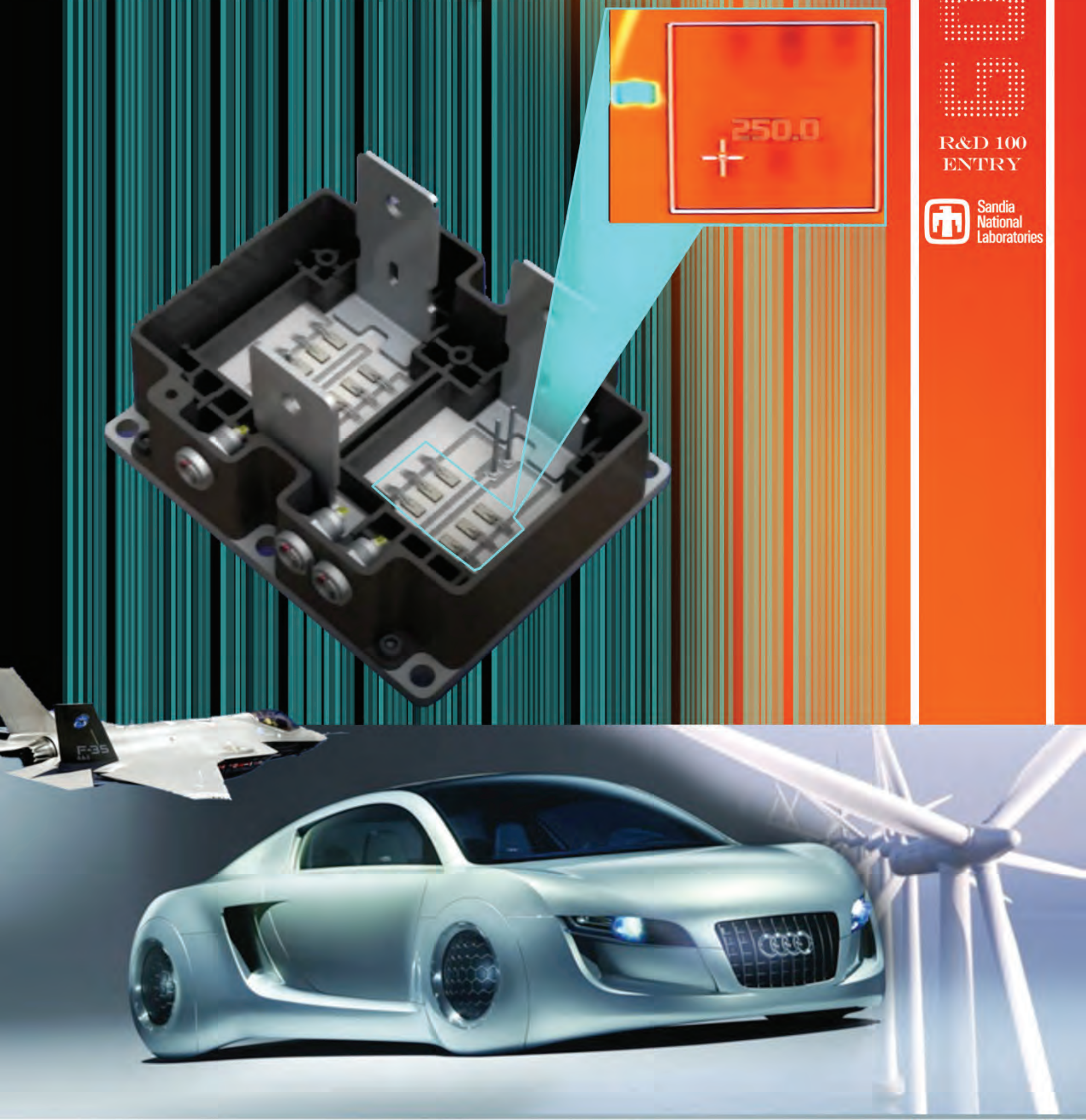
SiC Power Module

The World's First 250c Operating Power Module with SiC Devices

2009

R&D 100
ENTRY

Sandia
National
Laboratories



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AFFIRMATION: I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

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JOINT ENTRY

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Cover: The SiC Power Module (above). The images (bottom) are generic depictions of the SiC Power Module's various applications.

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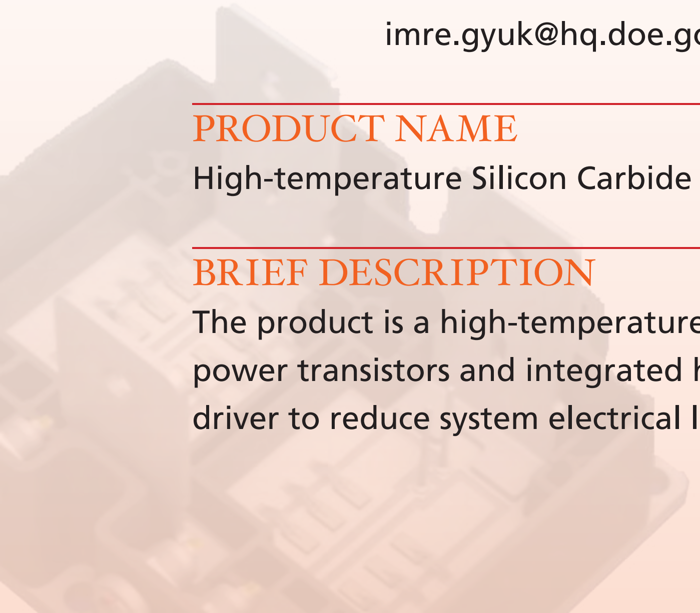
PRODUCT NAME

High-temperature Silicon Carbide (SiC) Power Module

BRIEF DESCRIPTION

The product is a high-temperature 250°C power module implementing silion carbide power transistors and integrated high-temperature silicon on insulator (HTSOI) gate driver to reduce system electrical loss by less than 50 percent.



PRODUCT FIRST MARKETED OR AVAILABLE FOR ORDER

The High-temperature SiC Power Module was first marketed via a public press release and floor demonstration at CEATEC 2008 (Combined Exhibition of Advanced Technologies), Japan’s premiere electronics trade show. CEATEC took place September 30–October 4, 2008, in Makuhari, Japan.

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PRODUCT PRICE

Product pricing depends upon volume and power rating:
(a) Initial low-volume price (maximum power—1200 V / 150 A): $11,500 each
(b) High-volume price target (maximum power—1200 V / 150 A): $2,500 each

PATENTS PENDING

N/A

PRODUCT'S PRIMARY FUNCTION

Power electronics modules are the core components of all power electronics systems. In essence, power electronics systems convert electrical energy from one form (provided by a source) into another form (consumed by a load). They are required to drive electric motors (such as those for electric and hybrid vehicles), convert energy from renewable sources (i.e., solar arrays or wind generators), and provide power for a wide variety of electronics and electronic systems (DC power supplies and inverters).

With applications in hybrid and electric vehicles, renewable energy interfaces, and more-electric aircraft, it reduces size and volume of power electronic systems by an order of magnitude over present state-of-the-art silicon-based solutions while simultaneously reducing energy loss by greater than 50 percent and offering the potential to save $100s of millions.

Our team's *high-temperature silicon carbide power module* is the **world's first commercial** high-temperature (250°C) silicon carbide-based power electronics module. The 50 kW (kilowatt) (1200 V (volt) /150 A (ampere) peak) silicon carbide (SiC) power modules are rated up to 250°C junction temperature and integrate high-temperature gate drivers.

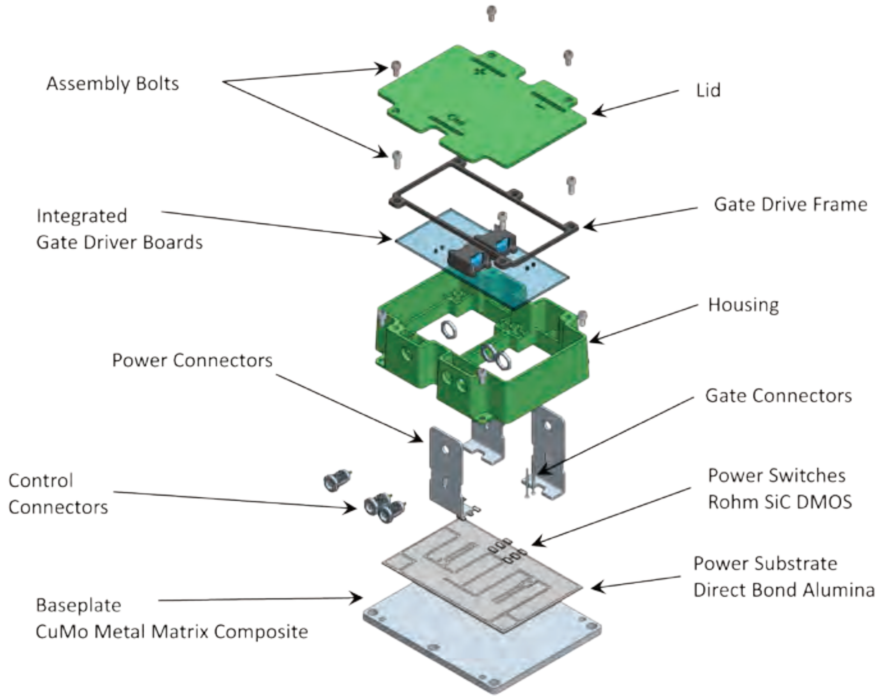


Figure 9.1. Exploded view of the high-temperature SiC half-bridge power module.

The power module functions to 250°C junction temperature, implements a two position half-bridge power topology (up to eight parallel power transistors per switch position), integrates a high-temperature silicon-on-insulator (HTSOI) gate driver board, and is packaged in a high-temperature plastic housing. The module can be built and is functional with SiC metal-oxide-semiconductor field-effect transistor (MOSFET), junction gate field-effect transistor (JFET), or bipolar junction transistor (BJT) power transistors, with no changes to the manufacturing process or gate driver board.

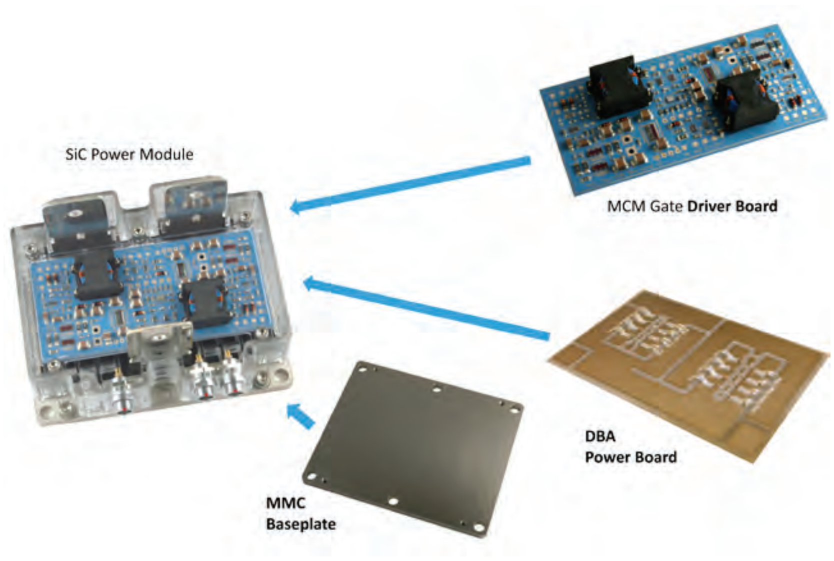


Figure 9.2. *Photograph of the major components of the high-temperature SiC power module and how those components are integrated into the module (the housing of this display module is translucent in order to allow visibility into the module).*

Silicon-Carbide (SiC) Power Switches

The power module implements up to eight parallel SiC power transistors per switch position (16 power transistors per module) that are capable of operating to junction temperatures greater than 250°C. The power transistors mount on the power substrate and are the electronic components that actually process the electrical energy conversion.

