FreedomCAR and DOE Roadmap for Automotive Power Electronics

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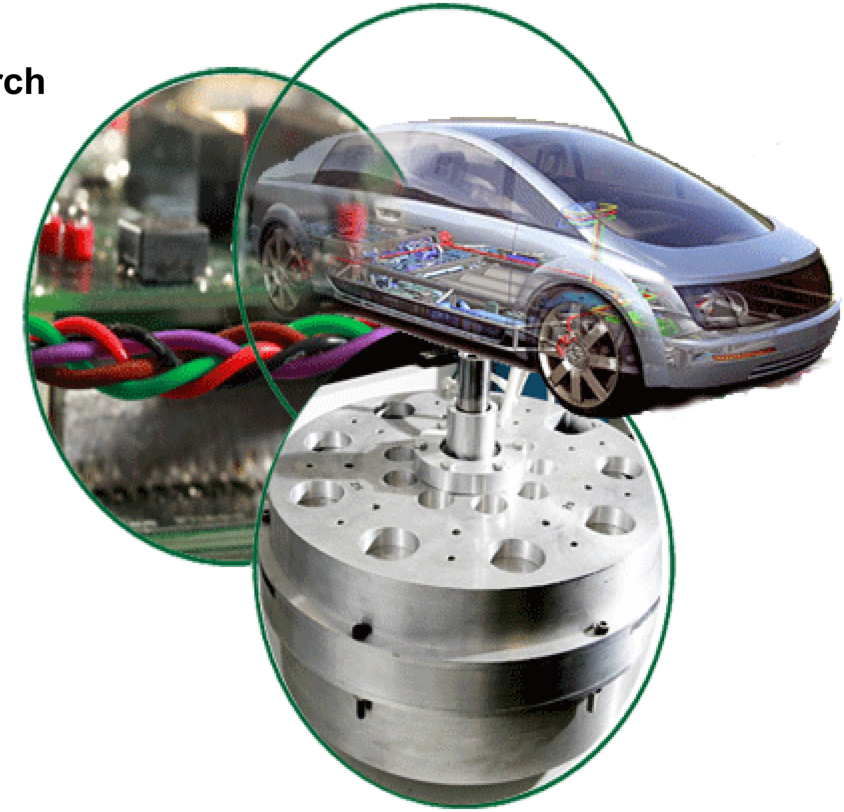

DOE Vehicle Technologies Program
Advanced Power Electronics and Electric Machines Research

APEC 2011
March 8, 2011

FreedomCAR & Fuel Partnership

U.S. DEPARTMENT OF ENERGY

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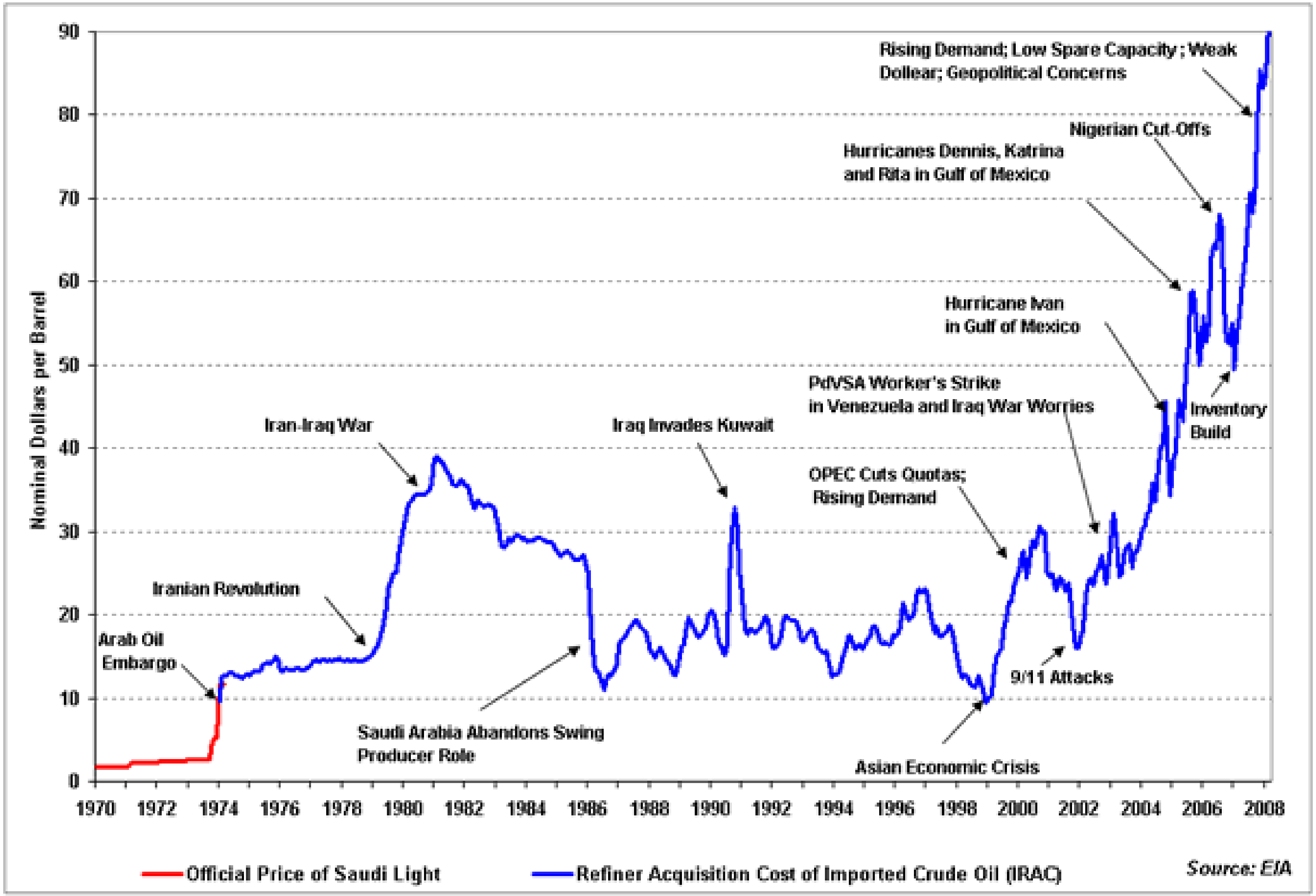
Presentation Outline

