Wide-bandgap next-generation semiconductor performance moving beyond standard technology

Giuseppe Vacca gives an overview summarizing the advantages of compound semiconductors compared with traditional silicon, including benefits from their use in many applications and where these new technologies are leading.

Silicon carbide (SiC) and gallium nitride (GaN) devices will increasingly replace established silicon technology because silicon has already reached the intrinsic limitations of its physical-electrical properties. Due to this, since 2007 silicon-based devices have no longer been able to keep pace with Moore's Law, and a plateau has appeared in the curve: Moore's prediction was that, every year, integrated circuit manufacturers should have been able to double the number of transistors that can fit on a single silicon chip. Instead, transistor size is decreasing at a slower rate; since 2007 the process of size reduction has slowed down notably.

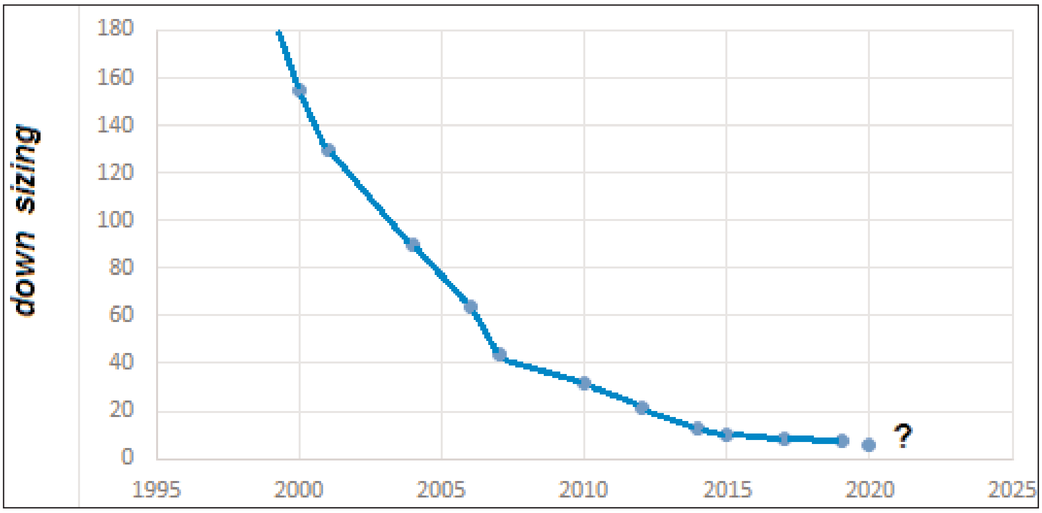

Figure 1. Moore's Law behavior.

The smallest silicon MOSFETs fabricated recently by Lawrence Berkeley National Labs (LBNL) have a width (channel length) of just 7nm, i.e. just one order of magnitude larger than the dimension of an individual silicon atom. With this geometrical size, quantum tunneling can occur and the device can lose the ability to control the flow of current. So, recent advances in development mean that silicon technology is approaching the theoretical physical limits of the material. Since the characteristics of silicon preclude further improvement in device performance, microelectronics R&D has become more challenging and requires great effort in terms of investment, and it sometime appears to be uneconomical because it is too expensive.

Post-silicon materials

To overcome and improve the above performance limitations from silicon, in recent years the world's most important semiconductor players have been starting to adopt compound semiconductor materials.

In doing so, many companies have moved towards devices manufactured using silicon germanium (SiGe), silicon carbide (SiC), gallium arsenide (GaAs) and gallium nitride (GaN). Amongst these, the most

MATERIAL PROPERTIES	4H-SiC	GaN	Si
Band Gap Energy [ev]	3.26	3.39	1.12
Critical Electrical Field [kV/cm]	3400	3550	300
Electron Mobility [$cm^2/V*s$]	950	1300	1400
Saturation Velocity [$cm*10^6/s$]	22	25	10
Thermal Conductivity [W/cm*K]	4	1.55	1.5

common are currently silicon carbide (4H-type) and gallium nitride, which are driving significant innovation in the semiconductor industry and are likely candidates to replace traditional silicon devices in the near future.

