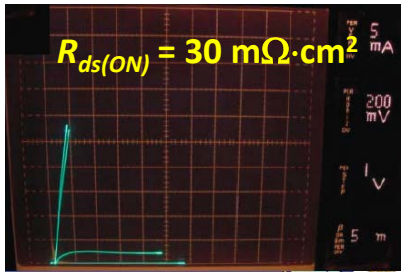


B. Narayan, et. al, ICNS-8, 2009

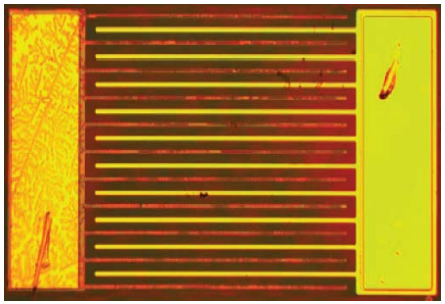
5-mm-Wg GaN/AlGaN Power HFETs

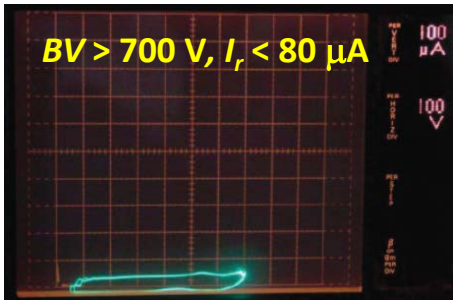


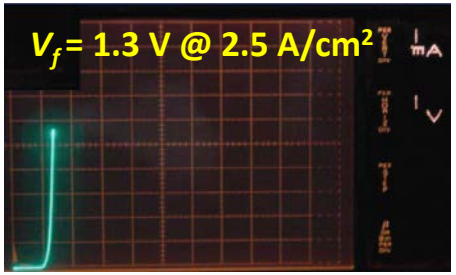




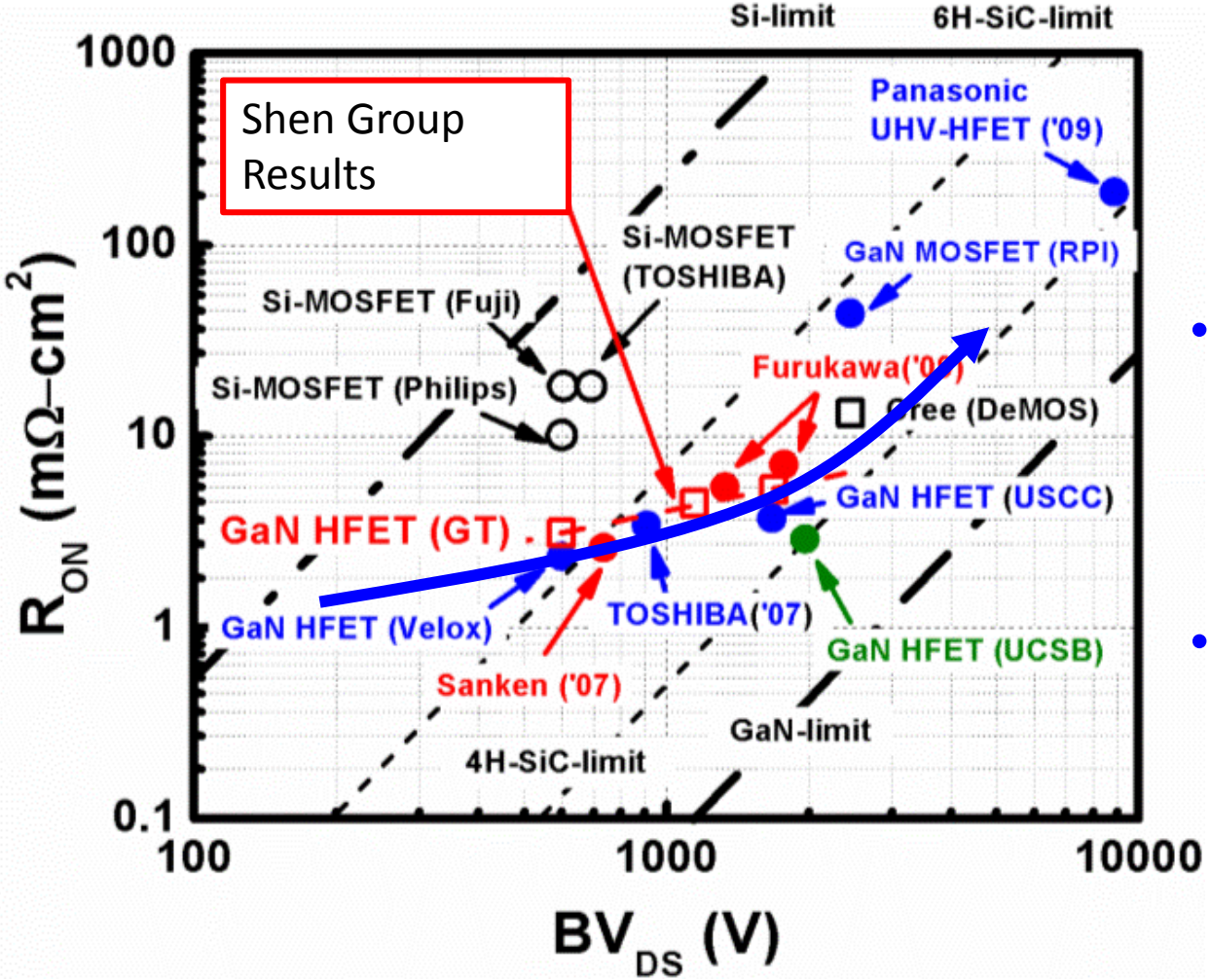
5-mm GaN/AlGaN power Schottky diodes







POWER SWITCHING PERFORMANCE FOR III-N HFETS



- GaN on Sapphire
- GaN on SiC
- GaN on Si
- GT's work (Shen group)

- **Laterally scaled GaN power FETs show no advantages over SiC devices for > 600-V applications.**
- **However, III-N FETs have tremendous impacts for low-voltage (<600V) power electronic systems.**

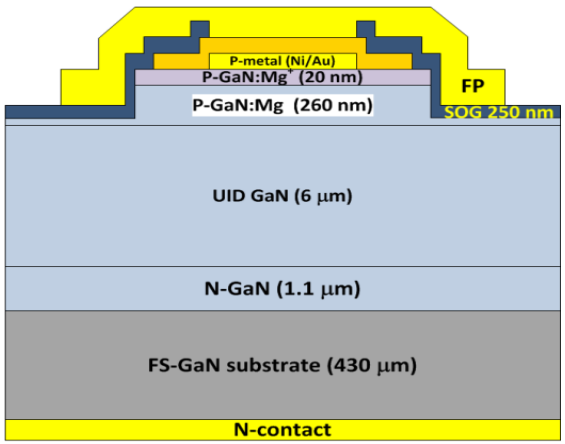
T. Kao, et. al, CSMANTECH, 2011.

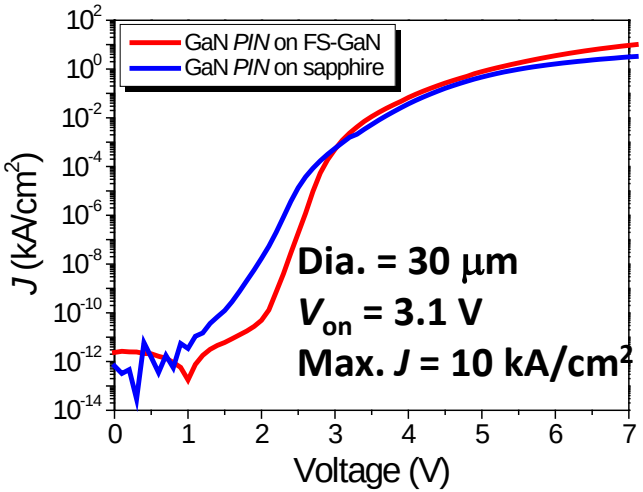
NEXT-GEN. III-N POWER DEVICES: UNIPOLAR FETS OR BIPOLAR TRANSISTORS?

