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Article

Role of Wide Bandgap Materials in Power Electronics for Smart Grids Applications

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Abstract: At present, the energy transition is leading to the replacement of large thermal power plants by distributed renewable generation and the introduction of different assets. Consequently, a massive deployment of power electronics is expected. A particular case will be the devices destined for urban environments and smart grids. Indeed, such applications have some features that make wide bandgap (WBG) materials particularly relevant. This paper analyzes the most important features expected by future smart applications from which the characteristics that their power semiconductors must perform can be deduced. Following, not only the characteristics and theoretical limits of wide bandgap materials already available on the market (SiC and GaN) have been analyzed, but also those currently being researched as promising future alternatives (Ga_2O_3, AlN, etc.). Finally, wide bandgap materials are compared under the needs determined by the smart applications, determining the best suited to them. We conclude that, although SiC and GaN are currently the only WBG materials available on the semiconductor portfolio, they may be displaced by others such as Ga_2O_3 in the near future.

Keywords: wide bandgap materials; power electronics; smart grids; distributed energy resources; technical requirements

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1. Introduction

At present, climate change represents a threat not only to specific regions around the world but to the entire world ecosystem. Therefore, there is an urgent need to deal with this situation and numerous initiatives have been developed to help in the cutting emissions mission [1].

Renewable energies (REs) have a crucial role in helping the world meet its future energy needs. Today, more than 30% of electricity generation in the European Union (EU) comes from renewable sources, whereas in 2000 it was only 12% [2]. In 2017, the EU planned to reduce greenhouse gas emissions during the following decade at least 40% from 1990 levels [3,4]. However this objective has recently been updated and, as part of the European Green Deal, the European Commission proposed in September 2020 to raise the 2030 greenhouse gas emission reduction objective, including emissions and removals, to at least 55% compared to 1990. This objective should be achieved by means of the following key targets: at least 40% cuts in greenhouse gas emissions (from 1990 levels), 32% share for renewable energy and 32.5% improvement in energy efficiency [5].

To achieve the 2030 targets for RE it is necessary to maintain the current growth levels. On the other hand, energy efficiency requires an inverse correlation with the RE need to achieve these targets. If energy efficiency is increased in 5%, the final requirement for the installation of RE will decrease in 7.5% approximately to achieve the same RE goal [3]. Thus, efforts to reduce greenhouse gas emissions made in both ways, RE share and energy efficiency, are equally valuable. Besides, cutting greenhouse emissions could be achieved by substituting fossil fuel power plants by RE power plants or by means of using RE sources to provide energy to other applications such as heating and transport, leading to a great growth of the energy sector electrification. In the following decades global electricity consumption will increase slightly faster than recent trends but, however, there will be abrupt changes in individual countries and specific locations. These include areas with rapidly expanding residential solar and/or electric vehicles (EVs), and where major thermal generators will be closed [3].

As consumer-scale technologies, such as photovoltaic (PV) and EV, become cost-competitive without subsidies, governments will lose the ability to control rates of deployment. The change can then become rapid, and may also be derived from increased electric heating and better energy management systems (EMSs) for buildings.

Therefore, the incoming electrification of the world makes especially important the role of smart grids. The next generation of smart grids must answer to a scenario with a higher number of devices connected, and with an improved capability of coordination between them. Indeed, this trend has already started. Figure 1 shows a scheme of the future electric grid. On the one hand, utility-scale power plants based on non-renewable sources (red) will be progressively substituted for utility-scale RE plants (green). On the other hand, smart cities will emerge (blue), and a high penetration of distributed energy resources (DERs) is expected, such as micro PV plants, EV, energy storage systems (ESSs), heat pumps, etc.

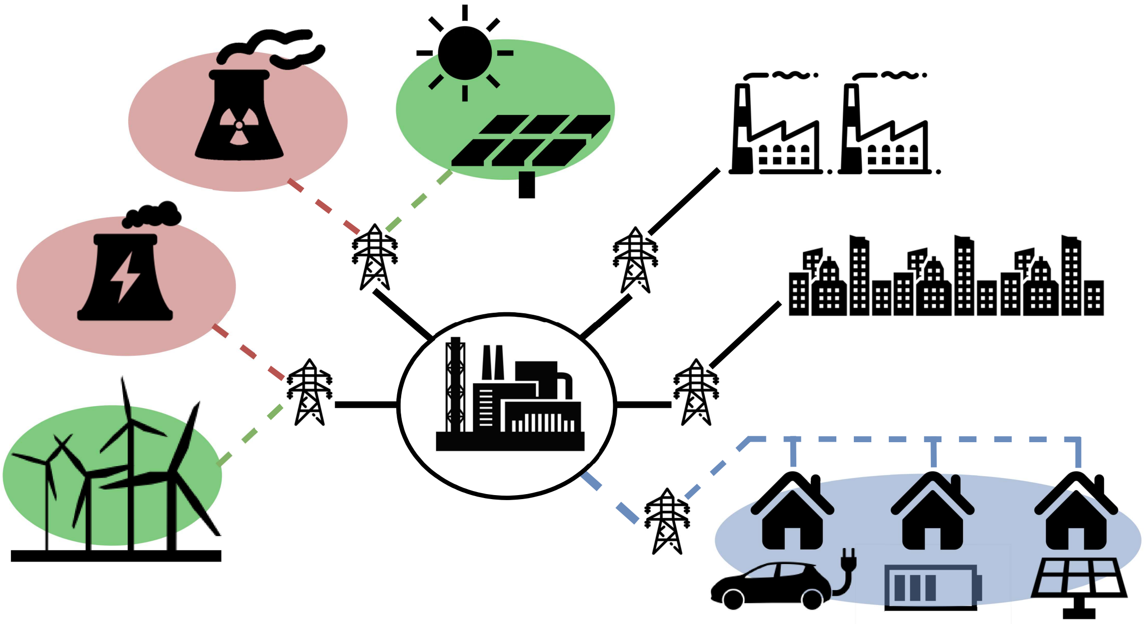

Figure 1. Current and future electric grid components: utility-scale non-renewable power plants (red), utility-scale RE plants; large factories and loads (black); future smart grid components such as energy storage systems (ESSs), electric vehicles (EVs), photovoltaic (PV), etc. (blue).

However, the new equipment in smart grids must fulfil several requirements in order to be accepted by consumers and thus help their market penetration: they have to be cost-effective; have a high efficiency (99% or higher); noiseless; reliable; and compact. To achieve these goals, power electronics have to evolve to produce new devices.

Nowadays power electronics products do not comply the requirements exposed above and, therefore, new devices should be developed. wide bandgap (WBG) materials are a series of promising new technologies that try to give an answer to the market needs.

This paper is organized as follows. Section 2 will analyze power electronics applications and requirements in smart grids. For this purpose, the different types of power electronics converters needed by smart grid equipment are studied, the features desired in this equipment are extracted, and these characteristics are translated into requirements for the semiconductor devices that will make up these power converters. Following, Section 3 will review the current state-of-the-art and future trends of WBG materials in power electronics; focusing on the electrical and physical properties of these semiconductor devices today and developments expected in the coming years, but also paying particular attention to the viability of these products on mass-market applications. Section 4 will introduce the most appropriate figures of merit (FOMs) in order to establish a relationship between the WBG technologies and the most appropriate materials for smart grid applications. Finally, Section 5 will present the most important conclusions of the study.

2. Applications and Requirements

Not all power converters are designed for the same type of applications. Besides, other considerations like communications capability or active and reactive power range, leads to particularities making them suitable for different uses. Table 1 establishes a classification of power converters in which only types 2, 3 and 4 are suitable for integrating DER into the smart grid. Following, each type is described briefly:

- Type 1 is usually power converters with a power rating lower than the following types. Moreover they do not have communications with external devices to provide them with the capacity to manage their demand. Thus, type-1 converters are fully controlled by the load or RE. Some of these devices cannot control their reactive power injection while others add a power factor correction (PFC) stage [6,7]. The PFC allows to regulate the reactive power output and cancel it. Some examples are mode-2 EV chargers and micro PV and wind generation.
- Type 2 is similar to type 1 but they also include a communication link that allows an external element to limit the power consumed or generated in order to allow demand management tasks. A typical example of this devices are large EV charging facilities with demand-side management systems.
- Type 3 adds some features to provide grid support tools; giving the possibility to regulate the active and reactive power, among others, in order to provide ancillary services to the grid [8,9]. This group include vehicle to grid (V2G) EV chargers and large wind and PV plants.
- Type 4 introduces, compared to type 3, the possibility of an independent control of the power references for each phase, giving the capability of providing additional grid support against unbalanced scenarios [10].

