Power semiconductor for hybrid and electric vehicles: state of the art, challenges and future roadmap

LIU Meng / 刘蒙
China Powertrain Segment Marketing
July 2012, EDN China Automotive Electronics Design Conference
# Table of contents

- Semiconductors as key enablers for EV architectures
- Trends and applications of high power semiconductor solutions
- Higher integrated power semiconductor solutions
- Automotive quality/reliability for high power semiconductors
- Summary and outlook
Paradigm shift: 
**IGBT’s are the Injectors of Tomorrow**

<table>
<thead>
<tr>
<th><strong>Today</strong></th>
<th>Fuel Injectors in Combustion Engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Driver of vehicle performance: <strong>Mechanical</strong> components and subsystems</td>
<td></td>
</tr>
<tr>
<td>- Assisted by <strong>semiconductors</strong></td>
<td></td>
</tr>
<tr>
<td>- On-board electrical power: ~1 kW</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Tomorrow</strong></th>
<th>IGBT’s in Electrical Inverters</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Driver of vehicle performance: <strong>Semiconductor</strong> components and subsystems</td>
<td></td>
</tr>
<tr>
<td>- Assisted by <strong>mechanicals</strong></td>
<td></td>
</tr>
<tr>
<td>- On-board electrical power: ~100 kW</td>
<td></td>
</tr>
</tbody>
</table>

Copyright © Infineon Technologies 2011. All rights reserved.
Electric Vehicle architectures drive demand for automotive power semiconductors

- Powertrain semiconductor bill-of-material (BOM) of an EV/HEV is approx. 2 times higher than today’s total Auto SC BOM
- Even at the low end of market projections this becomes a significant market for power semiconductors

* Source: IMS Research, Report on Hybrid and Electric Vehicles, 2010
Electric Vehicle architectures drive demand for automotive power semiconductors.

- **High-voltage battery**
  - High-voltage boardnet
  - HV-LV DC/DC
  - Inverter DC/AC
  - High-power DC/DC
  - Battery mgmt.
  - HV auxiliaries
  - Charger AC/DC

**Abbreviations**:
- **EV** = electric vehicle
- **HEV** = hybrid electric vehicle
- **HV** = high-voltage
- **LV** = low-voltage
- **AC** = alternating current
- **DC** = direct current
Application Power and Possible Semiconductor Solutions

<table>
<thead>
<tr>
<th>Power</th>
<th>Application</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>100kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td>HybridPACK™ 2</td>
</tr>
<tr>
<td>90kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td>Bare Die IGBTs, Diodes, MosFETs</td>
</tr>
<tr>
<td>80kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td>Driver IC for IGBTs, MosFETs</td>
</tr>
<tr>
<td>70kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td>Discrete IGBTs, MosFETs</td>
</tr>
<tr>
<td>60kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td></td>
</tr>
<tr>
<td>50kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td></td>
</tr>
<tr>
<td>40kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td></td>
</tr>
<tr>
<td>30kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td></td>
</tr>
<tr>
<td>20kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td>HybridPACK™ 1 Pin-Fin</td>
</tr>
<tr>
<td>10kW</td>
<td>Inverter / Generator for Full Hybrids and Electric Vehicles</td>
<td>HybridPACK™ 1</td>
</tr>
<tr>
<td></td>
<td>Aux Drives, Aux DC&amp;DC, Charger</td>
<td>Easy Modules</td>
</tr>
</tbody>
</table>

11/04/2010
HybridPACK™ Family Power Range Comparison

- HP1 200A/650V
- HP1 400A/650V
- HP1 Pin-Fin 400A/650V
- HP2 Pin-Fin 600A/650V
- HP2 Pin-Fin 800A/650V

Graph showing comparison of peak power range and typical continuous power range for different power modules.
Automotive Easy Modules

**EASY 1B & 2B Module**

**Module Properties**

**BENEFITS:**
- Power Density and Robustness
- Easy Mounting Processes
- PressFIT Technology
- Low System Cost
- Compact Design
- Reliable Isolation
- Automotive Quality & Reliability
- NTC for Temperature Sensing
- Low Stray Inductance (Module & System)
- Platform for different Topologies
- Fully Automotive Qualified Product
Today’s classic EV architecture faces many challenges

Challenges of today’s classical architectures

- High **system costs** due to several independent modules
- High-Voltage wiring and connector costs
- Weak **system efficiency**, high cooling effort and inverter size due to high power losses
- Low mileage and battery lifetime
- EV architectures require stringent safety integrity
Innovative semiconductors are key enablers for leading-edge EV solutions