- **Introduction**
  - **DOE and FreedomCAR Partnership**
- **Program Packaging Challenges**
- **Roadmap Overview**
- **Power Electronics in the Program**
- **Government/Industrial Partnerships and Opportunities**

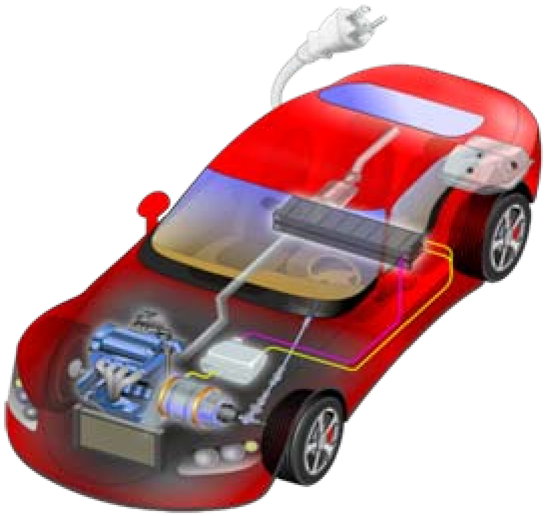
Largest Market Motivator



FreedomCAR & Fuel Partnership

The Partnership is an effort to advance pre-competitive, high-risk research needed to develop the component and infrastructure technologies necessary to enable a full range of affordable cars and light trucks, and the fueling infrastructure for them that will reduce the dependence of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice.

High Level Power Electronics Challenges



- **Cost – must be reduced by 50%**
  - –Cost of today's available propulsion inverters for HEVs, PHEVs and FCVs contributes to a higher cost/price premium for these vehicles, inhibiting consumer acceptance

    Costs driven by semiconductors
- **Inverter Volume & Mass –**
  - –Volume & mass driven by passives and thermal/mechanical packaging

    Volume driven by capacitors, structural and cooling requirements
- **Manufacturability – must be improved**
  - –Today's modules contain too many parts

    Manufacturing driven by packaging

    => too many manufacturing steps => quality, reliability and durability challenges, as well as high cost

APEEM Research Targets

Reduce Dependence on Oil

Via Electrification of Vehicle Drives

Requirements: 55 kW peak for 18 sec; 30 kW continuous; 15-year life

Technical Targets

Year	Traction Drive System				=	Power Electronics			+	Motors		
	($/kW)	(kW/kg)	(kW/l)	Efficiency		($/kW)	(kW/kg)	(kW/l)		($/kW)	(kW/kg)	(kW/l)
2010	19	1.06	2.6	>90%		7.9	10.8	8.7		11.1	1.2	3.7
2015	12	1.2	3.5	>93%		5	12	12		7	1.3	5
2020	8	1.4	4	>94%		3.3	14.1	13.4		4.7	1.6	5.7

Challenges

Research Areas

Traction Drive System

- Benchmarking technologies
- Innovative system designs

Power Electronics

- Innovative topologies
- Temperature-tolerant devices
- Packaging
- Capacitors
- Vehicle charging

Electric Machines

- Permanent magnet (PM) motors
- Magnetic materials
- High-performance non-PM motors
- New materials

PEEM Thermal Management

- Thermal system integration
- Heat transfer technologies
- Thermal stress and reliability

FreedomCAR EETT Roadmap: R&D Strategy

Develop technologies, not vehicles

The intent of the program is not to design or build a vehicle but rather to develop a set of technologies that can be adopted (and modified, if necessary) by the OEMs and their suppliers to enable them to manufacture a APEEM system that meets the program goals.

Explore multiple technologies.

Since different manufacturers will have different requirements and design strategies, and no single new technology will enable achievement of all of the targets, the APEEM program must deal with a wide variety of technologies.

