IPEM-Based Power Electronics System Integration

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***Abstract* - Power electronics products, to date, are essentially custom-designed and manufactured using non-standard parts. The products cycle times are long and manufacturing processes are labor-intensive, thus, resulting in poor reliability and high cost. The Center for Power Electronics Systems, established in 1998 as one of the National Science Foundation Engineering Research Centers, is charged in leading the nation in the development of an integrated power electronics system approach via integrated power electronics modules (IPEMs). A brief discussion of the center's research enterprise and strategic plan in addressing key technological areas and advancements needed to improve the characteristics of power electronics systems, such as increased levels of integration, standardization of parts and improved packaging techniques for enhanced thermal management and electrical performances. The technologies being developed for the realization of integrated systems include planar metallization to allow three-dimensional structural integration of power devices and control functions, integration of power passives, integration of RF and EMI filters, and integration of electrical/thermal design tools.**

I. ENERGY AND POWER ELECTRONICS

Throughout the world, electricity is used at an average rate of 40 billion kilowatt-hours every day of every year with a projected average annual growth rate of 2.3% for the next 20 years [1]. In the U.S., total electricity sales are projected to increase at an average annual rate of 1.9%, from 3,481 billion kilowatt hours in 2001 to 5,220 billion kilowatt hours in 2025. With few exceptions, much of the electricity is not used in the form in which it was initially produced. Rather, it is reprocessed to provide the type of power needed in the technology that is being employed. Power electronics is the engineering discipline utilized to convert electrical power from one form to another. Power electronics and related power processing technologies constitute an "enabling infrastructure technology" with a significant potential impact on U.S. industrial competitiveness. This is manifested through the increased energy efficiency of equipment and processes using electrical power, and through higher industrial productivity and higher product quality, which results from the ability to precisely control the electrical power for manufacturing operations. Sales of power electronics equipment exceed $60 billion each year, and, more importantly, it supports another $1 trillion in hardware electronics. According to a 1992 Electric Power Research Institute (EPRI) survey [2], more than 40% of the electrical power being used was processed through some form of power electronics equipment. It is expected that up to 80% of the electrical power will be processed by power electronics equipment and systems in the near future. With the widespread use of cost-effective and energy-efficient power electronics technology, the U.S. would be able to reduce its electrical energy consumption by 33%. The amount of energy savings, by today's measure, is equivalent to the total output of 840 fossil fuel-based power plants. This will result in enormous economic, environmental, and social benefits.

The 2003 EPRI Electricity Technology Roadmap identified high-efficiency end-uses of electricity as one of the key limiting challenges, with high-efficiency lighting systems and high-efficiency motor drives and power supplies among the highest priority capability gaps. Improvements in energy conservation and its associated environmental impact cannot be accomplished without a significant paradigm shift in power electronics technology. Today, motor and lighting loads represent more than 70% of total electrical power consumption. Due to the high cost associated with power electronics solutions, most motor and lighting equipment currently uses non-power electronics solutions. For example, almost all of the U.S. residential heat pumps and air-conditioning units are driven by constant speed motors. It is well known that replacing a constant speed motor with a motor driven by a variable speed drive can reduce electrical energy consumption by 33%. Lighting consumes about 20% of the total electrical energy. Replacing incandescent lamps with fluorescent lamps would result in a fourfold energy savings. Furthermore, if these fluorescent lamps were to be powered by electronic ballasts instead of the traditional magnetic ballasts, it would save an additional one-third of their energy consumption. The new generation of energy efficient lighting sources such as high-intensity discharge

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(HID), light-emission diode (LED), and liquid crystal display (LCD) all require specialized electronic ballasts to operate and represent a significant part of the total system cost. Another important area of fast growing applications is computer, communication, and network infrastructure equipment. Collectively, they have increased their power consumption from 5% a decade ago to 10% today and 15% in the near future. The prohibiting factor preventing the widespread use of power electronics solutions for the aforementioned energy-saving applications is their relatively high installation cost. The energy savings cannot be realized without a radical change in the design and manufacturing practice to provide more affordable power electronics products in mass quantities. The progresses of power electronics technology in the last few years and recent changes in the global economic climate have led to increased penetration of power conversion equipment.

II. THE VISION – AN INTEGRATED POWER ELECTRONICS SYSTEM APPROACH

Power electronics products, to date, are essentially custom-designed, with a long design cycle. The equipment is designed and manufactured using non-standard parts. Thus, manufacturing processes are labor-intensive, resulting in high cost and poor reliability. The current practice has significantly weakened the U.S. power electronics industry in recent years. In the 1980s, power electronics was considered as a core enabling technology for all the major corporations in the U.S. In the 1990s, the major corporations adopted an outsourcing strategy and spun off their power electronics divisions. What had been a captive market was transformed into a merchant market. Fewer resources were available to devote to technical advancement in power electronics. Consequently, innovative solutions were scarce. Products became commoditized and cost-driven. The result was increased mass migration of manufacturing to low-labor cost countries. The problem is further compounded by the more recent trend of outsourcing engineering to India and Asian countries, especially China. Today, much of U.S. industry is bottom-line focused and spends little in R&D, mostly in development rather than in research.

In order to bridge this gap between the increasing societal energy needs and the decreasing industrial capability to innovate, the Center for Power Electronics Systems (CPES) was established with the mission to develop advanced electronic power conversion technologies for efficient future electric energy utilization through multidisciplinary engineering research and education in the field of power electronics. The CPES vision is to enable dramatic improvements in the performance, reliability, and cost-effectiveness of electric energy processing systems by developing an integrated system approach via integrated power electronics modules (IPEMs). The envisioned integrated power electronics solution is based on advanced packaging of a new generation of devices and innovative circuits and functions in the form of building blocks with integrated functionality, standardized interfaces, suitability for automated manufacturing and mass production, and application versatility, namely IPEMs, and the integration of these building blocks into application-specific systems solutions.

The impact of improvements in power electronics technology and systems integration via the IPEM approach can be compared to the impact being realized by improvements in very-large-scale integrated (VLSI) circuit technology. Applications of VLSI circuit technology have enabled rapid advances in information technology and the digital revolution, accompanied by a steady increase in standardization, modularization, and functional integration; and a steady decrease in the manufacturing costs of equipment. Parallel to this integrated circuit development, the IPEM approach makes possible increased levels of integration in the components that comprise a power electronics system – devices, circuits, controls, sensors and actuators – which are integrated into manufacturable subassemblies and modules that, in turn, can be customized for a particular application. A competitive advantage will be gained by industries that can quickly and efficiently provide their customers with a level of customization and flexibility that is now routine in VLSI circuit technology. Moreover, as processes become established, industries that make use of standardized components, subassemblies and modules will be able to enjoy the savings associated with economies of scale.

III. INTEGRATED POWER ELECTRONICS SYSTEMS PROGRAMS AT CPES

CPES is aimed at developing the next generation of power electronics systems solutions that are tightly coupled with the multidisciplinary issues as described above. The IPEM-based systems solutions address, concurrently, the integration of active and passive components, packaging materials, interconnect structures, electromagnetic compatibility and electromagnetic interference, thermal management, as well as numerous application considerations. CPES was originally established with existing peaks of excellence in the area of high frequency power conversion, motor drives and control, and power semiconductor devices. In order to address the IPEM vision, we have augmented our existing strengths with expertise in materials science, electronic packaging, and thermal management. The five universities which comprise CPES: Virginia Tech, University of Wisconsin-Madison, Rensselaer Polytechnic Institute, North Carolina A&T State University and University of Puerto Rico-Mayagüez have made a significant investment to help us establish the research team as well as to provide the facilities for addressing system integration by incorporating integrated design methodology.

With the participation of five core universities, CPES has successfully developed a comprehensive power electronics curriculum by integrating power electronics courses across five campuses. The curriculum encompasses power semiconductor devices, power ICs, device characterization, analog/digital electronics, high-frequency magnetics, electric machines, modeling and control, power electronics packaging, high-frequency power conversion, motor drives and control, and power electronics systems integration. This comprehensive power electronics curriculum is not the result of simply integrating the existing curriculum within CPES, but also by offering 14 new courses, thus, providing a curriculum that is a true reflection of the integrated approach the Center has been pursuing.

