White Paper
10-2018

How GaN-on-Si can help deliver higher efficiencies in power conversion and power management

Introducing Infineon's CoolGaN™

Abstract

This paper describes the benefits of gallium nitride on silicon (GaN-on-Si) technology in power designs. Key differences between silicon (Si), silicon carbide (SiC) and gallium nitride (GaN) technologies are discussed as well as features and benefits of Infineon’s CoolGaN™ HEMTS are exposed.

By Andrea Bricconi, Head of Business Development Automotive GaN, Infineon Technologies AG

Table of contents

1 Introduction

Efficiency is a powerful driving force in all industries, as inefficiency often translates into unnecessarily high costs. In electronics, efficiency can also lead to limitations on overall performance or, if those limitations are not observed, a shortened product lifetime. The same market forces that impact all commerce and industry drive the pursuit of greater efficiency in power conversion. Just as significantly, however, is the need for increased efficiency in order to enable higher power density. This will not only allow for smaller, lighter and more reliable products, but help lift the limitations on performance and deliver increased levels of power in key infrastructure such as data centers, as well as emerging applications like electric vehicles.

Furthermore, as the number of connected devices increases on a daily basis, more efficient power conversion can, in part, reduce the overall financial cost of powering those many billions of devices. And because of the huge numbers involved it has, more recently, become equally important to improve overall efficiencies in order to lower the environmental cost of powering the modern world.

The law of conservation of energy states that energy is never destroyed or created, it merely changes state. In electronics we often refer to that change in state as losses, particularly when the resultant state is heat. Such losses are endemic in power conversion and heat is a particular enemy of semiconductor devices. The cost of removing unwanted heat from electronic equipment is unwelcome and environmentally damaging.

This has fueled the research and development into more efficient semiconductor devices in order to increase efficiencies in power conversion, improve power density and lower the overall financial and environmental impact of power management.

Power semiconductors have historically been based on a silicon substrate, however while silicon is an excellent general-purpose semiconductor it has well documented limitations when it comes to high voltages. The semiconductor industry has striven to overcome these limitations and has largely been relatively successful. However as the demand for more power continues unabated, the industry at large is moving away from silicon in favor of semiconductor materials that feature characteristics more suitable to power. These materials are classified as wide bandgap, which refers to the fact that they are physically different at the crystalline level to materials like silicon. These differences translate into several important characteristics, one of which is their ability to operate at higher switching frequencies while keeping the losses to a very low, manageable level.

2 HEMT, GaN and GaN-on-Si

Transistors are the basic building blocks of the electronics industry. Semiconductor substrates form the platform upon which transistors are constructed and so their properties dictate how those transistors operate. In most applications, transistors operate as voltage-controlled switches, which means the current flowing through the transistor is the same current that powers the application. The higher the power requirement of the application, the more efficient or, in some cases, physically large the transistor needs to be.

The wide bandgap materials now being used to create power semiconductors include silicon carbide (SiC) and gallium nitride (GaN). The supply chain for SiC wafers and GaN on Si wafers is still developing, and is not as mature as the huge infrastructure and supplychain already in place for silicon wafers.

To overcome this roadblock to higher efficiency, the industry has put significant efforts into developing new substrates while still leveraging the economies of scale presented by silicon. This approach isn’t without its own challenges, of course, but there is a concerted will to succeed which has been extremely effective in seeding the market for wide bandgap transistors for power conversion. Just as with conventional silicon process developments this has created a virtuous circle of reinvestment that is already showing significant signs of success.

The basic capability of a semiconductor material is dictated by the mobility of its charge carriers, generally referred to as electrons (although their counterpart, holes, are also referred to when talking about charge carriers). A material with high electron mobility offers greater current carrying ability, which is clearly a significant benefit when it comes to power electronics.