Pursue parallel paths

In order to meet the very challenging technical targets, it is necessary to pursue high-risk concepts. To reduce the overall risk of technical failure, it therefore is necessary to pursue more than one path toward each objective. Multiple parallel paths also are more likely to produce technologies that meet the needs of more than one manufacturer.

Ensure technology transfer

Although the basic mission of DOE is long-term, high-risk R&D, the program needs to contain some short-term R&D to carry the technologies to the point where industry can adopt them. In many cases, this shorter-term R&D will be conducted in partnership with industry or by industry alone.

FreedomCAR EETT Roadmap: Key Drivers and Issues

Topology Development

Avenue to achieve significant reductions in PE weight, volume, and cost and improve performance

•Reduce capacitance need by 50% to 90% yielding inverter volume reduction of 20% to 35% and associated cost reduction.
•Reduce part count by integrating functionality thus reducing inverter size and cost and increasing reliability.
•Reduce inductance, minimize electromagnetic interference (EMI) and ripple, reduce current through switches all resulting in reducing cost.
•Minimize Si content ---largest PE cost factor

Focuses on achievement of ALL targets

FreedomCAR EETT Roadmap: Key Drivers and Issues

Charging

Provide the vehicle charging function in a policy neutral manner at virtually no additional cost with bi-directional capability

- ***Safety***
- ***Ease of installation***
- ***Modularity***
- ***Choice (level 1 or level 2?)***
- ***Reliability (warranty)***

Developing specifications

FreedomCAR EETT Roadmap: Key Drivers and Issues

Component Development

Temperature Capabilities of Components

Increasing the operating temperature capability of components will enhance reliability and enable reduction in vehicle cooling requirements.

Switches and diodes
- **Wide bandgap—SiC and GaN**
- **High temperature Silicon**

Capacitors
- **Film**
- **Ceramic**

Magnets
- **Rare earth**
- **Ferrites**

Motor Materials
- **Laminations**
- **Hybrid wires**
- **SMC**

Material Emphasis

FreedomCAR EETT Roadmap: Key Drivers and Issues

Vehicle Integration and Manufacturing

- ***Scalable and flexible***
- ***Affordable***
- ***Ease to manufacture***
- ***Small and compact***
- ***Easy to install***
- ***Reduced cooling burden***

FreedomCAR EETT Roadmap: Key Drivers and Issues

Packaging

Provides opportunity for greatly decreased size and cost

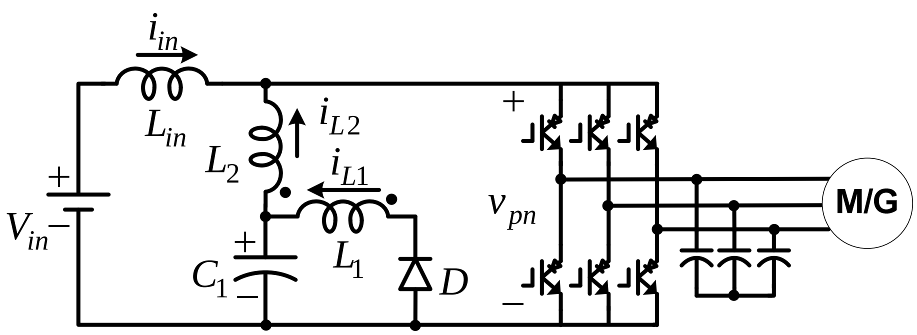
•Module packaging can reduce inverter size by 50% or more, cost by 40%, enable Si devices to be used with high-temp coolant for cost savings of 25%, and enable use of air cooling.
•Device packaging to reduce stray inductance, improve reliability and enable module packaging options.
•Increase modularity and scalability to support multiple system configurations
•When coupled with heat transfer improvements gains are enhanced

Device and Module level Packaging Seen as a key enabler

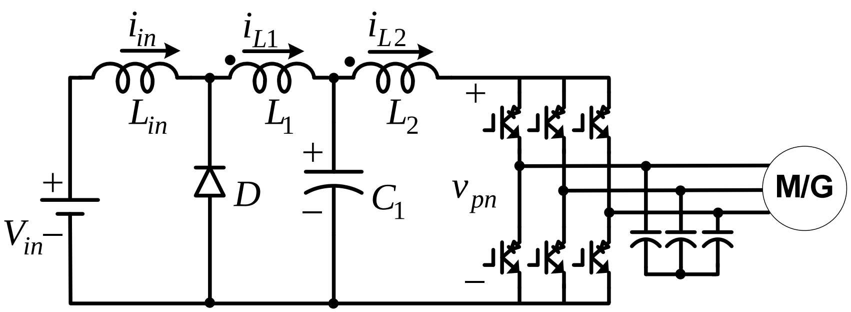
ORNL: Topology Development: CSI and Z source

CSI with a quasi-Z network (ZCSI):