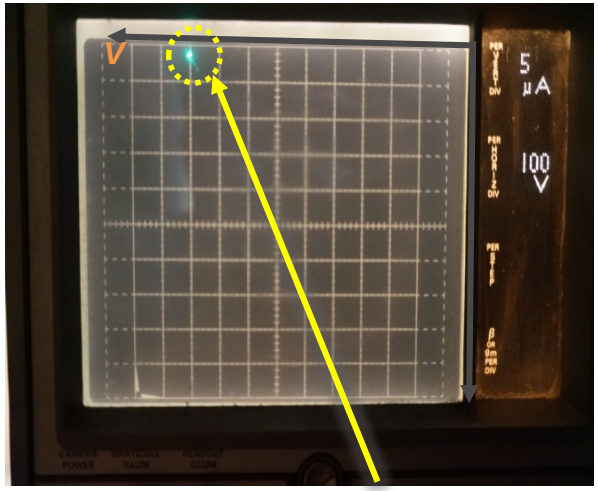
- Suitable power devices must
  - Conduct current vertically to maximize power handling & thermal management
  - Operate with single power supply for normally-off operation (non-galvanizing or galvanizing)

Assessment	III-N HBTs	III-N HEMTs
Advantages	• Normally-off • Uniform turn-on • Vertical conduction • High power density (>3 MW/cm^2) • Buried junction ($\mathcal{E}_C$>3MV/cm) • Vertical device scaling • Ultra-high-power operation	• Commercially available • Simple epitaxy and fabrication • $I_{d,max}$ > 1 A/mm
Challenges	• High p-doping • Low-defect substrate and epitaxy • Fabrication complexity	• V_{th} uniformity • Current collapse • Premature surface breakdown • Laterally scaled

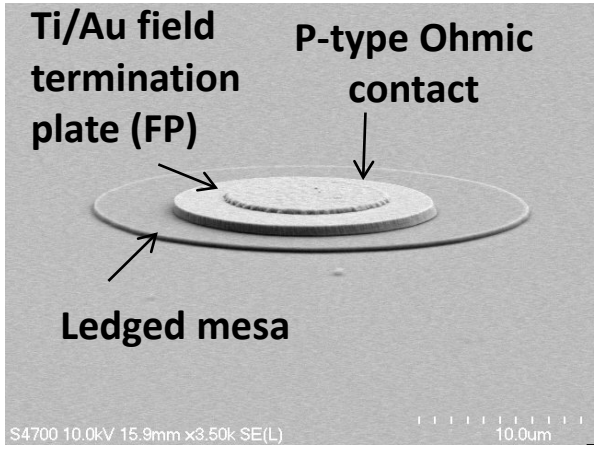
800-V GAN *PIN* RECTIFIERS







Reverse current ~ 1 μA @ -800 V

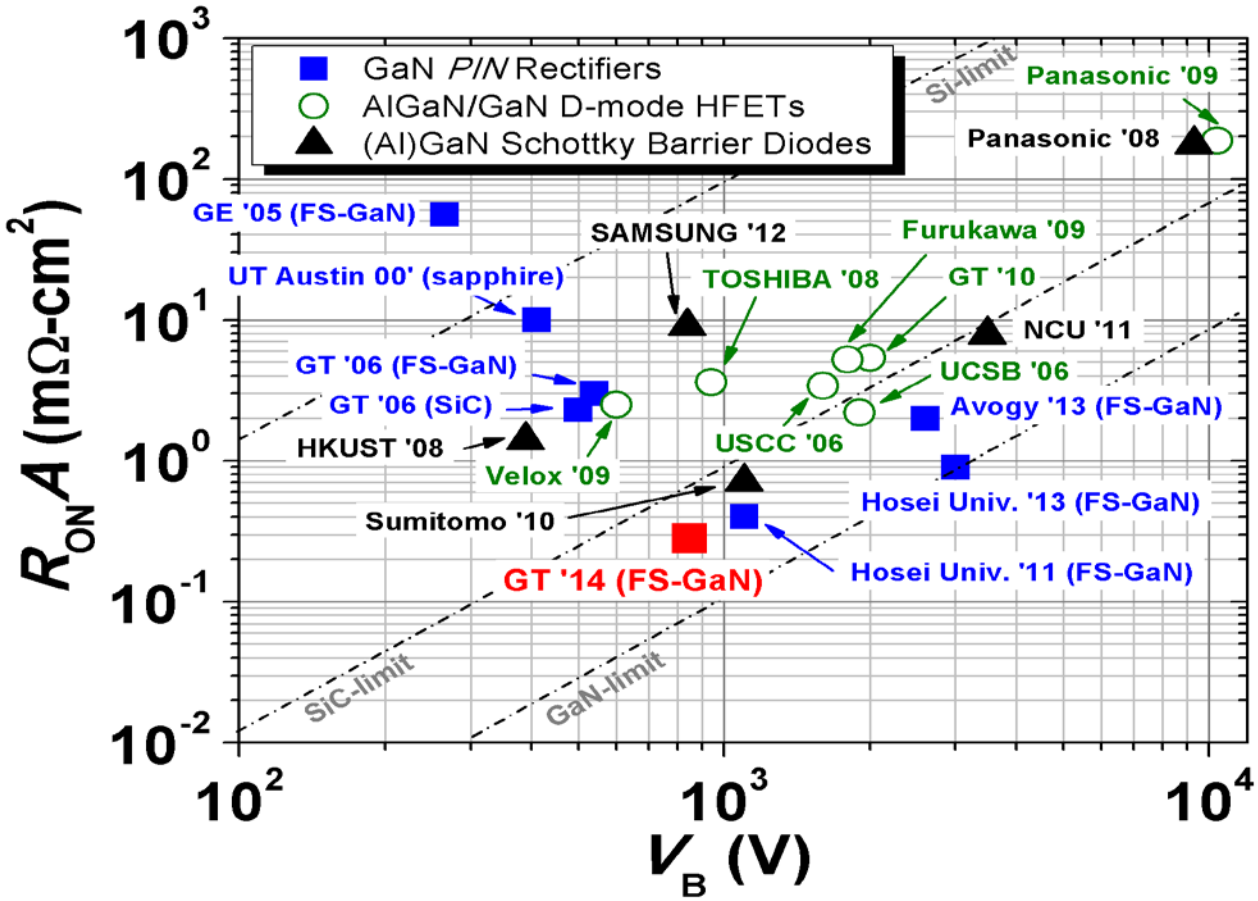


	PIN on FS-GaN	PIN on sapphire
J at -200 V	< 0.1 μA/cm²	1 mA/cm²
BV (V)	> 800	600
R_{ON} *A*@2.5kA/cm² (mΩ-cm²)	**0.28**	**0.7**
Baliga's FOM (GW/cm²)	> 2.5	~0.6

***T. Kao, et. al., IEEE Trans. Elect. Dev.*, 62(8), 2679, 2015**

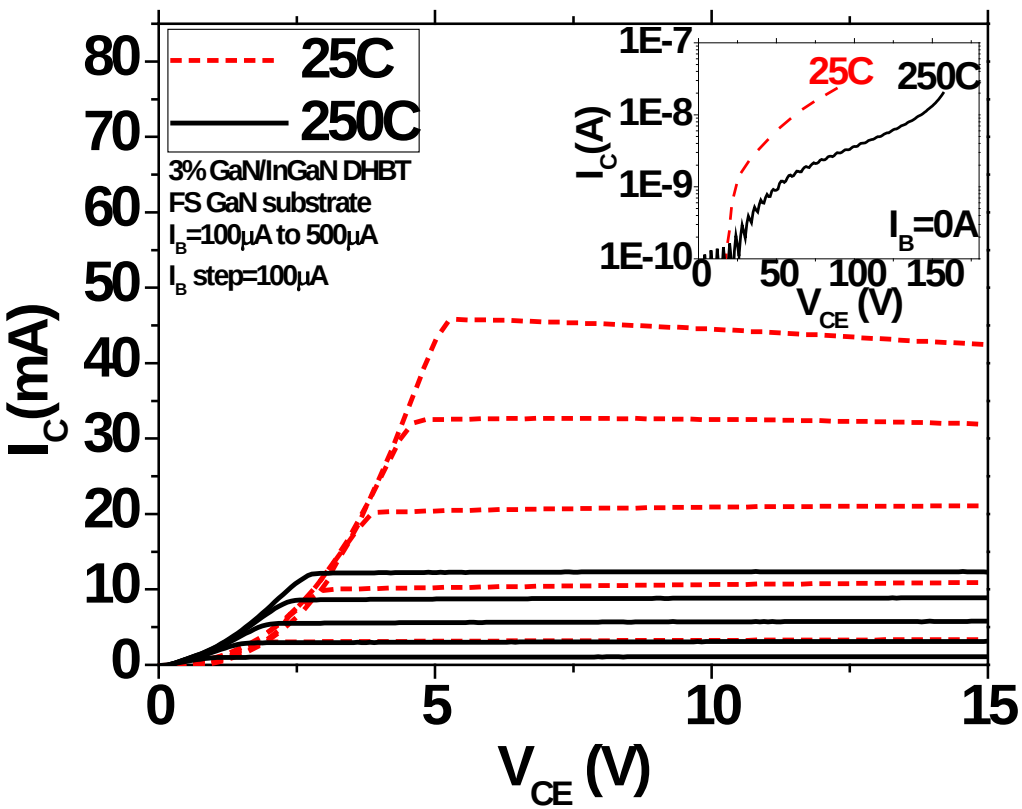
THE ULTIMATE III-N POWER DEVICES MUST BE IN THE VERTICAL CURRENT CONDUCTION FORM

Point of interest: GaN PIN power rectifiers



Vertical GaN PIN rectifiers demonstrated a nearly theoretical BFOM.