CPES's research program is aimed at developing the next generation of power electronics system solutions that are tightly coupled with the multidisciplinary issues [3]. The major research thrusts addressing these issues are shown in Fig. 1. The research thrusts in the Fundamental Knowledge Plane are focused on developing basic science, technology, and methodology needed for IPEMs. We have identified five major areas of research: (1) advanced power semiconductors; (2) integratable materials; (3) high-density integration; (4) thermal-mechanical integration; and (5) control and sensor integration. Within the Fundamental Knowledge Plane, the research thrusts are designed to be cross-coupled among them, and collectively they support the research in the Enabling Technology Plane as well as in the Engineered Systems Plane.

The major objective of the Electro-Magneto-Thermal-Mechanical Integration (EMTMIT) thrust on the Enabling Technology Plane is to integrate effectively the new CPES components and process technologies into integrated hardware assemblies (i.e., IPEMs) that can be applied in the IPEM-based Power Conversion System (IPEM-PCS) testbed. Within EMTMIT thrust, the research will focus on two types of IPEMs. The active IPEM represents the integration of active components within the module. The passive IPEM consists of integration of energy storage capacitors, inductors, and transformers. These IPEMs are considered standard, generic IPEMs, and are designed to support system integration for a wide range of applications. In addition, the thrust also includes research in two application-specific IPEMs. One is the integration of power electronics and motors, and the other is the integration of point-of-load power supplies (with microprocessors). These two applications represent significant technical challenges and will have significant economic impact due to their high volume usage.

In the Engineered Systems plane, our goal is to integrate the research with a chosen generic system testbed to demonstrate the viability of the technologies being developed. The testbed intends to showcase the IPEM vision and its application domain by employing standard-cell IPEMs and application-specific IPEMs that integrate converter with load to a generic power distribution system that could be applicable to telecommunications, computer, internet, aerospace, alternative energy/power conversion, automotive as well as future homes and other emerging applications. In order to evaluate the developed enabling technologies and especially to assess the broader impacts

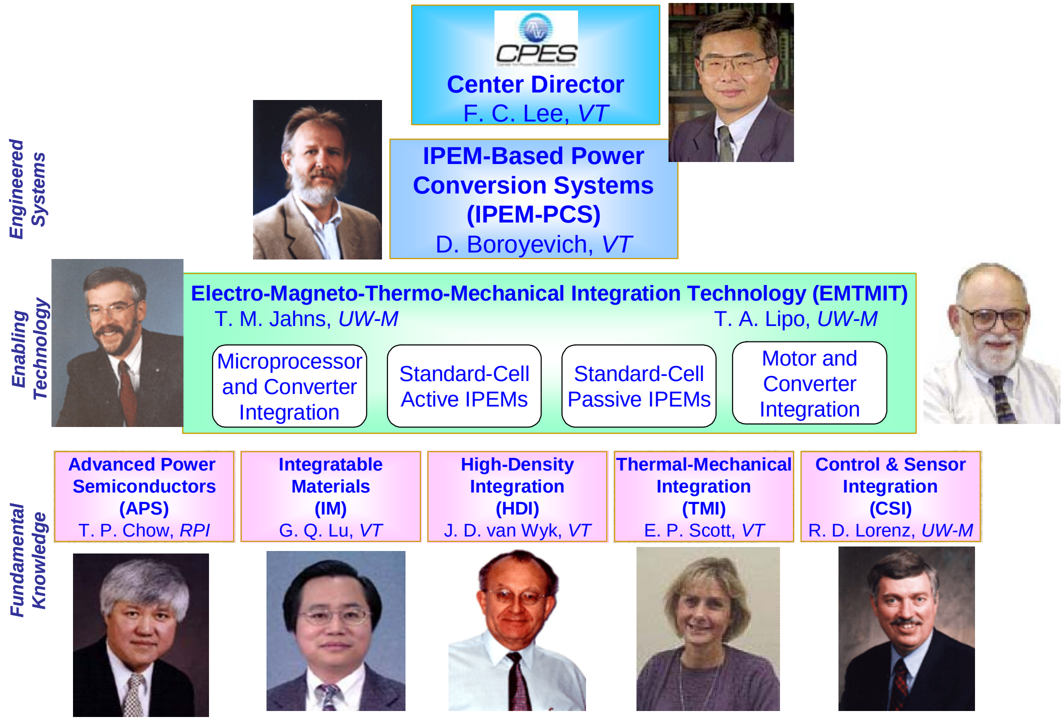


Fig. 1. CPES Research Program Structure and Thrust Leaders

they may have on the use of electrical energy in our society, we have selected a generic telecom data center for remote locations as a representative testbed. This testbed will provide an effective platform to integrate various research conducted at the Center in the area of power supplies and motor drives which are subjected to the same IPEM-based system integration and are subjected to the same system trade-off considerations, such as switching frequency vs. converter size and weight, which will allow for the exploration of true synergies between these two traditionally very separate application areas of power electronics. The testbed will address the total coupling of the thermal and electrical subsystems (practically all the heat is generated and removed electronically) and further enhance the multidisciplinary aspects of the CPES research. In addition to the hardware demonstration, the testbed program also involves of how the system can be modeled, partitioned, designed, optimized, and controlled.

One of the unique strengths of the Center is a strong industry consortium program, with 80 members participating. These member firms represent a broad spectrum of product lines, including power semiconductor devices, power ICs, passive components, power supplies, machines and drives, control ICs, packaging, system integration, and CAD tools. They are actively involved in the Center's research, serving as industry mentors and research champions, and providing the best conduit of technology transfer. In addition, the Industry Advisory Board (IAB) has actively organized working groups to help the Center address issues such as benchmarking, reliability, manufacturability and produceability.

A. ENGINEERED SYSTEMS THRUST: IPEM-Based Power Conversion Systems (IPEM-PCS)

The goal of this thrust is to develop an integrated system design approach to the electric energy processing systems based on IPEM and to explore the broader impact of the CPES-developed technologies on the electrical energy usage in our society. The IPEM-PCS thrust is formulated to validate the system integration concept by implementing a complex electronic power distribution test bed using IPEM and IPEM-related technologies developed in other thrusts. The two main focuses are: 1) develop demonstrative converters and system test beds encompassing advanced component, module, and integration technologies from CPES and elsewhere; and 2) develop integrated and generalized methodology and tools for converter system modeling, analysis, design, and optimization of IPEM based power conversion systems. A generalized, scaled down low-power, hybrid testbed architecture has been identified for these purposes. This testbed combines two renewable energy sources, solar cells and wind generation, with a feeder from the grid and battery energy storage (Fig. 2). The power conversion processing will consist of dc-ac, ac-dc, and dc-dc converters using both IPEM-based converters developed in CPES and commercial converters. One specific effort is the selection and installation of commercial components within the testbed. The implementation of phase-leg active IPEMs for building dc-ac inverters and motor drives is simultaneously ongoing. The design of the testable active IPEMs was improved and fabrication has been completed. On the study of system-level issues, the focus has been on IPEM-based converter modeling considering power flow, system dynamics, EMI, and thermal management. We completed the development and verification of a new, generic, modular-terminal-behavioral (MTB), frequency-domain EMI modeling of active IPEMs based on equivalent noise source with noise impedance. The new MTB models can be used to predict the converter conducted EMI for different propagation paths and different operating conditions accurately in the whole frequency range. The development of a modular terminal equivalent converter model is underway to characterize converters and likewise a system more