While SiC and GaN are both binary compounds containing equal proportions of their constituent atoms, the III–V compound GaN has a wurtzite-type crystal structure, whereas the IV–IV compound SiC has an hexagonal structure with two kind of polytypes: 6H-SiC and 4H-SiC. The latter has become prevalent because it exhibits identical electron mobility along the horizontal and vertical crystal planes, whereas 6H-SiC is anisotropic.

The table compares material properties for silicon carbide (4H-SiC), gallium nitride (GaN) and silicon (Si), showing how those properties have a major influence on the fundamental device performance.

Silicon carbide and gallium nitride are quite similar to each other in terms of physical characteristics of the material, yielding many important benefits compared with traditional silicon counterparts by offering fundamental advantages with features 3–4 times better than silicon.

In some parameters GaN appears slightly superior than SiC. However, SiC works well in high-temperature environments because its thermal conductivity is significantly better than that of GaN.

For both GaN and SiC, their high breakdown voltage, high electron mobility and saturation velocity make them suitable candidates for high-power applications. In particular, the higher critical electrical field makes these compounds very attractive for power systems due to having outstanding values of specific on-state resistance ($R_{ds\text{-}on}$). Based on these key factors, a significant reduction in on-state power conduction loss can be achieved. At the same time, such devices can reduce switching power losses due to the lower input capacitances compared with silicon transistors.

With these features, such new devices are becoming the best candidates for the management of very high-power systems. Indeed, GaN HEMTs and SiC MOS seem perfect for very high-speed switching equipment. Such wide-bandgap semiconductors show the best results in many key applications compared with traditional silicon switching power devices like insulated-gate bipolar transistors (IGBTs) and power-MOS.

Regarding the requirement for high power, researcher have no doubts that in the future switching frequencies will rise to exploit the full benefits obtainable from GaN and SiC device characteristics being much better than those of conventional devices. This will allow the achievement of improved performance combined with a significant downsizing of devices and related equipment.

GaN and SiC power semiconductors have emerged as such devices find application in inverters, hybrid & electric vehicles (HEVs), converters, uninterruptible power supplies (UPS) and other high-power applications, moving the field beyond silicon's limits; they are driving innovation in power semiconductors: scaling, costs, performance and design opportunities are all important factors for evaluating these two materials, which represent the new paradigm in power electronics.

Even for RF and microwave applications, the demand for higher frequencies is at the point where it is not easy to use only the available silicon RF power devices. Before the advent of wide-bandgap semiconductors, due to silicon's low breakdown voltage it was not possible to design and fabricate transistors that could yield radio-frequency output power of hundreds to thousands of watts, and this issue has seriously limited the use of solid-state technology in RF high-power and microwave applications. Recent improvements in the growth of compound semiconductor materials in SiC- and GaN-based devices have demonstrated impressive performance by offering the opportunity to now design and manufacture microwave transistors that exhibit performance previously achievable only by using vacuum tube technology.

The most promising electronic devices for these RF power applications are metal-semiconductor field-effect transistors (MESFETs) fabricated with 4H-SiC and heterojunction field-effect transistors (HFETs)