- Use a passive Z-network of inductor, capacitor, and diode in the CSI to enable
  - Single stage buck and boost conversion
  - Battery charging
  - Safe operation in open circuit events
- Eliminate antiparallel diodes
- Reduce total capacitance
- Produce sinusoidal voltages & currents to the motor
- Tolerant of phase-leg shoot-through and open circuit
- Extend constant-power speed range without a dc-dc boost converter

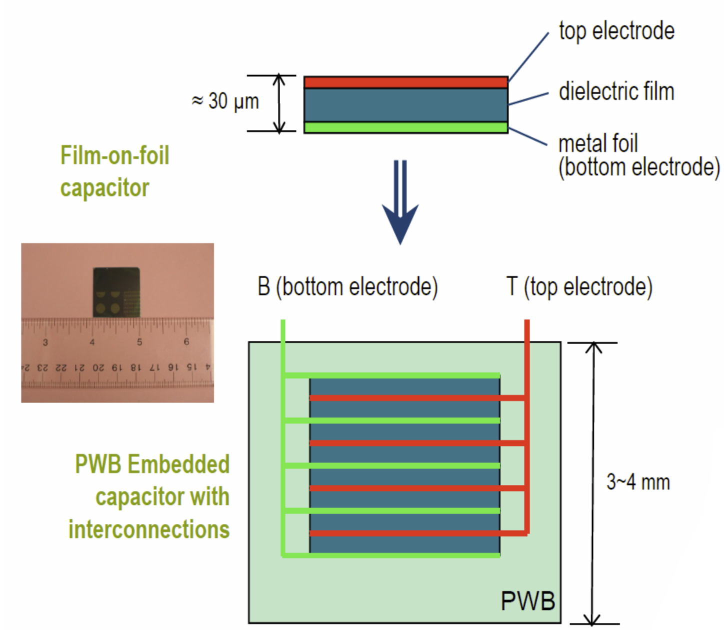


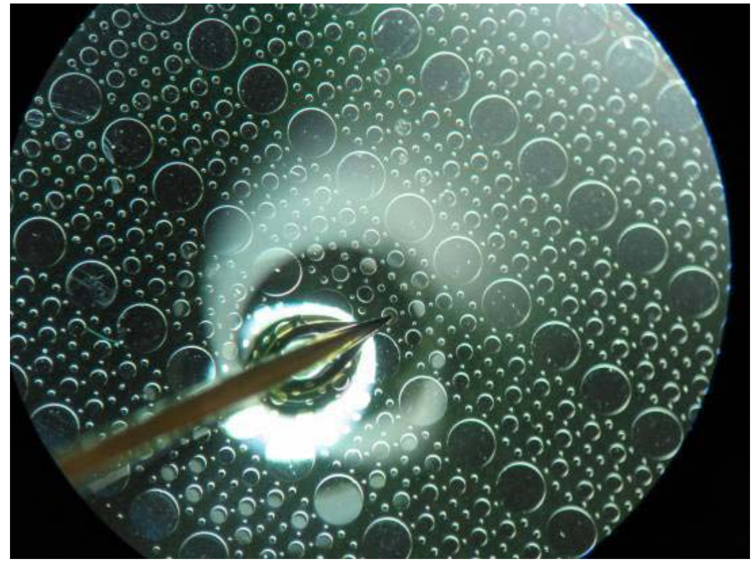
Current-fed Trans-qZSI



Current-fed Trans-ZSI

ANL: Film on Foil, Embedded Capacitors



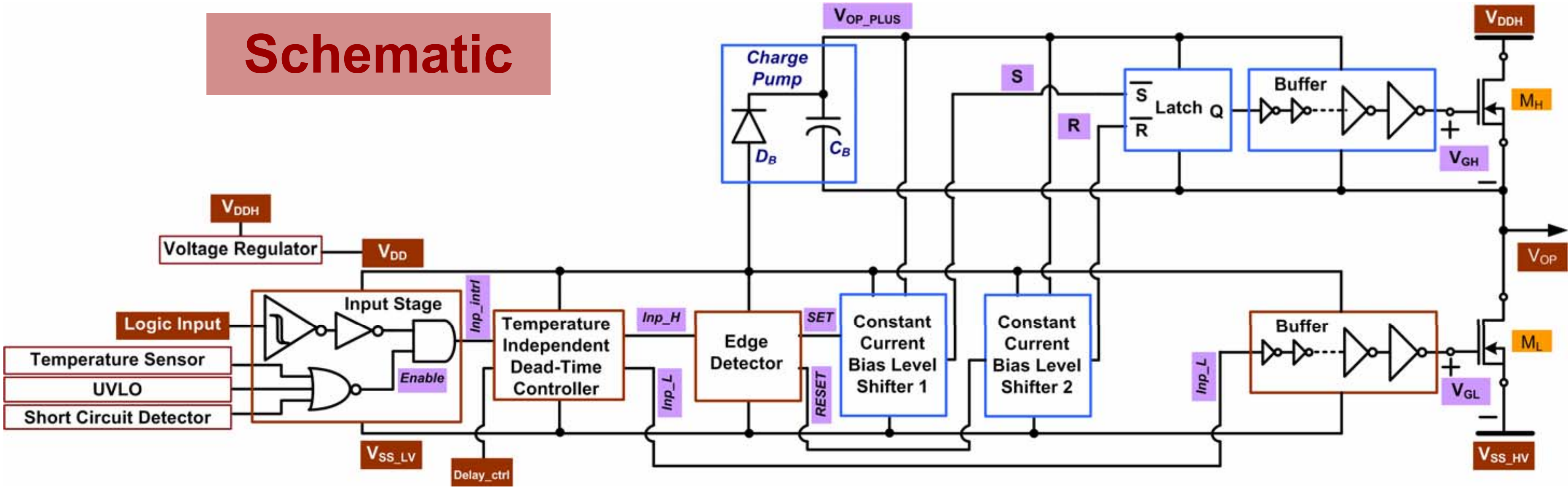


- Demonstrated dielectric films with k >1200, Eb≈6.5 MV/cm, and Ileakage<10-8A/cm2.
- Measured energy density ≈170 J/cm3in a ≈2 µm-thick PLZT film-on-foil.