Table 1. Power converter classification.

Type	Grid-Conditioned Communications	Active Power Control	Reactive Power Control	Topology	Examples
1	No	No	No	single-phase three-phase	Mode-2 EV charger; PV/wind generation
2	Yes	Yes	No	single-phase three-phase	Mode-3/4 EV charger; PV/wind generation
3	Yes	Yes	Yes	single-phase three-phase	V2G EV charger; PV/wind; BESS
4	Yes	Single-phase control	Single-phase control	four-wire	Unbalanced-load grid support

As described previously, type 2, but especially 3 and 4, allow the implementation of advanced functionalities in order to provide new services for a better management and regulation of the power grid. Consequently, they are important features to speed up the penetration of DER in urban environments. Following, some of the most interesting functionalities developed recently for power converters are explained. However, new behaviours could be implemented if future grid codes require them.

- Voltage and frequency disturbances clearance: nowadays, grid codes stablish some voltage and frequency curves in which voltage and frequency disturbances are related to a specific clearing time [11]. Grid codes ask for a safety disconnection if the disturbance lasts longer than the specified time; the objective is to guarantee the service and prevent a system blackout. On the other hand, the contrary is asked in some cases too; a disconnection previous to the maximum clearing time, in order to restore the stability of the system before its disconnection.
- Active power curtailment and slew rate: these two features help to mitigate grid instabilities due to load imbalances [12,13]. On one hand, a remote control signal to the DER imposing a maximum power reference will prevent the system of over production. On the other hand, a predefined active power slew rate guarantees a smooth starting, giving the whole system enough time to react consequently. This is especially useful after the clearing of faulty conditions, when a whole section of the system could start simultaneously to maximum power. Moreover, thanks to the advancement in communications on power converters, coordination techniques for a distributed starting could be implemented.
- Synchronism emulation curves: due to inertia, frequency disturbances produce a response in the active power output of the synchronous generators that mitigate this effect. However, power converters used for DER do not have such behaviour. They can regulate its output independently of frequency. Therefore, recent Minimum Technical Requirements (MTRs) are establishing a new concept called as synthetic inertia. The power plant is configured with an active power curve in function of frequency measurement [9,14]. In addition, some active power reserves could be asked to in order to increment the production over the nominal value in case of sub-frequency disturbances [12].
- Voltage regulation: grid codes usually include V-Q curves in order to define a criterion for DER. In the past, MTRs used to define the reactive power injection needed for a determined voltage deviation. However, nowadays recent grid codes define it as an increment because the utility grid usually sends also a reactive power reference to the converter [11]. Furthermore, power converters could be connected to the grid even there are not the needed conditions for power generation. In such cases, the power converter could be used as a static synchronous compensator (STATCOM), in order to inject reactive power and help the utility grid in its task.
- Anti-islanding techniques: the islanding phenomenon has been discussed widely in the literature, and there is a wide range of anti-islanding techniques to be implemented in power converters. The objective is to introduce a control algorithm that determines whenever the inverter is working in an undesired island condition that could produce hazards and damage in equipments, and proceed with a safety disconnection procedure [8,15–17].
- Low voltage ride through: some of the most common requirements present in grid codes for DER are the low voltage ride through requirements. Grid codes require of power converters to remain connected if the fault is not long enough and to help the system regulating the active and reactive current output of the converter conveniently [18].
- Black-start: black-start capability consists in the availability of power converters to restore by themselves the electric grid power supply without the need of the intervention of any central synchronous generator [19,20]. This feature is possible thanks to the development of grid-forming control strategies, in which the power converter works as a voltage source instead of a current source by different techniques: droop-based control, virtual synchronous machine, or power synchronization [21]. They are not asked in any grid code up to date, but actually, it has been discussed widely inside working groups to include it in the future.
- Controlled island operation: the opposite of anti-islanding techniques, controlled island operation tries to hold a micro-grid energized after an opening of the point

of common coupling. This have to be perfectly known by the utility grid in order to avoid hazards and its purpose is to prevent an unjustified cut of the power supply of the micro-grid. As well as with black-start feature, grid-forming control strategies are the way to achieve this goal [20].

The new range of functionalities that could be implemented by the new generation of power converters are specially useful for power electronics applications in urban environments. Following, some of the most promising applications are described briefly in order to determine in which aspects and requirements the efforts of the power converters design must be focused on:

- Micro-PV: Regarding urban use-cases there are three technologies of inverters with different features and cost: string inverters, microinverters, and optimizers. Within the systems designed for applications in urban areas we can differentiate two categories, commercial and residential. Commercial applications are characterized by offering a range of power that in most manufacturers covers from 10 to 100 kW. On the other hand, residential systems for connecting to the grid are from 1 to 10 kW.
  Within the residential inverters we find characteristics such as multi maximum power point tracking (MPPT) input, storage ready, EV charger integrated, built-in Revenue Grade Meter, additional power supply input, or network connectivity [22,23].
  Commercial grid-tied inverters include features as seamless switchover, prioritize self-consumption of renewable sources or stored battery, support large loads to avoid grid peak usage, efficient fast charge, scalable battery reserve, embedded controls for sell surplus generation or curtail the production, integrated reactive power regulation functions, multiple MPP trackers, WLAN or Wi-Fi access for system monitoring and control functions [22,23].
- EV charging systems: Nowadays there are four modes of EV charging systems defined by the IEC [24,25]. Mode 1 and 2 correspond to slow charging modes, making a direct connection between grid and vehicle via household socket-outlets. On the other hand, modes 3 and 4 correspond to smart charging modes, providing a communication link to control the active power charging reference. Currently, EV is a technology with an extremely high growing rate, and their penetration rate into the distribution grid will be high in a near future [26].
  Nowadays, mode 4 fast chargers in publicly available outlets are replacing slow chargers, due to the necessity of short charging times in stops during journeys: up to 50 kW and/or with vehicle to grid (V2G) functionality [27–29]. Moreover, recent efforts to bring into the market commercial ultra-fast chargers up to 350 kW, and 500 kW are being made [30–32].
  In addition, current research projects [33] lead the integration to a new stage, providing load-balancing techniques over charging points and, therefore, contributing to grid stability [34]. Finally, other research activities look for a final integration of load balancing over buildings, leads to an optimization of the available distributed resources and needs (demand, generation, and energy storage), as well as contributing to the grid stability [35].
- Battery energy storage systems (BESSs): BESSs are a key service in the new concept of electric power grid and to provide flexibility in a wide range of scenarios. The evolution of the technology associated to batteries has led to the development of a new generation of very competitive batteries, reducing both cost and volume. Therefore, BESS are growing at tremendous rates nowadays, by the hand of the EV market [26]. Growth in privately owned non-utility energy storage is driven by two primary factors. The first is regulatory initiatives that incentivize non-utility ownership of storage. The second is self-interest, i.e., profit from the use of BESS [36]. A new brand of products have appeared in the market just since a few years back related to domestic BESS [37,38]. The current state-of-the-art has allowed affordable, robust and compact designs able to be installed in most buildings and houses, developing a cutting-edge technology ready for a widespread across the entire electric power grid. Besides,

thanks to the technology improvements and cost reduction of the massive irruption of the EV market [26], nowadays its use as ESS is affordable. In addition, second-life applications could be an interesting low-cost alternative to facilitate the penetration of DER in the near future [39].

Urban BESSs offer a variety of services (peak shaving, load shifting, emergency back-up and demand response) related to flexibility needs in smart grids [40]. This is due they are usually associated with PV generation with a link through alternating current (AC), where both AC outputs are connected to the same house, or direct current (DC), in which case they share a common DC bus. Consequently, BESS can regulate the total power generation/consumption of the building, with available commercial models from up to 15 kW. However, manufacturers usually offer modular solutions in order to scale the product up to the needs of clients [38].

Finally, BESS are being studied under another perspective too. Recently, there are some efforts to develop distributed BESS into the low voltage distribution grid. The objective is not only to provide a device able to adjust the load curve of the grid, but also to deliver ancillary services typical of flexible alternating current transmission systems (FACTS) and to correct active power unbalances between phases to avoid overloads and overheating [41], becoming an interesting tool for distributed system operators (DSOs).