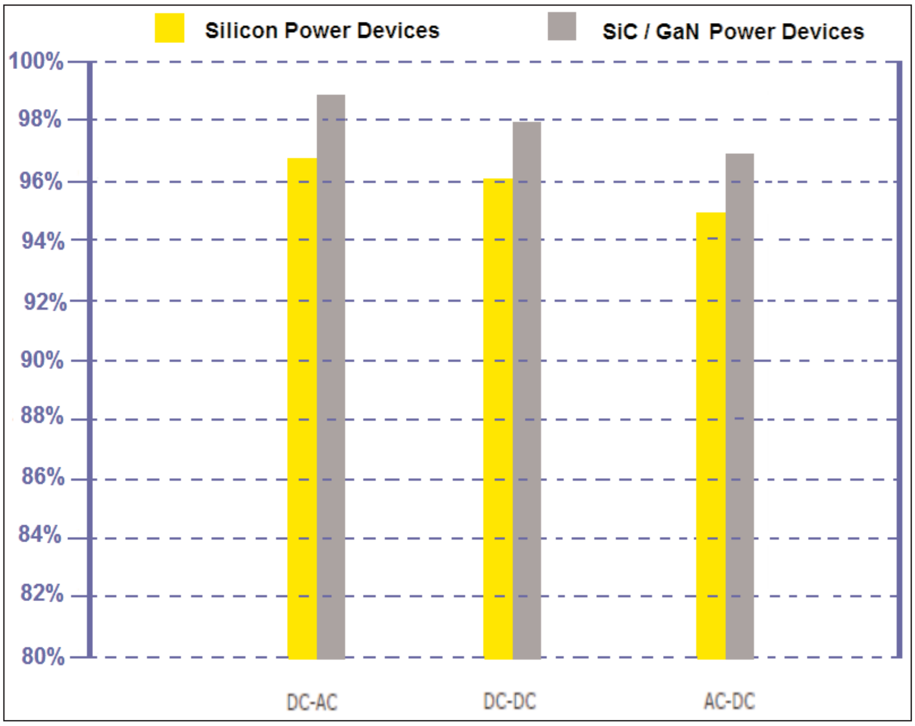

Figure 2. Expected efficiency improvement in switching power conversion using SiC/GaN devices.

fabricated using AlGaN/GaN heterojunctions; these devices can provide RF output power of 5–6W and 10–12W per mm of gate periphery, respectively.

4H-SiC MESFETs produce useful performance at least through X-band frequencies (7–12.5GHz) while AlGaN/GaN HFETs should produce useful performance well into the millimeter-wave region, and potentially as high as 100GHz.

GaN devices are expected to radically change the power electronics sector, starting with 100W power supplies and also impacting the field of RF power amplifiers thanks to the same characteristics that make them suitable for conversion and power systems.

SiC technology is finding application in higher-power products such as motors, electric drives and inverters or frequency converters, Powertrain inverters and on-board charger (OBCs) are playing in general an important role in the future of electronics because they have great potential in high-power applications and at radio-frequency and microwave frequencies over 10GHz. SiC can withstand higher temperatures before failure, and also its thermal conductivity is more than three times better than silicon. In practice these attributes promise high-frequency, high-temperature operation (managing working temperatures above 150°C) at high voltage and high power levels.

Why wide-bandgap materials?

Work on wide-bandgap materials and devices has been going on for a few years because the properties of these materials promise substantial performance improvements over their corresponding silicon-based devices.

In semiconductors, the bound electrons are located in distinct bands of energy levels (the valence band and the conduction band) around the atomic nucleus. Given an amount of energy corresponding to the difference in energy between the bands, electrons can jump from the top of the valence band to the bottom of the conduction band, making them available for current flow. The characterization of a material is related to the energy required for an electron to jump this gap between the energy bands. In wide-bandgap semiconductors this value is much greater than that for silicon. In general, materials that require energies typically larger than 2 electron volts (eV) are called wide-bandgap semiconductors.

Specifically, the bandgap energies of 3.26eV for SiC and 3.39eV for GaN are about three times higher than silicon's 1.12eV, which translates to a breakdown voltage and critical electric field at least one order of magnitude higher. The excellent performance resulting from these properties can conveniently be exploited in RF power amplifiers and efficient power electronics equipment and related systems, so wide-bandgap semiconductors allow new devices to operate at much higher voltages, frequencies and temperatures than conventional semiconductors.

As a direct consequence of this, using silicon carbide and gallium nitride technologies with their potential future developments allows them to provide higher energy in an extremely effective and efficient manner, reducing power loss and therefore improving average efficiency by up to 4% and simultaneously diminishing die size and enabling downsizing of 3–4 times.

On the other hand, new wide-bandgap (WBG) semiconductors can handle a much higher level of power than traditional devices with the same active area. So, fabricating devices with an equal level of performance, it is possible to achieve significant downsizing in dimensions, simplifying thermal management, saving on heatsinking and related costs.

The pursuit of higher power density paired with higher working voltages, frequencies and efficiency are the most important factors currently driving electronics innovation in numerous global industries, including data centers, renewable energy, consumer electronics, electric vehicles (EV) and autonomous vehicles (AV), in general making them very interesting for all future electronic applications.