Silicon carbide is a relatively new semiconductor material that is currently under substantial development for the fabrication of power electronic transistors (such as MOSFETs, JFETs, insulated-gate bipolar transistors (IGBTs), gate-turnoff thryistors ((GTOs), diodes, etc.). Theoretically, SiC can operate to temperatures up to 600°C (standard silicon transistors are typically limited to 150°C), can block 10-times more voltage than silicon, has a higher current density, can transition between the on- and it off-states 10-times faster than silicon, and has a lower on-resistance (i.e., it is more energy efficient). Figure 9.3 illustrates a comparison of the common, commercially available silicon MOSFETs and the new SiC vertical junction field-effect transistor (VJFET).

The power switch turns on and off, either conducting or blocking current. When the switch is on, it conducts current. When the switch conducts current, there is a power loss associated with it; often the loss is indicated by the "on-resistance curve" shown in Figure 9.3. On-resistance (RON) Ron=Vdrop / Iconducted. The smaller the RON, the smaller the energy loss associated with that switch. This figure shows the small RON for a silicon carbide switch in comparison with equivalent standard silicon switches. The on-resistance characteristic of a power transistor is directly related to the power efficiency of that device. As can be seen from this measurement, SiC components have a 5-times to 10-times smaller on-resistance in comparison with equivalent silicon components (even at room temperature), which correlates directly to a reduction in power loss within the component by 5-times to 10-times.

The second important aspect indicated in this measurement is that the SiC VJFET is operational to greater than 300°C, more than double the silicon component temperature range. The advantage of this high-temperature operation capability is two-fold: (1) it allows for the power modules to operate efficiently and reliably in high-temperature ambient environments, such us under the hood of a hybrid-electric vehicle or in the wing of an aircraft, and (2) it allows for a significantly smaller and lighter power electronics system through the reduction of the thermal management system, by an order of magnitude.

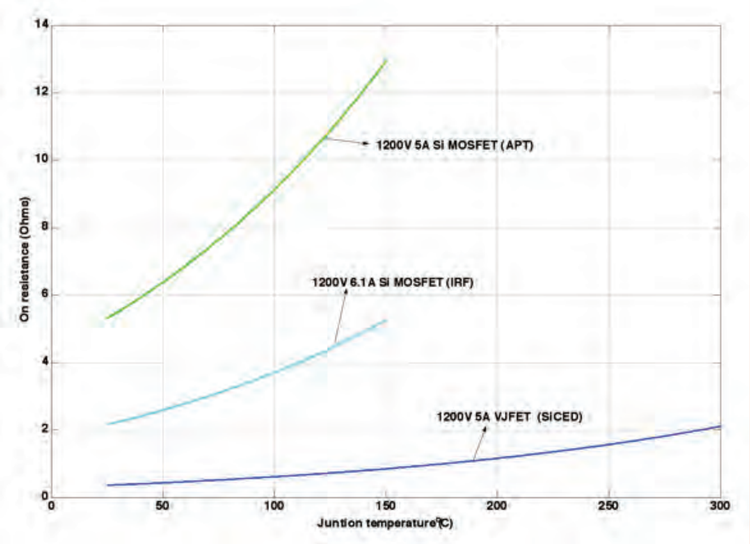


Figure 9.3. *Comparison of on-state vs. temperature for Si and SiC components.*

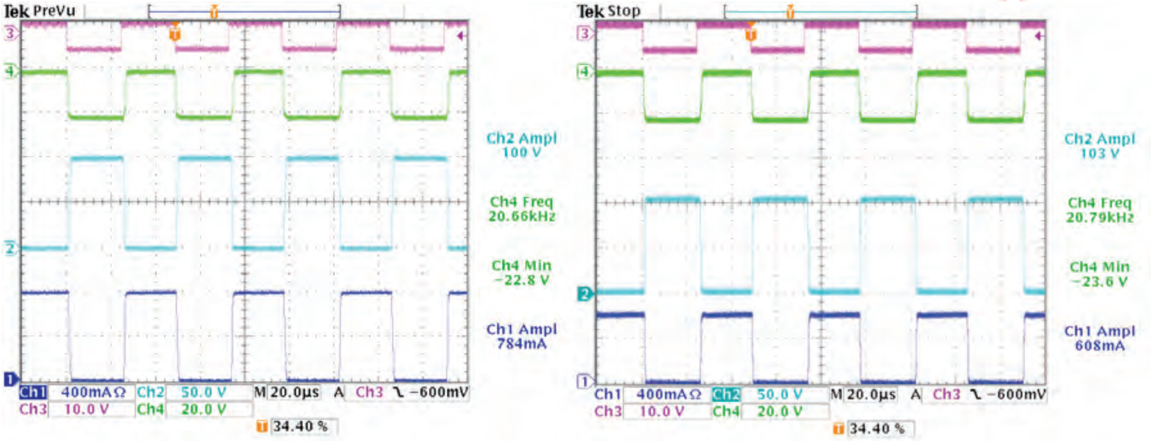


***Figure 9.4**. Switching operation of a SiC VJFET at 25°C (left, Ch 2) and 400°C (right, Ch2).*

High-Temperature Packaging

In order to take advantage of the high-temperature operational capability of the SiC power transistors, high-temperature electronics packaging is a vital aspect. Following are the packaging processes developed or utilized for this product:

1. High-temperature lead-free transient liquid phase (TLP) die attach and substrate attach
2. High-temperature wire bonding
3. Ceramic electronics board
4. High-temperature epoxy component attach
5. High-temperature plastic housing and framing components
6. Advanced, lightweight metal matrix composite (MMC) baseplate

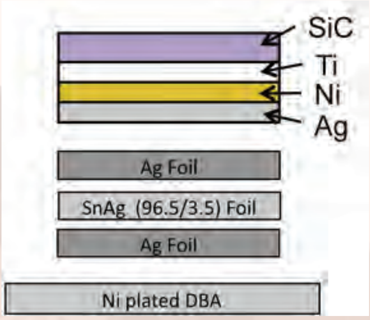


***Figure 9.5.** Cross-section of various layers in the lead-free 400°C Ag-Sn TLP die attach developed and patented for the high-temperature SiC power module.*

We developed a high-temperature, lead-free silver-tin TLP die attach process to connect the power transistors to a nickel-plated direct bond copper (DBC) or direct bond aluminum (DBA) power substrate (aluminum nitride or silicon nitride). This die attach process is capable of operation to temperatures in excess of 400°C.

We also developed a high-temperature, lead-free nickel-tin TLP attachment process to connect the nickel-plated DBC or DBA power substrate to the MMC baseplate. This substrate attach process is capable of operation to temperatures in excess of 400°C.

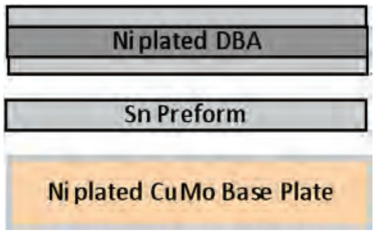


Figure 9.6. *Cross-section of various layers in the lead-free 400°C Ni-Sn TLP substrate attach developed and patented for the high-temperature SiC power module.*

Figure 9.7 illustrates the experimental results of wire bond pull testing of Arkansas Power Electronics International, Inc.'s (APEI, Inc.'s) high-temperature Aluminum 15 mil and 8 mil diameter (dia.) wire bond processing. We performed the pull tests according to military specification 883 (with the exception of extending the temperature range). Military specification 883 is the military standard for testing microelectronics, and the specs cover everything from wire bonds to die attaches and environmental survivability requirements. Military specifications require a 15 mil dia. wire to pass a pull strength of 250 gram force (gf) after cycling, and an 8 mil dia. wire to pass a pull strength of 75 gf after cycling. As can be seen from figure 9.7, APEI, Inc.'s 15 mil dia. wire bond processing passes 400°C cycling requirements, and the 8 mil dia. wire bond processing passes 350°C cycling requirements. Typically, the higher temperature that the component is cycled to the more stress it is going to see, and more failure mechanisms are introduced into the wire bond or wire bond

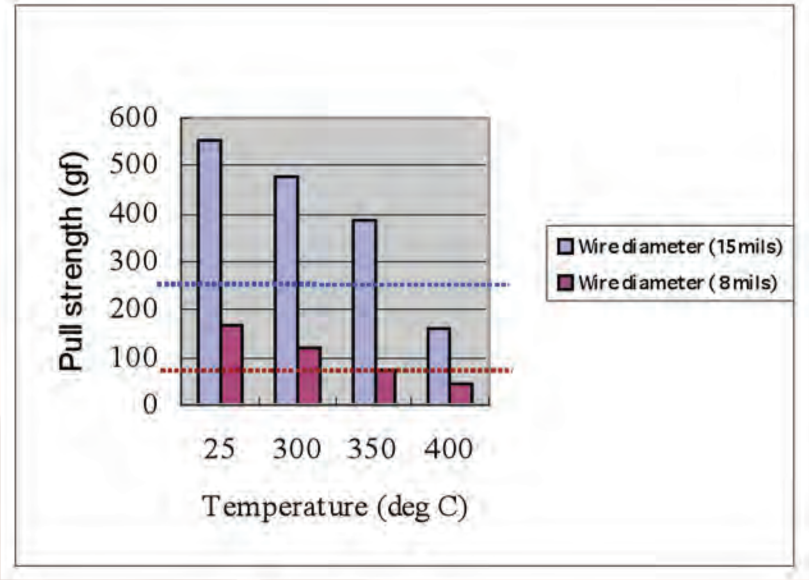


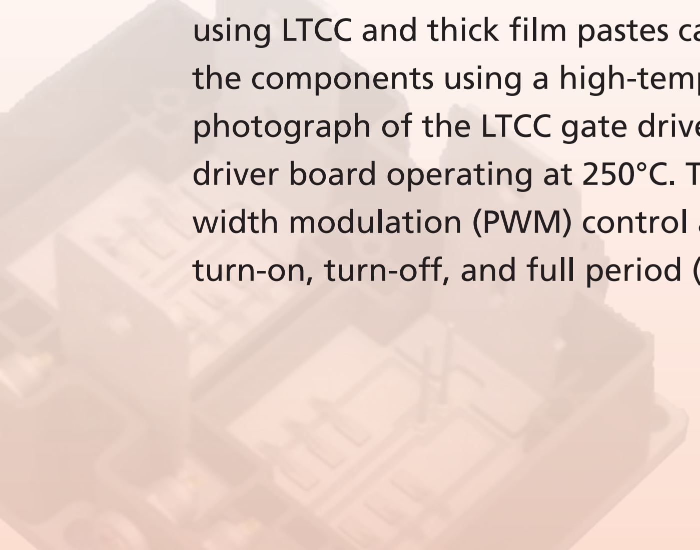
Figure 9.7. *Pull strength of APEI, Inc.'s Al wire bond power interconnects (15 mil and 8 mil) at 25°C, 300°C, 350°C, and 400°C cycling.*

interface. This results in less force being required to break the bond during testing. If the measured force is too low, the process fails military specifications.