<table>
<thead>
<tr>
<th>What counts</th>
<th>Semiconductors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter</td>
<td></td>
</tr>
<tr>
<td>Highest power density</td>
<td>IGBTs</td>
</tr>
<tr>
<td>High voltage and high current</td>
<td>Diodes (Si, SiC)</td>
</tr>
<tr>
<td>Temperature capability and cooling</td>
<td>HybridPACKs</td>
</tr>
<tr>
<td>Lifetime in harsh environment</td>
<td>Gate drivers</td>
</tr>
<tr>
<td>Weight and size</td>
<td></td>
</tr>
<tr>
<td>DC/DC (Low Voltage)</td>
<td></td>
</tr>
<tr>
<td>High power density</td>
<td>MOSFETs</td>
</tr>
<tr>
<td>Galvanic isolation</td>
<td>CoolMOS</td>
</tr>
<tr>
<td>High switching frequency (&gt; 100 kHz)</td>
<td>Gate Driver</td>
</tr>
<tr>
<td></td>
<td>EasyPACKs</td>
</tr>
<tr>
<td>Charger</td>
<td></td>
</tr>
<tr>
<td>Efficient AC/DC conversion</td>
<td>MOSFETs</td>
</tr>
<tr>
<td>Handling of high currents (fast charging)</td>
<td>IGBTs</td>
</tr>
<tr>
<td>High switching frequency (&gt; 100 kHz)</td>
<td>Diodes (Si, SiC)</td>
</tr>
<tr>
<td>Safety and communication</td>
<td>EasyPACKs</td>
</tr>
<tr>
<td>Battery Mgmt.</td>
<td></td>
</tr>
<tr>
<td>Extension of battery lifetime</td>
<td>MOSFETs</td>
</tr>
<tr>
<td>Monitoring and control of battery status by smart algorithms</td>
<td>Battery management ICs</td>
</tr>
</tbody>
</table>
ISO26262 ASIL is Achieved at “System Level”
AUDO MAX Overview

**EV/Hybrid Applications**

- **4 MB**
  - E-Motor Drive
    - E.g. 3-phase Permanent Magnet Stator Motor (PMSM)
  - TC1724
    - 80 MHz
  - TC1728
    - 133 MHz

- **2.5 MB**
  - TC1782
    - 180 MHz
  - TC1784
    - 180 MHz

- **1.5 MB**
  - TC1791
    - 240 MHz
  - TC1793
    - 270 MHz
  - TC1798
    - 300 MHz

**DC/DC Converter**
- High voltage supply for E-Motor

**Integrated Hybrid Control**
- Torque management & communication
- 3-phase control for up to 4 electrical motors

**Battery Management**
- Overall charging/discharging control of battery cells/packs (active balancing)

Frequency and Flash size are maximum values. Customer specific variants with lower values possible.
Table of contents

- Semiconductors as key enablers for EV architectures
- Trends and applications of high power semiconductor solutions
- Higher integrated power semiconductor solutions
- Automotive quality/reliability for high power semiconductors
- Summary and outlook
Power Semiconductors - Overview
Main characteristics: Power vs Frequency

- **Thyristor**
- **IGBT**
- **SiC**
- **CoolMOS™**

Power [W]

- Ultra high power
- High power
- Medium power

Frequency [Hz]
Power Semiconductors - Overview
Loss characteristics

• **MOSFET** → highest conduction loss for inverter application
• **IGBT** → lower conduction but slightly higher switching losses
• **SiC JFET** → the best future device for high inverter efficiency

*IGBT conduction loss as reference
**Heat loss: 400V (DC), 200A, 8kHz*
IGBTs - Silicon technology and manufacturing know-how enables optimized power density

- The IGBT is the preferred device for **higher currents** in typical inverter applications
- The **trench + field-stop** cell design enables **lower switching losses** and **high robustness**
- The **wafer thickness** is the key parameter to **reduce power losses** (ultra-thin wafer)
- Increasing **wafer size** from 6” to 12” will increase device output per wafer by 400%

**Wafer size will increase**

- 6” (2005)
- 8” (2010)
- 12” (future)

**Trench + Field-Stop Cell**

- Emitter
- Gate
- n⁻ base (substrate)
- Collector

**Equation:**

\[ P_{dis} \sim \text{Wafer}_{\text{thickness}}^2 \]
Silicon-Carbide (SiC) – the ideal material for high-performance power semiconductors