- Energy routers and Distribution (D-)FACTS: The introduction of BESS and small prosumers in the electric grid have changed the unidirectional power flow of a typical power grid. Currently, scenarios with a high penetration of BESS, EV and DER must consider the possibility of bidirectional power flows in the low voltage distribution grid. Consequently, new devices have appeared to optimize the response in such circumstances, substituting current conventional transformers located in the final part of the grid. The main objective is to regenerate the signal and to hold the voltage at its nominal value, in order to avoid disturbances in the consumers, as well as providing other functionalities such as power flow control, total harmonic distortion (THD) reduction, and voltage and frequency regulation and communications [42–44].

  Besides, other initiatives [45] are developing special designed D-FACTS for a high share of renewable energies scenarios. Such devices are able to inject reactive power to help in the voltage regulation issue and, at the same time, help the system with low voltage ride through issues, mitigate low order harmonics, and they are able to redistribute active power between the power-line phases in order to avoid overloads.

Summarizing, some conclusions about the power converters requirements could be extracted from the applications and features exposed above:

- Breakdown voltage values of 1200 V will be enough for most low voltage urban applications. Therefore, achieving higher voltages in bidirectional devices is not a priority for this specific use-case.
- The size of power semiconductors will not be relevant either. Their size is small regarding the complete size of the converter, where the heatsink and the passive filters are the most bulky parts.
- The size of the passive components will have a strong importance, and high switching frequencies will be required to reduce them.
- To get compact designs, is mandatory to reduce or remove completely the cooling systems. Consequently, a key design parameter will be to get devices able to hold high working temperatures and with good behaviour respect to thermal conductivity.
- Reducing conduction and switching power losses will improve the efficiency and help to reduce the necessities of the cooling system.
- Power electronics devices must be inaudible in order to avoid discomfort in the final users.
- Devices should fulfil requirements respect to electromagnetic compatibility (EMC) and electromagnetic interference (EMI). Power semiconductors are devices with fast

and abrupt transients and, therefore, are typically a source of problems regarding this issue if they have not been carefully designed [46].

- Finally, as it happens with any domestic product, the manufacturing of huge volumes require both: the use of available and affordable raw materials; and the use of cheap and reliable manufacturing process.

3. WBG Materials

Power electronics equipment is manufactured from semiconductor substrates, being silicon (Si) the most commonly used today. Si is a mature technology that has been present for power control applications since 1950s. However, the performance of Si-based power switching devices is reaching its theoretical limits [47]. The main limitations of Si-based devices are high power losses, low switching frequency and poor high-temperature performance. However, a new group of advanced materials known as WBG promises to satisfy DER integration needs, as well as to meet new requirements of urban areas to support the incoming electrification of society. Among others, silicon carbide (SiC), gallium nitride (GaN), diamond, gallium oxide (Ga_2O_3), aluminium nitride (AlN), boron nitride (BN) and zinc oxide (ZnO) exhibit better characteristics as semiconductors than Si, and they become in a promising choice for next generation of power conversion systems.

While high switching frequencies could be reached by unipolar devices like metal-oxide-semiconductor field-effect transistors (MOSFETs), they can only provide low rated voltage and current capabilities. However, bipolar Si semiconductors enable high power conversion devices but operating at a relative low frequency. Therefore, larger passive components are required, incrementing the size and weight of power converters. Besides, several applications with high constrains about weight and volume such as automotive, motor drives, aerospace, and power supplies have requirements outside the limits of Si, asking for new solutions to be developed.

WBG materials have demonstrated to be an attractive solution to Si limitations providing powerful characteristics as shown in Figure 2. For instance, they offer a higher electric breakdown field that enable greater voltage blocking capability, thinner layers, and allows deeper doping concentration. Therefore, it results in lower conduction losses and a low drift resistance. Thus, an on-resistant reduction in comparison with Si-based devices. In accordance, same on-resistance WBG can have smaller area implying less capacitance. Likewise, less capacitance and a high saturation drift velocity allow higher switching speeds and lower losses per switching cycle [48]. Additionally, the low intrinsic carrier concentration of WBG materials enables reduced leakage currents and robust high-temperature performance [49].

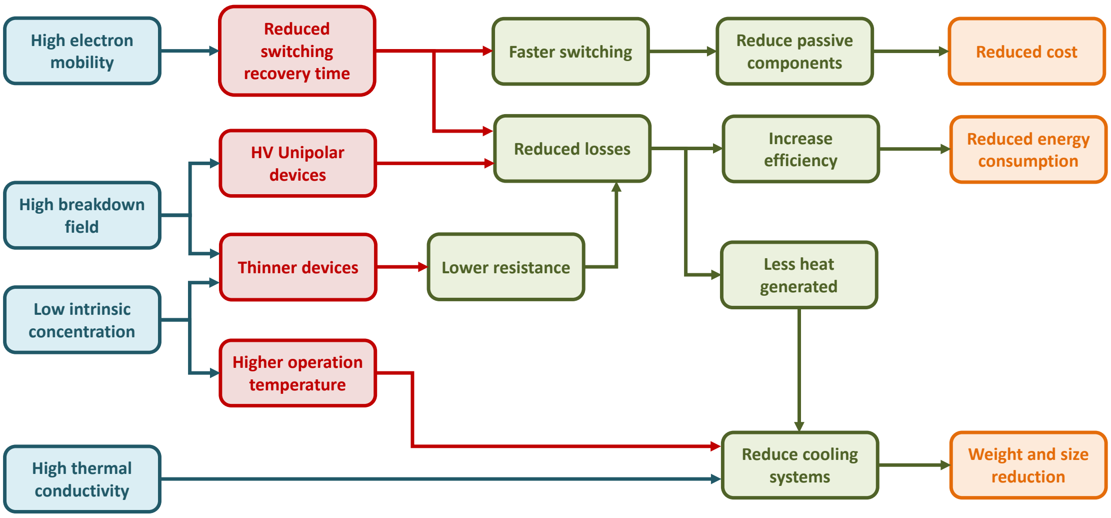

Figure 2. WBG semiconductor parameter capabilities (blue); physical properties affected by WBG advantages (red); power electronics characteristics (green); and product benefits (yellow).

As Figure 2 shows, all these features of WBG materials translate to high level output power equipment an improved efficiency, reduced system size, weight, and cost [50]. Low switching losses allow WBG semiconductors reaching efficiencies up to 99%. This means up to 75% energy losses reduction compared with Si devices [51]. Moreover, higher switching frequencies can be reached too. Frequencies higher than 20 kHz have not been possible in power levels of more than tens of kilowatts because of Si limitations so far; therefore, WBG materials allow simpler circuit topologies by reducing size and number of passive components (capacitors, inductors) [52] and offer a better output quality.

3.1. SiC

3.1.1. SiC Technology Evolution and Future Trends

Since 1987 SiC has experienced a great development, being currently the most mature of all WBG materials [53,54]. SiC is a crystalline compound of equal parts of carbon and Si; providing more than 170 different polytypes, 4*H-SiC* is the most interesting regarding power electronics applications due to its high carrier mobility, particularly in c-axis direction, and its low dopant ionization energy [55].

Due to its higher capabilities, it offers an electric-field breakdown voltage ten times higher than Si. In addition, high thermal conductivity and resistance make SiC useful in high power and temperature applications (up to 350 °C) [55]. Besides, Si is the second most abundant element in Earth crust, actually about 27% of the crust is composed of this material [56]. Its availability makes SiC an extremely attractive alternative to Si, as there is no lack of raw materials as it happens with other WBG choices.

Thanks to the development of SiC epitaxial wafers to form homoepitaxial SiC layers on SiC substrates, the SiC manufacturing technology has grown significantly in the last decades [57]. Moreover, the optimization of epitaxial and bulk processes in 4*H-SiC* has made possible to decrease the crystallographic (dislocations and stacking faults) and surface defects (at triangles, carrots, comets, pits), up to values of 0.1 cm^{-2} in surface defects density (dislocations), as well as zero micropipe defects [58]. Consequently, the advancement of SiC technology has allowed the increment in SiC wafer size along the last two decades. Nowadays, 150 mm wafers are commercially available, while 200 mm wafers were demonstrated in 2015 and currently there are some commercial examples [58].