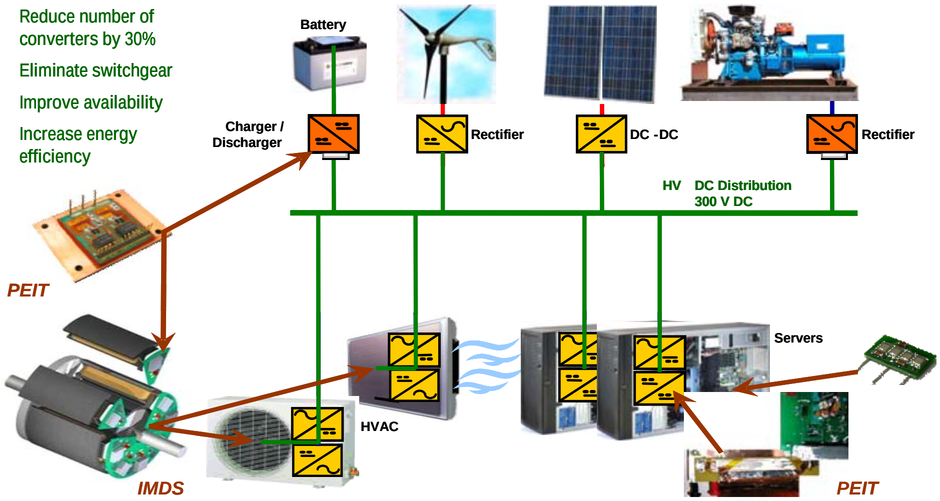


Fig. 2. IPCS Research Directions

generically and potentially more accurately than conventional system-level methods. The future modeling efforts will lead to a virtual test-bed suitable for the study of many system-level issues.

B. ENABLING TECHNOLOGIES THRUST: *Electro-Magneto-Thermal-Mechanical Integration (EMTMIT)*

The EMTMIT thrust focuses on two aspects of the IPEM. One is the development of integrated modules as a “standard-cell” IPEM and the other is the development of application-specific power electronics integration with loads such as motors and microprocessors. Using mainly the integration technologies from CPES fundamental knowledge thrusts, two basic types of standard IPEMs have been developed in the EMTMIT thrust: 1) active IPEM, which functions as a voltage source single-pole double-throw switch (i.e., a totem-pole half-bridge), integrates two active semiconductor switches, associated diodes, together with gate driver, sensor, protection, and heat transfer structure within the module; and 2) passive IPEM, consisting of integration of energy storage capacitors, inductors, and transformers.

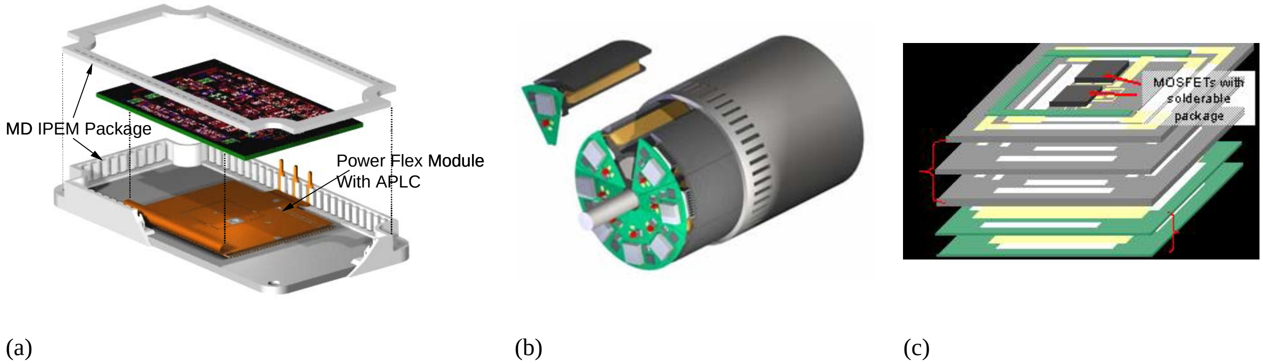


Fig. 3. (a) CPES Prototype IGBT active IPEM; (b) CPES integrated modular motor drive; (c) CPES 3-D integrated power supply converter module

(1) Standard-Cell IPEM (SC-IPEM)

The goal is to develop IPEM technology intended for standard configurations appropriate for use in a wide range of potential applications. Attention is directed towards carrying out proof-of-concept demonstrations that explore the compatibility of new CPES technologies for achieving high performance combined with rugged self-protection features and low cost. Fig. 3(a) shows a prototype IGBT-based active IPEM using CPES non-wirebond Embedded Power packaging technology. Demonstration has successfully been made in an inverter common-mode EMI reduction technique using the active dv/dt control of phase-lag switches within an algorithm that minimizes the switching loss penalty.

(2) Integrated Modular Motor Drive (IMMD)

The goal is to achieve significant manufacturability and reliability advantages by developing the integrated motor drive as a modular assembly. A promising approach for achieving this objective is to break the machine stator into individual segmented stator poles with concentrated windings. Fig. 3(b) illustrates the conceptual CPES IMMD that integrates power electronics and controller directly into the motor housing. Rather than simply placing the converter physically close to the motor as done in some commercial products, the IMMD integration is based on a modular configuration – one converter phase-leg per motor pole.

(3) Integrated Power Supplies (IPS)

The goal is to develop the technology needed to achieve a complete physical integration of high-performance power supplies in a three-dimensional multi-chip module. One application example is the integration of such a power supply with microprocessors to obtain the most efficient power management solution. According to the Intel roadmap, the future generations of microprocessors by 2010 will be well beyond the capabilities of VRM technologies known today, thus a dramatically different approach is required. Fig. 3(c) shows a CPES three-dimensional IPS module aimed at achieving physical integration of all active and passive components in a three-dimensional package. The IPS has a multi-coupled cell infrastructure with multi-stage, multi-MHz, multi-phase VRM; low temperature co-fired ceramics (LTCC) resonant converter processing technology for inductors and capacitors; and innovative packaging concepts to enable a System-in-Package (SIP) power module.

C. *FUNDAMENTAL KNOWLEDGE*

THRUST 1: Advanced Power Semiconductors (APS)

The goal of the APS thrust is exploration and demonstration of selected novel silicon and wide bandgap semiconductor (SiC and GaN) devices and ICs that will enable significant performance and reliability as well as cost improvements in power electronics systems. We have demonstrated enhancement mode GaN MOSFETs with blocking voltage up to 1 kV, by first obtaining much improved MOS properties on GaN capacitors with optimized oxide deposition and annealing conditions. Fig. 4 shows a proposed a GaN MOS-gated bi-directional switch, which consists of a pair of anti-parallel connected complementary MOSFET/Schottky rectifiers. Other significant accomplishments include: 1) proposed and demonstrated a novel SiC lateral channel JBS rectifier structure which has low leakage current and capacitance; 2) demonstrated 4 kV epi-emitter BJTs in 4H-SiC and performance superior to those of previously reported 3.2 kV devices; and 3) the refinement of 80V lateral trench Si MOSFETs with 30% better $R_{on} \times Q_g$ substrate performance than lateral DMOSFET or vertical UMOSFET. A 250 V lateral trench Si MOSFET was invented. This device offers 35% improvement in specific on-resistance over lateral DMOSFET.

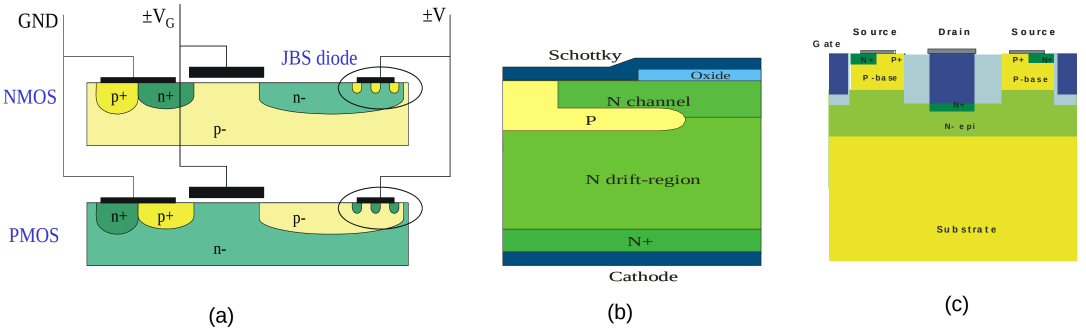


Fig. 4. (a) GaN Bi-Directional 4 Quadrant Switch (b) Super Junction Schottky (c) Trench MOSFET for Power ICs.