DEMONSTRATION OF HIGH-CURRENT-GAIN GAN HBT OPERATING AT 250°C

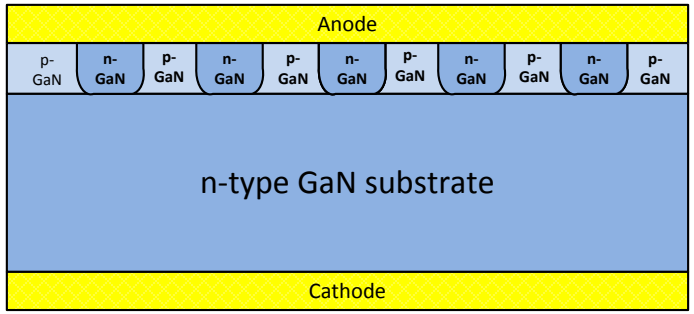


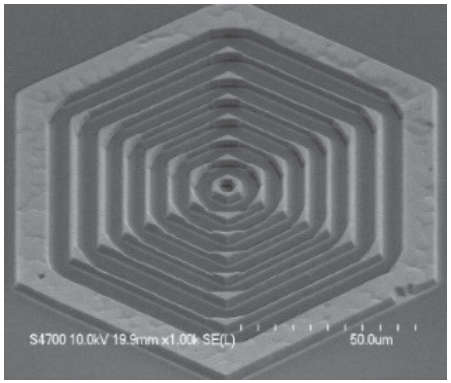
Lee, et al. Phys. Solidi Stat. 209(3) 497-500 (2012)

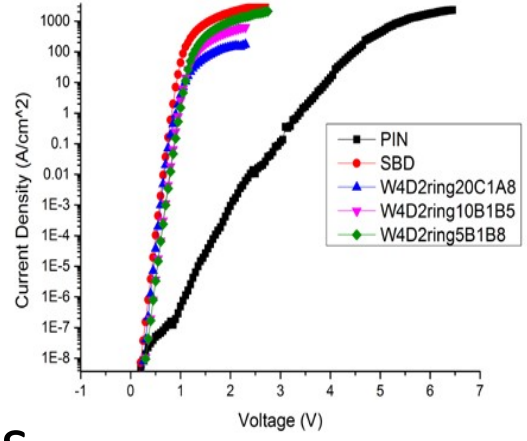
- InGaN HBT operation in elevated temperature
  - h_{fe} reduced from 115 to 43
  - BV_{CEO} increased from 90 to 157 V
  - V_{knee} & V_{offset} reduced as T goes up.
- InGaN HBTs work @ T>250°C, where Si devices are not functioning well.

NEXT STEPS IN GAN DEVICE RESEARCH

- We are currently developing novel GaN vertical junction-barrier Schottky (JBS) rectifiers for 600-V & scalable to higher voltage ratings.







- Ultimate technology development goals

Power GaN HFETs & MIS-HEMTs

Power GaN HBTs &Rectifiers

→ **GaN Thyristor & IGBTs**

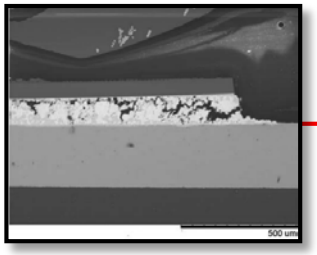
High-Power Packaging

- *High temperature*
- *High frequency*

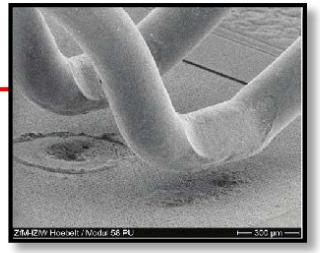
RELIABILITY: THE BALL AND CHAIN OF HIGH-POWER PACKAGING INNOVATIONS

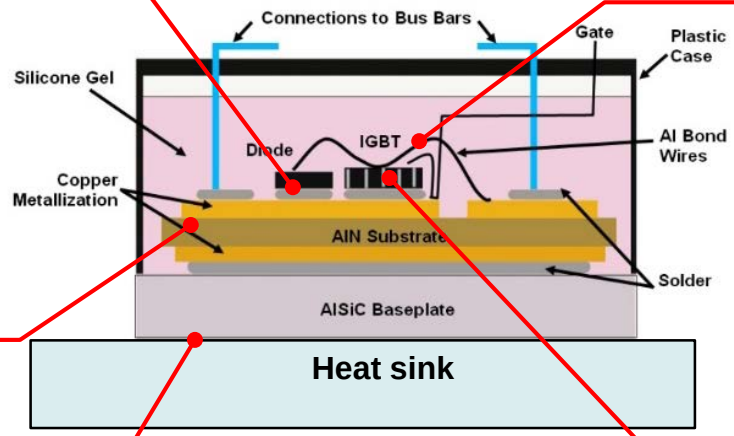
Failure modes in conventional IGBT modules well understood and documented but…

Die-attach

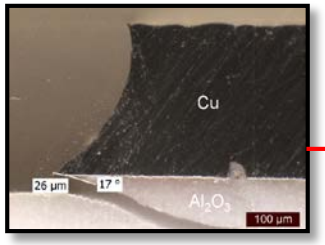


Wire bond

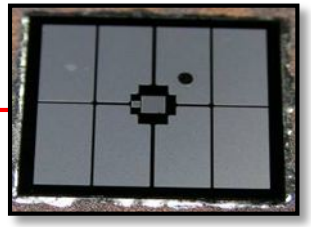




DBC substrate



Power switch



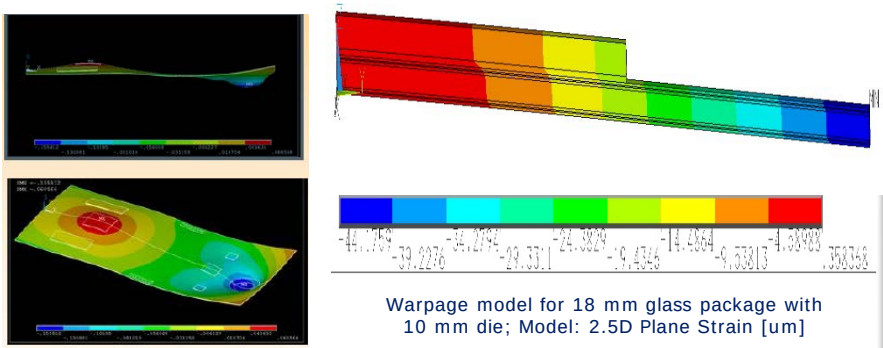
Liquid cooling

… what about reliability:

1) With higher operating temperatures?
2) New package structures?

MATERIAL, INTERFACE & PACKAGE DESIGN FOR RELIABILITY

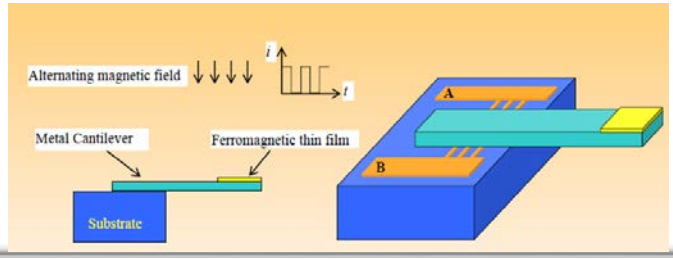
Process and design models to predict warpage stresses



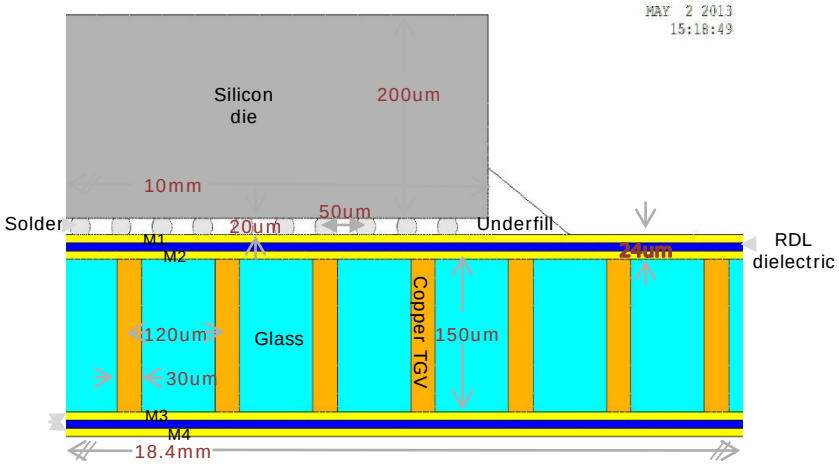
Warpage model for 18 mm glass package with 10 mm die; Model: 2.5D Plane Strain [um]

Interfacial adhesion modeling and characterization

- Mold compound and thinfilm adhesion and delamination at high temperatures
- Interfacial characterization

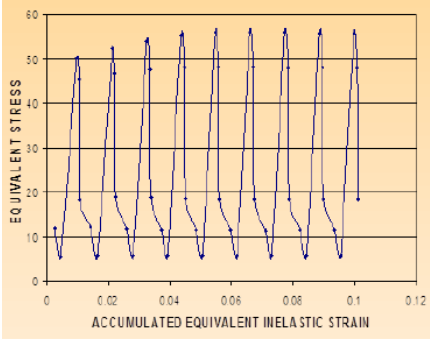


Package Design, Fabrication and Reliability Assessment

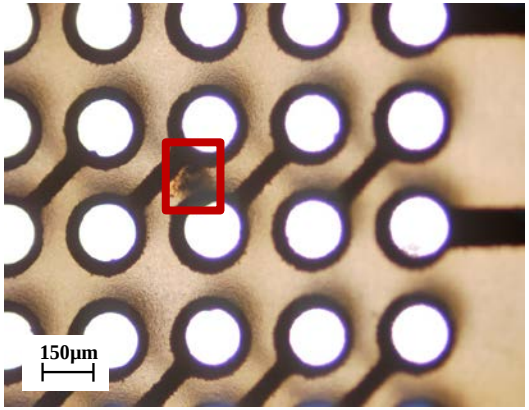


Predictive models for Long-term operational reliability

- Map and develop appropriate accelerated test conditions to develop field behavior
- Use damage metrics to map between accelerated testing and field condition



