WIDE-BANDGAP SEMICONDUCTORS

Gallium Nitride, GaN - Silicon Carbide, SiC

2022 Edition

Laser and Fiber Optics Educational Series

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About the Author of this Edition

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Preface

About the LASER-TEC Laser and Fiber Optics Educational Series

This series was created for use in engineering technology programs such as electronics, photonics, laser electro-optics, etc. This series of publications has three goals in mind: 1) to create educational materials for areas of laser electro-optics technology in which no materials exist, 2) to work with industry to use, adapt, and enhance available industry-created materials, 3) to make these materials available at no cost which, in turn, would generate more accessible education to everyone (including technicians). The Laser and Fiber Optics Educational Series is available for free online at www.laser-tec.org.

About Wide-Bandgap Semiconductors

New semiconductors based on silicon carbide (SiC) and gallium nitride (GaN) are now commercially available, which has been instrumental in removing obstacles that legacy silicon bipolar and metal-oxide-semiconductor field-effect transistor (MOSFET) devices could not overcome. These new devices have superior power-handling abilities due to their better thermal properties, higher switching frequencies, and lower conduction losses. Collectively, these properties make wide-bandgap devices the preferred technology for high-power conversion applications with efficiencies approaching 99%. For this reason, this new technology must be introduced to existing curricula, preparing engineers and technicians to tackle today's and tomorrow's power electronics challenges. This module is intended for use in technical programs after coverage of basic semiconductor theory and discrete devices such as silicon diodes, bipolar junction, field effect, and MOSFET transistors.

To the Student

This book is written at the technician level and can be used in post-secondary electronics engineering technology, photonics, electro-optics, and other related programs; it contains modern pedagogy and includes the following sections: introduction-motivation, learning outcomes, self-test questions for each section, summary, glossary, bibliography, and vivid illustrations. As you are using this book, please feel free to send us your feedback for future updates and improvements by emailing info@laser-tec.org.

To the Instructor

This book is intended for use in a certificate or associate degree program in electronics engineering technology. This will not only update course content but will also provide students with the latest industry-expected skills. A PowerPoint presentation and test bank are available by emailing a request to info@laser-tec.org from an official college email.

Acknowledgments

This text is based on work contributed by Dr. Michael Haralambous, under the direction of LASER-TEC's principal investigator Dr. Chrys Panayiotou. The content of this module has been reviewed for technical accuracy and pedagogical integrity by the industrial and academic reviewers listed below.

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WIDE-BANDGAP SEMICONDUCTORS

Gallium Nitride, GaN - Silicon Carbide, SiC

Introduction-Motivation

A new type of power transistor is becoming available that will impact the power electronics industry well into the twenty-first century. This transistor is fabricated using what is referred to as a *wide-bandgap* (WBG) semiconductor. The principle WBG semiconductors for use in power electronics are gallium nitride (GaN) and silicon carbide (SiC). Traditional silicon (Si) is, in contrast, a narrow-bandgap semiconductor. Compared to Si devices, WBG devices have several desirable characteristics. To name a few, they are more compact, have greater power density[1] and efficiency, are more reliable, and can operate at higher switching frequencies and temperatures.

In 1994, Shui Nakamura of the Nichia Corporation developed the high-brightness blue LED using wide-bandgap semiconductor indium gallium nitride (InGaN), for which he received the Nobel Prize in Physics in 2014.

A few distinct advantages of utilizing SiC devices in inverters[2] are demonstrated below. In the first example, the inverter provides the AC power to drive an electric vehicle motor; in the second example, the inverter is used to convert the DC voltage of a solar panel to AC.

Formula E all-electric vehicle performance enhancement through inverter size and weight reduction

The performance of the Venturi Formula E Electric Vehicle (Figure 1) is enhanced through the significant reduction of the size and weight of an inverter that is designed utilizing the ROHM SiC power module[3]. As shown in Figure 2, the season 4 SiC-based inverter was 43% smaller and 6 kg lighter than the Si-based inverter used in season 2.

Figure 1: Venturi Formula E Electric Vehicle (source: ROHM Semiconductor).

[1] Power density is a measure of power output per unit volume. If a device has high power density, then it can output large amounts of energy based on its volume. For example, a tiny capacitor may have the same power output as a large battery, but because the capacitor is so much smaller, it has a higher power density.
[2] Inverters are primarily used in high-power applications for converting DC to AC.
[3] "ROHM supplies Full SiC Power Modules to Formula E racing team Venturi." ROHM Semiconductor. https://www.rohm.com/news-detail?news-title=rohm-supplies-full-sic-power-modules-to-formula-e-racing-team-venturi&defaultGroupId=false.

Figure 2: Inverter size and weight reduction (source: ROHM Semiconductor).

Substantial decrease in size, weight, power losses, and material costs of PV string inverters

Figure 3 presents a comparison of a typical 50kW Si Insulated-Gate Bipolar Transistor (IGBT) string inverter and a Cree-designed 50kW SiC-based string inverter for solar energy conversion[4]. The SiC-based inverter is one-fifth the weight and volume of the Si IGBT-based inverter. Overall inverter losses are also reduced by 40%. These performance improvements are possible due to the fundamental properties of SiC technology, which will be discussed in a later section. As shown in Figure 4, the use of SiC technology in the string inverter also reduces the overall bill of materials cost by 15%.

Figure 3: Relative size comparison of a typical 50 kW Si IGBT string inverter and a Cree-designed 50 kW SiC-based string inverter demonstration unit (source: Cree).

[4] Schupbach, Marcelo. 2015. “The Impact of SiC on PV power economics.” https://www.electronicproducts.com/the-impact-of-sic-on-pv-power-economics/.

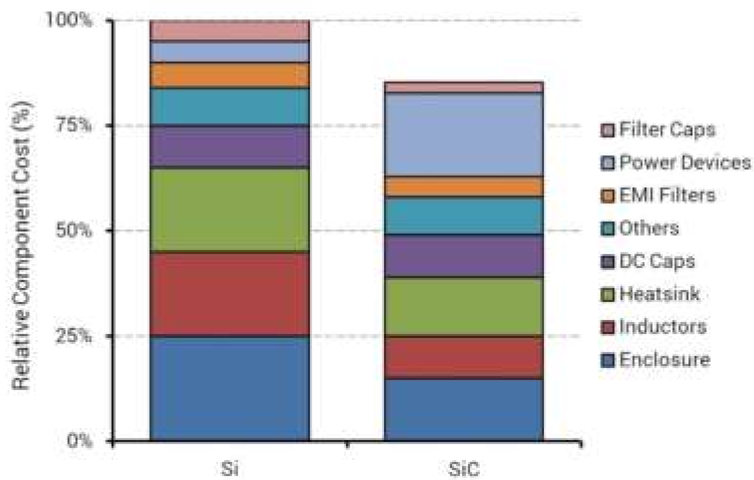

Figure 4: Relative component costs within Si IGBT-based and SiC MOSFET-based 50 kW string inverter (source: Cree).

Silicon (Si) has been the leading semiconductor material since the mid-twentieth century, and it has been one of the primary building blocks of the power electronics industry. However, the need for using energy more efficiently is bringing about a shift to WBG semiconductors which are smaller, faster, more reliable, more durable, and more efficient than silicon. The automotive sector is a prime example. Both GaN and SiC are becoming attractive in internal combustion engine (ICE), hybrid (H), hybrid electric (HE), and electric vehicle (EV) automotive applications (Figure 5). As 48 DC volts becomes the standard automotive DC bus voltage, conversion from 48v to 12v as well as other DC-DC, DC-AC, and AC-DC conversions will be needed in emerging automotive applications (such as LIDAR) for driver-assisted technology, high-intensity headlights, infotainment, etc. WBG semiconductors have the potential for significantly increasing the power efficiency in these subsystems.

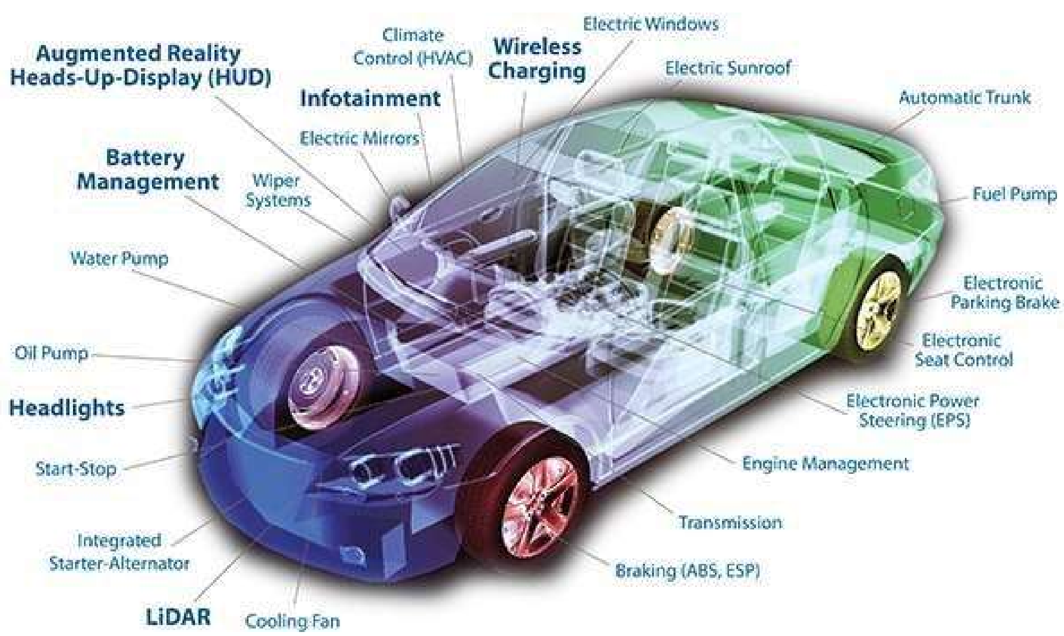

Figure 5: Application of WBG devices in the automotive sector (source: Efficient Power Conversion).

WBG semiconductors are expected to bring about energy-saving innovations in the following sectors of the economy:

Energy Delivery
- Solar inverters and grid integration
- Telecom/5G
- Uninterruptible power supplies (UPS)
- Data center server power supplies

Consumer
- Wireless chargers
- HDTV power supplies
- Audio amplifiers

Industrial
- DC/DC converters[5]
- Factory automation and robotics
- Medical imaging
- Motor drives
- Drones

Automotive
- AC traction drives
- Onboard/offboard chargers
- Light Distancing and Ranging (LIDAR)
- DC/DC converters

Module Overview

In section 1, the history of the development of WBG power devices is presented. This is followed in section 2 by a discussion of their numerous advantages, their use as switching devices, and their challenges. In section 3, the device structure, operation, and testing procedure are reviewed. The subjects of device driving issues and typical circuitry using WBG devices are both considered in section 4. In section 5, applications and sample circuit block diagrams are introduced. A case study of a high-power inverter with application to photovoltaics or electric vehicles is described in the final section.

Learning Outcomes

After studying this module, you will be able to:

- Describe the historical evolution of WBG device technology.
- List the major companies producing commercial WBG semiconductor devices.
- Describe the unique properties of SiC and GaN semiconductor devices.
- Name the major advantages of WBG devices compared to silicon ones.
- Explain the device structure and operation of planar and trench geometry SiC devices.
- Explain the device structure and operation of planar and trench geometry GaN devices.
- Demonstrate the need for special gate drivers in WBG devices.
- List the desirable characteristics of WBG device drivers.
- List the major applications of WBG semiconductor devices.
- Describe the operation of a high-power inverter realized with WBG MOSFETs.
- Draw the block diagram of high-power inverter realized with WBG MOSFETs.

[5] A voltage converter changes the voltage (either AC or DC) of an electrical power source. There are two types of voltage converters: *step up converters* (which increase voltage) and *step down* converters (which decrease voltage).

Section 1. History of the Development of WBG Devices and Future Applications

Since the invention of the bipolar junction transistor (BJT) in 1947, silicon (Si) has been the primary semiconductor in power electronics. With the invention of the metal-oxide-semiconductor field-effect transistor (MOSFET) in 1959 at Bell Labs and its first manufacture in 1964, future generations of Si-based MOSFETs have achieved performance and power density levels not possible with BJTs. Another major breakthrough in Si-based power electronics occurred in the 1980s—the Insulated-Gate Bipolar Transistor (IGBT). Recently, it has become more and more challenging to design new Si-based power electronic devices with greater power densities and efficiencies to keep up with market demands. This has created the need for a more advanced technology. SiC and GaN have emerged as alternatives to Si in high-power, high-temperature switching applications.

Since the early 1990s, several companies have made innovations in WBG technology. A sampling of these companies includes STMicroelectronics (Europe's largest semiconductor chipmaker), Infineon Technologies (automotive power semiconductors), Toshiba (SiC modules), ROHM Semiconductor (SiC power devices), Transphorm (GaN devices), GaN Systems (GaN E-HEMT), Cree, NXP Semiconductors, United Silicon Carbide (SiC FETs), Qorvo (GaN on SiC MMICs), and Texas Instruments. To get a sense of the historical development of WBG devices, we focus on Cree[6]. Cree was founded in 1987 and has pioneered much of the research and development in WBG semiconductors.

In 1994, Shuji Nakamura of the Nichia Corporation developed the high-brightness blue LED using wide-bandgap semiconductor indium gallium nitride (InGaN), for which he received the Nobel Prize in Physics in 2014[7]. The first large-scale use of GaN on SiC LEDs occurred in 1995 when blue LEDs developed by Cree were designed into the dashboard of Volkswagen vehicles. This signaled acceptance of the new WBG technology. The availability of SiC was, and remains, key to this acceptance. SiC crystal substrates have provided the foundation for LEDs and power electronic devices. In the early 1990s it was very difficult to grow SiC crystals; the largest substrates were only one inch in diameter. However, over the years and through many development cycles, Cree has produced increasingly larger SiC single-crystal boules[8] while minimizing crystal defects. Most recently 200 mm (~8 in.) SiC wafers have become available from Cree.

In the late 1990s and the early 2000s, along with the rise in the use of mobile devices, manufacturers began incorporating GaN on SiC LEDs into these devices—first to backlight keypads and then as light sources for color screens. These are tasks for which they are ideal due to their low energy consumption, reliability, and ability to be driven by a battery. In 2006 Cree introduced the industry's first lighting-class LED. It delivered 100 lumens per watt (compared with 70 lm/W for fluorescent lamps and 15 lm/W for incandescent lamps) and was mercury-free and long-lasting. In 2013, Cree released its own LED light bulb that had a retail cost less than $10 and delivered 303 lm/W.

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[6] (a) Wolfspeed. 2020. "The golden age of silicon carbide: 25 years of innovation." *Compound Semiconductor* 26, no. 6 (August/September). Wolfspeed, Inc. https://www.wolfspeed.com/knowledge-center/article/the-golden-age-of-silicon-carbide-25-years-of-innovation.
(b) Cree. n.d. "History and Milestones." Accessed March 1, 2021. https://www.cree.com/about/history-and-milestones.

[7] Lincoln, Don. 2014. "How Blue LEDs Work, and They Deserve the Physics Nobel." *NOVA* (October). https://www.pbs.org/wgbh/nova/article/how-blue-leds-work-and-why-they-deserve-the-physics-nobel/.

[8] Boule: A single-crystal semiconductor ingot produced by synthetic means. It can be made by various methods such as the Bridgman and Czochralski processes, both of which result in a cylindrical rod of material. The boule is sliced into thin wafers on which integrated circuits are formed.

In 1998, Cree developed the first high-power-density GaN on SiC high electron mobility[9] transistor (HEMT) for wireless and broadcast applications. Compared to the GaN on Sapphire variant at the time, it delivered four time the power density. In 2000, Cree developed the first GaN monolithic microwave integrated circuit (MMIC)—a superior power density alternative to gallium arsenide (GaAs).

In 2008, Cree introduced the first GaN radio frequency (RF) device that utilized the advantages of GaN on SiC to improve RF performance. Because of its high breakdown[10] electric field, GaN can operate at very-high voltages, thus at high power densities, without reducing reliability. Using SiC as the substrate, GaN sits on a high thermal conductivity[11] foundation. Such a base is ideal for accommodating high power density and maintaining device temperatures at a reasonable level. This allows GaN RF devices to deliver higher output powers without having to increase device size. These attributes enable the RF industry to design smaller, more efficient and powerful RF systems.

SiC was introduced into power electronics[12] in the early 1990s with the support of DOD, NASA, and DARPA. For SiC to establish itself as a mainstream technology, SiC wafers had to become cheaper, larger, and contain fewer defects. Micropipes[13] were a major impediment. Without a substantial decrease in defect density, it would not be possible to produce devices with sufficient area to operate at high currents. SiC oxides were considered to be unreliable, preventing the manufacture of a reliable MOSFET. Over time, these issues were resolved. Small Schottky barrier diodes (SBD) were introduced in 2001 by Infineon and in 2002 by Cree. The first commercial SiC power MOSFET was introduced in 2011.

The introduction of SiC diodes and transistors has resulted in faster switching frequencies, higher efficiencies, and superior power densities—all of which are essential to the continued development of power electronic systems. These attributes allow SiC power electronics to support various emerging industries, including renewable power conversion (such as solar and wind power), energy storage, and public transportation (such as electric trains and buses). SiC power devices can also be found in uninterruptible power supplies (UPS), industrial high-frequency power supplies, and motor drives. In all of these applications, systems containing SiC compounds operate with higher efficiencies, take up less space, and do not require extensive cooling systems.

There are substantial opportunities for SiC devices in electric vehicles; they are being used in internal combustion engine vehicles and manufacturers are including SiC technology in future designs. By replacing Si devices with those made of SiC inverters and on-board and off-board chargers, the range of electric vehicles can be extended 5-10%. Because range is a significant factor when considering the purchase of an electric vehicle, it has a large influence on sales. Furthermore, the use of SiC technology can lead to an overall decrease in cost compared with the use of Si. SiC use is also set to grow as electric vehicle manufacturers transition from less efficient Si-based 400 V busses to higher efficiency SiC-based 800 V busses.

Many advances have been made in WBG technology in the last 25 years. The next 25 years will likely be even more transformational. As mentioned earlier, in addition to Cree, several semiconductor companies have made and continue to make advances in the manufacturing and use of WBG devices.

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[9] Electron mobility is a measure on how quickly an electron can move through the material when subjected to an electric field.

[10] Breakdown field (in V/cm or kV/mm) is a measure of the dielectric strength of the material, just as tensile strength is for mechanical behavior.

[11] Thermal conductivity of a material is a measure of its ability to conduct heat.

[12] Power electronic systems (such as electric vehicles and the electric grid) range in power from kilowatts to megawatts, whereas RF systems range in power from a few watts to about 20 watts.

[13] A micropipe is a cavity that starts on the wafer surface and burrows into the wafer like a pothole. Micropipe defects can short-circuit an electronic device causing it to fail.

Gallium oxide (β-Ga_2O_3), aluminum nitride (AlN), and diamond are other WBG materials that are currently being explored for high-voltage or high-power applications.

Self-Test

1. When was the bipolar transistor (BJT) developed?
   a. 1980
   b. 1945
   c. 1947
   d. 1993

2. The Nobel Prize in Physics in 2014 was awarded to______________, who developed the high-brightness ______ LED using wide-bandgap semiconductor___________________.
Choose the correct combination:
   a. Hiro Nakamura, green, GaN
   b. Ryo Ishikawa, red, SiC
   c. Shuji Nakamura, blue, InGaN
   d. Shinsuke Nakamura, yellow, GaN

3. The Si-based MOSFET was invented in ____ at _______ and was first manufactured in ____.
   a. 1964, TI Inc., 1968
   b. 2011, Cree Inc., 2013
   c. 1959, Bell Labs, 1964
   d. 1964, Bell Labs, 1968

4. The Si-based IGBT breakthrough in power electronics occurred in the ____.
   a. 1990s
   b. 1980s
   c. 1970s
   d. 1960s

5. True or false: SiC and GaN have emerged as alternatives to Si in high-power, high-temperature switching applications.
   a. True
   b. False

6. Power density of a semiconductor power device refers to _______.
   a. the amount of energy per unit area (joules/m^2)
   b. the amount of power per unit volume (watts/m^3)
   c. the amount of energy per unit volume (joules/m^3)
   d. the amount of power per unit area (watts/m^2)

7. In what year was the first high-power-density GaN-on-SiC HEMT (high-electron-mobility transistor) developed for wireless and broadcast applications?
   a. 1993
   b. 2011
   c. 1998
   d. 2013

8. SiC was introduced into power electronics in the early______ with the support of DOD, NASA, and DARPA.
   a. 2000s
   b. 1990s
   c. 1980s
   d. 1970s

9. A ___________ is a cavity that starts on the _____________ and burrows into the wafer like a pothole. Micropipes can _____________ an electronic device, causing it to fail.
   a. micropipe, wafer interior, short-circuit
   b. micropipette, wafer surface, open circuit
   c. micropipette, wafer interior, short-circuit
   d. micropipe, wafer surface, short-circuit

10. The first commercial ____ power MOSFET was introduced in 2011.
    a. InGaN
    b. GaN
    c. GaAs
    d. SiC

11. SiC use is set to grow as electric vehicle manufacturers transition from less efficient Si-based _________ busses to higher-efficiency SiC-based __________ busses.
    a. 12 V, 24 V
    b. 12 V, 36 V
    c. 400 V, 500 V
    d. 400 V, 800 V

12. Systems containing SiC compounds operate with _______ efficiencies, take up ______ space, and do not require extensive ___________.
    a. higher, more, heating systems
    b. higher, less, cooling systems
    c. lower, less, heating systems
    d. lower, more, cooling systems

Section 2: Wide-Bandgap Devices: Advantages, Use as Switching Devices, and Challenges

In this section, we define the bandgap of a semiconductor, explain the switching behavior of a MOSFET power device, consider the properties and advantages of WBG devices, and review the challenges in implementing WBG devices.

2.1 Bandgap of a Semiconductor

Electrons exist in various states or energy levels around the nucleus of an atom. Some states are permitted while others are forbidden. Sets of possible states form regions called bands. Sets of impossible states form regions between these bands called bandgaps or energy gaps. Two specific bands are called the valence and conduction bands. Valence band electrons are kept tightly in place, whereas conduction band electrons are free to move around. The size of the bandgap separating these two bands represents the amount of energy needed to excite electrons from the material's valence band into the conduction band, and it is a major factor in determining semiconductor properties.

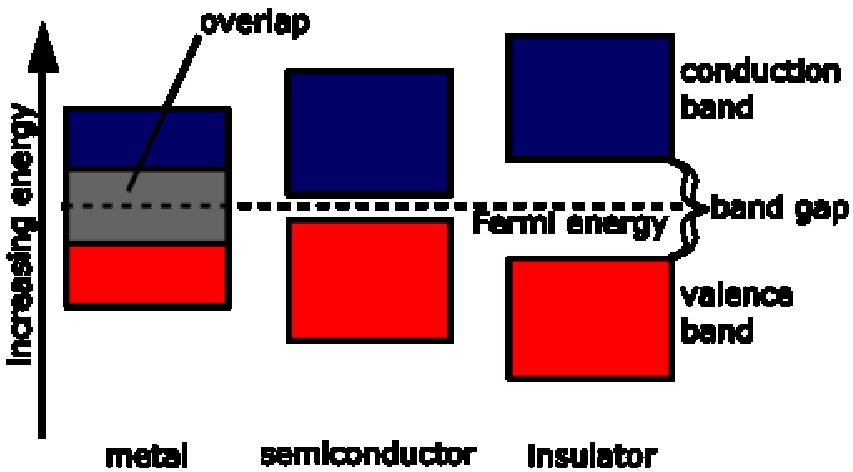

Figure 6: Distinguishing metals, semiconductors, and insulators from their bandgaps (source: Wikipedia, https://commons.wikimedia.org/wiki/File:Band_gap_comparison.svg).

Looking at Figure 6, note the difference in bandgap size or energy for metals, semiconductors, and insulators. In metals, where the valence and conduction bands overlap, electrons move easily into the conduction band so that electricity is conducted. In insulators, where the bandgap is large, it is almost impossible to energize or excite electrons sufficiently to allow them to jump from the valence band to the conduction band; this prevents the conduction of electricity. Semiconductors have electrical conductivities between those of metals and insulators. They have a sufficiently small bandgap so that when electrons are excited, the bandgap can be surmounted; this allows some electrons to reach the conduction band and results in controlled conduction (Figure 7). The three semiconductors—silicon (Si), silicon carbide (SiC), and gallium nitride (GaN)—have bandgap energies of 1.1 electron volts (eV), 3.2 eV, and 3.4 eV, respectively. The bandgaps of SiC and GaN are approximately three times that of Si, hence they are referred to as wide-bandgap (WBG) semiconductors.

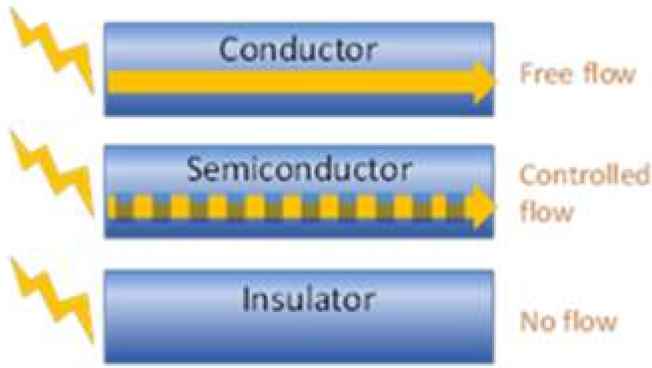

Figure 7: Comparison of conductors, semiconductors, and insulators (source: Power America).

2.2 Semiconductor Switching Devices

The BJT, MOSFET, and IGBT are three-terminal devices[14]. For amplification, they are said to operate in the active region. For switching, they are said to operate either in cutoff, where they act as an open circuit (in an "off" state, nonconducting), or in saturation, where they act as a short circuit (in an "on" state, conducting). Figures 8 and 9 present the basic operation of an N-channel MOSFET as a switching device.

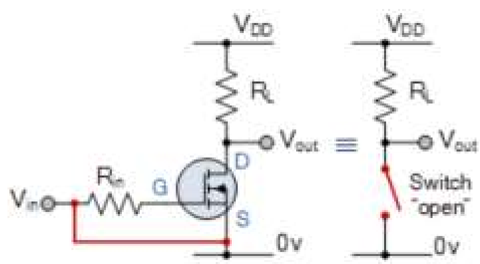

Figure 8: Zero gate voltage—nonconducting.

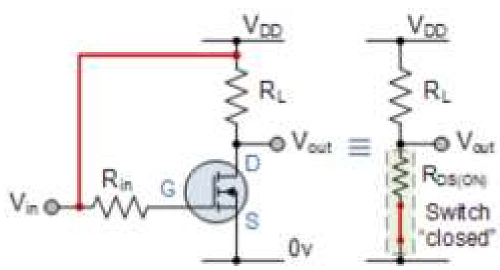

Figure 9: Positive gate voltage—conducting (source: Electronic Tutorials).

IGBTs and MOSFETs are used as switching devices in power conversion systems because of their ability to control and manipulate large amounts of power from input to output with relatively low power loss (or dissipation). Two types of power loss occur in switching devices—conduction and switching. Conduction

[14] BJT terminals: base, emitter, and collector; IGBT: gate, collector, and emitter; MOSFET: gate, drain, and source.

losses are determined by the product of the square of drain current and ON resistance[15] of the device. Small values of ON resistance minimize conduction losses. Switching loss of a Si or SiC FET is proportional to the product of drain-source voltage and drain current during switching transition. As the switching frequency increases, the switching losses also increase almost linearly. It is difficult to minimize switching losses, especially when the device must switch at high frequencies. The use of WBG semiconductor devices in power conversion systems—as alternatives to Si—can result in significantly lower power losses in many application areas.

To see why there is a loss of power during a switching transition, consider Figure 10. During a switching transition, drain current flows before the drain-source voltage decreases to zero. During this time, the power loss, equal to the volt-ampere product, can be very large. Increasing the speed of switching transitions will reduce this power loss.

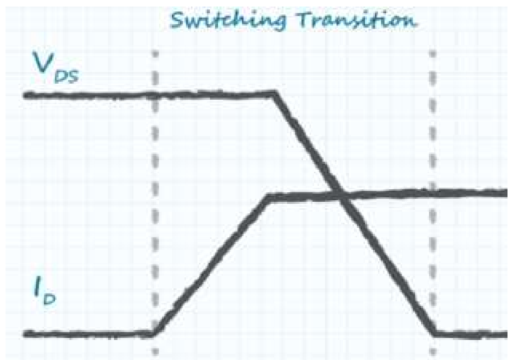

Figure 10: Drain-source voltage and drain current waveforms during switching (source: CUI Inc).

2.3 WBG Semiconductor Properties and Advantages Over Si

The importance of reducing carbon dioxide emissions and fossil-fuel use as an energy source is leading to the development of energy-efficient, compact, and robust systems[16]: Automotive manufacturers are committed to the development of efficient hybrid electric vehicles (HEVs) and all-electric vehicles (EVs); industrial high-power products such as motor drives, solar inverters, and servers for data centers are moving toward realizing higher system efficiency, longer lifetimes, and more compact designs. Si-based MOSFETs and IGBTs are approaching their theoretical limits in satisfying system performance specifications.

There are several issues with the current state of Si power devices. To sustain voltages beyond 200 volts, a Si MOSFET must be quite thick. This added thickness results in increased ON resistance and corresponding increased conduction losses. Si devices cannot process large amounts of power while simultaneously switching at high frequencies[17]. High voltage Si devices, such as IGBTs, operate at

[15] ON resistance, denoted by RDS(on), refers to the resistance from the drain (terminal D) to source (terminal S) in a MOSFET when conducting. Typical values for IGBT and MOSFET ON resistance are in the tens of milliohms.

[16] Sridhar, Nagarajan. 2019. "Silicon carbide gate drivers – a disruptive technology in power electronics." Texas Instruments. https://www.ti.com/lit/wp/slyy139a/slyy139a.pdf?ts=1609869140505&ref_url=https%253A%252F%252Fwww.bing.com%252F.

[17] Pendharkar, Sameer. 2018. "GaN and SiC enable increased energy efficiency in power supplies." Texas Instruments.

relatively low switching frequencies and therefore have high switching losses. Si devices also have poor high-temperature performance[18] (limited to 150 °C).

WBG semiconductor power devices are playing a critical role in extending the capabilities of Si. Many of their attractive properties stem from their wide bandgap[19]. As electrons in WBG materials need about three times as much energy as required by Si to reach the conduction band, they can withstand about ten times the maximum electric field before electrical breakdown[20] occurs; they can also tolerate much higher temperatures (over 300 °C), they have higher thermal conductivity, they have increased power-handling capability, they can operate at much higher frequencies, and they have increased reliability compared to Si.

The large breakdown values allow WBG power devices to have the same dimensions as Si-based devices but can withstand ten times the voltage. Furthermore, WBG devices can be less than one-tenth the thickness of a Si device but have the same voltage rating. These thinner devices have less ON resistance, meaning that less energy is lost to heat when conducting electricity. A thinner device also means that there is less distance for the electrons to travel, enabling the device to operate at higher frequencies compared to Si. Devices operating at higher switching frequencies have lower switching losses.

The primary reasons for embracing SiC and GaN are summarized in Figure 11.

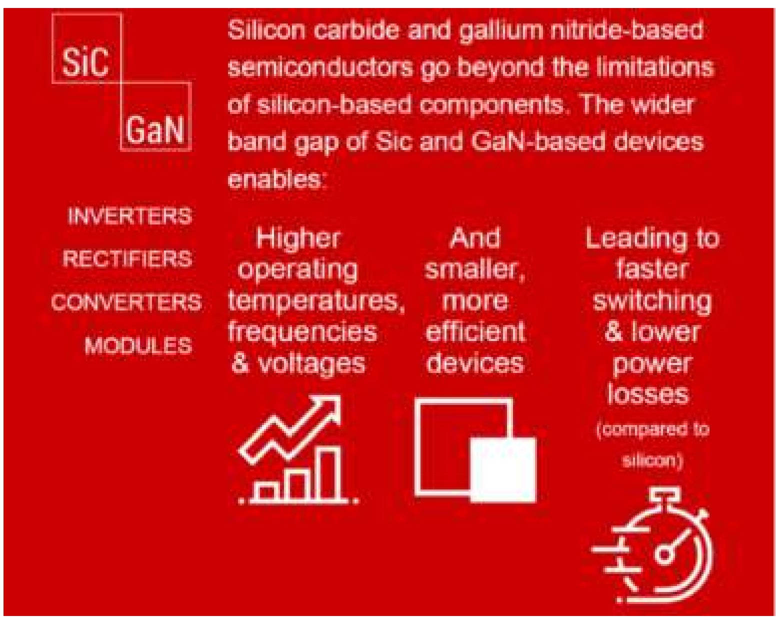

Figure 11: Primary reasons for using WBG materials (source: Power America).

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https://www.mouser.co.uk/pdfdocs/GaNandSiCtechnologiesenableincreasedefficiencyinpowersupplies.pdf,

[18] U.S. Department of Energy. 2013. "Wide Bandgap Semiconductors: Pursuing the Promise." https://www1.eere.energy.gov/manufacturing/rd/pdfs/wide_bandgap_semiconductors_factsheet.pdf.

[19] Ozpineci, Burak, and Leon Tolbert. 2011. "Silicon Carbide: Smaller, Faster, Tougher Silicon: Meet the material that will supplant silicon in hybrid cars and the electric grid." *IEEE Spectrum* (October). https://www.ieee.org/publications

[20] Breakdown for Si is 0.3 MV/cm, for SiC 3.5 MV/cm, and for GaN 3.3 MV/cm.

2.3.1 Silicon Carbide Versus Silicon

SiC has many superior material properties in comparison with Si[21]. As shown in Table 1, these include larger bandgap, high breakdown voltage, high saturation velocity, and high thermal conductivity[22].

Table 1: Intrinsic material properties of SiC (source: Texas Instruments).

Property	Definition	Si	SiC-4H
E_G (eV)	Bandgap Energy	1.12	3.26
E_{BR} (MV/cm)	Critical Field Breakdown Voltage	0.3	3.0
v_s (x107cm/s)	Saturation Velocity	1.0	2.2
μ (cm^2/V.s)	Electron Mobility	1400	900
λ (W / cm.K)	Thermal Conductivity	1.3	3.7

The higher breakdown voltage of SiC results in lower ON resistance compared to Si, thus realizing higher voltage and higher power operation with low conduction losses. The large bandgap of SiC also enables system operation at higher temperatures. Whereas Si-based power devices operate up to a junction temperature of 150 °C, SiC can operate at junction temperatures exceeding 200 °C. For example, power converters in hybrid electric vehicles (HEV) can create such a high-temperature environment.

The high saturation velocity of SiC compared with that of Si enables higher system operating frequencies and correspondingly lower switching losses. These benefits lead to a reduction in cooling demands as well as a decrease in the size of passive elements such as inductors, capacitors, and transformers. Consequently, these benefits also lead to a reduction in the size and weight of the overall system. The high thermal conductivity of SiC enables systems with fewer cooling requirements. Figure 12 shows a direct relationship between the intrinsic material properties of SiC and the resulting system benefits—including reduced size, cost, and weight. Figure 13 compares the performance of SiC-based MOSFETs against Si-based IGBTs, both operating at 40kHz. SiC MOSFETs clearly have significantly lower switching losses.

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[21] (a) Wolfspeed. 2019. "New SiC Power Modules Deliver Greater Power Densities in Smaller Packages Than Si IGBTs." Wolfspeed, Inc. https://www.wolfspeed.com/knowledge-center/article/new-sic-power-modules-deliver-greater-power-densities-in-smaller-packages-than-si-igbts.
(b) Wolfspeed. 2019. "What is a Silicon Carbide MOSFET?" Wolfspeed, Inc. https://www.wolfspeed.com/knowledge-center/article/what-is-a-silicon-carbide-mosfet.
(c) Saturation velocity is the maximum velocity that a charge carrier in a semiconductor attains in the presence of very high electric fields.
[22] The breakdown voltage is the drain-source voltage for which the drain-source current increases exponentially and MOSFET failure occurs.

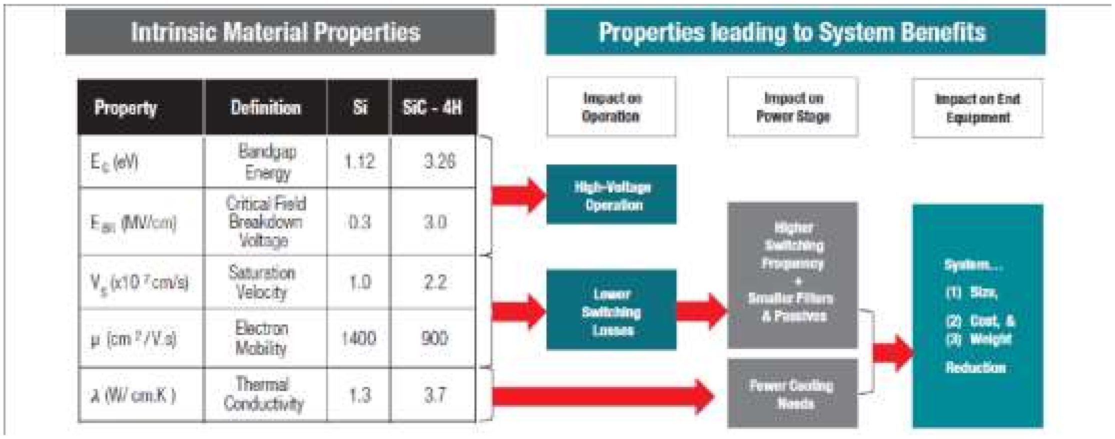


Figure 12: Material properties of SiC impacting system benefits (source: Texas Instruments).