The electronics driver boards are manufactured using low-temperature co-firable ceramics (LTCC) and thick film pastes that can reliably withstand ambient temperatures greater than 300°C. A high-temperature (300°C) epoxy is utilized for component attach on the gate driver board. The module housing is manufactured from a high-temperature Zytel® plastic, capable of reliably surviving ambient temperatures greater than 300°C. The baseplate of the power module utilizes an advanced lightweight copper-molly metal matrix composite (CuMo). MMC that has a coefficient of thermal expansion (CTE) characteristic closely matching that of the SiC power transistors. This CTE matching reduces thermal-stress mismatches, thus improving the long-term reliability of the power module.

Gate Driver

The power-switch control signals are created via a control board with a microprocessor or digital signal processor (DSP). Then the control signals are fed into the high-temperature SiC power module by control signal ports. These signals are pulse width modulation (PWM) gate control digital signals. The gate driver board accepts the digital control signals from the control board, amplifies and modifies the signals, and drives the SiC power switches into the required "on" and "off" states. WE designed the gate driver board to drive a variety of SiC power switches, including VJFETs, MOSFETs, and BJTs. The driver board utilizes high-temperature silicon on insulator (HTSOI) active integrated circuits (ICs), ceramic negative-positive-zero NPO-type capacitors, SiC diodes, and in-house designed/built high-temperature isolation magnetics. We fabricated the driver board substrate using LTCC and thick film pastes capable of reliable 300°C operation. We attached the components using a high-temperature 300°C epoxy. Figure 9.8 (top left) is a photograph of the LTCC gate driver board, and a thermal image (top right) of the driver board operating at 250°C. The oscilloscope (bottom) images show the pulse-width modulation (PWM) control and gate drive outputs of one of the signals at turn-on, turn-off, and full period (at temperature).



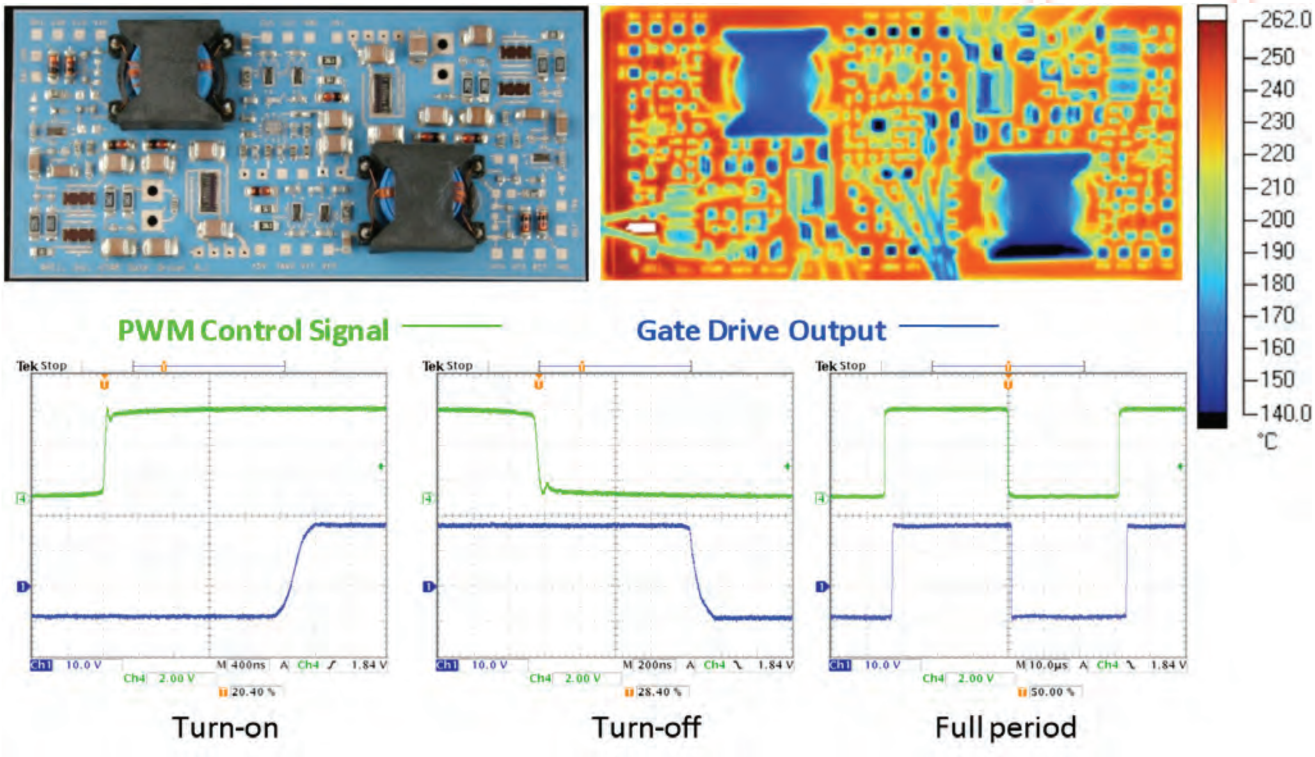


Figure 9.8. *(top left) photograph, (top right)thermal image, and (bottom)scope capture of the high-temperature LTCC gate driver board.*

High-Temperature SiC Power Module

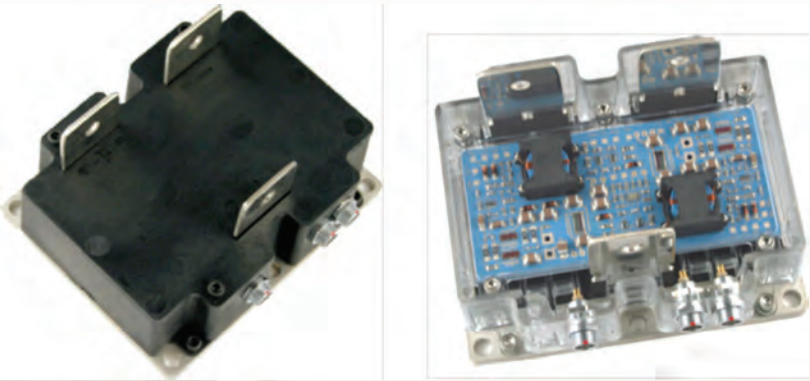


Figure 9.9. *Photographs of the high-temperature silicon carbide power module (left), and the unlidded translucent promotional display module (right).*

Figure 9.9 are photographs of the high-temperature SiC power module product and the promotional translucent promotional display module. Figure 9.10 is a photograph of the SiC power module demonstration at CEATEC 2008 in Makahuri, Japan. The demonstration operated an unlidded SiC power module (utilizing Rohm SiCdiffusion metal oxide semiconductor (DMOS) power transistors) with the gate drive control board in a separate module (configured so the SiC power switches could be exposed and thermally imaged for clear illustration of high-temperature operation to the audience and crowds).

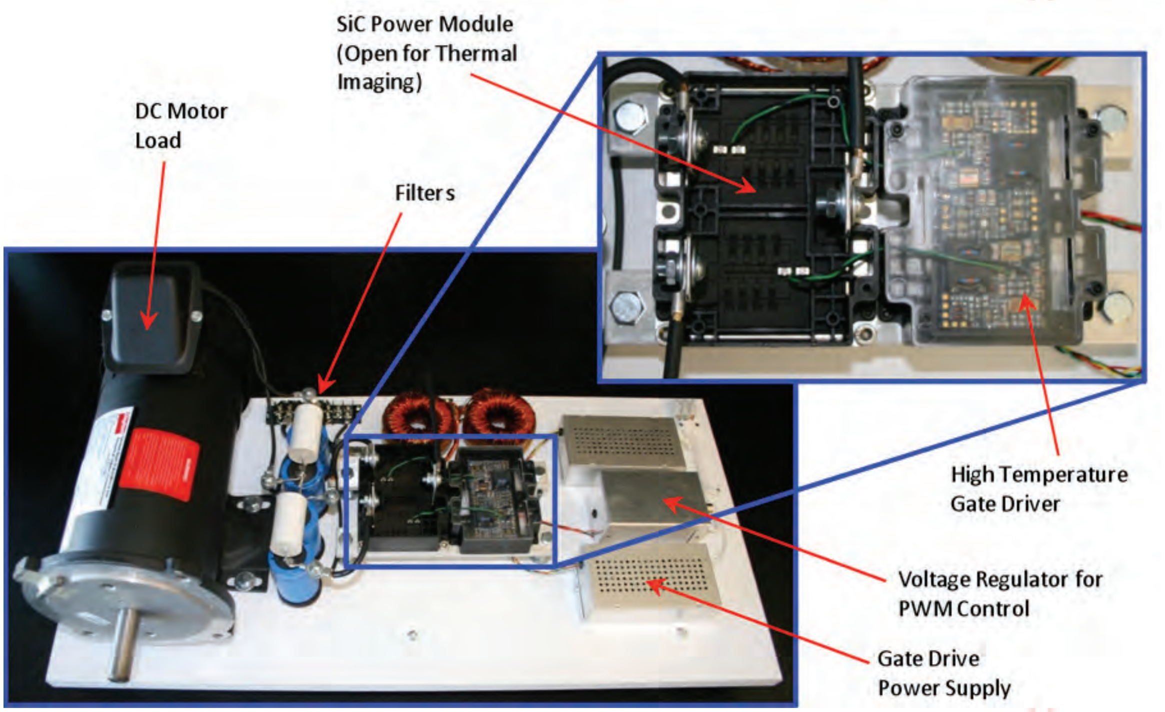


Figure 9.10. *Photograph of the high-temperature SiC power module motor drive demonstration performed at CEATEC 2008.*

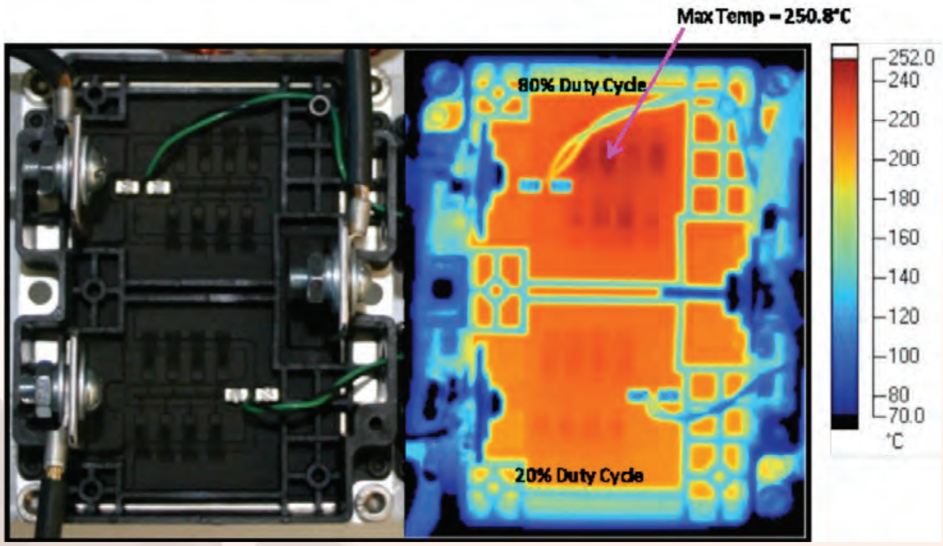


Figure 9.11. *Photograph of the unlidded high-temperature SiC power module (left) and thermal image (right) of a demonstration performed at CEATEC 2008.*

Figure 9.11 illustrates a thermal image of the high-temperature SiC power module driving the DC motor load at the CEATEC demonstration. As can be seen by the imaging, maximum junction temperature of operation of the power module is 250°C, using SiC MOSFETs. In the demonstration, the high-side power switching position is operating at 80 percent duty cycle (the measurement of how long a switch is on compared to how long it is off), while the low-side power switching position is operating at 20 percent duty cycle. The 250°C steady-state junction temperature in this demo is reached through the elimination of the heat sink.