The first SiC wafer was developed commercially in 1993, and thanks to its high voltage capacity, it has been applied to a wide range of different power devices. For instance, high-voltage trench U-shape MOSFET (U-MOSFET) of 1.4 kV, lateral 2.6 kV implanted deplection-type MOSFET (D-MOSFET) have been demonstrated since 1997 and, on the other hand, 1.8 kV and 4.5 kV vertical junction field-effect transistors (JFETs) (1998–2000). Besides, in 1999 positive-intrinsic-negative (PIN) diodes were developed with a blocking voltage of 8.6 kV (1999), Junction barrier Schottky (JBS) diodes with a blocking voltage of 3.6 kV, and SiC-Schottky Barrier Diodes (SBDs) with a blocking voltage of 4.9 kV [54]. In addition, bipolar devices as 27 kV PIN diodes [59], 2.6–15 kV gate turn-off (GTO) thyristors (1999–2013) [60,61] and SiC insulated-gate bipolar transistor (IGBT) have been experimentally demonstrated. In the same way, SiC modules (SiC MOSFETs with SiC Schottky diodes) prototypes have been presented with a blocking voltage of 6.5 kV/200 A [62] and 15 kV/10 A [63]. Due to the new features of SiC technology, new packaging designs have been implemented for SiC devices to allow: high-temperature operation, weight and size reduction, and the minimization of parasitic capacitances and inductances. Nowadays, on the one hand, available SiC products use packaging techniques that allow operating temperatures up to 210 °C. On the other hand, 1200–1700 V modules produce parasitic inductances lower than 5 nH, even with models up to high rated currents [52].

The SiC power electronics market is small compared with Si these days but, nevertheless, due to the dramatically cost reduction made during the last decade, and the increasing demand and market availability, a substantial growth is forecasted. In the following years, applications such as PFC, power supply, and PV inverters seem to go on adopting SiC technology progressively. Nowadays, Tesla is using SiC MOSFETs for its main inverters in the Model 3 and other automakers are evaluating the potential benefits of this technology for their futures EV [64]. In this way, the fast development and penetration of the EV market will contribute to a faster rise during the following decade.

In addition, SiC devices have been available in the market since 2001 with the introduction of the first SBD. In the last two decades, a commercial range of available devices have break into the market such as SiC unipolar diodes and SiC MOSFETs, that can reach breakdown voltages up to 1700 and 3300 V, and current handling capabilities up to 750 A, and some manufacturers are working on a next generation of 6500 V devices [62].

The next step in the advancement for cost reduction is the announce of 4H-SiC 200 mm wafer manufacturing [65]. However, most SiC manufacturers are still doing the transition to 150 mm epitaxial wafer. The incoming generation of 200 mm diameter wafers coupled with a decrease in defects density forecasts that the cost of SiC MOSFETs will drop to become competitive with Si devices. However, the transition will be slow, as it happened with the previous transition from 100 mm to 150 mm wafers.

Consequently, market analysts common conclusion is that SiC technology value for power electronics applications will grow from $250 M to $1.4 billion in 2022, and it will accelerate raising to more than $10 billion before 2027 [66].

However, SiC must not only solve the high device cost and lack of maturity but, it has also to face technical challenges at all levels, including issues related to device performance, module integration, packaging, and the need to define qualification standards. One of the most important challenges that several studies are currently looking for a solution to is the carbon cluster formation in the SiC/SiO_2 interface [67]. Some studies have shown that the formation of carbon clusters in SiC-MOSFETs can cause a reduction in field-effect mobility of up to 100 $cm^2V^{-1}s^{-1}$ [68].

Summarizing, SiC semiconductor technology has advanced enormously from the last three decades but, however, considerable efforts are still needed to achieve the full potential of this material. SiC has challenges to deal: performance, reliability, cost, manufacturing process, filter and thermal designs, system layouts, etc. Therefore, the market penetration of SiC technology is increasing but it is still limited to specific applications.

3.1.2. SiC Advantages and Disadvantages

Following, SiC main advantages are summarized:

- High efficiency: SiC semiconductors have lower switching power losses than Si devices. This feature allows getting efficiencies above 99.5%. This meant up to 75% energy losses reduction [69].
- Higher switching frequency operation: SiC allows to work at higher switching frequencies of operation than Si without increasing significantly power losses. Thus, units based on SiC reduce the size of passive components, decreasing the device size, weight and cost.
- High level of output voltage: due to their higher electric breakdown field, SiC-based devices can reach higher operation voltages.
- Withstanding high temperatures: SiC-based devices can handle up to 600 °C, while Si-based devices can operate at maximum temperatures of 175 °C.
- Higher thermal conductivity: SiC has 4.5 W/cm·K, therefore it has three times more thermal conductivity than Si. Besides, SiC power devices have a lower junction-to-case thermal resistance (0.02 K/W for SiC and 0.06 K/W for Si). It implies lower cooling requirements and, therefore, smaller and cheaper cooling systems.
- Higher reliability: forward and reverse characteristics of SiC power devices do not vary significantly with temperature and time.
- Component reduction: when replacing Si devices or by reducing active and passive components in both size and number [70].
- Short-circuit withstanding: traditional Si devices have short-circuit withstand times greater than 10 µs, SiC MOSFETs have a typical short circuit withstand time on the

order of 1 µs, but recent research reports SiC MOSFETs at levels higher than 3.3 kV having developed enhanced short circuit capability [71]. Thus, it benefits voltage source base high power conversion systems, giving reliability to SiC MOSFETs by demonstrating being capable of sustaining short-circuit currents up to 13 µs [52].

Many of these advantages are not yet mature and require further development; likewise, SiC technology have some challenges, such as those presented below, that need research and development to accelerate SiC adoption.

- High cost: reducing the cost of SiC is a key to accelerate its adoption. Currently SiC MOSFET plus SiC diode is significantly higher than Si IGBT plus Si diode [72].
- Packaging: this is the primary constraint for the performance of SiC. The advantages of SiC are not being realized when devices are embedded in traditional packages designed for switching at lower frequencies; they must be designed with a symmetrical layout to minimize loop inductance and be more thermally efficient. In addition, the carbon cluster issue must be faced.
- Availability: the availability of SiC devices is limited, there exist only a few wafer suppliers. Despite the investments in expanding production capacity, there is a short SiC wafer supply situation.
- Gate drivers: high-performance gate drivers are required to manage the switching speed of a SiC device. Fast fault response time is needed to protect SiC devices against short-circuits.

3.2. GaN

3.2.1. GaN Technology Evolution and Future Trends

GaN has been used in light-emitting diodes (LEDs) and radio devices for decades and, since 2000, has become an interesting option in power applications. GaN bandgap is slightly higher than SiC, and both have a similar breakdown voltage, although its most attractive feature is its high electron mobility which allows high switching frequencies. On the contrary, GaN low thermal conductivity, similar as Si, can be a significant problem in high power applications [55]. GaN devices are limited to 650 V, 150 A in the portfolio of most manufacturers [57,58] but, nevertheless, some studies have shown the development of 1200 V devices [73]. Moreover, some studies expect that GaN on Si semiconductors will achieve price parity with Si devices at the same performance shortly [61,62].

All these characteristics make GaN a promising alternative to substitute Si devices for high-frequency applications, for instance in resonant converters [74]. However, manufacturing of practical devices of this material is challenging. Si and SiC devices use vertical structures; vertical structures for GaN could take the most significant advantage of the superior material properties. Nevertheless, there is a limitation for vertical GaN device manufacturing due to the lack of availability of high quality and low-cost GaN wafers. Accordingly, commercial GaN devices are lateral heterojunction field effect transistors, known as High Electron Mobility Transistors (HEMTs).

Manufacturing of GaN wafers is made through epitaxial growth on GaN substrates. However, due to it is an expensive technique, only a small wafer diameter can be reached by this technique. Heteroepitaxial growth of GaN in different material substrates such as Si (GaN on Si), SiC (GaN on SiC) and sapphire have been carried out [75], choosing Si as the most attractive for commercial applications due to the large-size scalability of inexpensive Si substrates.

Following, a more detailed description of the different power devices developed with GaN is shown.

- Mature: GaN technology is mature in optoelectronics and radio frequency applications (low voltage). On the other hand, GaN-based devices for medium to high voltage power conversion applications are expected to grow significantly in the near future. Therefore, they will probably be ready for an upper scale deployment in the next decade.