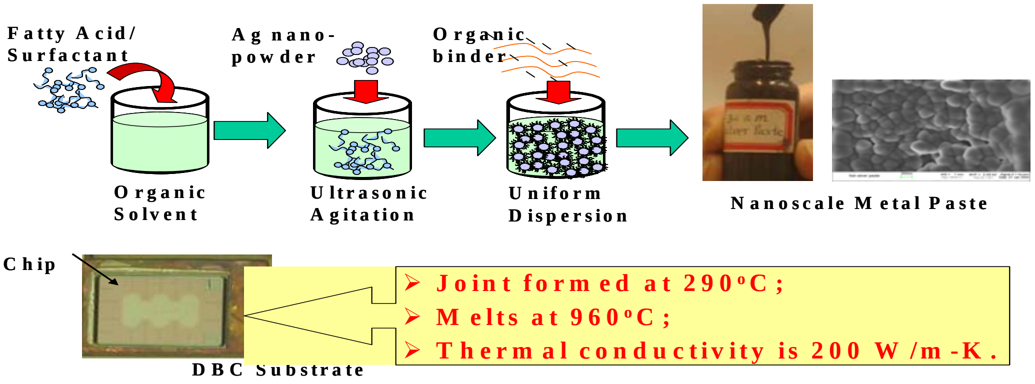


Fig. 5. A lead-free die-attach solution using low-temperature sintering of nanoscale metal paste for high-performance and high-temperature interconnection of semiconductor devices.

THRUST 2: Integratable Materials (IM)

The goal of the IM thrust is to conduct long-term, high-risk materials research aimed at addressing the needs of four technological areas that are critical to integration of power electronics systems: thermal management; passive integration using multi-functional materials; electromagnetic fields sensing; and understanding physical failure mechanisms. The general technical approach is to explore synthesis, processing, and integration of nanoscale materials that have novel chemical, thermal, and electromagnetic properties. Since its establishment three years ago, the IM thrust has made significant progress in understanding physical mechanisms governing the processing of nanoscale particles and their applications for integration in power electronics systems. Major achievements resulted include: (1) a novel nanoscale metal pastes sintered at low temperature for attaching semiconductor devices – the sintered attachment offers superior electrical, thermal, and thermo-mechanical properties (Fig. 5). The new die-attach solution can also support devices capable of operating at junction temperatures over 500°C. The technology has been successfully transferred to a start-up company for electronic packaging of microelectronics, power electronics, and optoelectronics devices; (2) synthesis of a multi-ferroic nanocomposite for making passive elements; the material system may be used as a platform for integrating passive elements; and (3) fundamental knowledge gained on competing physical processes between coagulation and coalescence aggregation of nanoparticles, and its successful application in formulating nanoscale metal pastes for die attachment.

THRUST 3: High-Density Integration (HDI)

The goal of the HDI thrust is to develop packaging technologies for integrating all the functions in a power electronic converter into modules. The research work in HDI is clustered into three areas: 1) process technology integration; 2) module integration technology for designable lifetime; and 3) functional integration of electromagnetic, switching, structural and thermal functions in a power processor module. CPES has been promoting the idea of replacing the conventional wirebond with direct bonding, and has introduced a number of techniques, such as the flip-chip-on-flex and the embedded power technology, as shown in Fig. 6(a), which offers high packaging density, double-sided cooling, the ability to contain the high frequency noises with build-in RF filter, and easy implementation of current and temperature sensors. In addition, CPES has developed technology for integrating electromagnetic power passives.

Fig. 6(b) shows a passive IPEM that includes four capacitors, two inductors and one power transformer. Functional and process integration with improved thermal management were successfully demonstrated for the first time.

Recently, CPES made a major advance in integrating EMI filters into a low profile, small volume integrated power electronics module (IPEM) with characteristics superior to an EMI filter constructed from discrete components, based on transmission line principles. This filter has already been shown to be effective between 1 MHz and 100 MHz for filtering both common mode (CM) and differential mode (DM) interference—a range where parasitics are already killing performance of other filters. This new technology will greatly simplify high frequency interference filters, reduce volume and profile, improve manufacturability, and match perfectly with the planar active IPEM technology (Embedded Power) developed by CPES, as shown in Fig. 6(c), where the integrated filter is packaged together with active IPEM.

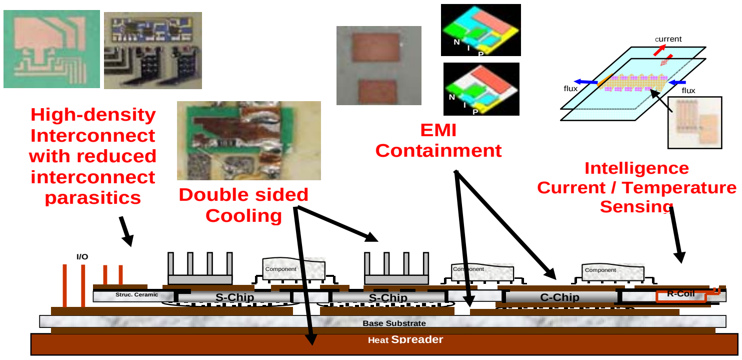


Fig. 6 (a) Embedded power packaging technologies

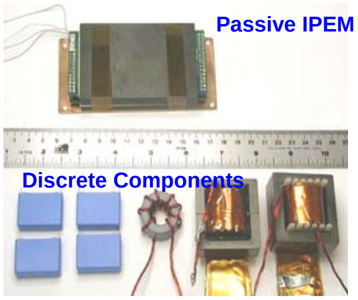


Fig. 6 (b) Passive IPEM vs. discrete components

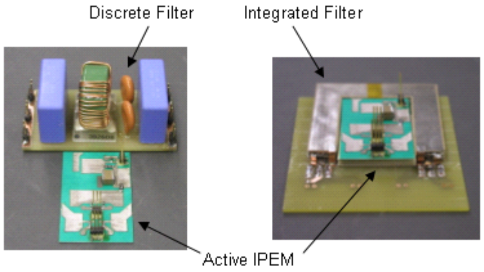
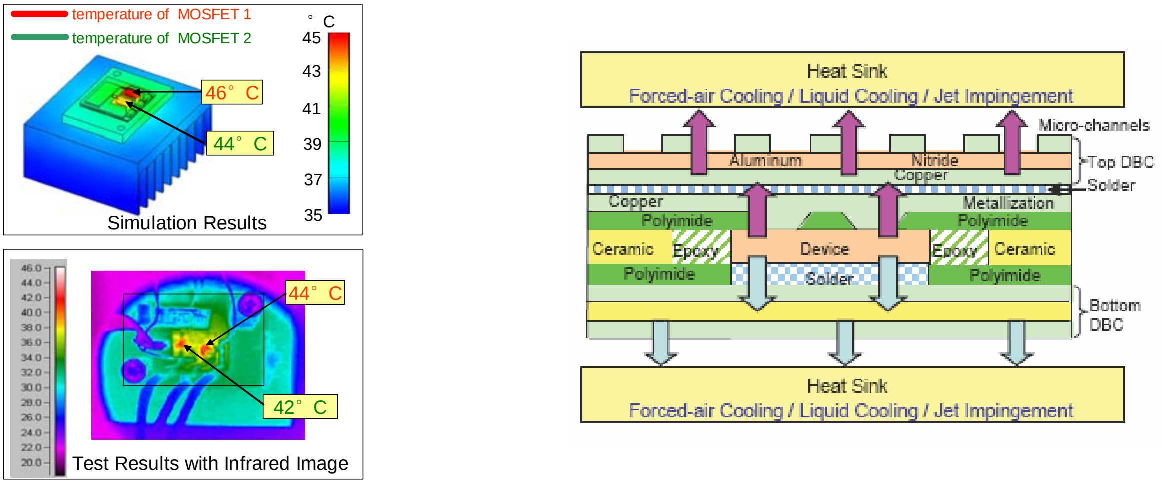


Fig. 6 (c) Integrated filter packaged with active IPEM

All process technology improvements for improving metal adhesion (improving reliability), for reducing thermal-mechanical stresses, etc., immediately apply across the entire large range of products, giving an incredible leverage to process development and integration. Finally, since the common technology applied to all projects is subject to the same common failure modes, research on improving reliability and designable operating lifetime immediately benefit all the systems served by results from these projects.