All energy loss in an electronics system results in thermal energy, and this thermal energy must be removed from the system in order to keep the temperature of the electronics low. Removal is done through a heat sink with a fan, or a thermal management system (e.g., liquid cooled baseplate). These are heavy and bulky, and they constitute much of the size and volume of a power system. SiC operates at high temperature. So the heat sink system can be smaller and can operate the module under self-heating conditions in a room-temperature ambient environment.

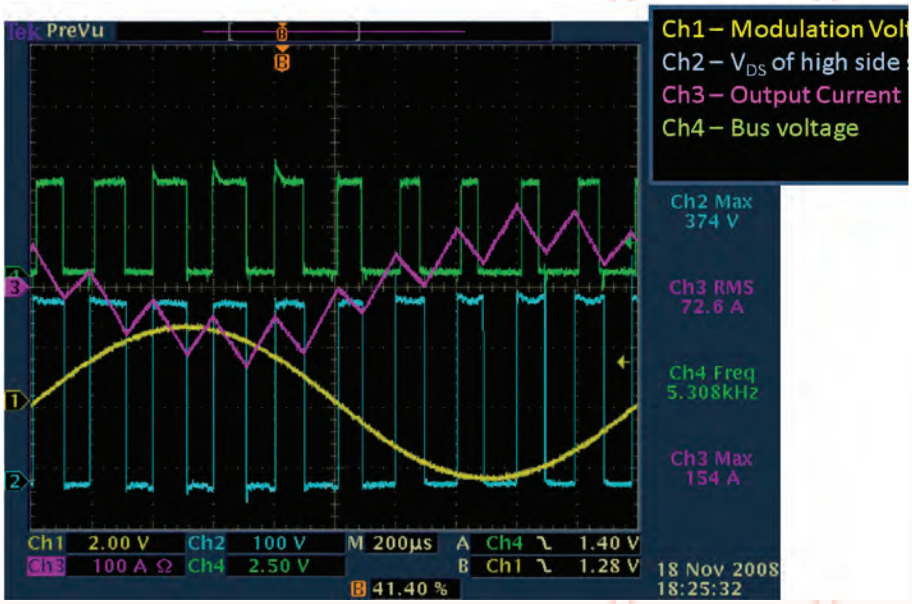


Figure 9.12. Scope capture of a high-power switching test of the SiC power module.

Figure 9.12 illustrates a scope capture of the high-temperature SiC power module operating under high-power conditions in a switching test. Channel 2 shows the drain to source blocking voltage across the high-side switching position (approximately 375 V blocking in this case), and Channel 3 shows the module output current (approximately 72 A rms, 250 A pk to pk is that case).

The high-temperature SiC power module (implementing SiC VJFET power switches) was inserted into a solar inverter renewable energy system level application test in a laboratory environment. In this case, the system inputs a 600 V DC bus emulating a high-voltage solar array, and converts power in a three-phase inverter configuration (three power modules). Figure 9.13 illustrates the three-phase voltage waveforms of the inverter system (left) and the three-phase current waveforms (right).

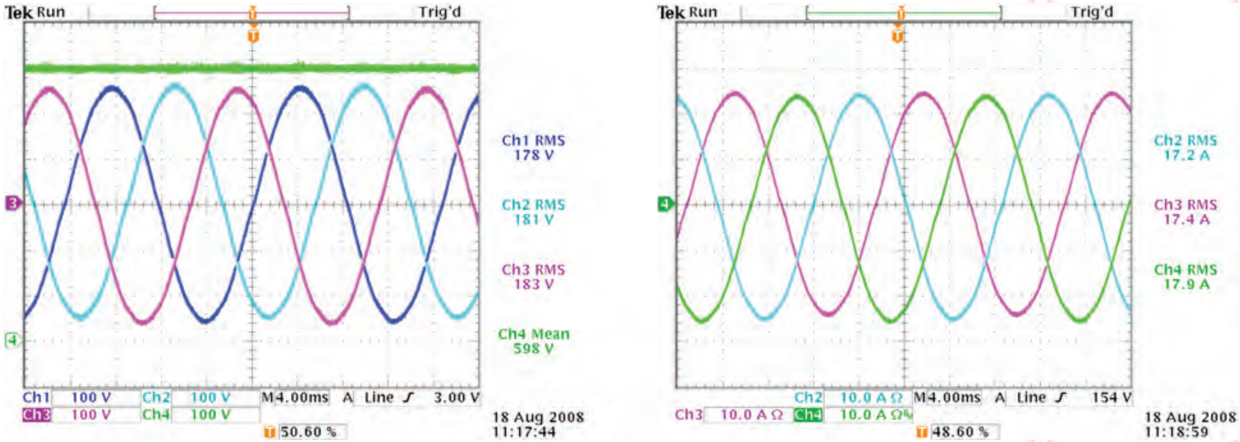


Figure 9.13. *Scope capture of the SiC power modules operating in a three-phase solar inverter application.*

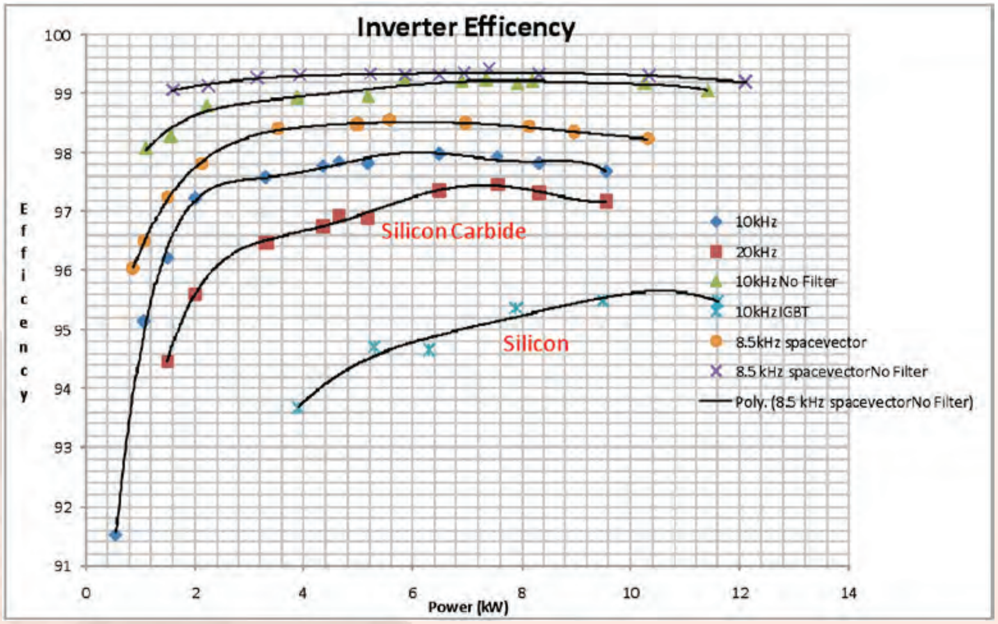


Figure 9.14*. Comparison of SiC vs. Si inverter efficiencies for various control schemes.*

As can be seen by Figure 9.14, the SiC power module technology has a very significant power efficiency improvement over state-of-the-art silicon technology. Peak efficiency of a state-of-the-art high voltage silicon IGBT solar inverter system is approximately95 percent, while the SiC system operating under identical conditions (10 kHz switching) achieves 98 percent efficiency—this is an energy savings of more than 50 percent ! Implementing space vector control and 8.5 kHz switching, the SiC three-phase inverter system reaches greater than 98.5 percent efficiency.

PRODUCT'S COMPETITORS

A wide range of potential competitive products exist. The following are the closest competitive products by the recognizable silicon-based product manufacturers:

- IXYS IGBT Modules
  MII 150-12 A3
- PowerEx Dual IGBTMOD
  CM150DY-12NF
- Microsemi Corp. Phase Leg IGBT Power Module
  APTGF180A60TG
- Infineon® HybridPACK™1

COMPARISON MATRIX

Key characteristics highlighted

Characteristic	**Product**					
Manufacturer	**APEI, Inc.**	**APEI, Inc.**	**IXYS**	**PowerEx**	**Microsemi Corp.**	**Infineon®**
Brand Name	SiC Power Module	SiC Power Module	IGBT Module	Dual IGBTMOD	IGBT Power Module	HybridPACK™1
Product Number			MII-145-12 A3	CM150DY-12NF	APTGF180A60TG	
Notes	High power module for hybrid vehicles	High speed, high efficiency module				State-of-the-art hybrid vehicle drive
Power Topology	Half-Bridge	Half-Bridge	Half-Bridge	Half-Bridge	Half-Bridge	3-Phase Half-Bridge
Power Device	SiC DMOSFET	SiC JFET	Si IGBT	Si IGBT	Si IGBT	Si IGBT
Voltage	600 V	1200V	1200 V	600 V	600 V	600 V
Current @ 25°C junction			160 A	150 A		400 A
Current @ 80°C junction			110 A		180 A	
Current @ 250°C junction	180 A	100 A	Catastrophic Failure	Catastrophic Failure	Catastrophic Failure	Catastrophic Failure
Maximun Junction Temp	250°C	250°C	150°C	150°C	150°C	150°C
On-resistance (Ron) @ 25°C	12.75 mΩ	15.5 mΩ	25 mΩ	15 mΩ	**RON = 15 mohm**	10 mΩ
Gate Charge	480 nC	160 nC	600 nC	600 nC	**660nC**	4,300 nC
Module Switching Speed Figure of Merit (FOMs)*	6.1 nΩC	2.5 nΩC	15 nΩC	9 nΩC	**9.9 n-ohm-c**	43 nΩC
Turn-off delay	300 ns	estimate < 100 ns	600 ns	300 ns	150 ns	490 ns
Max Short Circuit Time	1 ms	1 ms	10 µs	Unknown (10 µs est.)	Unknown (10 µs est.)	Unknown (10 µs est.)
Radiation Resistant	No	Yes	No	No	No	No
Integrated Gate Drive	Yes	No	No	No	No	No
250°C Gate Drive	Yes	No	No	No	No	No

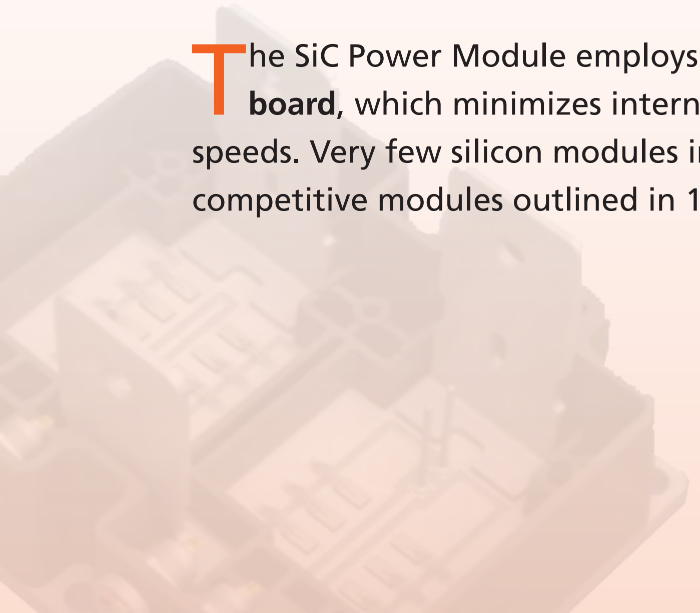
*** FOMs correlate directly to high switching speed capability (Low FOM = Fast Switching)**

HOW PRODUCT IMPROVES UPON COMPETITION

The SiC Power Module not only improves upon the competition, but it is a revolutionary step in power electronics systems. The new SiC power module technology operates at maximum **junction temperatures** (250°C)—impossible to achieve with silicon technology (150°C limit)—thus directly resulting in thermal system-level size reductions of more than 50 percent. Our competitors' devices feasibly go into catastrophic failure through thermal run away somewhere around 175°C. The SiC Power Module's unique **lead-free die attach technology** is operational to temperatures in excess of 400°C; therefore, near-term future changes will extend the power module temperature of operation to greater than 300°C. **High module switching speeds** and short delay times result in high-frequency power electronics systems with significantly reduced magnetic and filter sizes, again resulting in reduced electronic system sizes by up to 50 percent. High efficiency, **low-loss SiC switches** enable the reduction of system-level power loss by percent or more. All of these attributes, when combined, result in high-power density power systems with size reduction of an order of magnitude, while simultaneously improving the system-level energy efficiency.

