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Building Blocks and Opportunities for Power Electronics Integration

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APEC 2011
March 8, 2011

What's Driving Automotive Power Electronics?

- Across the globe, vehicle manufacturers are committing to more electric drive vehicle production programs
  - Fuel economy and emission regulations increasing drivers of OEM supply
    - Government policies based on energy security and environmental benefits
  - Consumer demand also stimulated by fuel cost savings
    - Higher crude oil costs and higher taxes (Europe and Asia) on petroleum fuels
- Higher fuel economy requirements are coupled with requirements for lower vehicle emissions
  - Need for more efficient powertrains (electric)
    - Requires higher voltages and currents than traditional car battery and alternator can supply
  - To meet fuel economy and emission requirements, in some cases electrified powertrains are currently the only option
    - No idle zones for commercial vehicles (engine off at idle)

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Products

- Inverters
  - From 5 kW to 150 kW+
- DC/DC converters
- Chargers
- Motor controllers
- Battery systems (on-board energy storage)
  - Battery cells, battery management, thermal systems, containment/retention structure, disconnect, etc.
- Electric machines

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Design for Automotive Challenges

- Temperatures
  - Can range from -40°C to 125°C ambient depending on mounting location
  - Coolant temps that range from 70°C to 105°C
- Vibration
  - Shock loads can range from 50Gs to 100Gs
- Reliability
  - Ground mobile operation ranges from 4,000 hours to greater than 60,000 hours
  - Single digit PPM
- High-volume manufacturing
  - Designed for automated assembly and test
- Cost
  - Pennies count
- Suppliers, engineers and designers
  - A full team is required to design a system of products that meet the automotive customers' requirements when manufactured in volume for low cost

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Component Opportunities

- Power devices
  - Higher junction temperatures
  - Lower losses
  - Better packaging
    - Volume manufacturable (low cost)
    - Lower thermal resistance
- Bulk capacitors
  - Capable of 125°C ambient operation
  - Smaller, lighter, benign failure, lower ESL and ESR
  - Higher usable operating frequencies
- Magnetics
  - Cost
  - Assembly process
    - Parts with no discernable mounting features
  - Higher operating temperature capable, possibly integral cooling
  - Lower parasitic loss (packaging included)
  - Smaller size and lower weight
- High current connections
  - Lower contact resistance, smaller size, fewer pieces, lower cost, reliable/durable
- Thermal systems
  - Use existing coolant loops within vehicle
  - Lower thermal resistance, smaller, lighter and lower cost
    - $2 extrusion could cost an extra $100 in silicon
    - Thermal interface materials
    - Target 0.05 cm^{2}C/W effective
- Energy storage systems
  - Smaller, lighter, more energy dense, at a lower cost

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Targets

Table 1. Technical Targets for Electric Traction System

	2010[a]	2015[b]	2020[b]
Cost, $/kW	<19	<12	<8
Specific power, kW/kg	>1.06	>1.2	>1.4
Power density, kW/L	>2.6	>3.5	>4.0
Efficiency (10%-100% speed at 20% rated torque)	>90%	>93%	>94%

[a] Based on a coolant with a maximum temperature of 90°C.
[b] Based on air or a coolant with a maximum temperature of 105°C.

Source: Table provided from DOE Advanced Power Electronics and Electric Motors Roadmap

- Targets we are seeing today
  - 30 kW continuous, 4.6 L or smaller, 4.6 kg or less, using 105°C engine coolant

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Power Electronics Objectives

- Focus on aggressively **lowering the cost of powertrain electrification**:
  - Redesign to reduce cost related to today's non-value-adding or unreliable features, via:
    - » System design and architecture
    - » Component design and development
    - » Controls and algorithm development
    - » Manufacturability
- Allow utilization of existing and validated manufacturing processes and capacities
- Reduce tooling cost
- Reduce mass and volume

Drive today's design of industrial power electronics technology into the high-volume automotive world

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Power Electronics Cost Drivers