THRUST 4: Thermal-Mechanical Integration (TMI)

The overall goal of the TMI thrust is to develop integrated cooling technologies and assess fundamental cooling limitations. The research focuses include the development of 1) multi-level, multi-physical analysis tools and experimental techniques to determine the limitations of performance; 2) integrated thermal management technologies; and 3) methodologies to characterize thermo-mechanical failure mechanisms. Fig. 7(a) shows the active IPEM thermal modeling and test result comparison. Fig. 7(b) shows the concept of integrated double-sided cooling based on the CPES Embedded Power packaging technology, which without using bond wires, allows for the possibility of double-sided cooling by soldering an additional direct-bond copper (DBC) substrate on top of the metallization layer. It was shown that the use of double-sided cooling with heat sinks on both top and bottom substrates improved thermal performance by 62%.



(a) (b)

Fig. 7. (a) Thermal modeling of IPEM; (b) Integrated Double-sided Cooling Based on Embedded Power Packaging

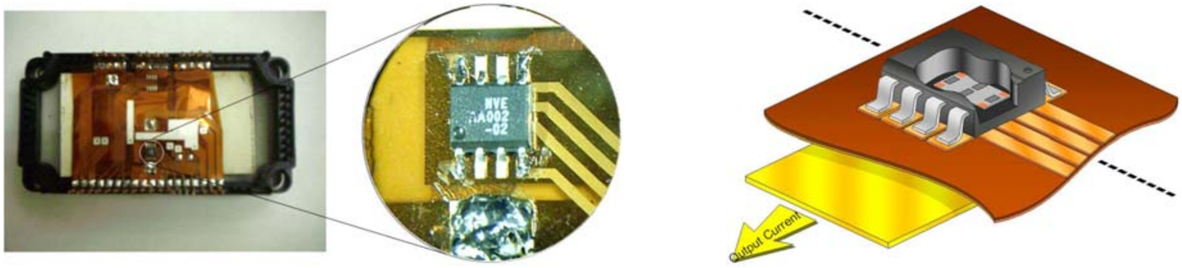


Fig. 8. Using the GMR field detector allows for a simplified compact integrated current sensor design

Other research includes experimental set up at Virginia Tech to study active cooling using transverse thermoelectric effects. Software to provide reduced order modeling capabilities has been developed using FEMLAB® at North Carolina A&T. Development of the microchannel flow models at RPI and Virginia Tech to study the use of microchannel cooling with sacrificial polymers.

THRUST 5: Control and Sensor Integration (CSI)

The goal of the CSI thrust is to create the fundamental knowledge needed to "intelligently" integrate sensors and controls into power electronics with technology approaches that have the potential to significantly improve both functionality and reliability while significantly reducing costs. To achieve this vision, the CSI research focuses on three critical aspects: 1) integrated current sensing internal to the IPEM structure; 2) spatial and temporal temperature sensing for load cycle thermal-mechanical stress control; and 3) relative thermal control of parallel IPEMs for robust power sharing. Fig. 8 shows a Giant Magneto-Resistive (GMR) field detection current sensor integrated in an IPEM. GMR temperature sensor was also developed. Other significant accomplishments include: active control of switching device junction temperature cycles in power converters to maximize reliability and device utilization; and “sensorless” control of junction temperature differences in parallel-acting power devices to improve reliability.

IV. INTEGRATED POWER ELECTRONICS SYSTEMS VIA IPEM – AN EXAMPLE

The distributed power systems (DPS) are widely used in telecommunication and computer applications. The front-end ac-dc converter is a standard module for power delivery, which achieves power factor correction (PFC) function and regulated 48 V output. This converter is chosen to demonstrate the advantages of integrating power electronics systems, using a selection of the technologies described previously.

In the DPS front-end converter shown in Fig. 9, two power-switching stages are cascaded serially to provide PFC and dc-dc conversion functions. The two stages are designed to operate at dc bus voltage of 400 V and power rating of 1 kW [4]. An advanced CoolMOSFET and SiC diode set, in a boost configuration, is chosen for switching at 400 kHz. For good thermal management, two parallel CoolMOSFETs and two parallel SiC diodes are adopted. The maximum operating junction temperature is limited to less than 125ºC.

The zero-voltage-switched asymmetrical half bridge converter (AHBC) provides isolated dc-dc conversion from 400 V to 48 V. It is composed of two MOSFETs in a totem-pole configuration and can utilize the MOSFET body diodes due to the zero-voltage switching. The converter secondary has the current-doubler topology. The switching frequency is 200 kHz, and the maximum operating junction temperature is limited to less than 125ºC. A high frequency capacitor is employed to decouple the parasitics of the connectors.

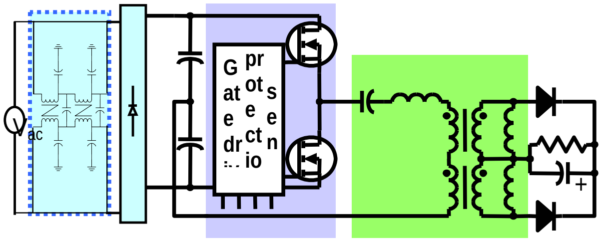


Fig. 9. Integrated front-end converter.

Fig. 9 identifies the three converter building blocks as an EMI filter IPEM, an active IPEM, and a passive IPEM. The active IPEM represents the integration of power MOSFETs and gate drivers, for both the PFC and DC/DC stage. The main goals of the overall integration are to reduce the component count, increase power density, develop a modular approach, improve thermal management, and reduce the overall number of interconnections at the system level.

A. *EMI – Filter IPEM*

Since the original work showed that much better form factor and improved density could be expected from integrated low pass filter [5-7], it was decided to develop technology suitable for integrating the (CM)/(DM) EMI-filter for switch-mode power supplies. The typical structure of an integrated passive structure to be used as EMI filters (Fig. 10). By using variations of this [8, 9], it is possible to develop an integrated filter.

In Fig.10, a dielectric sheet, metallized on both sides to form a winding, is inserted into a planar are ferrite core. The four terminals of the two-layer spiral winding are named A, B, C and D. The capacitance and inductance are distributed along the winding. So the equivalent circuit is like a transmission line. The lumped circuit is like a π-type EMI filter (Fig. 10).

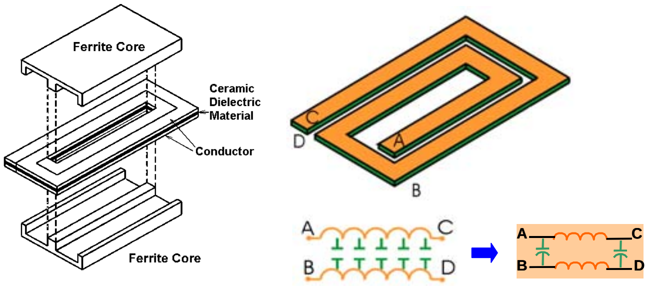


Fig. 10. Spiral winding planar integrated.