The SiC Power Module is capable of withstanding short circuit loads for more than 1 millisecond (ms), which is more than 100-times the state-of-the-art silicon systems. This capability results in a highly reliable and rugged power electronics component that has a significantly increased chance of surviving temporary control failures or interrupts. This is particularly important high reliability systems employed in military vehicles and the aerospace industry.

The SiC Power Module employs a high temperature (250°C) **integrated gate drive board**, which minimizes internal parasitic and allows for increased switching speeds. Very few silicon modules include integrated gate drivers, and none of the competitive modules outlined in 10B contain an integrated gate drivers.



PRODUCT'S PRINCIPAL APPLICATIONS

Power electronics modules are the core component of all power electronics systems. They drive electric motors (e.g., motors for electric and hybrid vehicles), convert energy from renewable sources (i.e., solar, wind, etc.), and provide power for electronic systems (DC power supplies).

This power module product can be utilized in any of these applications; however, the initial primary target system is the hybrid-electric vehicle. High-energy efficiency saves the automotive owner money through the reduction of energy losses. High temperature capability improves the long-term reliability of the "under the hood" power electronics and reduces the thermal management system requirements, both which result in improved performance and long-term cost savings.

Figure 11.1. *The images depicted are a Honda Civic hybrid-electric motor and a fictional Audi electric vehicle from the movie "I Robot." These images are meant as generic depictions of the application for the power module.*

OTHER APPLICATIONS

Renewable Energy

All renewable energy sources require power electronic converters in order to output energy in a form utilized by an end user. The majority of these conversion systems require a power inverter that outputs power in a single or three-phase AC (alternating current) configuration, often times tied directly to the power utility grid. Core to the power inverter is the power module that performs the actual energy conversion process (such as APEI, Inc.'s SiC power module) and the energy efficiency of that inverter system. The high-energy efficiency of the SiC power module reduces power loss by more than 50 percent in comparison to state-of-the-art silicon modules and makes it an excellent choice for all renewable energy applications.

Figure 11.2. *The SiC power module's high-energy efficiency and lightweight makes it an excellent choice for use in renewable energy power inverter applications.*

More Electrical Aircraft

Another important target application area for the SiC power module is in aerospace systems. In particular, the need to reduce aircraft maintenance costs and operational weights while improving fuel efficiency has led aircraft system designers to implement More Electric Aircraft (MEA) solutions. These solutions aim to replace conventional design methodologies with electric and electronic replacements. For example, the hydraulic systems typically used to move the flight control surfaces on the wings and flaps of the F-35 Joint Strike Fighter have been replaced with electric motors and electronic motor drives. These drives must be lightweight and reliably withstand extreme temperatures with minimal cooling. APEI, Inc. is working the U.S. Air Force to replace the present silicon solutions with the SiC power module outlined in this document. Another example of the MEA is the Boeing 787, which is replacing electro-mechanical switches with solid-state electronic solutions. The top requirement of the Boeing 787 is high fuel efficiency and lightweight applications; therefore, it is an excellent system to insert SiC power modules.

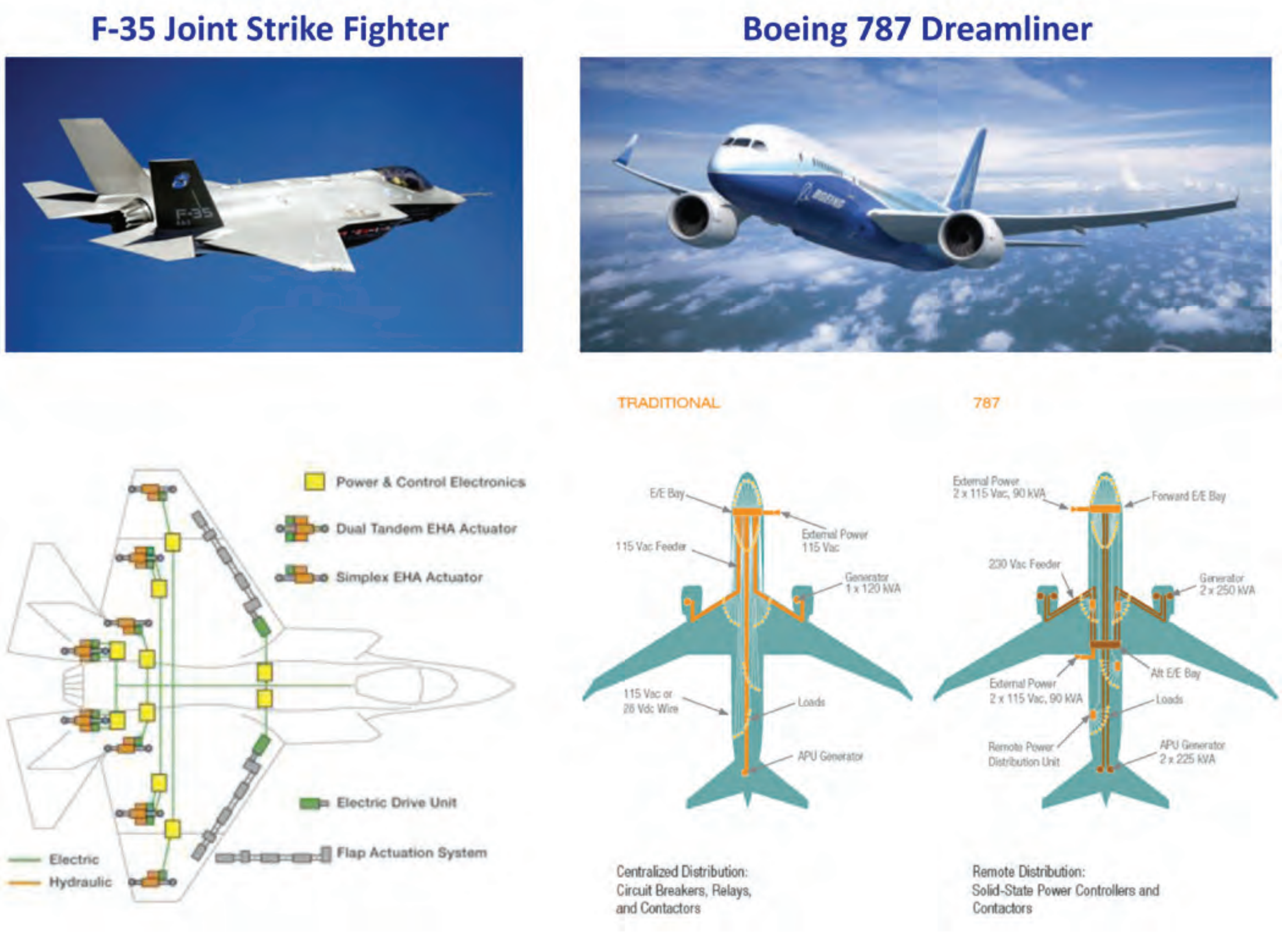


Figure 11.3. *The future of aviation is the More Electric Aircraft, such as the F-35 Joint Striker Fighter or the Boeing 787 Dreamliner. These aircraft replace traditional hydraulic and electro-mechanical systems with electric and electronic solutions—high-energy efficiency, lightweight, and reliability are all musts for these applications.*

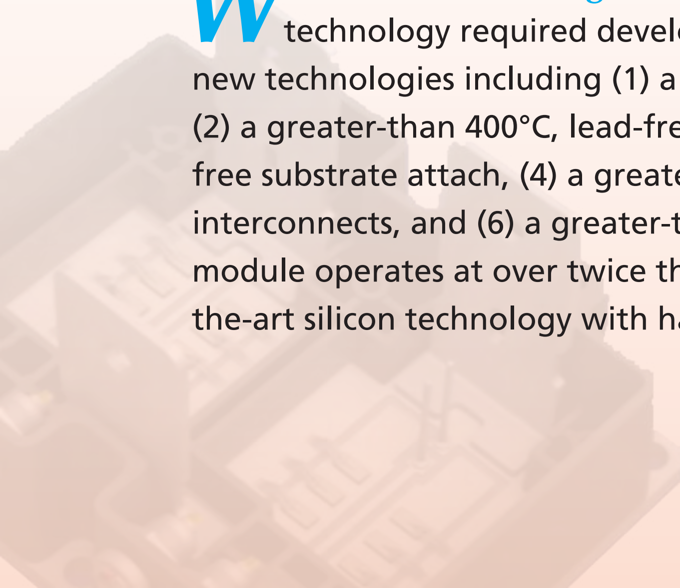
SUMMARY

What is it? The high-temperature silicon carbide power module is the world's first commercial high-temperature (250°C) silicon carbide- (SiC) based half-bridge power electronics module, with an integrated gate driver. The 50 kW (1200 V/150 A peak) SiC power modules are rated up to 250°C. They can reduce system size and weight up to an order of magnitude over present state-of-the-art silicon-based solutions and can reduce energy losses by more than 50 percent.

What does it do? Power electronics modules are the core component of all power electronics systems. They drive electric motors (e.g., motors for electric and hybrid vehicles), convert energy from renewable sources (i.e., solar or wind), and provide power for electronic systems (DC power supplies). This specific SiC-based power module technology is designed for driving electric vehicle motors or converting DC power supplied by solar arrays.

What technical, economic, or social problem does it address? Global demand for high-efficiency green energy technologies and products has placed new emphasis on the use of electric vehicles, the efficient use of renewable energy sources, and on electric-based solutions for aircraft systems. All of these applications require ultra-high-efficiency power electronics (to reduce energy loss) with high-temperature ratings (to reduce size, weight, and volume). Over $300 billion of energy is processed globally by power electronics and motor systems; cutting system energy losses by more than 50 percent will have tremendous economic and environmental benefits.

What is the technological advance? Successful creation of this new technology required developing, implementing, and integrating many new technologies including (1) a new high-temperature SiC MOSFET device, (2) a greater-than 400°C, lead-free die attach, (3) a greater-than 400°C lead-free substrate attach, (4) a greater-than 300°C gate driver, (5) high-temperature interconnects, and (6) a greater-than 300°C module housing. APEI, Inc.'s power module operates at over twice the maximum rated temperature of today's state-of-the-art silicon technology with half the energy losses.