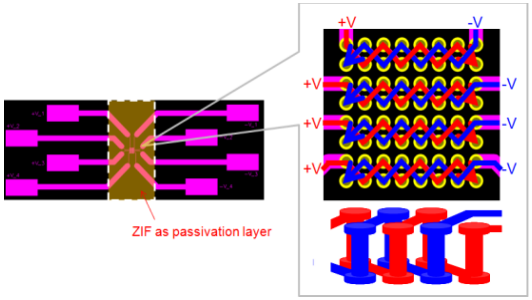
PRIOR WORK: HIGH-TEMPERATURE PACKAGING

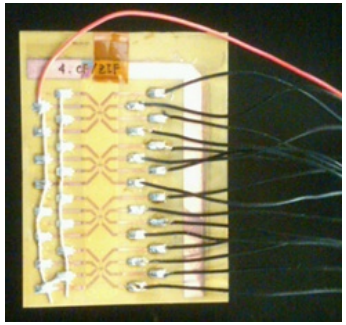


Core substrate

CAF in laminate TPVs

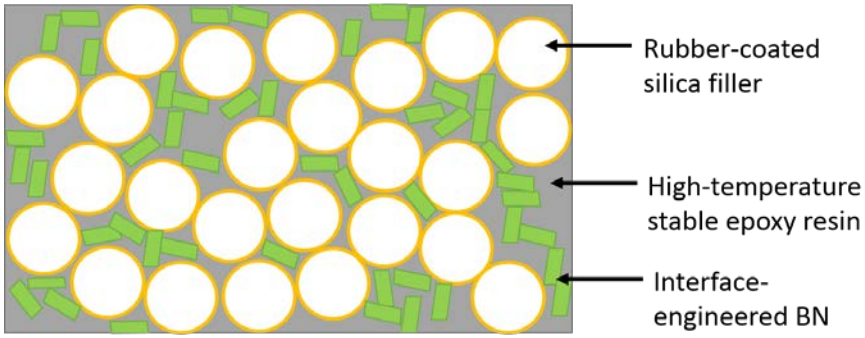
High-temp build-up dielectrics

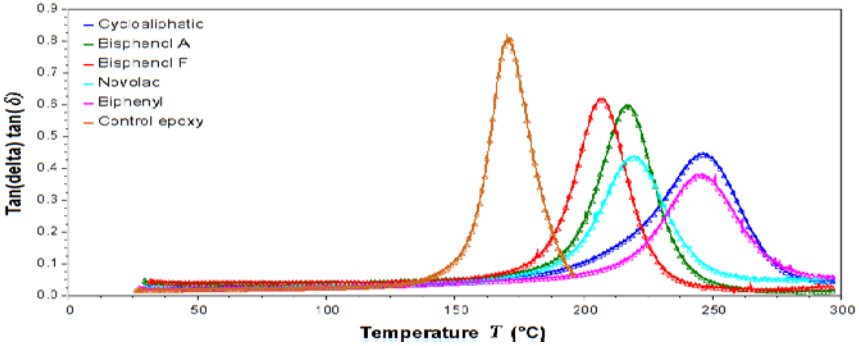




- *No Degradation of insulation resistance was observed during HAST testing.*
  - 130C, 85%RH, 100h (JEDEC JESD22-A110)
  - 100.0V bias

High-temp molding compounds



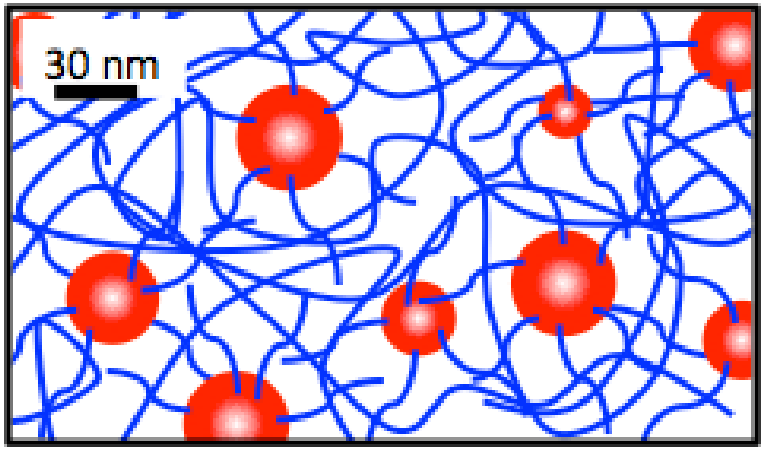


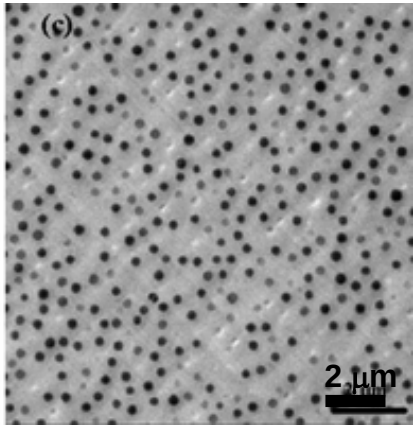
Property	Target
Thermal stability	200-250 C
CTE	10 ppm/C
Moisture Absorption	<0.5%
Thermal Conductivity	3-5 W/mK
Processability and substrate compatibility	Compatibility with standard mold infrastructure