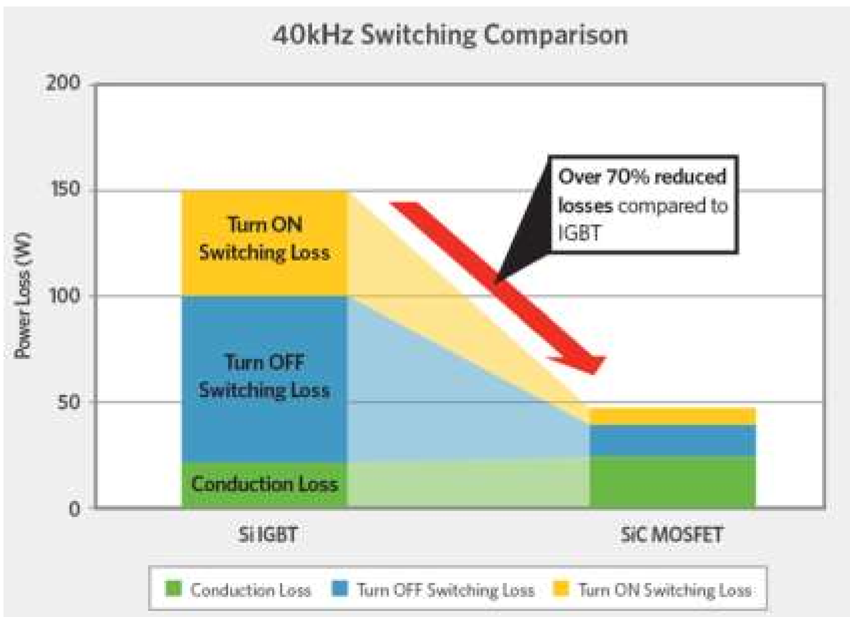


Figure 13: Performance advantages of SiC MOSFETs vs. IGTBs (source: Applied Materials, Inc.).

2.3.2 The Differences Between Si MOSFET, Si IGBT, and SiC MOSFET[23]

Si-MOSFET, Si-IGBT, and SiC-MOSFET power devices differ in their power levels, drive methods, and operating modes. Because the IGBT is internally a MOSFET driving a bipolar junction transistor (BJT), both IGBTs and MOSFETs are voltage-driven at the gate. Both also have low conduction losses. IGBTs carry more current than Si MOSFETs; for this reason, IGBTs are used in high-power applications.

SiC MOSFETs are similar to Si MOSFETs with respect to device type. However, SiC is a WBG material with properties that allow these devices to operate at the same high power levels as IGBTs while being able to switch at high frequencies. These properties translate into system benefits including higher power

[23] Texas Instruments. 2019. “IGBT and SiC Gate Driver Fundamentals.” Texas Instruments Incorporated. https://www.ti.com/lit/pdf/slyy169?keyMatch=SIC%20GATE%20DRIVER%20FUNDAMENTALS.

density, higher efficiency, and lower heat dissipation. Figure 14 provides comparisons of Si and SiC devices relative to ratings and applications.

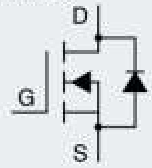
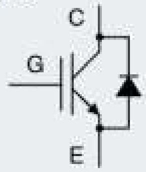
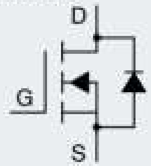
	Si MOSFETs	Si IGBTs	SiC MOSFETs
Circuit symbol			
Voltage rating	20 V-650 V	≥650 V	≥650 V
f_{sw}	Medium-high (>20 kHz)	Low-medium (5 kHz-20 kHz)	High (>50 kHz)
V_{GS}/V_{GE}	0 V-15 V (20 V)	-10 V-15 V (10 V-20 V)	-5 V-20 V (25 V-30V)
Typical applications	Power supplies – server, telecom, factory automation, offboard/onboard char-gers, solar inverters, string inverters	Motor drives (AC machines), UPSs, solar central and string power inverters, EV/HEV traction inverters	PFC – power supplies, solar inverters, DC/DC for EVs/ HEVs, traction inverters for EVs, motor drives, railways
Power level	<3 kW	>3 kW	>5 kW

Figure 14: Power device ratings and applications.

2.3.3 Gallium Nitride Versus Silicon Carbide

In this section, the mobility, switching losses, thermal conductivity, and blocking voltages of SiC and GaN are compared.

The most significant difference between GaN and SiC is in their electron mobility. GaN, SiC, and Si have electron mobilities of $2000\ \frac{cm^2}{Vs}$, $650\ \frac{cm^2}{Vs}$, and $1500\ \frac{cm^2}{Vs}$, respectively. The electron mobility of SiC is slower than that of GaN and Si. With such elevated electron mobility, GaN is nearly three times more suitable than SiC for high-frequency applications.

In a 2017 study[24], GaN Systems' enhancement-mode high electron mobility transistor (E-HEMT) technology was demonstrated to have lower switching losses than those of Cree's SiC MOSFET at frequencies of 100 kHz and 200 kHz. The bar graph of Figure 15 shows that, in synchronous buck DC/DC converter applications, GaN provides significant performance improvement over SiC. At 100 kHz, GaN provides 10 W savings, and in the same system at 200 kHz, 20 W is saved.

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[24] Xu, Jason. 2017. "A Performance Comparison of GaN E-HEMTs versus SiC MOSFETs in Power Switching Applications." *EE Power* (June). https://eepower.com/technical-articles/a-performance-comparison-of-gan-e-hemts-versus-sic-mosfets-in-power-switching-applications/.

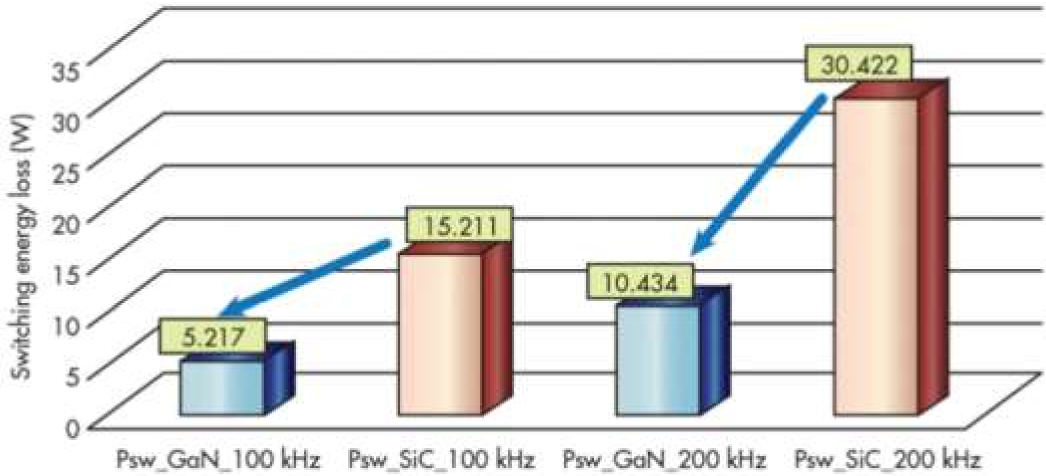


Figure 15: Switching loss comparisons (source: Power Electronics S.L.).

The thermal conductivity of a material directly influences its temperature. In high-power applications, material inefficiencies create heat, thus increasing the temperature of the material and subsequently changing its electrical characteristics[25]. GaN, SiC, and Si have thermal conductivities of 1.3 W/cmK, 5 W/cmK, and 1.5 W/cmK. Clearly SiC is nearly three times better at transferring heat than GaN, making SiC preferable in high-voltage, high-power, and high-temperature applications.

SiC MOSFETs with blocking voltage ratings[26] in the range from 650 V to 1700 V are commercially available while SiC devices with ratings of 3.3 to 15 kV are fast approaching. Commercially available GaN devices generally have blocking voltages below 650 V. The application areas of GaN and SiC devices as a function of voltage rating are depicted in Figure 16[27].

[25] Arrow Electronics, Inc. 2020. "Silicon Carbide (SiC) vs. Gallium Nitride (GaN)." Arrow.com. Accessed March 1, 2021. https://www.arrow.com/en/research-and-events/articles/silicon-carbide-and-gallium-nitride-compared.

[26] The blocking voltage rating of a device, also referred to as the rated voltage, is the maximum voltage the device can tolerate when it is not conducting.

[27] Vaughan-Edmunds, Llew. 2019. "Wide band gap—The Revolution in Power Semiconductors." *Nanochip Fab Solutions* (April). Accessed March 1, 2021. https://www.appliedmaterials.com/nanochip/nanochip-fab-solutions/april-2019/wide-band-gap.

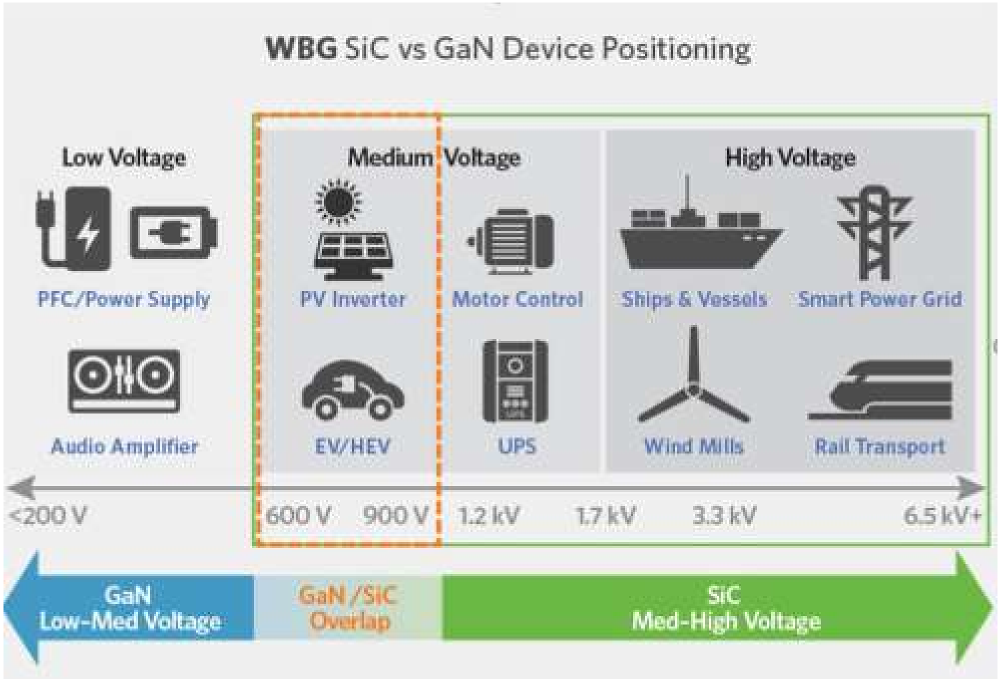


Figure 16: GaN focused on voltages at or below 650 V for high-power-density power supplies; SiC focused on voltages at or above 1200 V for industrial applications (source: Yole Développement).

2.4 WBG Challenges

Although WBG materials are rapidly gaining acceptance, several manufacturing challenges must be met to make them cost-effective and spur further commercialization including the following:

- Reduction in the cost of producing large-diameter wafers
- New device designs that exploit the properties of WBG materials to achieve the voltage and current ratings required in certain applications
- Alternative packaging designs to withstand high temperatures and inductive losses encountered in WBG devices
- Architectures that improve manufacturability
- System redesign to suit replacement of Si-based devices

Self-Test

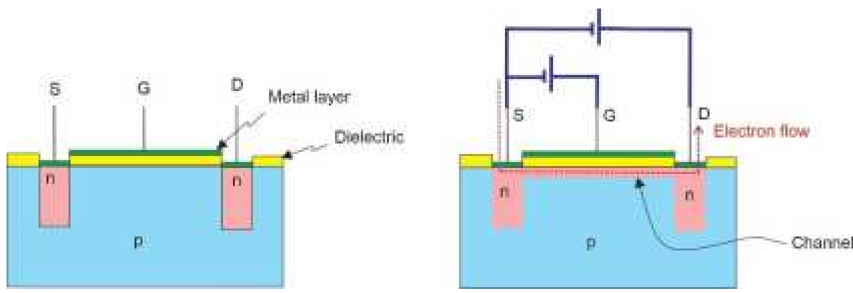
1. The bandgap energy of WBG devices is approximately ________ times that of Si.
   a. 10
   b. 20
   c. 3
   d. 100
2. The ON resistance for MOSFET devices is in the range of _______.
   a. tens of megohms
   b. thousands of ohms
   c. tens of milliohms
   a. 10-50 ohms
3. GaN is focused on voltages _______ for high-power-density power supplies while SiC focuses on voltages _______ for industrial applications.
   a. at or above 1000 V, at or below 1000 V
   b. at or below 750 V, at or above 800 V
   c. at or below 650 V, at or above 1200 V
   d. at or above 300 V, at or below 500 V
4. Because of its higher electron mobility, _____ is more suitable than _____ for high-frequency applications.
   a. GaN, SiC
   b. SiC, GaN
5. GaN HEMT operate at ______ switching frequencies than Si and SiC devices.
   c. lower
   d. higher
6. The higher breakdown voltage of SiC relative to Si results in ______ ON resistance and thus realizes _____ voltage and higher power operation with ______ conduction losses.
   a. higher, lower, low
   b. higher, lower, high
   c. lower, higher, low
   d. lower, higher, high
7. In metals the bandgaps _________, in insulators the bandgaps ________, and in semiconductors the bandgaps ________.
   a. are large, overlap, are small
   b. are small, are large, overlap
   c. are large, are small, overlap
   d. overlap, are large, are small
8. Referring to Figure 8, the larger values of _________ and __________ for SiC-4H have a direct effect on system high-voltage operation. Please select the two answers that apply.
   a. ON resistance
   b. bandgap energy
   c. electron mobility
   d. critical field breakdown voltage
9. Referring to Figure 8, the larger value of _________ for SiC-4H results in fewer cooling needs in the power stage.
   a. electron mobility
   b. saturation velocity
   c. thermal conductivity
   d. bandgap energy

10. Semiconductor power devices have two types of power loss: conduction losses and switching losses. Conduction losses are determined by the product of the square of _______ and ________. Switching losses are determined by the product of __________ and _________ during switching transition.
    a. drain-source voltage and ON resistance
    b. drain-source voltage, drain current
    c. drain current, ON resistance

Section 3: Device Structure, Operation, and Testing Procedure

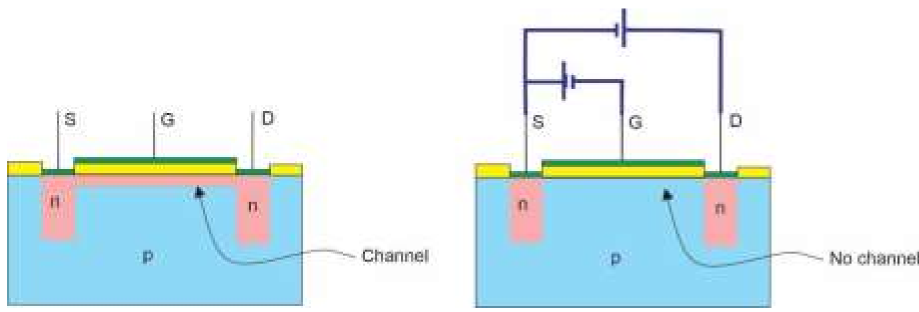
3.1 MOSFET Structure and physical operation

MOSFET[28] devices can be classified as either enhancement (E-MOSFET) or depletion (D-MOSFET). They are depicted in Figures 17 and 18. In each there are two wells, drain and source, immersed in a substrate. The space between the wells is referred to as the channel. Terminals attached to the MOSFET are identified as the drain (D), source (S), and gate (G). A fourth terminal (B) is attached to the substrate; this terminal is typically connected to the source S.



(a) (b)

Figure 17: N-channel E-MOSFET (a) nonconducting, (b) conducting.



(a) (b)

Figure 18: N-channel D-MOSFET (a) conducting, (b) nonconducting.

For the E-MOSFET, we may have n-type wells immersed in a p-type substrate (the N-channel E-MOSFET shown in Figure 17) or p-type wells immersed in an n-type substrate (this is a P-channel E-MOSFET, not shown). Similarly, for the D-MOSFET, we may have n-type wells immersed in an p-type substrate (the N-channel D-MOSFET shown in Figure 18) or p-type wells immersed in a n-type substrate (this is a P-channel D-MOSFET, not shown). For the D-MOSFET a physical channel exists between drain and source, composed of the same semiconductor material as that of the wells.

The E-MOSFET of Figure 17 remains in a nonconducting state ("normally open" switch) unless a voltage at the gate is present. The application of a gate voltage activates the channel current by inducing a layer of charge carriers between source and drain under the gate. The electric field produced by the gate voltage increases the charge carriers and, in effect, switches the device on (switch closes).

[28] Electrical4U. 2016. "MOSFET Transistor Basics & Working Principle." YouTube video. Accessed February 25, 2021. https://www.youtube.com/watch?v=p34w6ISouZY.

The D-MOSFET of Figure 18 remains in a conducting mode (“normally closed” switch) unless a voltage at the gate is applied. The voltage at the gate has the effect of switching the device OFF because the electric field produced by the gate voltage reduces the majority charge carriers.

MOSFET classification[29] is presented in Figure 19.

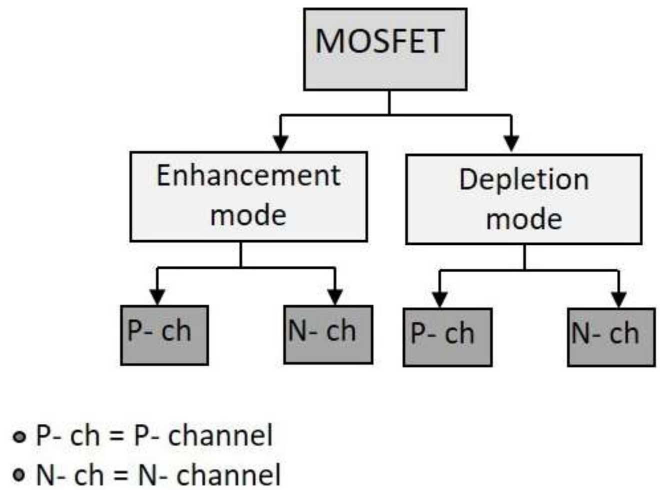


Figure 19: MOSFET classification (source: Tutorialspoint.com).

The schematic symbols for E-MOSFET and D-MOSFET are given in Figures 20 and 21, respectively. Both figures depict the devices out of a circuit without any electrical biasing. The broken lines in Figure 20 symbolize the absence of a physical channel between source and drain. In contrast, the continuous thick line connected between drain and source in Figure 21 symbolizes an actual physical channel. In both figures, the substrate arrow points inward for the N-channel and outward for the P-channel.

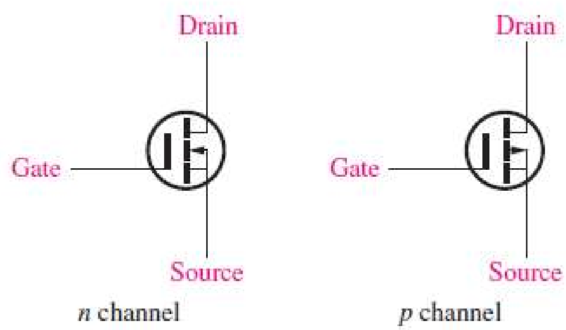


Figure 20: E-MOSFET schematic symbol.

[29] Tutorialspoint.com. 2021. “Basic Electronics – MOSFET.” *Learn Basic Electronics.* Accessed February 25, 2021. https://www.tutorialspoint.com/basic_electronics/basic_electronics_mosfet.htm.

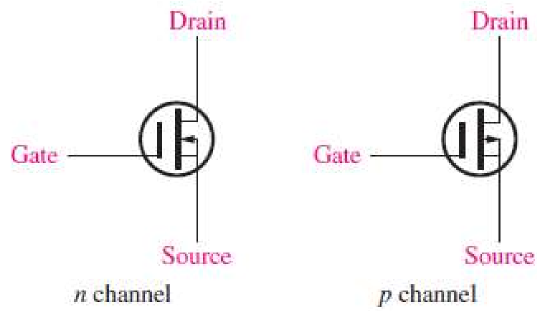


Figure 21: D-MOSFET schematic symbol.

3.2 Body Diode

A useful by-product of the Si and SiC MOSFET structure is an internal parasitic diode. In a discrete (standalone) MOSFET, the source and body are usually tied together for convenience to make a three-pin package. This results in a diode being formed between the source and drain, as shown in Figure 22. This intrinsic diode exists in both lateral and vertical MOSFETs; it is called the body diode. As shown in Figure 23, the body diode symbol is often depicted explicitly on the MOSFET symbol. The body diode is useful in circuits that require a path for the reverse drain current (called the "freewheeling current"). Examples of such circuits include half-bridge and full-bridge converters in motor control applications where inductive-load switching occurs[30].

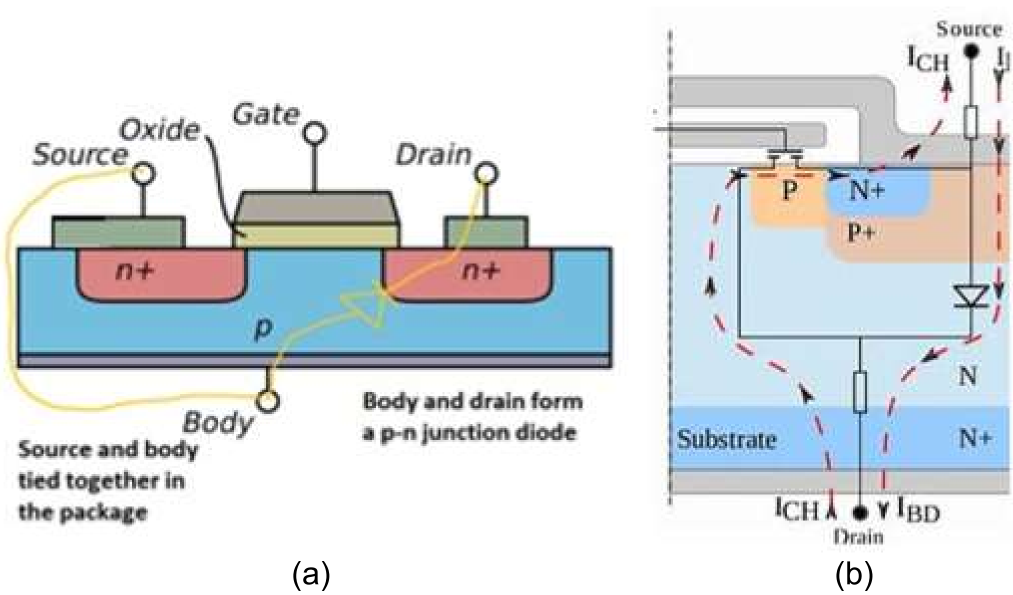


Figure 22: Source-drain body diode in (a) lateral device, (b) vertical device.

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30 (a) McAllister, Willy. "Inductor Kickback (2 of 2)."Khan Academy, video. Accessed February 25, 2021, https://www.khanacademy.org/science/electrical-engineering/ee-circuit-analysis-topic/ee-natural-and-forced-response/v/ee-inductor-kickback-2.
(b) ElectronicsHub. 2019. "What is a Flyback Diode?" electronicshub.org. Accessed February 25, 2021. https://www.electronicshub.org/flyback-diode-or-freewheeling-diode/.

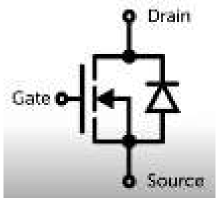


Figure 23: MOSFET with intrinsic body diode symbol.

The body diode becomes a design advantage in circuits where the MOSFET is switching inductive loads. This is because the body diode eliminates the need for an additional diode to conduct the inductive kickback voltage. To see this, consider the circuit of Figure 24, used to test the IXAN0061 power MOSFET ruggedness[31].

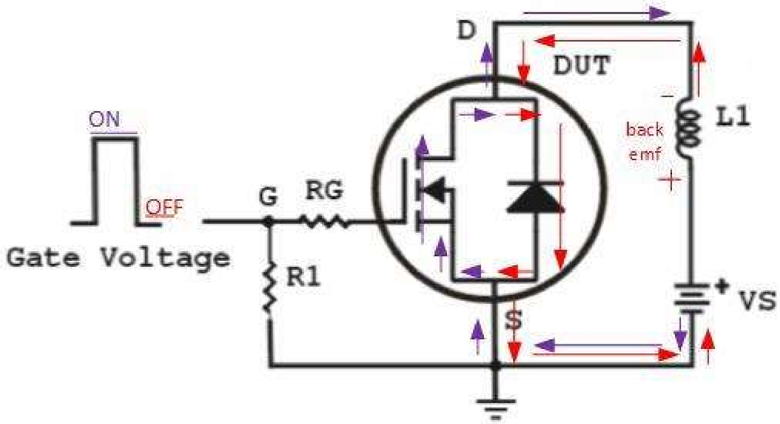


Figure 24: Power MOSFET ruggedness evaluation (source: IXYS Corporation).

During the positive part of the pulse, the MOSFET conducts and electrons flow in the direction of the purple color arrows. During this time a magnetic field is built in inductor L1. When the gate voltage goes to zero, the MOSFET turns off and disconnects L1 from the source Vs which maintained a magnetization of L1. At the moment the MOSFET turns off, the inductor produces a back emf with negative polarity on the drain terminal that could be as high as ten times Vs in order to maintain its magnetic field (Lenz's Law). This back emf, also called flyback or freewheeling voltage, forward biases the body diode and current (shown in red arrows) flows through it. This prevents the buildup of dangerously-high voltage between drain and source that can damage the MOSFET. In early MOSFETs or BJT transistors without body diodes, external diodes were included in the circuit to provide this protection.

3.3 MOSFET as a Switch

The MOSFET may be thought of as a variable resistance, where the gate-source voltage difference controls the drain-source resistance. A voltage at the gate produces an electric field which controls the

[31] Sattar, Abdus. n.d. "Power MOSFET Basics." IXYS Corporation. Accessed February 25, 2021, https://www.ixys.com/Documents/AppNotes/IXAN0061.pdf.

current flowing between the source and drain junctions. The ability to change the source-to-drain conductivity with applied voltage is used for amplifying or switching electronic signals[32].

MOSFET switching is analogous to that of a relay. As shown in Figure 25, when the relay coil is not activated, the switch is open; when the coil is activated, the switch is closed. This corresponds to E-MOSFET behavior. The relay analogy can be extended to the operation of D-MOSFET. However, in the case of D-MOSFET, the switch remains closed until the relay coil is activated. Once the relay coil is activated, the switch opens.

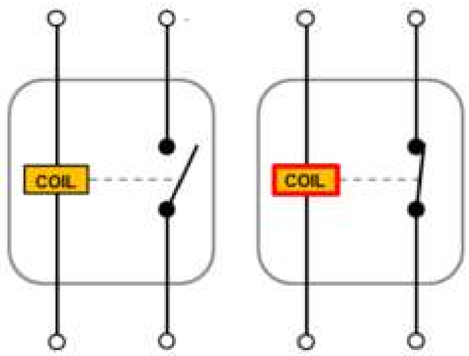


Figure 25: MOSFET relay analogy.

3.4 Power MOSFETs

Power MOSFETs are used for switching large amounts of current. Although the MOSFETs shown in Figures 17 and 18 have a *lateral* structure, Si and SiC *power* MOSFETs typically have a *vertical* channel structure where the source (S) and drain (D) are situated on the upper and lower surfaces of the chip, respectively. The vertical structure provides electrical and thermal paths of conduction from the top to the bottom of the wafer. This placement of source and drain allows the MOSFET to handle larger amounts of power than possible with the lateral structure. Vertical power MOSFETs have two general forms—planar and trench. The gate of the planar MOSFET lies on the upper surface while the gate of the trench MOSFET dips below the upper surface of the semiconductor. VMOS- and UMOS-type trench MOSFETs are shown in Figures 26 and 27 along with drain current pathways in each case during conduction.

---

[32] The main differences between a BJT and a MOSFET:

- The BJT is a bipolar device, meaning that operation is based on the use of both majority and minority charge carriers. A MOSFET is unipolar; this means the operation is based predominantly on the use of majority charge carriers (either holes or electrons).
- The operation of a BJT is dependent on base current while a MOSFET operation is dependent on the voltage at the oxide-insulated gate electrode.
- The BJT is used for low-current applications; a MOSFET is used for high-power applications.

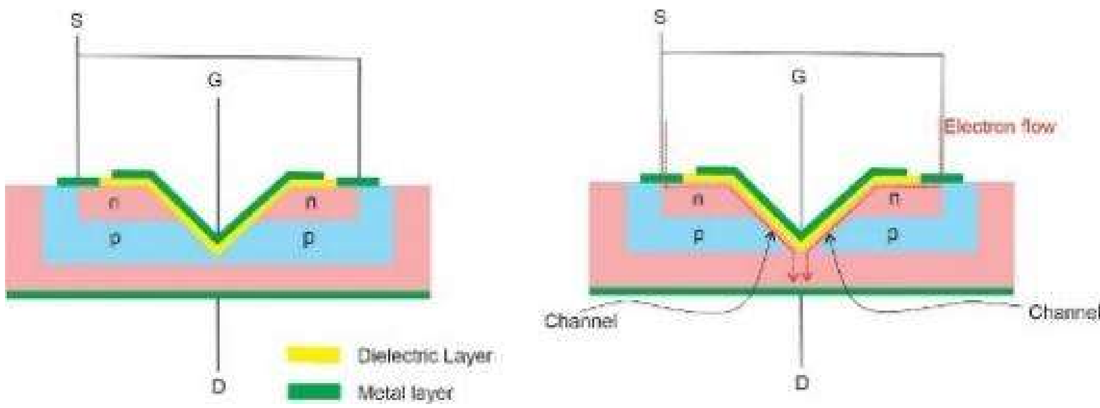


Figure 26: VMOS.

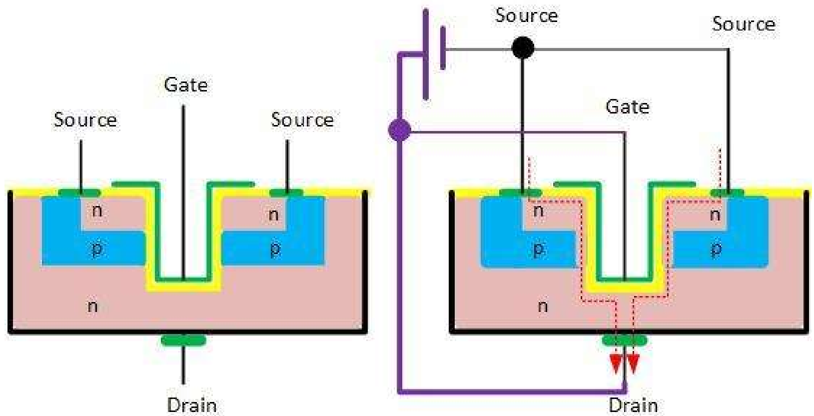
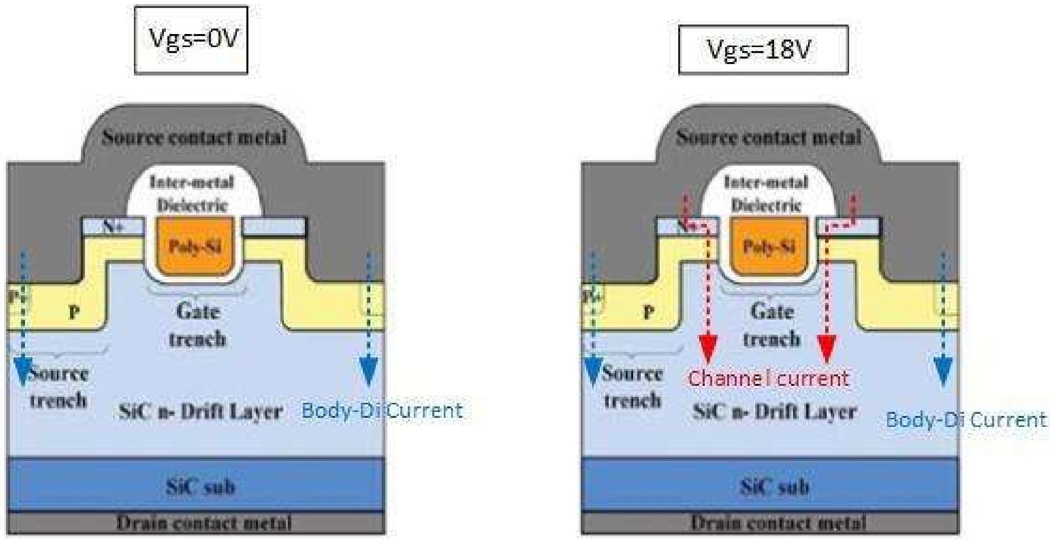


Figure 27: UMOS (source: rfwirelessworld.com[33]).

3.5 SiC MOSFET

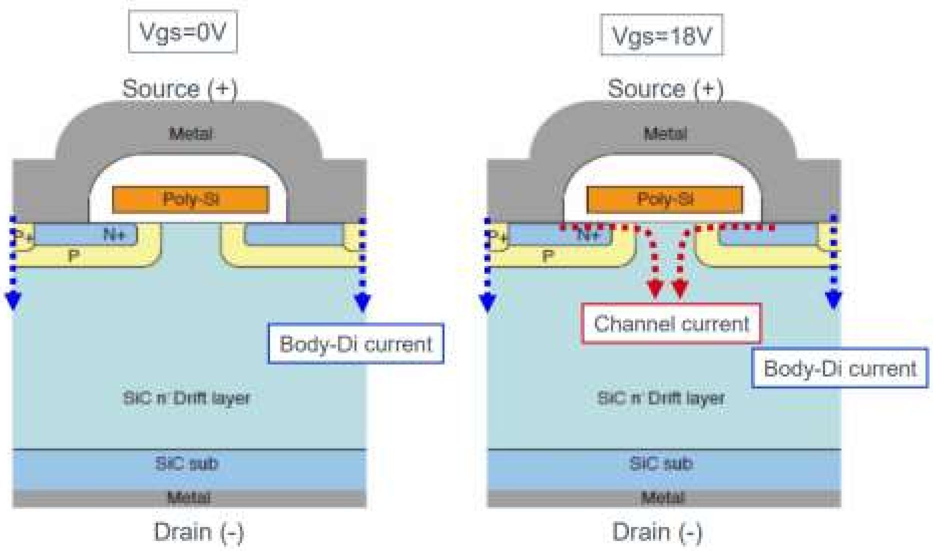
Figure 28 shows a vertical trench UMOS structure for a SiC MOSFET in (a) nonconducting (with $V_{gs} = 0$) state and in (b) conducting (with $V_{gs} = 18$) state. The active device is fabricated on top of an epitaxial (drift) layer (SiC epi). In relation to the substrate, the epi layer can either be the same (homoepitaxy) or different (heteroepitaxy) material. Also, in Figure 28, the SiC epilayer is the same as the substrate. Figure 29 shows a planar MOSFET in (a) nonconducting state and (b) conducting state along with drain current pathways during conduction. Note: In both figures, the body diode current is shown when the body diode has been forward biased, allowing the body diode current to flow, as explained in section 3.3.

[33] RF Wireless World. n.d. "Difference between VMOS FET and UMOS FET." Accessed April 8, 2021. https://www.rfwireless-world.com/Terminology/VMOS-FET-vs-UMOS-FET.html.



(a) Nonconducting (b) Conducting

Figure 28: Trench MOSFET (source: IEEE - ITEC).



(a) Nonconducting (b) Conducting

Figure 29: Planar SiC MOSFET (source: ROHM Semiconductor).

3.6 GaN Transistor

The GaN HEMT shown in Figure 30 has a lateral structure in contrast to the vertical structure of the SiC MOSFET. The buffer layer provides a match between the two different crystal structures. Current flows laterally through a two-dimensional area. Due to the formation of a two-dimensional electron gas by the heterojunction, GaN HEMT devices are capable of high-frequency operation (up to millimeter wave frequencies, 30-300 GHz). They are used in high-frequency products such as cell phones, satellite television receivers, voltage converters, and Radio Detection and Ranging (RADAR) equipment.

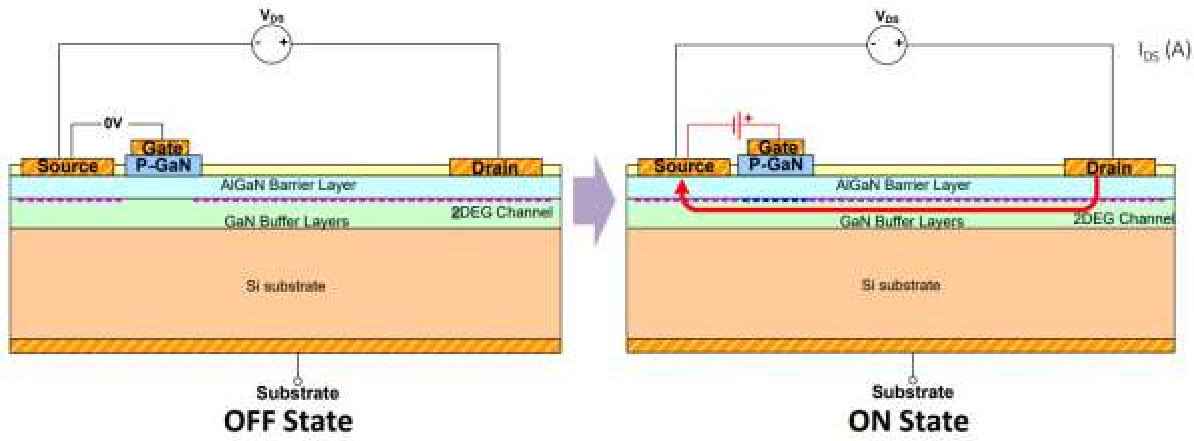


Figure 30: GaN HEMT Lateral Structure—note that conventional current flow is shown (source: GaN Systems).