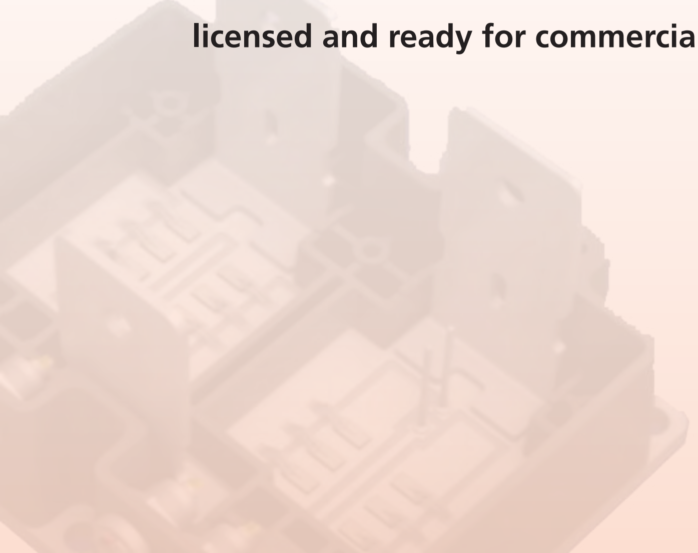


What is the social/economic significance? Currently, the technology is licensed to Rohm Electronics (one of Asia's largest providers of electronic components), which plans to begin commercial manufacturing in 2010 for use in three-phase motor drives for Honda's next-generation hybrid and electric vehicles. The power modules have also been used in prototype SiC-based solar inverter systems to improve system efficiency from approximately 95 percent to over 98.5 percent. Widespread use could result in $100s of millions or even billions in energy savings.

Currently, the technology is licensed to Rohm Electronics (one of Asia's largest providers of electronic components), which plans to begin commercial manufacturing in 2010 for use in three-phase motor drives for Honda's next-generation hybrid and electric vehicles.

How does this technology compare with the competition? What factors are crucial to the technology? APEI, Inc.'s SiC power modules outperform competitor's modules on every level—they are over 50 percent more energy efficient, they operate at temperatures greater than 250°C, and they can reduce system size and weight by 10-times or more. Additionally, the integrated high-temperature gate driver board eliminates the need for the end user to design and develop interface electronics to take advantage of the SiC capabilities.

Wow factor! SiC-based power electronics systems will revolutionize the power electronics industry. For the past decade, large amounts of R&D funding has been spent on developing SiC-based power switches (diodes and transistors), which are only now beginning to penetrate the commercial market. **This leading-edge device will be the world's first full high-temperature SiC power module, and it is licensed and ready for commercial manufacturing now.**



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APPENDICES ITEMS

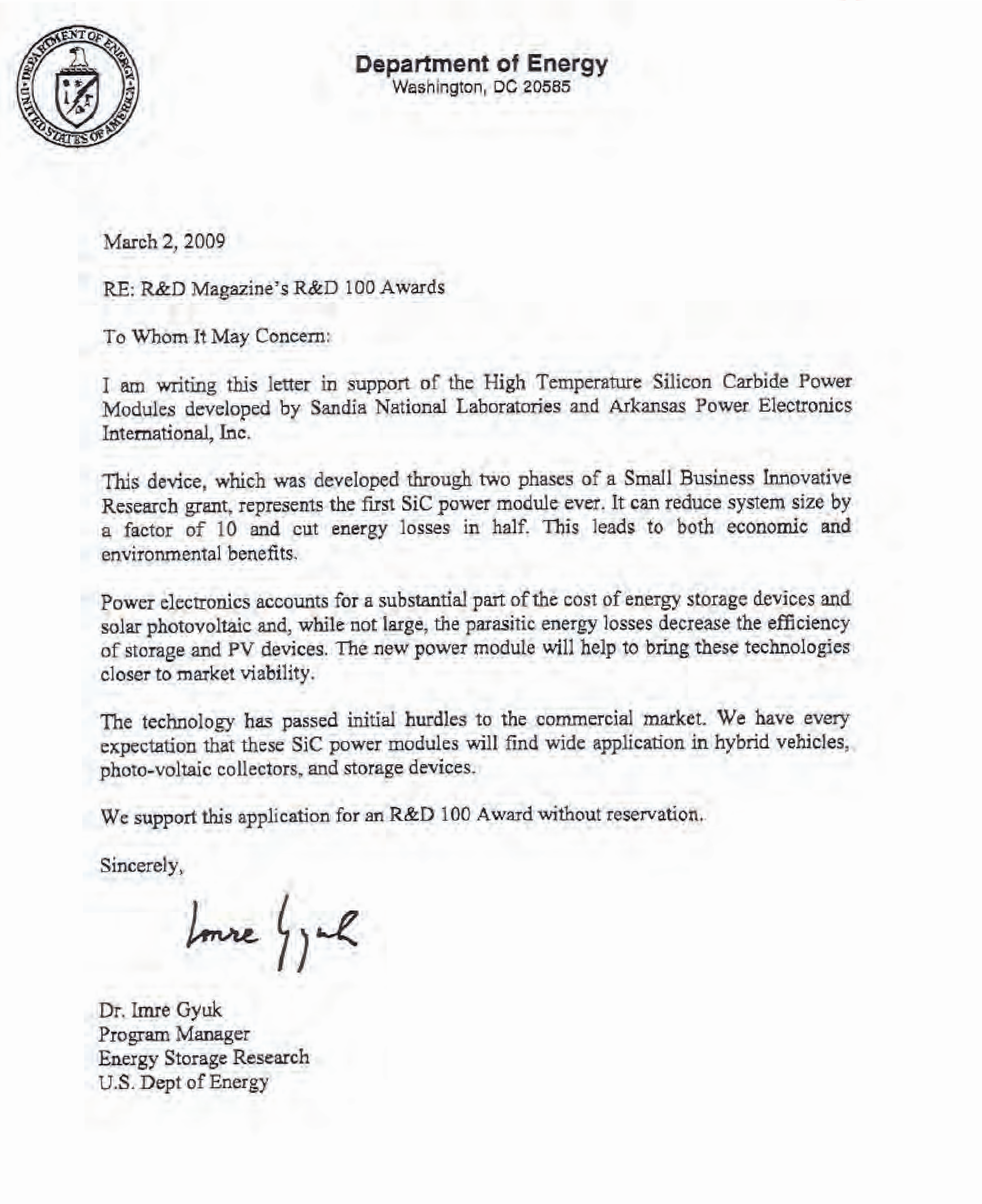
Appendix A
Letters of Support/Testimonials

Appendix B
Articles about the SiC Power Module

Appendix C
SiC Presentation Overview

APPENDIX ITEM A

Letters of Support/Testimonials



Department of Energy
Washington, DC 20585

March 2, 2009

RE: R&D Magazine's R&D 100 Awards

To Whom It May Concern:

I am writing this letter in support of the High Temperature Silicon Carbide Power Modules developed by Sandia National Laboratories and Arkansas Power Electronics International, Inc.

This device, which was developed through two phases of a Small Business Innovative Research grant, represents the first SiC power module ever. It can reduce system size by a factor of 10 and cut energy losses in half. This leads to both economic and environmental benefits.

Power electronics accounts for a substantial part of the cost of energy storage devices and solar photovoltaic and, while not large, the parasitic energy losses decrease the efficiency of storage and PV devices. The new power module will help to bring these technologies closer to market viability.

The technology has passed initial hurdles to the commercial market. We have every expectation that these SiC power modules will find wide application in hybrid vehicles, photo-voltaic collectors, and storage devices.

We support this application for an R&D 100 Award without reservation.

Sincerely,

Imre Gyuk

Dr. Imre Gyuk
Program Manager
Energy Storage Research
U.S. Dept of Energy

APPENDIX ITEM B

EXCERPT

Thermal Verification of a High-Temperature Power Package Utilizing Silicon Carbide Devices

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and

K. Okumura, T. Otsuka
ROHM CO., LTD.
21 Saiin Mizosaki-cho
Ukyo-ku, Kyoto 615-8585 Japan

Abstract

The researchers at Arkansas Power Electronics International, Inc. and ROHM CO., LTD. have simulated and tested high-temperature packaging technologies for SiC devices in an effort to develop more accurate modeling parameters for future applications. The laboratory test consists of parallel SiC power DMOSFETs, manufactured by Rohm, and SiC power VJFETs operating under self-regulating current sharing conditions.

To produce accurate thermal simulations, thermal models require numerous design parameters that are constrained to strict tolerances. Moreover, this presents an interesting challenge at junction temperatures (T_j) over 175 °C as most individual components have not been previously tested or verified at these temperatures. To extract these parameters at high-temperatures, the researchers have modeled a complete thermal system (including bare die, substrate, package, heatsink, and all thermal interfaces between said components) then built and tested an identical system to characterize the system's parameters over temperature. Specifically, the advantages between different types of thermal interfaces, including die attaches, substrate attaches, and thermal greases, were characterized over temperature. A high resolution thermal imaging camera was used to capture surface temperatures of the system to compare with simulation results. Due to mismatches in emissivity between components, multiple high-temperature conformal coatings were tested and characterized over temperature, as well. In this paper, the researchers will present the results of the laboratory testing that included the characterization of SiC DMOSFETs and SiC VJFETs operating up to 300 °C, as well as the thermal simulation results.

Key Words: High-temperature packaging, Extreme environment packaging, Thermal model verification

1.0 Introduction

Silicon carbide (SiC) power devices have long been a very attractive solution to high power modules due to their ability to operate at high-temperature (upwards of $T_j = 600$ °C) [1]. Thanks to recent improvements in manufacturing reliability, a few SiC power devices are readily available in the commercial market. As these devices become more prominent in the commercial arena, designers must adapt to the unique design rules that are required by operating at junction temperatures (T_j) over 175 °C.

By exploiting the high-temperature operation of SiC power devices, designers are able to reduce the volumetric and gravimetric impact that the cooling system can have for a given application [2-5]. However, this introduces the challenge of selecting appropriate packaging materials that can handle high-temperature operation.

This paper will introduce initial thermal characterization of two high-temperature die and substrate attach methods, 95Pb/5Sn solder paste and silver loaded glass epoxy. Also, thermal interface materials, including high-temperature thermal

APPENDIX ITEM B

Article announcing collaborative SiC Power Module work with Rohm, Co., LTD

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日刊工業新聞
Business & Technology
2008年（平成20年）
4 15
第20348号　火曜日
14版
発行所©日刊工業新聞社2008
本社 ☎03・5644・7000 東京都中央区日本橋小網町14−1　大阪支社 ☎06・5946・3321 大阪市中央区北浜東2−16　名古屋支社 ☎052・931・6151 名古屋市東区泉2−21−28　西部支社 ☎092・271・5711 福岡市博多区古門戸町1−1

三菱自、AT

変速機をめぐる乗用車各社の主な動き	
トヨタ自動車	世界初の8速ATを「レクサスLS」に搭載
日産自動車	「GT−R」にDCT搭載、7速AT実用化
ホンダ	軽自動車用の新型CVT開発に着手
マツダ	07年秋の東京モーターショーにDCTを参考出品
スズキ	日産系の変速機メーカーのジヤトコに出資
ダイハツ工業	全車CVT搭載へ
富士重工業	水平対向エンジン用の新型CVT開発へ

今回開発するのは、手動変速機（MT）のよう

な構造を持つ、クラッチ操作不要の変速機。車速に応じて2系統のクラッチを自動で切り替える。一般にデュアル・クラッチ・トランスミッション（DCT）と呼ばれ、10%程度の燃費改善が期待できる。独フォルクスワーゲンが採用するなど、2015年には世界の変速機の約2割に達するとみられ、注目されている。

三菱自は07年秋発売のスポーツ車「ランサー　エボリューションX」にDCTを初採用したが、独ゲトラグ・フォードから輸入している。これとは別に排気量1800―2000cc前後のエンジンに組み合わせる小型DCTを開発。Cセグメント級のスポーツ多目的車（SUV）やセダンなどに搭載する。