- **SiC devices are very efficient, fast, high-temp capable, and reliable**

- **SiC enables power devices in a significantly extended voltage range** (300 ... ~ 2500V)

- **SiC product implementation is challenging** (substrate size, crystal defects, transistor characteristics)

- Currently introduction of SiC in industrial applications

- **SiC roadmap** for automotive
  - Increase of wafer size: first step 4”→6” SiC in 2011
  - Diode introduction end of 2011
  - JFET introduction end of 2015

---

Physical properties of SiC

![Graph showing Band gap, Breakdown Field, and Thermal Conductivity comparison between Si and SiC](image)

---

Example: SiC JFET

![Diagram of SiC JFET structure](image)
EV/HEV application solutions
based on MOSFETs/CoolMOS and options for SiC

- High switching frequency (>100kHz) and medium power application (<10 kW)
- CoolMOS with fast body diode for system voltages > 300V
- MOSFET for synchronous rectification on low-voltage side
- Galvanic isolation required

- High switching frequency (>100kHz) and medium power application (<10 kW)
- CoolMOS and SiC for PFC stage
- CoolMOS with fast body diode for primary side of DC/DC stage
- SiC for secondary side of DC/DC stage to improve power efficiency
- Galvanic isolation required
EV/HEV application solutions
based on IGBTs and options for SiC

- High power application with high currents and high voltages
- Today: IGBT + Emitter Controlled Si Diode
- Further reduction of losses with usage of SiC diodes

- Requirements as for the inverter, but high switching frequencies (>10kHz) foster the introduction of SiC
EV/HEV application solutions
Battery management

Active Cell Balancing

- **Active Cell Balancing** enables 10% longer driving range or reduced battery size
- **Highly-integrated Cell Supervision Circuit (CSC)**
  - Very high Measurement Accuracy
  - Designed to support high SIL standard
  - MOSFET with very low $R_{DSon}$

Charge
- **STOP**
- when first cell is full

Discharge
- **STOP**
- when first cell is empty
Table of contents

- Semiconductors as key enablers for EV architectures
- Trends and applications of high power semiconductor solutions
- Higher integrated power semiconductor solutions
- Automotive quality/reliability for high power semiconductors
- Summary and outlook
The **different levels** of higher integrated power semiconductor solutions

- **Bare Die**
  - Suited for customers with own packaging technologies
  - Challenges in handling and product specification

- **Chip on Carrier**
  - Suited for customers with system integration know how
  - Tested quasi standardized sub system

- **Power Module**
  - Suited for customers with PCB and mechanical know how

- **Sensing**

- **Control**

**Mechanical Integration**

**Functional Integration**
Customer benefit from integration

- System cost reduction: Integration of cooling and wiring of the motor and the electronics
- Reduced effort for electric insulation
- Minimize EMC – EMI
- Subsystem assembly at vehicle line
- Reduced volume and weight

Integration requirements

- Cooling concepts
- Temperature capability
- Smart assembly

Source: European Center for Power Electronics, ECPE
Automotive power module with .XT technology

Chip-to-substrate joint

Si chip
DCB

Front side interconnect

Si chip
DCB

Substrate-to-base plate joint

Si chip
DCB
base plate

Standard Technology

Soft soldering with SnAg paste

Diffusion soldering

Cu wedge bonding

High reliability system soldering

Copyright © Infineon Technologies 2011. All rights reserved.
**Advanced XT technology enables higher thermal capability**

Improved thermal capability provides four leverages to optimization:

- Higher **output power**
- Longer **lifetime**
- Reduced **Silicon cost**
- Reduced **system costs**

200°C device junction temperature capability provides:

- more than 60%* higher output power per unit Si area at same lifetime
- more than 500%* larger lifetime per unit Si area at same output power
- more than 40%* reduction in Si area at same lifetime and output power
- Higher temperature coolant capability → eliminate low-temperature radiator

*compared to standard technology
Power density improvement of power modules by more than 180% since 1995

IFX long term experience in power modules

IGBT2
- 34mm module
- 1200 V
- 45 kW
- 0.46 kW/cm²
- Tj=125 °C

1995

IGBT3
- EconoPACK™2
- 1200 V
- 37.2 kW
- 0.89 kW/cm²
- Tj=125 °C

2001

IGBT4
- EasyPACK2B
- 1200 V
- 31.3 kW
- 1.16 kW/cm²
- Tj=150 °C

2007

IGBT4.XT
- PrimePACK™2
- 1200 V
- 600 kW
- 1.31 kW/cm²
- Tj=175 °C

2013

- 2010: Yearly power module production for industrial applications is ~10 Mio. pcs. HybridPacks for automotive solutions are ramped up.
Table of contents