Note: GaN transistors having a vertical structure are presently in the research and development stage. They are expected to significantly increase the voltage and current-carrying capability of lateral GaN devices.

While a GaN HEMT doesn't have a parasitic body diode as do Si or SiC FETs, the main channel itself acts as a conducting channel in the reverse direction if no biasing is applied—in effect, acting like a diode. However, for this conduction to happen when gate driving is not applied, the reverse voltage drop will be much higher than that of a typical Si or SiC body diode. If the gating signal is applied, then reverse conduction will be possible at a much lower drop equivalent to the $R_{ds\text{-}on}$.

GaN power devices require ~6 V to 7 V of gate-drive voltage, and they are usually sensitive to spikes caused by ringing/parasitics.

3.7 MOSFET Testing Procedure

Figure 31 shows an N-channel E-MOSFET in a TO-220 package along with the symbol used in electronic schematics. The TO-220 is a style of electronic package used for high-powered components. One notable characteristic of the T-220 is a metal tab with a hole which is used in mounting the case to a heatsink and allows the component to dissipate heat.

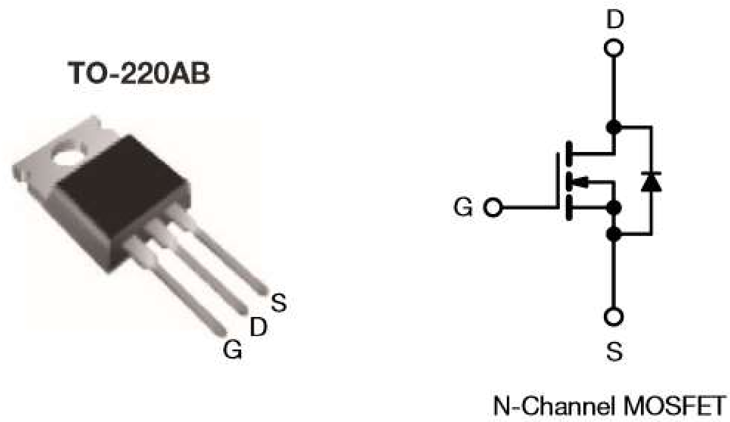


Figure 31: N-channel E-MOSFET TO-220 package (source: Vishay[34]).

For an N-channel E-MOSFET such as that shown in Figure 31, when there is no voltage on any of its terminals (gate, source, and drain), the drain-source resistance of the device is very high—as high as hundreds of Megohms (ideally infinite, or in other words, an open circuit between drain and source which can also be called the OFF-state). When a positive voltage applied between gate and source exceeds the threshold value, the drain-source resistance is very low (ideally zero, or in other words, a closed circuit between drain and source which can also be called the ON-state).

The following procedure can be used to test the ON- and OFF-states of a MOSFET using the resistance test function of a digital multimeter (DMM):

A data sheet for the SiC N-channel E-MOSFET (IMW65R027M1H) is given in the appendix.

Prior to testing, any stored charge on the terminals of the MOSFET should be removed. This can be done easily by connecting the three terminals together using long-nose pliers as shown in Figure 32 or by dipping the three terminals into a conductive foam.

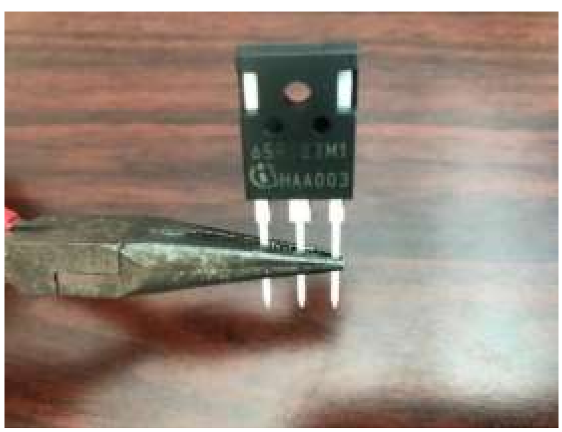


Figure 32: Shorting MOSFET leads using long-nose pliers.

- Testing the OFF-state:

Set the digital multimeter (DMM) to measure resistance (Ω) in an upper range. Connect the red (positive) lead to the drain and the black (negative) lead to the source as shown in Figure 33. Having no channel

[34] "IRF510 Power MOSFET." Accessed April 8, 2021. https://www.vishay.com/docs/91015/irf510.pdf.

inside the device from source to drain (OFF-state), the DMM will display OL, meaning that the resistance between the test leads is beyond the measuring limit of the DMM (which is more than 200 MΩ).

- Testing the ON-state:

While the DMM is connected to the MOSFET for testing the OFF-state, short the drain and gate terminals with a jumper wire (blue) as shown in Figure 35.

The positive voltage applied to the drain with the red lead of the DMM will charge the gate capacitor and induce a channel inside the device. The DMM will read a continuously decreasing resistance value between drain and source, indicating that as the gate capacitor is accumulating charge, a channel with decreasing resistance is forming. Eventually the DMM will read a low resistance value. The meter will not be able to read the minimum $R_{DS}(on)$ resistance because the DMM cannot apply a gate voltage above the threshold voltage needed to turn the MOSFET fully on.

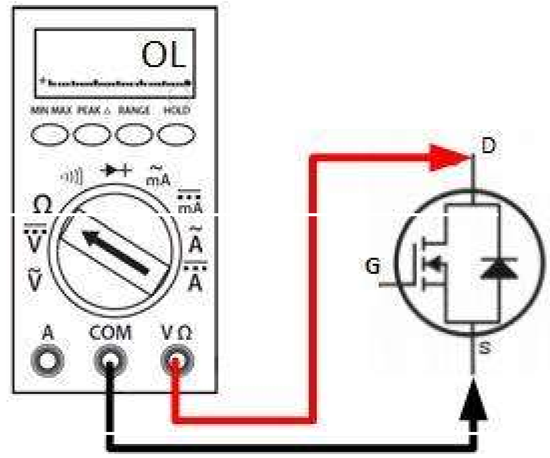


Figure 33: Testing the OFF-state.

Removing the jumper wire between the gate and source does not change the drain-to-source resistance. This is because the gate capacitance maintains the channel.

Use the jumper wire to short the gate to the source; this discharges the gate-to-source capacitance and eliminates the enhanced internal channel. This is verified in Figure 35 by the DMM displaying OL, meaning that the resistance between source and gate is back to its normal level.

If either of the tests described above fails, we can conclude that the MOSFET is defective.

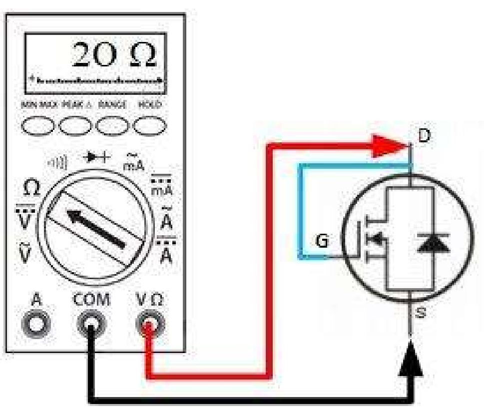


Figure 34: Testing the ON-state.

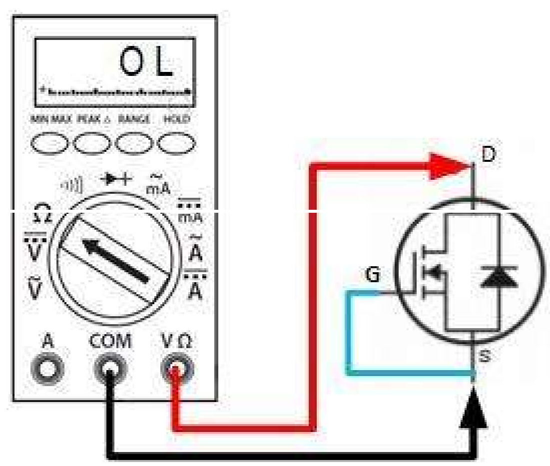


Figure 35: Turning the device off.

Self-Test

1. Choose all correct statements. We may have __________.
   a. n-type wells immersed in a p-type substrate—this is a P-channel E-MOSFET
   b. n-type wells immersed in a p-type substrate—this is a N-channel E-MOSFET
   c. p-type wells immersed in a n-type substrate—this is a N-channel E-MOSFET
   d. p-type wells immersed in a n-type substrate—this is a P-channel E-MOSFET
2. Choose all correct statements. We may have __________.
   a. n-type wells immersed in a p-type substrate—this is a N-channel D-MOSFET
   b. n-type wells immersed in a p-type substrate—this is a P-channel D-MOSFET
   c. p-type wells immersed in a n-type substrate—this is a N-channel D-MOSFET
   d. p-type wells immersed in a n-type substrate—this is a P-channel D-MOSFET
3. In the schematic symbols for E-MOSFET, the broken lines denote the absence of __________ between source and drain.
   a. a body diode
   b. conduction
   c. a physical channel
   d. resistance
4. A __________ by-product of MOSFETs is an internal parasitic structure. It is called a ___________.
   a. harmful, a bipolar transistor
   b. harmful, a Schottky diode
   c. useful, a bipolar transistor
   d. useful, a body diode
5. Even though the _________ is an intrinsic, parasitic characteristic of MOSFETs, it is _______ explicitly depicted on MOSFET symbols.
   a. Schottky diode, never
   a. body diode, often
   b. Schottky diode, always
   c. body diode, always
6. An E-MOSFET is normally __________ unless a voltage at the __________ is present.
   a. closed, drain
   b. open, source
   c. open, gate
   d. closed, gate
7. A D-MOSFET is normally __________ unless a voltage at the __________ is present.
   a. closed, drain
   b. closed, gate
   c. open, source
   d. open, gate
8. SiC power MOSFETs typically have a _________ channel structure. GaN power transistors have a ________ structure.
   a. lateral, vertical
   b. lateral, lateral
   c. vertical, lateral
   d. vertical, vertical
9. In testing the OFF-state, with no voltage applied between ________ and __________, connect the negative lead of the DMM to the ________ and the positive lead to the __________.
   a. drain, source, gate, source
   b. gate, source, source, drain
   c. source, drain, gate, drain

   d. gate, drain, source, drain

10. In testing the ON-state, a ________ voltage is applied to the gate. The negative lead of the DMM is connected to the _______ and the positive lead to the ________.
    a. negative, source, drain
    b. positive, drain, source
    c. positive, source, drain
    d. negative, drain, source
11. GaN transistors are ________ electron mobility transistors. They are __________ devices, meaning that they are formed on a substrate that is made of __________ GaN.
    a. low, homoepitaxial, the same material as
    b. high, heteroepitaxial, the same material as
    c. low, homoepitaxial, different material than
    d. high, heteroepitaxial, different material than
12. Si and SiC *power* MOSFETs typically have a _________ channel structure where the ____________ are situated on the upper and lower surfaces of the chip, respectively.
    a. lateral, gate and source
    b. vertical, gate and source
    c. vertical, drain and source
    d. lateral, drain and source

Section 4: Device Driving Issues and Typical Circuitry Utilizing WBG Devices

4.1 Overview

Gate drivers and voltage isolation are critical elements in many power-conversion systems. As shown in the generic system block diagram of Figure 36, they appear between the controller output and the power device gate input(s).

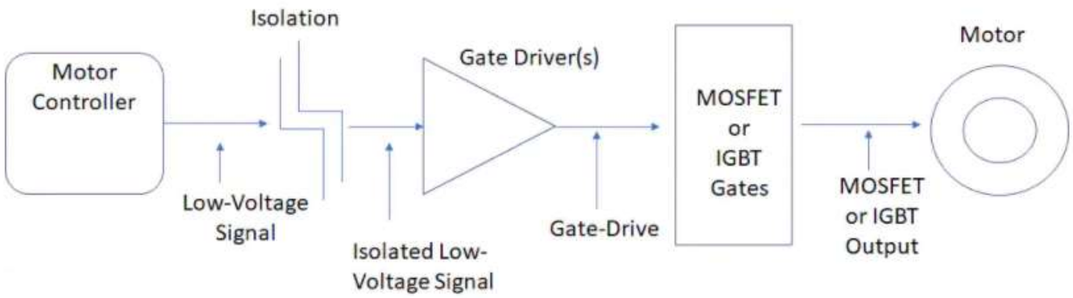


Figure 36: Overall system with voltage isolation and gate driver (source: Mouser Electronics).

This section begins with a review of various types of gate drivers and isolation methods. Gate drivers for WBG devices are next considered and then followed by examples of gate drivers for SiC and GaN power devices. Parasitic effects, printed circuit board (PCB) layout for gate drivers, the need for new PCB layouts for WBG devices, and the challenges encountered are then examined. This is followed by a review of thermal management in MOSFET designs and heatsinks for WBG devices. This section concludes with an efficient bidirectional power converter as an example of typical circuitry using WBG devices.

4.2 Introduction to Gate Drivers

Power MOSFETs, with their insulated gates, are voltage-driven devices. The gate of the MOSFET can be modeled as a simple capacitor (shown in Figure 37). Assuming the example of an enhancement-mode MOSFET, charging the gate by applying a voltage exceeding the threshold voltage[35] turns the MOSFET on. This allows the current to flow between the drain and source (the MOSFET conducts). Discharging the gate turns the MOSFET off, blocking a typically large voltage across the drain-to-source terminals. The MOSFET has a nonzero, finite switching time. During switching, the device may be in a high-current, high-voltage state, resulting in power dissipation in the form of heat. Consequently, transition from one state to another must be fast (on the order of a few nanoseconds) to minimize switching losses.

During MOSFET turn-on and turn-off, the value of the external gate resistor in the gate charge and discharge path affects the magnitude of the gate current pulses, their rise and fall times, and their switching losses[36]. Reducing the resistance value results in turn-on and turn-off times being shorter and

[35] The threshold voltage of a MOSFET is the minimum gate bias required for creating a conduction path between its source and drain.
[36] (a) Begue, Mateo. 2018. “External Gate Resistor Design Guide for Gate Drivers.” Texas Instruments Incorporated. Last modified March, 2020. https://www.ti.com/lit/an/slla385a/slla385a.pdf?ts=1612957460339.
(b) Infineon. 2015. “EiceDRIVER™: Gate Resistor for Power devices.” Infineon Technologies AG. https://www.infineon.com/dgdl/Infineon-EiceDRIVER-Gate_resistor_for_power_devices-AN-v01_00-EN.pdf?fileId=5546d462518ffd8501523ee694b74f18.

switching losses being reduced; however, this increases overshoot and ringing effects which can damage the device by puncturing the gate-to-source capacitance. Increasing resistance value increases the turn-on and turn-off times and subsequently increases switching losses. As a result, a tradeoff exists between gate resistance values and switching losses.

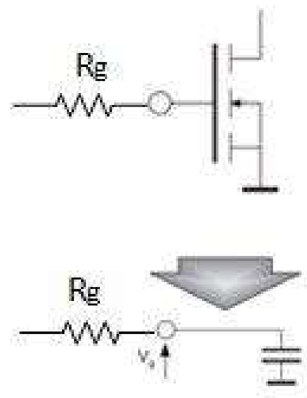


Figure 37: MOSFET gate as a simple capacitor (source: ST Microelectronics).

Figure 38 shows the ringing in the gate-source voltage waveforms for various values of gate resistance R_g. The blue waveform where R_g is ten ohms has the least overshoot. A range of R_g between seven and ten ohms is typical.

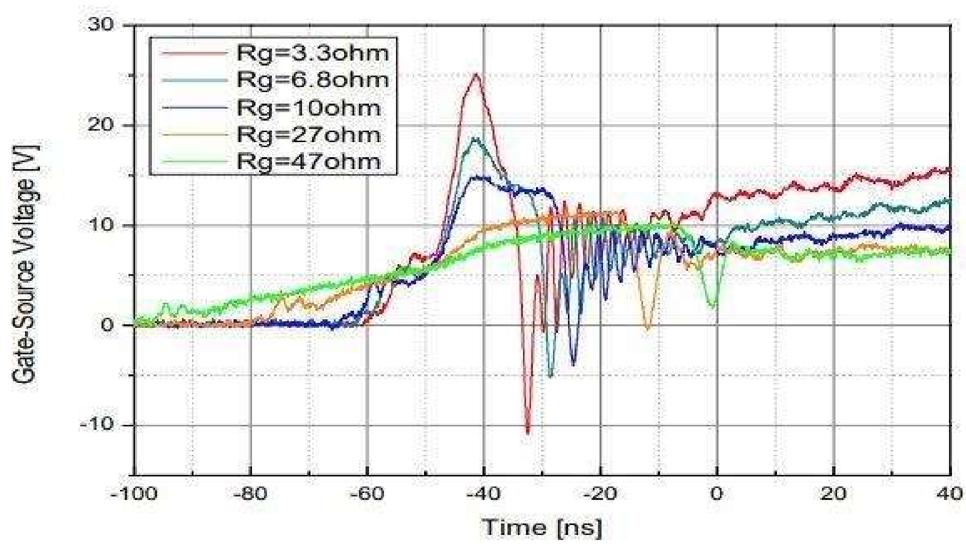


Figure 38: Gate-driver circuit responses as a function of gate resistance (source: ON Semiconductor[37]).

Power MOSFETs handle high current and voltage. Logic controllers such as CPU or MCU cannot provide sufficient gate voltage or current to switch the MOSFET. Because of the low-current capabilities of logic controllers, charging the gate capacitance would require an excessive amount of time. Consequently,

[37] ON Semiconductor. n.d. "Drive and Layout Requirements for Fast Switching High Voltage MOSFETs." Semiconductor Components Industries, LLC. Accessed March, 2021. https://www.onsemi.com/pub/Collateral/TND6242.PDF

MOSFETs require a gate driver as an interface to translate the on and off signals from the controller into power signals necessary to control the MOSFET. A gate driver is a power amplifier that accepts a low-power isolated voltage from the controller and produces a high-current drive input for the MOSFET gate. Gate-driver circuits are an integral part of power electronics systems.

4.2.1 Forms of Gate Drivers

MOSFET gate drivers are available in various forms[38]. Figure 39 depicts three (where the triangle symbolizes the driver). The first (a) is low-side, which is used for driving power MOSFETs that are ground-referenced and are typically used in DC/DC power supplies, inverters, motor, and solenoid applications. The second (b) is high-side, which is used for driving power MOSFETs that are floating and are typically used for protection, power distribution, relays, and motor applications. The last (c) is low-side or high-side, typically used in power distribution, protection and load switch applications.

Figure 40 depicts three synchronous MOFSET drivers: (a) half-bridge is typically used in DC/DC power supplies, inverters, and brushed and brushless DC (BLDC) motor applications, (b) full-bridge is typically used in DC/DC power supplies, inverters, and brushed motor applications, and (c) three-phase is typically used in BLDC motor applications.

Data sheets for low-side and half-bridge drivers are given in the Appendix.

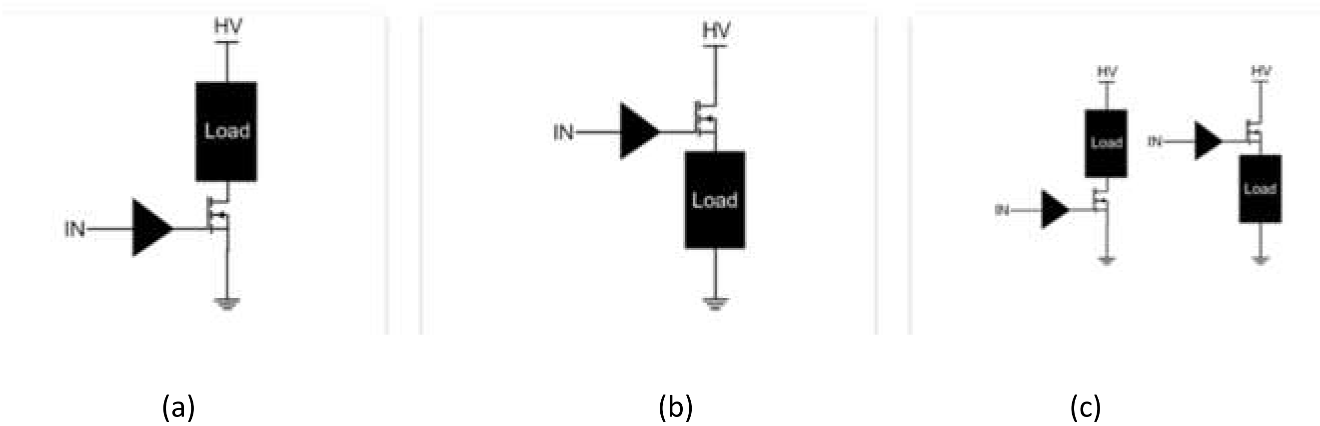
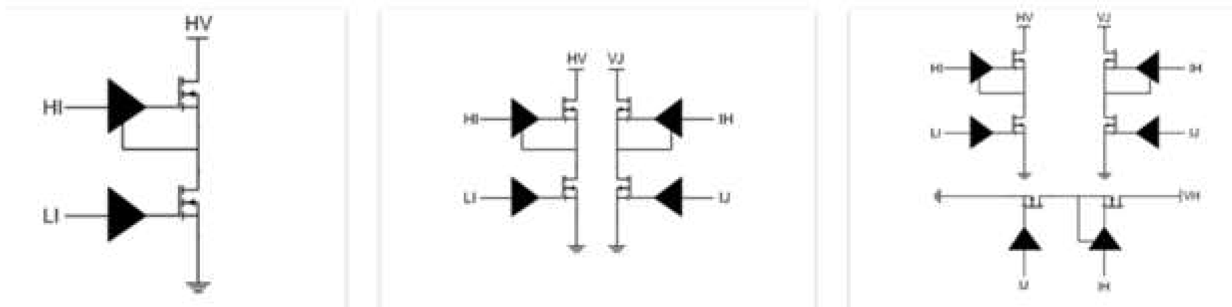


Figure 39: Gate drivers—(a) low-side, (b) high-side, and (c) low-side or high-side (source: Microchip.com).

[38] Microchip.com. n.d. "Comprehensive MOSFET Driver Configurations to Support Your Next Application Design." Microchip Technology Inc. Accessed February 25, 2021. https://www.microchip.com/en-us/products/power-management/mosfet-drivers.



(a) (b) (c)

Figure 40: Synchronous gate drivers—(a) half-bridge, (b) full-bridge, and (c) three-phase driver (source: Microchip.com).

4.3 Isolation

Isolation refers to the electrical separation between various subcircuits of a system such that there is no direct conduction path between them but signal and/or power can still pass between the subcircuits[39]. Consider an electromechanical relay analogy: The coil-drive circuit and the relay-contact circuit are completely isolated from one another, yet the 24 V DC signal of a few milliamperes of the coil-drive circuit controls the high-voltage, high-current AC signal of the relay-contact circuit. Regarding power electronic systems, isolation is provided for the protection of both the user and the electronics from faults on the high-voltage side.

There are three main forms of isolation[40]. Each uses a different means for reliably transferring signals between input and output without an actual electrical connection. We examine below the three common methods of isolation—optical, magnetic, and capacitive.

4.3.1 Optical Isolation

Optical isolation, shown in Figure 41, transmits a signal by driving an LED. The LED is located close to a phototransistor, which turns the light signal into a current.

[39] Schweber, Bill. “Motor Gate-Drive Isolation: Go Optocoupler, Transformer, or Other.” Mouser Electronics. Accessed March 3, 2021. https://www.mouser.com/applications/motor-gate-drive-isolation/.

[40] Texas Instruments. 2019. “IGBT & SiC Gate Driver Fundamentals: Enabling the world to do more with less power.” Texas Instruments Incorporated. https://www.ti.com/lit/eb/slyy169/slyy169.pdf?ts=1607633218299&ref_url=https%253A%252F%252Fwww.bing.com%252F.

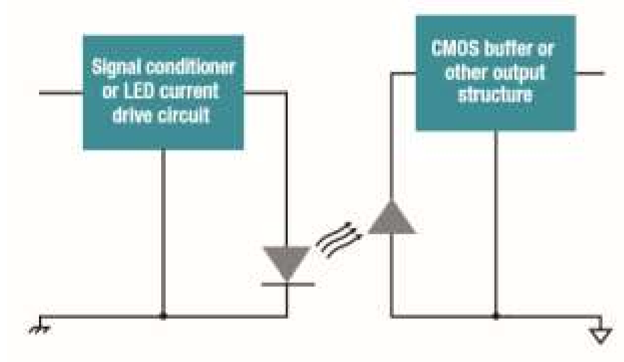


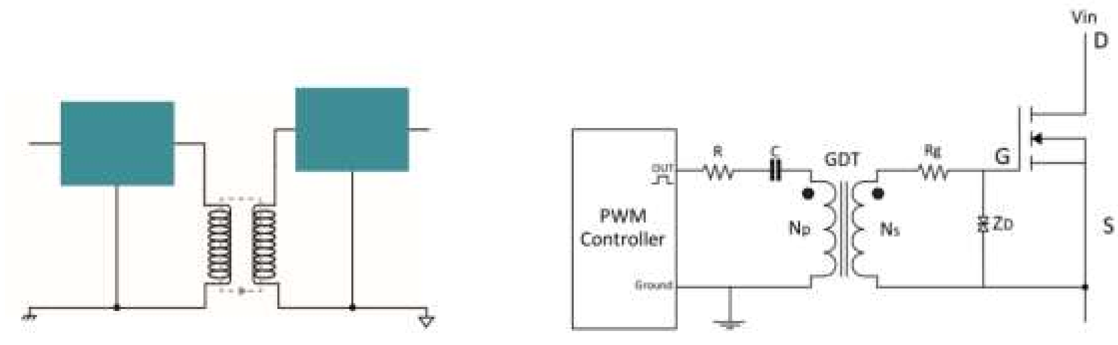
Figure 41: Opto-isolator (source: Texas Instruments).

An opto-isolator is used to block high voltages and transient surges so that a surge in one part of the system will not disrupt or destroy the other part; data is transmitted using light so there is no physical connection between the two sides, including grounds and data lines. This eliminates the problems of noise, voltage surges, and ground loops—an opto-isolator is immune to electrical and magnetic interference.

4.3.2 Magnetic Isolation

Magnetic (inductive) isolation, shown in Figure 42 (a), uses the windings of a transformer to transmit signals across an air gap through a magnetic field. The magnetic field at the primary coil induces a current through the secondary coil proportional to the original signal. In Figure 42 (b), showing a rudimentary gate driver, the transformer provides isolation so that if there is catastrophic failure on the high-voltage side, there is no electrical feedback path to destroy the low-voltage controller. Fully-integrated, reinforced isolation[41] solutions are available in a small package. For example, the Texas Instruments UCC12050 DC-DC converter (data sheet available in appendix) integrates the controller, drivers, transistors, and magnetics into a single package.

[41] Hadden, Will. 2020. "Isolation 101: How to find the right isolation solution for your application." Texas Instruments Incorporated. https://e2e.ti.com/blogs_/b/powerhouse/archive/2020/02/11/isolation-101-how-to-find-the-right-isolation-solution-for-your-application#:~:text=Many%20different%20levels%20of%20isolation%20exist,%20including%20functional,,voltage.%20It%20does%20not%20protect%20against%20electrical%20shock.



(a) (b)

Figure 42: Magnetic isolation (sources: Texas Instruments, Talema Group).

4.3.3 Capacitive Isolation

Capacitive isolation, shown in Figure 43, uses an electric field to transmit signals between two conductive plates. Texas Instruments uses a manufacturing process in which capacitive isolators can be integrated on the same chip as other circuitry. This process offers reliability, shock protection, and reinforced isolation equivalent to two levels of basic isolation in a single package.

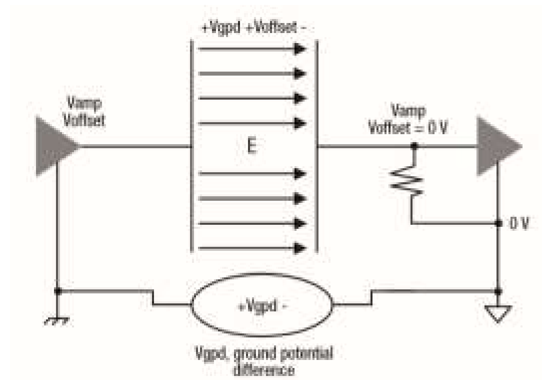


Figure 43: Capacitive isolation (source: Texas Instruments).

4.3.4 Choice of Isolation Method

Magnetic isolation may be the preferred option in high-power applications. However, it can be sensitive to electromagnetic interference (EMI). Opto-couplers do not suffer from EMI and are suitable in applications with high electrical noise. However, they can degrade as they age and may suffer from temperature drift and varying current gain issues. Capacitive isolators are not susceptible to EMI, can maintain high data rates, and keep power consumption low. Because of their high noise immunity and high data rates, capacitive isolation is the preferred choice for the Texas Instruments UCC217xx family of isolated gate drivers for SiC MOSFETs[42].

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[42] Sridhar, Nagarajan. 2019. "Silicon carbide gate drivers – a disruptive technology in power electronics." Texas Instruments Incorporated.
https://www.ti.com/lit/wp/slyy139a/slyy139a.pdf?ts=1609869140505&ref_url=https%253A%252F%252Fwww.bing.com%252F.

4.3.5 Traction Inverter Isolation Example

The general block diagram of a traction inverter is shown in Figure 44. The traction inverter converts DC power from an on-board high-voltage battery into AC power to drive the main motor or motors of an electric vehicle. Traction inverters also perform functions such as voltage boosting, switch protection, and regenerative braking. All these functions require galvanic isolation to separate control systems from high-voltage domains. This includes the low-voltage communication, control, and main power supply circuitry on the primary side. On the secondary side are the high-voltage circuits, including the motor drive, power stage, and auxiliary circuits. The controller uses feedback signals from the high-voltage side and is susceptible to high voltage and consequently damage if no isolation barrier is present. The high voltages and currents in many power designs are inherently dangerous. Safety standards require the isolation of potentially lethal voltages and currents from possible human contact.

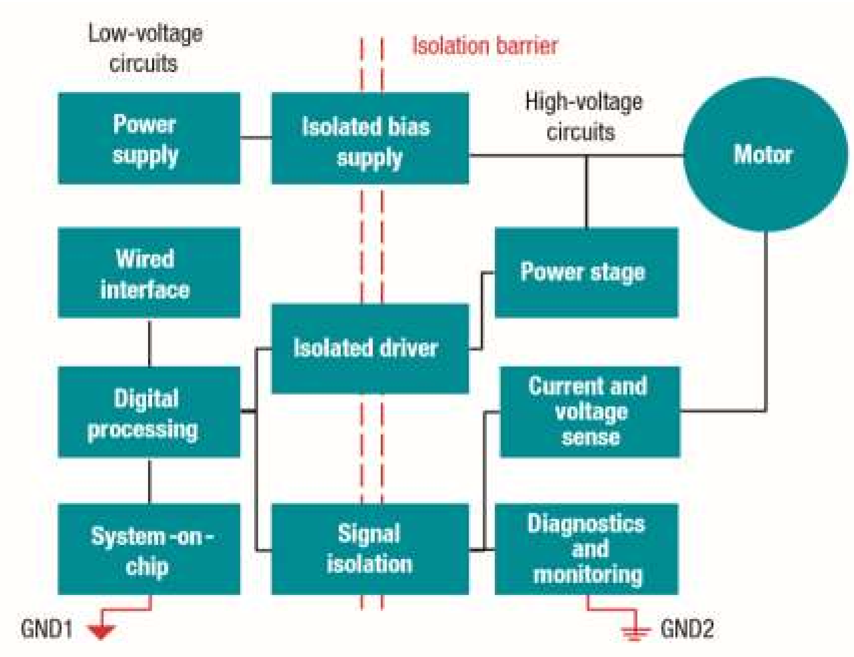

Figure 44: Traction inverter block diagram (source: Texas Instruments).

Figure 45 shows the Texas Instruments reference design[43] TIDA00366 for a reinforced isolation 3-phase inverter with current, voltage, and temperature protection**.** The design includes capacitive-isolated gate driver UCC21530 (Figure 46), capacitive-isolated amplifiers AMC1301 (Figure 47) and AMC1311, and MCU TMS320F28027. The inverter is designed to have protection against overload, short-circuit, ground fault, DC bus undervoltage and overvoltage, and IGBT-module overtemperature.

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[43] A reference design refers to a publicly-available hardware design that is intended for others to copy. It contains the essential elements of the system; third parties may enhance or modify the design as required. Every reference design has been built and tested and comes with comprehensive standardized documentation including a data sheet with detailed design notes, verification test results, schematics, bill of materials (BOM), and PCB artwork. The main purpose of reference design is to support companies in development of next-generation products using latest technologies. Reference design packages enable a fast-track to the market and help cut costs and reduce risks in the customer's integration project.

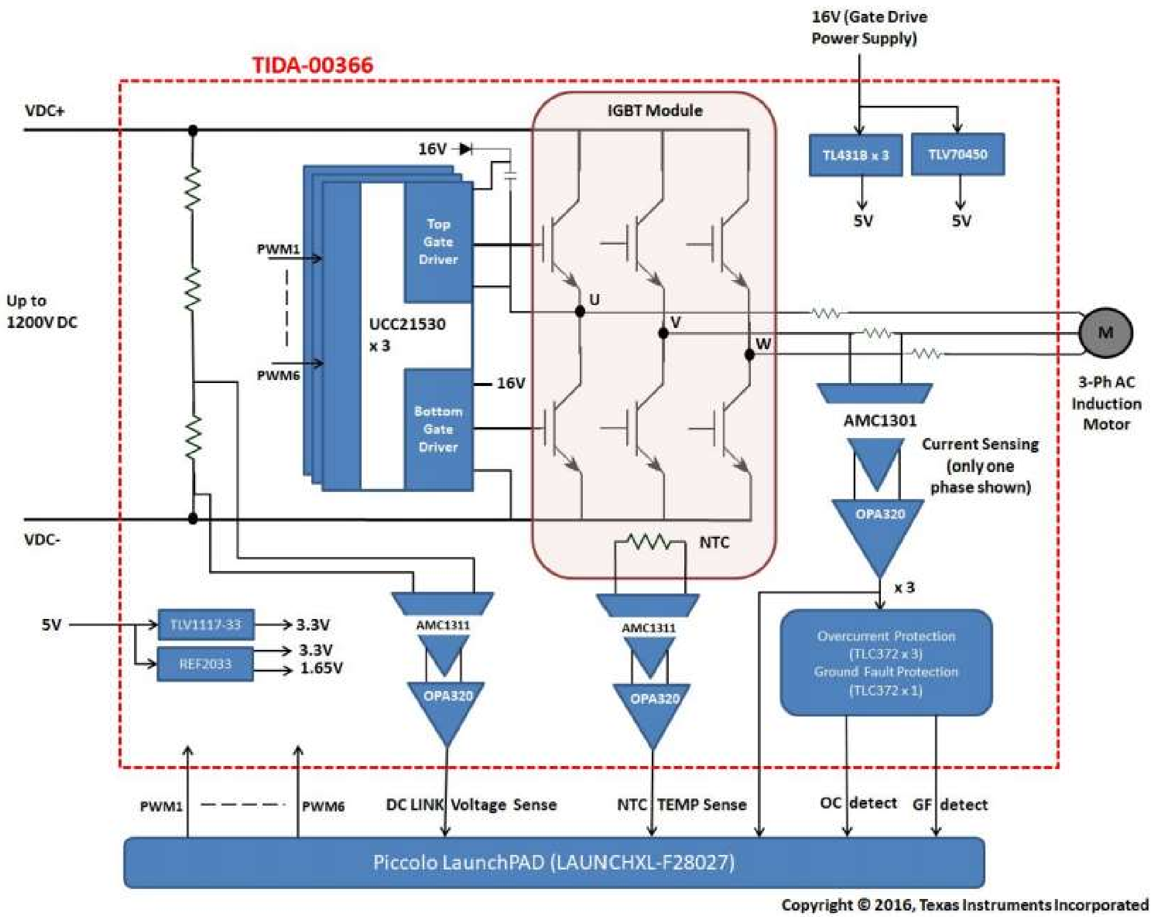

Figure 45: TI reference design TIDA00366 three-phase inverter (source: Texas Instruments).

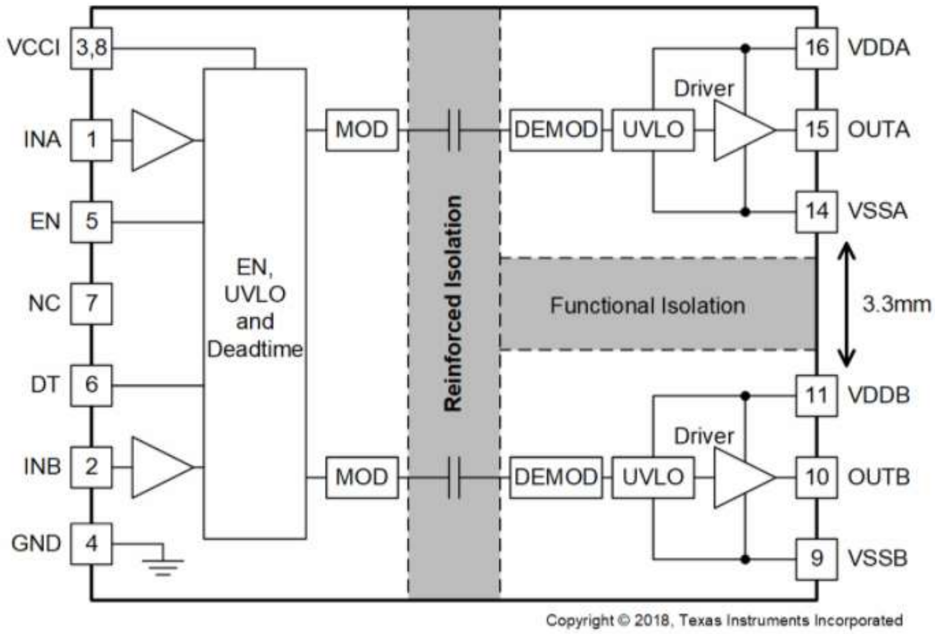

Figure 46: Gate driver UCC21530 for three-phase inverter.