GT'S MATERIAL INNOVATIONS: NANOCOMPOSITES VS "HOMOGENEOUS" HYBRID MATERIALS

Nanocomposites

Heterogeneous Hybrid Material

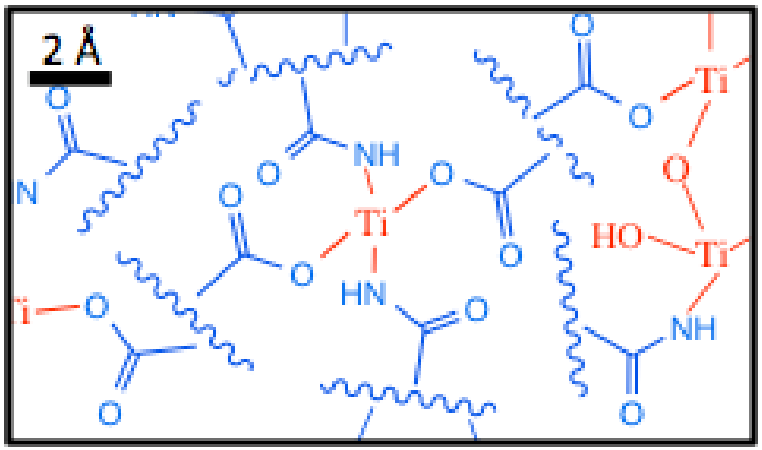


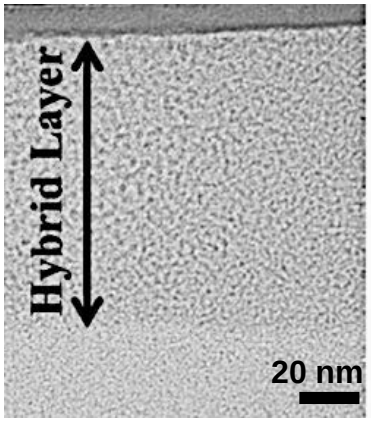


Nanocomposites ***have interfaces*** *between the two phases*

Hybrid Materials

Homogeneous Hybrid Material

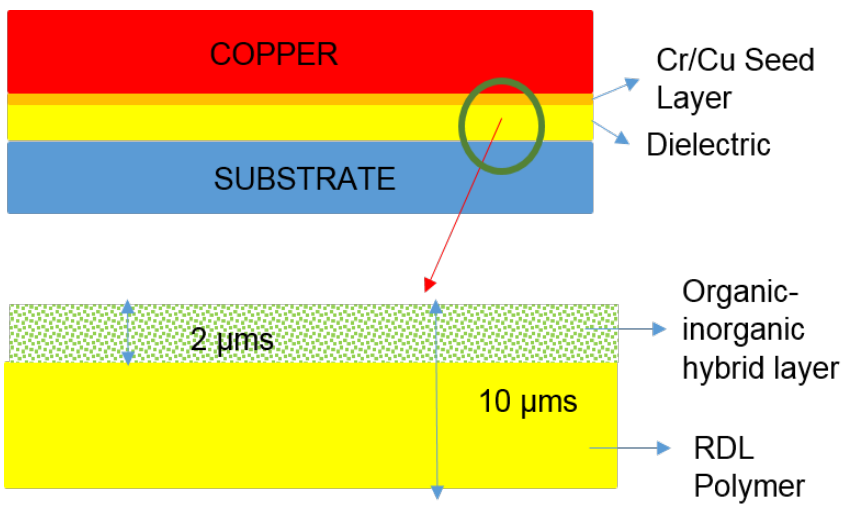


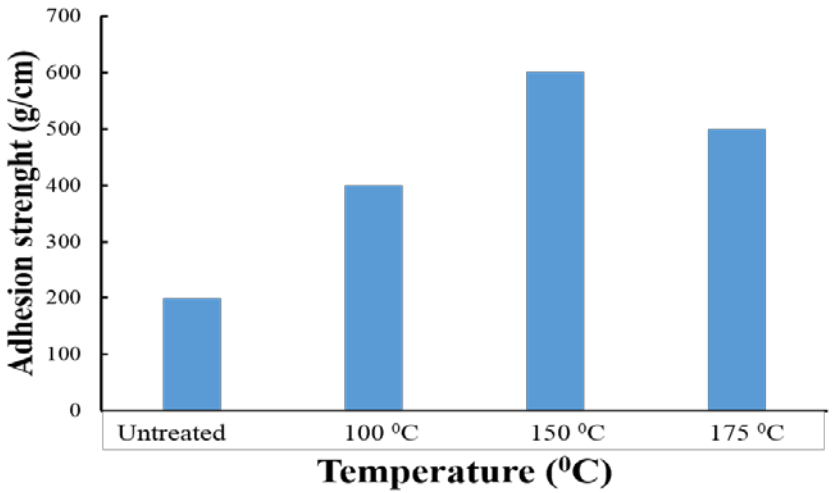


*Hybrid materials are homogeneous at the atomic-scale (****no interfaces****)*

ADVANCED METAL-POLYMER HYBRID INTERFACES FOR BETTER ADHESION

Inorganic hybridization of polymer surfaces using Vapor-Phase Infiltration



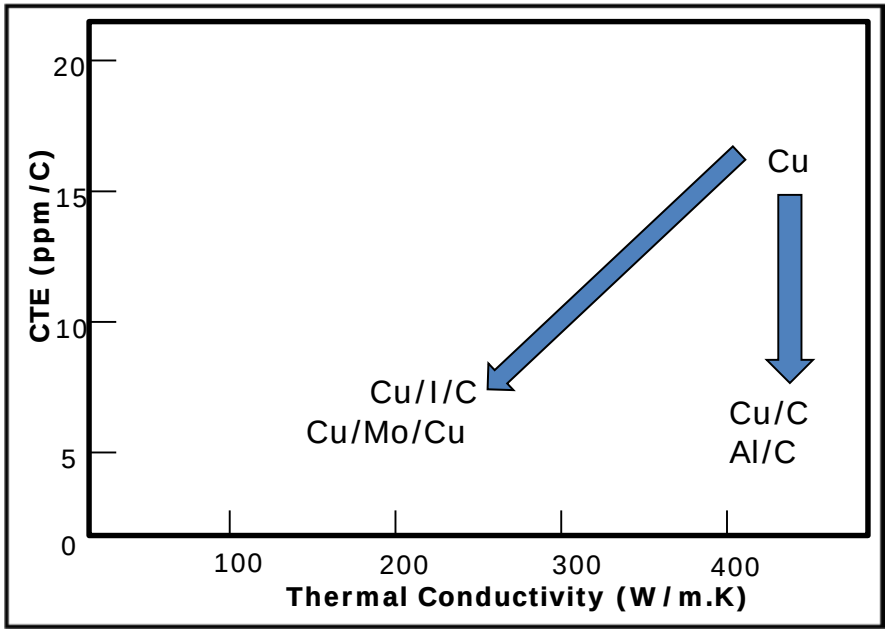


3X improvement in adhesion because of stronger covalent bonds between metal and polymer, mediated by the hybrid surface

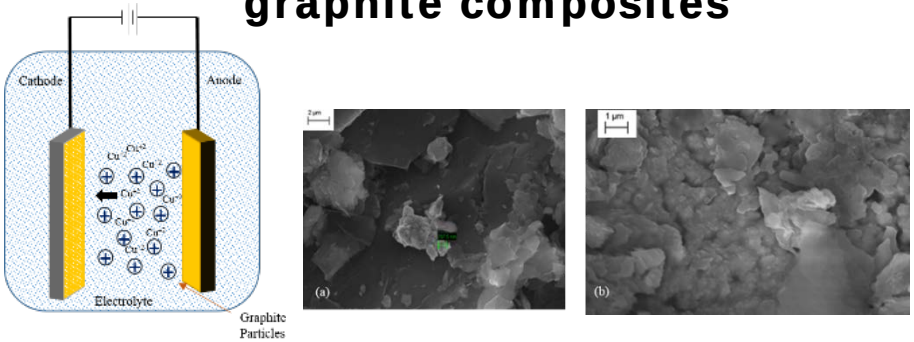
More thermal and humidity testing in progress

LOW-STRESS Cu COMPOSITE CONDUCTORS

- Zero-stress pkg from matched CTE:
  - Lower die stresses on lead-frame
  - Lower substrate and interfacial stresses with DBC, DBA and AMB substrates
  - Minimal compromise on thermal and electrical conductivities



Demonstration of plated copper-graphite composites



- CTE approach 7-9 ppm/C
- 2-3X reduction in package stress
- 2-3X reduction in warpage (μm/inch)

BEYOND TRADITIONAL SOLDERS, PANORAMA OF INTERCONNECTION AND DIE-ATTACH TECHNOLOGIES

Georgia Tech

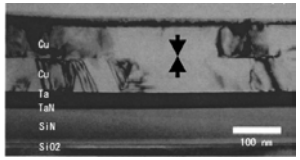
High-temperature lead-free Solders

- AuSn, AuGe

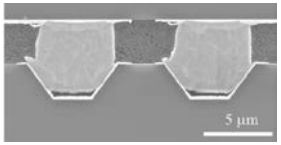
→ ***Cost, high bonding temperatures***

Solid-state bonding

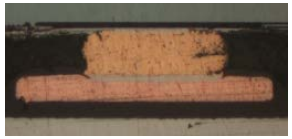
Direct Cu-Cu w/ surface activation



Cu-Au ultrasonic bonding



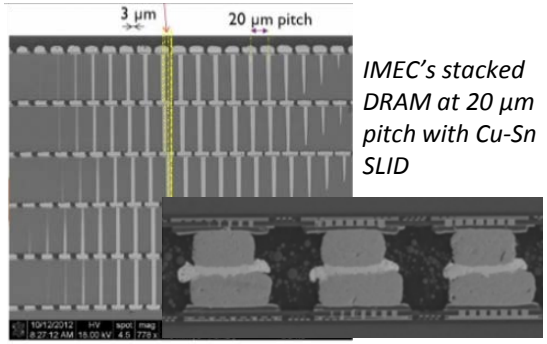
Au-Au ultrasonic / TCB bonding



→ ***Manufacturability, cost***

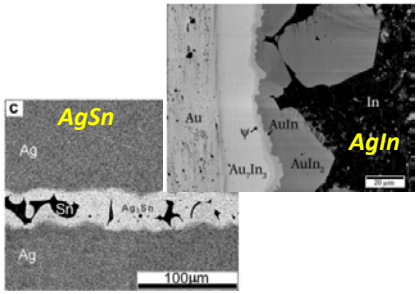
TLP / SLID bonding

Transient Liquid Phase / Solid-LIquid Interdiffusion

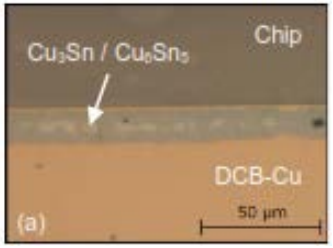


IMEC's stacked DRAM at 20 µm pitch with Cu-Sn SLID

TLP of Ag systems



Infineon's Cu-Sn SLID IGBT die-attach

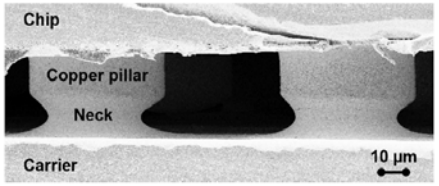


→ ***Kirkendall voids, long cycle times, microstructure stability***

Sintering

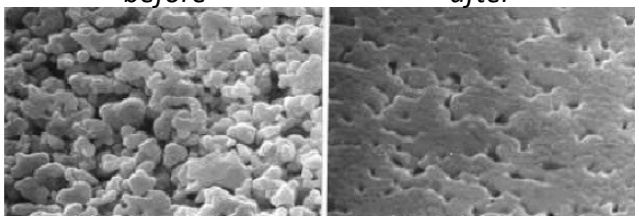
- Nanoscale for densification at low temp. / pressure

Nanocopper ink: self-assembly using capillary bridging (IBM Zurich)