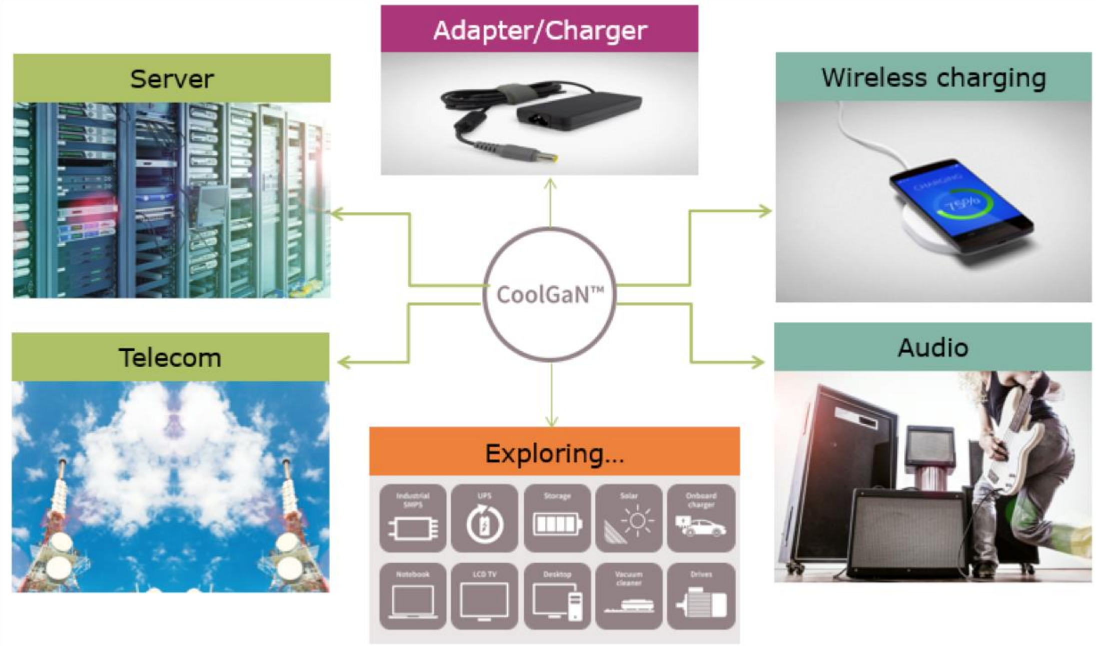

Figure 1 Applications for CoolGaN™ HEMT power transistors

The high electron mobility transistor, which is normally abbreviated to HEMT, is formed by bringing two structurally dissimilar substrates together, creating what is known as a heterojunction transistor. That basically means that the band-gaps of the two substrates are different, but it is this difference that promotes the higher electron mobility. Infineon has successfully developed a gallium nitride on silicon process (GaN-on-Si), which is now being used to manufacture its CoolGaN™ family of HEMT devices.

3 Achieving high efficiency with GaN-on-Si

As well as asking why we need more efficiency in power conversion, it is relevant to consider why GaN-on-Si power transistors are better able to deliver that efficiency than conventional silicon power transistors.

This is partly due to the topology of the converter and the demands that makes on the underlying technology. The topologies favored by power supply manufacturers today developed mainly because they were well-suited to the capabilities of CoolMOS™ power transistors. This technology has been the foundation of power supply design for many years. But now GaN removes one of the key limitations of CoolMOS™ - the performance of the body diode. GaN with zero reverse recovery charge enables it to be used in topologies that were not previously considered for power supplies - like the full-bridge totem pole PFC topology. It is this combination of newly enabled topologies used with the new GaN technology that helps to achieve new levels of power supply performance.

The characteristics of MOSFETs limit the performance of purely silicon power transistors in high voltage conversion, due to the features discussed in more detail in the following section. The technology developed by Infineon removes many of these characteristics, which means the transistors can operate at much higher frequencies without penalizing the efficiency, which can be kept at the highest value.

One of the key technologies that has enabled this significant leap in power conversion is the transition layers that bond the silicon substrate to the GaN structure. The intellectual property involved here is the subject of many patents, but suffice it to say that the Transition Layers are a fundamental element of manufacturing HEMT devices.