This spiral winding can be used to build different filter structures. Fig. 11 shows the CM filter, DM capacitor, DM and CM inductors. All are made of spiral windings. In Fig. 11, two two-layer spiral windings form a CM filter since each spiral winding has one layer grounded and the distributed capacitance and inductance form a distributed CM filter. For the DM inductor, the DM inductance is generated from the leakage flux of the CM inductor in a leakage layer inserted between the two planar windings. This integrated filter structure enable a far better control of the parasitics associated with each of the filter components as well as interconnected parasitics, which are detrimental to the filter's ability to attenuate the high-frequency noises. For example, it has been demonstrated that the equivalent parallel capacitance of the filter inductors detrimental to

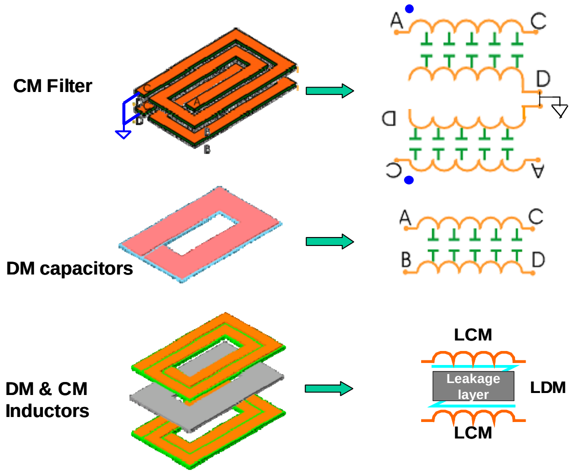


Fig. 11. Using spiral winding to build different filter structures.

high-frequency filter performance can be cancelled through proper shielding [10].

Applying the integration and equivalent parallel capacitor (EPC) cancellation technologies for integrated EMI filters, an improved integrated EMI filter prototype with structural winding capacitance cancellation was designed and constructed (Fig. 12). To evaluate its performance, a baseline discrete EMI filter with the same component values was also constructed.

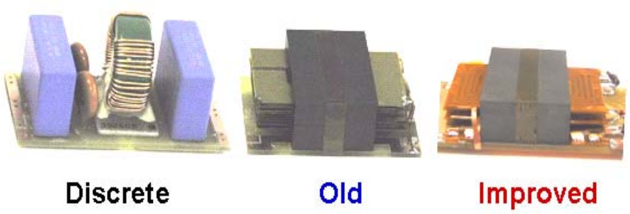
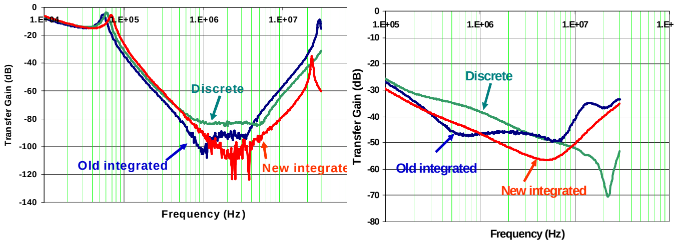


Fig. 12. Comparison of discrete and integrated EMI filter prototypes.



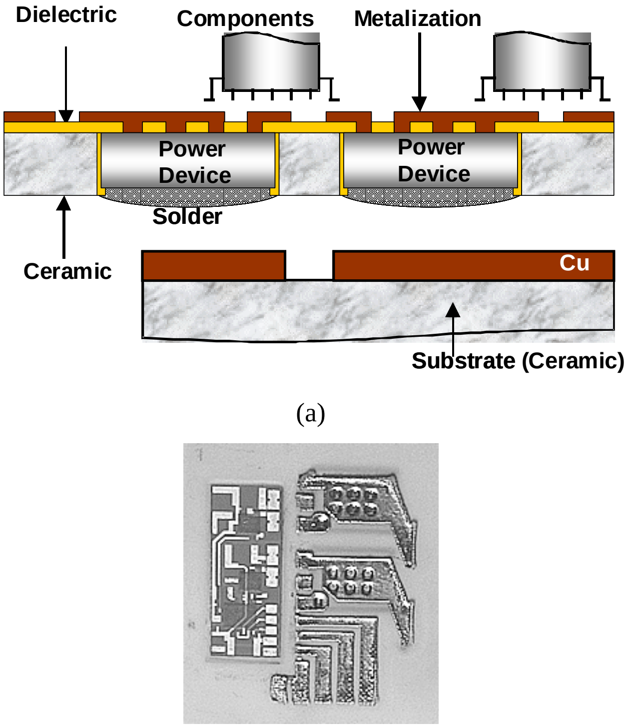
(a) DM transfer Gains (b) CM transfer gains

Fig. 13. Measured EMI filter transfer gain comparisons.

The CM and DM small signal transfer gains for the filter were measured (Fig. 13). From these measurement results, it can be concluded that the integrated EMI filters have the same function as the discrete versions, but with structural, functional and processing integration achieved. The improved integrated EMI filter has about half the total volume and profile as the discrete filter, but much better high frequency DM characteristics and similar high frequency CM characteristics.

B. Active IPEM

Since the use of wire bonding inhibits three-dimensional structural integration, a number of planar metallization technologies were developed. An example of one of these technologies is the Embedded Power Technology that has been implemented in the active power module of the previously referred DPS [11]. The principle of this technology is shown in Fig. 14(a), while a module for the DPS is shown in 14(b). Note that since one of the main structural elements of this planar technology is a ceramic carrier, the structure is amenable to mounting passive devices and advanced control functions in three-dimensional fashion directly on the carrier.



(a)

(b)

Fig.14. (a) Cross sectional view of an Embedded Power active module and (b) implementation.

The active IPEM components are selected based on the front-end converter specifications. The module layout is designed and optimized using solid-body CAD tools, thermal and electromagnetic analysis tools and circuit simulation [12, 13]. For high-density integration, the gate drive is assembled on a hybrid circuit with an Al_2O_3 substrate made by thick-film technology. The bare driver chips and components are mounted onto it through wirebond and surface mounting. This subassembly is considered as a single component in the module packaging.

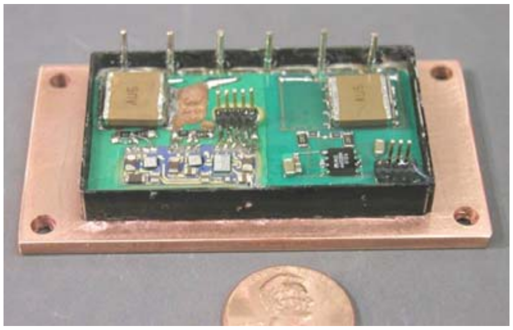


Fig. 15. IPEM for PFC and DC/DC converter.

The power MOSFETs and SiC diodes are integrated using the EP technology as described in the previous section. The associated components can be mounted onto the top metallization. Fig. 15 shows that the bus capacitors, components for gate drive, and input pins are mounted onto the top metallization of the PFC and dc-dc stages. The bottom side is wholly soldered onto a heat spreader made of Cu plate. The Cu posts are mounted on the top traces and form the power terminals.

C. *Passive IPEM*

Because of the current doubler configuration, the structure of the passive IPEM was now realized by stacking two transformers and using only one dc blocking capacitor, as illustrated in Fig. 16(a). The transformers are built with two planar E-cores that share a common I-core, as detailed in Fig. 16(b). The dc blocking capacitor of the AHBC is now implemented in only transformer T1 using the hybrid winding technology [14, 15]. This technology is implemented using Cu traces on both sides of the winding and a dielectric layer placed in the middle to enhance the capacitive component of that winding. The transformer T2 is a conventional planar low-profile transformer. The inductances of the current doubler output filter are realized by the magnetizing inductances of both transformers. Fig. 16(c) shows a picture of the final passive IPEM implemented for the AHBC.

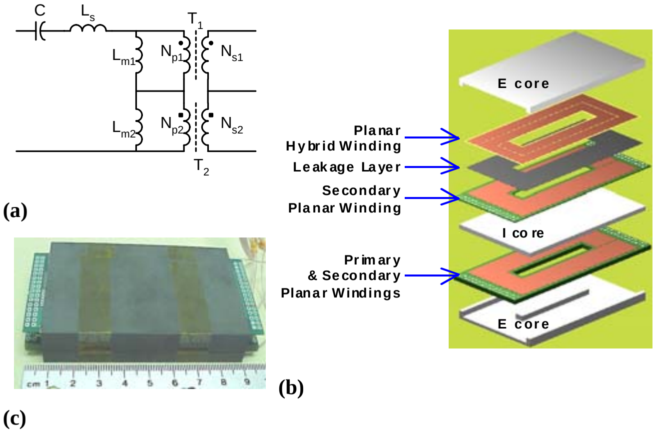


Fig. 16. Components of the passive IPEM: (a) equivalent circuit, (b) exploded view of the passive IPEM, and (c) 1 kW prototype.