- Market: with less than five years in the market, lateral enhanced mode GaN and cascade 600–650 V GaN HEMT devices are available from a dozen of suppliers, and the most recent 900 V GaN HEMT devices and 1200 V/180 A GaN modules are available from a couple of suppliers too.
- Prototype: three suppliers have announced prototypes of 1.2 kV GaN HEMT devices and are expected to be commercially shortly.
- Research: research on GaN power devices has grown exponentially since 2010 and numerous vertical devices as 1.2 kV GaN Schottky blocking diode, 3.7 kV GaN pn-diode [76], 1.5 kV JFET diodes, and GaN transistors with breaking voltage up to 2 kV have been demonstrated. Lateral devices as GaN transistors up to 3.5 kV, Polarization Super Junction (PSJ) GaN FET beyond 3 kV, flexible GaN chips [77], and GaN nanowire metal-semiconductor field-effect transistors (MESFETs) have also been reported experimentally.

Due to the particular characteristics of GaN some issues require efforts in R&D to exploit the full potential of this technology. In the case of achieving high switching frequencies, integration is critical. Active devices as transistors, flyback diodes, rectifiers or drivers can be monolithically integrated to reduce parasitic elements, in order to reach high-performance converters with a reduction over the system cost [78]. Other important aspects to take into account are the implications of the higher power density. GaN HFET area-specific on-resistances are two orders of magnitude smaller than Si-based lateral devices [76]. This considerable reduction in size of GaN devices requires to optimize process and packaging to improve thermal dissipation. Moreover, the worse threshold voltage stability of D-mode metal-insulator-semiconductor (MIS) HEMTs and E-mode MIS-FETs is one of the most important challenges [79], being one of the most discussed issues in the literature [80–86].

GaN-based power devices have similar prices than SiC-based devices for the same characteristics [87,88]. A lower price in GaN devices is possible because they can be developed on Si substrates that are readily available and incur fewer cost than SiC development process. Hence, the cost of GaN power devices is no longer a key driver in system cost. Therefore, efforts must be focus on volume production and research to achieve manufacturing maturity and reliability [89]. Meanwhile, analysts forecast a parity in price per ampere for GaN on Si based devices comparing with Si-based devices to be achieved shortly.

Nowadays, GaN on Si technology is the industry standard for wafer diameters up to 150 mm (6″). Low-voltage applications of GaN lateral devices up to 650 V based on 150 mm wafer are in the market since 2014, and recently 900 V GaN devices have been released by TransPhorm-Fujitsu [90]. After enabling 200 mm GaN on Si wafer different suppliers as Exagan, VisIC and Powdec have announced 1200 V lateral GaN devices shortly [91]. Moreover, Imec recently announced the development of high-performance enhancement-mode p-GaN power devices on 200 mm (8″) QST® substrates. This fact will enable commercial vertical GaN power devices suitable for high voltage and high current applications (1200 V and beyond) [92].

As mentioned above, breakdown strength and electron mobility allow designing smaller devices. Additionally, the high-frequency operation and lower switching losses allow reduction in size and number of magnetic and passive components. Initially, commercially available GaN-based PV inverters (2013) reduced size in 40% respect the Si-based inverters [93]. Futhermore, these inverters did not need a cooling fan and had a considerable reduction in weight too. A few years later, the Little Box Challenge (2016) presented a 2 kW PV inverter with a power density of 8.8 W/l [53], this single phase GaN-based inverter was more than 10 times smaller in comparison with commercial Si inverters. Currently, a lot of research is being carried out in order to develop more power density GaN-based inverters at commercial levels.

Bidirectional converters for high power and EES will be crucial for the future grid and, as well as SiC, the adoption of GaN in power electronics enables the integration of DER into the grid. High frequencies GaN-based grid-tied inverters generate less grid distortion, allowing applications that require connecting many inverters to the same grid. A prototype of three phases 8 kW inverter have been presented by Siemens and Texas Instruments with efficiencies of 99% [94], and ensuring easy manufacturing, while reducing cost and system size.

GaN and SiC offer a similar price for low-power semiconductor devices. Given its higher electron mobility, GaN have a place in small high-frequency products as on-board EV chargers or micro PV inverters. However, due to its lower power capability and thermal conductivity SiC will be preferable in larger power products [95,96]. Therefore, a rising demand for GaN high-frequency devices is expected. However, lack of availability of GaN material restrains the growth of the GaN power device market. The global market value for GaN power devices was estimated at 16 million in 2016, and different analysts forecast a significant compound annual growth rate around 49.8% and 79% to reach between $273 and $460 million by 2022 [97,98]. Power supply application will be the segment with more importance (50% of total market), and automotive and PV will sum 25%. of market share.

3.2.2. GaN Advantages and Disadvantages

The basic material properties of GaN offer a number of valuable advantages for power electronics applications, as shown below:

- High dielectric strength: this allows smaller devices for a given breakdown voltage requirement.
- High operating temperature: GaN has a theoretical maximum operating junction temperature above 400 °C.
- High switching frequency: higher electron mobility of GaN allows higher operation frequency than both Si and SiC. Some latest-generation GaN-based devices can operate in the hundreds of MHz, allowing downsize magnetic and passive components.
- High current density: due to higher carrier density and increased electron mobility, higher currents are possible with very low parasitic capacitance.
- Lower on resistance: due to its low on-resistance, lower conductance losses are achieved so that, GaN-based devices have efficiencies up to 99%.

Even though GaN has superior characteristics than Si, this technology is under development and has some challenges that must to be addressed. Below, some of them are detailed:

- Poor thermal conductivity: GaN has poor thermal conductivity compared to SiC and other WBG.
- Parasitic, packaging, controllability: due to tighter gate voltage margins compared to Si and SiC devices, the influence of parasitic inductances can lead to the device destruction and leg short circuits [77].
- Electromagnetic Interference (EMI): due to high switching speed, GaN-based devices enable higher power densities but require additional EMI filters.
- Reliability: long-term reliability qualification standards of these devices have been developed only recently.

3.3. Diamond

3.3.1. Diamond Technology Evolution and Future Trends

Diamond is well known for being an exceptional material. Actually, it has superior physical properties respect to all WBG materials. Due to its high breakdown field, high thermal conductivity, high electron mobility and low dielectric constant; diamond-based power devices are expected to considerably reduce both switching and conduction losses for high power and high-temperature applications. Initial research about the use of diamond for switching applications began in the 1980s, using natural diamond crystals, but obtaining pour results due to geometrical problems. Synthetized electronic grade single crystals became commercially available after the establishment of epitaxial growth by chemical vapor deposition (CVD) in the 2000s. Since then, there has been an increase in diamond power-device studies. However, diamond devices are still in the research phase, and they are not commercially available yet.

Historically, the practical application of diamond devices has been constrained by the lack of availability of single crystal wafer with large size, dislocation free, and low resistivity. Contrary to the other WBG materials, no significant advances in diamond wafer size have been seen in three decades. However, different approaches have been developed to enable both larger and relatively low defect density (<105 cm^{-2}) substrates [99]. Firstly, high-growth-rate CVD has made possible to prepare 15 mm × 15 mm substrates. Another approach to obtain large area substrates is mosaic wafer fabrication method. By this technique, several plates of approximately 1 cm^2 single crystal diamond are synthetized by combining the high rate homoepitaxial growth of CVD diamond and subsequent a lift-off process using ion implantation [100,101]. Through this technique plates, up to 50 mm have been reached and are commercially available [102,103].

Another significant advance has been efficient doping. Doped diamond layers are generally prepared by gas-phase doping during plasma-enhanced CVD growth on single-crystal diamond substrates. In the past decade, substantial progress has been made in p-type doping with boron, and just in the last few years, n-type doping with phosphorus has been demonstrated at a few laboratories [99].

These two advances, large area substrates and efficient doping, have allowed the development of diamond power devices with better results. For instance, a diamond-based SBD with up to 10 kV of breakdown voltage [104], and a bipolar junction transistor (BJT) with a breakdown voltage of 1 kV [99] and forward current density greater than 500 $\mathrm{A/cm}^2$.

As discussed before, diamond for power conversion technology is in a very early development stage. Therefore, most of the upcoming advances will be to accelerate the development of diamond for power electronics, in order to advance in the Technology Readiness Levels (TRL) scale. Hence, most of the actions will be aimed to overcome several challenges for the practical application of diamond devices.

Despite the improvement achieved in diamond devices performance due to homoepitaxial growth and doping control techniques, the lack of device fabrication techniques still limits a full technology development. Diamond devices need new processing techniques to form edge-termination structures to take advantage of all semiconductor properties; especially selectively doped substrates using ion implantation or selective area growth, together with metal-oxide-semiconductor (MOS) structures. Additionally, a deeper understanding of interface and defect structures are necessary in order to improve both, device fabrication and performance [105]. To operate at high-temperature, high-voltage and high-frequency, packing technology must advance to allow full diamond potential exploitation. As well as the challenges facing SiC and GaN devices, packaging technology with the suitable material, thermal, and electrical properties must be developed, but with even more stringent requirements for temperature and electrical performance [99].