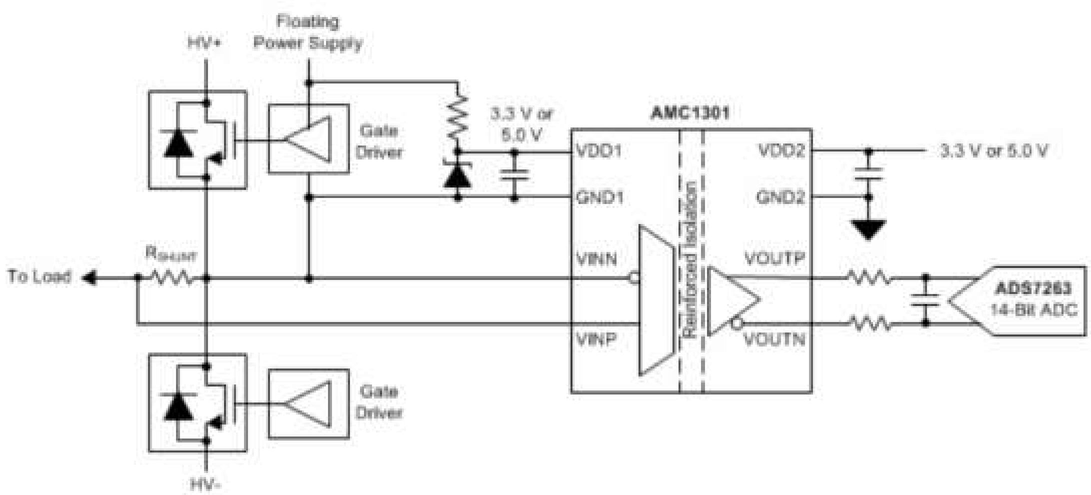

Figure 47: Isolation amplifier AMC1301 for three-phase inverter.

4.4 Gate Drivers for WBG MOSFETs

As shown in Figure 48, in transitioning from silicon to WBG technology and because of the significant difference in characteristics between Si and WBG semiconductors, design issues such as gate drivers, thermal considerations, packaging, magnetics, parasitic effects, as well as others must be reevaluated.

Gate drivers for WBG devices have different specifications from those of Si-based devices. The gate drivers should be able to operate at higher switching frequencies and provide precise voltages with sufficient drive capability to achieve fast turn-on and turn-off speeds with adequate isolation between the high- and low-voltage components[44]. These points make the gate-drive circuitry much more critical in WBG power devices. Without the proper gate drivers, WBG MOSFETs will not perform at the expected high switching frequencies and power levels.

Figure 48: Issues in transitioning to WBG devices.

4.4.1 Examples of Gate Drivers for WBG Devices

Although gate drivers are available in standalone form, the modular or integrated form is more common. Figure 49 shows the Texas Instruments UCC27524A[45] (datasheet in Appendix). UCC27524A is a dual-channel, low-side, high-speed, integrated gate driver that interfaces between a low-voltage, low-current pulse-width modulated (PWM[46]) output from a microcontroller and power transistors. It is capable of driving MOSFET and IGBT power switches and it ensures efficient and robust operation in high-frequency switching power circuits. It has several applications, including switched-mode power supplies, DC-to-DC converters, motor control, and photovoltaic inverters—all of which are increasingly adopting WBG devices such as GaN and SiC.

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[44] Bindra, Ashok. 2019. "Recent Advances in Gate Driver Integrated Circuits for Wide Bandgap FETs." September 2019, *IEEE Power Electronics Magazine* 6, no. 3 (September).
[45] Pickering, Paul. 2016. "Gate Drivers Help Power-System Designers Meet Requirements." ElectronicDesign. https://www.electronicdesign.com/power-management/article/21802219/gate-drivers-help-powersystem-designers-meet-requirements.
[46] PWM is a means for creating an analog-like signal by applying voltage in pulses or short bursts. PWM is one of the primary means by which MCUs drive analog devices like variable-speed motors, dimmable lights, actuators, and speakers.

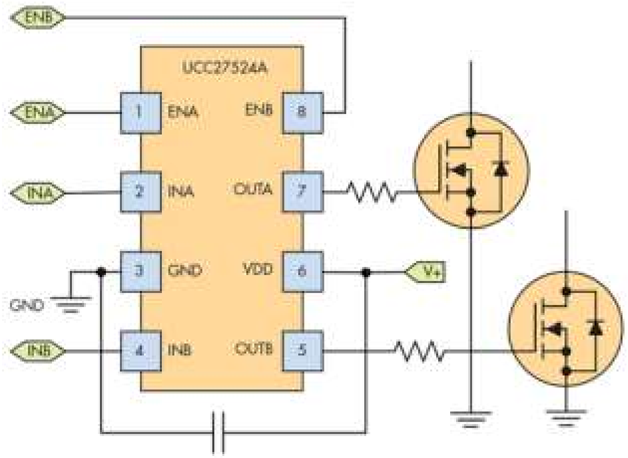

Figure 49: UCC27524A dual-channel gate driver (source: Texas Instruments).

The UCC21520 (datasheet in Appendix) block diagram shown in Figure 50 presents an isolated dual-channel gate driver. In this figure you can see the dual-gate driver driving a pair of power MOSFETs on the right and on the left you can see a microcontroller providing control signals to the driver. The driver is composed of input and protection circuitry, the modulation/demodulation blocks, and two different isolation barriers—reinforced isolation which provides a safety barrier against high voltage and functional isolation which is essential for correct system operation. Capacitive isolation is employed in each case. High-voltage silicon dioxide capacitors act as the isolation components. The UCC21520 is designed to drive power MOSFETs, IGBTs, and SiC MOSFETs. It can be configured as two low-side drivers, two high-side drivers, or a half-bridge driver. The microcontroller may, for example, be the MSP430G22x0 from TI (datasheet in Appendix).

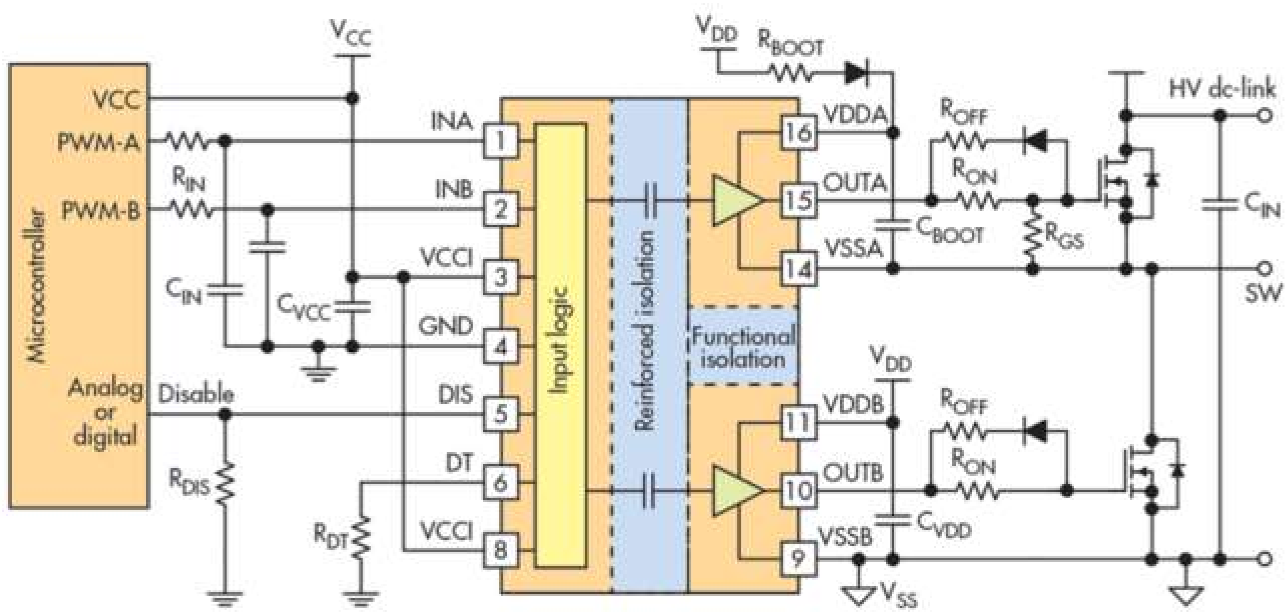

Figure 50: UCC21520 isolated dual-channel gate driver (source: Texas Instruments).

While the UCC 21520 is designed for driving SiC MOSFETs (as well as Si MOSFETs and IGBTs), the Texas Instruments LMG1205 driver (datasheet in Appendix), shown in Figure 51, is designed to drive GaN FETs. They can drive both the high-side and the low-side enhancement-mode GaN FETs in a synchronous-buck, boost, and half-bridge configuration.

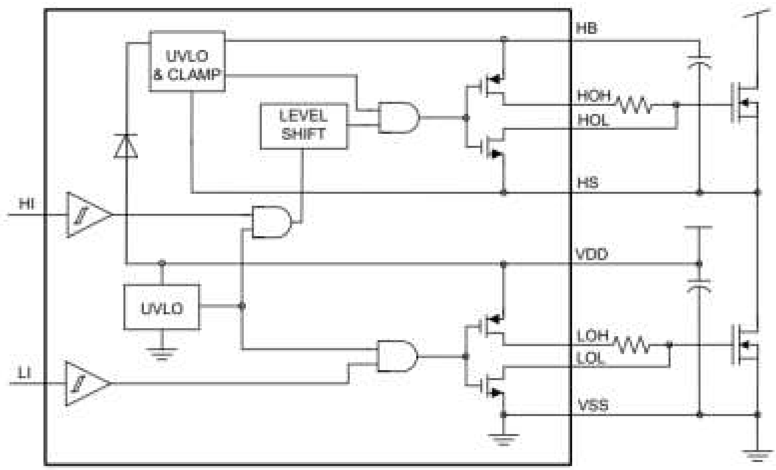

Figure 51: LMG 1205 GaN driver with half-bridge (source: Texas Instruments).

4.4.2 Parasitic Effects

One of the major benefits of WBG materials over Si is faster switching; this leads to higher power-conversion efficiency and smaller form factor[47]. Other benefits include lower ON resistance, improved thermal handling and, for SiC, higher voltage ratings.

Regardless of these benefits, significant barriers remain to the widespread adoption of WBG devices into mainstream electronics—including cost reduction, proving long-term reliability, and device and printed circuit board[48] (PCB) design for the minimization of parasitic and thermal effects. In general, WBG devices cannot be swapped for Si devices in a circuit due to the dramatically different properties of these devices. Novel PCB designs[49] are required that effectively exploit the properties of WBG devices.

The minimization of inductive and capacitive parasitic effects in any design benefits the overall performance and stability of the design[50] (see footnote[51] for an informative video from TI on PCB layout

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[47] Form factor is a hardware design aspect that defines and prescribes the size, shape, and other physical specifications of electronic components.

[48] Printed circuit boards (PCBs) are the most common method of assembling modern electronic circuits. They are comprised of a sandwich-like arrangement of one or more insulating layers and one or more copper layers which contain the signal traces, powers, and grounds.

[49] (a) Wikipedia. n.d. “Printed Circuit Board.” Accessed March 3, 2021. https://en.wikipedia.org/wiki/Printed_circuit_board.
(b) Keim, Robert. 2020. "What is a Printed Circuit Board (PDB)?" https://www.allaboutcircuits.com/technical-articles/what-is-a-printed-circuit-board-pcb/.

[50] Genereaux, Ben. 2021. “PCB layout guidelines to optimize power supply performance.” Texas Instruments Incorporated. Video. Accessed April, 2021. https://training.ti.com/pcb-layout-guidelines-optimize-power-supply-performance.

[51] Genereaux, Ben. “PCB layout guidelines to optimize power supply performance.” Texas Instruments Incorporated. Video. Accessed April, 2021. https://training.ti.com/pcb-layout-guidelines-optimize-power-supply-performance.

guidelines). With WBG devices, this is even more important. The unique combination of high voltage, high current, and increased switching speed of WBG devices requires careful consideration of the PCB layout to reduce the effects of parasitics. The level of parasitics that needs to be considered increases by an order of magnitude in comparison to that of Si devices. The impact of parasitic inductance and capacitance on WBG-device switching behavior consequently increases significantly. Failure to sufficiently minimize the effect of parasitics can lead to instability and oscillation in the switching waveform and subsequent degradation of performance in WBG power devices. Accounting for parasitic effects is therefore critical in the design and layout of PCBs that utilize WBG devices.

For high switching-speed devices such as SiC and GaN, PCB layout must be carefully arranged. PCB tracks introduce parasitic inductance and capacitance into the circuit that are often overlooked where Si-based devices are involved. A PCB is composed of parallel conducting elements that are separated by an insulator, basically forming parasitic capacitance and typically on the order of picofarads. Similarly, traces on a PCB will usually form complete loops, creating parasitic inductance that are generally on the order of nanohenries[52].

In addition to taking steps to minimize parasitic inductance and capacitance in PCBs employing WBG devices, properly-designed thermal management is also required. The higher temperature limits of wide-bandgap devices (relative to Si) must be considered when designing a PCB.

4.4.3 Minimizing PCB Parasitic Inductance in Using the LMG3410x[53] Family of GaN FETs

The design rules that help improve performance for one parameter may cause another parameter to become worse, so it is important to understand the tradeoffs in creating an optimized PCB layout.

The induced voltage across a parasitic inductor is given by—

$$V = L\frac{\Delta i}{\Delta t}$$

where

V is the induced voltage

i is loop current

L is parasitic inductance

$\frac{\Delta i}{\Delta t}$ is the current slew rate (rate of change of current with time)

A high slew rate can result in a large, induced voltage across a PCB parasitic inductance. As high slew rates are desired to minimize switching transitions and reduce losses, to minimize the induced voltage across the inductor it is important to keep parasitic inductance L as small as possible (so that the product $L\frac{\Delta i}{\Delta t}$ is minimized).

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52 Cadence PCB Solutions. n.d. “How Parasitic Capacitance and Inductance Affect Your Signals.” Cadence Design Systems, Inc. Accessed April, 2021. https://resources.pcb.cadence.com/blog/2019-how-parasitic-capacitance-and-inductance-affect-your-signals.

53 Eric, and Jie Mao. 2016. “High Voltage Half Bridge Design Guide for LMG3410x Family of Integrated GaN FETs.” Texas Instruments Incorporated. Last modified November, 2018. https://www.ti.com/lit/an/snoa946a/snoa946a.pdf?ts=1618244539326&ref_url=https%253A%252F%252Fwww.bing.com%252F.

Consider the parasitic inductance of a current loop for a half-bridge[54] (DC-DC converter) configuration. A portion of the half-bridge circuit, consisting of a bypass capacitor and two LMG3410 GaN FETs, is shown in Figure 52. Figure 53 gives a side view of the PCB layout of a half-bridge circuit.

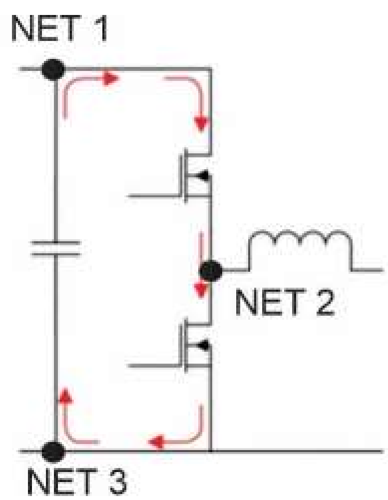

Figure 52: Half-bridge current loop (source: Texas Instruments).

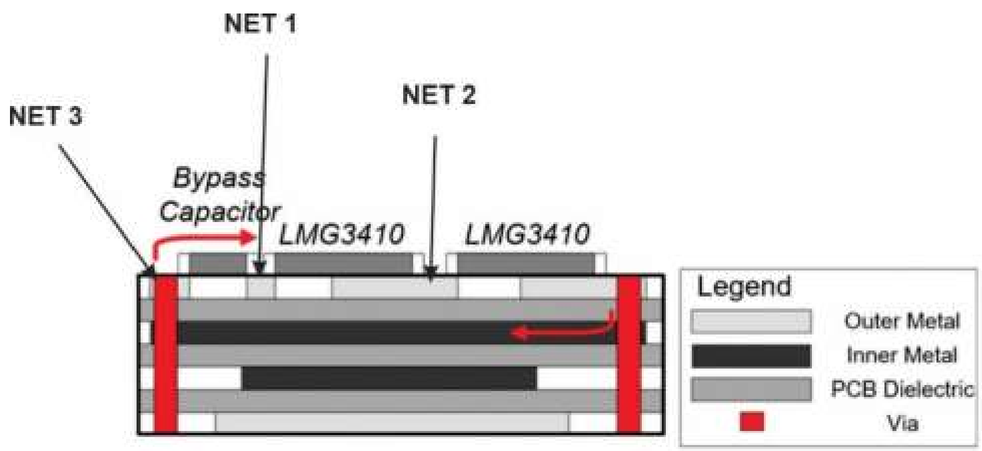

Figure 53: Multilayer half-bridge cross-section (source: Texas Instruments).

The current loop (denoted by the red arrow in each figure) generates a parasitic inductance that can be approximated by—

$$L \approx \frac{\mu_0 \mu_r h l}{W}$$

where

L is the parasitic inductance

[54] The half-bridge, also referred to as the bidirectional switching power pole (BSPP), can be used as a basic building module for different power electronics converters.

μ_0 is the permeability of free air

μ_r is relative permeability

h is the space between conductors (or PCB traces[55])

l is the length of the conductor (or PCB trace)

W is the width of the conductor (or PCB trace)

Parasitic inductance L can be minimized by reducing h and l and increasing W. However, increasing W also increases parasitic capacitance so that a tradeoff is necessary. The conductors on the PCB are labeled in the legend of Figure 54 as outer and inner metal traces. Assuming fixed values of l and W, the space h between traces (the thickness of the dielectric) is significantly reduced by placing the bypass capacitor and two FETs on the top layer of the PCB with the return path on the copper layer just below this layer.

Parasitic inductances stem from long trace lengths; the longer the trace, the greater the parasitic inductance[56]. The PCB trace from net 2 to the inductor should be as short as possible. The inductor must be placed as close as possible to the switch node, otherwise the PCB trace parasitic inductance becomes part of the inductor on net 2. The layout shown leads to improved performance by minimizing parasitic inductance which, in turn, minimizes voltage overshoots[57].

4.4.4 Parasitic Capacitance

4.4.4.1 PCB Layout

PCBs on which GaN is mounted are designed as multilayer boards (Figure 53). In such designs, copper overlaps between key nets[58] must be minimized to minimize parasitic capacitance. A key net to consider is the switch node. Figure 54 depicts a top view of the PCB layout. Any parasitic capacitance between the switch node and ground or input voltage results in additional energy dissipation through the GaN FETs during turn-on, increasing switching losses.

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[55] Trace: A line of copper that makes an electrical connection between two or more points on a PCB.
[56] Consider an analogy: Just as PCB trace lengths are short to minimize parasitic inductance, in Tesla vehicles, the inverter is placed in very close proximity to the induction motor (located at the drive wheel) to minimize parasitic inductances.
[57] Reusch, David, and Johan Strydom. 2014. "Understanding the Effect of PCB Layout on Circuit Performance in a High-Frequency Gallium-Nitride-Based Point of Load Converter." *IEEE Transactions on Power Electronics* 29, no. 4 (April). https://ieeexplore.ieee.org/document/6531683.
[58] A net is a connection between two or more components on a PCB.

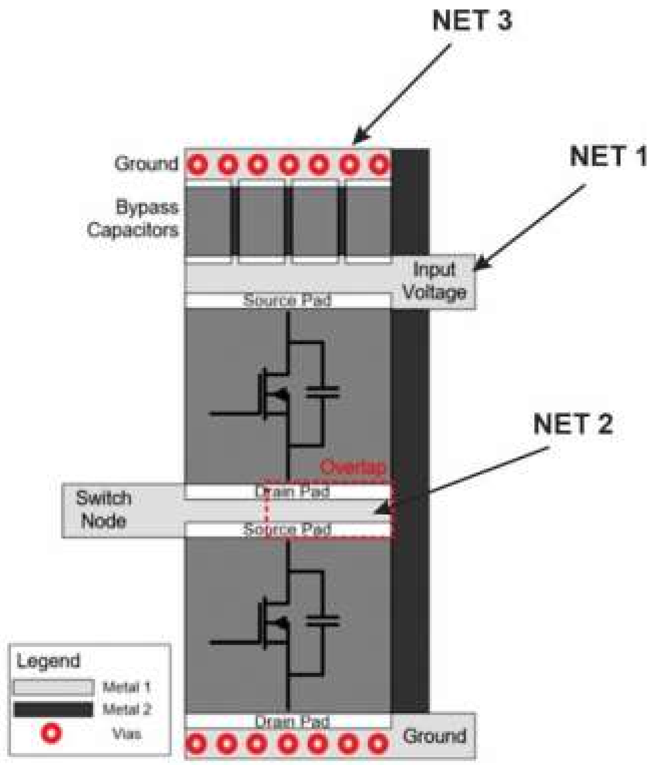

Figure 54: PCB parasitic capacitance.

PCB parasitic capacitance can be approximated by—

$$C \approx \frac{0.0886\varepsilon_r A}{h}$$

C is the parasitic capacitance in pF

ε_r is the relative permittivity (4.5 for FR-4)

h is the distance between copper layers in cm

A is the overlapping area in cm^2

The parasitic capacitance can be minimized by minimizing copper overlap area A and increasing the distance between copper layers h.

The PCB designer must be aware of the tradeoff between the minimization of inductive and capacitive parasitics because layouts that minimize parasitic inductance with large ground-return current-loop widths can result in large parasitic switch-node capacitance if not properly accounted for.

4.4.4.2 Parasitic Capacitances Created with the Introduction of a Heatsink

A heatsink provides a source of parasitic capacitance. Consider the half-bridge configuration in Figure 55. Using a single heatsink to cool two LMG3410x family devices requires an insulating thermal interface material (TIM) between the FETs and the heatsink. The LMG3410 family of devices dissipates heat through the die-attached pad[59] which is also electrically connected to the source in a half-bridge

[59] Pads: Small areas of copper on a PCB used for connecting component pins.

configuration. This results in the heatsink being coupled to the switch node and ground with parasitic capacitance (shown dashed in the figure).

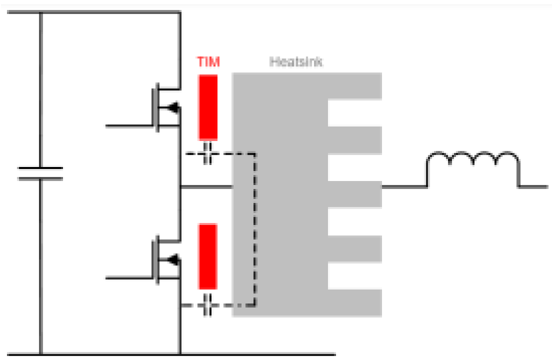

Figure 55: Parasitic capacitance arising from the floating heatsink connection in a half-bridge configuration.

4.4.4.3 PCB Design Guidelines

When designing gate-driver PCBs, the following circuit layout guidelines are recommended[60].

To minimize parasitic capacitance, make the critical traces as narrow as the PCB process can handle, keep a good distance from nearby traces, minimize overlap between traces, and have no other traces or ground plane underneath the trace.

1. To minimize parasitic inductance, make gate-drive traces as wide and short in length as possible.
2. For gate drivers, route the high-side gate and the switch-node trace as close as possible to minimize inductance, loop area, and the possibility of noise caused by dv/dt switching.
3. Do NOT use right-angle traces.
4. Route traces in parallel pairs when routing around an object.
5. Have separate grounding for the analog and digital parts of the circuit.
6. Locate the driver device as close as possible to the power device to minimize the length of high-current traces between the output pins and the gate of the power device.
7. Locate the VDD (positive supply voltage) bypass capacitors between VDD and ground as close as possible to the driver with minimal trace length to improve the noise filtering. These capacitors support high-peak current being drawn from VDD during turn-on of a power MOSFET. The use of low-inductance surface-mounted-device (SMD) components such as chip resistors and chip capacitors are highly recommended.
8. The turn-on and turn-off current loop paths (driver device, power MOSFET, and VDD bypass capacitor) must be minimized as much as possible to keep the stray inductance to a minimum. High di/dt is established in these loops during turn-on and turn-off transients which, in turn,

[60] (a) Texas Instruments. 2013. “UCC27524A Dual 5-A, High-Speed, Low-Side Gate Driver with Negative Input Voltage Capability.” Texas Instruments Incorporated. Last modified October. 2014. https://www.ti.com/lit/ds/symlink/ucc27524a.pdf.
(b) Texas Instruments. 2018. “Best Practices for Board Layout of Motor Drivers.” Texas Instruments Incorporated. Last modified January, 2019. https://www.ti.com/lit/an/slva959a/slva959a.pdf?ts=1598023913297&ref_url=https://www.ti.com/motor-drivers/brushed-dc-bdc-drivers/technical-documents.html.
(c) Armet,Pablo. ”Design 3: PCB Layout Guidelines for Motor Drivers.” Texas Instruments Incorporated. https://training.ti.com/sites/default/files/docs/motor_drivers_pcb_layout_precision_labs.pdf.

induces significant voltage transients on the output pin of the driver device and the gate of the power MOSFET.

9. Wherever possible, parallel the source and return traces to take advantage of flux cancellation.
10. Separate power traces and signal traces, such as output and input signals.
11. Star-point grounding is a good way to minimize noise coupling from one current loop to another. The GND of the driver is connected to the other circuit nodes such as the source of the power MOSFET and the ground of PWM controller at one, single point. The connected paths must be as short as possible to reduce inductance and be as wide as possible to reduce resistance.
12. Use a ground plane to provide noise shielding. Fast rise and fall times at output may corrupt the input signals during transition. The ground plane must not be a conduction path for any current loop. Instead, the ground plane must be connected to the star point with a single trace to establish the ground potential. In addition to noise shielding, the ground plane can help in power dissipation as well.

4.5 Thermal Management

4.5.1 HEMT

The power dissipated by any power device needs to be managed and removed. With each switching action of a MOSFET, its junction temperature will increase. Consider the surface-mount GaN HEMT of Figure 56, depicting top (left) and bottom (right) views of the transistor. The pad to be connected to a heatsink is the large light area. Removing heat from the junction is challenging because the junction is essentially buried inside the device. Figure 57 models the path from the junction to the external ambient atmosphere for the surface-mount package. Thermal resistance is shown for each segment. The objective is to achieve low total thermal resistance. The vias, depicted as vertical copper conductors in the figure, provide a low-resistance thermal path through the multilayer PCB to the heatsink.

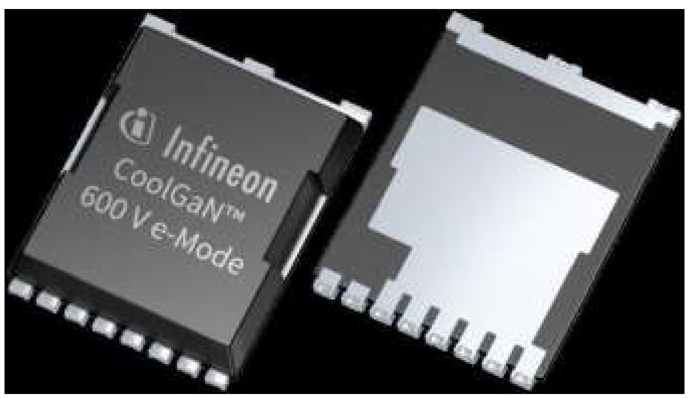

Figure 56: Surface mount GaN HEMT.

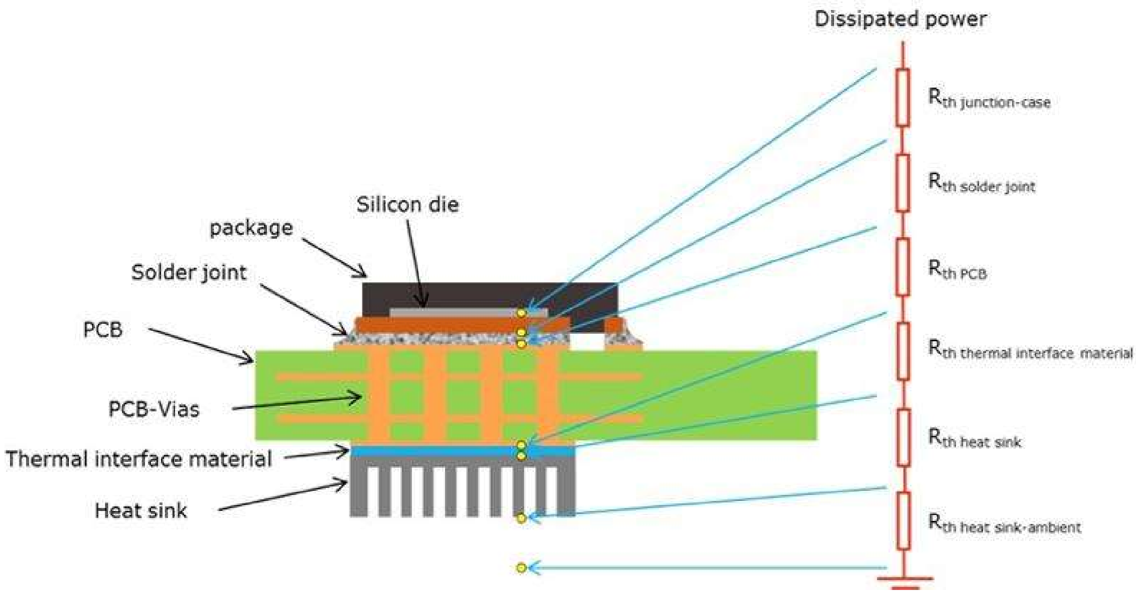

Figure 57: GaN HEMT mounted on PCB with vias conducting heat to heatsink below.

4.5.2 Heatsink Attachment Methods

Consider four possible heatsink-attachment methods[61] for the ON Semiconductor Motion SPM ® 5 Module—an inverter for small power motors (the module integrates the optimized gate drive of the built-in MOSFETs to minimize EMI and power losses):

1. Attachment using a thermal adhesive material, Figure 58. The thermal adhesive makes heat transfer easier between the module and the heatsink used. This method would not be applied where there is severe vibration because the heatsink may become detached.

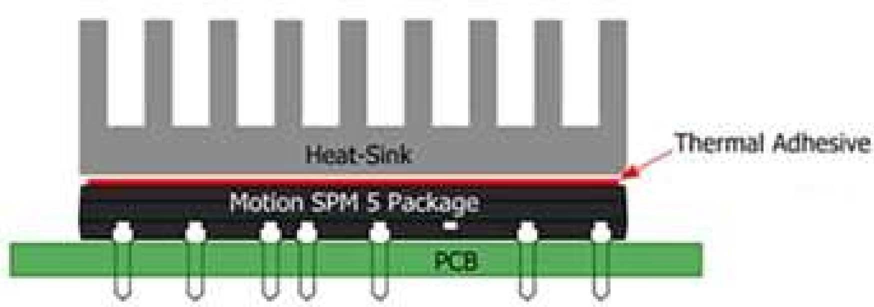

Figure 58: Heatsink with thermal adhesive.

2. Direct assembly using screws, Figure 59. This method is stable against external vibration, which may be common in motor applications. Care must be taken to avoid bending the PCB when assembling the heatsink to the package; excessive bolt-tightening can cause solder to crack around mounting holes.

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[61] Han, Steve. 2014. "How to Attach a Heatsink on a SPM-5 Package." Digi-Key Electronics. https://www.digikey.com/en/articles/how-to-attach-a-heatsink-on-a-spm-5-package.

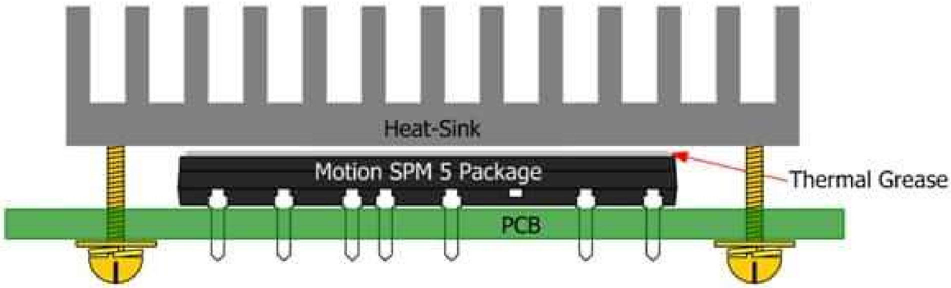

Figure 59: Heatsink with screw attachment.

3. Direct assembly using screws, Figure 60. This is an improved version of the heatsink of (b). It has legs for support and the gap between the heatsink and the SPM 5 package should have a thermal conductivity pad or be filled with thermal grease.

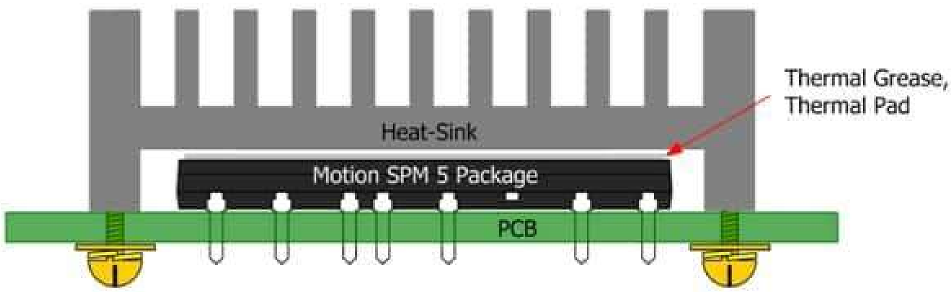

Figure 60: Improved version of a heatsink with screw attachment.

4. Heatsink clip. The SPM 5 package has a trench at the bottom center of the package. The clip is designed so that the package can be assembled to the heatsink by this clip (Figure 61). In this method, no contact is made with screws.

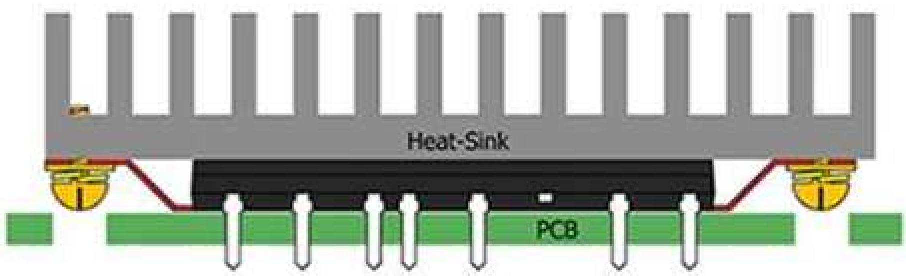

Figure 61: Heatsink with clip attachment.

Before applying a particular method in real production, the operating conditions must be considered. The effectiveness and reliability of the attachment method should first be verified (for example, through vibration testing).

4.5.3 Cooling Methods for PCBs[62] Using WBG Devices

WBG devices allow for operation at higher temperatures compared with Si-based devices. Appropriate heatsinks must be designed to maintain PCB-mounted components at reasonable temperatures. The higher heat loads and smaller packaging both mean that conventional (passive) heatsinks may not be sufficient.

Liquid cooling provides an alternative for increasing the rate of heat transfer to the atmosphere. One approach comes from Advanced Thermal Solutions (ATS). Their cold plate, shown in Figure 62, transfers heat from the device to a liquid that flows to a remote heat exchanger and dissipates into either the ambient or to another liquid in a secondary cooling system.

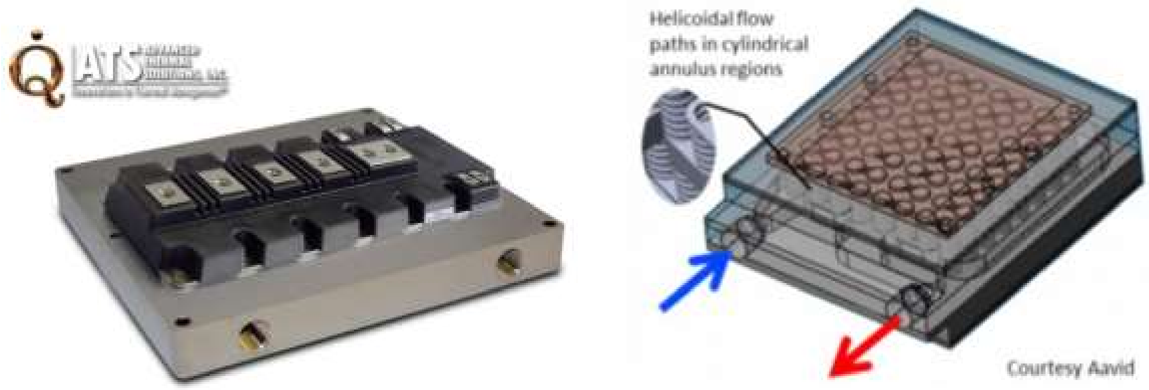

Figure 62: ATS cold plates providing uniform surface temperature.