- Demonstrated graceful failure by self-clearing method in single layer dielectric films.
- Film-on-foil dielectrics were thermally cycled (≈1000 cycles) between -50°C and +150°C with no measurable degradation in k.

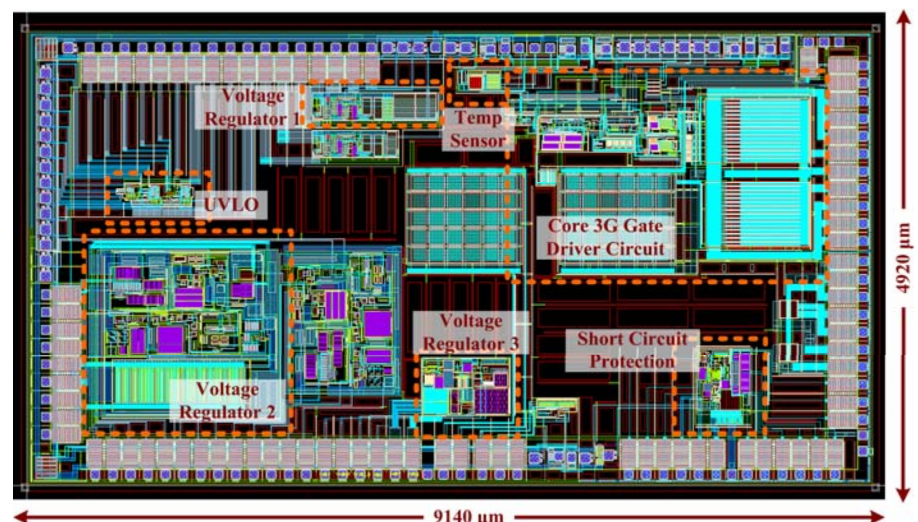
Embed bus capacitors in PC boards to achieve significant volume reduction

ORNL: High Temperature Operation: SOI Gate Driver

Schematic



Successfully tested with SiC MOSFETS and JFETS to 200°C with no heat sink or cooling mechanism

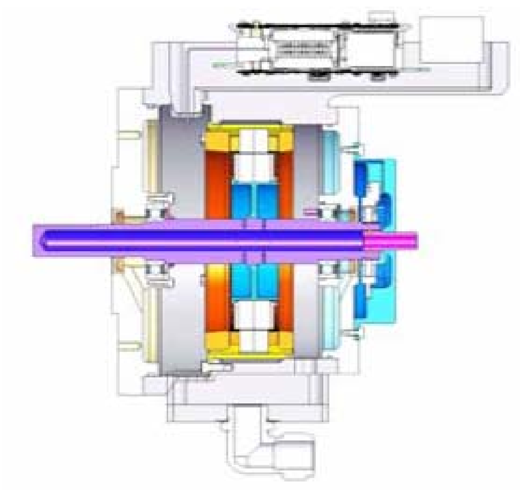


Layout

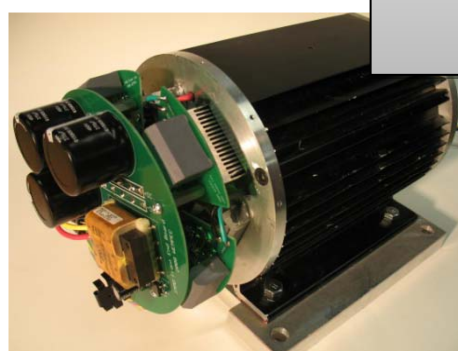
System Packaging towards Integration of Technologies

- **Initial emphasis was on discrete power electronics and electric motor modules**
- **Expanded focus towards integration for cost and volume savings**