There is a joint effort of governments and companies to promote the device research at companies and universities. For example, ambitious projects as GreenDiamond has the objective to develop the first high power electronics device (6.5 kV, 10 kV and then 20 kV MOSFETs) based on diamond and build up the first power converter using diamond devices [103]. The project has tried to use 2 inches diamond plates and packing material to support 300 °C [103]. Other projects with similar objectives are under progress too [106,107].

The main target application for diamond devices is high voltage and high power applications. These applications require vertical device structure and a corresponding diamond wafer to achieve a device over 100 A. In order to reach these high voltages and high currents levels, a 6-inch wafer is a target. However, according to research roadmap for diamond technology, it will not be available until 2030 [108].

In conclusion, the diamond power market is in the emerging stage and the cost of diamond materials is exceptionally high compared with its counterparts. The adoption of diamond for power devices manufacturing has been limited due to the high cost of diamond wafers. As a result, low demand is expected in the short term and no investment in fabrication facilities is expected. There is a growing challenge regarding high investment cost principally in synthetic diamond production and the process equipment to support its production [109].

3.3.2. Diamond Advantages and Disadvantages

Diamond intrinsic properties offer an alternative to current semiconductors with more potential benefits for high power applications. Some of the most important characteristics of diamond as a power semiconductor are presented below.

- High switching frequency: diamond-based devices may have faster switching and lower losses compared with the other technologies as has been partially demonstrated by SBD [110].
- High-temperature operation: diamond has the highest thermal conductivity known for any semiconductor material (five times better than copper, 15 times better than Si) and low thermal expansion. This property allows diamond devices more heat to dissipated, operate at higher junction temperatures than other technologies enabling applications without cooling systems. Thereby, a diamond-based diode has been demonstrated to operate at 1000 °C [111].
- Radiation hardness: thanks to the high atomic displacement energy (42 eV/atom) and low atomic number, diamond can demonstrate a higher stability to radiation than other solid state materials [112].
- High output power: diamond has higher electric breakdown field than both SiC and GaN materials. Therefore, diamond has the ability to isolate massive voltages with a small fraction of the material required compared to current technologies. For example, the amount of diamond needed to isolate 10 kV is 50 times lower than the required for Si [113]. theoretically, a single diamond power device could switch power at voltages approaching 50 kV [114].
- Composition: diamond is a solid form of carbon that can be synthesized by CVD process into a single crystal to be used for electronic devices; hence it is free from natural resources depletion problem.

In spite of all the advantages of using diamond for power electronics, some disadvantages have to be overcome before the technology could achieve a commercial level. Following this, the main important issues are pointed out:

- Maturity: using diamond for power electronics is still in the research and development phase. Further research about the designing and processing stage is needed to obtain diamond's full potential.
- Cost and availability: due to its incipient development, processing problems have not been solved yet. There is not a reliable technique to produce the desirable wafer size and diamond-based devices in mass at affordable commercial costs.

3.4. *Ga_2O_3*

3.4.1. Ga_2O_3 Technology Evolution and Future Trends

Gallium (III) oxide, commonly called gallium oxide, has emerged as a new semiconductor material for power electronics devices. Whereas Ga_2O_3 has been reported since 1952 [115] and was used as an insulator on GaAs wafers during the 1970s [116], it has been only in the last decade when research has been intensified in Ga_2O_3 as a WBG semiconductor. Ga_2O_3 has five known polymorphs α, β, γ, δ and ϵ. Its most stable beta crystal structure (β-Ga_2O_3) is attracting the interest for power electronics devices. It has a larger band gap (4.9 eV) and expected breakdown field (8 MV/cm) than both SiC and GaN. Thanks to its excellent characteristics, Ga_2O_3 is suitable for high voltage and high power switching applications, and potentially offers better performance than Si, SiC and GaN.

β-Ga_2O_3 has the possibility to produce large native substrate areas by standard melt growth techniques. The melt-growth is a low-energy-consumption, low-cost method of making large substrates. The most common methods of crystal growth for Ga_2O_3 are

Verneuil Method, Floating Zone (FZ) Method, Flux Method, Czochralski (CZ) Method, Edge-defined Film-fed Growth (EFG) Method and CVD [116]. EFG and CZ are commercial methods, offering large crystal sizes of 2-inch diameter. Additionally, the FZ method may be used commercially for growing large crystals. With the EFG method, Tamura company has demonstrated 4- and 6-inch substrates [117]. Moreover, for β-Ga_2O_3 thin film growth, many of the techniques developed for SiC and GaN epitaxy can be applied. Some of these techniques are molecular beam epitaxy (MBE), halide vapor phase epitaxy (HVPE), metal-organic chemical vapor deposition (MOCVD), and mist chemical vapor deposition (MIST CVD). An additional growth technique is a hybrid of MOCVD and HVPE (HOVPE). Unfortunately, these technologies do no reach to produce 20 µ m or greater thick films at a commercially viable rate [118].

Nevertheless, a recent breakthrough was presented in 2018 by FLOSFIA in Japan. FLOSFIA use the corundum structure α-Ga_2O_3, which has superior properties respect to β-Ga_2O_3. In addition, FLOSFIA applies the p-type Ir_2O_3 compatibility with n-type Ga_2O_3 to demonstrate normally-off MOSFET. The device is made of a novel p-type corundum semiconductor which works as an inversion layer [119].

Besides the high intensity of Ga_2O_3 research as WBG semiconductor in the last decade, further developments are needed about high-quality bulk crystal growth, epitaxial thin film growth, and device process technologies; as well as a better understanding of Ga_2O_3 properties: p-type conductivity, dopants and defects such as oxygen vacancies and thin films properties. Nowadays, one of the most challenging points is the absence of p-type dopants, where researchers have demonstrated several effective solutions [120]. In addition, thermal management approaches for power devices will be another challenge to enable the adoption of Ga_2O_3. Other areas of research with some importance will be the radiation damage effect on Ga_2O_3 and related heterostructures as well as process patterning and contacting conditions [121].

According to the exposed above, Ga_2O_3 can provide superior performance in high voltage applications than other semiconductors in the market. Due to its low cost and the possibility of mass production, Ga_2O_3 is a firm candidate to substitute both Si, SiC and GaN semiconductors in current and future applications. In spite of that, due to its low grade of maturity, Ga_2O_3 technology adoption is not expected for several years yet. According to estimations of automotive council UK, it could provide a step change in performance compared to SiC and GaN for the automotive industry in the late 2020s [122].

Given the availability of high quality and large size substrates, the development of electronics devices based on Ga_2O_3 has been facilitated, and proof of concept of different Ga_2O_3 power devices have been demonstrated. For instance, a 8.03 kV β-Ga_2O_3 MOSFET has been recently demonstrated [123]. Furthermore, regardless of the early stage of Ga_2O_3 development, Denso Corporation announced the adoption of α-Ga_2O_3 based semiconductors (provided by FLOSFIA) for its EV power control units targeting commercial production [124], that presumably will take place in the following years.

3.4.2. Ga_2O_3 Advantages and Disadvantages

Ga_2O_3 has been a material of eager interest over the last years due to its exceptional potential as a semiconductor. Following, some of the benefits of using Ga_2O_3 are pointed out:

- Large breakdown electric field: its breakdown field, which exceed the double of GaN and SiC breakdown electric fields, allows us to expect higher breaking voltage than SiC and GaN-based devices while maintaining acceptable low on-resistance. Researchers have demonstrated critical field strength of 3.80 MV/cm from a β-Ga_2O_3-based MOSFETs, which is beyond the theoretical limits of SiC and GaN [116].
- Thermal stability: the monoclinic structure of β-Ga_2O_3 has concentrated almost all research efforts because it is the most stable with a melting point of 1740 °C [125]. Recently, developments have used the semi-stable phase corundum-structured α-Ga_2O_3. Using enhancement thermal stability process on sapphire substrates, the α-Ga_2O_3 film can grow at a temperature as high as 800 °C [126].