4.5.4 Thermal Management in Automotive Systems Employing WBG Devices

In an EV, the inverter provides AC power to the traction motor. Inverter systems consist of several components in addition to power devices. Thermal management is needed at both the device and system level. WBG devices have allowed automotive suppliers to achieve significant reductions in inverter size and weight for greater efficiency. New thermal management techniques have been developed in order deal with the increased operating temperatures of WBG devices. For example, Hitachi Automotive Systems has developed a double-sided cooling approach[63] that uses liquid cooling for their high-voltage EV inverter (Figure 63). Direct double-sided cooling greatly improves the thermal conductance, enabling higher current loading and power density. The third-generation model features a power density of 35 kW/L, 5.6 times that of first-generation versions. It operates at junction temperatures of 175-200 °C.

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[62] Slovick, Murray. 2019. "Using Wide Bandgap Materials in Power Electronics Presents a New Set of Thermal Challenges." Lectrix. https://www.electronics-cooling.com/2019/02/using-wide-bandgap-materials-in-power-electronics-presents-a-new-set-of-thermal-challenges/.

[63] Paul Shepard, Paul. 2019. "Hitachi in Mass Production of High-Voltage and High-Output EV Inverter." EE Tech Media, LLC. https://eepower.com/news/hitachi-in-mass-production-of-high-voltage-and-high-output-ev-inverter/.

Figure 63: Hitachi double-sided cooling power module (source: Hitachi).

4.6 Example of Circuitry Using WBG Devices: Efficient Bidirectional Power Converter

The Texas Instruments TIDA-010054 bidirectional dual-active-bridge DC-DC converter[64] is presented. It is composed of two modular PCBs—a gate-driver board and dual H-bridge board—both utilizing SiC MOSFETs. In such a power conversion system, power can flow in either direction. It has a variety of applications such as:

- Solar cell installations: Excess DC solar power is fed into the AC grid during the day, and when the local storage batteries are depleted, they can be charged from the grid through a bidirectional converter/inverter.
- Electric vehicles (EVs): Bidirectional DC-DC converters are used to drop a high-traction battery voltage (approximately 400 V) down to 12 V to drive auxiliary equipment, and, if the voltage of the traction battery falls too low, it can convert 12 V back to 400 V (Figure 64). Bidirectional DC-DC converters can also be used in EV-charging stations (Figure 65) to provide a fast, efficient recharge. We consider the bidirectional DC-DC converter for use in EV charging stations.

[64] Texas Instruments. 2019. "Bi-directional, dual active bridge reference design for level 3 electric vehicle charging stations." Texas Instruments Incorporated, https://www.ti.com/tool/TIDA-010054.

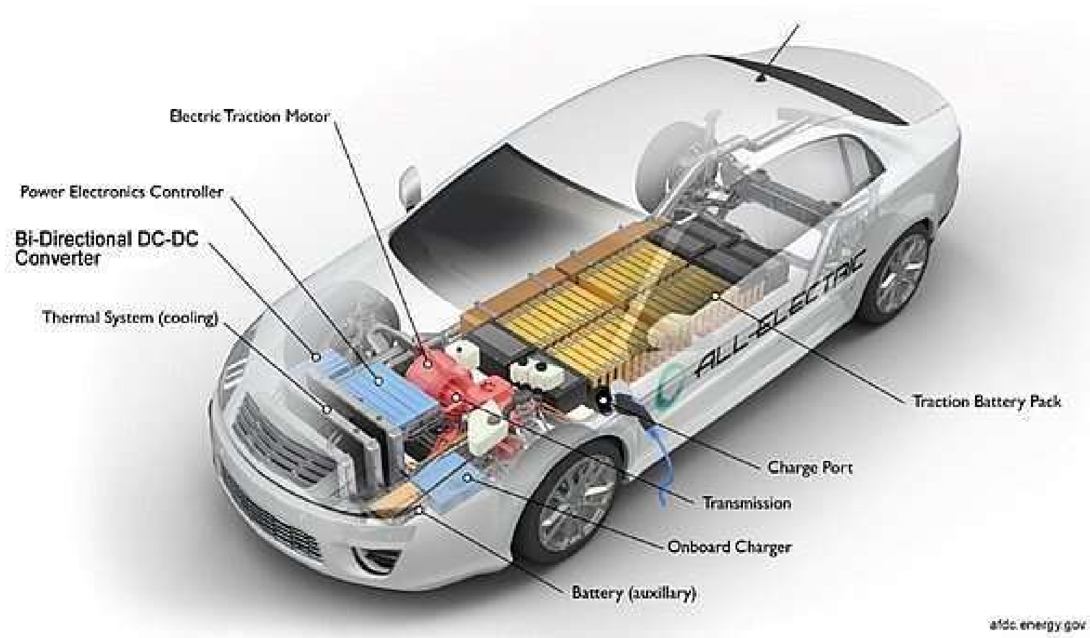

Figure 64: Typical EV battery system (source: U.S. Department of Energy).

Figure 65: Charging station.

The TIDA-010054 is beneficial where power density, efficiency, cost, weight, galvanic isolation, high-voltage conversion ratio, and reliability are critical factors; these benefits make it ideal for EV-charging stations and energy-storage applications. Its modular design and dual active bridge (DAB) symmetrical structure permit the stacking of converters to achieve high power throughput and facilitate a bidirectional mode of operation to support battery-charging and battery-discharging applications. It is designed for use in level-3 EV charging stations[65]. Top and side views of the TIDA-010054 dual active bridge PCB are depicted in Figure 66. The gate-driver boards are mounted vertically (two on the left and two on the right). The heatsink is mounted below the PCB.

[65] Level-3 EV charging stations offer the fastest charging speeds. While a level-2 station recharges an electric vehicle in 4 to 8 hours, some level-3 EV charging stations can do it in less than an hour.

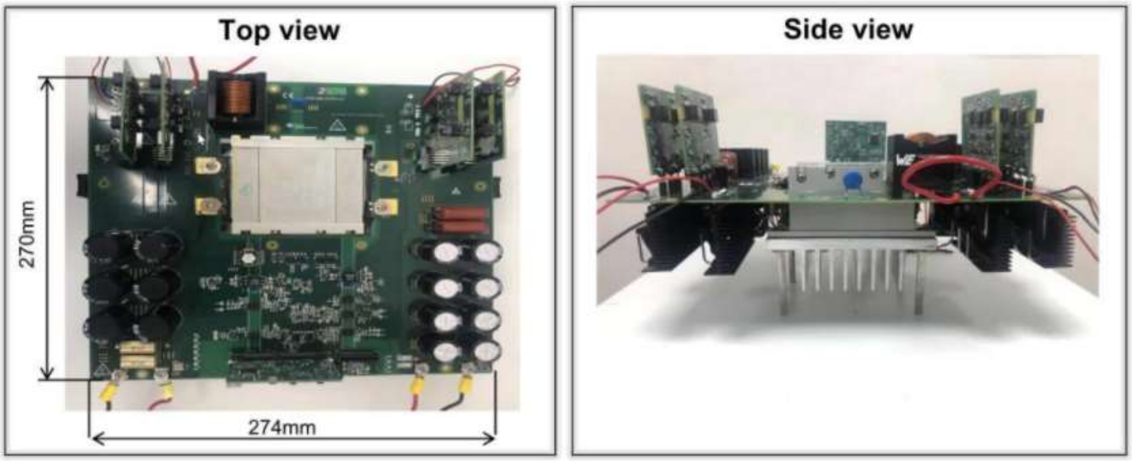

Figure 66: TIDA-010054 dual active bridge board with vertically mounted UCC51230 drivers and heatsink mounted below the PCB (source: Texas Instruments).

Bidirectional flow of energy is feasible if the energy loss in either direction is minimal. Wide-bandgap devices are ideally suited for bidirectional converters. The TIDA-010054 uses SiC MOSFETs together with the SiC gate-driver technology from Texas Instruments, providing high efficiency and power density. The gate-driver board is shown in Figure 67.

Figure 67: TIDA-010054 gate-driver board (source: Texas Instruments).

The overall bidirectional conversion system schematic and block diagram is shown in Figure 68. Magnetic coupling provides galvanic isolation of the high- and low-voltage stages of the converter. The high- and low-voltage stages (left side and right side, respectively), utilizing SiC MOSFETs, are driven by the TMS320F280049 digital controller and UCC51230[66] dual active bridge gate drivers. Each UCC51230 drives a half-bridge.

[66] Shepard, Shepard. 2019. "10 kW Bi-Directional, Dual Active Bridge Reference Design with SiC MOSFETs." EETech Media, LLC. https://eepower.com/news/10kw-bi-directional-dual-active-bridge-reference-design-with-sic-mosfets/.

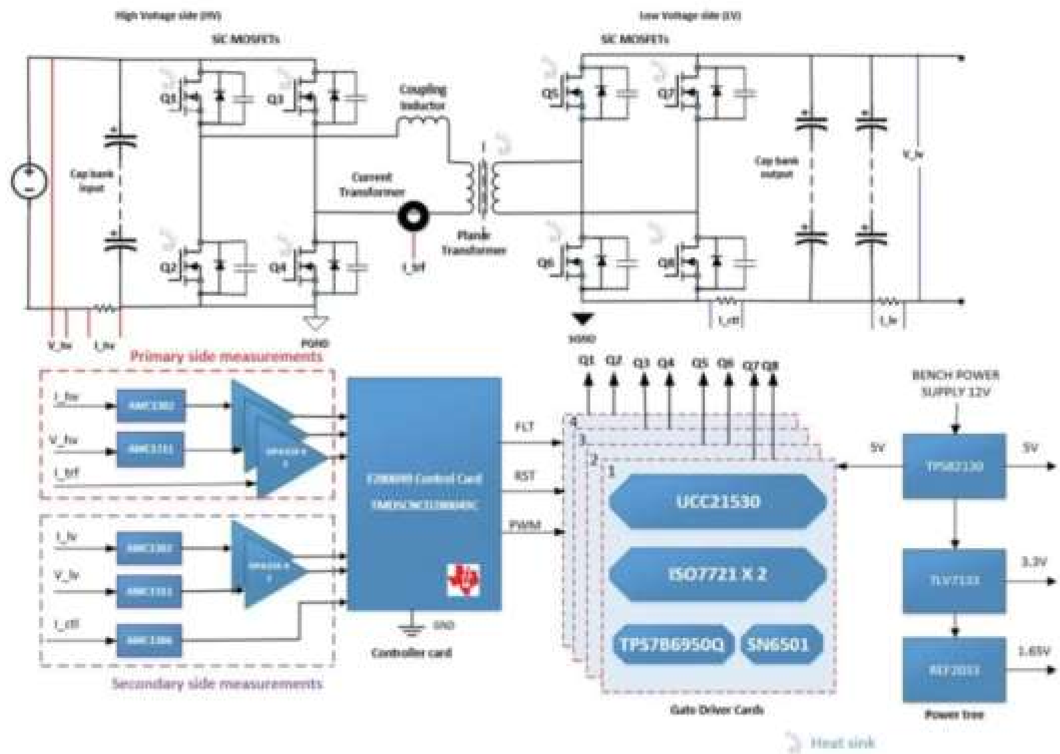

Figure 68: TIDA-010054 block diagram (source: Texas Instruments).

Self-Test

1. MOSFETs are _________-driven devices. The gate of the MOSFET can be modeled as a simple ________.
   a. current, inductor
   b. voltage, inductor
   c. voltage, capacitor
   d. current, capacitor
2. __________ the gate resistance results in turn-on and turn-off times to be _________ and switching losses to be _________.
   a. increasing, shorter, reduced
   b. increasing, longer, increased
   c. reducing, longer, reduced
   d. reducing, shorter, reduced
3. A gate driver accepts low-power input voltage from the _________ and produces a high-current input for the _________ of a MOSFET.
   a. gate, drain
   b. controller, drain
   c. gate, source
   d. controller, gate
4. In power electronics, there are three forms of isolation. They are:
   a. magnetic, optical, and capacitive
   b. inductive, resistive, and capacitive
   c. optical, magnetic, and resistive
   d. optical, resistive, and capacitive
5. The traction inverter converts ______ power from an on-board ________-voltage battery into ________ power to drive the main motor or motors of an electric vehicle.

a. AC, low, DC
b. AC, high, DC
c. DC, high, AC
d. DC, low, AC

6. Traction inverter functions require _________ to separate ___________ from ________ domains. This includes the low-voltage communication, and control and main power supply circuitry on the primary side.
   a. galvanic isolation, high-voltage, high-impedance
   b. high resistance, low-voltage, high-voltage
   c. high resistance, high-voltage, low-voltage
   d. galvanic isolation, control systems, high-voltage
7. The ___________ of inductive and capacitive _________ effects in any design benefits the overall performance and stability of the design. With ____________ devices, this is even more important.
   a. maximization, parametric, wide-bandgap
   b. minimization, parasitic, wide-bandgap
   c. minimization, parasitic, narrow-bandgap
   d. doubling, parametric, wide-bandgap
8. New _________-management techniques have been developed to deal with the __________ operating temperatures of WBG devices.
   a. thermal, decreased
   b. voltage, increased
   c. thermal, increased
   d. voltage, decreased
9. Thermal adhesive, screw, and clip are valid heatsink attachment methods.
   a. False
   b. True
10. Magnetic coupling provides galvanic isolation of the high- and low-voltage stages of a converter.
   a. True
   b. False

Section 5: Applications and Sample Circuit Block Diagrams

5.1 Overview

Silicon carbide and gallium nitride are becoming the technology of choice for next-generation power designs in a variety of applications such as hybrid and electric vehicles, aircraft and spacecraft, industrial power supplies, solar power systems, data centers, grid infrastructure, and more[67]. In this section, several applications of WBG power electronic devices are reviewed.

A variety of applications are represented graphically in Figures 69, 70, and 71. In Figure 69, applications are represented as a function of output power level, frequency of operation, and the specific WBG device they are benefitting from. In general, SiC devices are superior to Si in terms of their higher power capability, whereas GaN devices are superior to Si in terms of their higher frequency of operation.

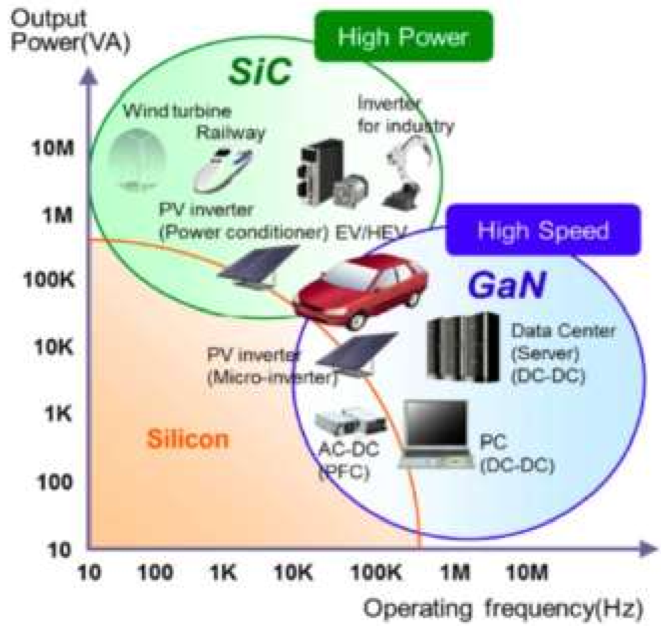

Figure 69: WBG application space (source: Wikipedia).

Figure 70 depicts a range of electronic power devices (SiC and GaN-based devices as well as Si-based devices such as BJTs, MOSFETs, IGBTs, and thyristors) as a function of power level, frequency, and device size. Applications (listed in the left panel) are also given as a function of numerical power level. On the low-power, low-frequency ranges, Si MOSFET devices are predominant. At higher-power, low-frequency ranges, discrete IGBTs and IGBT modules are typically used. For medium and high power and for higher frequency, SiC MOSFETs and SiC modules are appearing. At low power and high frequencies, GaN HEMTs are appearing.

[67] Wolfspeed. 2020. "Silicon Carbide and the Future of Industrial Applications." Wolfspeed, Inc. https://www.wolfspeed.com/knowledge-center/article/silicon-carbide-and-the-future-of-industrial-applications.

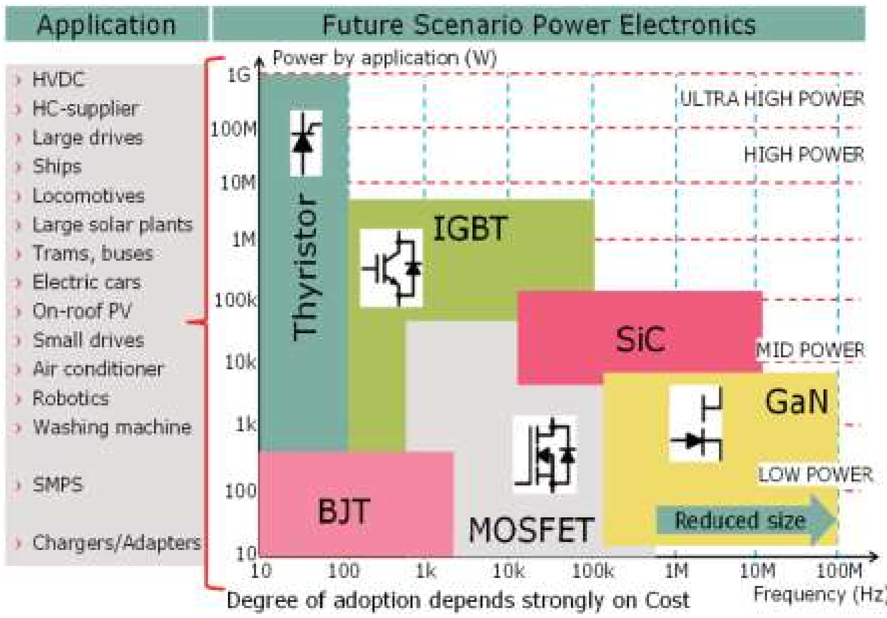

Figure 70: Switching power-device application space (source: CPSS Transactions on power electronics and applications[68].

Figure 71 presents a linear display of applications in terms of a specific numerical range of output power as well as the WBG device they can benefit from. IT and consumer power electronics appear at the lower power end, automotive power electronics at the mid-power levels, and industrial power electronics at high-power levels. For power levels up to 100 kW, both SiC and GaN devices are applied in all three electronics areas, whereas for industrial electronics with power levels above 100 kW, SiC devices are predominant.

[68] Quinn, Conor A., and Dhaval B. Dalal. 2017. "Empowering the Electronics Industry: A Power Technology Roadmap." *CPSS Transactions on Power Electronics and Applications* 2, no. 4 (December). https://www.researchgate.net/publication/322630199_Empowering_the_Electronics_Industry_A_Power_Technology_Roadmap.

Figure 71: Applications where WBG devices can displace Si (source: Yole Développement).

5.2 Automotive

Figures 72 and 73 show several automotive subsystems where WBG devices are replacing silicon. Below we consider LIDAR and the 48-12 V automotive power-distribution system.

Figure 72: Automotive applications of WBG devices (source: Efficient Power Conversion).

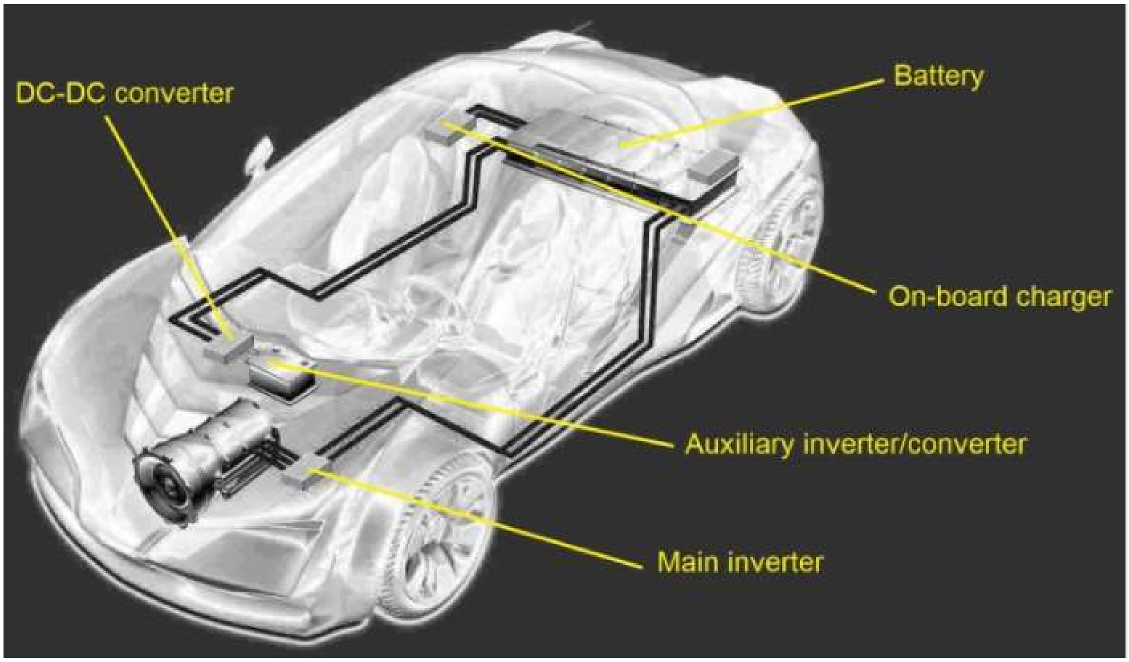

Figure 73: Automotive applications of WBG devices (source: EE Times).

5.2.1 LIDAR

LIDAR[69] is an acronym for Light Detection and Ranging (remote detection and measurement by electromagnetic radiation in the optical band). This device applies the same principle as that of RADAR by using a beam of light composed of laser pulses. The technique used to calculate the distance between the source of the ray and any object is called time-of-flight (TOF) and is depicted in Figure 74. LIDAR has a higher resolution than RADAR and is therefore able to obtain well-detailed three-dimensional images for control and navigation in autonomous vehicles.

LIDAR requires fast switching of high-current pulses to meet performance specifications. Si-based components are unable to provide the necessary features for the implementation of the laser driver in effective LIDAR systems[70]. The Si-based MOSFET channel must be very large to provide elevated control; this leads to objectionable charging times of parasitic capacitances and results in switching frequencies that are too low for the application. Furthermore, bulky heat sinks are required for cooling.

The electronic mobility of GaN devices is greater than that of Si. In contrast to their silicon counterparts, GaN devices have lower conduction losses, higher switching speeds, better thermal performances, and

[69] LIDAR is a method for measuring distances (ranging) by illuminating the target with laser light and measuring the reflection with a sensor. Differences in laser return times and wavelengths are used to make digital 3-D representations of the target.
[70] Di Gesualdo, David. 2020. "GaN Quells LIDAR's Barriers." Power Electronic News. https://www.powerelectronicsnews.com/gan-quells-lidars-barriers/#:~:text=Present-day%20electronic%20engineers%20can%20use%20the%20innovative%20Wide,silicon,%20with%20an%20energy%20gap%20of%203.4%20eV.

smaller sizes and costs. Taken together, these features satisfy the needs of the switching component of the driver circuit[71]

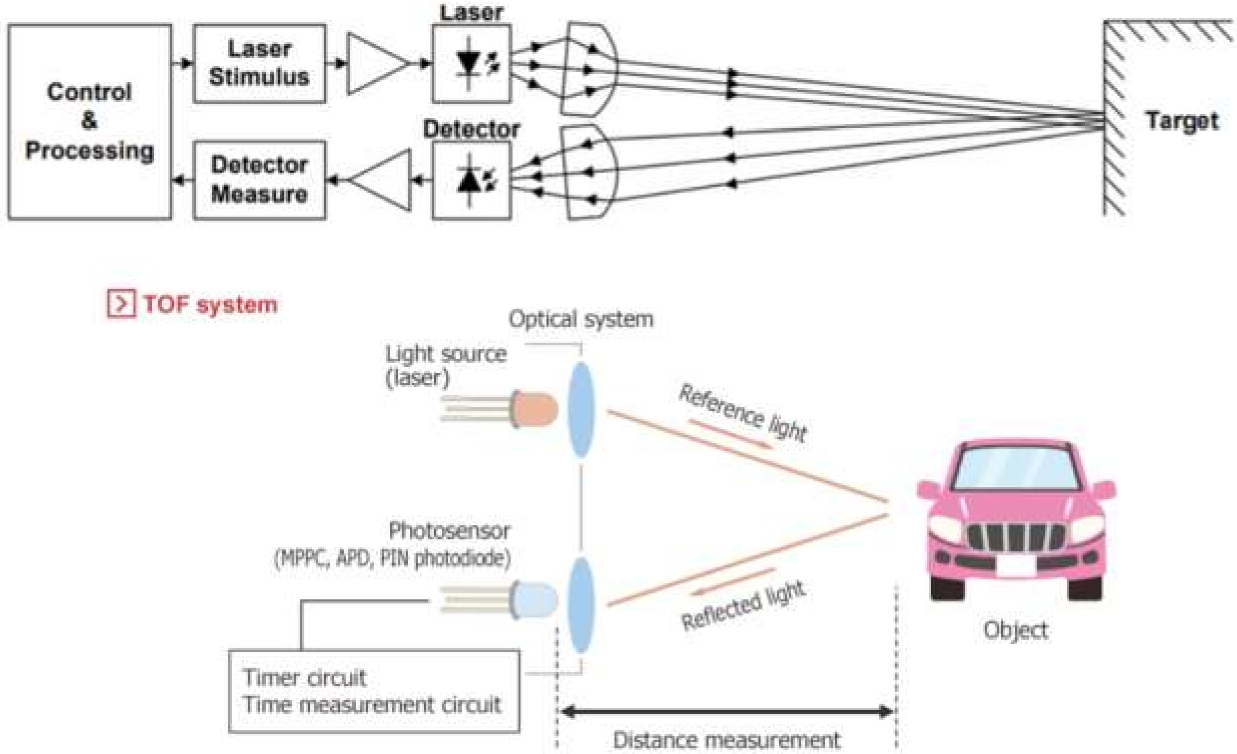

Figure 74: Simplified LIDAR system block diagrams.

5.2.2 The 48-12 V Automotive Power Distribution System

With increasingly strict emission regulations, growing power-load requirements of advanced automotive electronics, and the conversion from mechanical components to electronic functions, the traditional 12 V automotive battery has reached its current-carrying capacity[72]. In response, automakers and their suppliers have developed a second electrical system at 48 V which delivers greater power at lower currents than a traditional 12 V battery can produce alone. For a given amount of power, the increase in voltage to 48 V reduces the current requirement[73] $(P = VI)$. That, in turn, allows for a smaller wire gauge, which reduces cable size, weight, and cost without sacrificing performance. Most new hybrid vehicles now include a 48-V system, and standard vehicles with internal-combustion engines are moving in that direction as well.

[71] Pickering, Paul. 2018. "GaN Devices Power the Next Generation of LiDAR Systems." Electronic Design. https://www.electronicdesign.com/power-management/article/21806644/gan-devices-power-the-next-generation-of-lidar-systems.

[72] Panacek, Jiri. 2018. "Bridging 12 V and 48 V in dual-battery automotive systems: How a bidirectional buck-boost controller helps support a dual-bus topology." Texas Instruments Incorporated. https://www.ti.com/lit/wp/slpy009/slpy009.pdf?ts=1612820011004&ref_url=https%253A%252F%252Fwww.ti.com%252Fapplications%252Fautomotive%252Fhev-ev-powertrain%252Foverview.html.

[73] Given the power formula $P=VI$, for a fixed value of P, an increase in V requires that I decrease proportionately.

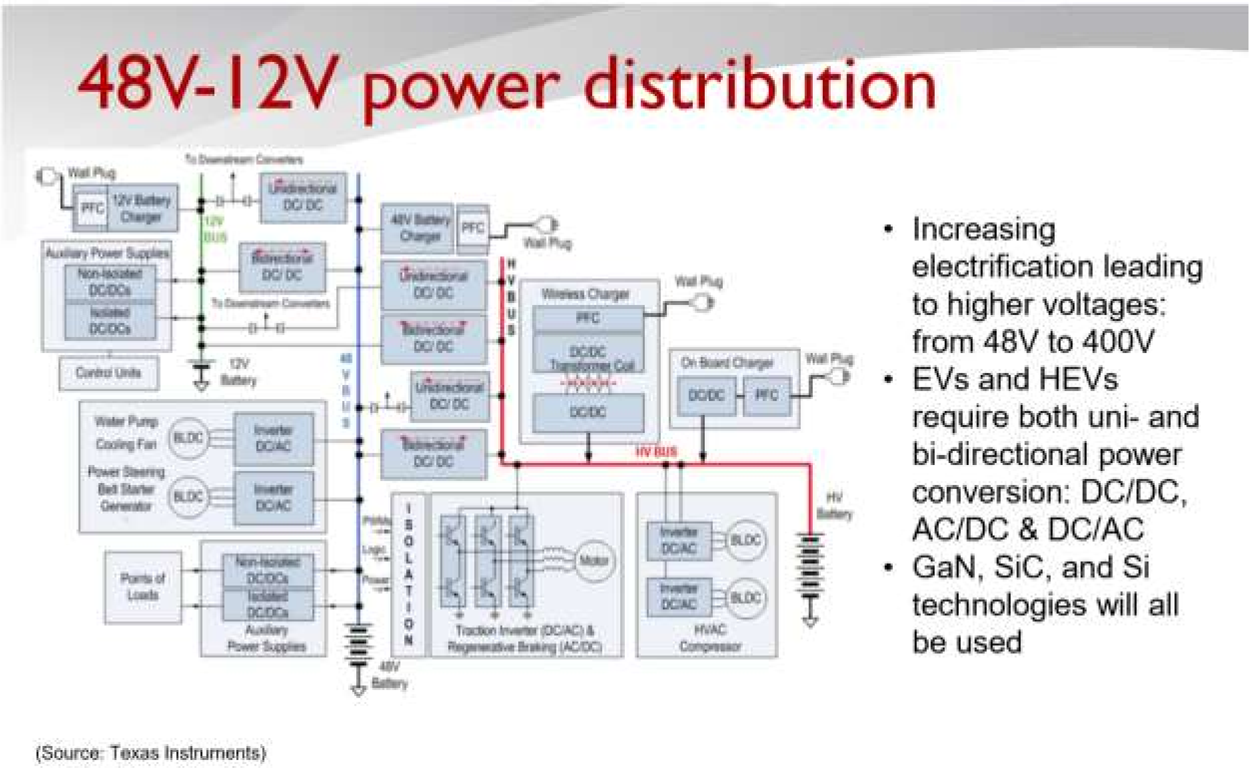

Figure 75: 48-12 V power distribution system (source: Texas Instruments).

The 48-12 V power distribution system, shown in Figure 75, consists of two separate branches. The traditional 12 V bus uses a conventional lead-acid battery for customary loads such as infotainment, lighting, and windows; the new 48 V system can support heavier loads such as starter generator units, air-conditioning compressors, active chassis systems, and regenerative braking.

The block diagram of the power-distribution system shows the various forms of power conversion that are required. It includes both unidirectional and bidirectional power conversions: DC/DC, DC/AC (inverters), and AC/DC (chargers and regenerative braking). The traction inverter and regenerative braking subsystem are key components in electric vehicles (EV). The inverter controls the electric motor while the regenerative braking subsystem returns captured braking energy to the battery. As is evident from the block diagram, HEV and EV also have a variety of other inverters and converters. WBG devices, having several superior attributes relative to Si (compactness, higher thermal conductivity, breakdown voltage, low ON resistance, higher efficiency, and operation at higher temperatures), are being used to improve the performance of inverters and converters used in EV and HEV. The use of WBG devices not only enables electric vehicles to drive a longer distance on the same charge, but also makes the on-board chargers smaller, more efficient, and have lower system costs. Additionally, off-board fast DC charger stations are more efficient and are capable of higher power.

5.3 Aircraft

Aircraft and spacecraft systems are increasingly becoming electrified. Many of the subsystems found in automotive systems also appear in aircraft. The use of WBG devices in these systems has advantages that mirror those found in automotive systems (ability to manage high power levels, weight reduction, high-temperature operation, high-switching frequencies, low noise, low power losses, and high efficiency as well as insensitivity to radiation for spacecraft).

The aircraft industry is working on the development of various categories of aircraft that employ power electronic devices and systems[74]. Two of the categories are more electric aircraft (MEA) where secondary aircraft systems (such as mechanical, pneumatic, and hydraulic) are gradually replaced by electrical systems (Figure 76) and electric propulsion aircraft (EPA) where the electrical propulsion architecture is changed fundamentally by incorporating new electrical technology (Figure 77).

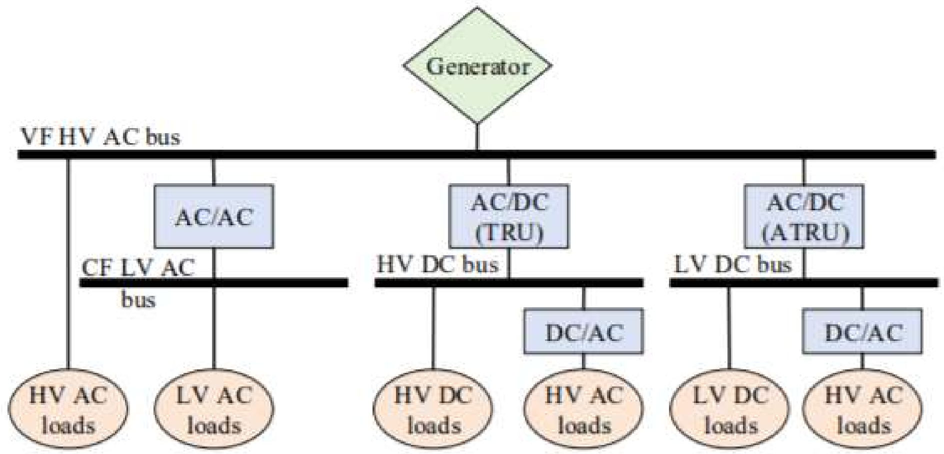

Figure 76: More electric aircraft, otherwise known as MEA (source: IEEE).

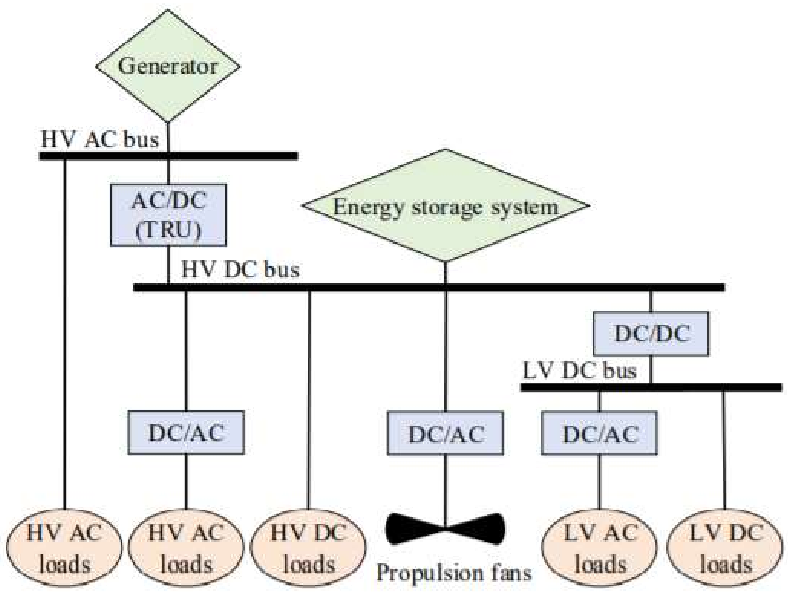

Figure 77: Electric propulsion system (EPS).

Each of these categories of aircraft is composed of both AC and DC electrical subsystems systems. And requires the utilization of much larger amounts of electric power than prior aircraft designs have used. As the diagrams show, power electronic converters and inverters play a major role in the management of

[74] Dorn-Gomba, Lea, John Ramoul, John Reimers, Ali Emadi. 2020. "Power Electronic Converters in Electric Aircraft: Current Status, Challenges, and Emerging Technologies." *IEEE Transactions on Transportation Electrification* 6, vol. 4 (December). IEEE. https://ieeexplore.ieee.org/document/9130749.

power between electrical networks. With their increased utilization, WBG power electronic devices in future aircraft designs will be essential in minimizing power losses and increasing reliability.

5.4 Alternative/Renewable Energy

Photovoltaics (solar power) and wind power are the most-deployed forms of renewable energy[75]. Of these, solar generates almost twice the power output of wind and is accordingly becoming the dominant technology. There is a large market for the proliferation of solar power.

Figure 78 depicts a typical solar power system. The solar panels generate a DC voltage. A bank of storage batteries is charged by connecting the solar-panel output to a DC/DC converter. An AC voltage is generated by connecting the solar panel output to a DC/DC boost converter followed by a DC/AC inverter.