- Power semiconductors and packaging
  - Comprises largest share of cost required for today's power electronics components (55-60% BOM of today's inverters and converters)
  - Modules or discrete components
- Passive components
  - Depends on system voltage, current, and architecture
  - Regardless, bulk capacitors (DC Link) and magnetic components are a significant contributor to overall power electronics costs, as well as volume and mass
- System packaging and thermal
  - Chassis and thermal solution can be comparable in cost to semiconductors and packaging

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Power Stage Needs

- Lower the cost and improve reliability
  - Minimize or eliminate the wire bonds
  - Minimize the use of expensive materials
    - AlSiC, Platings, DBC or DBA
  - Remove the requirement for machined surfaces
  - Simplify the interconnect
    - Eliminate the bus bars
    - Eliminate small signal harness
- Simplify testing
  - High current testable
- Simplify repair

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Possible Approaches

- Move away from traditional power modules
  - Use discrete power packages
  - Work with suppliers to develop Si with a solderable top side metallization
- Move away from channels cast in housings
  - Utilize high-performance heat exchangers
  - Work with suppliers to develop low-cost, high-performance geometries for heat sinks
- Minimize or eliminate high current interconnects
  - Buss the current within the circuit board
  - Work with circuit board suppliers to improve their processes
- Find low-cost alternatives to polypropylene film bulk capacitors
  - Work with suppliers and the DOE to advance the technology

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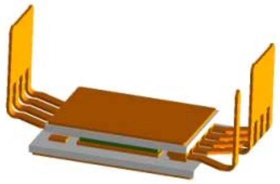
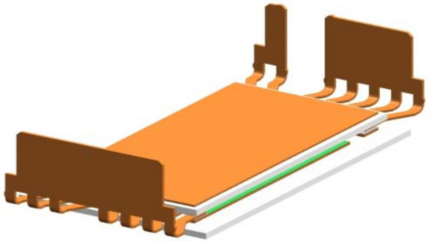
Discrete Power Packages

Feature	Benefits
No wire bonds	Uniform current distribution through the IC. Higher current density. Low package resistance.
No AlSiC or Cu/CuMo/Cu substrates	Removes thermal layers from the die to the coolant. Lowers cost.
Low thermal resistance	Device can be kept cooler.
The packaging allows for double-sided cooling	Allows for higher current densities. Possibly smaller die sizes.
Each discrete package is individually testable	Bad devices can be thrown away as singles not as an entire module.
Designed for compatibility with circuit board reflow or wave solder operations	Ease of assembly.
Package can be a stick lead or surface mount configuration	Flexibility of design



Single Device
Discrete Power Package



IGBT and Diode Co-packaged
Discrete Power Package

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High-performance Heat Rail

Feature	Benefits
High convection coefficient	Allows for higher inlet coolant temperatures or smaller die size
Brazed aluminum construction	Completely sealed, no sealant materials required, no post machining operations required
Compatible with automotive fluids and assembly processes	Designed for the automotive environment
Small size	Slightly larger than total power silicon area
Light weight	Typically less than 200g
Flat	0.05 mm per 35 mm
Low pressure drop	Comparable to cast channel heat sinks Requires low flow rates while cast channel heat sinks require high flow rates Pump requirements reduced or eliminated