- Large area single crystal substrates: the good material workability of Ga_2O_3 and the availability of melt-grown allow the fabrication of a large single crystal.
- Low on-resistance: apart from diamond, Ga_2O_3 exceed others semiconductors on-resistance characteristics. An SBD has been reported with an outstanding specific on-resistance of 0.1 mΩ cm^2 [127]. This represents 86% less than any SBD SiC-based devices available on the market.
- Cost: single crystal bulk could be grown by using the same melt growth methods than the ones used for sapphire. Consequently, substrates of a large area in a single crystal are available at low cost; this allows the development of high-quality epitaxial layer.

Despite all the properties that made Ga_2O_3 an excellent semiconductor material, there are three main drawbacks of Ga_2O_3.

- Low thermal conductivity: with 0.13–0.21 W/cmK Ga_2O_3 has the lowest thermal conductivity of the WBG materials. This will be one of the most critical challenges to develop Ga_2O_3 power devices.
- Lack of a p-type dopant: Ga_2O_3-based devices are n-type unipolar, limiting the application of β-Ga_2O_3 to unipolar Schottky and heterojunction devices. In order to achieve an optimal performance, the device requires controlled n-type and p-type doping of β-Ga_2O_3 epitaxial layers. Si, Sn, and Ge [118,128] have been demonstrated to be effective n-type dopant materials for Ga_2O_3. However, due to the nature of metal-oxides, p-doping is not impossible but challenging. Some works present evidence of p-type conduction [129] and the possibility of doping Ga_2O_3 by substituting Ga atoms with Zn [130] or by N substituting O [131] atom or both, nevertheless, a considerable research effort is needed before the Ga_2O_3 potential could be exploited.
- Early-stage development: Ga_2O_3 technology is a far less mature technology than SiC and GaN, and it is evolving in a small number of laboratories.

3.5. Other WBG Materials

While GaN, SiC, Ga_2O_3, and diamond have attracted most of the attention in the recent years, other WBG materials such as AlN, BN and ZnO have had relatively less development but, nevertheless, are worthy to be discussed briefly.

3.5.1. AlN

AlN has been used for ceramic packages since the 1960s, but not until the 1980s its potential for electronic applications was realized. AlN stands out with a wider band gap than diamond (6.2 eV). Additionally, its high hardness value, thermal stability at high temperature, high thermal conductivity (340 W/m K) and large critical electric field (12 MV/cm) are attractive for high power electronics applications [132]. However, due to the challenges in material growth, high processing cost and device fabrication, very limited work has been reported on AlN electronics.

Recently, researchers from Arizona State University achieved high-quality AlN epilayers on sapphire substrates allowing to create a 1 kV AlN SBD [133]. This work presents a cost-effective route to AlN-based SBD. Another innovation in the early development of AlN-substrates for power devices is carried out by projects as InRel with the goal to the manufacturing of AlN devices with even higher breakdown voltage (>2.5 kV) and proven reliability [134].

The AlGaN alloy has exceptional properties as semiconductor combining advantages of GaN and AlN, such as high bandgap (3.4 to ∼6.0 eV), high breakdown fields (>10 MV/cm for AlN), high electron mobility (up to 1000 cm^2/(V·s)), high saturation velocities (>107 cm/s), and relative ease at being doped n-type with Si. Besides, having the same crystal structure of InGaN, could take advantage of knowledge and manufacturing infrastructure associated with InGaN LEDs [99].

However, the AlGaN development faces challenges such as the ability to be doped controllably and selectively, the availability of single-crystal substrates with the necessary quality for epitaxial growth and the knowledge to control heteroepitaxial growth [135].

Recent research at Sandia National Laboratories has presented results about devices based in AlGaN alloys. A 30% aluminium mole fraction AlGaN alloy was used over sapphire substrates to develop Quasi-vertical PIN diodes. The highest measured breakdown voltage recorded was 1627 V. These diodes present better performance in comparison with vertical GaN-based diodes. Likewise, an 810 V lateral AlGaN HEMT was demonstrated based in Al-rich epilayers, 85 and 70% of aluminium alloys were used over sapphire substrates [135]. After demonstrating a 2-dimensional electron gas in an $Al_{0.85}Ga_{0.15}N/Al_{0.70}Ga_{0.30}N$ (barrier/channel) heterostructure, current efforts are focus to achieve a normally-off 5 kV, 5 m $\Omega\cdot$ cm^2 device [136].

AlGaN, with Al composition in the range of 70–100%, could be a viable material for next-generation of power electronics, in the near future is expected to be used in applications where both extremely high power and a constrained volume are required, and cost may not be a primary constraint.

3.5.2. BN

BN is known to be the second hardness material and has low chemical reactivity like the diamond. In its cubic structure (c-BN) BN is isoelectronic with diamond. n-type and p-type doping BN can be manufactured with Si and *Be* respectively. c-BN has advantageous properties such as a bandgap of 6.4 eV, and current research forecasts a breakdown field greater than 15 MV/cm. Finally, it has the second-highest thermal conductivity of all materials (theoretically $\sim$2145 W/(m·K) for isotopically pure material) [99].

c-BN has even better properties than the diamond to be used for high power electronics. However, the development of BN technology faces enormous challenges like growing process of cubic BN, strain, growth temperature, adhesion to the substrate, and crystal quality in the c-BN films. Due to these challenges, progress toward realizing device technologies has been very slow up to date [99].

3.5.3. ZnO

The fundamental semiconductor properties of ZnO were extensive study during the late 1950s and the 1960s, including the study of its energy band structure, band gaps, the electrical transport properties of the intrinsic (undoped) material, and others. However, the impossibility of p-type doping and the lack of large, bulk single crystals of ZnO hampered the progress in the development of ZnO-based electronic devices [137].

Nowadays, ZnO is being used as an electronic material in photonics, optoelectronics, varistors, transparent power electronics, surface acoustic wave devices, piezoelectric transducers, ultra-violet (UV) light emitters, sensors, and solar cells [138]. Nevertheless, ZnO properties such as wide band gap (3.3 eV), high melting point (1975 °C), low thermal expansion, and high electron mobility (2000 cm^2/(Vs)) [137] give ZnO the advantages of high breakdown voltage, ability to sustain large electrical fields, lower electronics noise, high temperature and high-power operation.

Some recent results on the steady-state and transient electron transport within ZnO suggest that this material, having a higher peak and saturation electron drift velocities than SiC and GaN, may also be considered as an alternative material to SiC and GaN for high-power and high-frequency field effect transistors [139].

4. Discussion

In the field of semiconductor materials, a figure of merit is a numerical expression taken as representative of the performance of a given material. As seen above, in power electronics several characteristics, such as breakdown voltage, switching speed or thermal conductivity, can be desired. Consequently, different figures of merit have been used throughout history to evaluate the semiconductor performance of different materials.

Critical breakdown field (E_C) increase has been one of the main objectives in the development of WBG materials in order to reduce the number of components needed in applications whose voltages are higher than those supported by Si. However, is expected that all WBG materials have breakdown voltages higher than typical values in most low voltage applications, in the range of 1200 V to 6500 V [140].

In 1965, Johnson [141] presented a new material figure of merit

$$JFOM = \frac{E_C v_S}{2\pi} \tag{1}$$

which depends on the critical breakdown field (E_C) and the carrier saturation drift velocity (v_S) of the semiconductor. Johnson's Figure of Merit (JFOM) defines the power-frequency product and it is commonly used to determine the frequency capability for a transistor.

In 1972, Keyes [142] derived a figure of merit

$$KFOM = \lambda \left[\frac{c \cdot v_S}{4\pi\epsilon} \right]^{1/2} \tag{2}$$

where λ is the thermal conductivity, c the velocity of light and ϵ the dielectric constant. Keyes' Figure of Merit (KFOM) provides a thermal limitation of the transistors used in semiconductor devices. In this way, the lower KFOM, the higher thermal constraint.

In 1983, Baliga [143] derived his first material figure of merit

$$BFOM = \epsilon \mu E_G^3 \tag{3}$$

where μ is the carrier mobility and E_G is the bandgap of the semiconductor. Baliga's Figure of Merit (BFOM) defines the conduction losses in unipolar devices. BFOM is based upon the assumption that the power losses are dominated by the dissipation due to the current flow through the on-resistance of the power device. Thus this figure of merit does not apply to system operating at high frequencies where switching losses are significant.

In this way, in 1989, Baliga [144] proposed his second figure of merit

$$BHFFOM = \mu E_C^2 V_G^{1/2} V_B^{3/2} \tag{4}$$

Here, V_G and V_B are the gate drive voltage and the breakdown voltage respectively. These parameters are related to the actual semiconductor device which does not depend on the material itself. In this way, the Baliga's High-Frequency Figure of Merit (BHFFOM) cannot be used to compare different materials but for semiconductor devices.