Tech differences between SiC and GaN

Currently there is a great deal of on-going discussion, questions and different approaches regarding gallium nitride versus silicon carbide in order to make the right choice, what kind of devices can be fabricated, and what kind of device or material is best suited for various switching and RF power applications. Material properties, device architectures, size reduction and cost saving are all important and inter-related factors that drive this decision. In any case, SiC and GaN will surely play important roles in the future, although each will settle into its own niche.

An analysis of the differences between the two main WBG material platforms GaN and SiC allows us to understand which solution is more advantageous regarding possible requirements such as output power, voltage level, performance capabilities and cost saving. The key criterion for choosing a system design is primarily how GaN or SiC can increase the competitive advantage and at the same time reduce operating expenditure (OpEx) and capital expenditure (CapEx), as well as grow profit and market share, compared with silicon-based devices (being the baseline standard in the semiconductor industry for many years).

GaN systems offer users more options due to being a robust and easy-to-manage solution, reducing the time to market compared with SiC devices. Recently GaN devices have achieved significant gains in this sector, with increases in efficiency and power density having benefits for consumers and enterprises alike, whether it's a smaller form factor and a faster charging

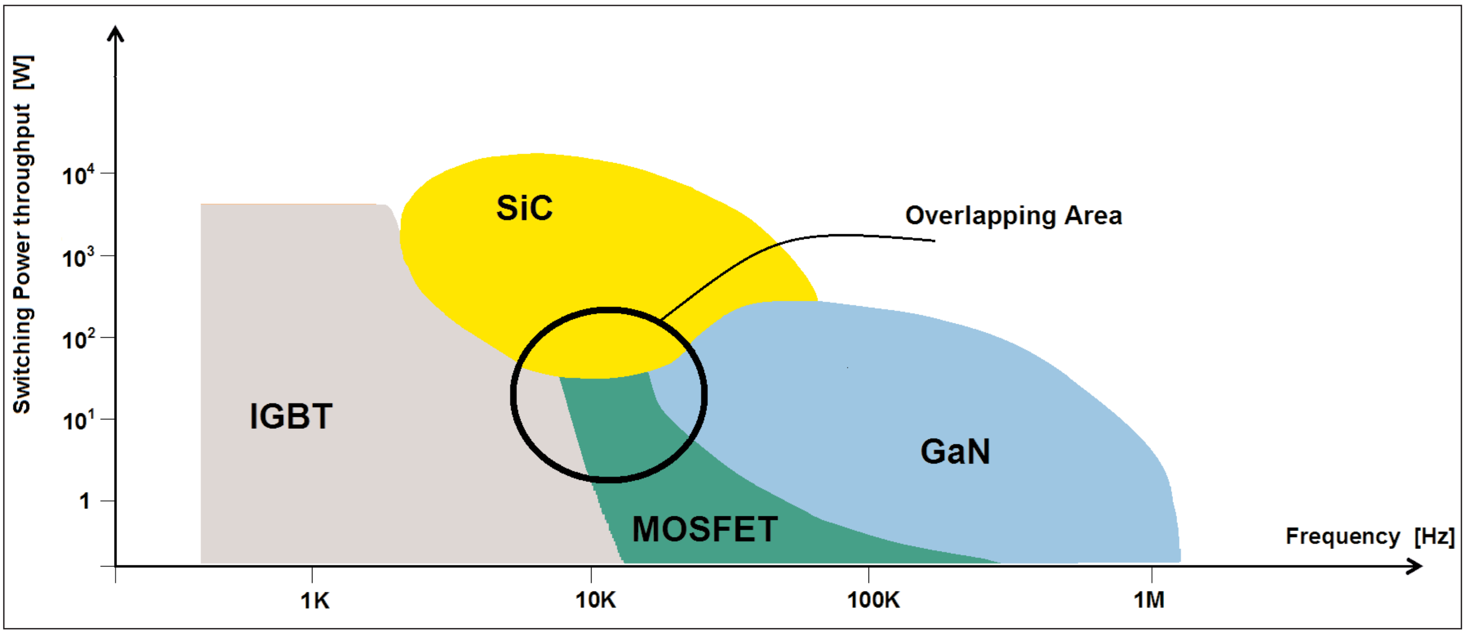

Figure 3. Overlapping area in Power versus Frequency diagram.

rate in consumer adapters or reductions in cooling costs and wasted energy for data centers and other applications in which SiC is involved to some extent.