Heat Rail

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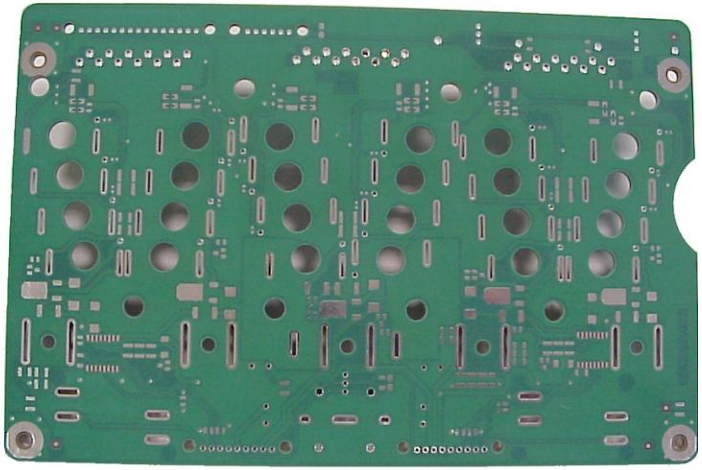
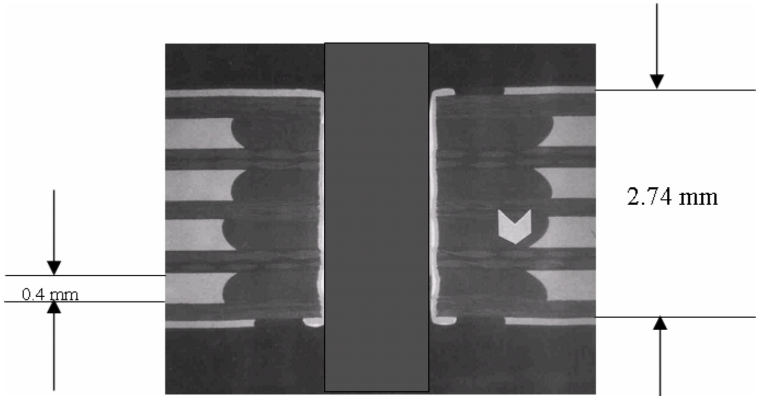
High Current Circuit Board

Feature	Benefits
Single substrate solution	High current capability with fine line geometry. Power and logic go on the same board. Reduces power module size and mass.
Reduces inverter component count	Can eliminate buss bar assemblies and current sensor assemblies.
Simplifies power module assembly	Only reflow and wave solder process required .





6 layer, No connect

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Bulk Capacitor

- Bulk capacitors represent up to 40% of today's inverter volume
- Polypropylene (PP) film is today’s material of choice
  - Low dielectric constant (Dk)
  - Limited temperature range which may require cooling
  - Expensive
- Baseline is 3.8um biaxially-oriented polypropylene (BOPP)
  - 1000 uF (scaled to 170uF modules), 100A ripple current, 1 kg, 1 L, $100 price
  - Processing cost dominates material cost
  - Baseline material cost is just $2.20 ($1/lb.)
- Need for smaller, lighter, lower cost, lower ESL, lower ESR and higher temperature capacitor
  - Higher Dk
  - Higher Tg
  - Benign failure mode