Nanosilver paste: IGBT die-attach (Semikron)

before *after*

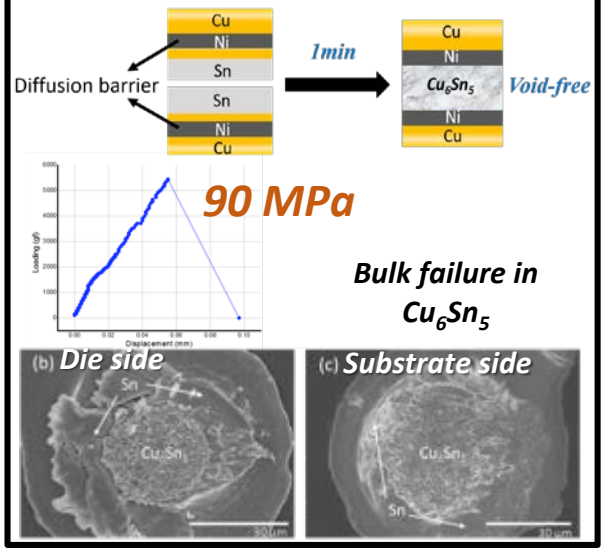


→ ***Variability in paste composition, manufacturability, retained porosity, stress management at large die size, ..***

METASTABLE Cu-Sn SLID BONDING: DESIGN FOR PERFORMANCE, RELIABILITY & MANUFACTURABILITY

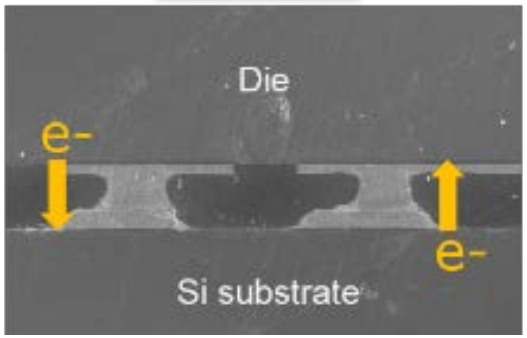
- **20X reduction in assembly cycle time vs. standard SLID: 3s TC-NCP + 1 reflow**

Superior shear strength



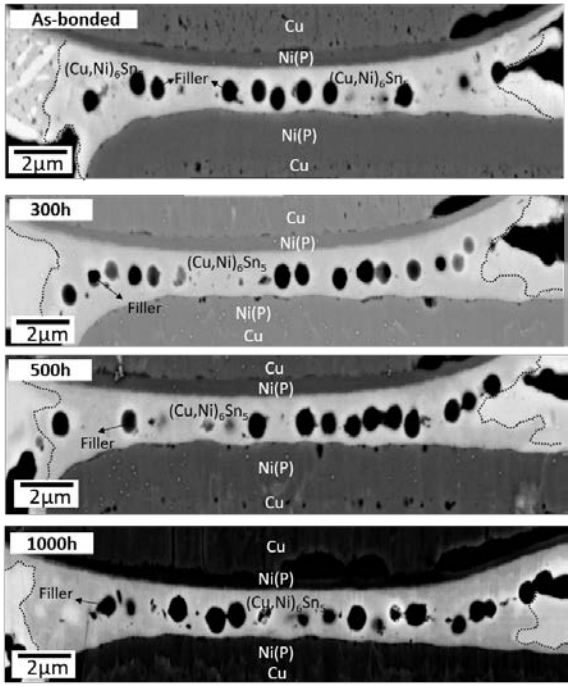
1000h EM at 10^5A/cm^2, 150°C

Superior electromigration performance at high current densities



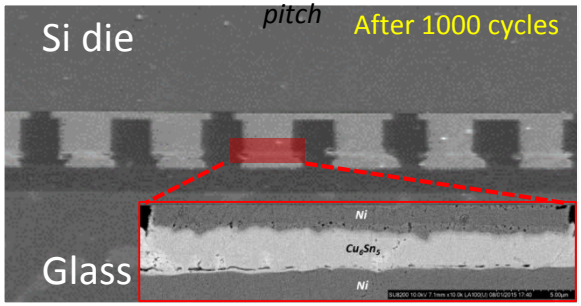
Thermal stability

HTS 1000h at 200C

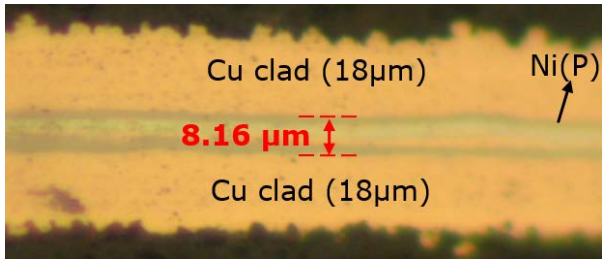


Reliability & Manufacturability

Thermal cycling test on glass at 50um pitch



5mm x 5mm die-attach



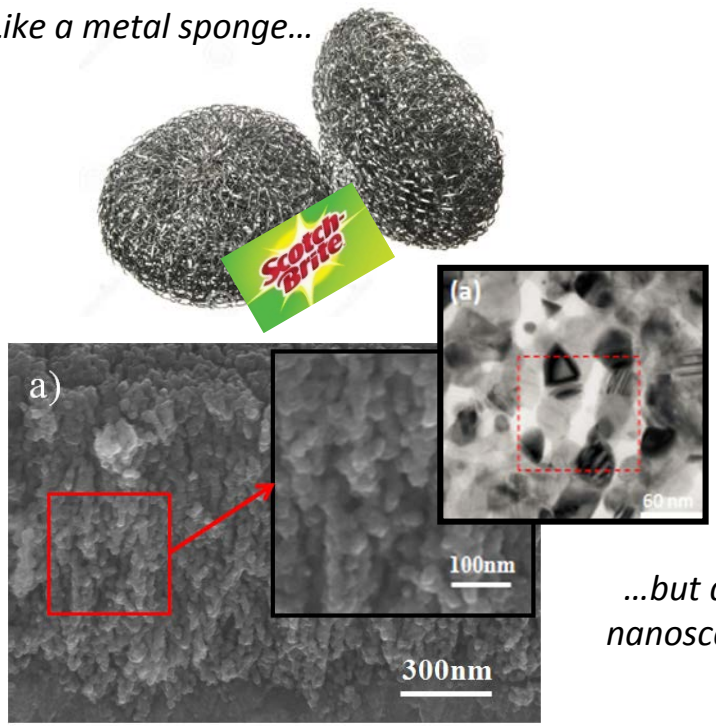
- **Void-free interface**
- **High assembly throughput**
- **High composition tolerance**

NANOCOPPER FILM SINTERING
A LOW-COST ALTERNATIVE TO SILVER SINTERING

Georgia Tech

What are metal foams?

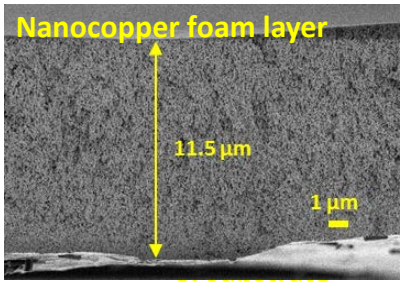
Like a metal sponge…

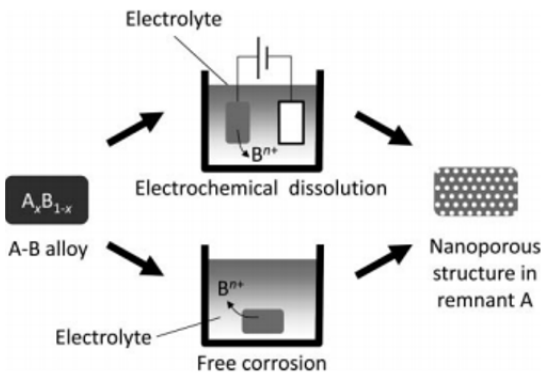


…but at nanoscale

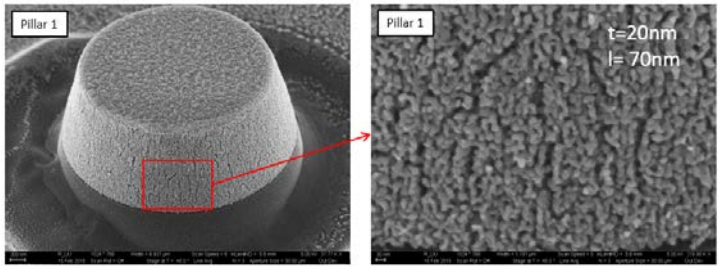
Synthesis by chemical dealloying

- Co-plating
- Furnace melting





Preform or patterning with standard lithography processes

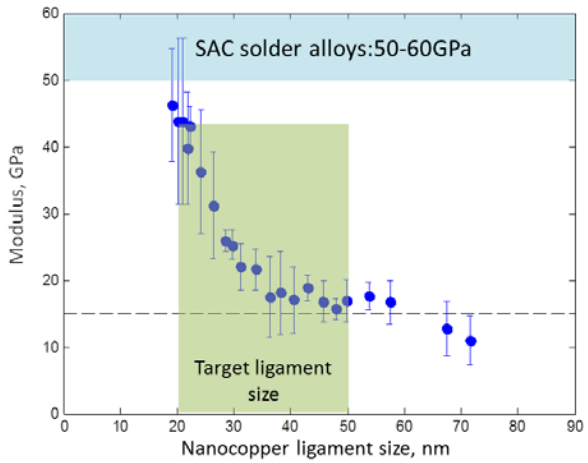


- 3D interconnected structure with nanoscale features: no volatiles, high surface energy, oxidation management with reducing atmosphere, fine control of BLT and shrinkage
- Low-cost processing as patterned interconnections on wafer or substrate, or as a preform film for modular supply chain (also with Al, NiAl)