三菱自が国内で販売す

段階的にATを新型DCTに置き換えていく。

三菱自は02年に日産自動車系の変速機大手、ジヤトコと事業統合する形式でAT・CVT生産を打ち切り、現在は同社か

境技術をめぐり、富士重工業が自前のハイブリッド技術を断念し、トヨタ自動車との提携に切り替えるなど、コア技術の選択と集中、他社との事業提携などに動いている。

ダイハツ、福岡に拠点
2010年にも車両・内装開発

ダイハツ工業は14日までに、福岡県に車両開発拠点を設置する方針を固めた。2010年代初頭から稼働させる。生産子会社のダイハツ九州（大分県中津市）が、自社で生産する新型車を中心に車体などの開発を手がける計画。ダイハツ九州は07年に大分県で第2工場を稼働、8月には福岡県にエンジン工場も完成する。新たに開発拠点が加わることで、本社がある関西地区に匹敵する車両生産拠点となる。

車両開発拠点は、福岡県久留米市のエンジン工場周辺になる見通し。主に車体や内装などの開発や設計を担当する。ダイハツが九州で本格的な開発・設計機能を持つのは

炭化ケイ素パワー半導体
ハイブリッド車向け開発
ロームなど実用化へ

ロームと東京エレクトロン、京都大学は共同で、08年度内に炭化ケイ素（シリコンカーバイド、用語参照）製の半導体を搭載したパワーモジュールの実用化に乗り出す。炭化ケイ素半導体は現在主役のシリコン半導体に比べて高温、高出力動作が可能で、電力制御などを担うパワー半導体の次世代材料に有力とされる。先陣争いが激化するなか、ハイブリッド自動車や電気自動車、産業機器への採用をにらみ、顧客の囲い込みを狙う。

（26面に関連記事）

ロームと京都大学は今年1月、米航空宇宙局（NASA）が開発した月面探査車などに炭化ケイ素半導体の納入実績を持つ米アーカンソー大学と研究契約を結び、実用化に向けた共同開発プロジェクトを発足した。

【用語】炭化ケイ素＝シリコンと炭素が結合した化合物半導体。SiC（シリコンカーバイド）と表記する。シリコン製パワー半導体に比べて耐圧が高く、大電流が扱える。厚さは約10分の1、冷却装置が簡素にでき小型化が可能。課題は低コスト化だが、環境面からも実用化の期待が高い。

▲ロームなどが開発を目指す炭化ケイ素製パワーモジュール（米アーカンソー大学提供）

炭化ケイ素半導体のパワー素子を並列に多数つなぎ、駆動回路や周辺素子などを組み込んでモジュールに実装する。想定する出力性能は300キロワット級。シリコン半導体の動作限界を100度C上回る250度Cの高温動作が可能になる。次世代自動車や、掘削機など大電力が必要な特殊産業用途に採用を働きかける。

ロームは、九州の半導体生産拠点に東京エレクトロンと共同開発した炭化ケイ素半導体の製造装置を順次導入、量産体制を早期に立ち上げる。

一方、東京エレクトロンは同装置市場が2015年には100億円規模に広がると予測。収益が見込めることから宮城県に工場を新設、事業化する方向で検討に入った。

炭化ケイ素パワー半導体は電力変換時の損失が少なく省エネルギーのため、環境対応型の部品として自動車メーカーなどが採用へ意欲的。次世代モデルに搭載が進めば、自動車市場に新風を吹き込むことになりそうだ。

APPENDIX ITEM B

Japanese public press release on the CEATEC tradeshow where the SiC Power Module was first marketed.

電　波　新　聞　　日刊（土曜・日曜を除く）　2008年（平成20年）10月3日（金曜日）　第15015

電波新聞
発行所 電波新聞社
東京本社
大阪本社
西部本社

電子部品メーカー
資本・業務提携相次ぐ
外部の資源を活用
国際競争力高める

勢力図が塗り替わる可能性も

200億円の増販めざす

効率的な製品開発
販売機会の拡大を図る

友好的にTOB提案

50%超の株を取得へ

主要電子部品メーカーの提携、買収（08年1月以降）

社名	相手企業	契約締結年月	内容
TDK	エプコス（ドイツ）		エプコス株式の公開買い付け。買い付け期間10月7日まで
日本電産	・富士電機モータ（FDM）およびFDMが所管する海外現地法人3社（FDMグループ） ・東洋電機製造	08年9月基本合意	FDMグループを日本電産の子会社にする 東洋電機製造に株式公開買い付け（付け）提案。買い付け期間12月15日まで
パナソニック電工	本多通信工業	08年4月基本合意	5月に本多通信工業の筆頭株主に。コネクタ事業の強化
村田製作所	キャップ・エックス社（オーストラリア）	08年3月事業提携	電気二重層コンデンサを共同開発、小型品から商品化

（50音順）

CO₂ 500トン削減目標
パナソニック グループ社員が世界で環境活動

ローム
250度C以上で駆動
次世代電気自動車向け
SiCインバータパワーモジュール

ロームは1日、世界初の250度C以上で駆動する次世代電気自動車用高温駆動SiC（シリコンカーバイド）インバータパワーモジュール（IPM）のサンプルを来春から出荷開始することを明らかにした。

アーカンソー大学、同大学発のベンチャー企業アーカンサス・パワー・エレクトロニクス・インターナショナル（略称=APEI、アーカンソー州フェイエットビル市、アレクサンダー・ロステッター社長）および大阪大学が07年12月から米国のラボで共同開発している高温駆動SiC IPMで、最高温度250度C以上で駆動するSiCパワーMOSFETを採用したSiCパワーモジュールとゲートドライブ回路からなる。SiC IPMが250度C以上で動作することを確認し、サンプル出荷を始めることにした。

APEIで技術確立している500度Cまでの高温用ゲートドライブ技術などを用い、09年中に300度C以上で駆動する高温駆動の要素技術を開発。10年には次世代電気自動車の電源用としての量産に向けて最終テストを行う計画である。

250度C高温駆動のSiC IPMは、1相200A1200Vの大電流高耐圧を実現。ジャンクション温度250度Cで駆動可能。

ロームのSiC DMOS技術と、アーカンソー大学のマルチチップモデリング・高電圧大電流測定・高耐熱パッケージの技術、APEIの高耐熱のゲートドライブ設計技術・パッケージシミュレーション技術・接合・封止技術、大阪大学の回路設計・測定回路技術を持ち寄った。

250度C高温駆動SiCインバータモジュールとゲートドライブ回路

電波時評
コンビニでも売れる家電品

メーカーの新たな戦略

オール電化住宅 着実に拡大
2015年度、800万戸超へ

ミリ波

金曜日の主要ニュース
土曜付Webで配信

金曜日の主要ニュースは土曜日にインターネットで閲覧できます。記事閲覧にはログインコードが必要です。同コードは週ごとに変わるため、毎週金曜日付本紙1面に翌日分のコードを掲載します。

電波新聞土曜版の専用URLと10月4日付閲覧のログインコードは次の通りです。

http://www.pressdempa.net/webnews/

コード=07ha12ya（半角英数字）

—電波新聞社—

APPENDIX ITEM B

Article for the upcoming Electric Energy Storage Application Technology 2009 Conference

Update on the Development of a 10-kW Silicon Carbide (SiC) Based Inverter for Renewable Energy Applications

Roberto Marcelo Schupbach (Arkansas Power Electronics International, Inc. (APEI, Inc.)), Edgar Cilio (APEI, Inc.), Gavin Mitchell (APEI, Inc.), Jared Hornberger (APEI, Inc.), Alexander Lostetter (APEI, Inc.).

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Mailing Address: 535 W. Research Center Blvd. Suite 209, Fayetteville, AR 72701
Phone: 479-443-5759 ext. 8210
Fax: 866-515-6604

Introduction

This paper provides an update on the development of a 10-kW three-phase all SiC inverter for renewable energy applications (see Figure 1). APEI, Inc. researchers achieved an approximate 5× increased gravimetric density over state-of-the-art Si technology, and a reduction in energy loss by more than 50% has been demonstrated. Figure 2 illustrates a photograph comparing the natural convection heat-sinks required for a silicon power module (left) and a SiC power module (right) operating under the identical three-phase power conditions in this project. Table 1 below summarizes the performance characteristics of the silicon three-phase power module in comparison with SiC, under various conditions and according to a variety of international efficiency standards. The results in the table show that even at high power density and high temperature of operation, the SiC inverter system reduces power loss by ~ 50% (97.5% peak efficiency in comparison to silicon's 95% peak efficiency). Utilizing identical thermal management systems, the SiC inverter reduces power loss by more than 66% !

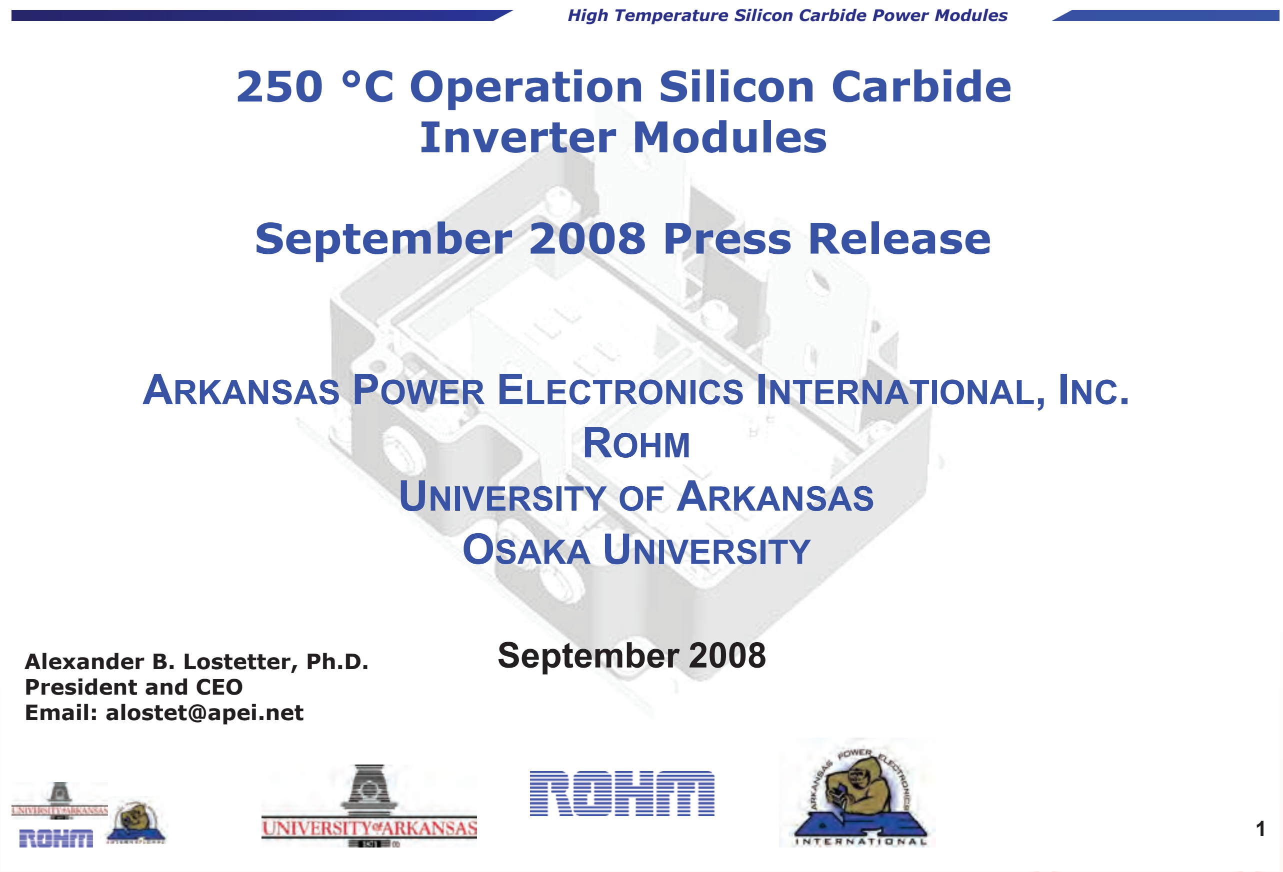
Table 1. Comparison of Si vs. SiC three-phase inverter operational characteristics.