D. *Integrated Front-End Converter*

To demonstrate the benefits of the IPEM concept at the system level, two 1 kW front-end converters were built using exactly the same topologies, one using discrete devices and the other one using IPEMs. The converters are designed for a universal input of 90 V~264 V, and will derate below 150 V to 600 W. The hardware of the two converters are shown in Fig. 17.

Through integration, the density and the form factor of the active and passive devices are appreciably improved. Consequently, the system-level power density of the converter improved by 2X. By replacing the discrete active and passive devices by IPEMs, the whole system only consists of a few modules, which is well suitable for automated assembly. Not only has the system structure been improved, but the system electrical performance has been dramatically better, as well. The system efficiency is increased more than 2% at the high line voltage range, and more than 3% at 90 V. Since the conduction loss of the IPEM is roughly the same for the same operating condition, the major improvement is due to the switching loss reduction by minimizing the circuit parasitics.

At the same time, due to the smaller parasitic inductance in the critical path of the converter, less voltage stress on the devices occurs. For the discrete PFC switch, with turn off current 7 A, the voltage overshoot is 123 V. But with an active IPEM, turn off at the higher current of 10 A, results in a voltage stress of only 72 V.

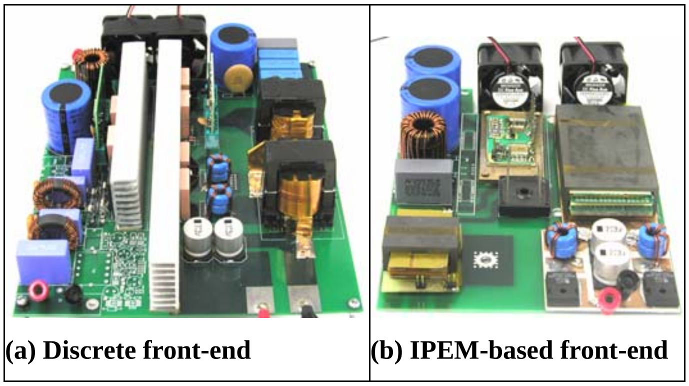

(a) Discrete front-end **(b) IPEM-based front-end**

Fig. 17. Comparison of hardware of front-end converters.

In summary, over the past ten years CPES was able to lead the development of the IPEM building block concept for power electronics system integration for applications covering almost the entire power range, as illustrated in Fig. 18. The research was supported by several federal agencies and major industrial corporations and partners. The CPES research results have directly impacted the companies listed in Fig. 18 to pursue commercialization of the IPEM-based modular approach. The NSF-ERC-sponsored research focused on the 1-10 kW range and, as described above, had a major impact on the module packaging and motor drives industries. The innovative passive IPEMs and EMI filter IPEMs are generating tremendous interest from industry, including automotive and space industry. The CPES research results in the low-power range, mainly supported through the VRM consortium, had an even broader impact because an integrated, modular approach was practically nonexistent in the computer and telecom power supply industry prior to this effort. Fig. 18 also shows two VRM IPEMs

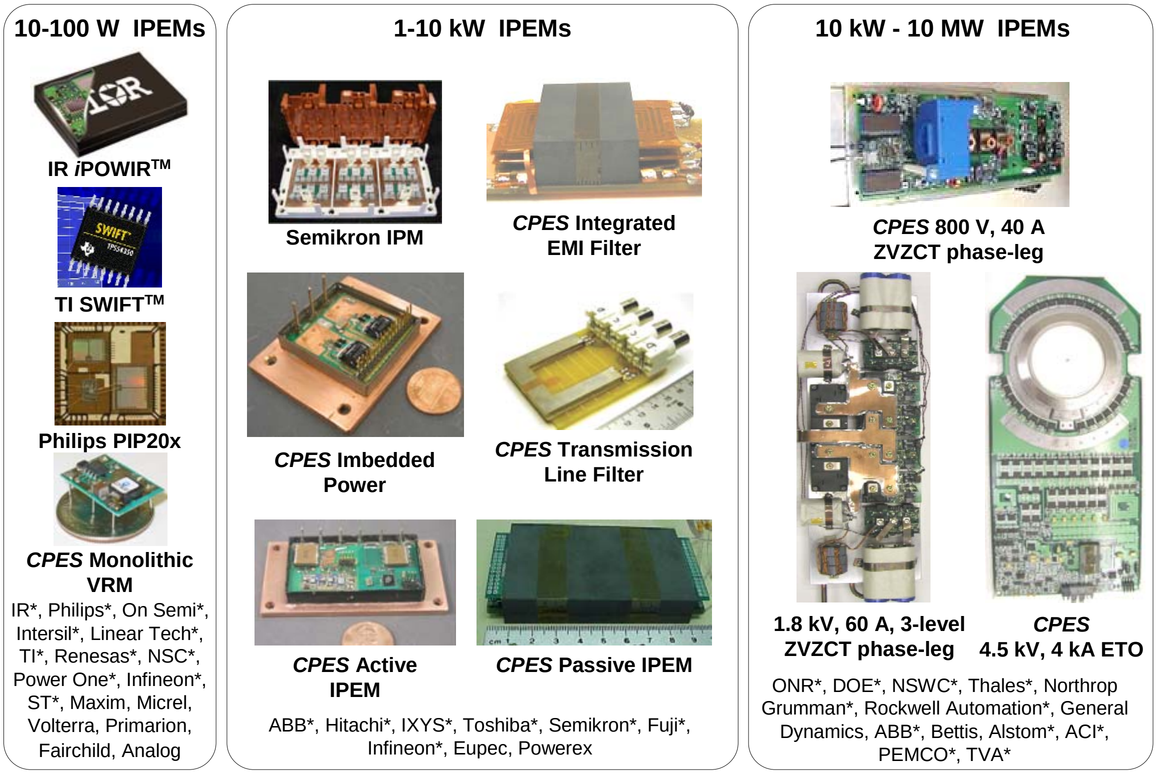


Fig. 18. The range of IPEMs developed at CPES and the organizations directly impacted by these efforts;

commercialized by our industry partners, International Rectifier and Philips, in 2002 and 2003, respectively. The development of the IPEM concept for the medium and high power applications was championed by the Office of Naval Research (ONR) as the Power Electronics Building Blocks (PEBB) approach. This is having significant impact on several electrical equipment suppliers for ships, cars, airplanes and power utilities.

V. TECHNOLOGY TRANSFER AND IMPACTS

CPES has been promoting the IPEM concept over the last 15 years. The research was first funded by ONR under the PEBB program and then later under NSF-ERC. The IPEM-based system integration vision has been demonstrated by the CPES research team with successful technology transfer in a number of areas, such as distributed power systems for computer and communication equipment and motor drives. In particular, many of the IPEM concepts and approaches have been successfully transferred to industry and have been commercialized. For example, the multiphase VRM proposed by CPES in early 1997, has been adopted by the industry as the standard industry solution for powering microprocessors as well as many other applications that require point-of-load power supplies. All major semiconductor companies have participated in development and commercialization of this technology and have offered new products. For example, Fairchild, Siliconix, Texas Instruments, National Semiconductor, Semtech, Intersil, ON Semiconductor, Linear Technologies, Maxim, Primarion, Silicon Lab, Analog Devices, Volterra, Microsemi, and STMicroelectronics, have produced integrated control ICs for the multiphase solution. Other power electronics industry leaders, such as International Rectifier, Renesas, Philips, PowerOne, On-Semi, and Intersil, also introduced the integrated module in their product lines referred to as “Dr. Mos” in a form similar to that of the IPEM developed at CPES. Texas Instruments, Enpirion and Linear Technologies took the IPEM concept one step further and commercialized a monolithically integrated power IC for the entire buck converter. It not only integrates power devices, drivers and controls monolithically in the silicon chip, but also an inductor on the backside of the silicon chip. All these have taken place in the past several years and have created a multi-billion-dollar industry.