FILM SINTERING: INITIAL TECHNOLOGY STATUS

Tailorable physical properties

Sub-20GPa modulus



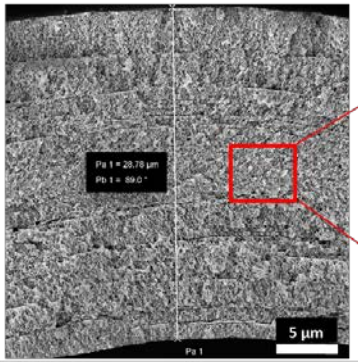
- Material design from 1st principle: pre- and post-sintering properties

Nanocopper foams as die-attach films

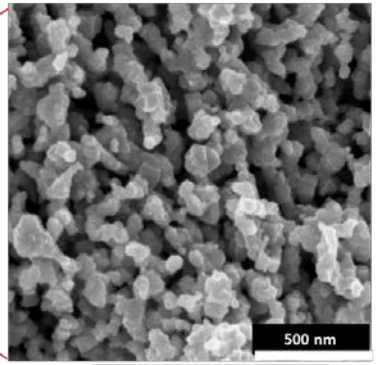
*Cu-Zr-Al ribbons: **~55µm** thick*
10mm x 3mm

Free dealloying

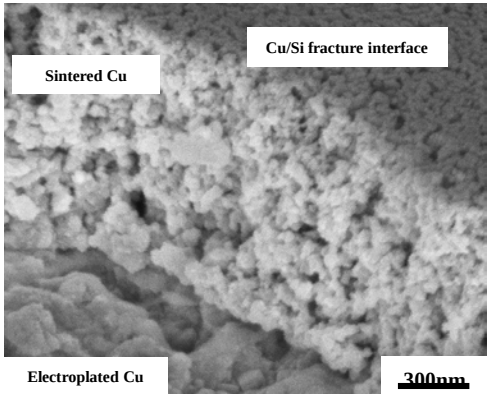
Nano-Cu ribbon
10mm x 2mm

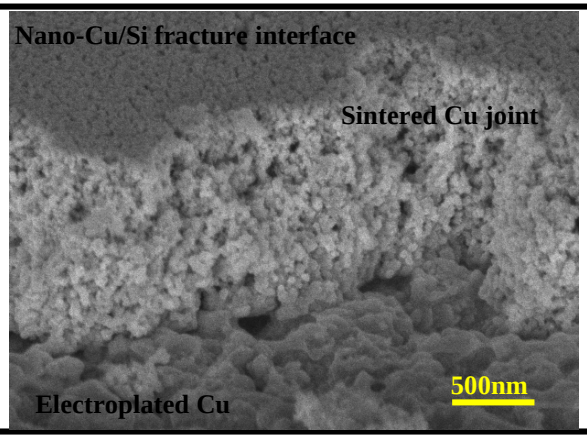


~30µm-thick nano-Cu film



25-60 nm ligament size

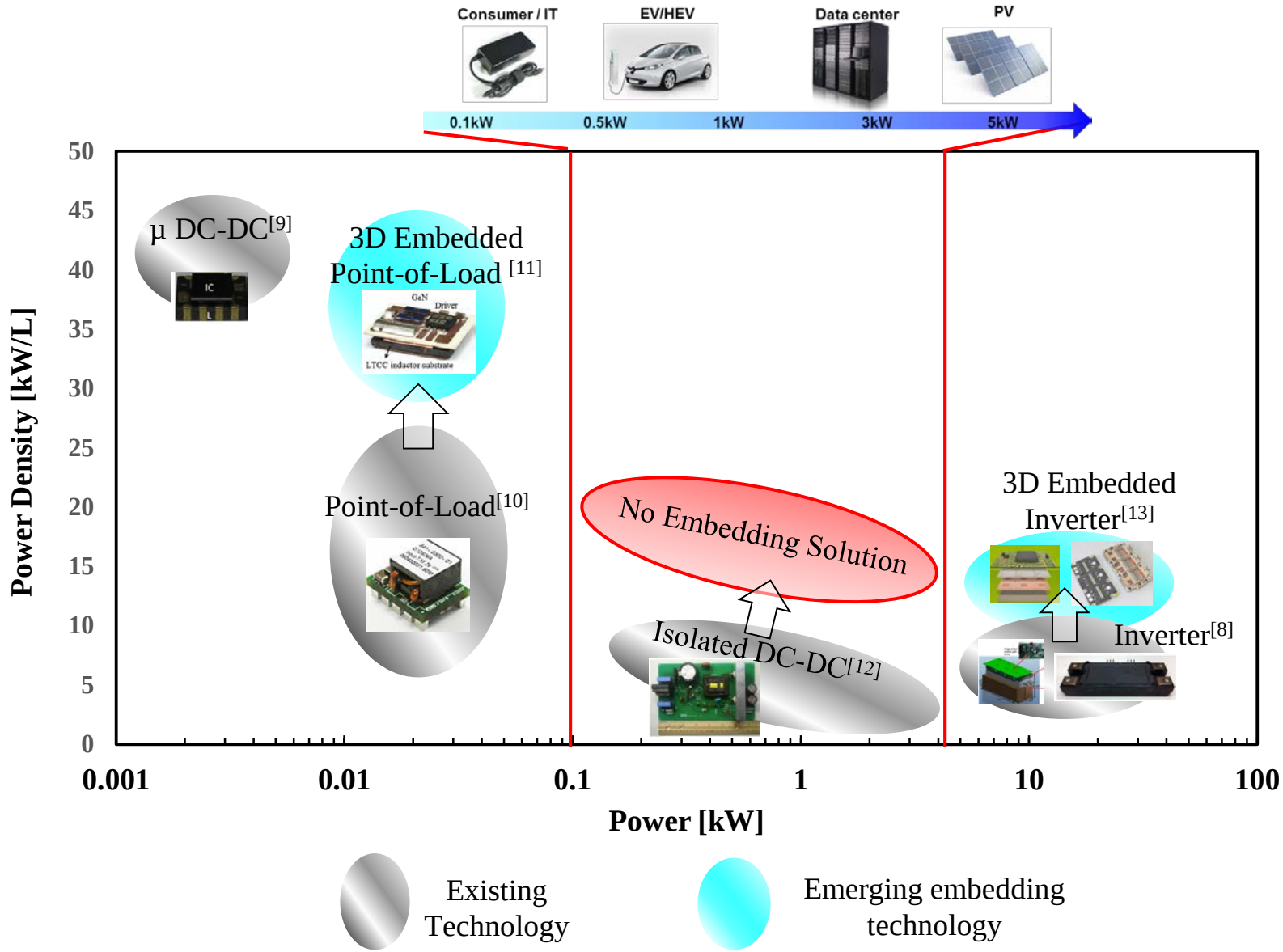




Assembly trials

- Sintering on bulk Cu
- Bonding at 200C / 6MPa / 15min with over 85% density
- Shear strength over 4kgf

CRITICAL NEED FOR EMBEDDING SOLUTIONS IN ISOLATED DC-DC CONVERTERS



INTEGRATION OF MAGNETIC COMPONENTS FOR HIGH-DENSITY CONVERTERS

Conventional

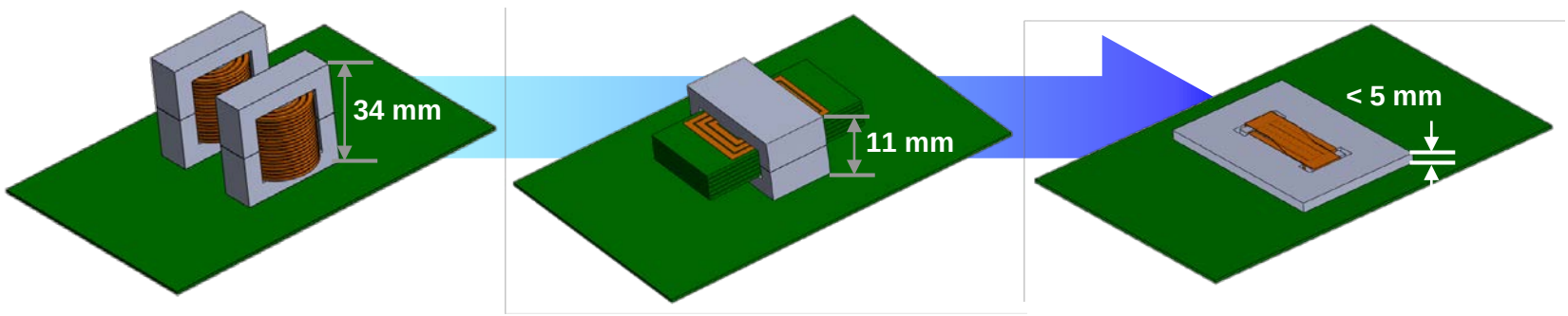
- Conventional discrete transformer and resonant inductor