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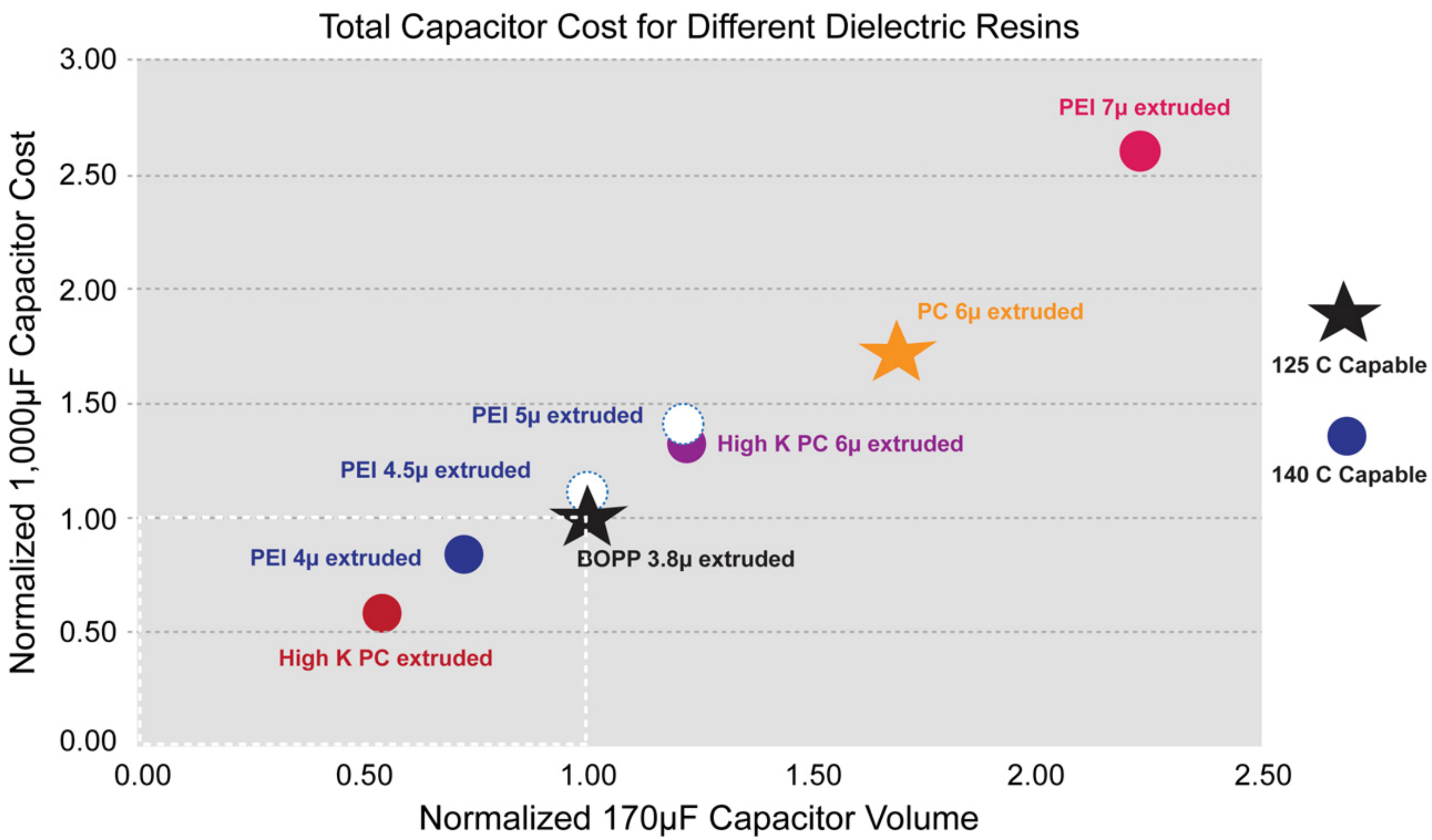
Film Capacitors



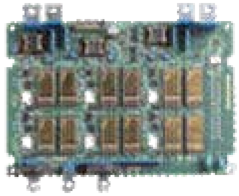
The processing cost per unit volume of capacitor module was kept constant, the same as that for the BOPP, although it may be different for resins other than BOPP, especially in those cases in which the raw material cost or the processing cost to make the film by extrusion, or both, are substantially higher than the values assumed for BOPP;

The cost to make the High Dk 4 µm extruded polycarbonate polymer commercially was estimated based on the information presently available, and it will strongly depend on the cost to make the monomer required to build the polycarbonate molecule and the final volume of resin produced, which are both unknown at this point in time.

Delphi's Path to the Future

- Work with our suppliers and government labs to develop the building blocks for lower thermal resistance packaging with lower device losses
  - This allows for less silicon for the application
  - Less silicon enables less silicon packaging
  - Less silicon, less silicon packaging and smaller bulk capacitor enables smaller package volume, lower weight, and lower cost
  - Smaller Package Volume – Lower Weight – Easier to Manufacture – Lower Cost

Discrete packaged Silicon
Unique to Delphi



Integrated PCB

Advanced Inverter

Delphi's Path to - Smaller, More Robust, Cost-Effective Power

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Acknowledgment of Support

- *Acknowledgment*: "This material is based upon work supported by the Department of Energy under Award Number DE-FC26-07NT43121."

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Questions?