High-Power Devices, High-Temperature Materials and Packaging for Electric Cars
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
POWER FLOW IN ELECTRIC VEHICLES

Grid
120~240 VAC

On-Board Charger
120VAC → 400VDC

AC
PFC
DC
DC

Integrated function

HV Battery
400VDC

Main Inverter
600~700VDC

Electric motor
30kW (continuous)
55kW (peak)

HV DC-DC
400 → 48VDC

LV Battery
48VDC

ADAS & Auxiliary: low power (<100W IVR power module)

12~48V

Radar
Stereo Camera
Infotainment
Air conditioning
Cooling pump

Lighting, Power steering, sensors, etc...
PRIOR ART – THE ONGOING WBG REVOLUTION
SiC IN POWER TRAIN

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

Double-sided cooling

Power embedding

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

Conventional Si IGBT inverter package

Controller board
Gate driver unit
Power module

Multi-chip module on DBC substrate with bond wires

Source: Keysight

Schweizer p² Pack

Multi-chip module on DBC substrate with bond wires

Source: Semikron

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

Double-sided cooling

Power embedding

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

Schweizer p² Pack
Recent trends: GaN FETs, integrated magnetics for high-frequency designs

Monolithic integration of transformer and resonant inductor on single magnetic core

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

3.3kW – 0.5-1MHz GaN LLC resonant converter with embedded magnetics, power density >200W/in³ and efficiency >97%

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

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

HIGH-VOLTAGE III-N HEMTS – GAN ON SAPPHIRE

• GT device performance summary
  – GaN/AlGaN HFET
    • $BV_{ds} > 1.4$ kV, $R_{dON} < 20$ m$\Omega$·cm$^2$ on 1 Amp power FETs
    • Gate leakage current $< 10$ $\mu$A/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
    • $R_{ds(ON)} = 0.8$ $\Omega$

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

Shen Group Results

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

<table>
<thead>
<tr>
<th>Assessment</th>
<th>III-N HBTs</th>
<th>III-N HEMTs</th>
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<tbody>
<tr>
<td>Advantages</td>
<td>NORMALLY-OFF</td>
<td>Commericially available</td>
</tr>
<tr>
<td></td>
<td>Uniform turn-on</td>
<td>Simple epitaxy and fabrication</td>
</tr>
<tr>
<td></td>
<td>Vertical conduction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High power density (&gt;3 MW/cm²)</td>
<td>( I_{d,\text{max}} &gt; 1 \text{ A/mm} )</td>
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<tr>
<td></td>
<td>Buried junction ( E_C &gt; 3 \text{MV/cm} )</td>
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<tr>
<td></td>
<td>Vertical device scaling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ultra-high power operation</td>
<td></td>
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<tr>
<td>Challenges</td>
<td>High p-doping</td>
<td>V_{th} uniformity</td>
</tr>
<tr>
<td></td>
<td>Low-defect substrate and epitaxy</td>
<td>Current collapse</td>
</tr>
<tr>
<td></td>
<td>Fabrication complexity</td>
<td>Premature surface breakdown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Laterally scaled</td>
</tr>
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800-V GaN PIN RECTIFIERS

Reverse current ~ 1 µA @ -800 V

<table>
<thead>
<tr>
<th></th>
<th>PIN on FS-GaN</th>
<th>PIN on sapphire</th>
</tr>
</thead>
<tbody>
<tr>
<td>J at -200 V</td>
<td>&lt; 0.1 µA/cm²</td>
<td>1 mA/cm²</td>
</tr>
<tr>
<td>BV (V)</td>
<td>&gt; 800</td>
<td>600</td>
</tr>
<tr>
<td>$R_{ON} <a href="mailto:A@2.5kA">A@2.5kA</a>/cm²$</td>
<td>0.28</td>
<td>0.7</td>
</tr>
<tr>
<td>Baliga’s FOM (GW/cm²)</td>
<td>&gt; 2.5</td>
<td>~0.6</td>
</tr>
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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

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

… 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

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

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

High-temp molding compounds
- Rubber-coated silica filler
- High-temperature stable epoxy resin
- Interface-engineered BN

High-temp build-up dielectrics
- ZIF as passivation layer

<table>
<thead>
<tr>
<th>Property</th>
<th>Target</th>
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<tbody>
<tr>
<td>Thermal stability</td>
<td>200-250°C</td>
</tr>
<tr>
<td>CTE</td>
<td>10 ppm/C</td>
</tr>
<tr>
<td>Moisture Absorption</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>3-5 W/mK</td>
</tr>
<tr>
<td>Processability and substrate compatibility</td>
<td>Compatibility with standard mold infrastructure</td>
</tr>
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</table>
GT’S MATERIAL INNOVATIONS: NANOCOMPOSITES VS. “HOMOGENEOUS” HYBRID MATERIALS

Nanocomposites

Hybrid Materials

Nanocomposites have interfaces between the two phases.

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

- 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

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

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)

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

1000h EM at $10^5$A/cm$^2$, 150°C

Superior electromigration performance at high current densities

Reliability & Manufacturability

- Void-free interface
- High assembly throughput
- High composition tolerance
What are metal foams?

Like a metal sponge...

...but at nanoscale

Synthesis by chemical dealloying

- Co-plating
- Furnace melting

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Nanocopper foam layer

Electrolyte

A-B alloy

A-B_{1-x}

Electrochemical dissolution

Nanoporous structure in remnant A

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**

- 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

Existing Technology

Emerging embedding technology

Power Density [kW/L]

Power [kW]

0.1kW

0.5kW

1kW

3kW

5kW

μ DC-DC [9]


Point-of-Load [10]

No Embedding Solution

Isolated DC-DC [12]

3D Embedded Inverter [13]

Inverter [8]
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**

- 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*

- Real-time, in-situ monitoring
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