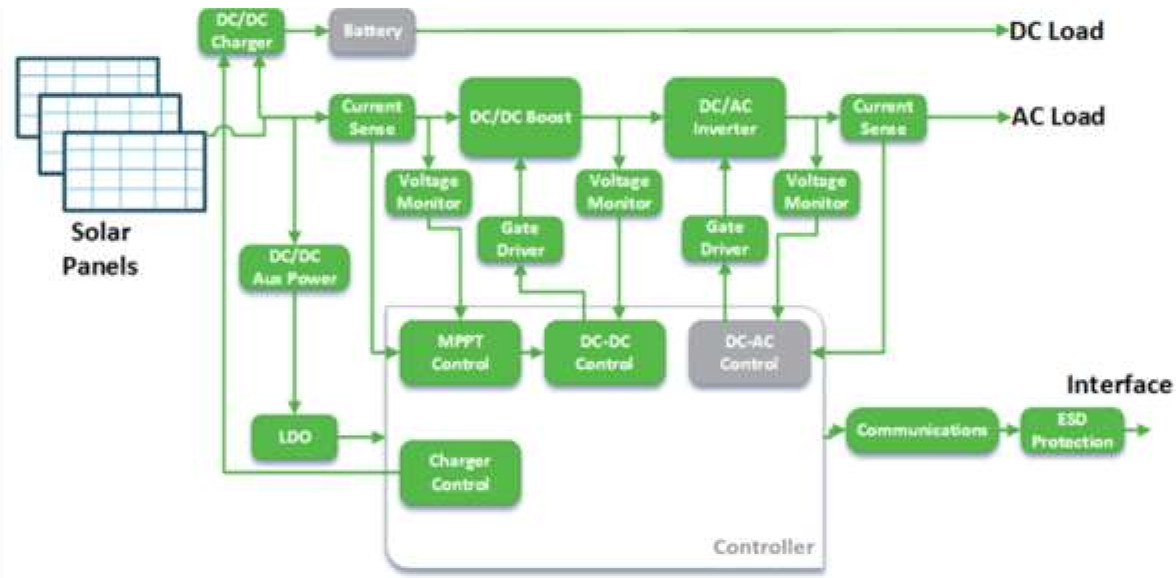

Figure 78: Block diagram of a typical solar power inverter system (source: ON Semiconductor).

As for any power electronic system, efficiency is one of the key goals of the solar power generating system. The most important elements of a power converter or inverter are the switching devices. WBG switching devices are essential for increasing the efficiency beyond that available with Si devices. Due to their high efficiency and ability to operate at high temperatures and high frequencies, the use of WBG devices such as SiC MOSFETs enhances the performance of solar power systems. In addition, the higher frequency of operation significantly reduces the size and cost of such components as inductors and capacitors, and the higher temperature of operation simplifies cooling requirements.

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[75] Becker, Brandon. 2020. "Wide Bandgap Enabling a Bright Future for Solar Power." Power Systems Design. https://www.powersystemsdesign.com/articles/wide-bandgap-enabling-a-bright-future-for-solar-power/22/16654.

5.5 Data Centers and Consumer Electronics

Data centers[76] and consumer electronics are pervasive in society. Companies such as Facebook, Google, Microsoft, and Amazon are investing in new data centers to meet the growing demand for cloud-based services. Data centers—composed of equipment such as routers, switches, security devices, storage systems, and servers—also require a supporting infrastructure that includes uninterruptible power supplies (UPS), backup generators, and cooling systems (Figure 79). The UPS is a critical component. Every data center must have a stable and continuous supply of power, typically provided by the UPS[77], to avoid the potentially catastrophic impact of a line power failure or interruption. In addition to being an important component in data centers, the UPS is also important in other areas such as industrial manufacturing processes, telecommunications, medical appliances, and in small offices and home office environments.

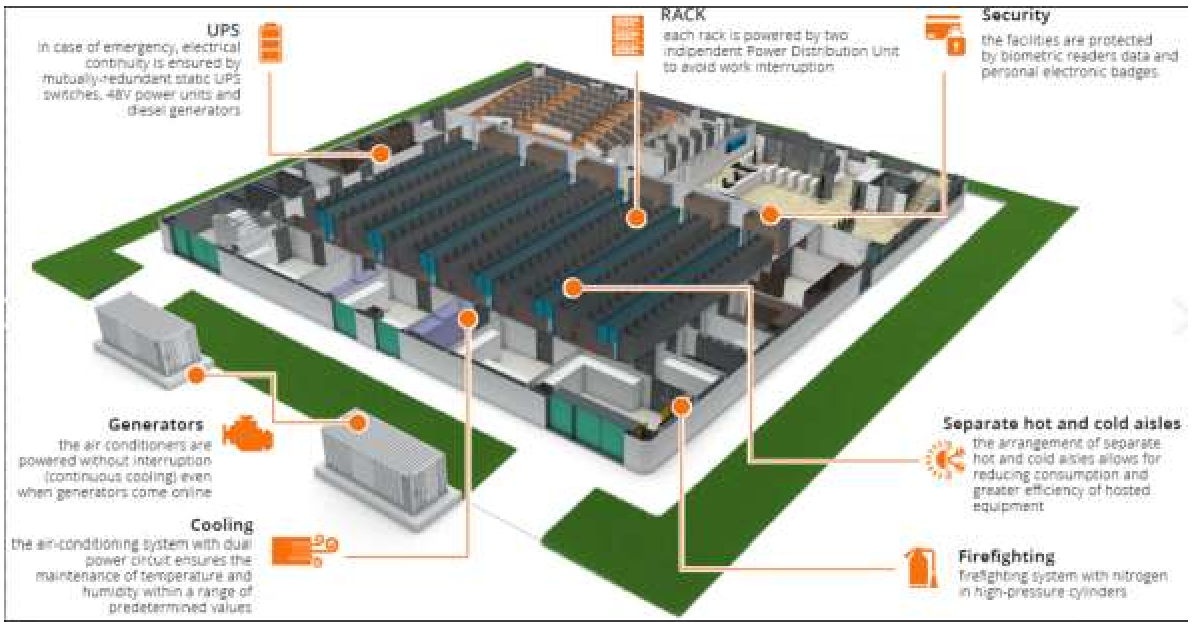

Figure 79: Data center layout.

Consumer electronics—including electronic devices such as televisions, computers, and smartphones—require DC power, typically provided by the switched-mode power supply (SMPS). Below we consider the basic operation of the UPS and SMPS. These systems operate more efficiently, with significantly fewer power losses, when WBG devices replace Si-based devices.

5.5.1 The UPS

The two basic types of UPS[78], offline/standby and online/double-conversion, are briefly described.

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[76] Data centers are physical facilities for the remote storage, processing, or distribution of large amounts of data.
[77] Editorial Staff. 2020. "SiC Semiconductor for Data Center." Power Electronics News. https://www.powerelectronicsnews.com/sic-semiconductor-for-data-center/.
[78] Infineon. "Uninterruptible Power Supply (UPS)." Infineon Technologies AG. Accessed March, 2021. https://www.infineon.com/cms/en/applications/solutions/power-supplies/uninterruptible-power-supply-ups/.

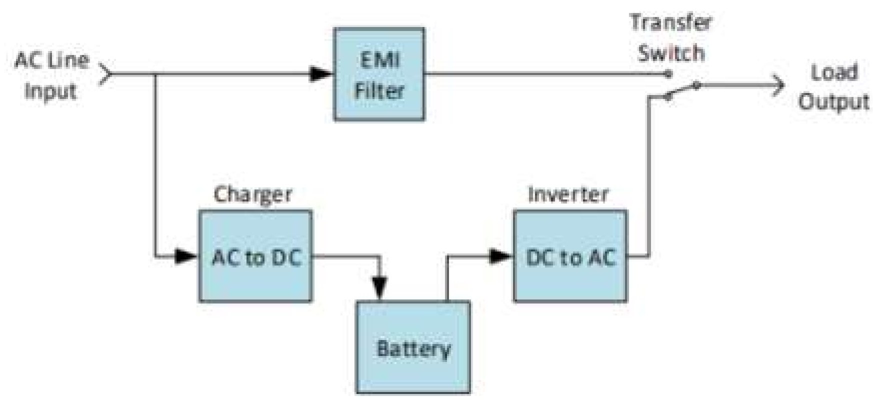

Figure 80: Offline/standby UPS (source: Infineon).

Offline/standby UPS (Figure 80): When AC line voltage is present, the switch is in the upward position; the inverter remains off during this time. The battery charger operates continuously to maintain full charge. If the AC power fails, the switch moves downward so that, after a few milliseconds, the inverter supplies back up power.

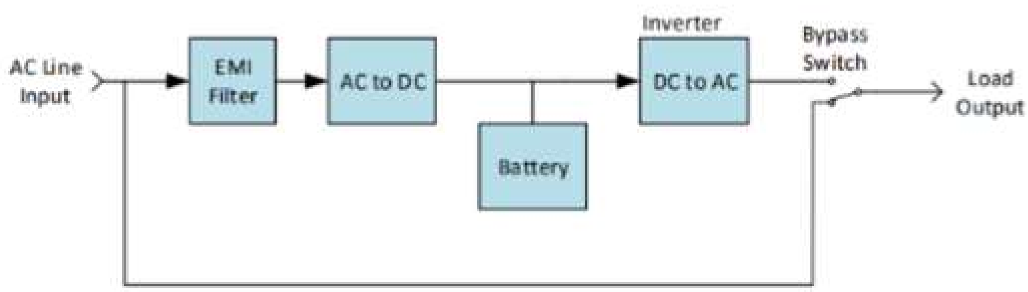

Figure 81: Online/double conversion UPS (Source: Infineon).

Online/double-conversion UPS (Figure 81): The AC input is converted to DC at the battery charge level and then converted back to AC so that in the event of an AC line failure the system will switch to battery backup.

5.5.2 Switched-Mode Power Supply

Consumer electronics require DC power. The type of DC power supplies used in consumer electronics are predominately switched-mode. There are three basic types of switched-mode power supplies. They can be used as AC to DC converters, in circuits powered from the AC line voltage, or for DC-to-DC (either stepping the DC voltage up as a boost converter or down as a buck converter) in battery-powered systems. SMPS are more complex than linear-regulated power supplies[79], however, the advantage of the added complexity is that they deliver more power for a given size, cost, and weight than a linear-regulated power supplies. The block diagram for a typical SMPS having an AC input and a regulated DC output is shown in Figure 82.

[79] Coates, Eric. 2007. "Switched Mode Power Supplies." *Learn about electronics: Power Supplies*. Last modified December 29, 2020. https://www.learnabout-electronics.org/PSU/psu30.php.

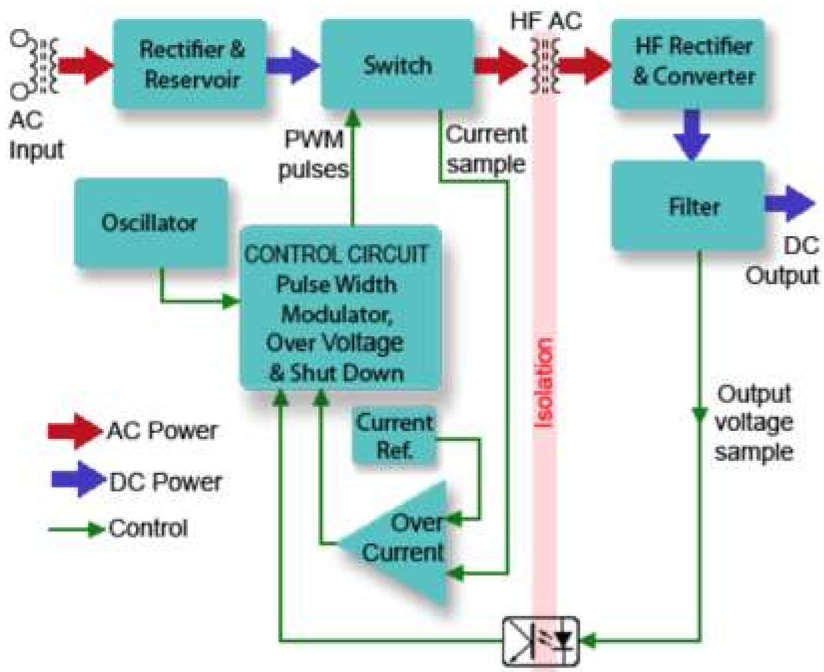

Figure 82: A typical SMPS block diagram (source: learnabout-electronics.org).

The output rectifier and filter are isolated from the high-frequency switching section by a transformer, and voltage control feedback is realized by means of opto-isolation. A high-frequency pulse-width modulated square wave converts the DC input to the electronic power-switching circuit into high-frequency AC which is reconverted into a regulated DC output. By using this double-conversion process, passive components such as transformers, inductors, and capacitors—needed for conversion back to a regulated DC supply—can be much smaller and cheaper than those needed to do the same job at the line frequency.

5.6 Grid infrastructure

The electric grid is gradually transitioning from centralized power generation based on unidirectional flow of fossil-fuel power to bidirectional power flow utilizing renewable (solar and wind) power sources. Wide-bandgap power electronic devices such as SiC and GaN will play an important role in the ongoing process of grid modernization toward a smart grid. The smart grid describes an electrical grid that is integrated with a computerized, two-way communication network. Whereas older electrical grids send electrical power in one direction only (from a power plant to homes and offices), a smart grid provides bidirectional flow of power and instantaneous feedback on systemwide operations. The smart grid utilizes technologies, standards, and practices that contribute to a more efficient and reliable power grid. The smart grid concept was introduced by the U.S. Department of Energy in 2007[80]. Figure 83 contrasts the traditional grid with the smart grid.

[80] (a) Office of Electricity. 2021. "Grid Modernization and the Smart Grid." U.S. Department of Energy. https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid.
(b) Litos Strategic Communication. "What the Smart Grid Means to America's Future." U.S. Department of Energy. Accessed February, 2021. https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/TechnologyProviders.pdf#:~:text=The%20U.S.%20Department%20of%20Energy%20(DOE)%20is%20charged,for%20increasing%20awareness%20of%20our%20nation%E2%80%99s%20Smart%20Grid.

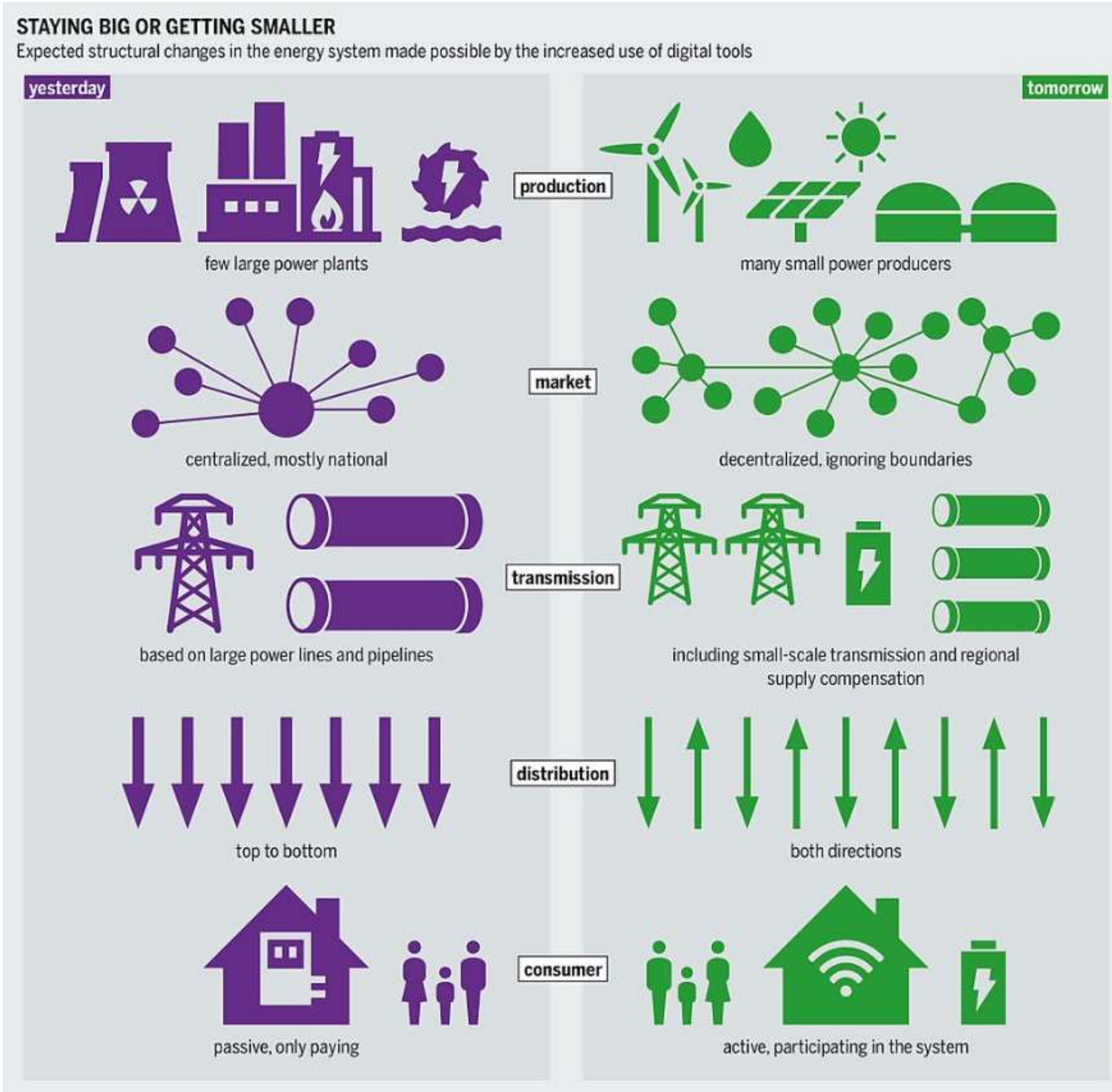

Figure 83: Traditional grid (left), smart grid (right).

The independent small power producer in the figure above is more commonly known as a microgrid (Figure 83). A microgrid is a compressed version of the national grid. A modern AC or DC microgrid is typically supplied by renewable energy sources (solar, wind, fuel cells, etc.).

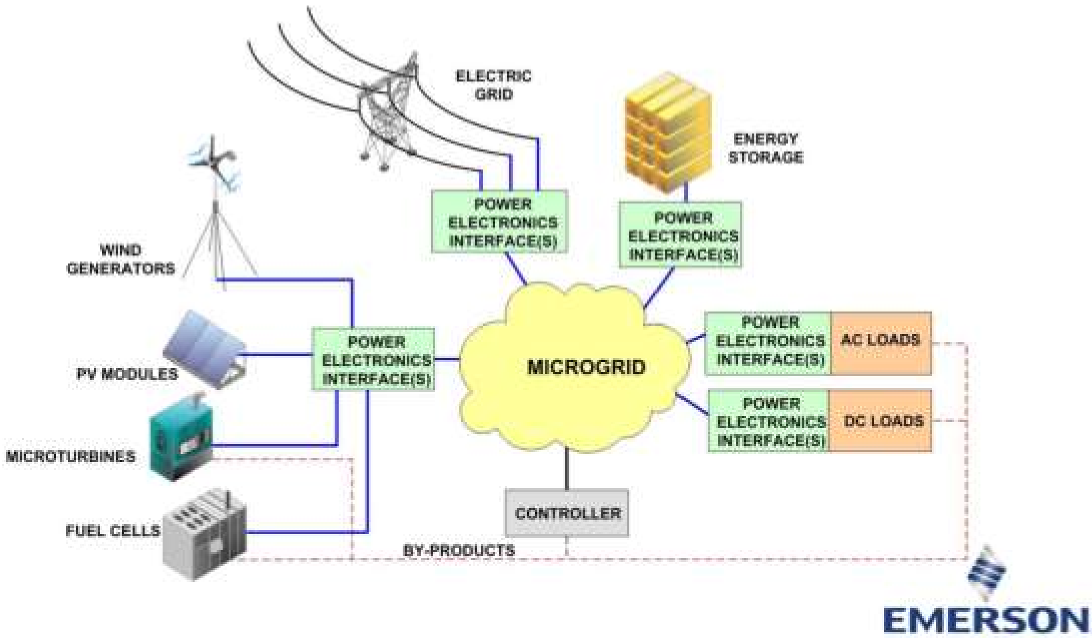

Figure 84: WBG devices find potential application in the power electronic interfaces of modern microgrids.

Domestic and industrial scale microgrids[81] are depicted in Figures 85 and 86. Careful consideration must be given to electrical efficiency in each. In the simple domestic installation shown in Figure 85, electronic power conversion has several stages—the DC output of the solar panels must be converted to the storage battery voltage using a DC-DC converter, an inverter transforms the battery DC-to-AC line voltage, a battery charger ensures that the battery is maintained at full capacity when there is no solar input, and a bidirectional converter charges the EV battery from AC to DC and transfers power in reverse. In an industrial environment, there is a great deal of more complexity. In both the domestic and industrial environments, in each power conversion stage, efficiency and minimization of power loss is a major concern.

[81] Lee, Paul. 2020 “How New Technology Benefits Microgrids.” Mouser Electronics, Inc. https://www.mouser.com/applications/new-technology-benefits-microgrids/.

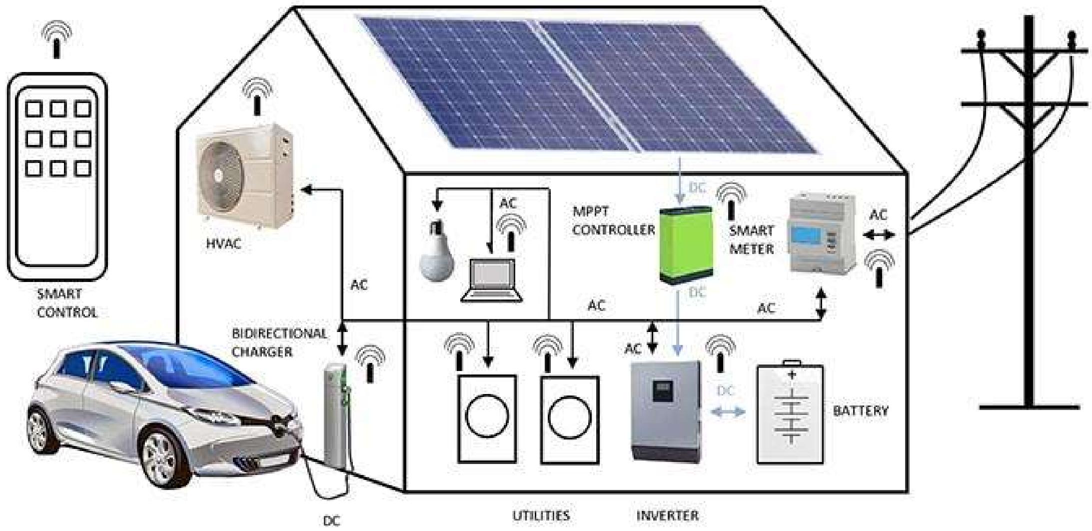

Figure 85: Domestic microgrid arrangement (source: Mouser).

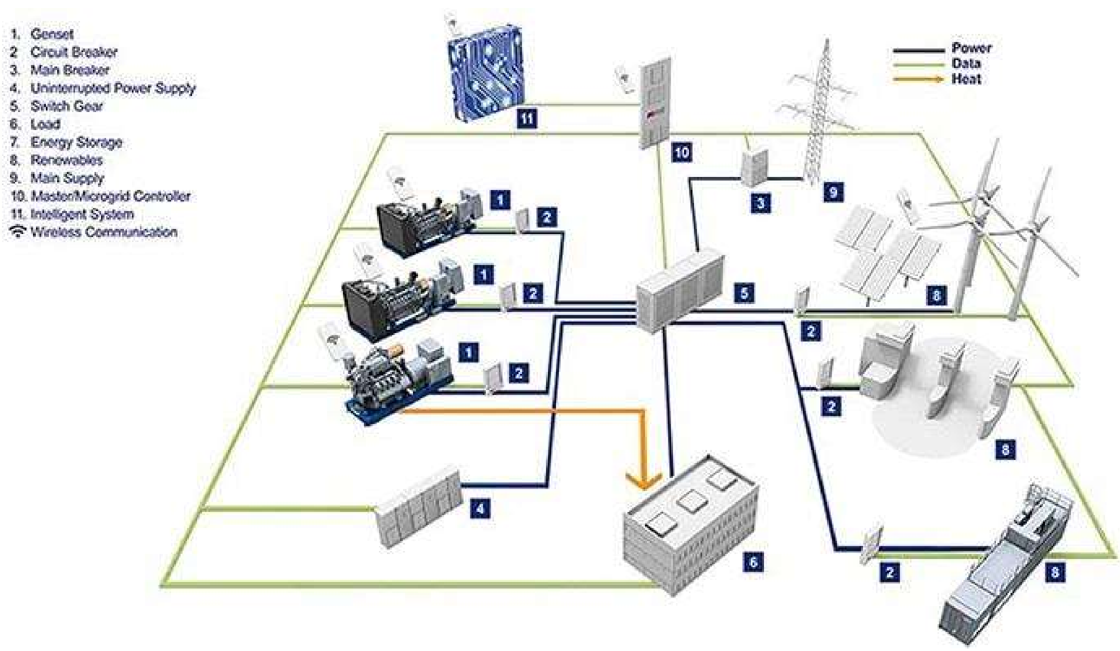

Figure 86: Microgrid arrangement in a factory environment (source: Mouser).

The various power conversion stages in a microgrid use switched-mode techniques. Semiconductor switches chop the input DC or rectified AC voltage at high frequency. This is followed by a transformer for scaling and isolation, then conversion back to DC through rectifiers or to AC through filters. Regulation of outputs to a constant DC or 50/60Hz AC is achieved by pulse-width modulation (PWM) of the semiconductor switching action.

All the power-conversion stages in a microgrid lose some energy, so high efficiency is important. Until about 2010, high-power semiconductor switches had been limited to IGBTs. For acceptable efficiency, these devices must be switched relatively slowly. They dissipate no power when they are off and have some conduction loss when on, however, as they transition between the two states, they consume power that is measurable in kilowatts (Figure 87). The higher the transition frequency, the higher the dissipation. For this reason, switching frequencies have been limited to a few tens of kilohertz for IGBTs. As a result, transformers and other magnetic components such as filters must be large and are therefore costly.

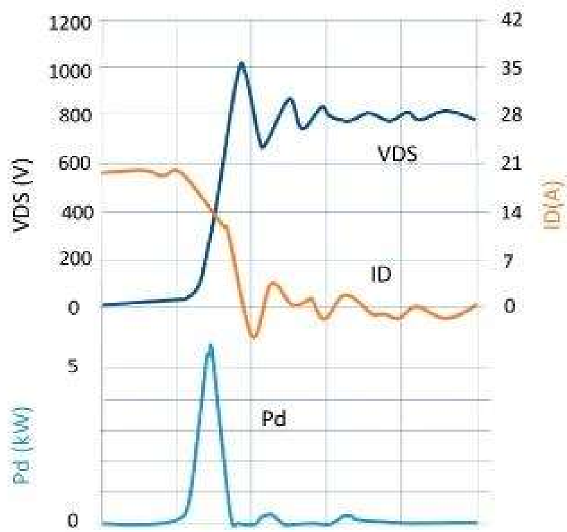

Figure 87: Power dissipation during switching transition (source: Mouser).

Si-based MOSFETs can operate at higher a switching frequency and have lower switching losses than IGBTs. However, they have limited power ratings and their conduction losses can be higher than those of IGBTs. WBG semiconductors can switch much faster in comparison with silicon so that any transient dissipation is much smaller. Combined with very low ON resistances and inherent high-temperature capability, equipment designed with WBG technology is smaller and more efficient. This is due not only to the devices themselves but also because the higher switching frequency enables smaller associated components such as transformers and filters.

5.7 Robotics[82]

Robots consist of several functional components including the manipulator arm, image and position sensing, and motor and sensor control units. They also have a variety of power subsystems such as AC/DC conversion, battery management, DC/DC conversion, multiphase converters, point-of-load (POL) conversion[83], linear regulation, and motor drivers (Figure 88). Each subsystem must operate efficiently,

[82] An informative video reference describing the role of wide-bandgap devices in improving the performance of various types of robotic devices can be found at https://ieeetv.ieee.org/the-future-of-power-electronics-in-robotics-apec-2019. IEEE Power Electronics Society, IEEE Industry Applications Society. “The Future of Power Electronics in Robotics: APEC 2019.” IEEE. Video. Accessed February 18, 2021.

[83] POL converters are placed near the processor that is consuming the power, avoiding long wiring distances between the converter and processor.

reliably, and at high levels of power density so that the robot design is small and nimble[84]. Key to achieving this is the use of WBG power devices.

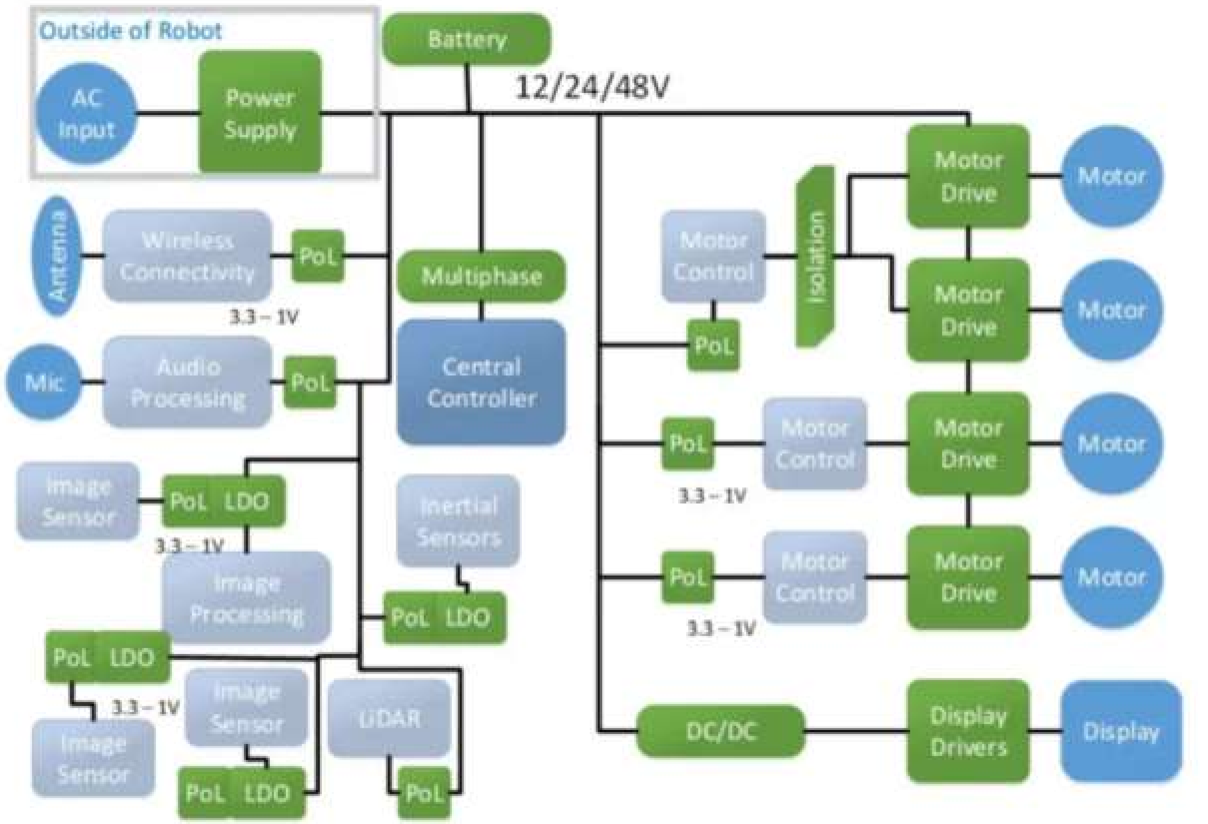

Figure 88: Block diagram of a typical 48 V robot system (source: Power Electronics News).

There are four types of robots, each subsequent type requiring larger amounts of electrical power to operate: (1) Service robots, such as the robot vacuum, (2) Collaborative robots—humans in close proximity or direct human-robot interaction, (3) Mobile robots—also known as automated guided vehicles (AGV)—for transporting loads and which are taking the place of forklift trucks, conveyors, or manual transport, and (4) Industrial robots, such as those carrying very large payloads and those assisting in the assembly of automotive vehicles. We will briefly consider mobile and industrial robots.

As shown in Figure 89, using WBG power devices in the design of mobile robots allows them to be built more compactly. Other features include increased power density, reduced weight, improved performance in terms of shorter charging times, and lower losses. Lower losses translate to extended range of mobile robots.

[84] Editorial Staff. 2020. "The rise of the 48V robots." Power Electronics News. Accessed February 10, 2021. https://www.powerelectronicsnews.com/the-rise-of-the-48v-robots/.

Figure 89: Mobile robots utilizing WBG devices (source: Infineon).

The industrial robot arm shown in Figure 90 has rather massive external cabling for motor and drive connections. Efficient, high-power-density WBG devices can be used in novel designs to integrate the motors and drivers into a compact design, allowing the cabling, motors, and drives to be brought inside the arm. This results in reduced complexity and cost (Figure 91).

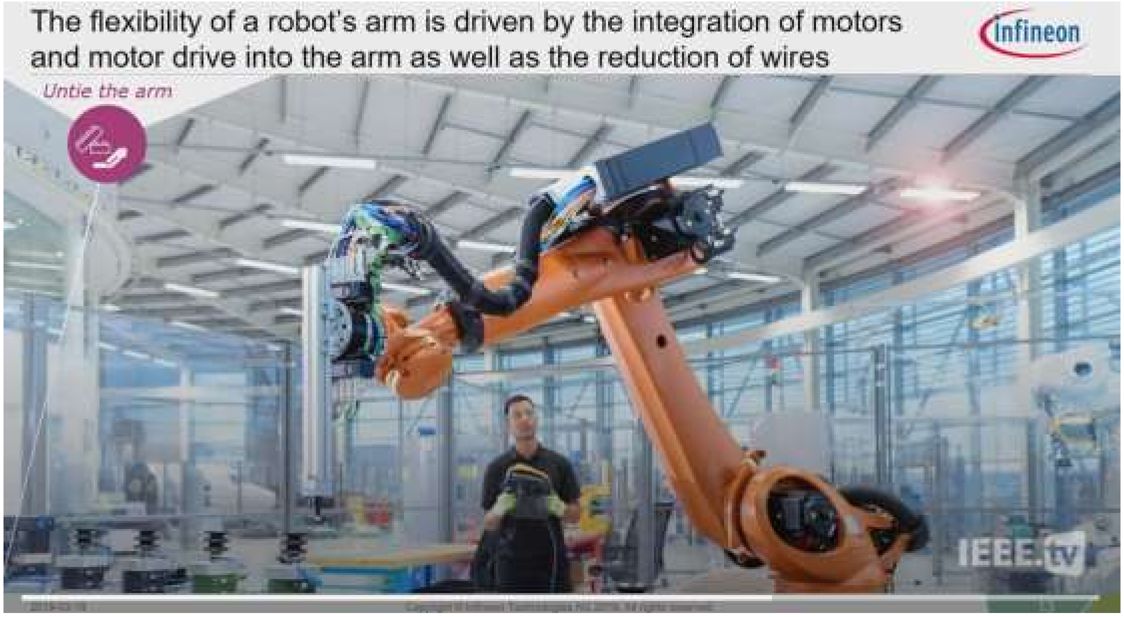

Figure 90: Industrial robot arm with external cabling, drive, and motor (source: Infineon).

Figure 91: Reduced complexity robot arms.

Self-Test

1. Referring to Figure 71, ____________ power electronics appear at the lower-power end, __________ power electronics at the mid-power levels, and ___________ power electronics at high-power levels.
   a. automotive, IT and consumer, industrial
   b. IT and consumer, automotive, industrial
   c. industrial, automotive, IT and consumer
   d. automotive, industrial, IT and consumer
2. Si-based components can provide the necessary features for the implementation of the laser driver in effective LIDAR systems.
   a. True
   b. False
3. LIDAR has a _________ resolution than RADAR and is therefore able to obtain well-detailed ____________ images for control and navigation in ____________ vehicles.
   a. lower, three-dimensional, semiautonomous
   b. higher, two-dimensional, semiautonomous
   c. lower, two-dimensional, autonomous
   d. higher, three-dimensional, autonomous
4. Automakers and their suppliers have developed a second, additional electrical system at _______ which delivers _________ power at _________ currents than a traditional 12 V battery can produce alone.
   a. 24 V, lower, lower
   b. 48 V, greater, greater
   c. 48 V, greater, lower
   d. 24 V, greater, lower
5. In the MEA category of aircraft, the electrical propulsion architecture is changed fundamentally by incorporating new electrical technology; in the EPA category, secondary aircraft systems are gradually replaced by electrical systems,
   a. True
   b. False

6. The higher frequency of operation of WBG devices significantly __________ the size and cost of components such as __________ and capacitors; the ________ temperature of operation __________ cooling requirements.
   a. increases, resistors, higher, complicates
   b. reduces, resistors, lower, simplifies
   c. reduces, inductors, higher, simplifies
   d. increases, inductors, lower, complicates
7. Every data center must have a stable and continuous supply of power, typically provided by ________, to avoid the potentially catastrophic impact of a line power failure or interruption.
   a. a photovoltaic system
   b. an uninterruptible power supply
   c. the electrical grid
8. SMPS are _________complex than linear regulated power supplies[85]; they deliver _________ power for a given size, cost, and weight than a linear regulated power supply.
   a. less, more
   b. more, less
   c. less, more
   d. more, more
9. The electric grid is gradually transitioning from ___________ power generation based on ___________flow of fossil fuel power to __________ power flow utilizing renewable (solar and wind) power sources.
   a. decentralized, unidirectional, bidirectional
   b. centralized, unidirectional, bidirectional
   c. centralized, bidirectional, unidirectional
10. In a simple domestic microgrid installation, electronic power conversion has several stages—the DC output of the solar panels must be converted to the storage battery voltage using a(an) _______ converter, an inverter transforms the battery DC to ________ line voltage, a battery charger ensures that the battery is maintained at full capacity when there is no solar input, and a bidirectional converter charges the EV battery from _______ and transfers power in reverse.
    a. AC-DC, AC, DC to AC
    b. DC-DC, DC, AC to DC
    c. DC-DC, AC, AC to DC
    d. AC-DC, AC, AC to DC
11. WBG semiconductors can switch much faster in comparison with silicon so that any transient dissipation is much larger.
    a. True
    b. False
12. The power density of WBG devices is two to five times that of Si-based devices.
    a. True
    b. False

[85] Coates, Eric. 2007. "Switched Mode Power Supplies." *Learn about electronics: Power Supplies*. Last modified December 29, 2020. https://www.learnabout-electronics.org/PSU/psu30.php.