In 2004 Huang [145] presented three new figures of merit for unidirectional devices

$$HMFOM = E_C \sqrt{\mu} \tag{5}$$

$$HCAFOM = \epsilon \sqrt{\mu} E_C^2 \tag{6}$$

$$HTFOM = \frac{\lambda}{\epsilon E_C} \tag{7}$$

Huang's Material Figure of Merit (HMFOM) determines the best material for high-frequency applications. This figure of merit can be considered as a simplification of the BHFFOM, where the device dependent term has been omitted. Secondly, the larger Huang's Chip Area Figure of Merit (HCAFOM), the smaller size of the device is required. Finally, similar to KFOM, the Huang's Thermal Figure of Merit (HTFOM) defines the maximum working temperature but pays particular attention to the fact that materials with a higher breakdown voltage can be embedded in smaller devices and, therefore, small packages present a lower dissipation area.

Table 2 summarizes the main physical properties of the semiconductors analyzed in Section 3. With this values, the figures of merit detailed above have been calculated and they are shown in Table 3, normalized respect to Si values.

Table 2. Main physical properties of different semiconductor materials [54,146,147].

	Si	**GaAs**	**4H-SiC**	**2H-GaN**	**β-Ga$_2$O$_3$**	**2H-AlN**	**Diamond**
E_g (eV)	1.12	1.42	3.26	3.49	4.9	6.2	5.0
ϵ_r	11.7	13.1	9.7	9.0	10.0	8.5	5.7
μ_n (cm^2/(V·s))	1480	8400	1000	1200	200	300	2800
E_C (MV/cm)	0.3	0.4	3.18	3.0	8.0	12.0	5.7
v_{sat} (10^7 cm/s)	2.3	4.4	2.2	1.5	2.0	1.7	2.7
λ (W/(cm·K))	1.48	0.52	4.5	1.3	0.27	2.85	20.0
T_{max} (°C)	175	150	600	400	600	250	700

Table 3. Comparison of different semiconductor material figures of merit (normalized against Si).

	Si	**GaAs**	**4H-SiC**	**2H-GaN**	**β-Ga$_2$O$_3$**	**2H-AlN**	**Diamond**
JFOM	1	2.6	10.1	6.5	23.2	29.6	22.3
KFOM	1	0.5	3.3	0.8	0.2	1.9	21.0
BFOM	1	13.0	13.8	18.9	9.7	25.0	82.0
HMFOM	1	3.2	8.7	9.0	9.8	18.0	26.1
HCAFOM	1	4.7	76.6	69.3	223.4	523.3	241.9
HTFOM	1	0.24	0.35	0.11	0.01	0.07	1.46
Availability	5	2	4	2	2	2	1
Manufacturing	5	4	4	3	2	1	1

The criteria used to compare the different WBG materials are presented below:

1. Market viability of the semiconductors in the short-medium term.
2. Ability of the material to withstand the typical voltages required by the most common converters in smart grids.
3. Properties that improve the characteristics of the electronics converters, based on three factors:
    (a) Electrical properties.
    (b) Thermal properties.
    (c) Material availability and manufacturing cost.

Between the materials analyzed above, 2H-AlN and diamond are far from reaching a technical and economic viability that would make them accessible for mass-market applications. Besides, all WBG materials reach a sufficiently high breakdown field and a size small enough for the applications analyzed in this work. Therefore, Figure 3 compares the most important properties for urban and smart grid applications: switching frequency in high power applications (JFOM and HMFOM), thermal properties by means of heat dissipation (KFOM) and maximum operation temperature (T_{max}), and feasibility of these products on the market, availability of raw material and manufacture of high-quality wafers (Availability) and estimated device-production (doping, packaging, etc.) costs (Manufacturing).

From Table 3 and Figure 3 it can be concluded that, although Ga$_2$O$_3$ presents the best electric properties; as to JFOM and HMFOM point out it will have the highest breakdown field and switching speed. In addition, it presents a great maximum temperature, similar to SiC. However, due to its poor thermal behaviour, it could not be feasible to be used in most of the applications studied. These characteristics will force strong requirements in the cooling systems, increasing the cost and size, and losing the benefits that these materials provide. However, due to soft-switching converters strongly reduce power losses in semiconductors, these applications could take advantage of the high breakdown voltage and high switching frequency provided by Ga$_2$O$_3$ without being penalized by the low thermal conductivity feature of this material.

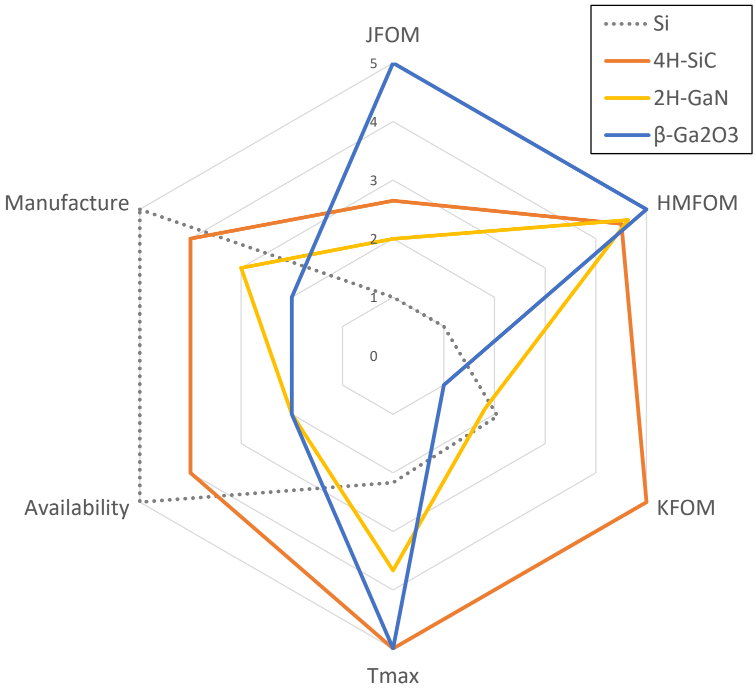

Figure 3. Comparison of the most important properties of semiconductors for smart grid applications. (The values have been scaled by assigning 1 to the worst material and 5 to the best)

Power electronics converters for smart grids require high switching frequencies, but also medium-high powers. Although GaN is known for its high switching frequencies, its ability to handle high currents is relatively low. This explains the apparently low value of its figures of merit compared to other materials. On the other hand, SiC presents a thermal conductivity three times higher than Si and GaN, and 16 times higher than Ga_2O_3. In addition, SiC has much better electrical properties than Si and similar to GaN. These characteristics, together with the fact that this material is abundant and easily extracted from the Earth crust, will make SiC devices suitable for most consumers equipment.

5. Conclusions

The current energy model, based on the combustion of fossil fuels, will inevitably be replaced by a new model where electricity generation is based on clean energies. The policies carried out by governments have led to an increase in the distributed generation of renewable energies in recent years; however, forecasts highlight that this will be even more quick in the coming years due to the maturity reached by these technologies. This will require the massive deployment of power electronics converters. However, the current state of the art of this equipment does not meet some of the desirable requirements in urban environments, thus an improvement in the performance of these devices is required.

Since Si devices are reaching the theoretical limits of this material, a new generation of WBG semiconductor materials have appeared in the last years, surpassing the properties of Si in many applications. Nowadays it is possible to find SiC and GaN devices in the market. Others materials such as Ga_2O_3 are beginning to show its potential, while others like diamond seem more like a fascinating material to study than a commercially viable alternative.

DER designed for urban and smart grids applications have some requirements that differentiate them from other applications. These devices must be compact, inaudible and economically affordable to be deployed in an urban environment. Consequently, it is mandatory to increase the switching frequency above the limits of Si, holding a competitive cost.

Finally, some figures of merit for the different WBG materials have been analyzed in order to compare the physical properties of these materials and find the most suitable semiconductor for the new generation of DER. SiC, GaN and Ga_2O_3 are the only materials that seem viable in the medium term and they have shown completely different trends. Since Ga_2O_3 presents the best electrical properties, its extremely low thermal conductivity makes this material suitable for only a few applications such as soft-switching converters. On the other hand, SiC has more balanced properties. It exceeds the Si electrical properties while having good thermal conductivity, avoiding the need for bulky and expensive heat dissipation systems.

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