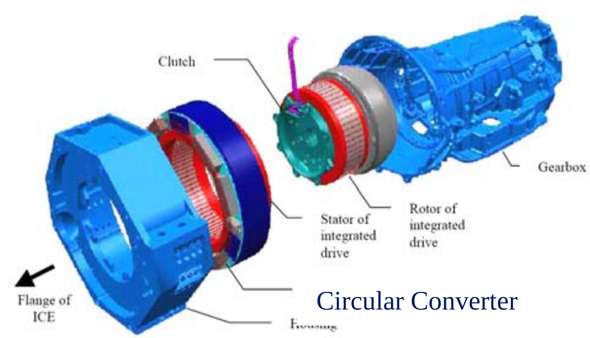
- **Incorporate PE, EM, and thermal management advances into traction drive system design**
- **Initiating advanced PEEM system development addressing 2015 targets**



Integrated Motor and Inverter Concept



ORNL/UWM Integrated Motor and Inverter



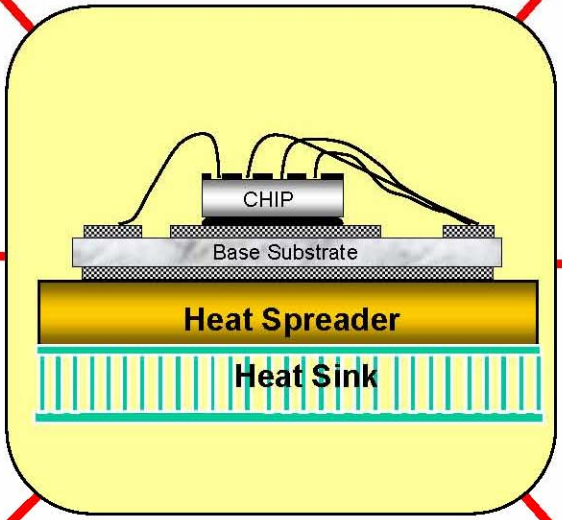
Circular Converter

Power Semiconductor Packaging State of the Art

Asymmetric Structure
Poor thermo-mechanical (Reliability)

Top Wire Interconnection
Large parasitic Parameters
Bulky

Multilayer Stack
Poor Thermal Dissipation

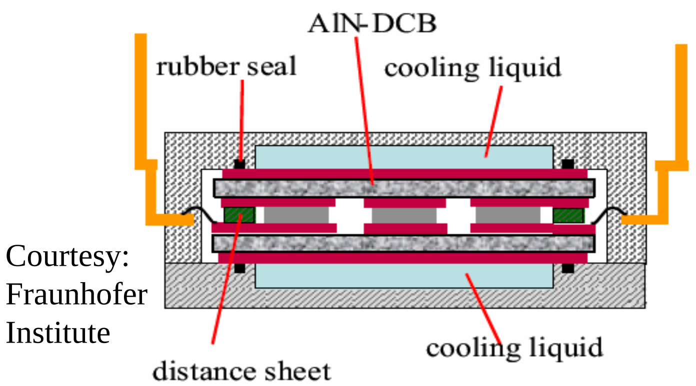


One Sided Cooling
Poor Thermal management

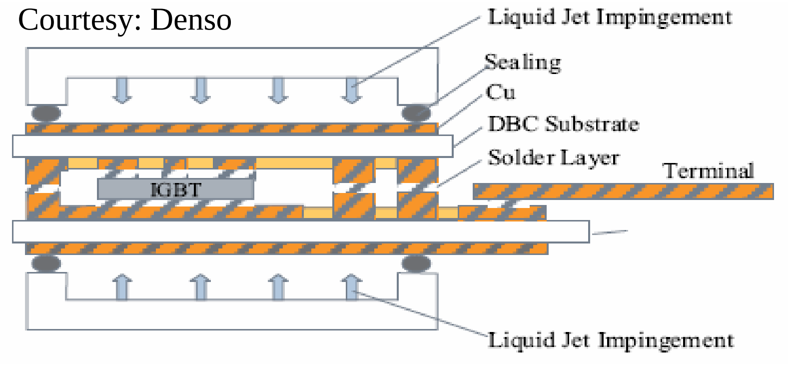
Organic Material
Limited Operation Temperature

Hybrid Technology
High manufacture Cost

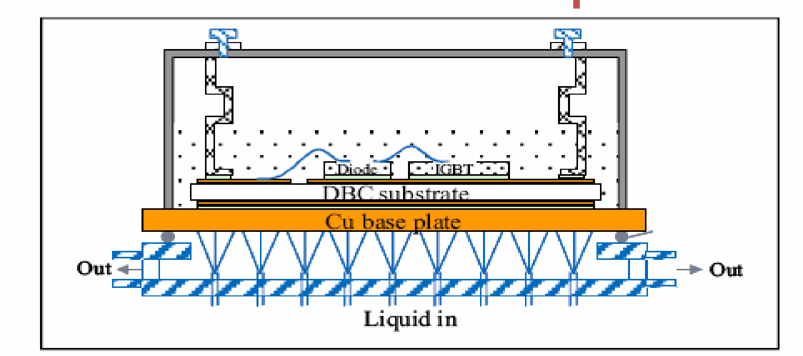
Advanced Packaging with Cooling Innovations



Double sided coldplate[1]