It is possible to compare first-generation GaN devices with the recent fifth generation of SiC devices. The performance gap is expected to widen, with GaN performance growing 5–10 times in the mid to long term because systems built with GaN will have greater power density improvement than those built with SiC. With GaN, new power systems with smaller size are emerging because SiC cannot be used to create systems as small as GaN.

SiC semiconductors are more expensive and, above all, SiC displays supply-chain limitations compared with GaN; as the industry has proven repeatedly, when volumes go up, prices come down, and GaN prices can easily be projected to be competitive with silicon over time, especially since GaN can be produced on silicon wafers (using CMOS processing).

SiC has limited supply due to a small number of suppliers and supply-chain constraints, resulting in lead times of up to a year. Due to this it is thought that SiC is not expected to meet the demand of electric vehicle manufacturing in 2025 and beyond.

While SiC is in short supply, the demand for GaN is rising steadily, with manufacturing and material costs declining. Automotive, industrial and other applications that require smaller size, lighter weight and more efficient operation are increasingly being designed using GaN.

Regarding production, GaN is infinitely scalable as it can be made on the same silicon wafers with similar machines and equipment that is used to fabricate CMOS devices. This is not true for SiC. GaN will soon be capable of being fabricated on 8”-, 12”- and even 15”-diameter wafers, while SiC MOSFETs are typically only fabricated on 4” wafers currently and are migrating to 6” wafers.

From an electrical point of view, in the case of the requirements of the low-to-medium voltage range, GaN shows more favorable results, whereas SiC results prevail if used in high-voltage applications, i.e. greater than 1200V, because in the low-to-medium voltage range (below 1200V) GaN’s switching losses are about three times less than SiC at 650V. Regarding operating frequency, most silicon-based designs today work at 60–300kHz. Doubling the switching frequency to 120kHz achieves some improvement (more so with GaN than with SiC), yet the power density issue is not well solved. The need is to go to 500kHz or higher, and this can only be accomplished with GaN; it has superior ability to meet a power system’s voltage levels from 30V to 1200V, so it supports key power-dependent sectors such as consumer electronics, renewable energy, automotive, and industrial applications.

SiC is generally designed for working voltages of 1200V and higher, with some product availability at 650V. With a restricted solution set below 1200V, SiC is limited in the design of a wide variety of power systems. In fact, there is no role for SiC in important markets such as 30–40V devices in consumer electronics, and 48V in hybrid electric vehicles and data centers. Silicon carbide’s most important feature is the maximum junction temperature, which reaches at least 200°C, i.e. 50°C higher than the absolute maximum temperature rating of other semiconductors (150°C typical). This advantage allows SiC power devices to work well in hot and hostile environments, avoiding performance de-rating and related problems regarding mean time to failure (MTTF) and life-time, while achieving an appreciable increase in quality and reliability.