This approach has been adopted in many other applications, such as the dc-dc converters for telecommunications, network products and various forms of distributed power systems. In the DPS architecture, the single-stage isolated converter is replaced by the two-stage approach. A “bus converter” is used for the first stage to convert 48 V into an intermediate voltage, and the multiphase buck converter was adopted at the post-regulation stage. This architectural change is based on the infrastructure of multiphase buck converter and provides an overall more cost-effective system solution on this sector of industry with a market size even greater than that of the VRM.

CPES researchers have developed a number of wirebond-free packaging techniques for IPEMs in the past five years, such as flip-chip-on-flex, dimple-array, and embedded power technologies [16-21]. In late 2002, industry began to introduce a range of products that utilized packaging techniques similar to what CPES developed earlier, including Fairchild's bottomless and BGA packaging, Renesas's lead-free packaging (LFPAK), International Rectifier's FlipFet and DirectFET, Siliconix's PowerPAK, and STMicroelectronics FLAT package. Features typically claimed in these new products include reduced contact resistance, reduced parasitic inductance and improved thermal management, which are what we reported in the literature a few years ago.

In the motor drives industry, we have begun to see widespread use of Intelligent Power Modules (IPMs), a concept very similar to the CPES IPEM for low horsepower motor drives. Major industry leaders, including Toshiba, Mitsubishi, Siemens, ABB, Semikron, and Powerex have introduced IPM products. More specifically, key concepts embodied in the motor drive IPEM architectures developed during the first five years are being adopted in new power module products produced by major power semiconductor manufacturers, including Fuji, International Rectifier, and Semikron, which are members of CPES Industrial Partnership Consortium. These features include active gate drives, current sensors, and phase-current regulators that are all key elements of the CPES motor drive IPEM architecture. Semikron has included the GMR-based point field detector approach conceived by CPES for integrated current sensing in its newly introduced, highly integrated automotive IPMs. Within the past several years, industry has begun to rigorously pursue commercializing the IPEM-based modular approach in the motor drives industry. For example, more than 40% of appliances in Japan are using module-based inverter drives.

VI. FUTURE RESEARCH DIRECTIONS

Over the past ten years, CPES has developed a variety of promising new power electronics technologies. Many of these are associated with the focused effort to develop Integrated Power Electronics Modules (IPEMs) that incorporate new types of power semiconductor devices, planar interconnect processes, sensor integration techniques, thermal management configurations, and high-temperature materials. These core technologies offer rich opportunities for future generations of power electronics systems that require higher performance at lower cost with improved reliability. Such systems are critical to a wide range of applications extending from home appliances to automobiles and aircraft.

In view of the many attractive features of these technologies, there is optimism that they will generate a substantial number of new opportunities for sponsored research in the coming years. Technology areas that are expected to gain increasing importance in the future research and development activities include:

A. High Temperature Power Electronics

Advances in this area are being actively sought for many military, automotive, commercial, and residential applications in order to increase power density and reliability. The emergence of wide bandgap semiconductors such as SiC makes it possible to operate power converters at increasing temperatures up to and beyond 200°C. Higher operating temperatures enable increased power density and applications under harsh environments, such as military systems, transportation systems, and outdoor industrial and utility systems. On the other hand, high temperature power electronics require much more than just high-temperature devices; materials, packaging, passive components, and cooling must all be taken into consideration. Significant progress has already been achieved towards the development of high-temperature power semiconductor devices and their associated packaging, but there is much more that needs to be done.

B. Electromagnetic Interference and Compatibility

Power quality and, more specifically, electromagnetic interference and compatibility (EMI/EMC) are soon becoming the limiting factor as the industry continues to push for higher switching frequencies and higher power density. Furthermore, as the power electronics content of future systems increases – whether in a home, in an automobile, or in an aircraft or a large ship – the problems associated with ensuring that all of the loads and sources can co-exist with appropriate levels of power quality and EMC characteristics are taking on ever-increasing significance.

One of the most effective ways to deliver the needed power quality and EMC performance is to integrate these features directly into the power electronic modules. This approach avoids the bulky and expensive filter blocks that would otherwise have to be added as engineering afterthoughts. This integrated approach has shown substantial promise for meeting power quality and EMC requirements in future power electronics systems for a wide variety of applications.

C. Energy Efficiency and Power Management

Energy efficiency is a key concern for all electrical systems, from sources and delivery systems to loads. Energy management is important for small wireless devices, mobile units such as laptops, and medical devices, as well as for large server and data centers, buildings, transportation systems, and utility microgrids with distributed power sources. Many disciplines of power electronics, from components, sensors, control, system architecture, and thermal management, must be involved in order to provide a superior energy management solution.

In the continuous search for more energy-efficient power management solutions for a wide range of applications, power density improvement has always been an indicator for the advance of power converter technology. Higher density will eventually lead to better performance and lower cost. In the past, density growth has been naturally achieved through newer, faster, and lower-loss switching devices that resulted in a reduced need for energy storage devices, filters, and cooling systems. As the switching frequency continues to increase, the thermal and electrical limitations of materials, especially for passive devices, become barriers.

The above stated technology trends serve as the basis for a number of new and emerging applications. The key new application areas identified are as follows.

Many new and distributed energy resources are emerging, including alternative energy sources, such as solar and wind, fuel cells, microturbines, as well as energy storage devices such as battery, super capacitors, super conduction magnetic energy storage (SMES), and flywheels. All of these sources need power converters for grid and load interfaces. Proliferation of power converters in distribution networks has been slow, especially in high power applications, despite the obvious potential advantages from better dynamics and reduced need for margin, to enhanced control and communication. For example, all-electric ships and more electric airplanes offer tremendous opportunity for power electronics research.

Lighting loads represent about 20% of electric power consumption. Power electronics based ballast, together with various gas discharges lighting such as fluorescent and HID lights, have resulted in significant energy savings. Future solid-state lighting, such as white LED based on GaN, will further improve the system efficiency and reliability, and revolutionize illumination. Materials, packaging, and thermal management, together with power electronics control, are key enabling technologies for solid-state lighting.

VII. CONCLUSION

It is well recognized in the industry sector that performance improvements and size, weight and cost reduction of power electronics systems are largely due to higher switching frequencies which were made possible with advances in semiconductor technologies during the last four decades. This increase in switching frequency and reduction in size has led to an increased electromagnetic and thermal coupling in the circuit layout. Further increasing in switching frequency beyond the current practice will require innovative device-level packaging and circuit interconnect technologies that will provide significant reduction of structural parasitics and likewise, system level packaging to improve thermal management. In this respect, it is essential to develop an integrated systems approach to standardize power electronics components and packaging techniques in the form of highly Integrated Power Electronics Modules (IPEMs). The primary research focus of the Center for Power Electronics Systems is to develop advance semiconductor devices and innovative packaging technologies that will provide functional integration for not only of power devices with associated drivers, control and sensors, but also electromagnetic integration of passive components, such as inductors, capacitors and transformers.

Moving from typical power electronics systems that use non-standard components to a highly integrated system will require better integration technologies to increase power density, improve electrical performance and improve thermal management. It is also essential that the RF and EMI noises associated with IPEM be reduced and contained. Moreover, integrated analysis and design tools are necessary to develop breakthrough integration technologies that fully exploit the physical properties of available materials. It is evident that further development and innovations will be necessary as IPEM technologies gain maturity. The impact of system integration via IPEMs will enable a rapid growth of power electronics applications with reduced costs and design cycles that can be compared to the impact in advancement of IT industries brought up by the VLSI circuit technology.

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