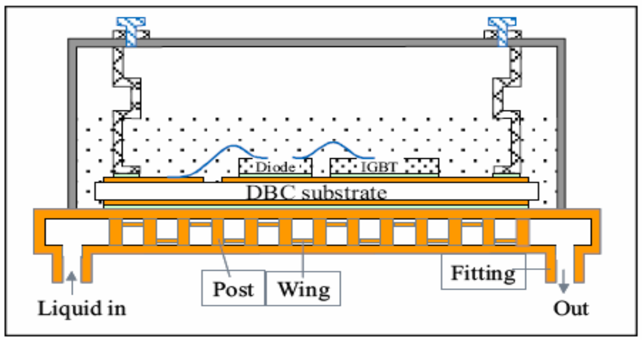


Double sided jet impingement [2]



Phase change jet impingement [3]

Courtesy: Teledyne

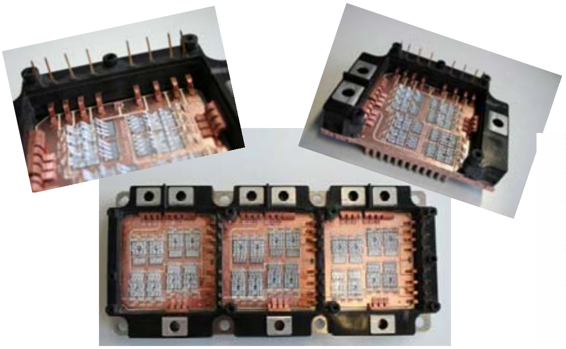


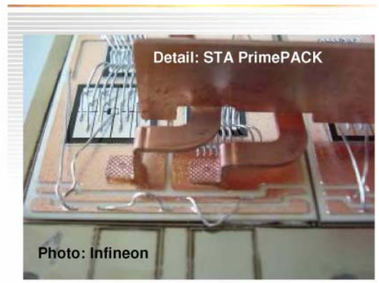
Micro-channel cooling [4]

Courtesy: Fraunhofer Institute

[1] Schneider-Ramelow et. al, CIPS 2008; [2] Buttay et. al., EPE 2006
[3] Bhunia et. al. IEEE Trans. on CPT 2007; [4] Erhardt et. al., CIPS 2006

Industry Advances





Infineon – Hybrid Pack II

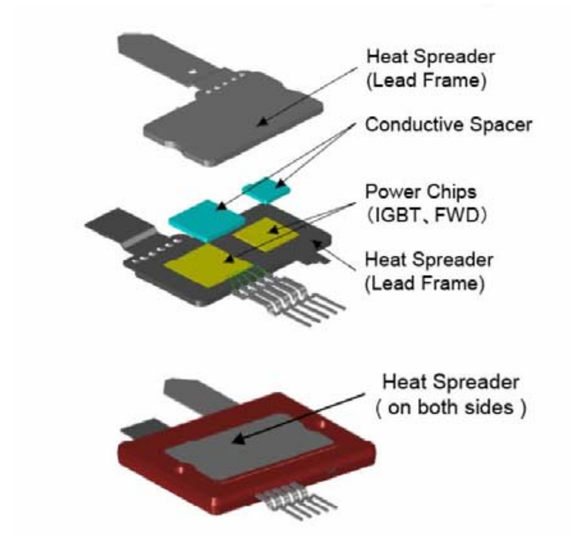
–Thinner devices

–New terminal bonding

–Integrated cold plate

–Improved DBC

Courtesy: Infineon

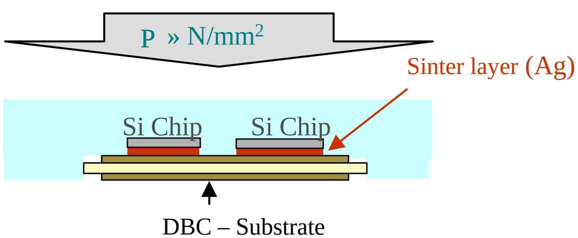


Denso – Lexus Inverter

– 30% volume reduction

– 20% weight reduction

– 60% higher output power/unit volume



Semikron – Sintered Die Attach

– Increased reliability

– Over temperature

Delphi – VIPER Packaging

– Reduced IGBT package size

– Elimination of wire bonds

– Enabler for double sided cooling

ARRA Manufacturing Awards

Company - Location	Manufacturing Focus: (total funding)
Remy, Inc. - Indiana & North Dakota	Hybrid Electric Motors & Controls ($146M)
General Motors Corp. – Maryland & Michigan	Global Rear Wheel Drive Electric (GRE) Drive Units ($278M)
Ford Motor Co. - Michigan	HEV & PHEV Transaxles ($125M)
Magna E-Car Systems of America, Inc. - Indiana & Michigan	Electric Drive Systems ($130M)
Delphi Automotive Systems. LLC - Indiana	Electric Drive Power Electronics ($219M)
Allison Transmission, Inc. - Indiana	Commercial-duty Hybrid Systems ($183M)
UQM Technologies - Colorado	Drive Electronics & Electric Motor/Generator ($90M)
KEMET Corp. - South Carolina	DC Bus Capacitors ($37M)
SBE, Inc. - Vermont	DC Bus Capacitors ($18M)
Powerex, Inc. – Pennsylvania	Semiconductor Devices ($12M)