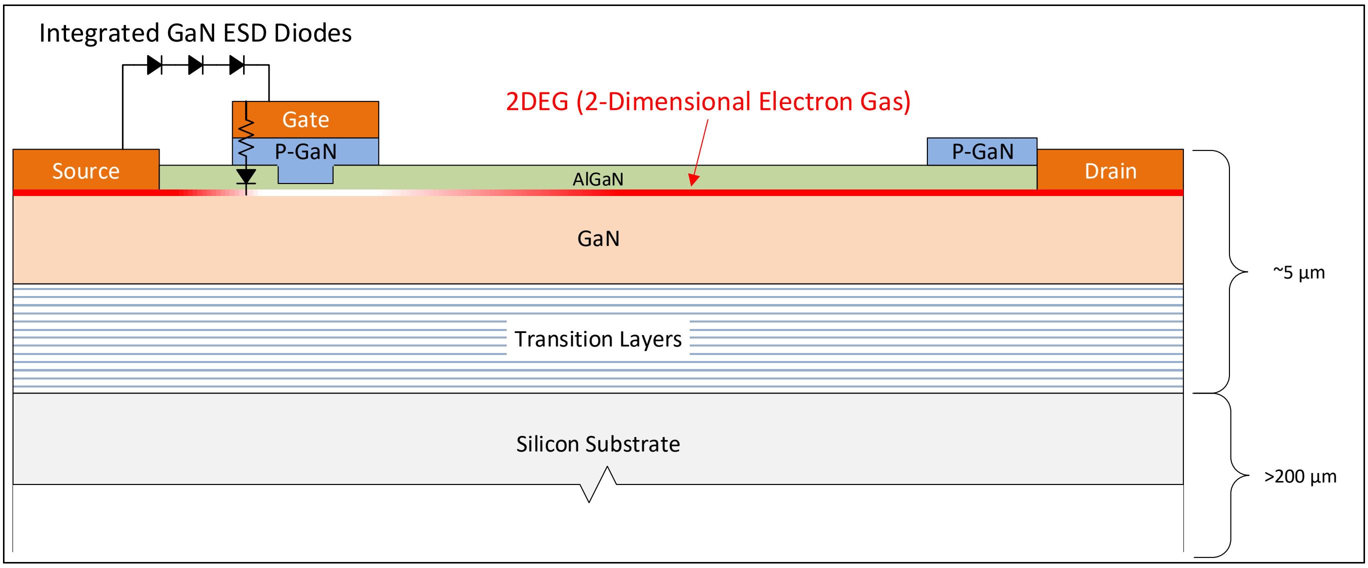

Figure 2 A diagram of the CoolGaN™ GaN-on-Si HEMT, showing the transition layers

The transition layers are grown epitaxially on to the silicon substrate, allowing the GaN HEMT structure to be built on the top of these layers, to form a planar transistor, whereby the charge carriers move laterally across the device. This is in contrast to a typical silicon transistor, in which the charge carriers predominantly travel vertically.

As with the majority of transistors, HEMTs feature three terminals, in the case of FETs and HEMTs these are the drain, the source and the gate. As the name may imply, the gate controls the device, which can be thought of as a voltage-controlled switch. Transistors are designed to be either normally-ON or normally-OFF, the gate controls the state and the aim is to have the lowest possible resistance in the channel whenever the device is on and conducting. Infineon´s CoolGaN™ are normally-OFF transistors, which is considered nowadays a must-have by the electronics industry.

The resistance between the drain and source terminals, $R_{DS(on)}$, is one of the key parameters when selecting a power transistor, as is the speed at which the 'switch' can react to the gate voltage's polarity (that is, turn on or off). Using GaN-on-Si to create HEMT power devices delivers significant advantages in figures of merit (FOM). However, to take full advantage of these benefits it is necessary to match the power transistor with the best gate driver. The approach taken by Infineon Technologies is to develop a full complement of technologies that come together to deliver the right solution for the application. In high power conversion and switching, that solution is the CoolGaN™ family, which will comprise 600 V, 400 V, 200 V and 100 V devices (200 V and 100 V are still in development), supported by the new GaN EiceDRIVER™ series of gate drivers.

4 The benefits of CoolGaN™

While ostensibly similar to other types of FET, the HEMT has one significantly beneficial characteristic, in that it features no intrinsic body diode between the source and drain. This enables what is arguably the single most important feature of GaN transistors, which is their reverse recovery performance. The absence of a body diode removes its impact, which in other types of transistors is a limiting factor. With the reverse recovery charge comes an associated peak current which can be so large in silicon power transistors that they cannot be used in conversion topologies that feature repetitive reverse recovery, including half-bridge topologies. This is not the case with GaN-on-Si HEMTs.

As CoolGaN™ transistors have no minority carriers and no body diode they do not exhibit a reverse recovery, which makes them well suited to half-bridge topologies and will also allow them to support the development of entirely new power conversion topologies that were previously impossible to realize, without major (and costly) adjustments on the control technique.

Resistance is by its very nature a liming factor, which is why it is so important to have transistors with a low on resistance, $R_{DS(on)}$. This figure can be interpreted as a conduction loss, which for many transistors is temperature-dependent. The temperature coefficient of $R_{DS(on)}$ in a CoolGaN™ transistor is significantly lower than in silicon transistors, less than 2.0 as opposed to 2.4. This difference means CoolGaN™ transistors´ conduction losses scale more favorably with respect to silicon transistors at high temperature.