Planar

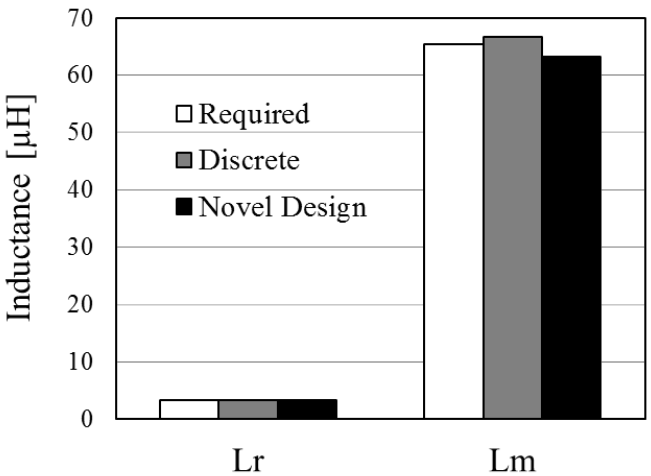
- Planar transformer with integrated resonant inductor

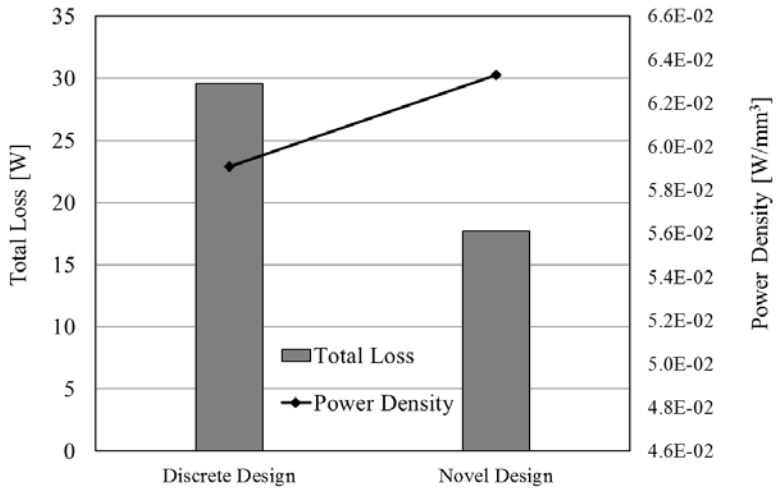
PRC's approach

- "Flat" transformer with integrated resonant inductor



- Low profile core and winding designs maintaining low-loss and high-power density for substrate embedding
- Accurate control over integrated resonant inductor using magnetic slab

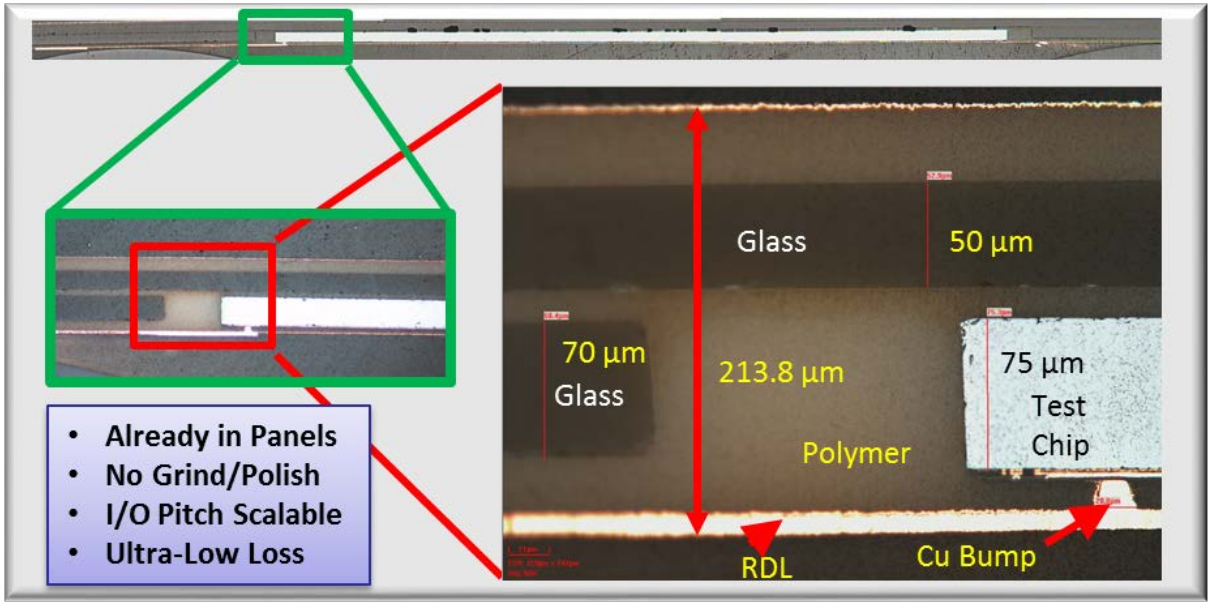




~40% reduction in total loss with 7% increase in power density

POWER EMBEDDING: NEW FRONTIER FOR HIGH-FREQUENCY CONVERTERS

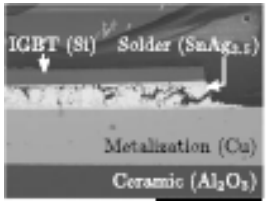
- Low-inductance package
  - Glass fanout for chip-scale hermetic packaging of GaN-on-Si devices
  - At module level, co-integration of power, driver and controller circuits
- Ultra-thin glass as high-temp. dielectric
  - Reduced stress on device compared to molded package
  - High breakdown voltage
  - Tailorable CTE for reliability

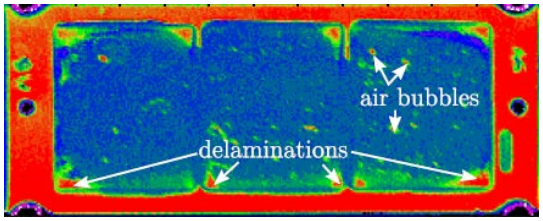


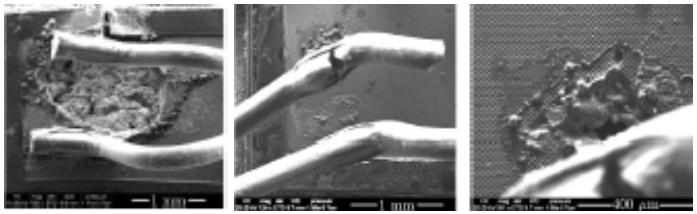
RELIABILITY, PROGNOSTIC & CONDITION MONITORING

Reliability

- Failure modes in new architectures (embedding)
- Accelerated test conditions for high-temp. operations
- Design of materials and package for stress management



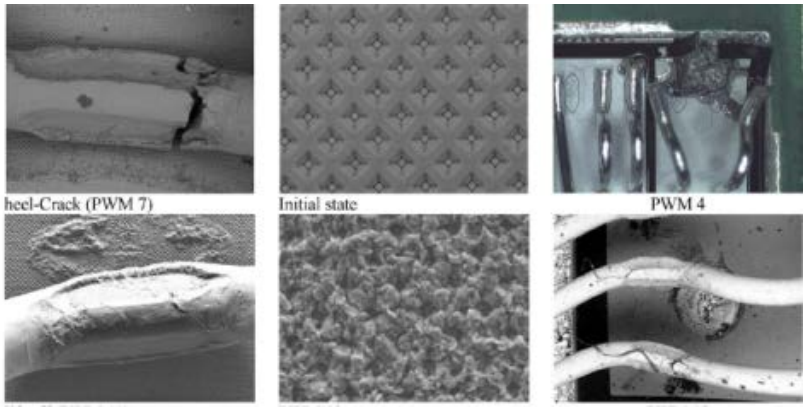




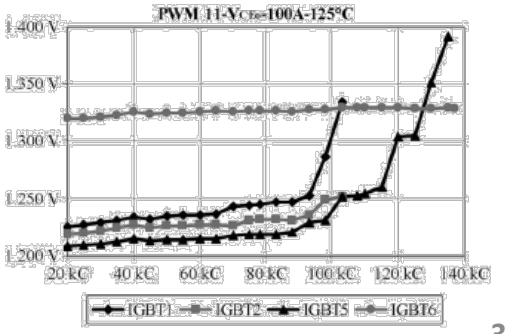
Prognostic & condition monitoring

- Sensor integration in package / device
- Aging indicators for predictive maintenance, failure detection and prevention

Power cycling reliability: wire bond failures, recrystallization of Al metallization, device failure



Failure prediction by V_{CE} monitoring



- Real-time, in-situ monitoring

SUMMARY

GT-PRC and its industry partners are advancing high power-electronics including device, component and packaging technologies:

- High-frequency converters with low-inductance embedded packages with:
  - Glass fanout for hermetic GaN package
  - Integration of thick thermal Cu structures
  - Miniaturized and embedded magnetic components

- High-temperature, high-reliability converters with:
  - Vertical-conduction GaN devices
  - High-temperature dielectrics with engineered interfaces
  - Low-CTE high-conductivity conductors
  - Film sintering with nanofoams