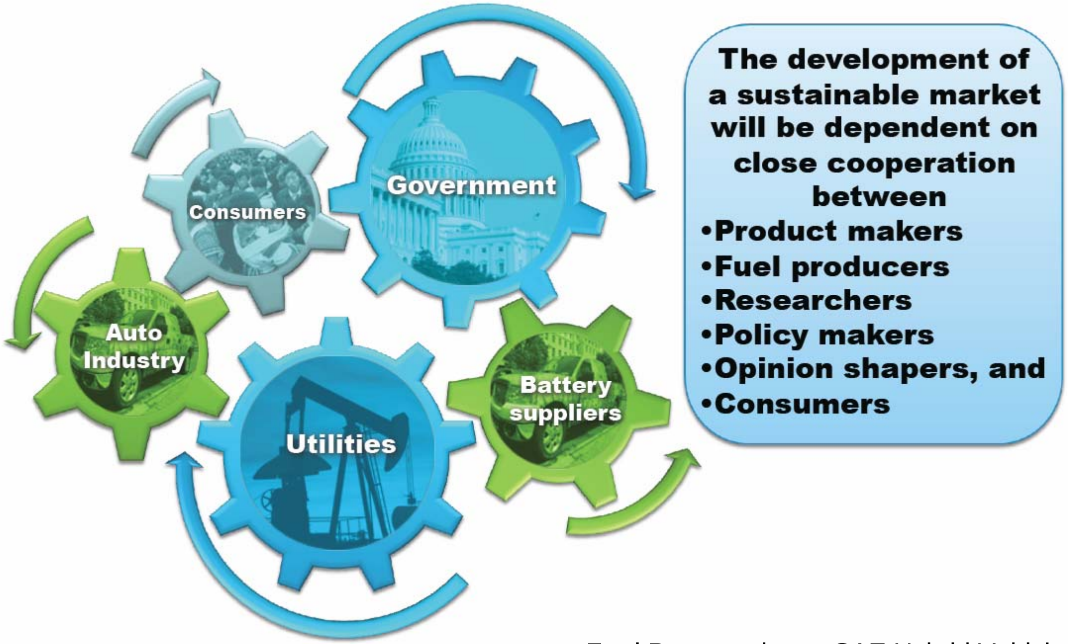
ARPAe ADEPT Awards

Company - Location	R&D Focus: (total funding)
Arkansas Power Electronics International, Inc	Circuit Topology/Switches—Automobiles: Low Cost, Highly Integrated SiC Multichip Power Modules for Plug In Hybrids (3,914,554)
Case Western Reserve Univ	Capacitors—Automobiles: High Power Titanate Capacitor for Power Electronics (2,254,017)
Cree, Inc.	Switches—Transmission: 15kV SiC IGBT Power Modules for Grid Scale Power Conversion (3,736,291)
CUNY Energy Institute	Capacitors □Lighting: Metacapacitors (1,568,330)
GE Global Research	Magnetics □Photovoltaics: Nanostructured Scalable Thick□Film Magnetics (949,545)
GeneSiC Semiconductor	Switches-□Transmission: Monolithic Silicon Carbide Anode Switched Thyristor for Medium Voltage Power Conversion (2,450,000)
Georgia Tech Research Corp	Magnetics □Consumer Electronics: Highly Laminated, High Saturation Flux Density Magnetic Cores for On□Chip Inductors in Power Converter Applications (999,017)
Georgia Tech Research Corp	Circuit Topology/Switches □Transmission: Dynamic Control of Grid Assets Using Direct AC Converter Cells (981,619))
HRL Laboratories	Switches – Automobiles: GaN Switch Technology for Bi□directional Battery□to□Grid Chargers (5,058,803)
MIT	Switches/Magnetics □Lighting: Advanced Technologies for Integrated Power Electronics (4,414,009)
Teledyne Scientific & Imaging	*Magnetics/Switches □Lighting: Integrated Power Chip Converter for Solid State Lighting* (3,439,494)
Transphorm, Inc.	*Switches □Motors: High Performance GaN HEMT Modules for Agile Power Electronics* (2,950,000)
Virginia Tech	Magnetics/Capacitors □Electronics: Isolated Converter with Integrated Passives and Low Material Stress (900,000)

Funding Opportunities

Funding Office	R&D Focus: (total funding)
ARPAe	TBD
DOE VTP Solicitation	Awards Pending --$184M to be awarded

Conclusion



Ford Presentation at SAE Hybrid Vehicle Symposium, Feb 2010

- ***Power Electronics Packaging is a Critical Technology to fulfill Future Targets***
- ***Comprehensive Approach Needs Multidiscipline Research***
  - ***Thermal, Electrical, Mechanical, Materials***
- ***Integration of Advanced Cooling is an Enabler for High Temperature, High Reliability, Cost Effective Power Modules***