Linearity is another important factor when considering the operating characteristics of a power transistor during the transition between ON and OFF states. The output capacitance of super junction silicon power transistors is very non-linear; the voltage across the device (V_{DS}) increases slowly at the beginning, then exhibits a very steep increase, and finally additional time is needed to achieve V_{BUS} (typically 400 V in most of the HV applications where 600 V transistors are utilized). CoolGaN™ transistors exhibit a linear behavior with an output charge that is approximately one tenth of that seen with silicon transistors. The smaller, linear output charge means that switching transitions are linear and nearly ten times faster compared to Silicon transistors. The reduced output charge also results in a 25% smaller energy stored in that output charge E_{OSS}.

In high frequency operations, above 200-250 kHz, switching speed is key to determining how the transfer of energy occurs. CoolGaN™´s superfast switching speed enable very short dead time. With conventional silicon transistors, higher I_{RMS} has to be considered, which inevitably increase losses. This means CoolGaN™ can deliver high efficiency even at high switching frequencies.

Furthermore, as the size of passive components scales with switching frequency, using a semiconductor transistor that guarantees high efficiency at high frequencies will enable the reduction in size and weight of power converters.

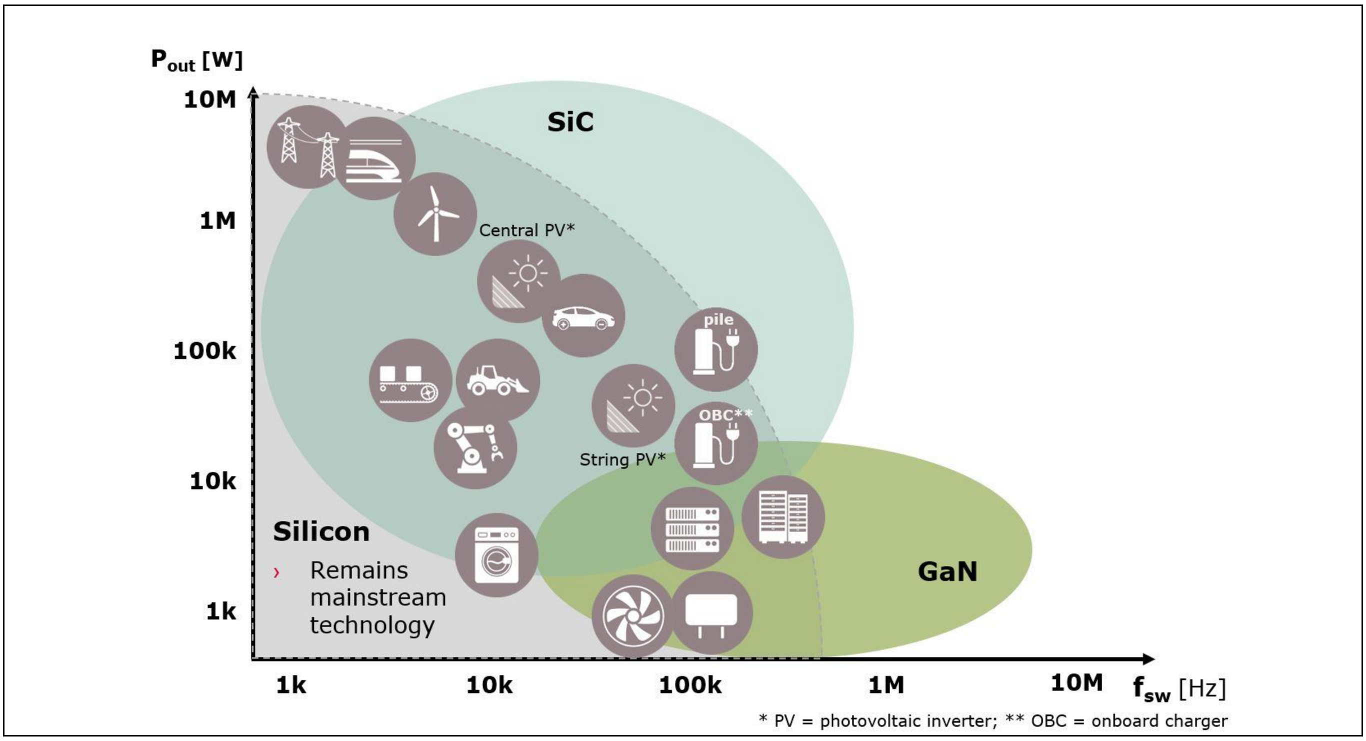

Figure 3 GaN offers higher efficiency at higher switching frequencies than conventional silicon or silicon carbide for specific applications

5 A system-level solution

Infineon is actively developing silicon and silicon carbide MOSFET devices alongside GaN-on-Si. As such it fully understands the application areas where each technology excels, and how to achieve the best from that technology.