Section 6: Case Study—High-Power Inverter

6.1 Introduction

In this concluding section, concepts and subsystems discussed in previous sections are brought together through the presentation of a state-of-the-art three-phase inverter (for converting DC to AC). A basic inverter is first explained[86] and is followed by a brief description of the CRD300DA12E-XM3 (300 kW) three-phase inverter reference design[87] manufactured by Wolfspeed/Cree[88]. Although the reference design guide describes both the 200 kW and 300 kW inverters, only the 300 kW inverter is considered. The inverter reference design will be referred to as **the three-phase inverter**, and the reference design guide will be referred to as **the guide**. The complete guide appears in the appendix.

In Figure 92, a DC voltage between the top and bottom rails can create current in two different directions by turning pairs of switches on or off. The current alternates at the switching frequency. The two pairs of switches in the figure make up a single-phase inverter. Adding one more pair of switches makes a rudimentary three-phase inverter. Figure 93 depicts a basic three-phase inverter with load.

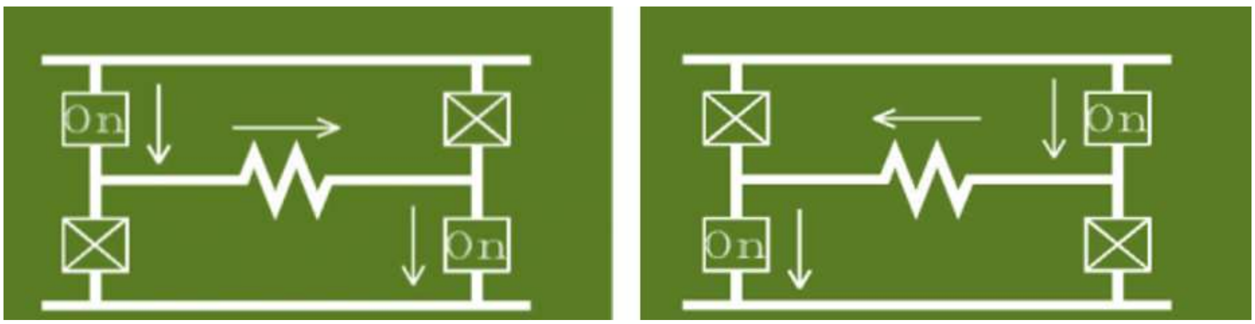

Figure 92: Basic single-phase inverter.

The three-phase inverter output consists of three AC sinusoidal waveforms which are uniformly separated in phase angle. Amplitudes and frequencies of all three waves generated are same while the waveforms are phase-shifted by 120° from each other.

[86] FCX Systems. "What is a 3-Phase Inverter?" Accessed February, 2021. https://fcxinc.com/what-is-a-3-phase-inverter/.
[87] Wolfspeed offers time-saving reference designs for some of the most in-demand devices in power systems—inverters, power converters, chargers, and many more. These reference designs come complete with application notes, user guides, and design files to allow designers to create rugged and reliable systems with optimized power density, performance, and efficiency. Many other semiconductor manufacturers also offer reference designs.
[88] (a) Wolfspeed. 2019. "XM3 Three-Phase Inverter Reference Design User Guide." Wolfspeed, Inc. https://www.wolfspeed.com/crd300da12e-xm3.
(b) Wolfspeed. 2019. "New SiC Power Modules Deliver Greater Power Densities in Smaller Packages Than Si IGBTs." Wolfspeed, Inc. https://www.wolfspeed.com/knowledge-center/article/new-sic-power-modules-deliver-greater-power-densities-in-smaller-packages-than-si-igbts.

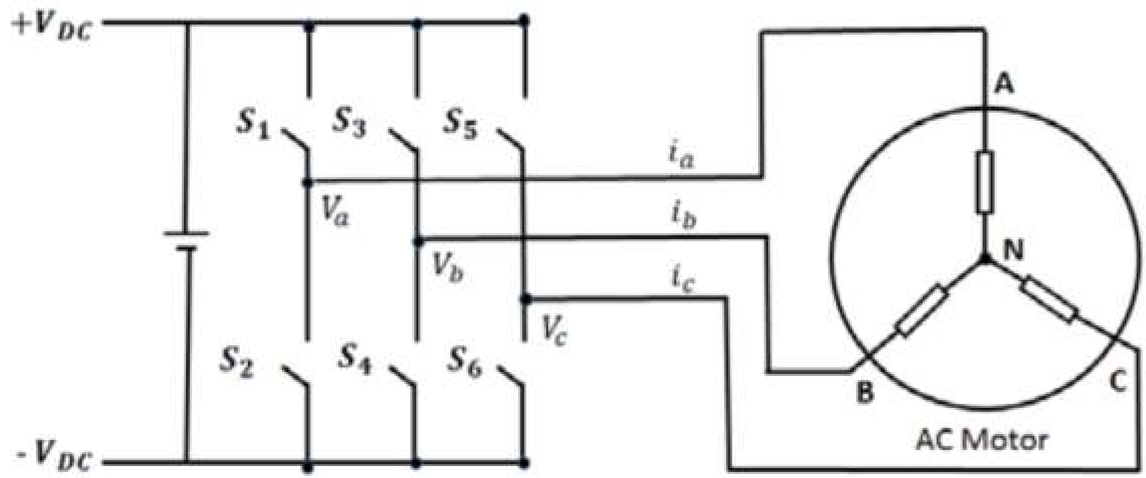

Figure 93: Basic three-phase inverter (source: Circuitdigest.com[89]).

Sample sinusoidal waveforms produced by the Wolfspeed three-phase inverter circuit of Figure 94 (guide Figure 16) are shown in Figure 95 (guide Figure 15). The rough edges are created by turning the MOSFETs of the inverter on and off in a pulsating manner multiple times per cycle[90]. This is known as pulse-code modulation (PCM) for sinusoidal-waveform generation. The cycle is broken up into several smaller segments where the controller tells the MOSFET switch how long to close during each one. By opening and closing the switches at varying lengths of time during each segment of every cycle, the MOSFETs allow varying amounts of current to flow through the circuit. The more segments the cycle is broken into, the smoother the waveform will be and the closer it will resemble a true sinusoidal waveform. In transferring the power to the grid or other load such as a motor, the jagged waveform does not present a problem because the inductance of the grid or motor acts as a low-pass filter, consequently tending to further smooth the edges out.

[89] Raja,Dilip. 2019. "Three Phase Inverter Circuit Diagram - 120 Degree and 180 Degree Conduction Mode." Circuit Digest. https://circuitdigest.com/tutorial/three-phase-inverter-circuit-diagram-120-degree-and-180-degree-conduction-mode.

[90] Evans, Paul. 2017. "How Inverters Work." TheEngineeringMindset.com. https://theengineeringmindset.com/how-inverters-work/.

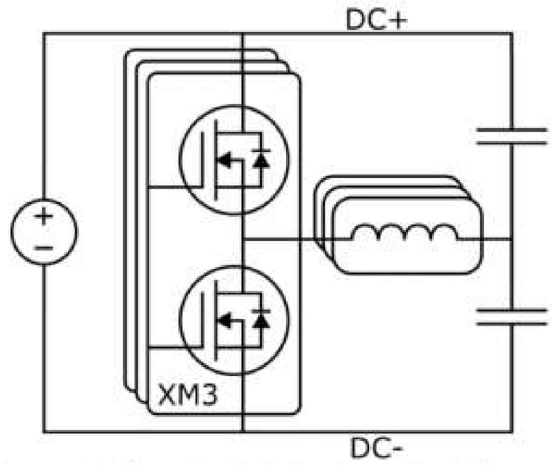

Figure 94: Wolfspeed three-phase inverter with inductive load.

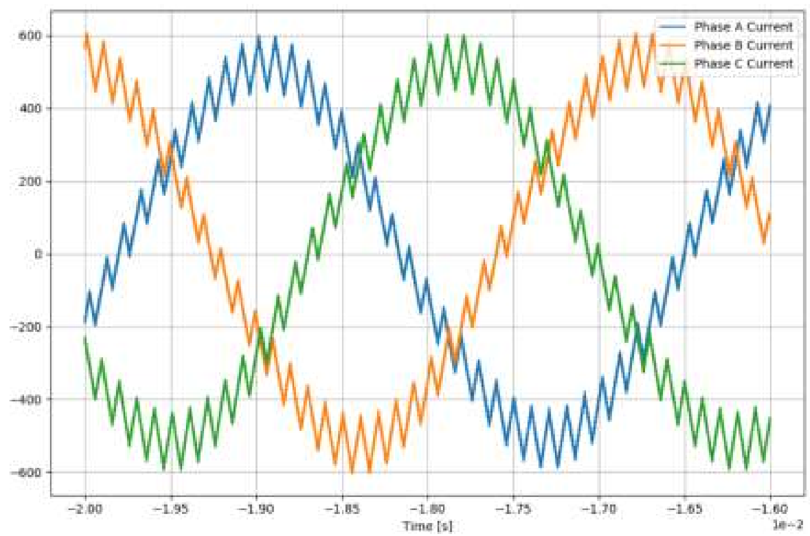

Figure 95: Wolfspeed three-phase inverter current waveforms.

6.2 Physical features and layout of the Wolfspeed/Cree three-phase Inverter

Figure 96 (guide Figure 1) shows a general block diagram of the CRD300DA12E-XM3 (300 kW) three-phase inverter. The inverter is composed of three XM3 half-bridge power modules with three built-in current and temperature sensors, three CGD12HBXMP gate drivers, and a controller using the TMS320F28379D DSP. The controller supports three external high-voltage measurements.

As indicated in Figure 97 (guide Figure 2), the XM3 (shown on the left) has a 40% reduced volume relative to the industry standard IGBT EconoDUAL package manufactured by Infineon (shown on the extreme right). Figure 98 shows the complete assembly of the 300 kW 3-phase inverter[91]. The overall physical dimensions of the inverter are 279 mm x 291 mm x 115 mm (11 in. x 11.5 in. x 4.5 in.) and with

[91] Feurtado, Matthew, Brice McPherson, Daniel Martin, Ty McNutt, Marcelo Schupbach, W. A. Curbow, Jonathan Hayes, and Brett Sparkman. 2019. "High-Performance 300 kW 3-Phase SiC Inverter Based on Next Generation Modular SiC Power Modules." https://www.wolfspeed.com/knowledge-center/article/high-performance-300-kw-3-phase-sic-inverter-based-on-next-generation-modular-sic-power-modules.

an equivalent volume of 9.3 L. The letters U, V, and W refer to the three-phase outputs for powering a motor or feeding the grid (various other means of identification—such as A, B, and C as well as L1, L2, and L3—are also used, the choice depending on national preference). The plus and minus denote the DC input to the inverter. On the lower-right side of the package are a grounding terminal and input and output ports of the cold plate that is providing heat dissipation. The inverter cutaway depicted in Figure 99 shows (from lower right to upper left) sensors, XM3 modules, PCB bussing, gate drivers, and controller.

The inverter is fully instrumented with sensors, drivers, and controller to implement motor drive or photovoltaic-inverter applications. It is well-suited for operation in extreme environments and heavy-equipment industries and can be used in rugged applications such as traction and photovoltaic systems.

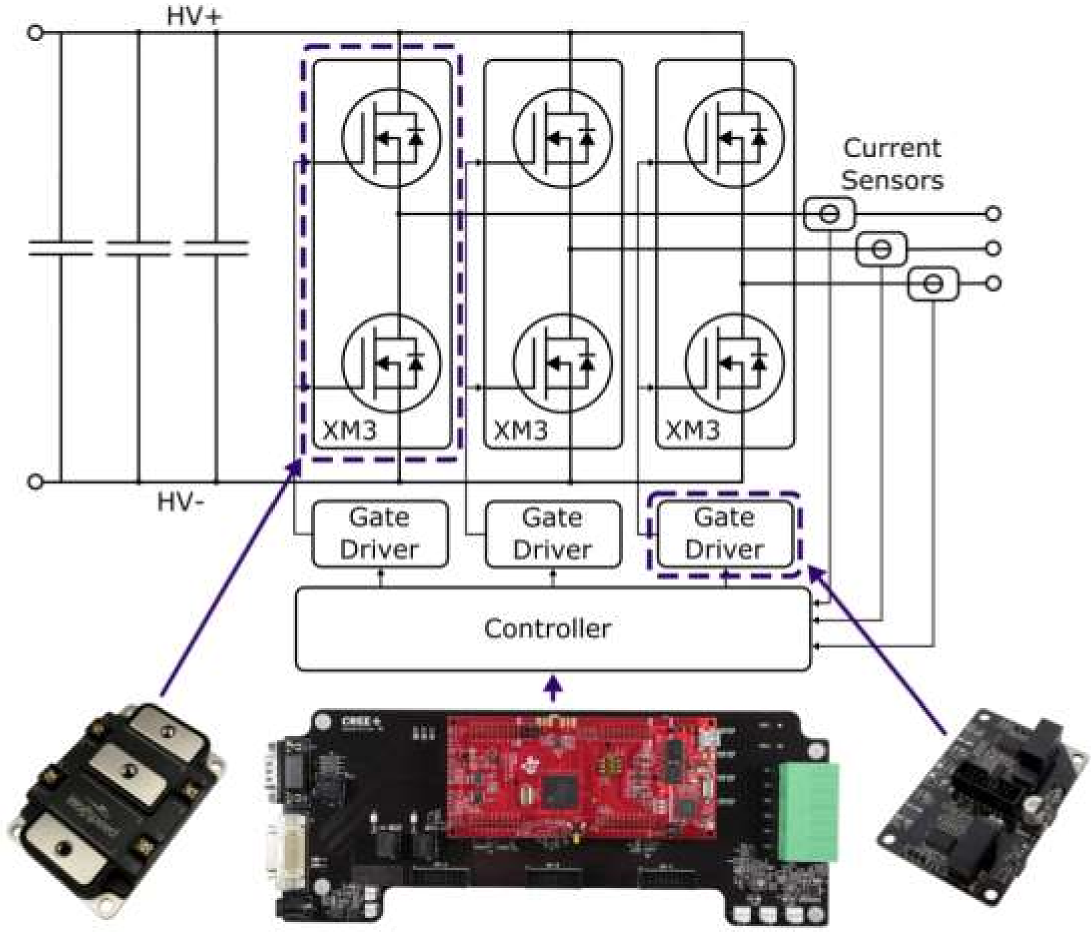

Figure 96: System block diagram—Wolfspeed 300 kW three-phase inverter reference design.

Figure 97: Size comparison of XM3 power module with existing packages.

Figure 98: The Wolfspeed 300 kW three-phase inverter.

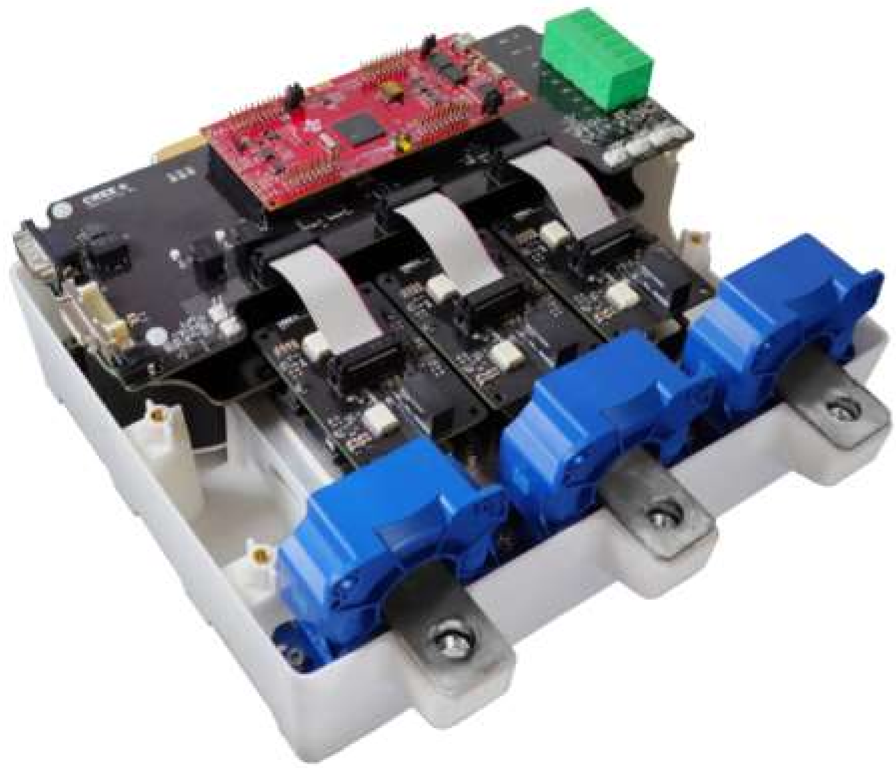

Figure 99: Inverter cutaway.

In the remaining subsections, a brief description of features and characteristics of the inverter is given together with reference to relevant sections or locations in the guide where detailed information can be found (indicated in parentheses).

6.3 System Overview (guide pages 9 and 10)

The inverter features minimal stray inductance, resulting in low peak overshoot and oscillation in switch voltages. This enables faster turn-on and turn-off times and consequently lowers switching losses. The low-inductance XM3 power modules used in the inverter have a power density approaching 32.25 kW/L; this is more than twice that of comparable Si -based modules. The XM3 utilizes 650-1700 V Wolfspeed C3M SiC MOSFETs.

6.3.1 XM3 Inductive Switching Losses (guide 2.1.3)

The XM3 power modules utilize internal gate resistors with a short-gate signal loop and wide, low-inductance paths; these power modules can be safely used with zero external gate resistors when a low-inductance bus structure and low-inductance capacitors are used. The fast[92], clean XM3 MOSFET switching waveforms given in Figure 100[93] demonstrate that the inverter can achieve very low switching loss with little ringing and zero external gate resistance.

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[92] Note that the switching speeds are on the order of tenths of microseconds.

[93] Feurtado, Matthew, et al. https://www.wolfspeed.com/knowledge-center/article/high-performance-300-kw-3-phase-sic-inverter-based-on-next-generation-modular-sic-power-modules.

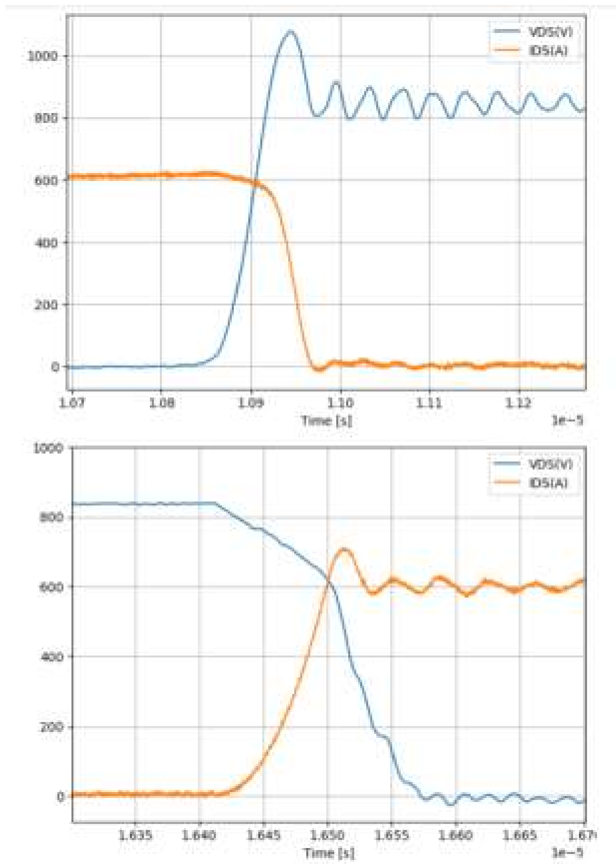

Figure 100: XM3 MOSFET drain-source voltage and current during turn-off (top waveforms) and turn-on (bottom waveforms) (source: OnSemiconductor[94]).

6.4 Control System

6.4.1 Overview (guide 2.2)

The inverter includes sensors, interfaces, power supplies, and controller all necessary for a complete motor-drive or photovoltaic-inverter system. Isolated gate drivers are connected by means of ribbon cable to the controller PCB, which provides power, differential, and control signals.

6.4.2 Current, Voltage, and Temperature Sensors (guide 2.2)

Current, voltage, and temperature sensors monitor the condition of the inverter.

Three-phase current sensors (LEM LF 510-S, 500 A, closed-loop current transducers) are included at the output terminals of the inverter.

Three external high-voltage measurements are supported by the controller.

A NTC[95] temperature sensor, built into the power module and positioned as close as possible to the power devices while remaining electrically isolated from them, provides approximate device temperature.

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[94] ON Semiconductor. “Drive and Layout Requirements for Fast Switching High Voltage MOSFETs.” onsemi.com. Accessed March, 2021. https://www.onsemi.com/pub/Collateral/TND6242.PDF

[95] NTC: negative temperature coefficient.

6.4.3 DSP (guide 2.2.6)

The TMS320F38379 floating-point digital signal processor is used to run the control loop for the inverter and handle I/O; the dual-core (two microprocessors in one), 200 MHz, 32-bit processor with built-in peripherals is targeted at real-time control applications.

6.5 CGD12HBXMP Gate Driver (guide 2.3)

Each of the three power modules is driven by a Wolfspeed CGD12HBXMP gate driver, extracting peak performance from Wolfspeed's C3M SiC MOSFETs. Voltage rails of +15 V / -4 V are used for the output stage of the driver to match the recommended V_{GS} rating for the C3M MOSFET devices.

6.5.1 Protection Features (guide 2.3.1)

Protection features of the gate drivers include tunable over-current detection with soft shutdown, undervoltage lockout[96], and anti-overlap of PWM inputs to prevent shoot-through.

6.5.2 Differential Signal Communication (guide 2.3.2)

The extremely fast turn-on and turn-off times during switching in a SiC power system create electromagnetic interference[97] (EMI) that can couple onto gate control signals. For this reason, differential signaling[98] (Figure 101) is used between the gate driver and controller board, reducing the impact of radiated noise from the switching events of the power module.

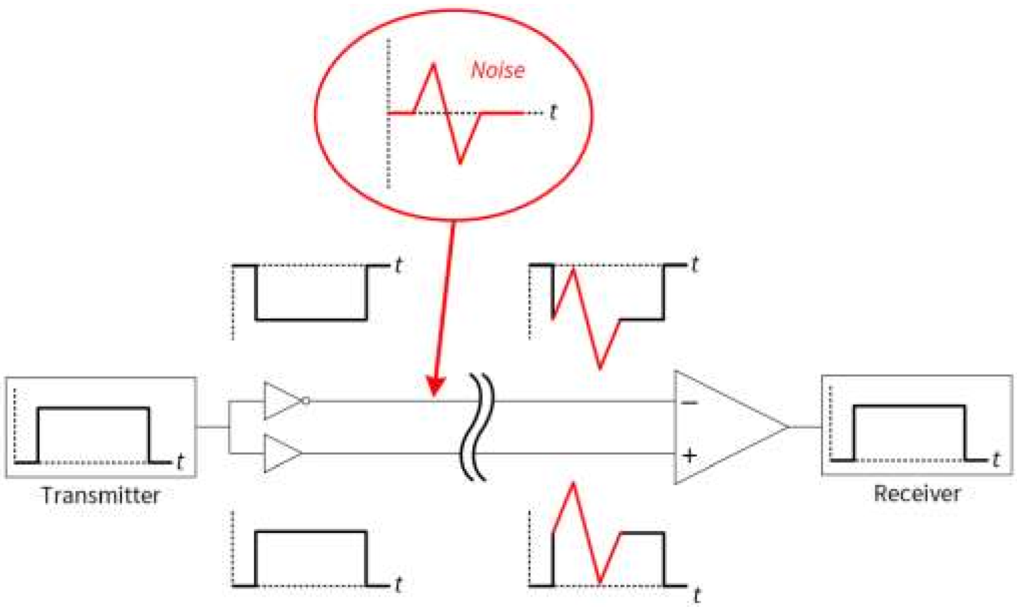

Figure 101: Noise immunity of differential signals.

6.6 Coolant (guide 2.6)

A custom liquid-cooled cold plate developed by Wolverine is used to meet the high-performance thermal requirements of the XM3 package.

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96 Undervoltage-lockout (UVLO): The action taken by an electronic circuit to turn off the power of a device in the event of the voltage dropping below the operational value.

97 Electromagnetic interference (EMI): Interference caused by an electromagnetic disturbance affecting the performance of a device, transmission channel, or system.

98 Differential signaling: Both the original signal and its complement are transmitted in two closely coupled wires. At the receiver, the two signals are compared to reconstruct the original signal. It is used to reduce the impact of radiated noise.

6.7 Ground Connection (guide 2.7)

The safety grounding terminal must be connected to earth ground. Failure to do this when the system is energized could damage the inverter and/or any connected equipment. The grounding terminal is connected internally to the cold plate and module baseplates.

6.8 Performance Data

6.8.1 Short-Circuit Operation (guide 3.1)

The Wolfspeed CGD12HBXMP gate driver is designed to quickly detect and respond to short-circuit events and to safely limit the duration to less than $2\ \mu s$.

6.8.2 Power Testing Results (guide 3.2)

Exercise caution when operating the inverter:

- Very-high voltages are present on the inverter when connected to an electrical source.
- Inverter components can reach temperatures above 50^o C (122^o F).
- High voltage may persist after disconnecting electrical source until the bulk capacitors are fully discharged.

6.8.3 Full-Power Testing (guide 3.2)

The purpose of full-power testing is to determine the efficiency of the inverter by creating the conditions the inverter would face if connected to the electrical grid. Figure 102 (guide Figure 16) presents the full-power test setup with the three XM3 half-bridges connected to three coils and a capacitor bank.

Referring to Figure 103 (guide Figure 15), the inverter was run at a fundamental frequency of 300 Hz (1 cycle/0.0033 sec) and a switching frequency of 10,000 Hz (1 cycle/0.0001 sec) with a maximum load current of approximately 510 A ($which\ is\ equivalent\ to\ 510/\sqrt{2} \approx 360\ A\ RMS$). The inverter processed (converted) 300 kW of power. Total inverter losses were 2.6 kW.

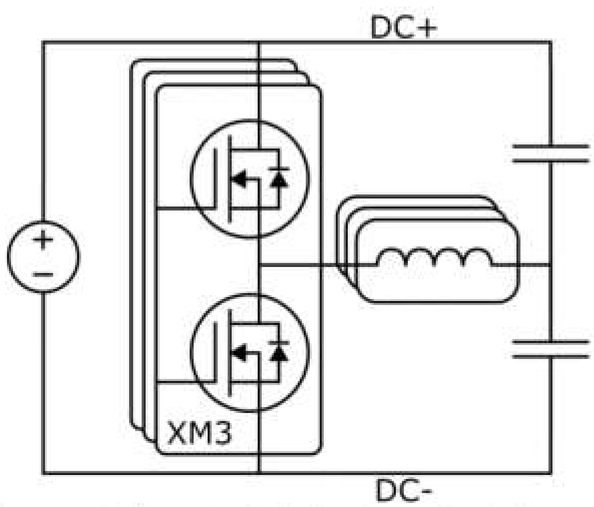

Figure 102: Wolfspeed three-phase recirculating-power test schematics with inductive load.

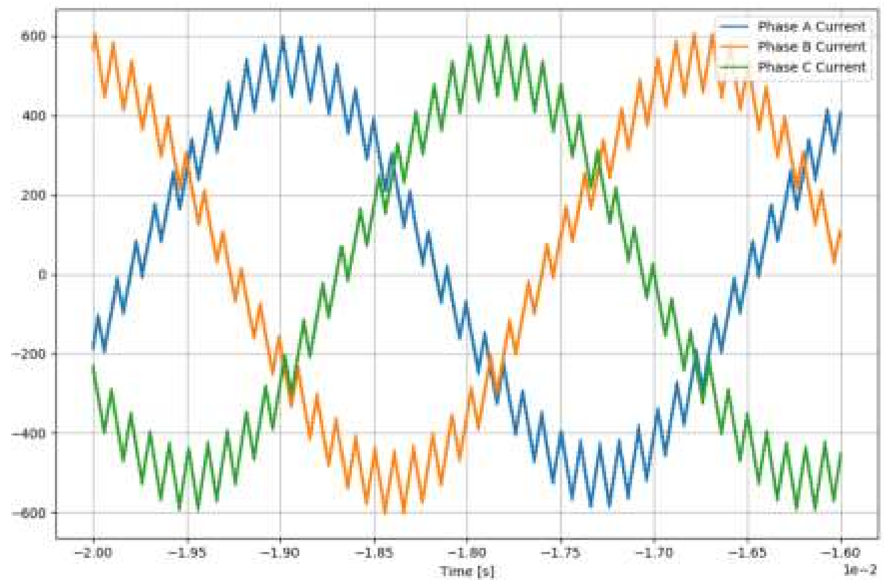

Figure 103: Wolfspeed three-phase inverter testing waveforms.

6.9 Applications

Two applications are shown. The first (Figure 104) is a variable frequency motor drive application and the second (Figure 105) is grid-tied distribution system.

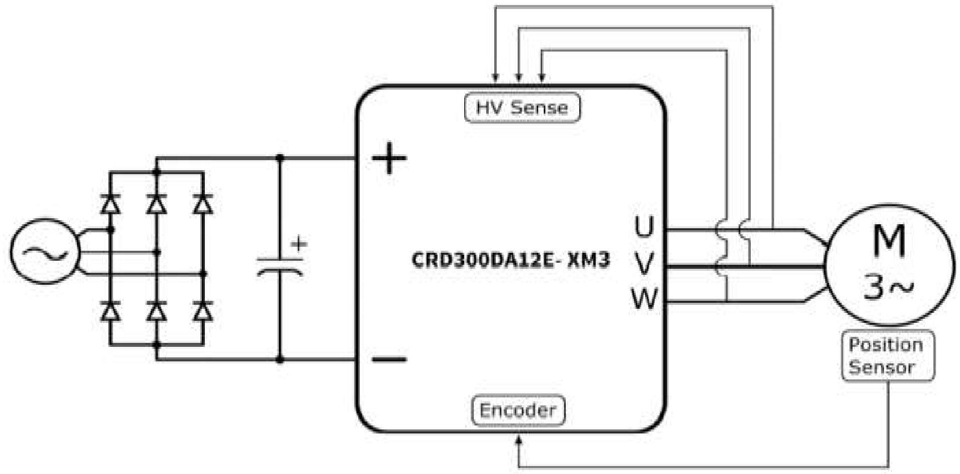

Figure 104: Variable frequency motor drive.

In a variable frequency drive (VFD), the inverter produces the three waveforms U, V, and W with 120^0 phase difference between them. Under program control, the inverter is able to change the frequency of the three phases while maintaining the 120^0 phase shift, which varies the speed of squirrel-cage induction motors.

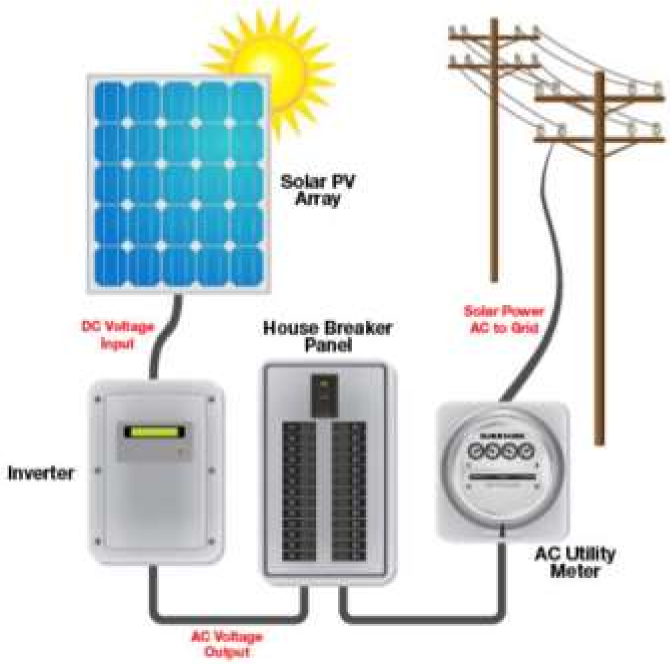

Figure 105: Grid-tied distributed generation (source: Wikipedia[99]).

The function of the inverter in a grid-tied system is to produce an AC voltage synchronized with the grid voltage and connect to the grid. When the grid is down, it automatically turns off and prevents the transfer of voltage to the grid lines while utility workers may be working to restore power (anti-islanding).

Self-Test

1. The inverter shown in Figure 96 is composed of three _________half-bridge power modules, three _________ gate drivers, and the controller using the ___________DSP.
   a. CGD12HBXMP, XM3, TMS320F28379D
   b. XM3, CGD12HBXMP, TMS320F28379D
   c. CGD12HBXMP, TMS320F28379D, XM3
   d. TMS320F28379D, CGD12HBXMP, XM3
2. The XM3 has a ______ reduced volume relative to the industry standard Infineon EconoDUAL (IGBT) package.
   a. 20%
   b. 50%
   c. 30%
   d. 40%
3. The three-phase output voltages of the inverter are designated by either U, V, & W, A, B, and C or L1, L2, and L3.
   (a) True
   (b) False

[99] Wikipedia. "Grid-tied electrical system." Accessed April 8, 2021. https://en.wikipedia.org/wiki/Grid-tied_electrical_system#:~:text=A%20grid-tied%20electrical%20system%2C%20also%20called%20tied%20to,the%20mains%20grid%20can%20make%20up%20the%20shortfall.

4. the XM3 is a low-inductance, high-power-density module utilizing ________ V Wolfspeed C3M SiC MOSFETs and is capable of carrying high currents (from _____ to more than _____ A) while operating at a maximum junction temperature of _______ .
   a. 500-1000, 400, 800, 175 °C
   b. 500-1000, 300, 600, 185 °C
   c. 650-1700, 300, 600, 175 °C
   d. 650-1700, 400, 800, 185 °C
5. The XM3 power modules utilize _________ gate resistors with a short gate signal loop and _______, low-inductance paths to guarantee that the paralleled devices remain stable during high switching speeds.
   a. external, wide
   b. external, narrow
   c. internal, wide
   d. internal, narrow
6. The TMS320F38379 floating-point digital signal processor is used to run the control loop for the inverter and handle I/O. It is a _______, _______, _______ processor with built-in peripherals targeted at real-time control applications.
   a. fixed-point single-core, 100 kHz, 16-bit
   b. floating-point dual-core, 200 MHz, 32-bit
   c. fixed-point dual-core, 200 MHz, 32-bit
   d. fixed-point single-core, 200 MHz, 16-bit
7. One feature of the gate drivers of the inverter is anti-overlap of PWM inputs. It will set _______output channel(s) low if _____ PWM input signal(s) is/are _____ to prevent a controller error from leading to a shoot-through event.
   a. one, one, high
   b. both, both, low
   c. one, both, high
   d. both, both, high
8. The ______ turn-on and turn-off times during switching in a SiC power system can create significant ______ that can easily couple onto the gate control signals. For this reason, _______ signaling is used between the control board and gate driver.
   a. slow, PWM, single-ended
   b. slow, EMI, differential
   c. fast, EMI, differential
   d. fast, PWM, single-ended
9. Very-high voltages are present on the inverter when in operation. Inverter temperatures can reach 50 °C (122 °F). High voltage may persist after disconnecting the electrical source until the bulk capacitors are fully discharged.
   a. False
   b. True
10. Referring to Figure 103, the inverter was run at a fundamental frequency of _______and a switching frequency of ________ with an RMS load current of approximately _______.
    a. 300 Hz, 10,000 Hz, $360\ A\ RMS$
    b. 10,000 Hz, 300 Hz, $510\ A\ RMS$
    c. 300 Hz, 1,000 Hz, $360\ A\ RMS$
    d. 300 Hz, 10,000 Hz, $510\ A\ RMS$

Module Summary

Introduction-Motivation

- Principle WBG semiconductors for use in power electronics: Gallium nitride (GaN) and silicon carbide (SiC).

- Compared to Si-based devices, WBG devices:

  - are more compact
  - have greater power density and efficiency
  - are more reliable
  - can operate at higher switching frequencies and temperatures
- Power density: A measure of power output per unit volume of a power device or module.
- Utilizing SiC devices in inverters results in a significant reduction in inverter:
  - size and weight
  - power losses and material costs
- Both GaN and SiC are becoming attractive in internal combustion engine (ICE), hybrid (H), and hybrid electric (HE) automotive applications.
- WBG semiconductors are expected to bring about energy-saving innovations in a variety of areas, including:
  - energy delivery
  - consumer
  - industrial
  - automotive

Section 1: History of the Development of WBG Devices and Future Applications

- The Si-based metal-oxide-semiconductor field-effect transistor (MOSFET) was invented in 1959 and was first manufactured in 1964.
- The design of new Si-based power electronic devices with greater power densities and efficiencies to meet market demands is becoming more challenging. SiC and GaN have emerged as alternatives to Si in high-power, high-temperature switching applications.
- Shui Nakamura developed the high-brightness blue LED in 1994 using wide-bandgap semiconductor indium gallium nitride (InGaN).
- Beginning in the early 1990s, several companies have made advances in WBG technology. A sampling of these companies includes:
  - STMicroelectronics (Europe's largest semiconductor chipmaker)
  - Infineon Technologies (automotive power semiconductors)
  - Toshiba (SiC Modules)
  - ROHM Semiconductor (SiC power devices)
  - Transphorm (GaN devices)
  - GaN Systems (GaN E-HEMT)
  - Cree
  - NXP Semiconductors
  - United Silicon Carbide (SiC FETs)
  - Qorvo (GaN on SiC MMICs)
  - Texas Instruments
- Micropipes were a major impediment in the development of SiC wafers in the early 1990s.
- The first large-scale use of GaN-on-SiC LEDs occurred in 1995 when blue LEDs developed by Cree were designed into the dashboard of Volkswagen vehicles.