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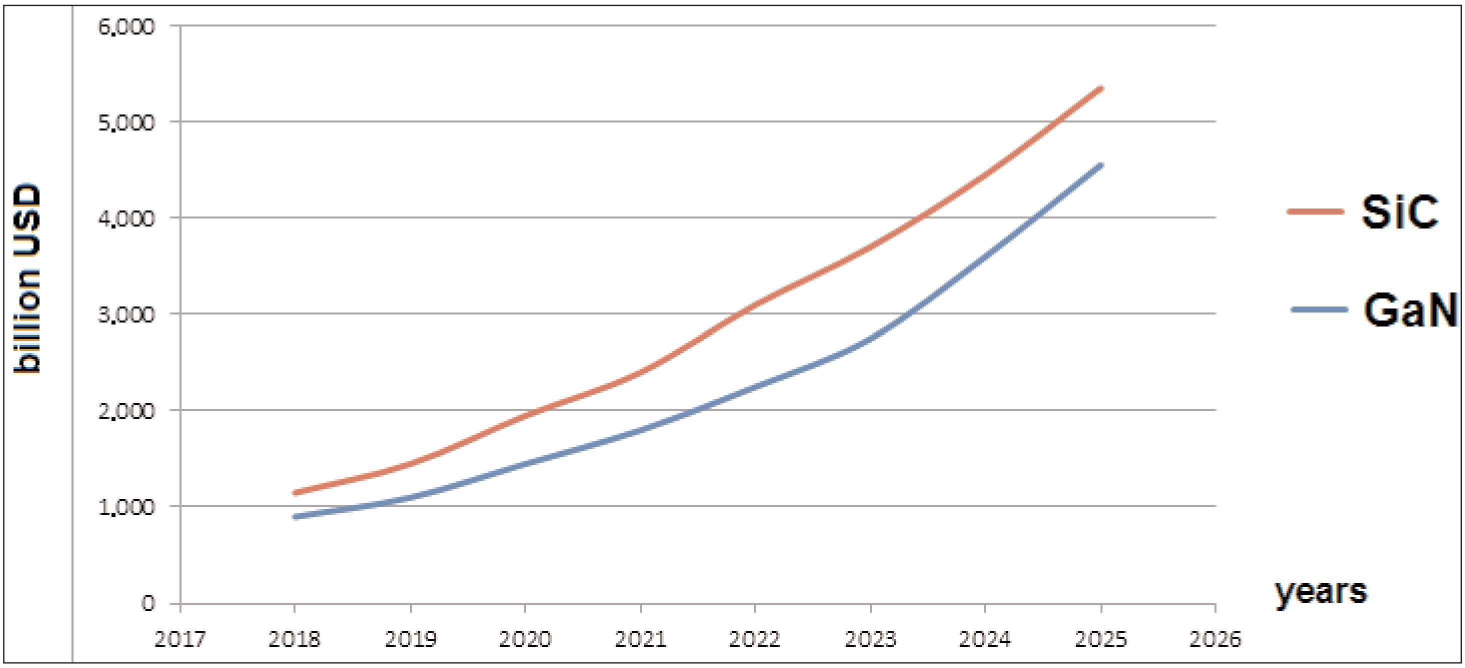

Figure 4. GaN and SiC device market forecast for next five years.

A common area where all solutions can be applied is in the Power versus Frequency relationship (see Figure 3): only in the future will one particular technology prevail over other technologies.

Users currently relying on SiC will need to move to GaN soon for two reasons: limited material supply and the rising cost of keeping up with the increasing power demands in industries ranging from data centers to automotive applications. Shifting directly from silicon to GaN now can save the need to transition from SiC to GaN later in order to catch up with the competition. GaN-powered devices are superior due to benefits such as a low gate charge, zero reverse recovery current and flat output capacitance, all of which yield high-quality switching performance.

GaN foundry is a way to not only improve existing product offerings but also to create innovative solutions to remain competitive. Regarding the semiconductor industry transition, GaN is now going from 'early adoption' to 'mass production'.

SiC and GaN forecast

Even if GaN seems to be projected as a great protagonist in the future, at the moment SiC represents the main semiconductor material used to manufacture innovative power devices, because SiC currently comprises the largest share of investment in R&D, both by microelectronic design centers and foundry.

In the next five years, silicon carbide is forecasted to comprise the largest wide-bandgap power market, followed by gallium nitride (considering power and RF devices together).

Figure 4 shows that, in the next few years, the SiC and GaN sectors will develop rapidly. Sales of SiC and GaN power devices have brought a lot of opportunities, and more companies will enter the industry, especially in developing countries. Specifically, the graph focuses on SiC and GaN devices in the global market, including North America, Europe and Asia-Pacific, South America, Middle East and Africa.

Regarding the wide-bandgap device market for power semiconductors specifically, the compounded average growth rate (CAGR) is expected to be greater than 32% over the next five years; reaching about US$2000m in 2024.

Looking further afield, according to another study, the GaN and SiC power semiconductor market will grow at a CAGR of 35% from $1bn in 2020 to about $10bn in 2027. ■

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