The target applications for the CoolGaN™ family require enhancement mode (normally-OFF) HEMT devices, which deliver greater benefits in a typical power conversion application as they require less power to operate. Most of the operational benefits of the CoolGaN™ HEMT device come from their ability to switch at very high frequencies, but this is a feature that can be impacted by the parasitic impedance of the package leads. For this reason the CoolGaN™ devices are packaged using SMD (surface mount device) technology as opposed to through-hole packaging.

As with all of Infineon’s power transistors, the CoolGaN™ series is supported by its range of gate drivers, which includes the GaN EiceDRIVER™ family. These provide isolation between input and output channels, with fast switching and accurate timing. Using a GaN EiceDRIVER™ as the gate driver for CoolGaN™ power transistors will deliver the gains and low losses possible with GaN-on-Si technology to achieve higher overall efficiencies and greater power density.

6 Reliable power

Delivering a reliable source of power is fundamental to any application and this starts with using reliable components, built on proven and reliable technology.
This philosophy has been at the heart of Infineon’s development of CoolGaN™: the qualification plan is based on a specific application profile, on a quality requirement profile and on the basis of extensive reliability investigations conducted during the development phase, as well as a sound understanding and modeling of all failure and degradation mechanisms.

The CoolGaN™ 600 V portfolio of devices has been qualified, and offers a predicted lifetime of more than 15 years with a failure rate less than 1FIT. Since the beginning of mass production, Infineon has shipped more than 100,000 CoolGaN™ 600 V 70 mΩ devices, without a single failure reported either in the field or during customer qualification tests.

For more details, please download the Reliability and qualification of CoolGaN™ white paper.

7 Conclusion

The need for more efficient power conversion, including AC-DC, DC-AC and DC-DC, is present in every vertical industry where electronics is an enabling technology. This includes SMPS for telecommunications and servers, as well as mobile and wireless chargers and power supplies.

In all of these applications the overarching requirement is greater efficiency and higher power density. While silicon MOSFETs still play a role in power conversion, and will certainly keep improving over time, with Infineon being the market leader, wide bandgap devices have the FOM needed to deliver real gains in high and low voltage applications. For the range between 100 V and 600 V, Infineon believes that GaN-on-Si in general and its CoolGaN™ family in particular leads the industry in being able to deliver a fully qualified and reliable solution, one that is supported by a strong, reliable portfolio of complementary products. This includes the CoolMOS™ and OptiMOS™ power transistors and the EiceDRIVER™ family of gate drivers.

Published by
Infineon Technologies AG
85579 Neubiberg, Germany

© 2018 Infineon Technologies AG.
All Rights Reserved.

Order Number: B152-I0735-V1-7600-EU-EC
Date: 10 / 2018

Please note!
THIS DOCUMENT IS FOR INFORMATION PURPOSES ONLY AND ANY INFORMATION GIVEN HEREIN SHALL IN NO EVENT BE REGARDED AS A WARRANTY, GUARANTEE OR DESCRIPTION OF ANY FUNCTIONALITY, CONDITIONS AND/OR QUALITY OF OUR PRODUCTS OR ANY SUITABILITY FOR A PARTICULAR PURPOSE. WITH REGARD TO THE TECHNICAL SPECIFICATIONS OF OUR PRODUCTS, WE KINDLY ASK YOU TO REFER TO THE RELEVANT PRODUCT DATA SHEETS PROVIDED BY US. OUR CUSTOMERS AND THEIR TECHNICAL DEPARTMENTS ARE REQUIRED TO EVALUATE THE SUITABILITY OF OUR PRODUCTS FOR THE INTENDED APPLICATION.

WE RESERVE THE RIGHT TO CHANGE THIS DOCUMENT AND/OR THE INFORMATION GIVEN HEREIN AT ANY TIME.

Additional information
For further information on technologies, our products, the application of our products, delivery terms and conditions and/or prices please contact your nearest Infineon Technologies office (www.infineon.com).

Warnings
Due to technical requirements, our products may contain dangerous substances. For information on the types in question please contact your nearest Infineon Technologies office.

Except as otherwise explicitly approved by us in a written document signed by authorized representatives of Infineon Technologies, our products may not be used in any life endangering applications, including but not limited to medical, nuclear, military, life critical or any other applications where a failure of the product or any consequences of the use thereof can result in personal injury.