- In 1998, Cree developed the first high-power-density GaN-on-SiC HEMT for wireless and broadcast applications.
- In 2008, Cree introduced the first GaN RF device that utilized the advantages of GaN-on-SiC to improve RF performance.
- SiC was introduced into power electronics in the early 1990s with the support of DOD, NASA, and DARPA.
- The introduction of SiC diodes and transistors has resulted in increased switching frequencies, higher efficiencies, and superior power densities.
- The first commercial SiC power MOSFET was introduced in 2011.
- Most recently, 200 mm (~8 in.) SiC wafers have become available from Cree.

Section 2: Wide-Bandgap Devices

- Bandgap is an energy range between the valence band and the conduction band where electron states are forbidden.
- The size of the bandgap represents the amount of energy needed to excite electrons from the material's valence band into the conduction band, and it is a major factor in determining semiconductor properties.
- The bandgaps of SiC and GaN are approximately three times that of Si; this is why they are referred to as wide-bandgap (WBG) semiconductors.
- Two types of power loss occur in switching devices: conduction losses and switching losses. Small values of ON resistance minimize conduction losses. To minimize switching losses, the device must switch at high frequencies.
- The use of WBG semiconductor devices in power conversion systems—as alternatives to Si—results in significantly lower power loss in many application areas.
- SiC- and GaN-based semiconductors go beyond the limitations of Si-based components. The wider bandgap of SiC and GaN-based devices enables higher operating temperatures, frequencies, and voltages. SiC and GaN-based devices are faster in switching, smaller, more efficient, and have lower power losses.
- Because of its higher electron mobility, GaN is more suitable than SiC for high-frequency applications.
- GaN devices generally have blocking voltages below 650 V while SiC devices have blocking voltages in the range from 650 V to 1700 V.
- Although WBG materials are rapidly gaining acceptance, several manufacturing challenges must be met to make them cost-effective and spur further commercialization. For example:
  - reduction in the cost of producing large-diameter wafers
  - alternative packaging designs to withstand high temperatures and inductive losses encountered in WBG devices
  - system redesign to suit replacement of Si-based devices

Section 3: Device Structure, Operation, and Testing Procedure

- MOSFET devices can be classified as either enhancement (E) or depletion (D).
- Terminals attached to the MOSFET are identified as the drain (D), source (S), and gate (G).
- For the D-MOSFET—in contrast to the E-MOSFET—a physical channel exists between drain and source.
- In the schematic symbols for MOSFETs, the broken lines for the E-MOSFET symbolize the absence of a physical channel between drain and source while the continuous thick line connecting drain and source in a D-MOSFET symbolizes an actual physical channel.
- The body diode is a useful by-product of the Si and SiC MOSFET structure. The body diode is useful in circuits that require a path for the reverse drain current (such as half-bridge circuits with inductive loads).

- A voltage at the gate of the MOSFET produces an electric field which controls the current flowing between the source and drain junctions.
    - The E-MOSFET remains in a nonconducting state ("normally open" switch) unless a voltage at the gate is present.
    - The D-MOSFET remains in a conducting mode ("normally closed" switch) unless a voltage at the gate is applied.
- Power MOSFETs are used for switching large amounts of current.
    - Si and SiC *power* MOSFETs typically have a *vertical* channel structure, where the source (S) and drain (D) are situated on the upper and lower surfaces. This placement of source and drain allows the MOSFET to handle larger amounts of power than possible with the lateral structure.
    - Vertical power MOSFETs have two general forms—planar and trench.
- GaN HEMT devices are capable of high-frequency operation (up to millimeter wave frequencies, 30-300 GHz). They are used in high-frequency products such as cell phones, satellite television receivers, voltage converters, and RADAR equipment.
- MOSFET testing with a DMM:
    - In testing the OFF-state, the DMM will display OL.
    - In testing the ON-state, the DMM will read a continuously decreasing resistance value between drain and source which indicates that as the gate capacitor is accumulating charge, a channel with decreasing resistance is forming. Eventually the DMM will read a low-resistance value. The meter will not be able to read the minimum $R_{DS}(on)$ resistance because the DMM cannot apply a gate voltage above the threshold voltage needed to turn the MOSFET fully on.

Section 4: Device Driving Issues and Typical Circuitry Utilizing WBG Devices

- Gate driver:
    - appears between the controller output and the MOSFET gate input
    - required as an interface to translate the on/off signals from the controller into power signals necessary to control the MOSFET
- The MOSFET gate can be modeled as a simple capacitor.
- Power MOSFETs are voltage-driven devices.
- Charging the gate of an E-MOSFET turns the device on (the MOSFET conducts); discharging the gate turns the MOSFET off, blocking a typically large voltage across the drain-to-source terminals.
- The MOSFET has a nonzero, finite switching time.
    - During switching, the device may be in a high-current, high-voltage state. This results in power dissipation in the form of heat.
    - Transition of the MOSFET switch from one state to another must be fast to minimize switching losses.
- During turn-on and turn-off of the MOSFET, the value of the external gate resistor in the gate charge and discharge path affects:
    - magnitude of the gate current pulses
    - pulse rise and fall times
    - switching losses
- Tradeoff exists between gate resistance values and switching losses.
- MOSFET gate drivers are available in various forms:
    - low-side
    - high-side
    - low-side or high-side
    - half-bridge
    - full-bridge

    - three-phase
- Isolation:
    - electrical separation between various subcircuits of a system so that there is no direct conduction path between them but signal and/or power still pass between the subcircuits
    - protection of both the user and electronics from faults on the high-voltage side.
    - three main forms of isolation are—
        - optical
        - magnetic
        - capacitive
- A traction inverter converts DC power from an on-board high-voltage battery into AC power to drive the main motor or motors of an electric vehicle.
- Galvanic isolation in traction inverters:
    - This separates controllers on the primary side from high-voltage circuits on the secondary side.
    - Safety standards require the isolation of potentially lethal voltages and currents from possible human contact.
- A reference design refers to a publicly-available hardware design that is intended for others to copy.
    - It contains the essential elements of the system.
    - Third parties may enhance or modify the design as required.
    - Its main purpose is to support companies in development of next-generation products using the latest technologies.
    - Reference design packages enable a fast-track to market. This can cut costs and reduce risk in the customer's integration project.
- Gate driver designs for WBG devices are much more critical than those for Si-based devices—
    - The gate drivers should be able to operate at higher switching frequencies and provide precise voltages with sufficient drive capability to achieve fast turn-on and turn-off speeds.
    - Without the proper gate drivers, WBG MOSFETs will not perform at the expected high switching frequencies and power levels.
- Semiconductor companies, such as Texas Instruments and Infineon, manufacture several types of modular gate drivers that serve as an interface between a low-voltage, low-current PWM output from a microcontroller and power switches like MOSFET and IGBT.
    - UCC27524A, a dual-channel, low-side, high-speed, integrated gate driver—able to drive Si and SiC MOSFETs as well as IGBTs.
    - UCC21520, an isolated dual-channel gate driver—able to drive Si and SiC MOSFETs and IGBTs. It has two types of isolation barriers, reinforced and functional isolation. Capacitive isolation is employed in each case. It can be configured as two low-side drivers, two high-side drivers, or a half-bridge driver.
    - LMG1205, designed to drive GaN FETs. They can drive both the high-side and the low-side enhancement-mode GaN FETs in a synchronous buck, boost, and half-bridge configuration.
- The unique combination of high voltage, high current, and increased switching speed of WBG devices requires careful consideration of the PCB layout to reduce the effects of these parasitics. Failure to sufficiently minimize the effect of parasitics can lead to instability and oscillation in the switching waveform and subsequent degradation of performance of WBG power devices.
- In addition to taking steps to minimize parasitic inductance and capacitance in PCBs having WBG devices, properly-designed thermal management is also required.
- The PCB designer must be aware of the tradeoff between the minimization of inductive and capacitive parasitics because layouts that minimize parasitic inductance with large ground-return

current loop widths can result in large parasitic switch-node capacitance if not properly accounted for.

- To minimize parasitic capacitance, make the critical traces as narrow as the PCB process can handle, keep a good distance from nearby traces, minimize overlap between traces, and have no other traces or ground plane underneath the trace.
- To minimize parasitic inductance, make gate-drive traces as wide across and as short in length as possible.
- For gate drivers, route the high-side gate and the switch-node trace as close as possible to minimize inductance.
- Removing heat from the junction of the surface mount HEMT of Figure 57 is challenging because the junction is essentially buried inside the device. The pad to be connected to the heatsink is the large light area. Figure 58 models the path from the junction to the external ambient atmosphere for the surface mount package. Thermal resistance is shown for each segment. The objective is to achieve low total thermal resistance. The vias, depicted as vertical copper conductors in the figure, provide a low-resistance thermal path through the multilayer PCB to the heatsink.
- Heatsink attachment methods (for the ON Semiconductor Motion SPM ® 5 Module, an inverter for small power motors)—before applying a particular method, the operating conditions must be considered:
    - Attachment using a thermal adhesive material, Figure 59.
    - Direct assembly using screws, Figure 60. This method is stable against external vibration, which may be common in motor applications.
    - Direct assembly using screws, Figure 61. This is an improved version of the previous heatsink. It has legs for support.
    - Heatsink clip, Figure 62. No contact is made with screws. The SPM 5 package has a trench at the bottom center of the package. The clip is designed so that it can be used to assemble the package to the heatsink.
- The higher heat loads and smaller packaging of WBG devices mean that conventional (passive) heatsinks may not be sufficient. Liquid cooling provides an alternative for increasing the rate of heat transfer to the atmosphere.
    - One approach comes from Advanced Thermal Solutions. Their cold plate, shown in Figure 63, transfers heat from the device to a liquid that flows to a remote heat exchanger.
    - Hitachi Automotive Systems has developed a double-sided cooling approach that uses liquid cooling for their high-voltage EV inverter (Figure 64). Direct double-sided cooling greatly improves the thermal conductance, enabling higher current loading and power density.
- Texas Instruments TIDA-010054 bidirectional dual-active-bridge DC-DC converter is composed of two modular PCBs—a gate driver board and dual H-bridge board, both utilizing SiC MOSFETs.
    - Top and side views of the TIDA-010054 PCBs are depicted in Figure 67. The gate driver boards are mounted vertically (two on the left and two on the right). The heatsink is mounted below the PCB.
    - The overall bidirectional conversion system schematic/block diagram is shown in Figure 23.
        - Magnetic coupling provides galvanic isolation of the high- and low-voltage stages. The high- and low-voltage stages are driven by the TMS320F280049 digital controller and UCC51230 dual active-bridge gate drivers.
    - Applications:
        - solar cell installations
            - excess DC solar power is fed into the AC grid during the day

        - when the local storage batteries are depleted, the installations can be charged from the grid through a bidirectional converter/inverter.
    - electric vehicles (EVs)
        - the bidirectional converter can be used to drop a high-traction battery voltage (approximately 400 V) down to 12 V to drive auxiliary equipment
        - if the voltage of the traction battery falls too low, it can convert 12 V back to 400 V
        - can also be used in EV charging stations to provide fast, efficient recharge

Section 5: Applications and Sample Circuit Block Diagrams

- Regarding Figure 69, SiC devices are superior to GaN in terms of their higher power capability while GaN devices are superior to SiC in terms of their higher frequency of operation.
- WBG devices can displace Si in several key areas:
    - IT and Consumer
        - PFC and power supplies in electronic appliances and computing
        - converters and inverters in uninterruptible power supplies
    - automotive
        - DC/AC inverters and DC/DC converters in hybrid and electric vehicles
    - industrial
        - inverters in power distribution, rail transport, photovoltaics, motor control, water turbines
- LIDAR:
    - a detection system which works on the same principles as RADAR by using laser light
    - determines detailed three-dimensional images for control and navigation in autonomous vehicles
    - requires fast switching of high-current pulses to meet performance specifications
    - GaN devices—having much higher switching speeds than Si—satisfy the needs of the switching component of the laser driver circuit
- 48-V automotive batteries:
    - Most new hybrid vehicles now include a 48-V system, and standard vehicles with internal combustion engines are moving in that direction.
    - For a given amount of power, the increase in voltage from 12 V to 48 V reduces the current requirement. This allows for smaller wire gauge. This reduces cable size, weight, and cost without sacrificing performance.
- More electric aircraft (MEA) and electronic propulsion systems (EPS) require the utilization of much larger amounts of electric power than prior aircraft designs have used. With the increased utilization of converters and inverters, WBG power electronic devices in future aircraft designs will be essential in minimizing power losses and increasing reliability.
- Solar power (photovoltaic) systems:
    - the dominant form of renewable energy
    - operation of photovoltaic systems:
        - solar panels generate a DC voltage
        - a bank of storage batteries is charged by connecting the solar panel output to a DC/DC converter
        - an AC voltage is generated by connecting the solar panel output to a DC/DC boost converter followed by a DC/AC inverter
    - use of WBG devices in photovoltaics:
        - high efficiency and ability to operate at high temperatures and frequencies enhances the performance of solar power systems

    - high frequency of operation significantly reduces the size and cost of components such as inductors and capacitors
    - high operating temperature simplifies cooling requirements
- UPS and SMPS:
  - Uninterruptible power supplies (UPS) provide a stable and continuous supply of power for data centers, industrial manufacturing processes, telecommunications, medical appliances, and small offices.
  - Switch-mode power supplies (SMPS) provide DC power for consumer electronics (including electronic devices such as televisions, computers, and smartphones).
  - When WBG devices replace Si-based devices, these systems operate more efficiently and with significantly fewer power losses.
- The smart grid:
  - The smart grid describes an electrical grid that is integrated with a computerized, two-way communication network. While older electrical grids send electrical power in one direction only—from a power plant to homes and offices—a smart grid provides bidirectional flow of power and instantaneous feedback on systemwide operations.
  - Wide-bandgap power electronic devices such as SiC and GaN will play an important role in the ongoing process of grid modernization toward a smart grid.
- A microgrid is a compressed version of the national grid. A modern AC or DC microgrid is typically supplied by renewable energy sources (solar, wind, fuel cells, etc.).
- Robots consist of:
  - Several functional components including a manipulator arm, image and position sensing, and motor and sensor control units.
  - A variety of power subsystems including AC/DC conversion, battery management, DC/DC conversion, multiphase converters, point-of-load (POL) conversion, linear regulation, and motor drivers.
  - WBG devices. The use of WBG devices in robot subsystem allow them to operate efficiently, reliably, and at high levels of power density. This results in small, nimble robot designs.
- There are four types of robots. Each subsequent robot type requires larger amounts of electrical power to operate:
  - service
  - collaborative
  - mobile, also known as automated guided vehicles (AGV)
  - industrial

Section 6: Case Study – High-Power Inverter

- A three-phase inverter converts DC into three-phase power. This provides three AC sinusoidal waveforms which are uniformly separated in phase angle by 120^o and equal in amplitude and frequency.
- The jagged-edged sinusoidal waveforms produced by the Wolfspeed CRD300DA12E-XM3 (300 kW) three-phase inverter circuit are created by turning the MOSFETs of the inverter on and off in a pulsating manner multiple times per cycle.
  - This is known as pulse-code modulation (PCM) for sinusoidal-waveform generation.
  - The jagged waveforms do not present a problem because the load acts as a low-pass filter that tends to smooth the edges out.
- The CRD300DA12E-XM3 (300 kW) three-phase inverter is composed of:
  - three XM3 half-bridge power modules with built-in current and temperature sensors
  - three CGD12HBXMP gate drivers
  - a controller using the TMS320F28379D DSP (the controller supports three external high-voltage measurements)

- The overall physical dimensions of the inverter are 279 mm by 291 mm by 115 mm (11 in by 11.5 in by 4.5 in) with an equivalent volume of 9.3 L.
- The inverter features minimal stray inductance that results in low-peak overshoot and oscillation in switch voltages and enables faster turn-on and turn-off times. This results in lowering switching losses.
- The low-inductance XM3 power modules used in the inverter have a power density approaching 32.25 kW/L—more than twice that of comparable Si -based modules. The XM3 utilizes 650-1700 V Wolfspeed C3M SiC MOSFETs.
- The XM3 power modules utilize internal gate resistors with a short-gate signal loop and wide, low-inductance paths, and can be safely used with zero external gate resistors when a low-inductance bus structure and low-inductance capacitors are used.
- Protection features of the gate drivers include tunable over-current detection with soft shutdown, undervoltage lockout, and anti-overlap of PWM inputs to prevent shoot-through.
- Undervoltage-lockout (UVLO) is the action taken by an electronic circuit to turn off the power of a device in the event of the voltage dropping below the operational value.
- In differential signaling, both the original signal and its complement are transmitted in two closely-coupled wires. At the receiver, the two signals are compared to reconstruct the original signal. It is used to reduce the impact of radiated noise.
- Differential signaling is used between the gate driver and controller board to reduce the impact of radiated noise from the switching events of the power module.
- A custom, liquid-cooled cold plate developed by Wolverine is used to meet the high-performance thermal requirements of the XM3 package.
- The safety grounding terminal must be connected to earth ground. Failure to do this when the system is energized could damage the inverter and/or any connected equipment. The grounding terminal is connected internally to the cold plate and module baseplates.
- Exercise caution when operating the inverter.
    - Very-high voltages are present on the inverter when connected to an electrical source.
    - Inverter components can reach temperatures above 50 °C (122 °F).
    - High voltage may persist after disconnecting the electrical source until the bulk capacitors are fully discharged.
- The full-power test determines the efficiency of the inverter by creating the conditions the inverter would face if connected to the electrical grid. The inverter processed 300 kW with a 2.8 kW power loss.

Module Review Questions

Introduction-Motivation

1. Name the principle WBG semiconductors for use in power electronics.
2. List several advantages of WBG devices over Si devices.
3. Identify several areas in which WBG semiconductors are expected to bring about energy-saving innovations.
4. Define power density.

Section 1: History of the Development of WBG Devices and Future Applications

1. When was the first MOSFET manufactured?
2. When was the blue LED discovered and by whom?
3. List ten semiconductor companies that have made innovations in WBG technology.
4. What are micropipes? Why are they problematic?
5. The first large-scale use of GaN-on-SiC LEDs occurred when?
6. When did Cree develop the first high-power-density GaN-on-SiC HEMT for wireless and broadcast applications?
7. When was SiC introduced into power electronics? What national institutions supported this introduction?
8. When was the first commercial SiC power MOSFET introduced?
9. What SiC wafer size has recently become available from Cree?

Section 2: Wide-Bandgap Devices

1. What is bandgap and what does the size of the bandgap represent?
2. Why are SiC and GaN called wide-bandgap semiconductors?
3. What two types of power loss occur in switching devices?
4. List several advantages of WBG devices in comparison with Si-based devices.
5. What is the range of blocking voltage for GaN devices and for SiC devices?
6. What are the manufacturing challenges that must be met to make WBG devices cost-effective and spur further commercialization?

Section 3: Device Structure, Operation, and Testing Procedure

1. What are the two main classifications or types of MOSFET devices? For which does a physical channel exists between drain and source? In the schematic symbol for the MOSFET, the broken lines symbolize which type?
2. Which type of MOSFET device remains nonconducting unless a voltage at the gate is present?
3. Power MOSFETs are used for switching large amounts of current. What type of channel do they typically have—vertical or lateral?
4. In testing the OFF-state of a MOSFET with a DMM, what will the DMM display?
5. In testing the ON-state of a MOSFET, is it possible to obtain an accurate measurement of $R_{DS}(on)$? Explain.

Section 4: Device Driving Issues and Typical Circuitry Utilizing WBG Devices

1. What serves as an interface to translate the on/off signals from the controller into power signals necessary to control the MOSFET?
2. Transition of the MOSFET switch from one state to another must be fast to minimize what?
3. During turn-on and turn-off of the MOSFET, the value of the external gate resistor in the gate charge and discharge path affects what?
4. List the various forms of MOSFET gate drivers.
5. What are the three main forms of electrical isolation?
6. What is the purpose of a traction inverter?
7. What is the purpose of a reference design?
8. Why is the performance of WBG devices more susceptible to PCB parasitic capacitance and inductance than Si-based devices?
9. How can parasitic capacitance be minimized? How can parasitic inductance be minimized?
10. The higher heat loads and smaller packaging of WBG devices mean that conventional (passive) heatsinks may not be sufficient. Name an alternative cooling method.
11. Can gate-driver designs for Si-based devices be used for WBG devices? Explain.
12. List various heatsink attachment methods.
13. Regarding the Texas Instruments TIDA-010054 bidirectional dual-active-bridge DC-DC converter:
    (a) What two modular PCBs is it composed of?
    (b) What two functions can the converter perform in solar-cell installations?
    (c) What functions can the converter perform in electric vehicles (EVs)?

Section 5: Applications and Sample Circuit Block Diagrams

1. Regarding Figure 69:
    (a) SiC devices are superior to Si in terms of which—their higher frequency of operation or their higher power capability?
    (b) GaN devices are superior to Si in terms of which—their higher frequency of operation or their higher power capability?
2. List several key areas in which WBG devices can displace Si.
3. What is LIDAR? What WBG device satisfies the fast switching of high-current pulse requirements of LIDAR laser driver circuits?
4. List the advantages of using 48-V automotive batteries. What brings about these advantages?
5. Explain the operation of photovoltaic systems for producing AC.
6. List several of the advantages of using WBG devices in photovoltaics.
7. Describe a smart grid; describe a microgrid.
8. List the functional components of a robot and the power subsystems.
9. What are the four types of robotic systems?

Section 6: Case Study—High-Power Inverter

1. What method is used in creating the sinusoidal waveforms of the Wolfspeed CRD300DA12E-XM3 (300 kW) three-phase inverter? Do the jagged-edged sinusoidal waveforms produced present a problem? Explain.
2. What are the building blocks of the CRD300DA12E-XM3 (300 kW) three-phase inverter?
3. How does low stray inductance affect the performance of the inverter?
4. What protection features are built into the gate drivers of the inverter?

5. What is UVLO?
6. What is differential signaling and how is it used in the inverter?
7. What type of cooling is used in the inverter?
8. What cautions must be exercised when operating the inverter?
9. What is the purpose of full-power testing?

Glossary

1. **Blocking voltage:** The rating of a device, also referred to as the rated voltage—the maximum voltage the device can tolerate when it is not conducting.
2. **Boule:** A single-crystal semiconductor ingot produced by synthetic means. It can be made by various methods, such as the Bridgman and Czochralski processes (both of which result in a cylindrical rod of material). The boule is sliced into thin wafers on which integrated circuits are formed.
3. **Breakdown field (in V/cm or kV/mm):** A measure of the dielectric strength of the material (just as tensile strength is for mechanical behavior).
4. **Breakdown voltage:** The drain-source voltage for which the drain-source current increases exponentially and MOSFET failure occurs.
5. **DARPA:** Defense Advanced Research Projects Agency.
6. **Data center:** A physical facility for the remote storage, processing, or distribution of large amounts of data.
7. **Differential signaling:** Both the original signal and its complement are transmitted in two closely coupled wires. At the receiver, the two signals are compared to reconstruct the original signal. It is used to reduce the impact of radiated noise.
8. **DOD**: Department of Defense.
9. **Electromagnetic interference (EMI):** Interference caused by an electromagnetic disturbance affecting the performance of a device, transmission channel, or system.
10. **Electron mobility:** A measure on how quickly an electron can move through the material when subjected to an electric field.
11. **Form factor:** A hardware design aspect that defines and prescribes the size, shape, and other physical specifications of electronic components.
12. **Inverter:** An electronic circuit primarily used in high-power applications for converting DC to AC.
13. **LIDAR:** A method for measuring distances (ranging) by illuminating the target with laser light and measuring the reflection with a sensor. Differences in laser return times and wavelengths can then be used to make digital 3-D representations of the target.
14. **Micropipe:** A cavity that begins to form on the wafer surface and burrows into the wafer like a pothole. Micropipe defects can short-circuit an electronic device causing it to fail.
15. **NASA:** National Aeronautics and Space Administration.
16. **Net:** A connection between two or more components on a PCB.
17. **Trace:** A line of copper that makes an electrical connection between two or more points on a PCB.
18. **Pads:** Small areas of copper on a PCB used for connecting component pins.
19. **ON resistance:** The resistance from the drain (terminal D) to source (terminal S) in a MOSFET when conducting. Typical values of IGBT and MOSFET ON resistance are in the tens of milliohms. It is denoted by $R_{DS}(on)$.
20. **POL converters:** Converters placed near the processor consuming the power, avoiding long wiring distances between the converter and processor.
21. **Power density:** A measure of power output per unit volume. If a device has high power density, then it can output large amounts of energy based on its volume. For example, a tiny capacitor may have the same power output as a large battery, but because the capacitor is so much smaller, it has a higher power density.
22. **Printed circuit boards (PCBs):** The most common method of assembling modern electronic circuits. They are comprised of a sandwich-like arrangement of one or more insulating layers and one or more copper layers which contain the signal traces, powers, and grounds.

23. **PWM (pulse width modulation):** A means for creating an analog-like signal by applying voltage in pulses or short bursts. PWM is one of the primary means by which MCUs drive analog devices like variable-speed motors, dimmable lights, actuators, and speakers[100].
24. **Reference design:** A hardware design that is intended for others to copy. It contains the essential elements of the system; third parties may enhance or modify the design as required. Every reference design has been built and tested and comes with comprehensive, standardized documentation including a data sheet with detailed design notes, verification test results, schematic, bill of materials, and PCB artwork. The main purpose of reference design is to support companies in development of next-generation products using latest technologies. Reference design packages enable a fast-track to market to cut costs and reduce risk in the customer's integration project.
25. **Saturation velocity:** The maximum velocity that a charge carrier in a semiconductor attains in the presence of very high-electric fields.
26. **Shoot-through:** A short-circuit condition occurring when both the high-side and low-side MOSFETs are on at the same time.
27. **Thermal conductivity:** A measure of the ability of a material to conduct heat.
28. **Threshold voltage (of a MOSFET):** The minimum gate bias required for creating a conduction path between its source and drain.
29. **Undervoltage-lockout (UVLO):** The action taken by an electronic circuit to turn off the power of an electronic device in the event of the voltage dropping below the operational value.
30. **Voltage converter**[101]**:** A circuit that changes the voltage (either AC or DC) of an electrical power source. There are two types of voltage converters: *step-up converters* (which increase voltage) and *step-down* converters (which decrease voltage).

[100] Heath, Janet. 2017. "PWM: Pulse Width Modulation: What is it and how does it work?" https://www.analogictips.com/pulse-width-modulation-pwm/.
[101] "What is a Power Converter?" Analog IC Tips. Accessed March, 2021. https://www.analogictips.com/pulse-width-modulation-pwm/.

Answers to Self-Tests

Section 1:

1. c	7. c
2. c	8. b
3. c	9. d
4. b	10. d
5. a	11. d
6. b	12. b

Section 2:

1. c	6. c
2. c	7. b
3. c	8. b, d
4. a	9. c
5. b	10. c, b

Section 3:

1. b, d	7. b
2. a, d	8. c
3. c	9. b
4. d	10. c
5. b	11. d
6. c	12. c

Section 4:

1. c	6. d
2. b	7. b
3. d	8. c
4. a	9. b
5. c	10. a

Section 5:

1. b	7. b
2. b	8. d
3. d	9. b
4. c	10. c
5. b	11. b
6. c	12. a

Section 6:

1. b	6. b
2. d	7. d
3.a	8. c
4. c	9. b
5. c	10. a

Appendix A
Datasheets

Vishay IRF510 Power MOSFET:

http://www.irf.com/product-info/datasheets/data/irf510.pdf (irf.com)
https://www.vishay.com/docs/91015/sihf510.pdf (vishay.com)

Macon NPT1012B GaN Power Transistor:

https://cdn.macom.com/datasheets/NPT1012B.pdf (macom.com)

Rohm SCT3160KW7 N-channel SiC power MOSFET:

https://www.mouser.com/datasheet/2/348/sct3160kw7_e-1901413.pdf (mouser.com)

Microchip MCP14A0051/2 MOSFET Driver:

https://ww1.microchip.com/downloads/en/DeviceDoc/20005369A.pdf (microchip.com)

Microchip MIC4604 Half bridge Driver:

https://ww1.microchip.com/downloads/en/DeviceDoc/20005852A.pdf (microchip.com)

Texas Instruments UCC21520 Gate Driver:

https://www.ti.com/lit/ds/symlink/ucc21520.pdf (ti.com)

Texas Instruments MSP430G22x0 Mixed Signal Microcontroller:

https://www.ti.com/lit/ds/symlink/msp430g2230.pdf?HQS=dis-dk-null-digikeymode-dsf-pf-null-wwe&ts=1609708079241 (ti.com)

Texas Instruments LMG1205 Half Bridge GaN Driver:

https://www.ti.com/lit/ds/symlink/lmg1205.pdf?ts=1612258059863 (ti.com)

Infineon IMW65R27M1H SiC Trench Power MOSFET Datasheet:

https://www.infineon.com/dgdl/Infineon-IMW65R027M1H-DataSheet-v02_00-EN.pdf?fileId=5546d4626f229553016f85ab88170463 (Infineon.com)

Texas Instruments UCC12050 DC-DC Power Converter Module:

https://www.ti.com/lit/ds/symlink/ucc12050.pdf?ts=1612285050327&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FUCC12050 (ti.com)

Appendix B
Wolfspeed XM3 three-phase 300 kW inverter guide

Appendix C

Solar Energy (Photovoltaic) Systems

Three basic types of solar-power-generating system block diagrams—central, string, and micro—are first considered. This is followed by the description of a solar inverter block diagram.

Figure 106 depicts the three basic solar system configurations. The inverter is a key element of these systems and each system utilizes at least one inverter. It converts the variable direct current output of photovoltaic panels into a 60 Hz alternating current that is then applied directly to the commercial electrical grid or to a local off-grid network.

The level of power required determines the choice of configuration. The micro-inverter-type system is for low power (50-400 W), the string inverter type is for medium power (1-20 kW), and the central inverter type is for high power (above 20kW)[102].

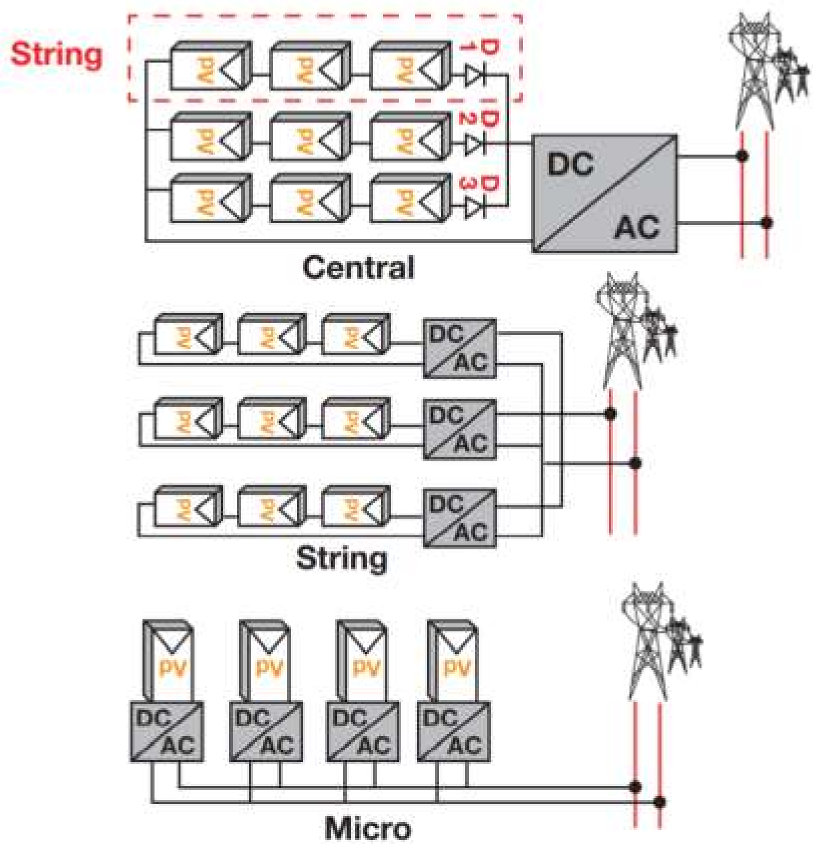

Figure 106: Types of solar energy systems (source: Texas Instruments).

Main characteristics of each inverter type

Micro Inverters

- A separate inverter is integrated into each solar panel.

[102] Sridhar, Nagarajan. 2018. "Demystifying high-voltage power electronics for solar inverters." Texas Instruments Incorporated. Accessed February, 2021. https://www.ti.com/lit/wp/slyy143/slyy143.pdf?ts=1614102222982&ref_url=https%253A%252F%252Fwww.bing.com%252F.

- If one or more panels are shaded or are performing at a lower level than the others, the performance of the remaining panels will not be jeopardized.
- They are more efficient than string inverters.

String Inverters

- The solar panels are installed in rows in a serial or string arrangement—nine panels with three rows of three panels—where each string is connected to a single inverter.
- They can be scaled up, meaning that rows can be conveniently added.
- Of the three system types, string inverters are the most in demand.

Central Inverters

- These are rows of serially coupled solar panels are connected in parallel.
- They use a single inverter.
- They require fewer component connections than string inverters.
- They are well-suited for large installations.

The system block diagram of the solar inverter is shown in Figure 107. It is composed of solar panels, a DC/DC converter, a DC/AC inverter, a gate driver, an isolation section, a controller, and communication. The controller acts as the brain of the system. It executes the algorithms required to invert the variable DC voltage output of the solar panels to AC. Solar inverters employ switched-mode power electronics. Power switches, typically MOSFETs and IGBTs, are gate-controlled. Once the gate driver senses an incoming signal from the controller, it provides the power needed for the rapid turn-on and turn-off of the power switch.

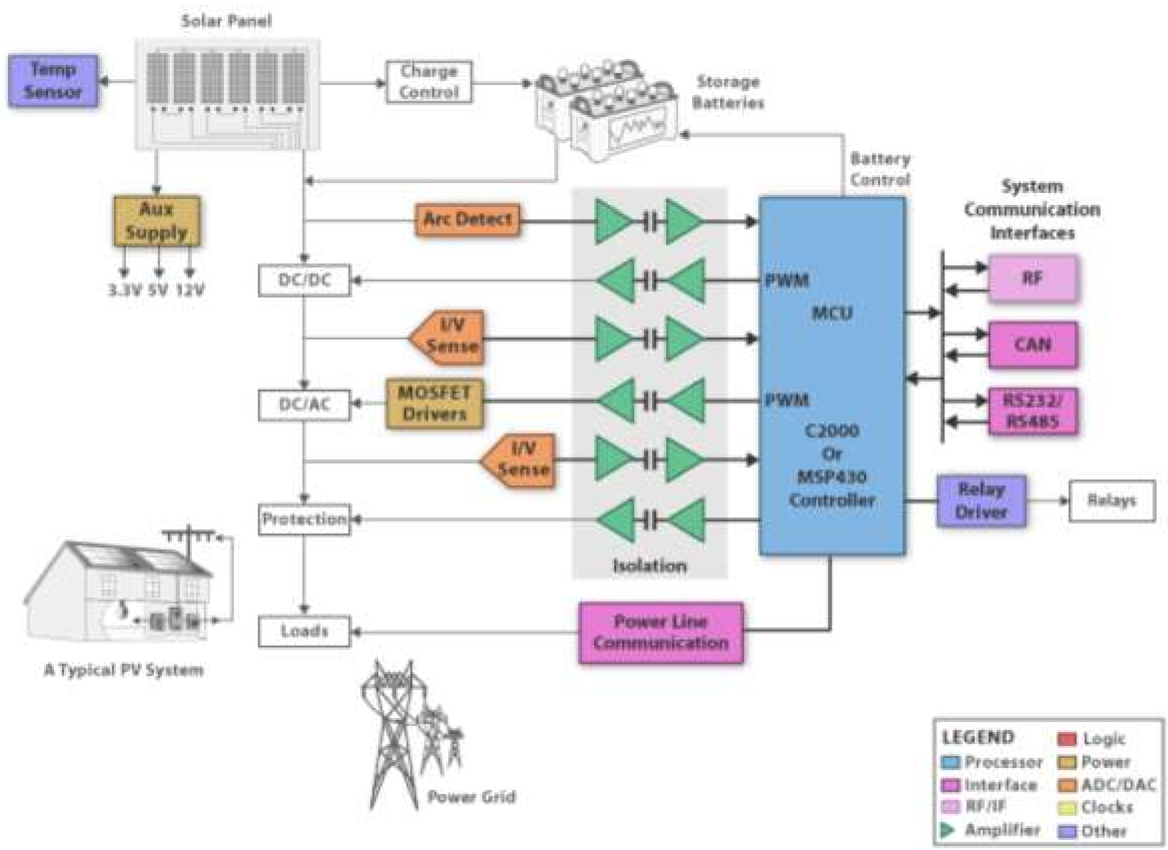

Figure 107: Solar inverter block diagram.