- Semiconductors as key enablers for EV architectures
- Trends and applications of high power semiconductor solutions
- Higher integrated power semiconductor solutions
- Automotive quality/reliability for high power semiconductors
- Summary and outlook
### Different quality requirements, processing and testing of automotive qualified products vs. industry products

<table>
<thead>
<tr>
<th>General</th>
<th>Automotive</th>
<th>Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualification</td>
<td>▪ AEC-Q 101</td>
<td>▪ Jedeck</td>
</tr>
</tbody>
</table>
| Change Management / PCN | ▪ According ZVEI  
▪ Lead time: 6 months, customer approval required | ▪ According Jedeck 46  
▪ Lead time: 3 months |

<table>
<thead>
<tr>
<th>Frontend</th>
<th>Automotive</th>
<th>Industry</th>
</tr>
</thead>
</table>
| WAC (wafer acceptance criteria) | ▪ 100% automatic scrap  
▪ 80% stop / disposition | ▪ 80% automatic scrap  
▪ 60% stop / disposition |
| Statistical Bin Alarm (SBA) | ▪ Required | ▪ Optional |
| PAT (Part Average Test) | ▪ Required | ▪ Optional |
| Pattern Recognition | ▪ Required | ▪ Optional |
| Defect Density | assessment for DD (screening + monitoring) required. | DD monitoring critical layers; no scrap limits |

<table>
<thead>
<tr>
<th>Backend</th>
<th>Automotive</th>
<th>Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrap limits</td>
<td>Based on electrical test yield and assembly step yield scrap requires 8D</td>
<td>On demand</td>
</tr>
<tr>
<td>Re-work / Re-test</td>
<td>Implemented for most package types. Goal: 100% 1st pass yield</td>
<td>On demand</td>
</tr>
<tr>
<td>Tracking</td>
<td>For individual material</td>
<td>On lot basis</td>
</tr>
<tr>
<td>EOL Test Coverage</td>
<td>Multi Temperature / D-PAT</td>
<td>Single Temperature</td>
</tr>
</tbody>
</table>
Infineon Automotive Excellence Program covers also xEV

Infineon’s Automotive Excellence Program

Goals:
- Sustainable quality improvement
- Zero Defect Culture

Measurables:
- Decrease of number of customer returns and quality spills
- Increase of customer satisfaction

Toyota’s „Honor quality award“
First time ever that a non-Japanese company was honored with this award

<table>
<thead>
<tr>
<th>Class</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honor quality award</td>
<td></td>
<td></td>
<td>IFX</td>
<td></td>
<td></td>
<td>IFX</td>
<td></td>
</tr>
<tr>
<td>Excellent quality award</td>
<td>IFX</td>
<td>IFX</td>
<td>IFX</td>
<td>IFX</td>
<td></td>
<td>IFX</td>
<td></td>
</tr>
<tr>
<td>Superior quality award</td>
<td>IFX</td>
<td>IFX</td>
<td>IFX</td>
<td>IFX</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grateful diploma</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Product: CAN transceiver TLE6250G

Improvement Examples
- Advanced Process Control
- Excellent Requirement Management

Additional product QA measures for xEV applications
- Statistical bin analysis
- Automatic optical inspection
- More static and dynamic testing
- Post processing regression tests

Our quality is clearly seen as industry benchmark by almost all of our customers
Reliability and life time of power modules

Spontaneous Failures
- Electrical failures
  - Over-temperature
  - Overvoltage
  - Overcurrent
  - Dynamic f.

Wearout Failures
- Mechanical failures
  - Eol bond wire connections
  - Eol solder connections
  - Destruction of housing / terminals
- Other failures (climatic stresses, chemical stresses)
Technical support: simulations

Driving profile

Module temperature profile

Cooling conditions

Passive cycle (environment)

Life time expectation
Summary

- Semiconductors will be the **key drivers** to improve **vehicle performance and cost** of future automobiles

- **High temperature capable device** (Si and SiC) and **advanced packaging technologies** will be the key in meeting **cost & quality** requirements for xEV

- The semiconductor industry is ready to support the trend in powertrain electrification

Thank you!
Electric Drive Train – EDT

EDT - driving e-mobility