	Efficiency			Passive Cooling System	
	California Energy Commission	European	Peak	Heat Sink Size Volume (cm^3) / Weight (kg)	Volumetric Power Density (W / cm^3)
Si IGBT Inverter	95.0 %	94.8 %	95.5 %	7 / 6.12	1.75
SiC JFET Inverter	98.3 %	98.1 %	98.6 %	7 / 6.12	1.75
SiC JFET Inverter @ 150 °C	97.5 %	97.3 %	97.8 %	2.3 / 1.4	8.6

The paper will present detailed information on the design, fabrication and testing of this inverter. The authors will also provide electrical and thermal characterization data as well as preventative operating waveforms. In addition, the paper will discuss a new generation of intelligent SiC power modules presently under development. These new 1200 V / 150 A SiC power modules, depicted in Figure 3, include high temperature gate drivers and are rated to a maximum junction temperature of 250 °C. The power module implements up to 8 parallel SiC power transistors per switch position (16 power transistors per module) that are capable of operating to junction temperatures greater than 250 °C. In this paper, the authors will present electrical and thermal characterization data for the new intelligent SiC power modules as well as preventative operating waveforms.

APPENDIX ITEM B

September 2008 Press Release EXCERPT



High Temperature Silicon Carbide Power Modules

250 °C Operation Silicon Carbide Inverter Modules

September 2008 Press Release

Arkansas Power Electronics International, Inc.
Rohm
University of Arkansas
Osaka University

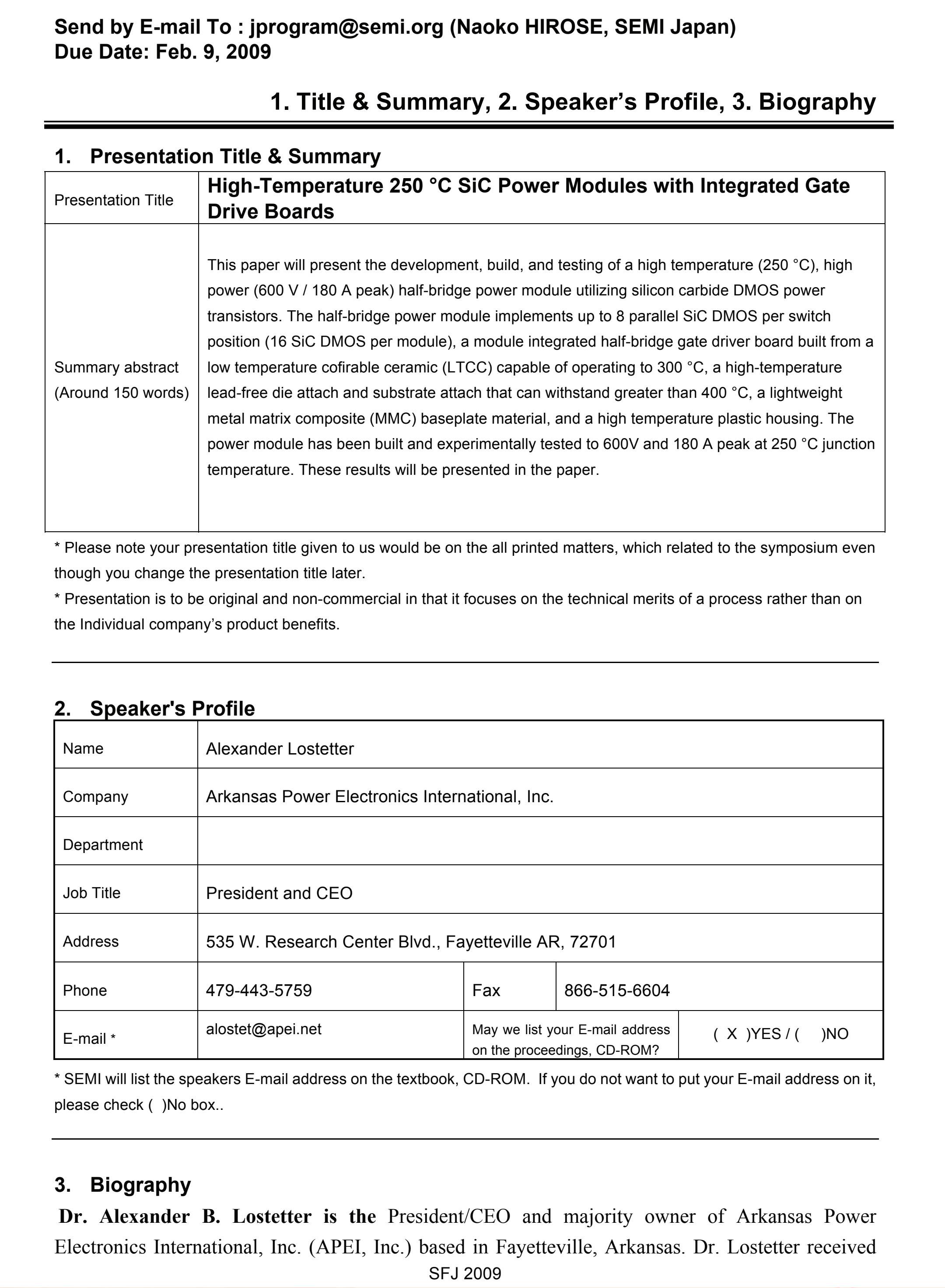
Alexander B. Lostetter, Ph.D.
President and CEO
Email: alostet@apei.net

September 2008

1

APPENDIX ITEM C

Arkansas Power Electronics International, Inc. Presentation Title and Speaker's Biography



Send by E-mail To : jprogram@semi.org (Naoko HIROSE, SEMI Japan)
Due Date: Feb. 9, 2009

1. Title & Summary, 2. Speaker's Profile, 3. Biography

1. Presentation Title & Summary

Presentation Title	**High-Temperature 250 °C SiC Power Modules with Integrated Gate Drive Boards**
Summary abstract (Around 150 words)	This paper will present the development, build, and testing of a high temperature (250 °C), high power (600 V / 180 A peak) half-bridge power module utilizing silicon carbide DMOS power transistors. The half-bridge power module implements up to 8 parallel SiC DMOS per switch position (16 SiC DMOS per module), a module integrated half-bridge gate driver board built from a low temperature cofirable ceramic (LTCC) capable of operating to 300 °C, a high-temperature lead-free die attach and substrate attach that can withstand greater than 400 °C, a lightweight metal matrix composite (MMC) baseplate material, and a high temperature plastic housing. The power module has been built and experimentally tested to 600V and 180 A peak at 250 °C junction temperature. These results will be presented in the paper.

* Please note your presentation title given to us would be on the all printed matters, which related to the symposium even though you change the presentation title later.
* Presentation is to be original and non-commercial in that it focuses on the technical merits of a process rather than on the Individual company's product benefits.

2. Speaker's Profile

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3. Biography

Dr. Alexander B. Lostetter is the President/CEO and majority owner of Arkansas Power Electronics International, Inc. (APEI, Inc.) based in Fayetteville, Arkansas. Dr. Lostetter received

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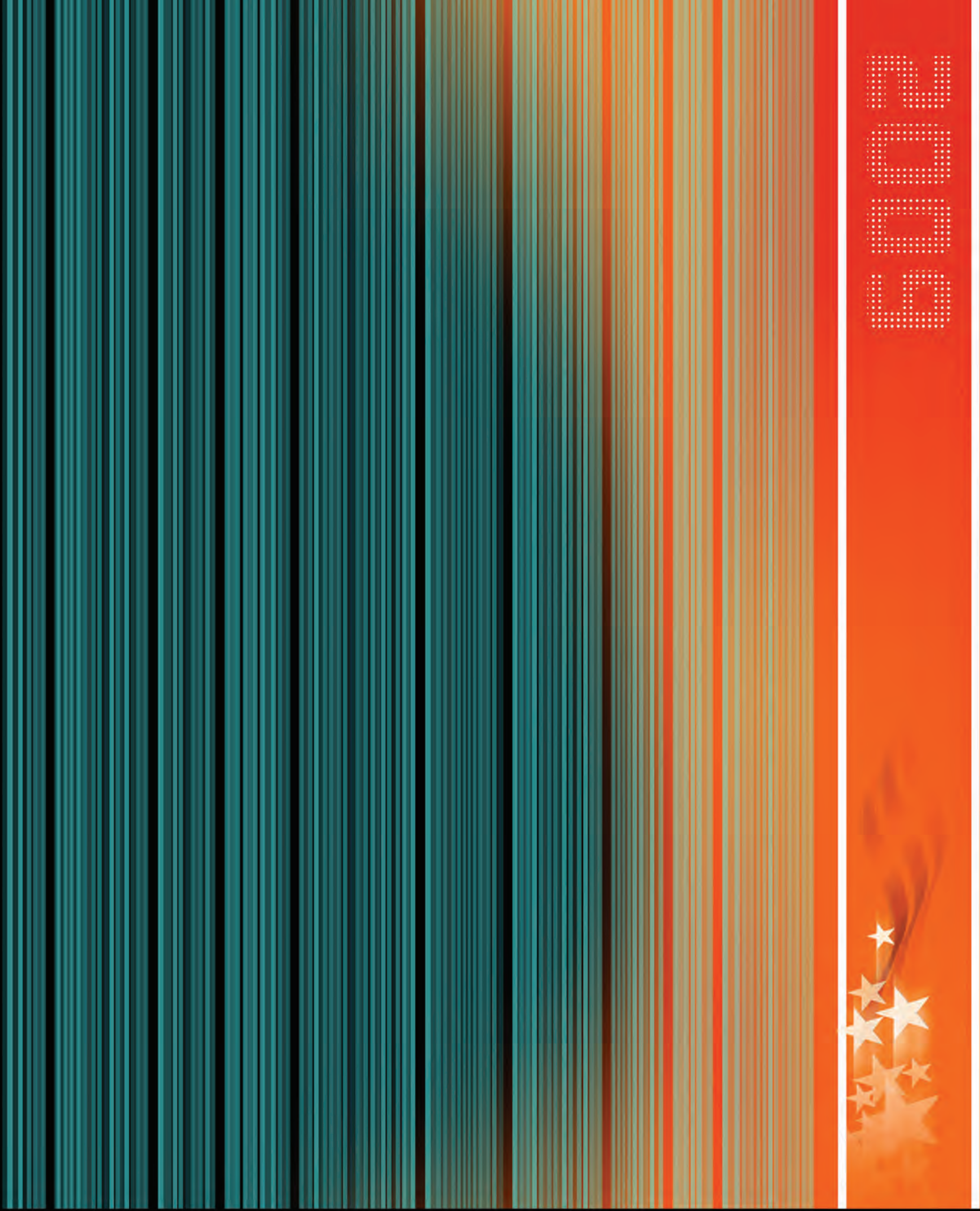

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